Apollo Lessons Learned: Contamination Control for Samples



Judy Allton

Astromaterials Curation

Johnson Space Center

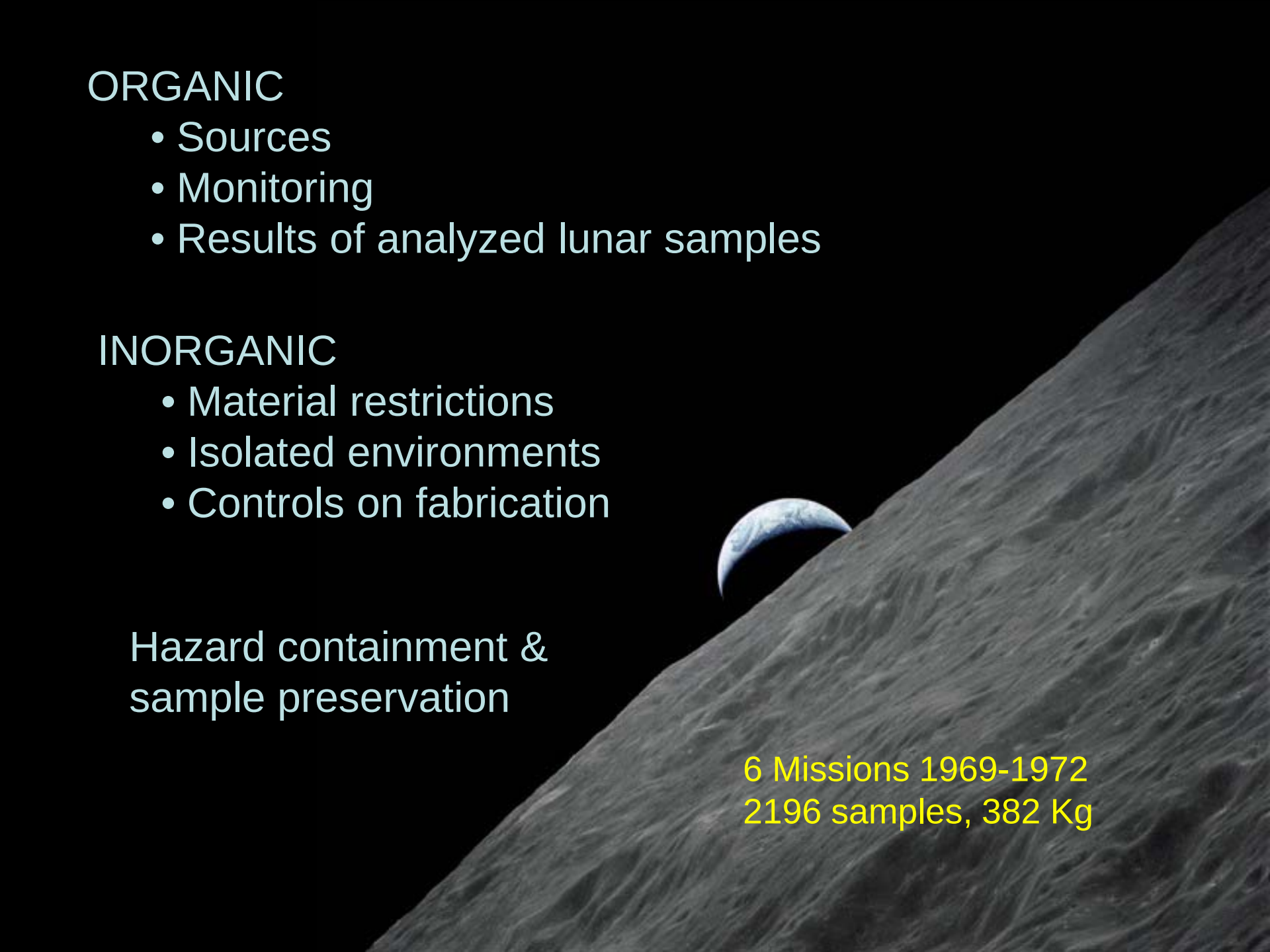
ORGANIC

- Sources
- Monitoring
- Results of analyzed lunar samples

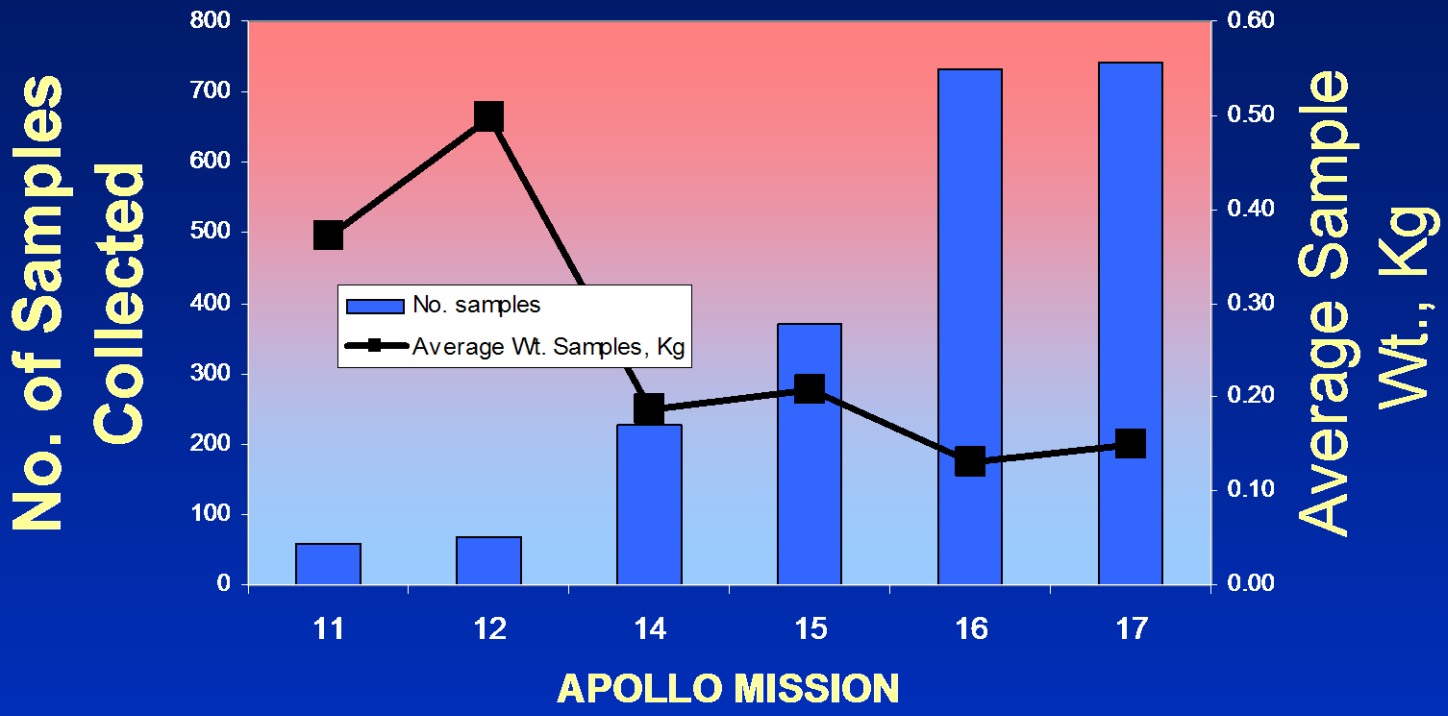
INORGANIC

- Material restrictions
- Isolated environments
- Controls on fabrication

Hazard containment &
sample preservation



6 Missions 1969-1972
2196 samples, 382 Kg



Reference: J. H. Allton (1989) Catalog of Apollo Lunar Surface Geological Sampling
Tools and Containers, JSC-23454
Link:
http://www.lpi.usra.edu/lunar_resources/documents/LunarSampleToolCatalog.pdf

SOURCES OF ORGANIC CONTAMINATION

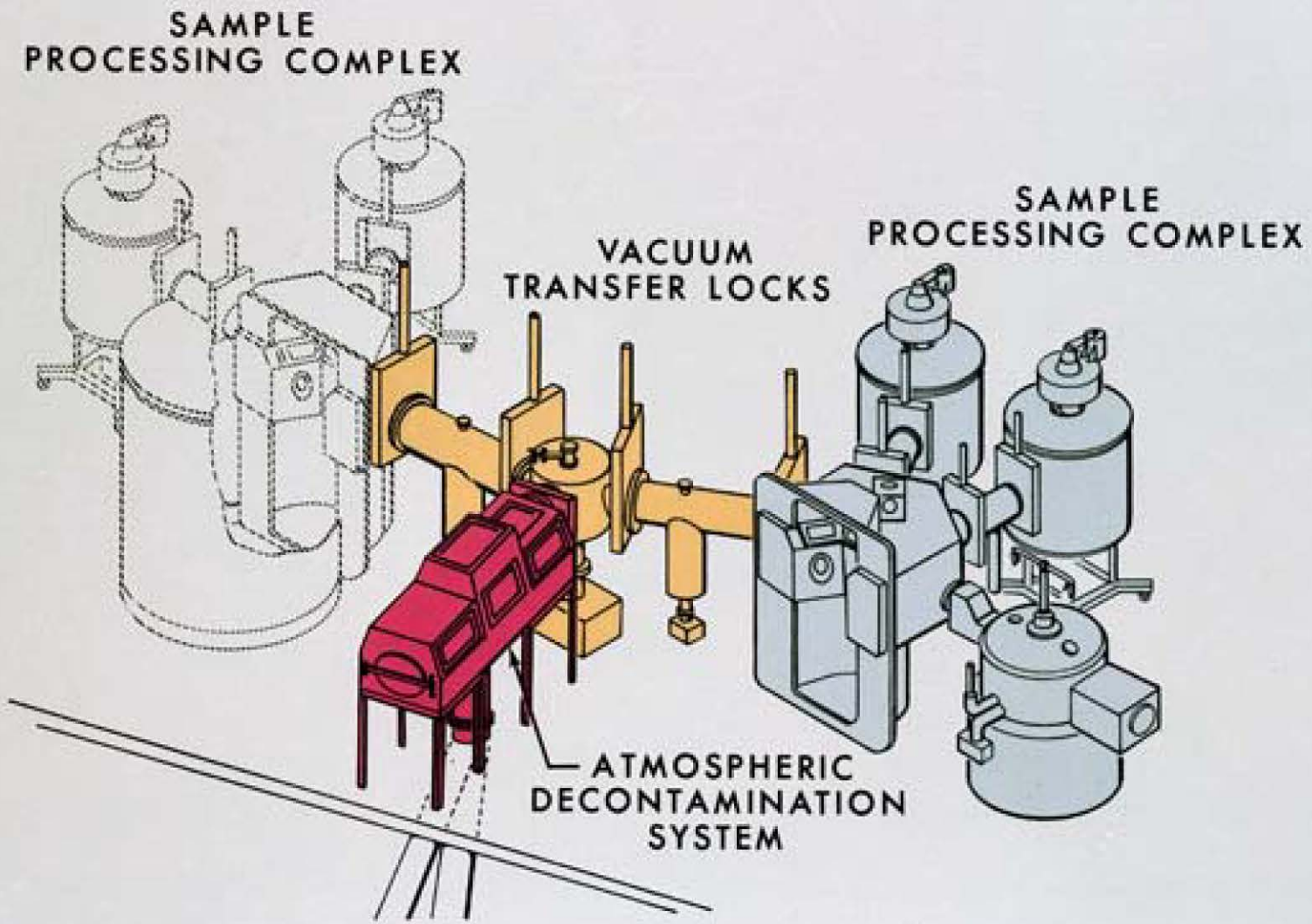
Simoneit & Flory

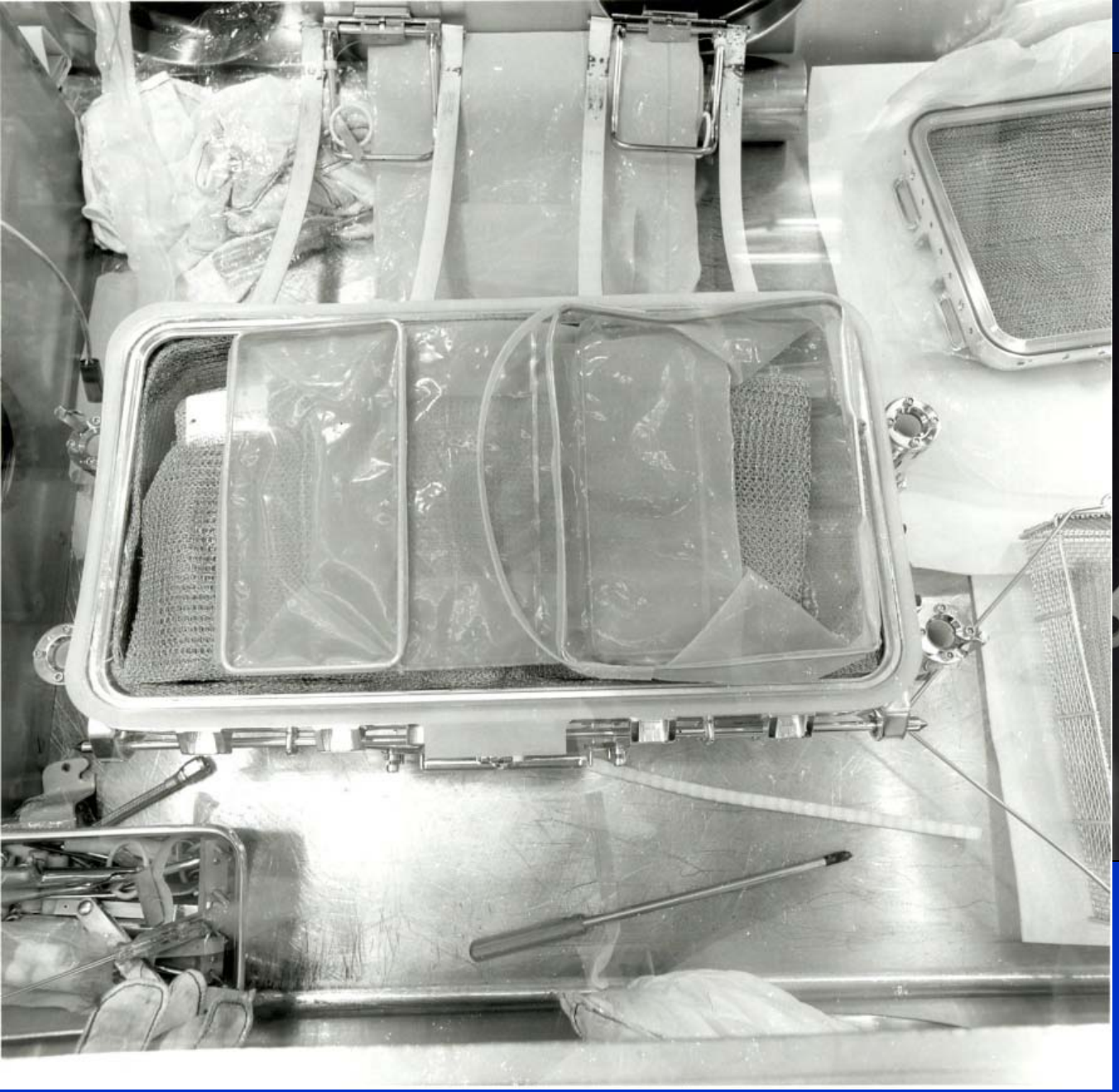
1. Surface contamination of lunar-bound rock box
2. Surface contamination of tools used to acquire samples
3. Exhaust products from descent engine and RCS
4. Lunar Module outgassing
5. Astronaut spacesuit leakage
6. Particulate material abraded from spacesuit, etc. during EVA
7. Venting of Lunar Module fuel and oxidizer tanks, cabin and waste systems
8. Venting of life support backpack
9. Exposure to LRL vacuum and nitrogen gloveboxes
10. Surface contamination of sample processing tools & containers
11. Surface contamination of containers sent to PI s

Reference: B. R. Simoneit and D. A. Flory (1970) Apollo 11, 12 and 13 Organic Contamination Monitoring History, UC Berkeley – also a similar document is available electronically, call Debra Baxter 281-483-7432 Johnson Space Center.

NASA-S-67-694

PRIMARY VACUUM LABORATORY







ROCK BOX PACKED FOR LAUNCH.
Boxes closed in vacuum.

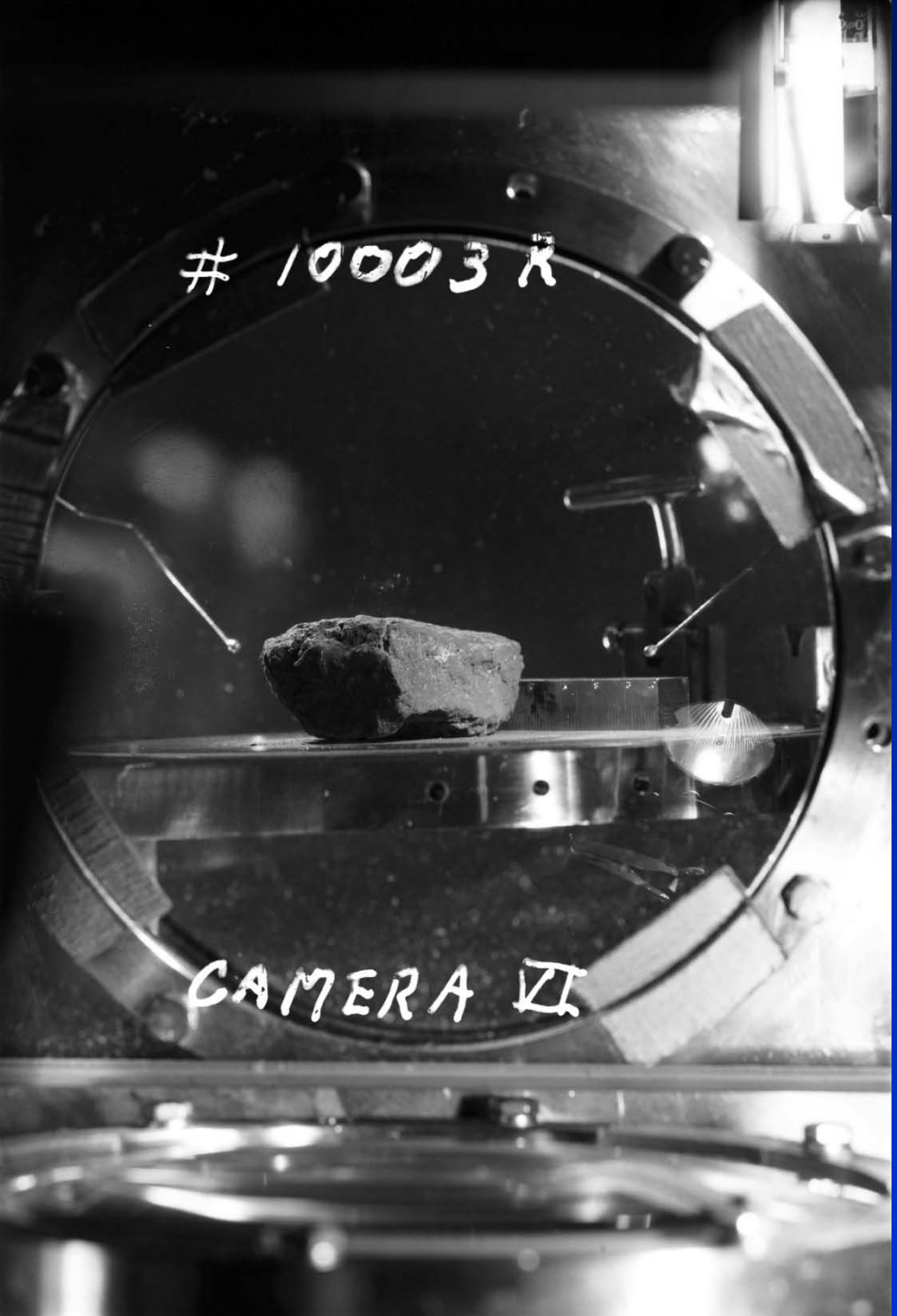


Apollo 11 first box opened in vacuum





Scientists waiting to view rocks in Apollo 11 vacuum glovebox.





Curator Elbert King discussing the sample inside of vacuum glovebox.





Nitrogen-filled Gloveboxes with samples and sieving tools.

Apollo 15 astronauts Dave Scott and Jim Irwin discuss geology with planetary scientists.



Organic monitors:

- Ottawa sand in cabinet
- York mesh in Moon-bound box

1 µg/cm2 inside rock boxes from York mesh for Apollo 11 – IMPROVED for Apollo 12 and later: 10 to 100 ng/cm2

Most frequently measured contamination from tool & cabinet rinsings hydrocarbons, fatty acids, plasticizer for polyethylene bags.

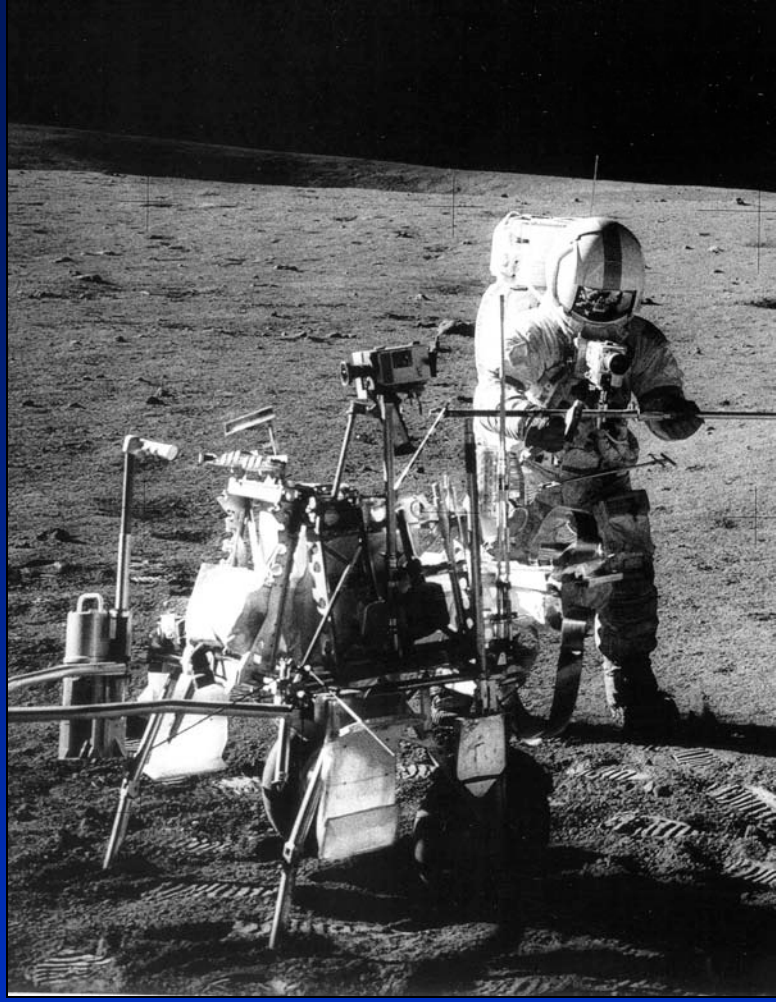
Reference: B. R. Simoneit and D. A. Flory (1970) Apollo 11, 12 and 13 Organic Contamination Monitoring History, UC Berkeley – also a similar document is available electronically, call Debra Baxter 281-483-7432 Johnson Space Center.

Measured Contamination on Lunar Samples

- Apollo 11 samples 1ng/g organics
- Apollo 12 samples 0.1 ng/g
- Range of contamination reported by investigators
- Porphyrin-like entities: trace ng to pg (possible rocket exhaust) **1970**
- Amino acids: 50 ng/g **1970**
- Indigenous lunar carbon about 100 ppm

J. H. Allton (1998) A Brief History of Organic Contamination Monitoring of Lunar Sample Handling, Lunar and Planetary Science XXIX, abstract #1857.
Link: http://www.lpi.usra.edu/meetings/LPSC98/pdf/1857.pdf







Spacesuit leakage & shedding

Vacuum bakeout of rock box added organics



Special Organically Clean Lab at Berkeley

- Two glove boxes in tandem, preceded by vacuum entry chamber, all located in Class 100 room (ISO 5)
- For repackaging for PI allocations, along with Ottowa sand
- Access to low level analytical instruments



ORIGINAL MATERIAL RESTRICTIONS

- Organics – fluorocarbon-based materials for elastomer gaskets, lubricants, sample bags
- Inorganics – sensitive elements prohibited, interfere with science analyses
  - EXAMPLES: Pb, Sr, U, Th, Li, Be, K, Rb
- Nitrogen acceptable cover gas – no noble gases
- Select alloys for tools and containers (7075, 6061 – 316L)

SUBSEQUENT ISSUES

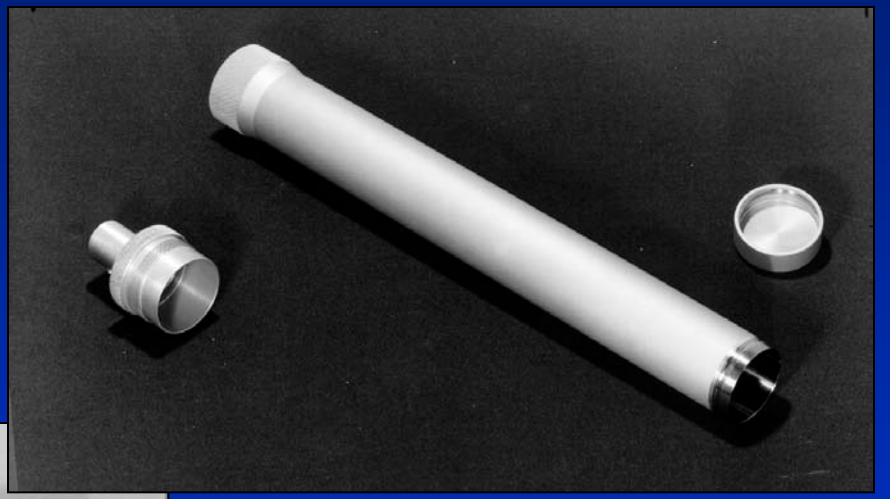
- Pb from surface treatment of core tubes
- Indium from container seals
- Moly sulfide from lubricants
- Xylan – not pure teflon

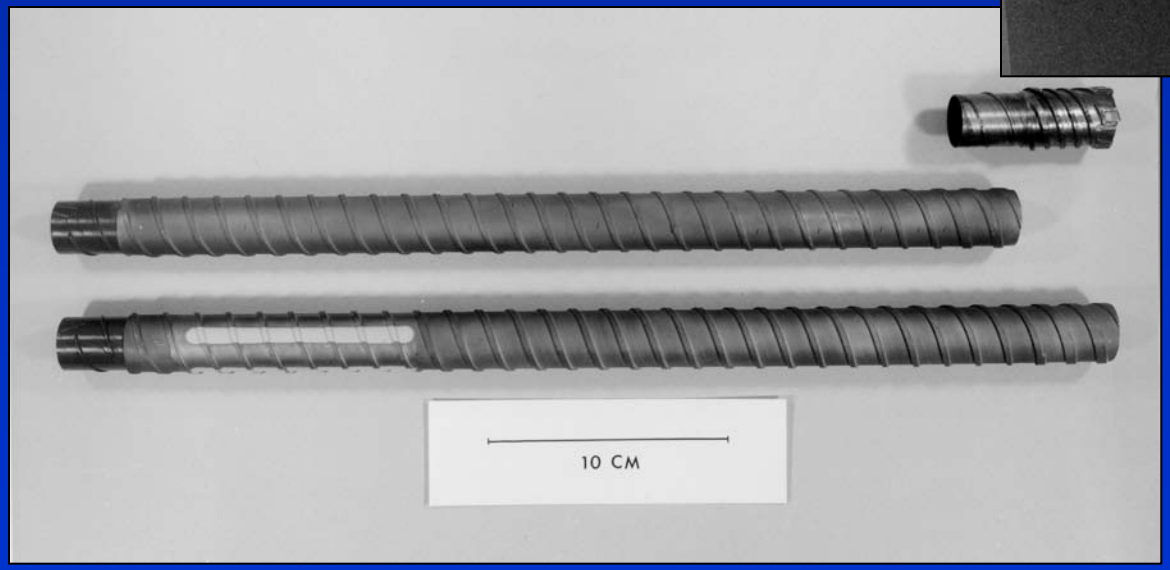

ALSRC 1009



CORE TUBE SURFACE TREATMENT

Tube body titanium alloy Al-4V, threaded joints treated via electrochemical process called Canadizing which impregnated TFE





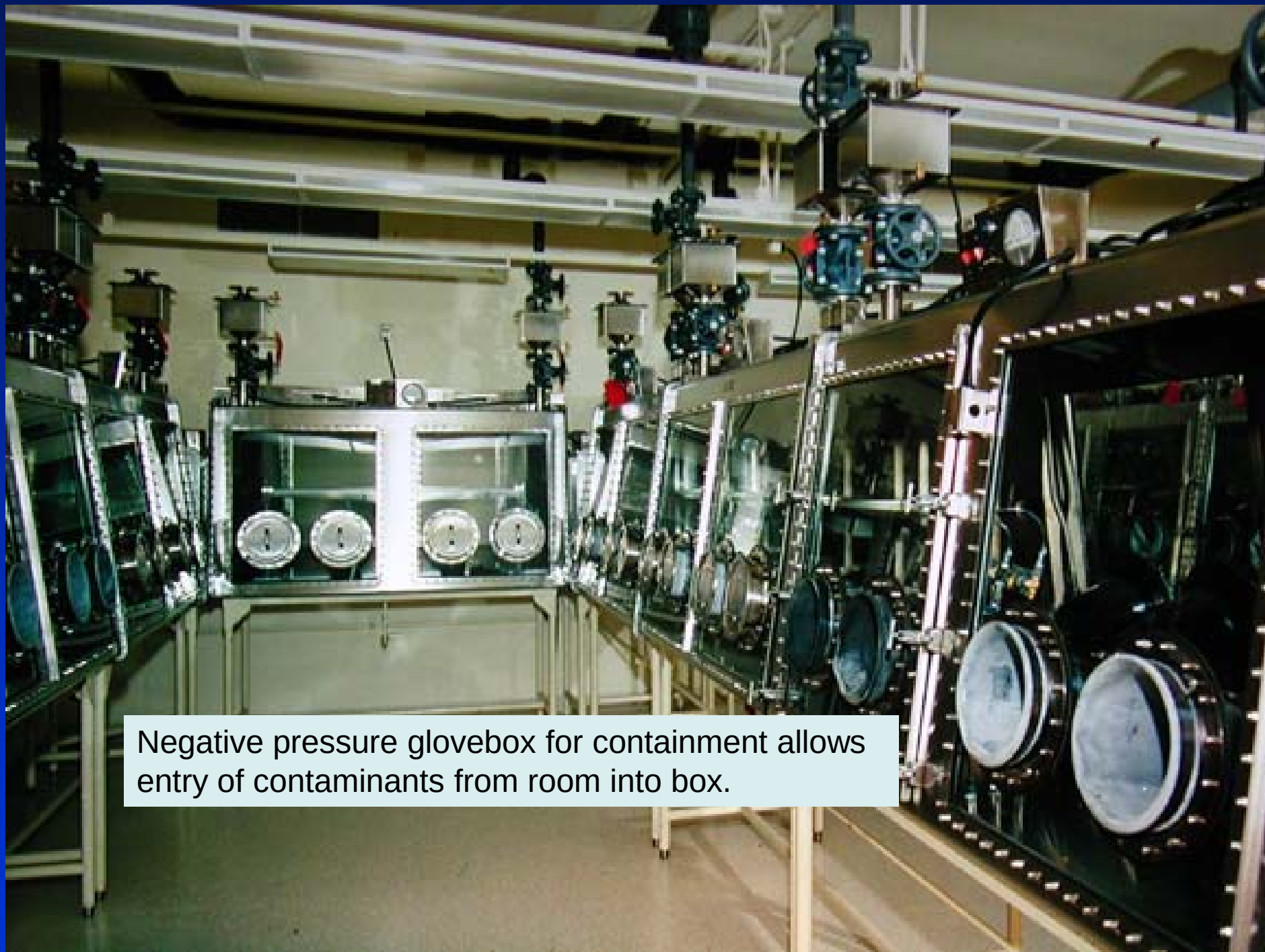
Soil sample within were contaminated with trace amounts of lead (Pb) which interfered with age dating analyses.

GAS-TIGHT CAN



Fig. 86. Gas Analysis Sample Container (GASC). The knife-edge on the can and indium alloy sealing surface on the lid are visible (NASA photo S88-52660 taken from Union Carbide photo no. 121372).

Container used knife edge into soft metal seal. Seal was 90% indium with 10% silver. The metal seal carried trace contaminants with interfered with scientific analyses.



Negative pressure glovebox for containment allows entry of contaminants from room into box.


Biohazard testing resulted in many sources of organic contaminants not found in cleanrooms: animals, sterilants.



Current Lunar Sample Curation: Samples are handled in positive pressure nitrogen-filled gloveboxes.

Contamination Control from the start:

- Mission sampling requirements
- Materials specification
- Sample facility oversight

Sample tools & containers cleanliness – PAY ATTENTION TO DETAILS, especially fabrication techniques and surface finishes

ATLAS Beam Steering Mechanism Lessons Learned

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Abstract

This paper describes the design, testing, and lessons learned during the development of the Advanced Topographic Laser Altimeter System (ATLAS) Beam Steering Mechanism (BSM). The BSM is a 2 degree-of-freedom tip-tilt mechanism for the purpose of pointing a flat mirror to tightly control the co-alignment of the transmitted laser and the receiver telescope of the ATLAS instrument. The high resolution needs of the mission resulted in sub-arcsecond pointing and knowledge requirements, which have been met. Development of the methodology to verify performance required significant effort. The BSM will fly as part of the Ice, Cloud, and Elevation Satellite II Mission (ICESat II), which is scheduled to be launched in 2017. The ICESat II primary mission is to map the earth's surface topography for the determination of seasonal changes of ice sheet thickness and vegetation canopy thickness to establish long-term trends.

Introduction

The primary purpose of this paper is to focus upon "Lessons Learned" that came about during the development of the ATLAS Beam Steering Mechanism (BSM). A secondary purpose is to review the configuration and design features of the BSM, as well as to gain understanding of the reasoning behind some of the design features.

Light, Detection, and Ranging (LiDAR) systems have been used for numerous spaceflight missions. High powered laser pulses fired from the spacecraft are reflected off the earth's surface and back to the spacecraft, where they are detected. Measurement time from firing to detection determines the distance to the surface, and signal characteristics reveal additional properties of the atmosphere and surface. ATLAS maps the topography of our planet to monitor seasonal changes in ice sheet and vegetation canopy thickness, which is very important in gaining understanding of long term trends.

As technology advances, there is always desire to gain better resolution of measurements. ATLAS has the smallest transmitted beam, smallest receiver field of view, and smallest alignment margin among NASA/GSFC space-borne laser altimeters. This resulted in the stringent requirements imposed upon the BSM, which led to further challenges in verifying that those requirements were met.

Design

Overview

An exploded view of the BSM is in Figure 1. Not shown in that figure are both the actuators and the position sensors, which can be seen in the cross sections of Figure 2.

Mirror

The BSM mirror, which reflects a high powered laser, required a dielectric coating to provide very high reflectivity at the wavelength of the laser. A metal mirror would not support a dielectric coating, resulting in lower reflectivity, causing more heat on the mirror, thus degrading figure requirements. For a dielectric coating, a glass substrate is required, coated both front and back of the mirror to cancel stresses.

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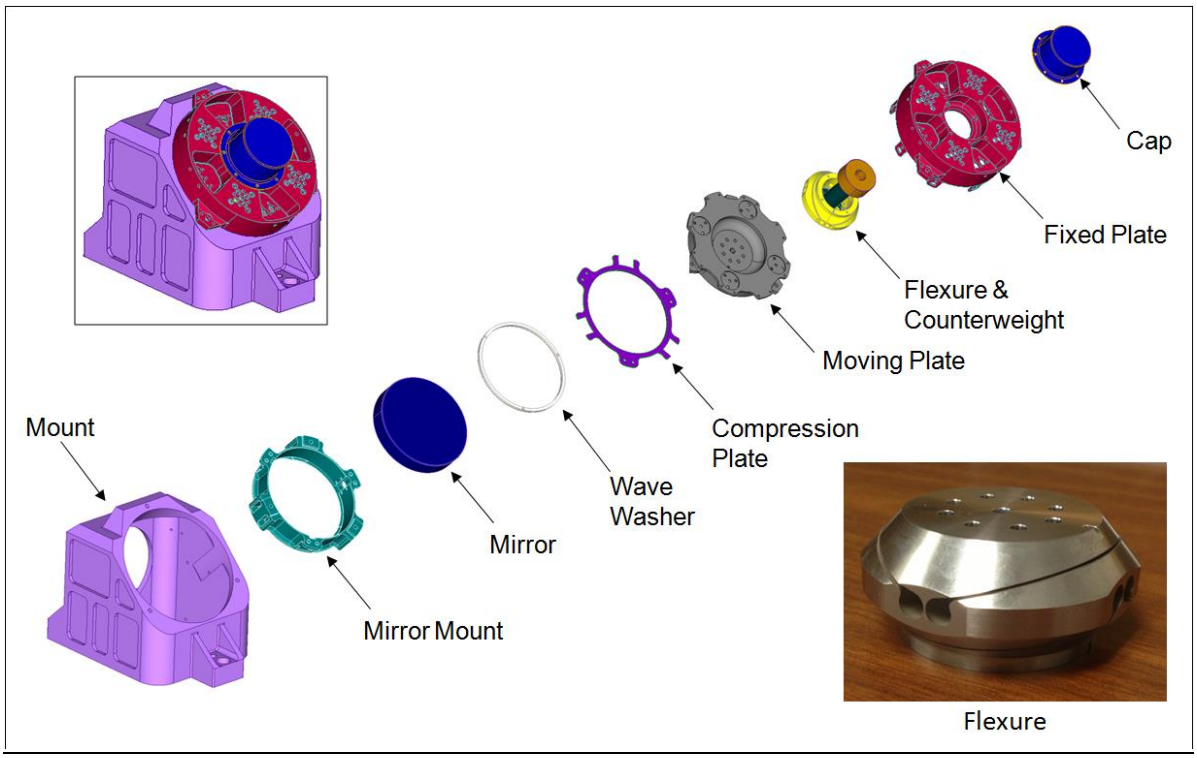


Figure 1. BSM Exploded View

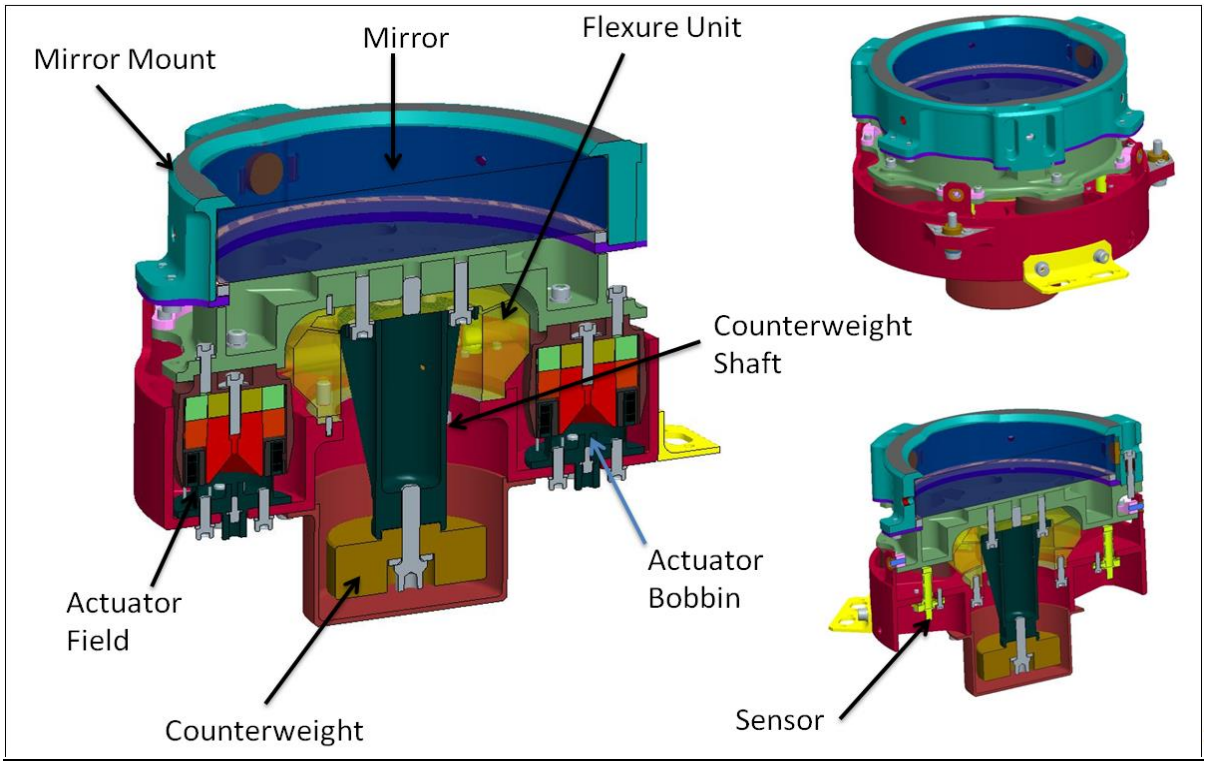


Figure 2. Cross Sections

To meet figure requirements, a rather thick mirror was required, resulting in a significant mass. This mirror mass was a significant design driver. An increase in mirror mass results in the need for a larger counterbalance mass, together increasing the total moving mass. The total moving mass is supported by the flexures, which need to survive launch loads without degradation.

Flexures

The flexures were electrical discharge machined (EDM) from conventionally machined titanium. Arrangement of the flexures allows the mirror to rotate about two orthogonal axes. Finite Element Method (FEM) structural and modal analysis was used to trade structural mode frequencies to determine the optimal flexure geometry. Flexures were designed to keep stresses within levels to result in infinite life.

Actuators

A pair of voice coil actuators is used to control each axis. The actuators were of an in-house custom design to achieve high efficiency, utilizing high performance cobalt-iron alloy along with an arrangement of axial and radial magnets. Cobalt-iron shaping put most of the cobalt-iron near saturation, saving mass. The actuators have redundant windings, with a primary winding in the bobbin center and a secondary winding split inner and outer of the primary winding. This arrangement equalized actuator performance of primary and secondary windings. Equalizing was needed as a result of the air gap magnetic field drop when moving away from the magnet side of the actuator. High damping was incorporated by the inclusion of a copper damping sleeve as a part of each actuator.

Damping

High damping adds greatly to the disturbance rejection capability of the system. Disturbances can originate externally, as a result of jitter from momentum wheels and other sources propagating through the spacecraft structure; or internally, from electrical noise or quantization error in the control system. Damping can be provided by closing a velocity loop, which does not have to waste power to overcome the damping during slew operations.

Implementing a velocity loop, however, results in several issues, including the need for a very sensitive velocity sensor to detect low velocities, and could even result in decreased pointing stability as the result of added electronics noise. Such architecture could result in a very large and heavy velocity sensor with very fine, non-robust wire to achieve a high turn count, and might require pre-amplification near the sensor. Deriving velocity from a position sensor also has its limitations, especially when trying to sense low velocities.

Passive damping with a shorted coil, such as a solid copper sleeve, can waste power when slewing. In the case of the BSM, operational mirror velocities are very small, thus there is insignificant impact upon operational power required to overcome shorted coil passive damping. Thus, shorted coil damping was implemented in the BSM actuator design. Figure 3 shows actuator cross section and component views.

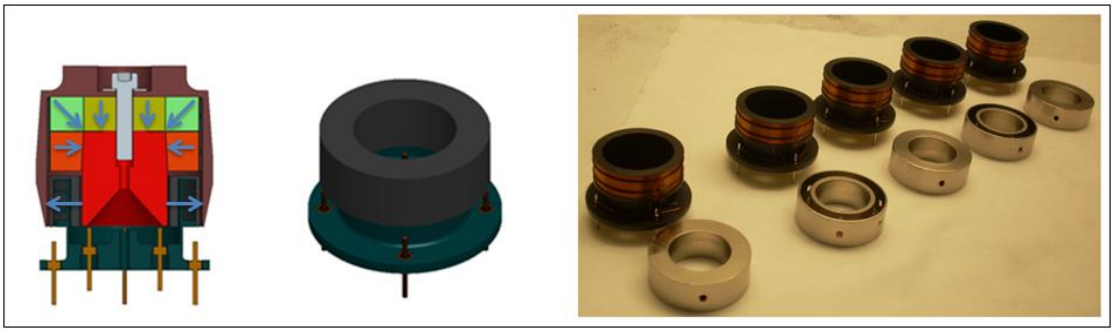


Figure 3. BSM Actuator Cross Section, Bobbin Assy., and Bobbins with Sleeves

Damping also proved very useful for minimizing loads during launch. The mirror is free to move until hard stops are contacted. Much of the energy is absorbed by the passive damping. This prevented the need for implementation of a launch lock mechanism.

Position Sensors

Differential Impedance Transducer (DIT) position sensors were chosen from Blue Line Engineering. A pair of sensors was used to sense the angle of each axis. Sensor targets were located on the rotation axes as one function of the aluminum "moving plate," to which the mirror mount assembly attaches. The surface was machined to be planar. Keeping the targets close to the rotation axis minimizes target translation, which is a source of sensor error. Ensuring a planar surface minimizes sensor error that would result from target translation.

Modal Considerations

Precision pointing mechanisms require closed-loop control for fast response and required disturbance rejection, which results in the need for high controller bandwidth. It is of critical importance to design the mechanism such that its structural modes are compatible with the controller bandwidth--typically the minimum structural mode must be several times the controller bandwidth frequency. However, high Q modes (high amplitude modal peak) may need to be farther from the controller bandwidth frequency, and lower Q modes could be closer. Also, modes that are in a different direction than the controlled direction might be less of a problem. It is difficult to accurately assess how the structural modes will affect performance until after the hardware is built.

All mechanism components were analyzed for modal frequencies, with the goal of keeping those frequencies to at least four times the controller bandwidth of 70 Hz. In some cases, it was not practical to achieve modal frequencies of four times the controller bandwidth. Most exceptions were modes that analysis showed to be occurring in directions other than in directions that the mirror is controlled.

Thermal Stability

Absolute position knowledge required tight thermal stability, dictating the mechanism materials. The BSM Engineering Model had an aluminum structure that mounted onto an aluminum housing. The housing interfaced with a composite bench with titanium inserts. Analysis found thermal instability to be greater than acceptable, so the housing and BSM structure material was changed to titanium for the BSM Flight Model. So, all is titanium up to and including the flexure. The moving side of the flexure comprises the moving plate and the mirror mount, all of which are aluminum. The titanium flexure to aluminum moving plate interface, with its symmetrical and small diameter connection, did not pose any thermal interface issues.

Lessons Learned

Overview

Various issues came about during the development of the BSM, as happens with any engineering development. Most issues were resolved in short order. Some of these issues and their lessons learned will be discussed. For this project, verification of requirements was a major focus throughout the development, which will be touched upon.

Performance Verification Challenge

Performance verification required a high data sample rate along with highly accurate dynamic measurements over the operating environment, so it was determined that a lab interferometer would be a necessary verification instrument. However, due some measurement non-linearity errors resulting from BSM mirror properties being incompatible with the laboratory interferometer wavelength as well as temperature stability issues of the set-up, static measurements were employed to compensate for these shortcomings. Thus, utilization of multiple measurement instruments along with a data acquisition approach was devised and successful requirements verification was achieved. Pre-planning of the data

acquisition approach and the proposed data reduction methods were approved by the project science team early on, paving the way for a very successful outcome.

Verifying the BSM pointing requirements necessitated the use of three separate optical references: a three-axis displacement-measuring interferometer from the Zygo Corporation, a Leviton Inter-target Differential Electronic Autocollimator (IDEA), and a Leica T3000 Theodolite. There was no single metrology solution that could provide high resolution, high accuracy, and absolute position verification over the BSM mirror's full range of motion. Rather, it was necessary to utilize information from multiple reference instruments in order to verify the requirement.

The Zygo interferometer setup consisted of a 3-axis High Stability Plane Mirror Interferometer (HSPMI), driven by a Zygo laser and measured by a Zygo ZMI4100 measurement board (Figure 4). This setup provided both the highest time and spatial resolution, achieving a 10 kHz cadence and having an advertised resolution of just over 20 nanoradians. Unfortunately, its field-of-view (FOV) of ±3 milliradians, compared to the 5.6 milliradian range to be measured, resulted in the need to realign the interferometer to capture the full FOV. The pitch axis was prone to significant non-linearity, in part caused by a polarization effect of the BSM mirror's dielectric coating, which was tuned to the 532nm ATLAS laser, but not the 633nm Zygo laser wavelength. This non-linearity meant that only the yaw axis data of the Zygo was trusted, and led to inconveniently taking Zygo measurements of both BSM axes using only the Zygo yaw axis. The Zygo has no reference, so is not an absolute, but rather is an incremental sensor. The characteristics of the Zygo made it impractical for TVac testing, but it was extensively used for the bulk of testing.

The IDEA autocollimator has a FOV of roughly ±10 milliradians, is very compact and lightweight, has a very high accuracy of 2.5 microradians, and is very stable. IDEA makes use of a reference flat to measure against, which minimizes measurement drift, making it an absolute measurement instrument. No optical adjustments are required to measure the difference between the reference flat and the mirror of interest, which in this case was the BSM Mirror. An aperture select mechanism is required to alternate IDEA's view between the reference flat and the BSM mirror. The IDEA characteristics made it ideal for measuring thermal stability during Thermal Vacuum (TVac) (Figure 5), though it was also used for non-TVac testing. IDEA is a low bandwidth device, able to achieve a maximum cadence on the order of 5 Hz.

The theodolite offered similar performance as IDEA, though large and bulky, but unlike IDEA, it required manual operation for each measurement. Theodolites have significantly more heritage as an optical reference than IDEA, which is a fairly new development not yet commercially available. Measurements taken with a theodolite were used to determine the BSM sensor scale factors and axis orientation.

Optical measurements during TVac were taken using IDEA, whose wider FOV could tolerate gross motion of the BSM mount due to temperature changes in the vacuum chamber. IDEA measurements were used to make temperature-dependent adjustments to the scale factor, determined before TVac. Performance over the full range was quantified using interferometer data which had been post-processed to remove non-linearities. Processing a combination of data from these three instruments verified BSM pointing performance over its full required range of motion and temperature.

The photo of Figure 6 shows optical references used by the measurement instruments. The BSM cube was used by the theodolite as a position reference. The reference flat was used by IDEA as its position reference.

As position knowledge and pointing requirements for similar systems in the future become more demanding, verifying these requirements will require not only the synthesis of measurements from multiple references, but also deep understanding of the limitations of each reference chosen.

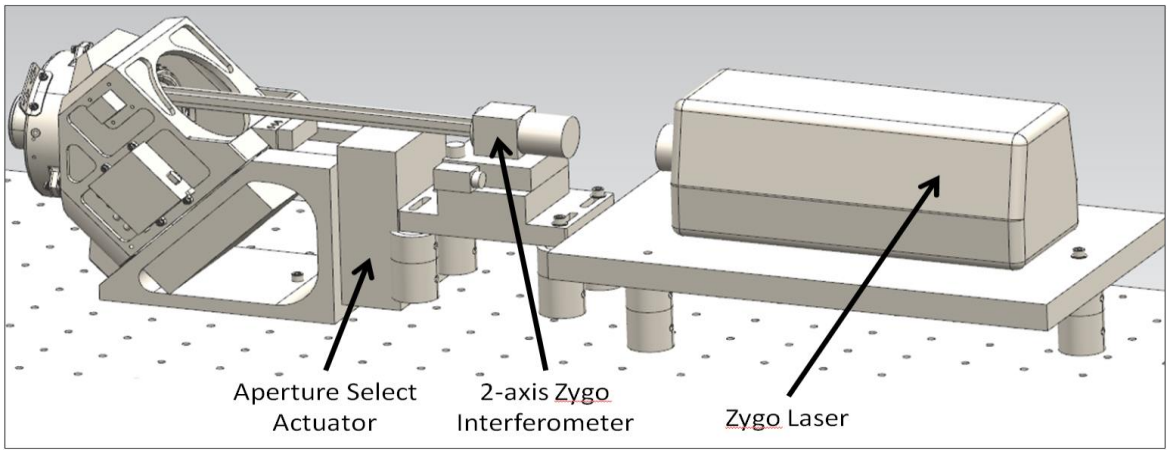


Figure 4. Interferometer Setup

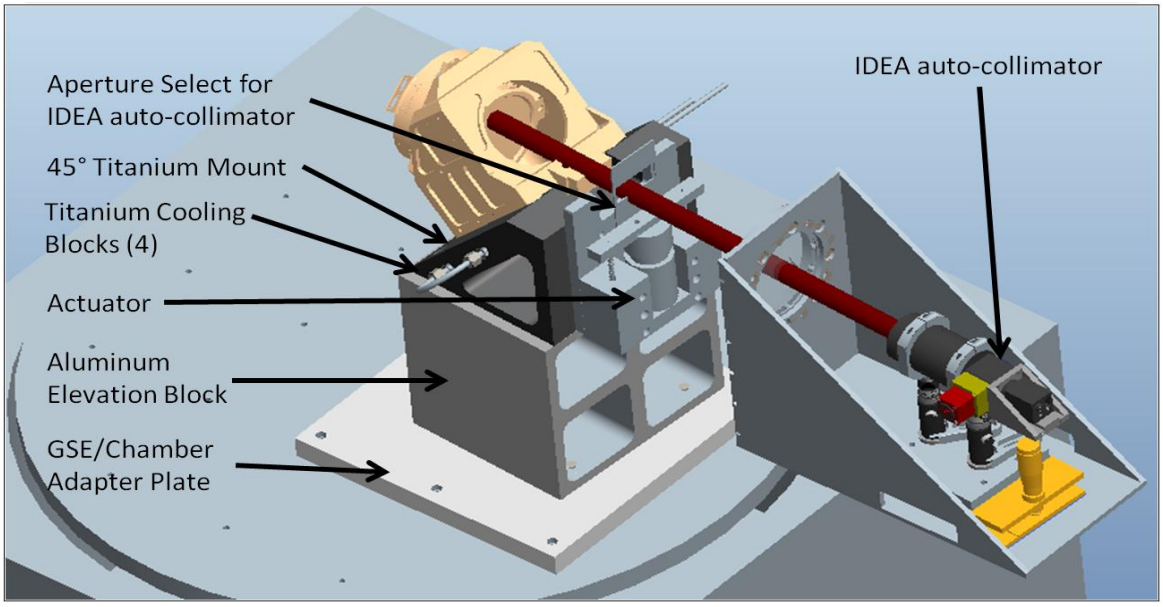


Figure 5. TVac Configuration Using IDEA

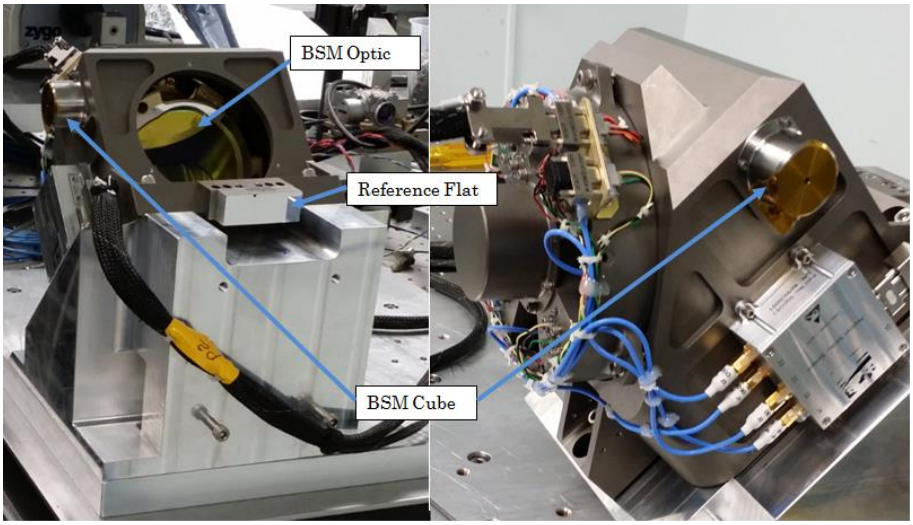


Figure 6. BSM Optic and Optical References

Initial Inconsistent Performance

When the BSM Engineering Model was available for testing, it was mounted to an optical bench and initial frequency response testing was performed. The controls engineers were finding inconsistency upon taking successive frequency responses and it was further found that changing the torque of the mounting hardware changed those responses. Due to the fact that proper hardware for mounting the BSM to the bench was not yet ready, the BSM housing was clamped to the bench using machine tooling. The surface of the honeycomb optical bench is made of a thin section of steel with threaded holes on 1 inch centers. There certainly was not concern over the stiffness of the bench that also happened to sit on a very thick granite table, which was floating on a seismic block. However, local attachment threaded holes did not provide adequate stiffness, thus affecting response measurements. The issue was eliminated by adding a half-inch-thick aluminum plate between the bench and BSM hardware.

Undesirable Structural Mode

Measurement of the frequency response found there to be a very undesirable structural mode near 900 Hz. While this frequency was quite far from the controller bandwidth, the mode had a very high Q, which made it troublesome. Very unusual was the wide frequency range of the base of this mode, such that it did not have behavior consistent with that of a structural mode. One of the controls engineers was able to implement filtering in order to deal with this mode, sacrificing some phase margin, but still leaving adequate phase margin.

Careful study was made of the modal analysis to determine the source of this behavior, but it is typical to find that modes revealed in the model do not match the measured modes. Using FEM modal analysis, we were unable to determine the source of this very troubling behavior. The modal analysis software tool does not specify an input location, or an output location. Furthermore, guesses are made to choose damping values for the materials to input into the analysis tool. In the physical world, the frequency response input is the current to the actuators, which becomes localized force inputs, and the frequency response output is the position sensor signal, which is the motion of the sensor targets. So, the modal analysis cannot be expected to give an accurate representation of the measured frequency response. We would be pleased to be made aware of analysis tools that can better predict frequency response for a mechanism with actuators and sensors intended for closed-loop control.

Certainly, management was concerned that effort was being expended to correct this modal behavior issue. The question was posed, “Do we meet requirements?” The answer was that we did on the bench, but the possibility of structural mode behavioral changes after integration, or even on-orbit, requires having capability to deal with such changes. The controls engineer had designed in the capability for a maximum number of poles for filtering, but with the unusual mode, there was risk that filter capability could be insufficient to deal with structural mode changes that might potentially come about.

We hit a dead end using FEM analysis, so we chose a brute force method to find out what was causing the troubling structural mode. The BSM does not have many parts. Trial and error changing of parts with modified parts was the technique implemented. Since the BSM required a rather heavy tungsten counterweight, it was theorized that a lack of stiffness of the titanium counterweight shaft could be responsible. The drawing was revised and parts were put into fabrication. After planned testing of the BSM Engineering Model was completed, the new and stiffer ribbed titanium counterweight shaft was installed. The new frequency response showed that the massive and wide structural mode was replaced by small, typical looking structural modes. Problem solved. The before and after open loop frequency responses (of mechanism and controller together) are shown in Figure 7.

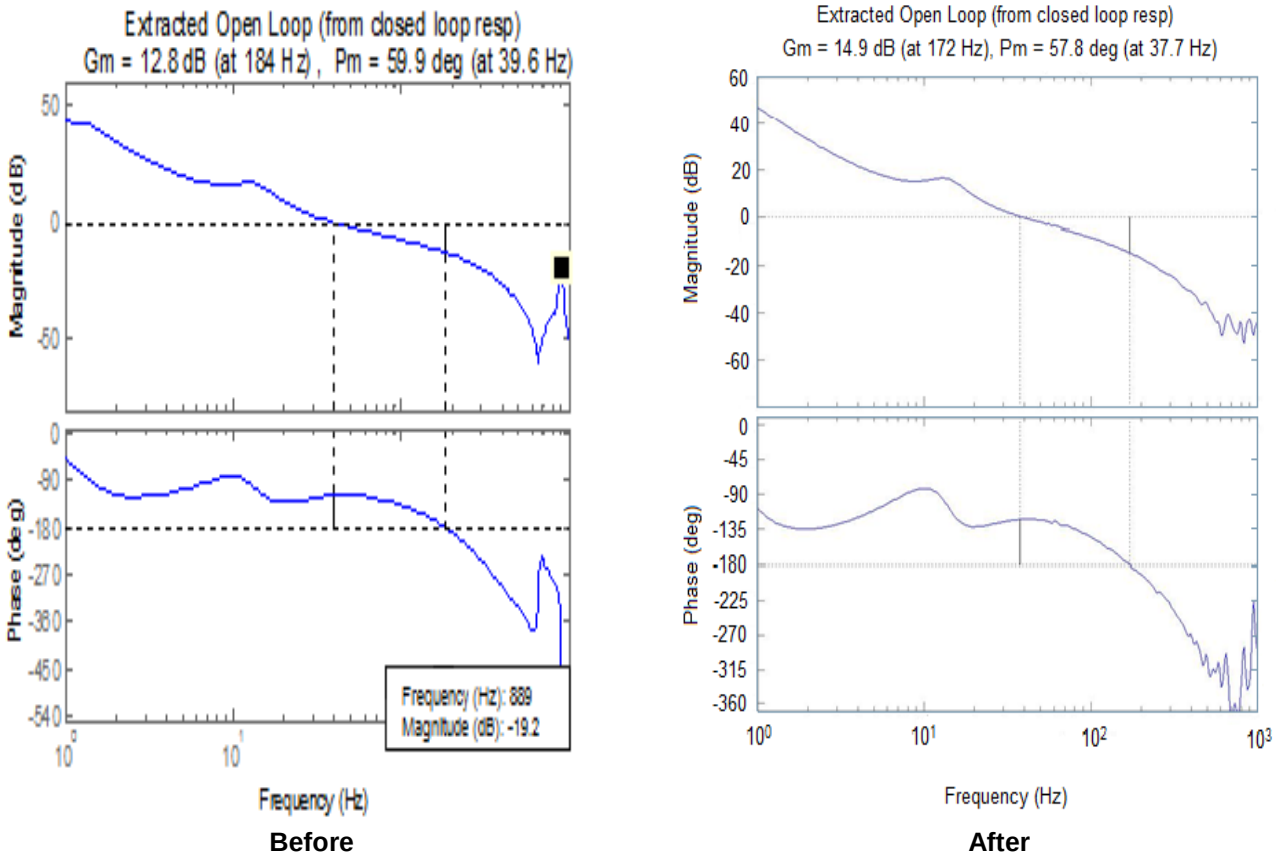


Figure 7. Frequency Response Before and After Counterbalance Shaft Change

Hipot Overtesting Failure

Qualification of the in-house voice coil actuators required high potential (hipot) and insulation resistance testing to be performed. We referred to one of our test specifications documents, and applied a test voltage of over 1,000 volts, which resulted in a failed actuator winding. After investigation, it turned out that our test specifications were really intended to be used for cable and connector testing. Furthermore, we found out that lower voltages were regularly being used for most cable testing, more so for cables with miniature connectors. Since our operational voltage was no more than 12 volts, it was decided to test at 250 volts, after which all hipot and insulation resistance tests were passed without issue. So, the lesson learned is to not blindly follow documentation. We should have surveyed the standard practice for motor winding hipot and insulation resistance testing rather to follow a test specification that was not applicable. Another factor was that we were probably overly confident that our design was bullet proof. It is not prudent to overtest.

Undesirable Behavior of the Flight Model

The BSM Flight Model had completed its testing just at the point ready for environmental testing to begin. The controls engineers discovered puzzling behavior of the BSM Flight Model not seen in the BSM Engineering Model. When making mirror motions from one point to another, the trajectory would miss the commanded go-to point and then circle back before arrival to that point. While such behavior was always seen in the BSM Engineering Model, it was not seen at the magnitude observed in the BSM Flight Model.

We were privileged to have one of our top technicians perform the assembly of all the BSMs. During our investigation, it was revealed that our technician observed an unusual behavior during the balancing process. The balancing process was dependent upon usage of the highly sensitive internal position sensors. The BSM Flight Model was mounted into a cubical framework that allowed the mechanism to be oriented with gravity in six different directions, two with the counterbalance shaft vertical, and four with the counterbalance shaft horizontal, with vectors in plus/minus X, Y, and Z (Figure 8). Once balanced, changing the gravity vector direction by 180 degrees should not result in mirror positional changes. However, when checking balance in the X vector, the technician was observing changes in Y, and when checking balance in the Y vector, he was seeing changes in X.

Our technician was advised to not pay attention to changes in the axes he was not balancing since it would only create confusion in the balancing process. That instruction allowed the technician to complete the balancing, but we should have paid attention to the resulting magnitude of the non-gravity-aligned axis. We realized that changing the gravity vector by 180 degrees of what we believed to be a balanced BSM resulted in significant motion in the orthogonal non-gravity aligned axis. This was a very puzzling behavior.

If mirror motions were constrained to flex either one flexure or its orthogonal flexure, axes A and B, that motion would be rotated from the sensor axes X and Y by 45 degrees. The counterweight, its position location Z at the end of the counterbalance shaft, is adjusted by shims to achieve balance. However, flexure rotation locations on Z need to be identical. If flexure rotation locations are different, it is only possible to achieve balance upon one flexure axis or the other. A compromise could be made, such that one flexure axis would be mirror light and the other axis could be equally mirror heavy. The lack of co-alignment of the flexure axes with the sensor axes is important to understanding the behavior observed.

Refer to Figure 9 for the imbalance phenomena explanation that follows. Assume the balance is perfect and the Y axis is aligned with the gravity direction. The mirror will point to position 0 at the origin. Let us move one of the flexure axes in +Z to make the moving assembly mirror light, and then move the other flexure axis in -Z to make the moving assembly mirror heavy. Remember that the flexure axes A and B are such that mirror motion on either flexure axis A and B is constrained to be in a direction that is 45 degrees from the sensor axes. If looking from the back of the mirror along the counterbalance shaft, assume that the mirror light flexure axis A pointed the mirror up and to the right, following the blue arrow to position 1. Motion on the mirror heavy axis B would then be down and to the right, following the red arrow to position 2. The net result is that imbalance did not affect the Y sensor axis in the gravity direction, but rather, the net motion was to the right in the X horizontal, non-gravity-aligned axis, following the purple arrow from position 0 to position 2. It does seem counterintuitive that changing the gravity vector 180 degrees results in motion on an axis that is orthogonal to the gravity vector, yet such motion is an indication of imbalance. Had the flexure axes been aligned with the sensor axes, it would have been apparent that balancing one axis would result in the other axis not being balanced.

The root cause turned out to be that flexure manufacturing tolerances were not met, with the two flexure rotation locations separated in Z by about 0.009 inches. Inspection reports were incorrect, due to improper fixturing and confusing geometric tolerances. New flexures needed to be manufactured, unfortunately resulting in significant schedule slip. Had there been better awareness of the behavior anomaly, we could have caught the issue sooner.

Unknown Pole

An unknown pole of 150 Hz was present in the frequency response, but was accommodated with filtering. The pole is unknown in that a MATLAB/Simulink model of the BSM, based upon the mechanical and electrical specifications, did not reveal such a pole. Similar behavior was observed on the Cassini Composite Infrared Spectrometer (CIRS) Scan Mechanism developed in the early 1990s, which also had damping designed into its custom actuator. Since in both cases, we needed to deliver hardware on a tight

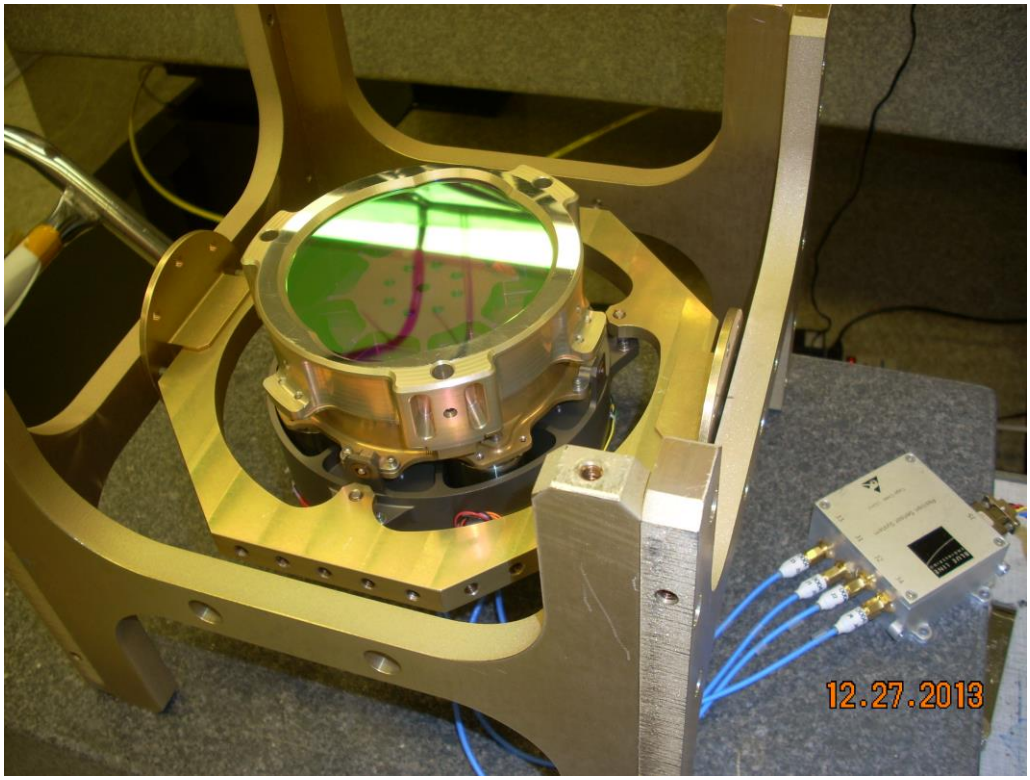


Figure 8. BSM Flight Model Mounted in the 6-Axis Balancing Fixture

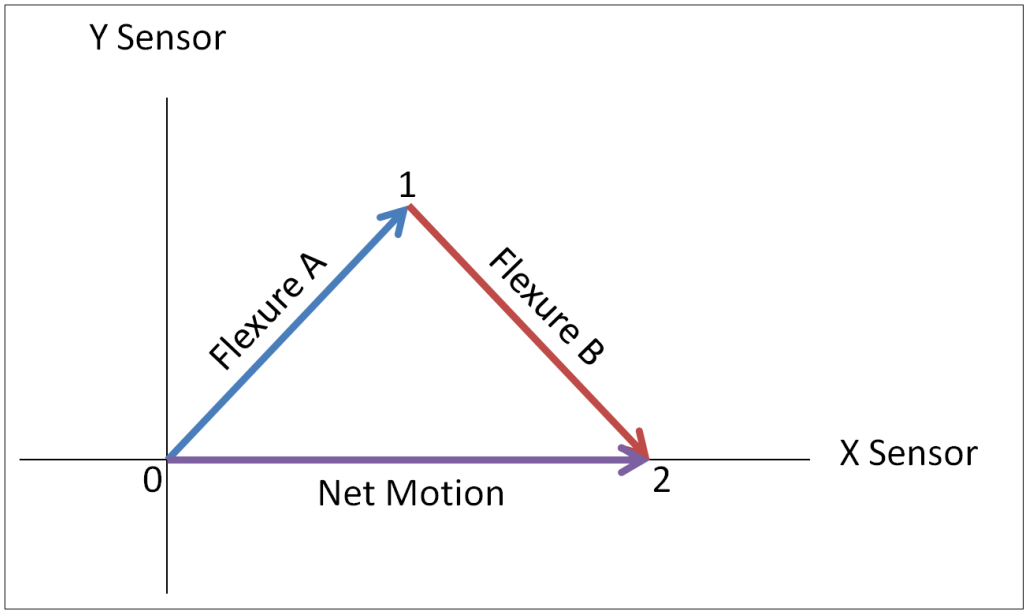


Figure 9. Imbalance Phenomena Explanation Graphic

schedule and we were able to meet performance requirements with the extra pole, we moved forward. In both cases the project ended without the opportunity to spend the time to fully understand the physics behind the behavior. However, we believe the unknown pole to be the result of coupling between the actuator windings and the damping sleeve, which were arranged coaxially in both projects (Figure 10).

We did design and fabricate actuator bobbins that separated the windings from the damping sleeves such that they would not be coaxial, but we never had the opportunity to test them. The more prevalent pole was the BSM, and the BSM was designed to have much greater damping than the Scan Mechanism, so it appears that there is a relationship between the amount of damping and the prevalence of the pole. If a non-coaxial design would reduce or eliminate the pole, phase margin could be greater resulting in reduced compensation output, better performance, and increased robustness.

Sensor Fabrication Issue

Our Differential Impedance Transducer (DIT) sensors vendor, Blue Line Engineering, did an excellent job of providing sensors to meet our specifications. The raw sensor behavior is non-linear, so the sensor electronics undergo a tuning process to trade off various performance parameters. The vendor was able to predict very well what they could achieve. We pushed them to the limits of what was achievable for our application and for their technology.

While the vendor certainly was under schedule pressure, there are usually multiple reasons for explanation of any mishap. An error occurred during manufacture of the flight sensors. The epoxy used for potting the cables into the sensor bodies did not cure, which was one of the final steps in manufacturing the sensors. The root cause was an error in computing the mass of the components that were mixed, so the mix ratio was incorrect. It was necessary to build a new set of sensors, resulting in a small schedule slip. The vendor was very responsive and manufactured a new set of sensors very quickly.

While samples of pucks were provided for all epoxy mixes for outgassing testing, this process did not alleviate the risk of an error, but would catch the error after it occurs. Since significant work was at risk if an error in mixing occurred, it would have been prudent to have more checks in place. One possibility could have been to use premixed epoxy stored at cold temperature that had already been tested for outgassing.

A process error such as this can always happen. This lesson is a reminder to elevate checks to prevent such errors, dependent upon the amount of rework that is as stake if a process fails.

Schedule Pressure

In more recent times, pressure to meet schedule and budget has come under higher levels of scrutiny than in the past. For this particular project, the in-house engineering team was turned on at the 11th hour to produce the entire mechanism from concept to flight. This put us on a tight schedule.

The BSM was initially determined to be supplied from a vendor, but the work was taken in-house after an environmental test failure. The project originally chose the vendor as a cost savings measure since it is more cost effective to buy already developed hardware than it is to develop hardware. However, it turned out that the vendor's hardware had design shortcomings such that flight qualification would require redesign, so the perceived cost savings evaporated. The project further benefited going in-house since BSM requirements were compromised in order to utilize the vendor's hardware, so once the work was brought in-house, optical requirements tightened up significantly.

Being on a tight schedule put us in the spotlight. Management was very concerned and preferred to have hardware sooner than later. Sometimes it is useful to develop some hardware early on to help with the design process if analytical methods lack fidelity, such that the easier path is to build and test. In this case, we determined that any early hardware development would not be of benefit, and also that early

hardware development would hurt cost and schedule. Though management desired a quick hardware cycle, we were thankful that the team was permitted to take the necessary time to design and analyze to the degree deemed most efficient.

It takes time and effort to develop hardware. Significant time is expended for procurement and fabrication, followed by time and effort for assembly and testing. The proper approach is to do all your homework and design it right the first time. Ideally, changes to the Engineering Model should be minimal in the Flight Model.

Thus, schedule pressure should not be permitted to result in cutting corners in the design cycle. If by cutting corners in the design cycle, you don't get it right, there is likely not time to do it again. If major changes to the initial configuration are needed, it could result in the need for an additional hardware iteration before the flight build. It could also result in sticking with a troublesome architecture and suffering with performance issues throughout the development and beyond, adding to cost and schedule. Cutting corners in the initial design cycle is a risk not likely to be worth taking. Performing the necessary engineering analyses in the initial design cycle is of key importance in successfully developing hardware efficiently.

Conclusion

The team was very motivated to be tasked with meeting requirements not faced before. In the past, we have developed pointing mechanisms and scanners requiring arcsecond levels of pointing, but we never before developed hardware to meet sub-arcsecond levels of pointing. Pointing requirements were met with margin (Figure 11). If we used the BSM to point a laser from NASA/ARC to San Francisco International Airport, a distance of 40 km, we could keep the center of that beam on a dime.

Various lessons learned have been discussed. Most of the lessons learned dealt with problems that appeared and were in short order, understood and solved. However, throughout the BSM development, verification of pointing was a major focus. In particular, verification of systematic error throughout mission life, full range of motion, and full range of temperature, was extremely challenging. The details of the methodology used for pointing verification go well beyond the scope of this paper, requiring a paper solely on this topic.

Being challenged with each issue that arose, understanding the problem, and finding the solution, is what fulfills us as engineers as each team member can attest. The team is very proud of the BSM development and was recognized by upper management for the outstanding achievements of this very challenging task.

The BSM Flight Model was integrated into ATLAS as shown in Figure 12. The BSM location on ATLAS is identified in Figure 13.

Acknowledgements

Willie E. Barber*, Gregory A. Bowers*, William G. Bowers*, Thomas L. Capon*, Eric L. Holt**, Douglas B. Leviton***, Andrea O. Poulin*, Joseph P. Schepis*, and David S. Schwinger*.

* NASA Goddard Space Flight Center, Greenbelt, MD
** Stinger Ghaffarian Technologies, Inc., Greenbelt, MD
*** Leviton Metrology Solutions, Inc., Boulder, CO

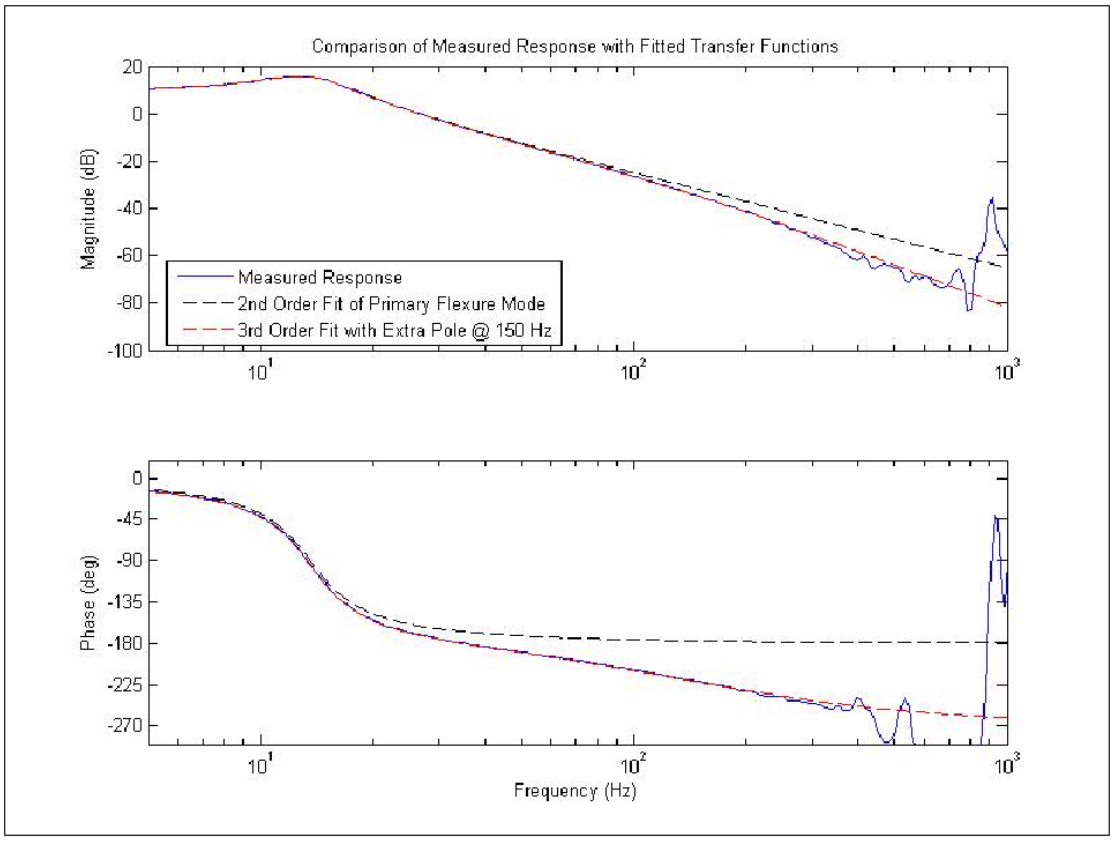


Figure 10. Unknown Pole

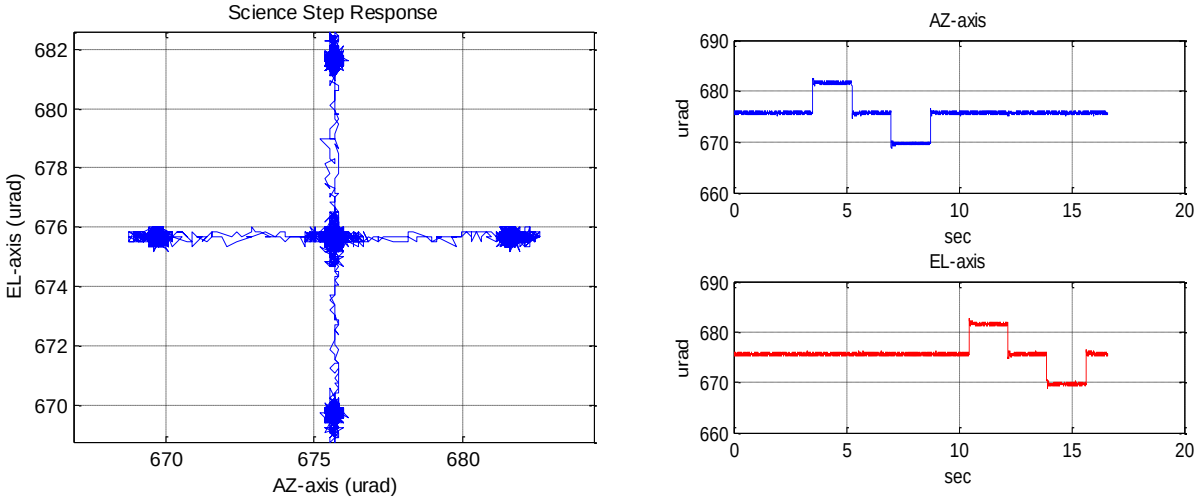


Figure 11. BSM Pointing Stability

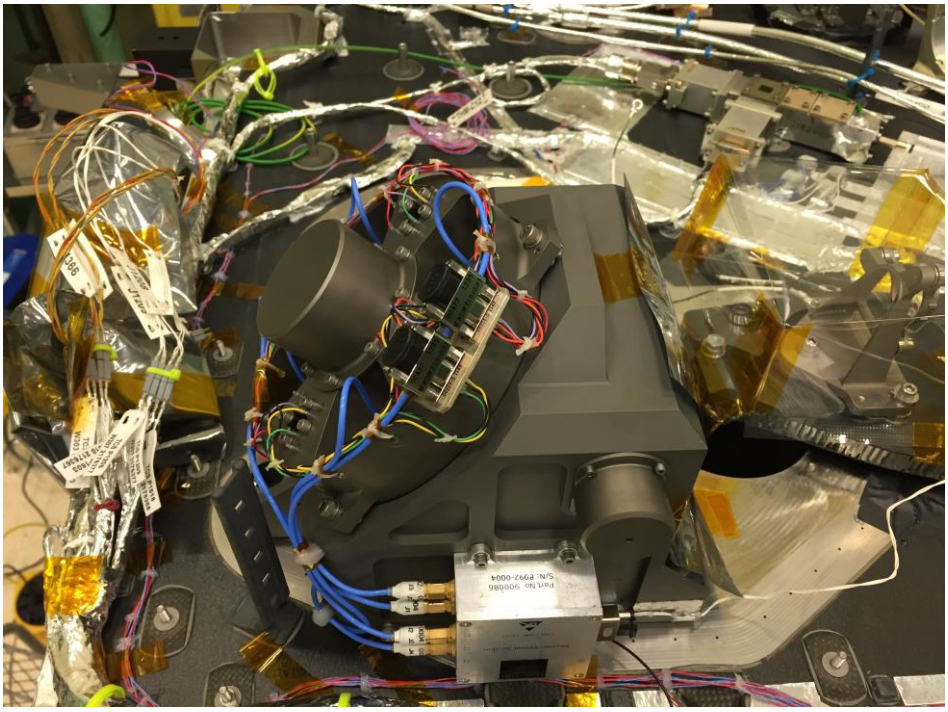


Figure 12. Initial Integration of Beam Steering Mechanism Flight Model onto the ATLAS Bench

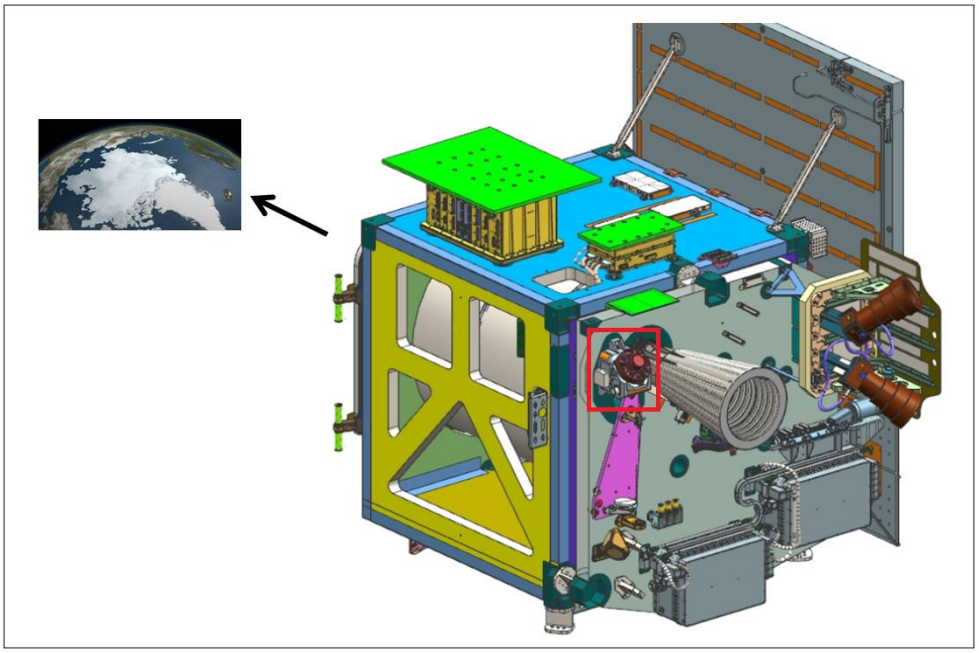


Figure 13. ATLAS Instrument with a Red Rectangle Indicating the BSM Location

Source of Acquisition
NASA Johnson Space Center

Challenger and Columbia Lessons Learned

William C. Hoffman III
Deputy Chief, Energy Systems Division
NASA

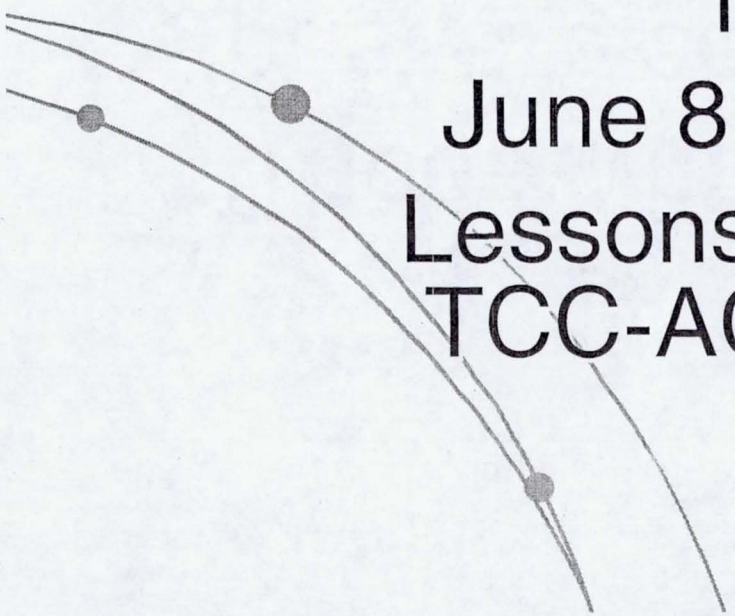
The Space Shuttle Challenger and Columbia accidents resulted in tragic loss of life and national assets, and investigations into both accidents produced important lessons to prevent future accidents.

Challenger and Columbia Lessons Learned

William Hoffman
NASA-JSC

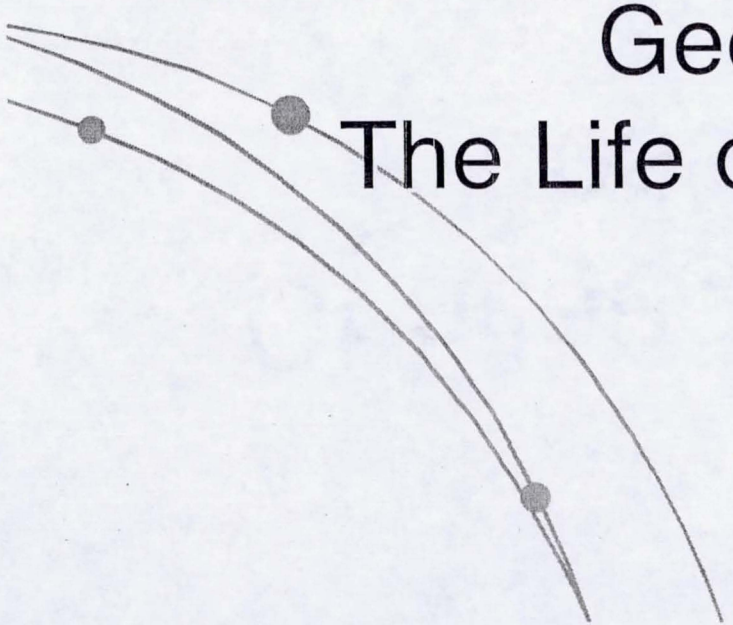
June 8, 2004, 9:00 A.M.

Lessons Learned Session
TCC-ACIT EHS Seminar



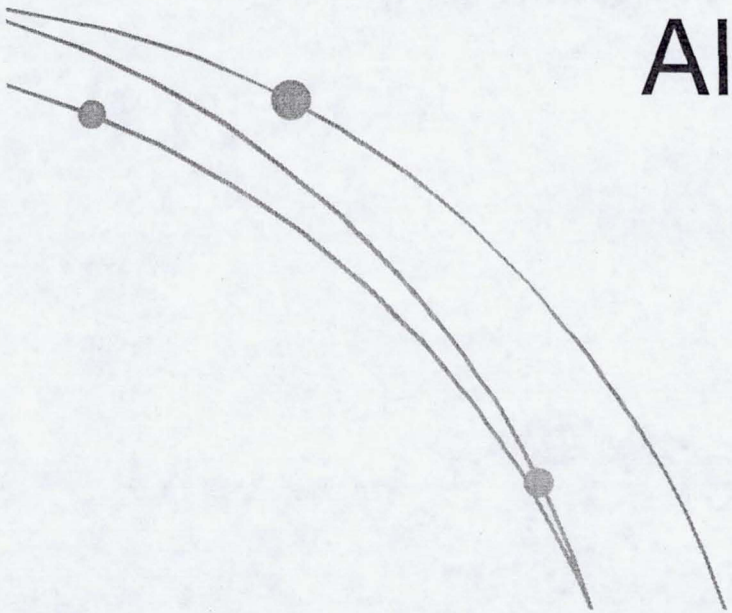
"Those who cannot remember the past are condemned to repeat it."

George Santayana,
The Life of Reason Vol. 1, 1905



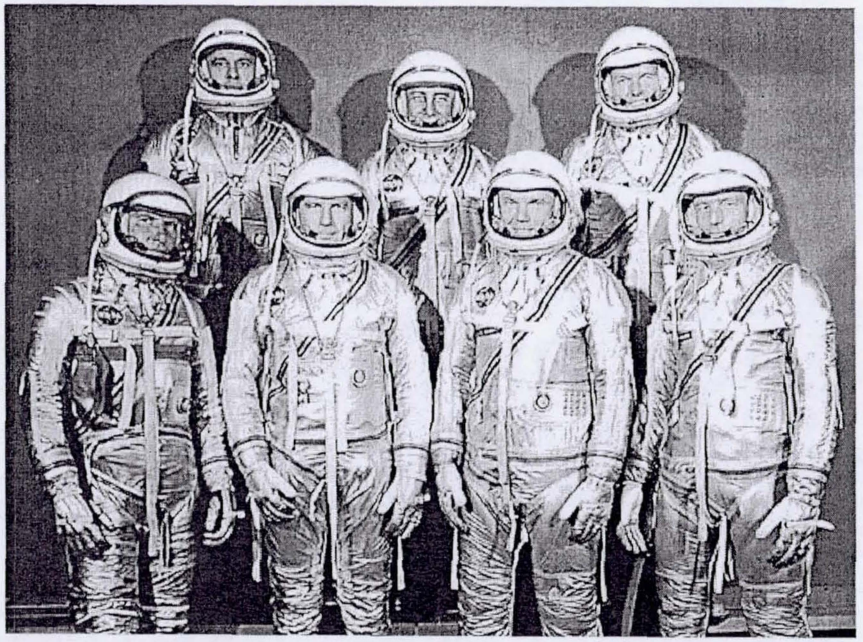
"Insanity is doing the same thing and expecting different results."

Albert Einstein



NASA's Legacy Prior to Challenger

- Mercury
  - 1st American in Space
  - 1st American in Earth Orbit
  - 6 missions
  - 34 hours longest mission duration



Challenger and Columbia Lessons Learned

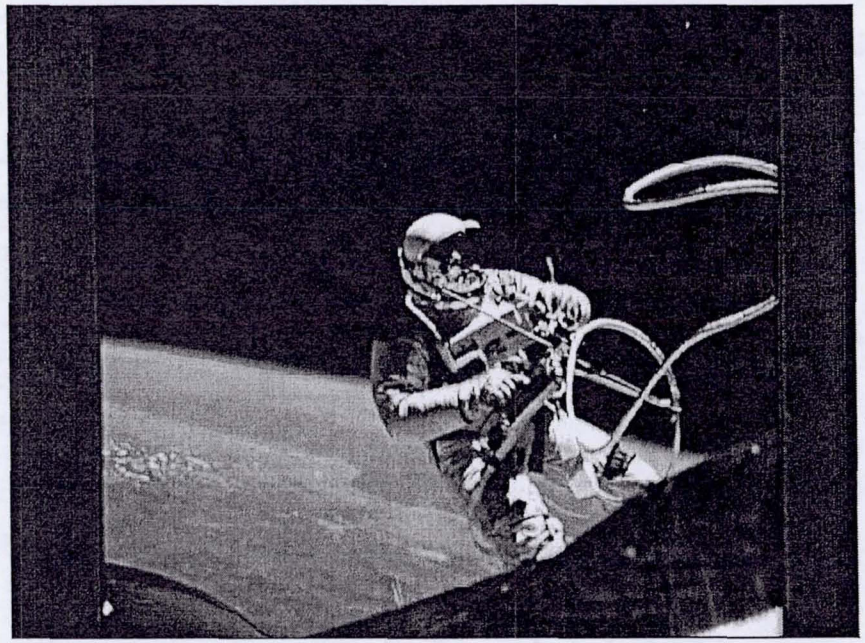
Agenda

- Legacy of NASA Prior to Challenger
- Challenger Accident
- Challenger Findings
- NASA Response to Challenger
- Columbia Accident
- Columbia Findings
- NASA Response to Columbia
- Common Lessons Learned

The Future

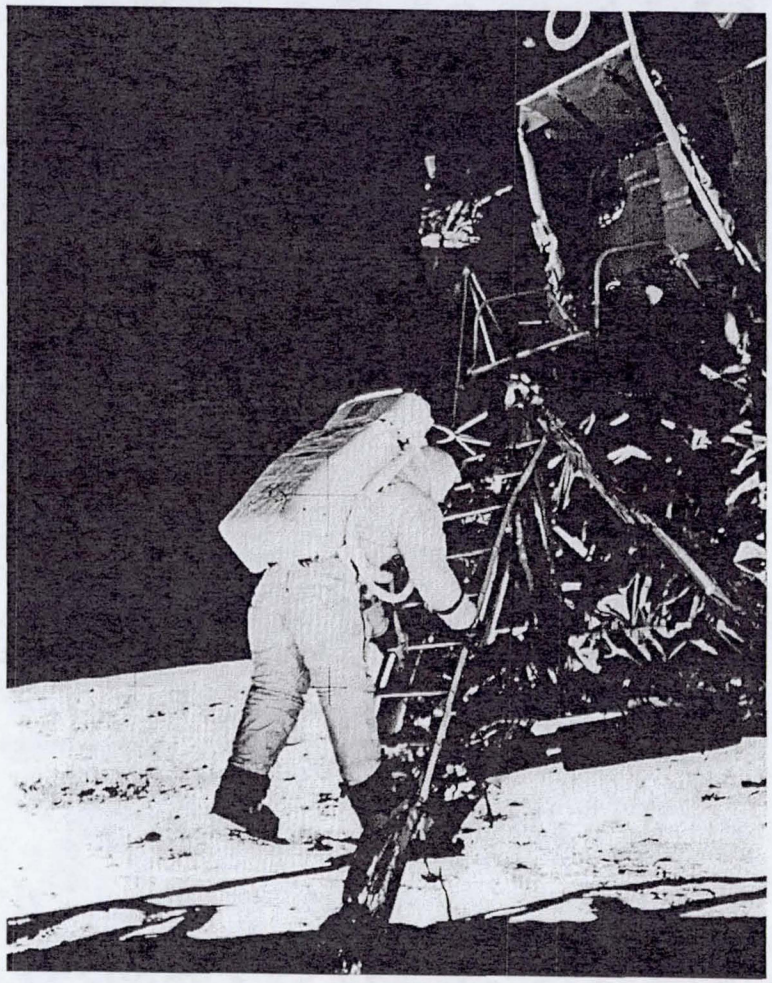
NASA's Legacy Prior to Challenger

- Gemini
  - Two crew members in space for up to 2-weeks
  - 1st Space walks
  - Orbital docking and maneuvering
  - 10 manned flights



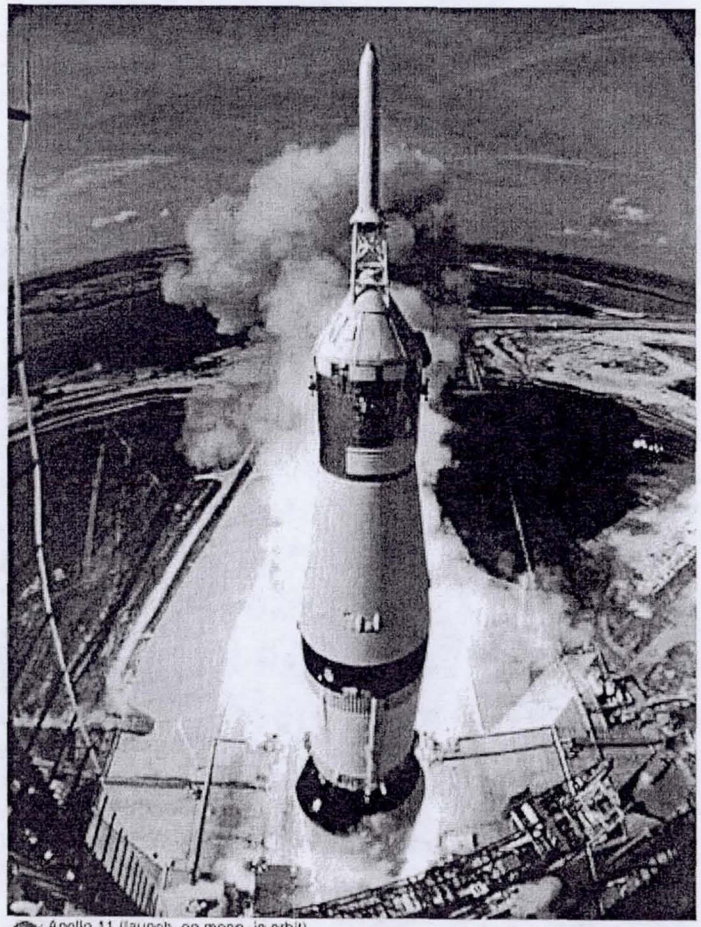
NASA's Legacy Prior to Challenger

- Apollo
  - Lunar landing and return to Earth
  - 11 crewed missions
    - 2 earth orbit
    - 2 lunar orbit
    - Lunar swingby
    - 6 lunar landings



NASA's Legacy Prior to Challenger

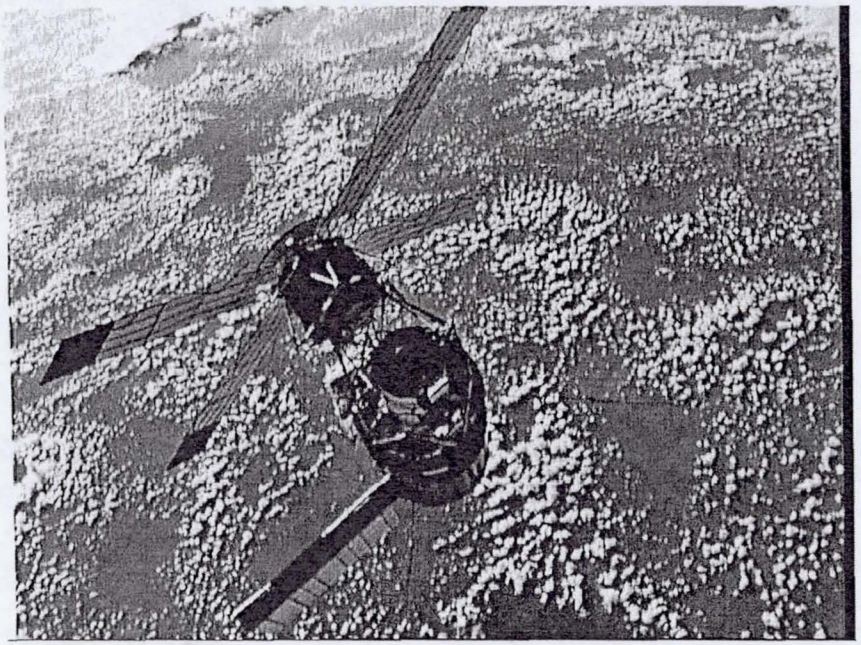




Apollo 11 (launch, on moon, in orbit)
NASA Langley Research Center 6/16/1969 Image # EL-2001-00482

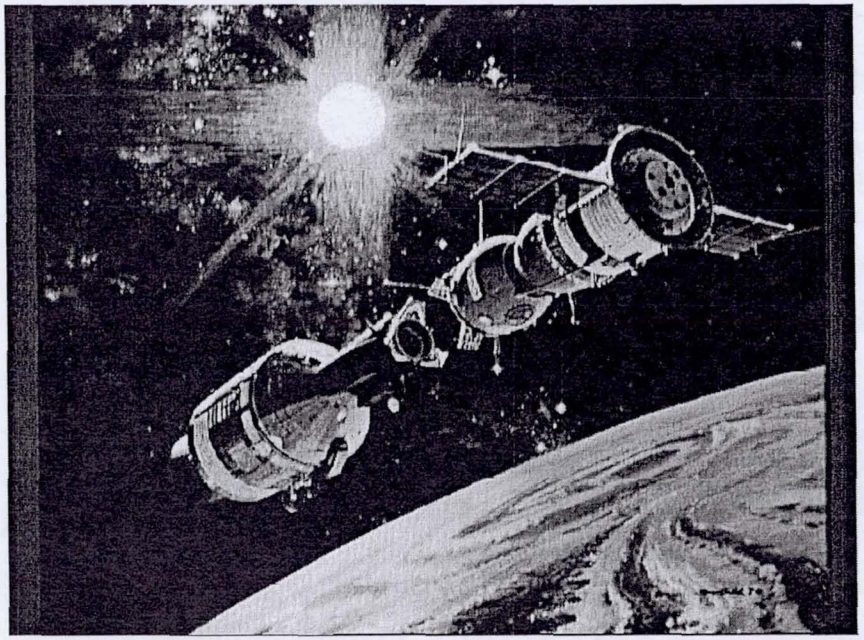
NASA's Legacy Prior to Challenger

- Skylab
  - 1st US space station
  - 3 crew members
  - 3 missions, 29, 59, and 84 days
  - Experimental and observational platform



NASA's Legacy Prior to Challenger

- Apollo-Soyuz
  - 1st international manned spaceflight
  - Test rendezvous and docking system compatibility
  - Opening for future manned spaceflights
  - 1975

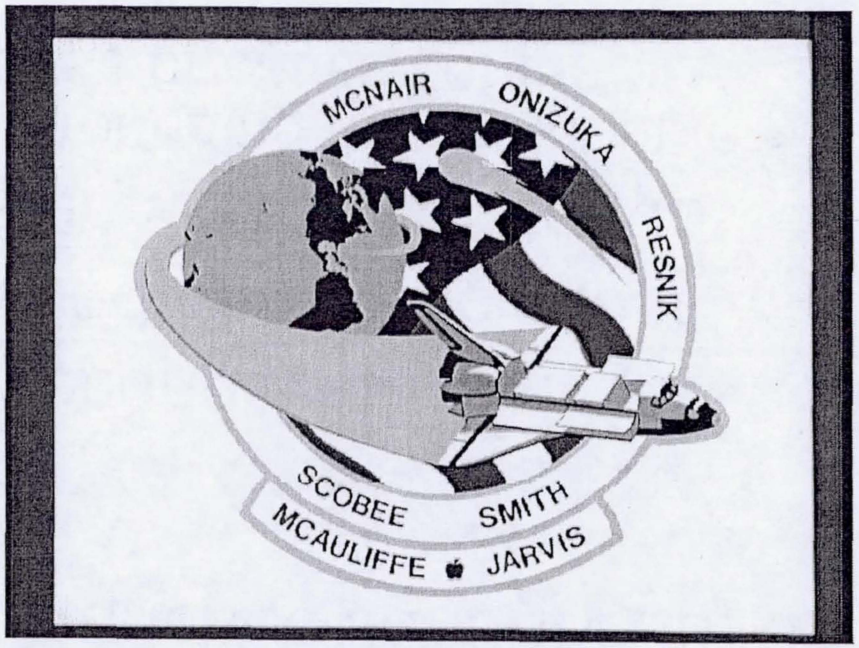


The Challenger Accident

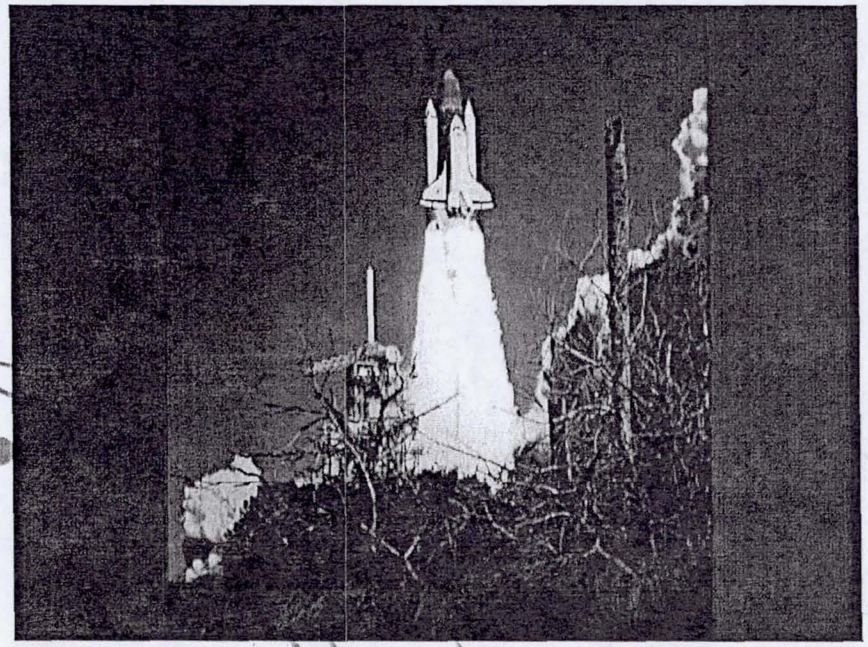
- Challenger mission 51L launched January 28, 1986
  - 25th Space Shuttle Mission
- Challenger was lost 73 seconds into its flight
- 7 crew members were killed, the vehicle lost
- A Presidential Commission was appointed to
  - Review circumstances surrounding the accident to establish the probable cause or causes of the accident; and
  - Develop recommendations for corrective or other action based upon the Commission's findings and determinations.

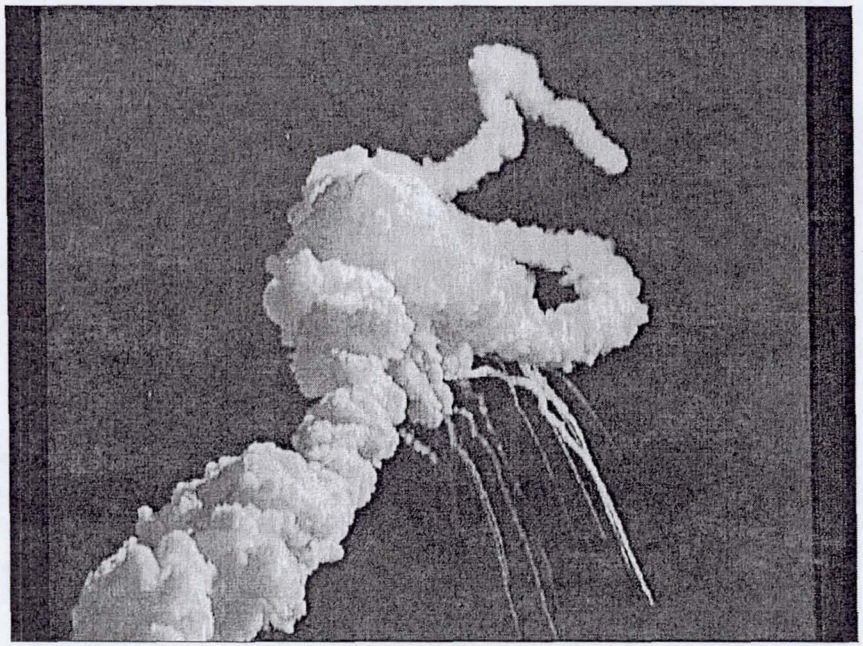
Challenger Accident





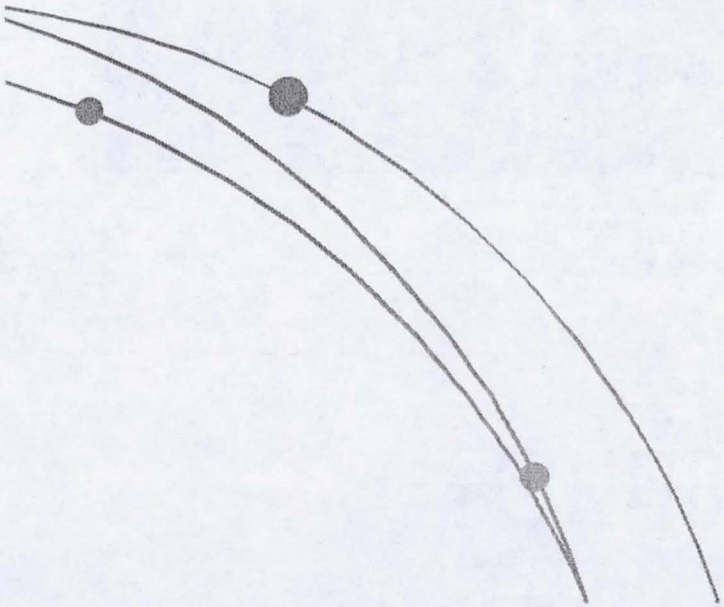
Challenger Accident



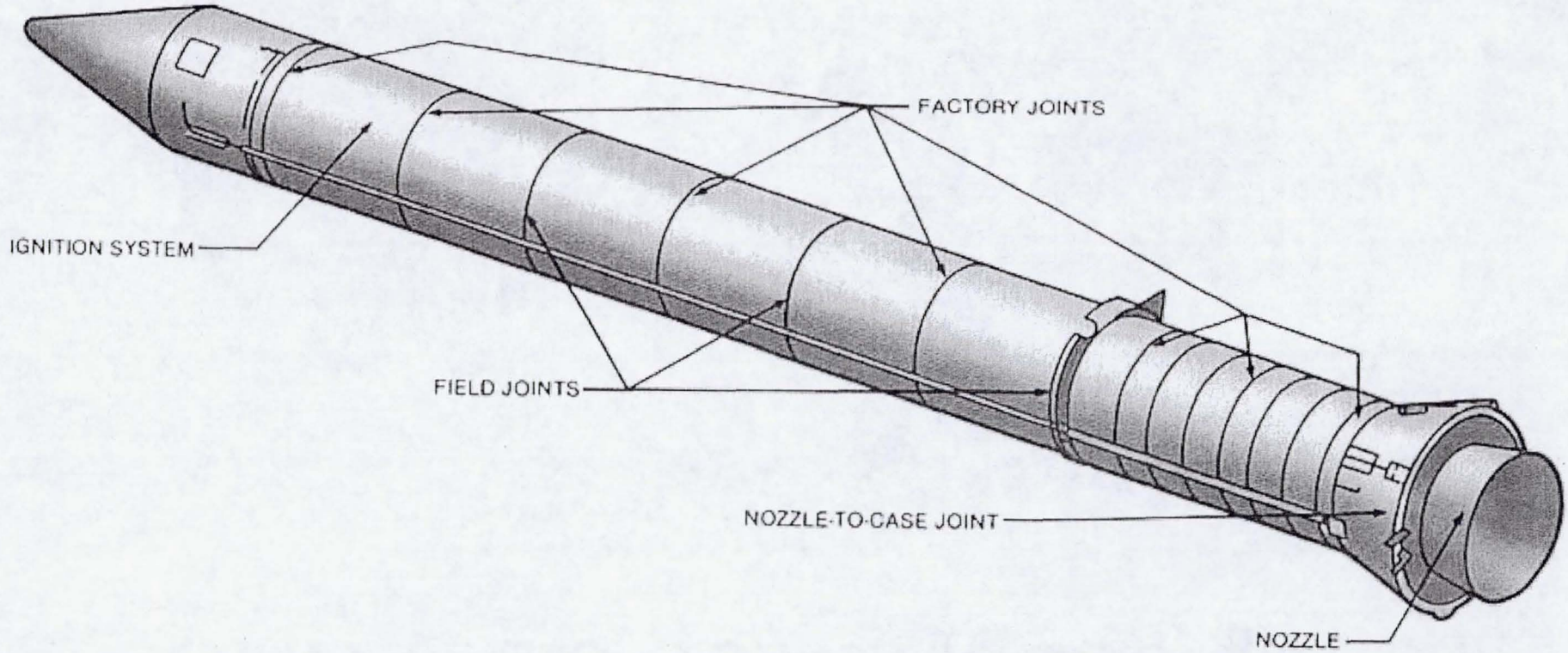


Challenger Commission Findings

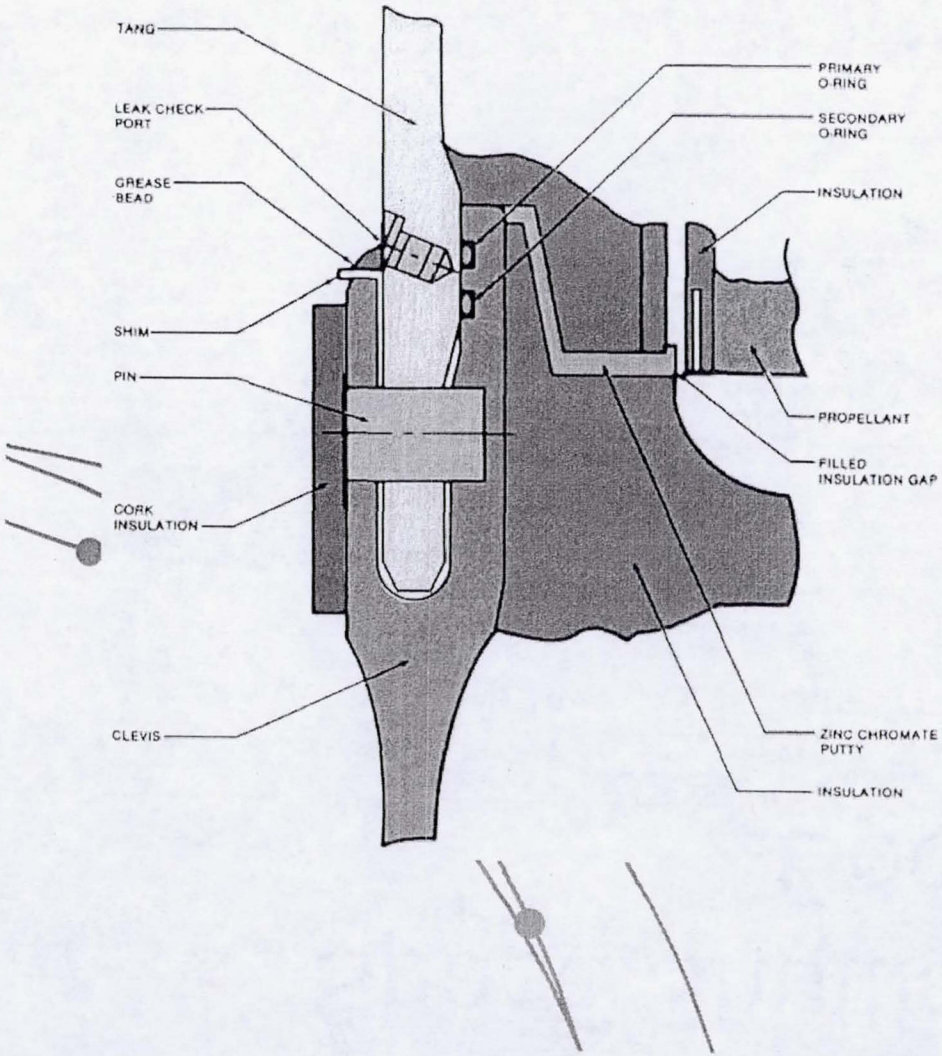
- The cause of the Challenger accident was the failure of the pressure seal in the aft field joint of the right Solid Rocket Motor.

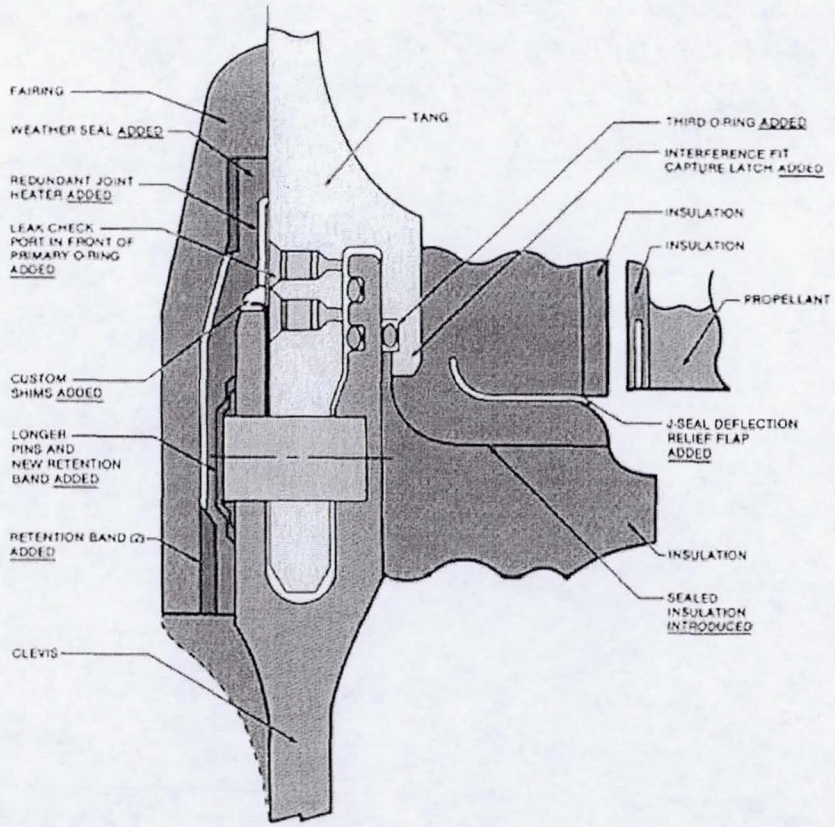


Space Shuttle Solid Rocket Booster



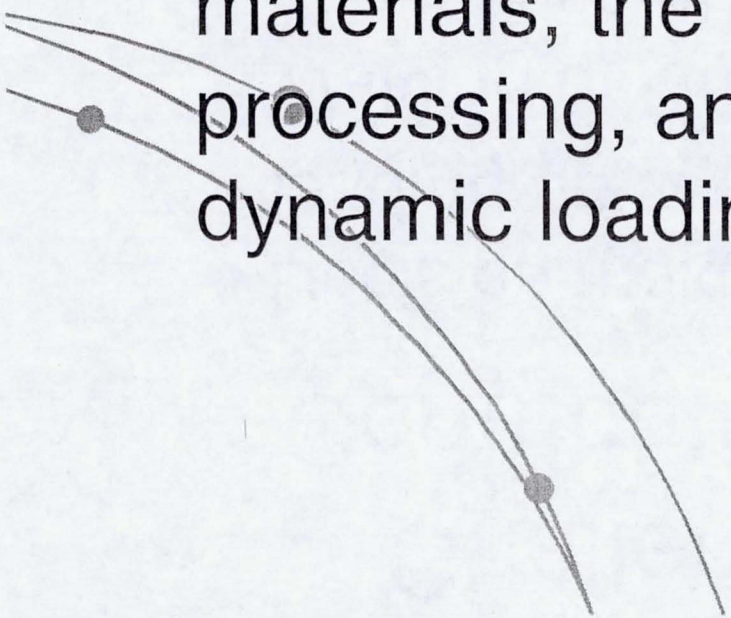
SRB Field Joint Redesign





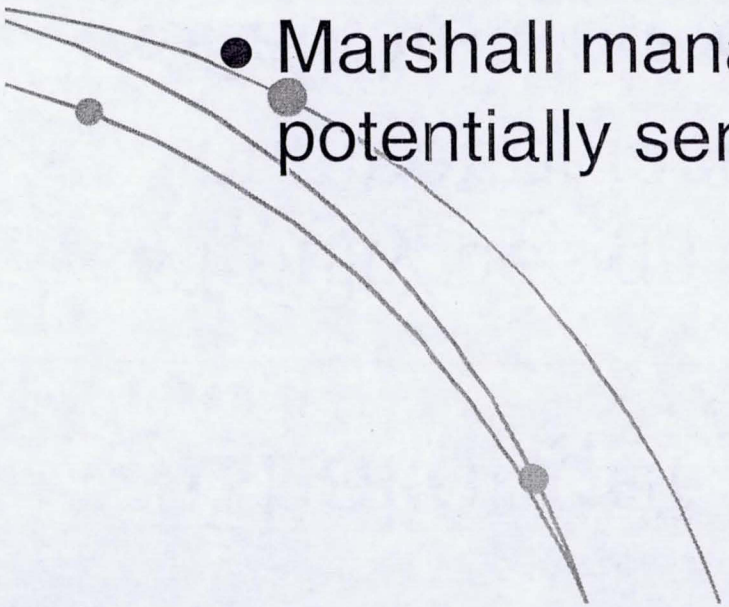
Challenger Commission Findings

- Faulty design unacceptably sensitive to a number of factors
- Factors were effects of temperature, physical dimensions, the character of materials, the effects of reusability, processing, and the reaction of the joint to dynamic loading



Challenger Commission Contributing Cause Findings

- Decision making process seriously flawed leading up to launch of Challenger
- Waiving of launch constraints appeared to be at expense of flight safety and was not reviewed by all levels of management
- Marshall management appears to hold potentially serious problems internally



Challenger Commission Contributing Cause Findings

- Rockwell recommendation regarding ice-on-the-pad was ambiguous
- NASA's response did not indicate appropriate consideration of Rockwell's input
- Freeze protection on the pad was inadequate

Challenger Commission Findings
Accident Rooted in History

- SRM joint test and certification program inadequate
- Neither NASA nor Thiokol understood join sealing mechanisms
- NASA and Thiokol accepted escalating risk because they " got away with it last time"

Challenger Commission Findings
Accident Rooted in History

- Tracking of anomalies for Flight Readiness Reviews failed in not identifying joint seal failures on previous flights
- O-ring failure history presented to NASA Level I August 1985 was sufficient to require corrective action before next flight
- A careful flight history analysis would have revealed the correlation of O-ring damage with low temperatures

Challenger Commission Findings Silent Safety Program

- Reductions in Marshall safety, reliability, and quality assurance work force limited capability in those functions
- Organization structures at Kennedy and Marshall place safety, reliability, and quality assurance offices under the offices whose activities they are to check
- Problem reporting requirements are not concise and fail to communicate to proper management

Challenger Commission Findings
Silent Safety Program

- Little or no trend analysis on O-ring problems
- As flight rate increased, safety, reliability, and quality assurance workforce at Marshall was decreasing, adversely affecting safety
- Five weeks after the Challenger accident, the criticality of the SRM field joint was not properly documented in the Marshall problem reporting system

Challenger Commission Findings
Pressures on the System

- Shuttle flight processing and training system capabilities were stretched to limit due to flight rate
- Spare parts were in critically short supply
- When flights occur in rapid succession, no system in place to ensure anomalies are addressed before next flight

Challenger Commission Recommendations

I. Redesign SRB with Independent Oversight

II. Place more authority with Program Management

Assign Astronauts to Management

Establish a Shuttle Safety Panel

III. Review critical items and hazards analysis

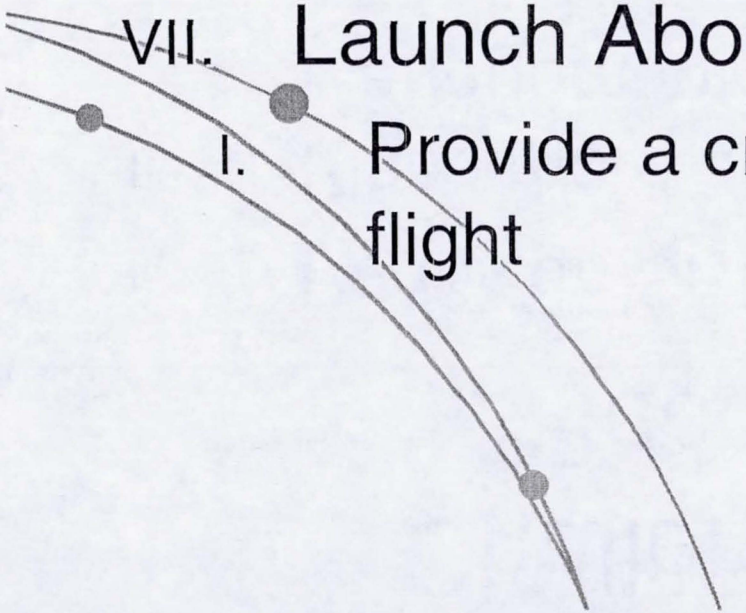
IV. Establish an Office of Safety Reliability and Quality Assurance at Headquarters

Challenger Commission Recommendations (continued)

V. Improve Communications
   I. Constraints
   II. FRR records and attendees

VI. Landing Safety

VII. Launch Abort and Crew Escape
   I. Provide a crew escape system for gliding flight



NASA Response to Challenger

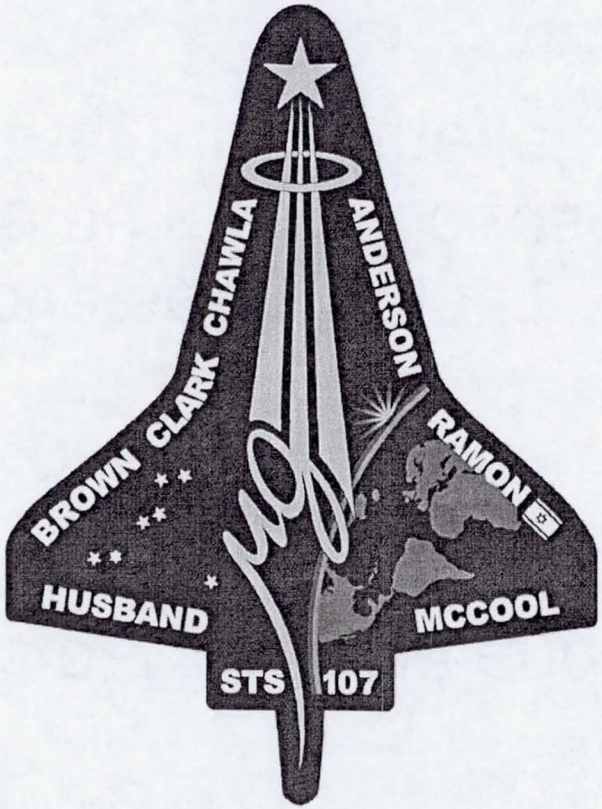
- Redesigned SRM with Independent Oversight of Design Activities
- Reorganized Shuttle Management to Report to Headquarters
- Appointed Astronauts to Management Positions (Associate Administrator for Space Flight)
- Established Shuttle Safety Panel

The Columbia Accident

- Columbia's mission STS-107 launched on January 16, 2003
  - 113th Space Shuttle Mission
- Columbia was lost during atmospheric reentry February 1, 2003
- 7 crew members were killed
- NASA Administrator Appointed Investigation Team
- Determine the facts, as well as the actual or probable causes of the Shuttle mishap in terms of dominant and contributing root causes and significant observations and, recommend preventive and other appropriate actions to preclude recurrence of a similar mishap.

Columbia Accident

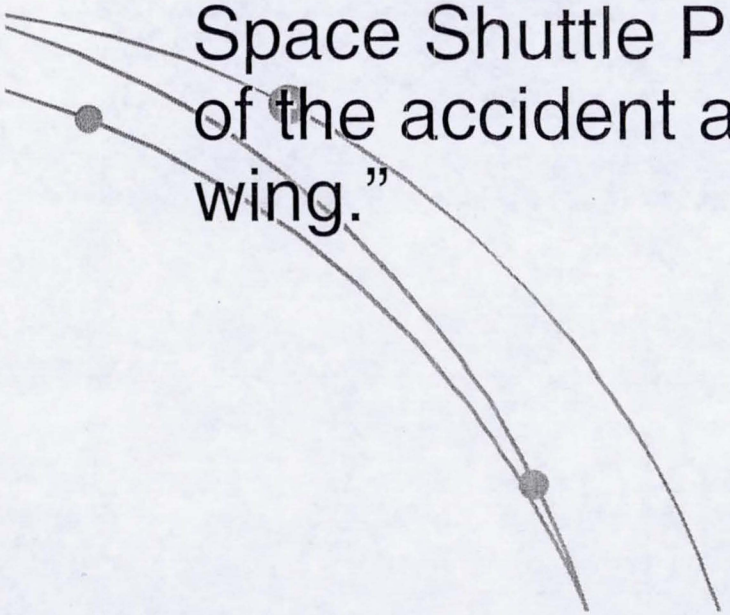




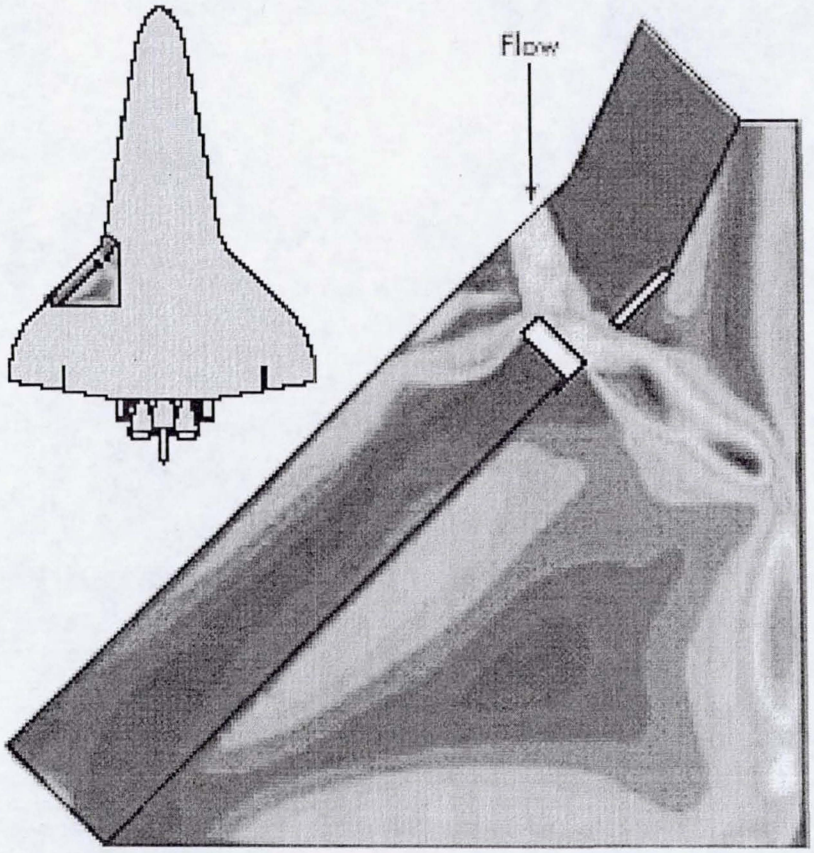
Columbia Accident Investigation Board Findings

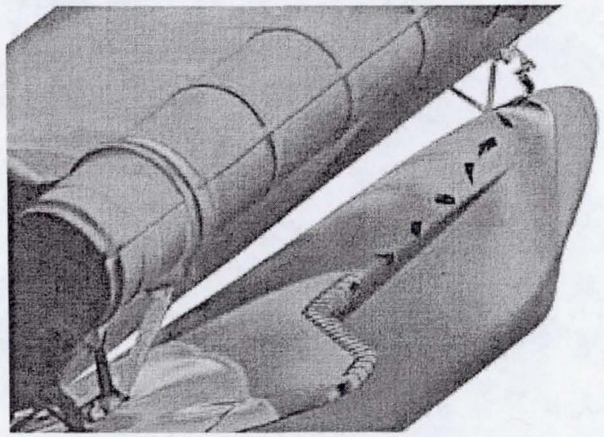
"The physical cause of the loss of Columbia and its crew was a breach in the Thermal Protection System on the leading edge of the left wing."

"..the management practices overseeing the Space Shuttle Program were as much a cause of the accident as the foam that struck the left wing."

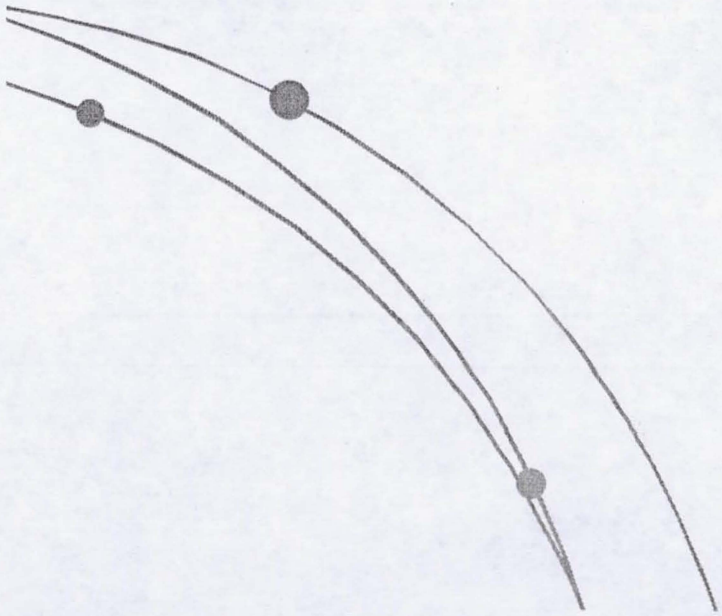


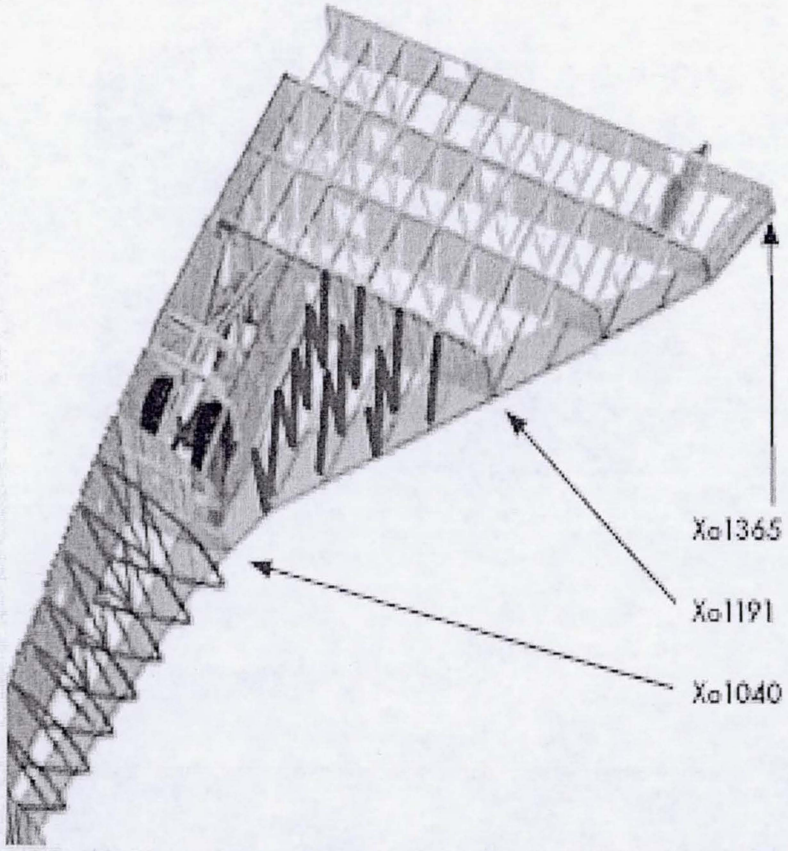
Columbia Accident





Columbia Accident





Columbia Findings

Technical

- NASA does not fully understand External Tank (ET) foam loss mechanisms
- 80% of 79 missions with imagery have had ET foam loss
- Reinforced Carbon-Carbon (RCC) not required to have impact resistance
- Inspection techniques inadequate for RCC
- Two foam closeout processes on ET able to be performed by one-person

CAIB Findings

Technical

- Photographic evidence indicated foam projectile impacted leading edge of left wing in area of RCC panels 6 through 9
- Data on foam was adequate to determine its effect on both thermal tiles and RCC
- Columbia entered atmosphere with preexisting breach in left wing
- NASA debris impact analysis tools inadequate

NASA Response to Columbia

Technical

- SRB bolt catcher certification done by analysis
- Quality assurance on bolt catchers not adequate to assure product acceptability
- Unknown metal object seen separating from Shuttle during SRB separation on 6 missions

CAIB Findings

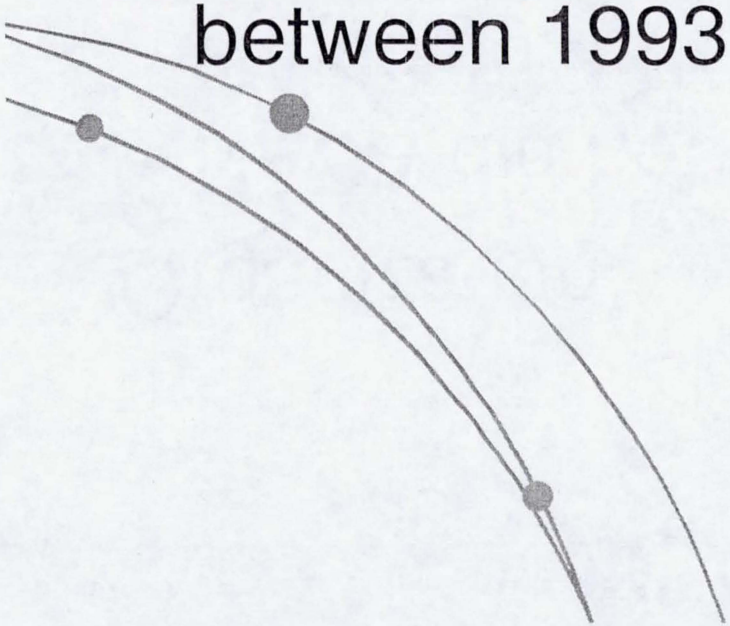
Organization

- By Columbia, many institutional practices in place at Challenger had returned
  - Silent Safety Program
  - Acceptance of deviations from expected performance
  - Schedule pressure
- Space Flight Operations Contract

CAIB Findings

Organization

- Shuttle budget reduced 40% over last decade
- Shuttle workforce reduced by 42% between 1993 and 2002



CAIB Findings

Organization

- NASA did not follow its rules on foam shedding
- Foam shedding evolved from serious safety concern to in-family or no safety of flight risk or accepted risk
- Lack of feedback among projects on in-flight anomalies

CAIB Findings

Organization

- Resolution of STS-112 foam loss in-flight not due until after Columbia mission
- No trend analysis performed on foam loss
- NASA headquarters focus on ISS schedules
- System capabilities stretched to support schedule

CAIB Findings

Organization

- NASA safety system historically deficient
- Administrator for SR&QA not responsible for execution but instead policy
- Little progress in integrated Shuttle hazards analysis
- Shuttle Systems Integration office handles all systems except Orbiter
- Lessons learned are not part of process

CAIB Findings

Decision Making

- Foam strike identified during photo review on flight day 2 larger than any seen before
- Outside imagery of Orbiter for damage assessment requested by Chair of photo working group on flight day 2
- Debris team model used outside calibrated database
- Uncertainties in analysis not communicated to management
- RCC damage not mentioned in management briefings

CAIB Findings

Leadership

- Management not engaged in foam analysis
- Management had belief that foam strike not a safety of flight issue
- Management required engineers to prove debris strike was unsafe instead of safe
- Management did not challenge presentations

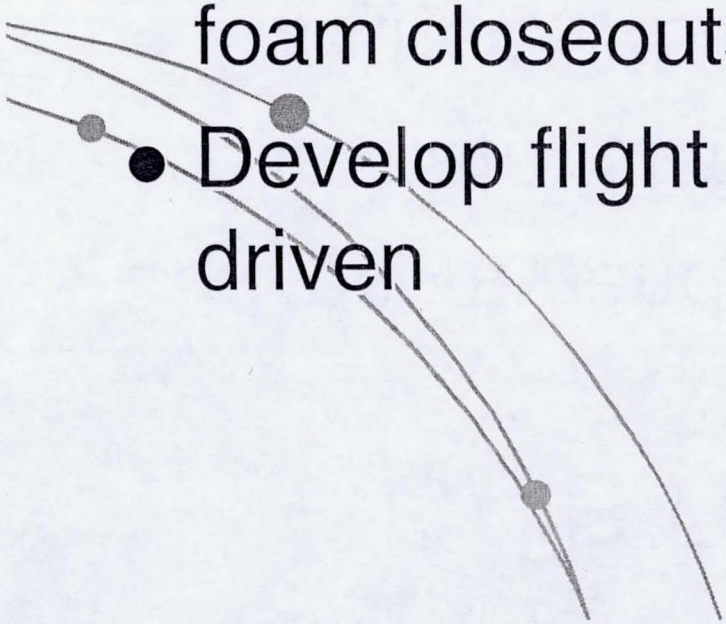
CAIB Recommendations

29 Recommendations

- Eliminate ET foam shedding
- Toughen Orbiter TPS
- Improve inspection of RCC
- Develop on-orbit inspection and repair of TPS and RCC
- Develop validated analysis models for debris assessment

CAIB Recommendations

- Provide sensors on Orbiter for vehicle health and monitoring
- Develop wiring inspection techniques
- Require at least 2-employees attend all ET foam closeouts
- Develop flight schedule that is resource driven



CAIB Recommendations

- Conduct mission management team training
- Establish independent technical authority responsible for requirements and waivers
- Establish Safety and Mission Assurance with line authority over program
- Update drawings and verify configuration accuracy with closeout photos

NASA's Response to CAIB

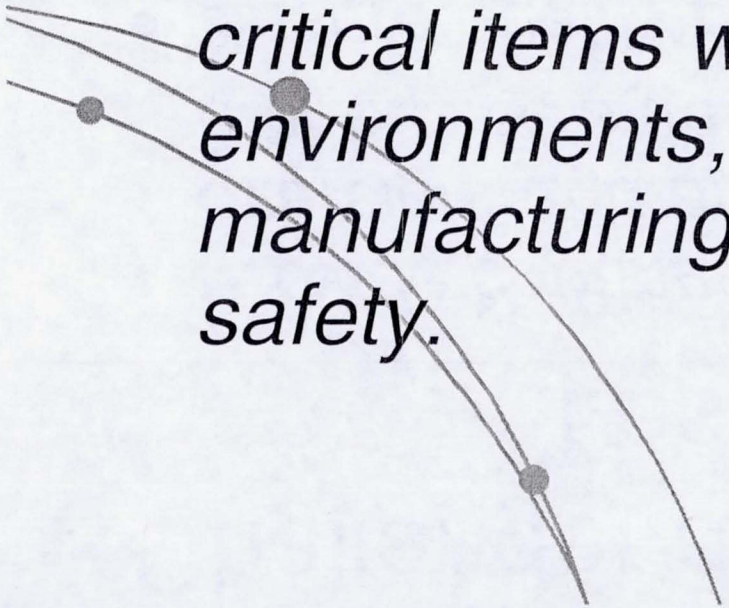
- NASA is addressing technical and organizational causes of accidents
- Formed NASA Engineering and Safety Center for technical oversight of programs
- NASA Implementation Plan for Space Shuttle Return to Flight and Beyond
  - Addressing all CAIB recommendations and observations
- Return to Flight Oversight Committee
- Addressing cultural issues through management structural changes, assessment, and training

Challenger and Columbia Common Lessons Learned

- *Provide continual, independent, program oversight and program review functions that emphasize safety.*
- *Ensure quality program and safety management that have clear definition of authority and responsibility and have resources commensurate with requirements.*
- *Maintain comprehensive and effective program processes and systems that support the safety risk management function.*

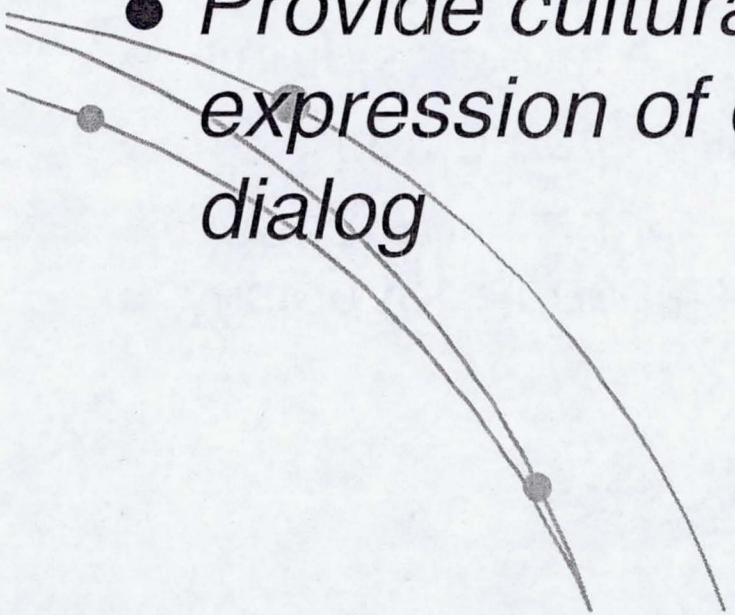
Challenger and Columbia Common Lessons Learned

- *Maintain realistic plans that have provisions for flexibility, minimize outside pressures and stress flight and ground safety.*
- *Control effectively the development of critical items with respect to performance environments, tolerances, margins, manufacturing processes, testing and safety.*



Challenger and Columbia Common Lessons Learned

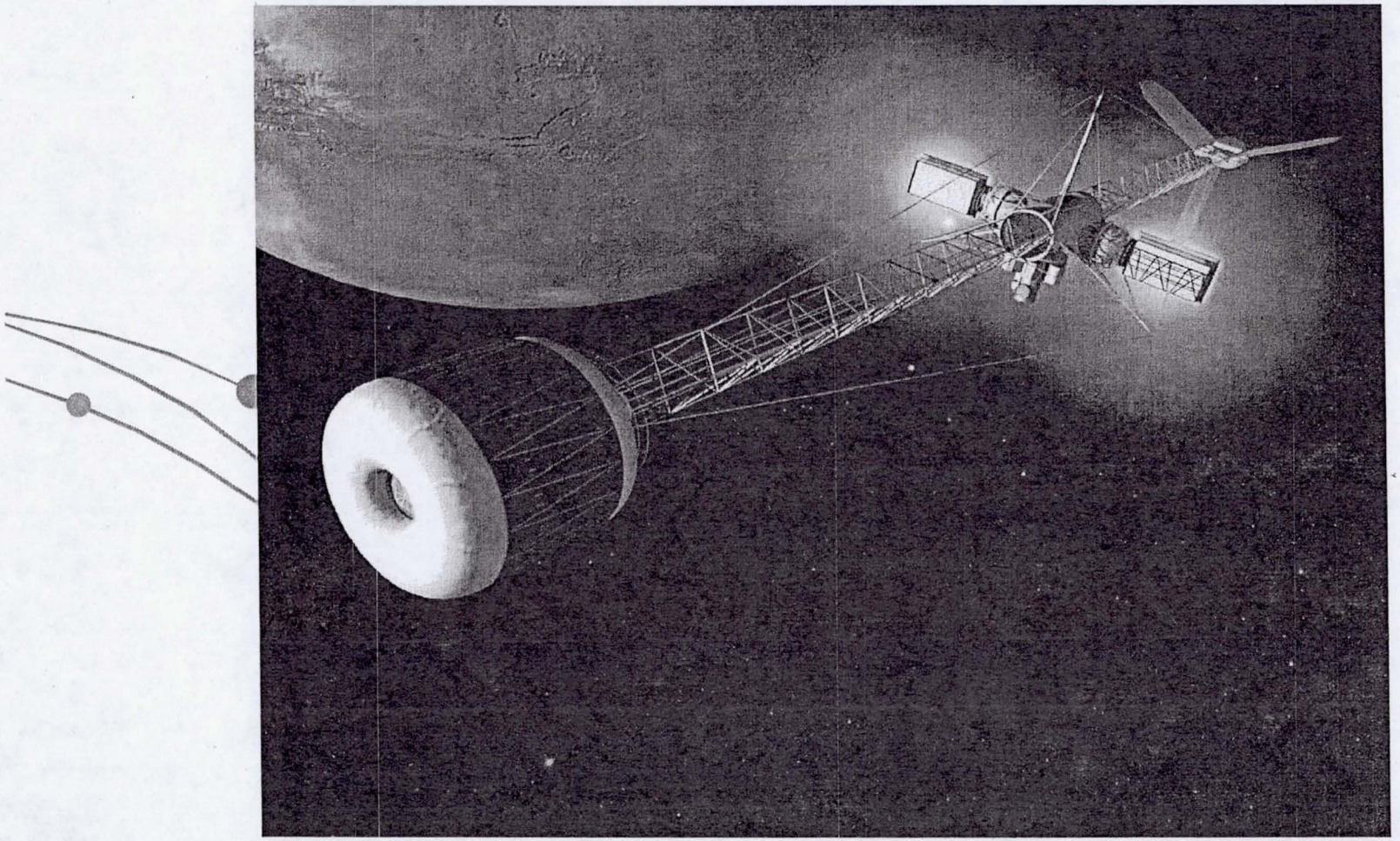
- *Ensure quality performance of work force involved in safety critical operations including adherence to required procedures and constraints.*
- *Provide cultural climate conducive to expression of differing opinions and open dialog*



The Future

- Vision for Space Exploration issued by President Bush January 14, 2004
- Fly Shuttle until 2010
- Complete Space Station Assembly
- Focus Station research on space exploration goals
- Begin robotic missions to moon by 2008, human missions to moon by 2020
- Continue Mars robotic exploration
- Conduct human missions to Mars after capability exists
- Develop a Crew Exploration Vehicle to support exploration

"This cause of exploration and discovery is not an option we choose; it is a desire written in the human heart"
President George W. Bush



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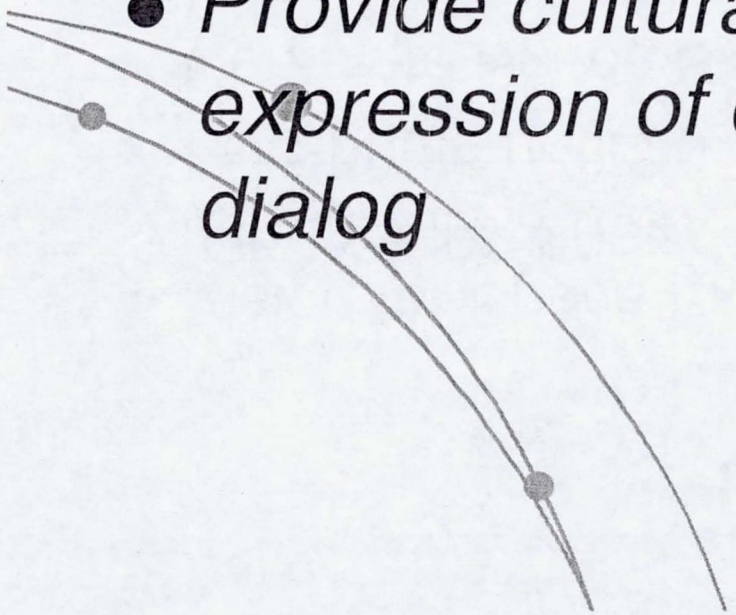

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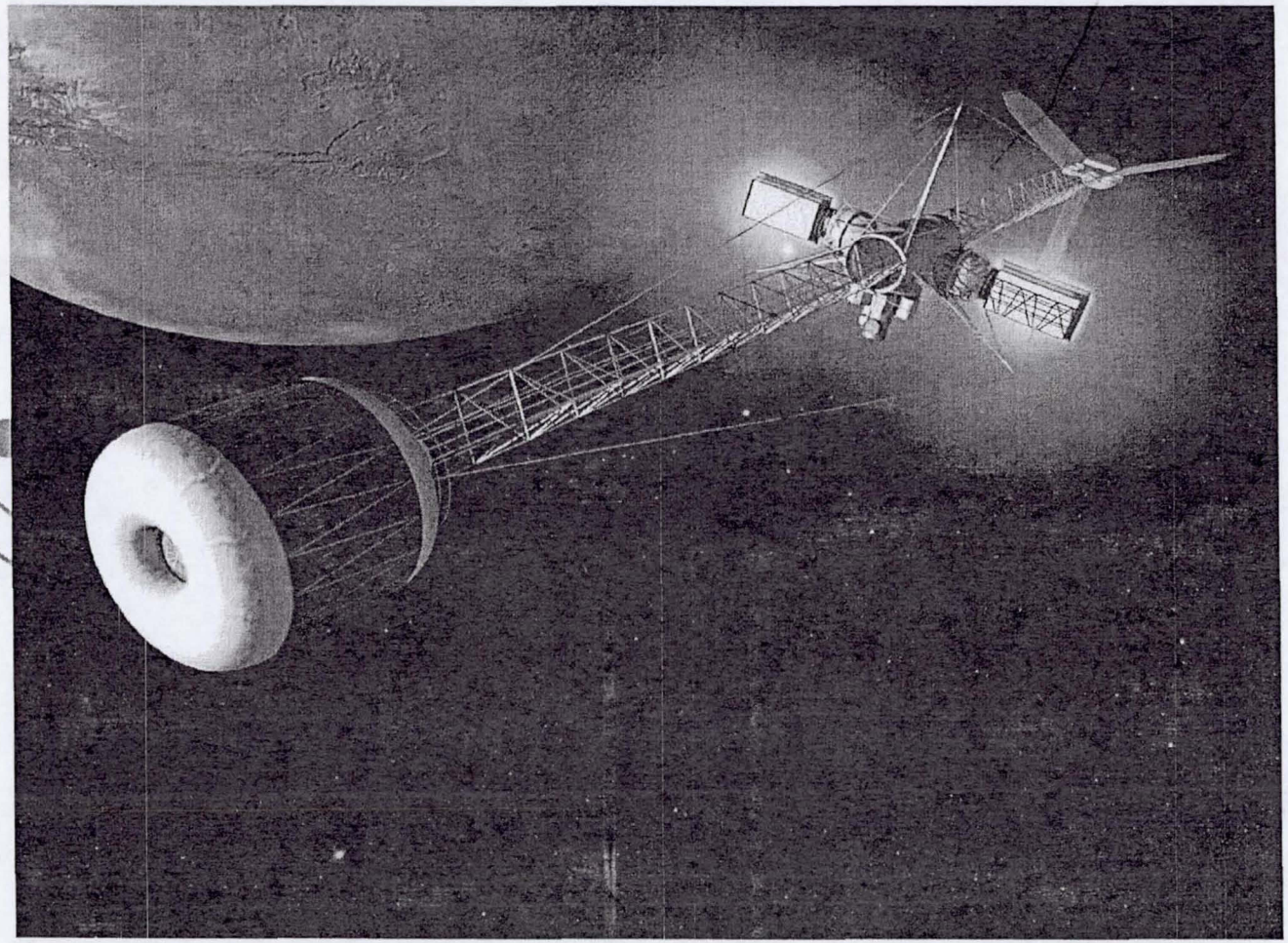

Commissioning MMS: Challenges and Lessons Learned

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***Abstract*—This paper discusses commissioning of NASA's Magnetospheric MultiScale (MMS) Mission. The mission includes four identical spacecraft with a large, complex set of instrumentation. The planning for and execution of commissioning for this mission is described. The paper concludes by discussing lessons learned.**

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1. INTRODUCTION

MMS [1] consists of a constellation of four (4) identical spin-stabilized spacecraft (S/C) with numerous instruments and processing modules making up the Solving Magnetospheric Acceleration, Reconnection, and Turbulence (SMART) Instrument Suite (IS). The S/C fly in a tetrahedral formation in highly elliptical orbits, necessitating precise maneuvers and onboard navigation. As the purpose of these S/C is scientific study, they are normally referred to as observatories, and, when we are referring to the entire satellite, we will use that term. The observatory is logically broken into two (2) pieces, the spacecraft bus, and the payload. We will discuss commissioning both.

MMS commissioning included many activities such as spacecraft bus activation, low-voltage turn on, deployments, and initial high-voltage activities; a shadow season with specialized commissioning activities; a post-shadow commissioning period including high-voltage activation, cross-calibration, and interference campaigns; and preparation for nominal science operations. In addition, each spacecraft performed thirty-two (32) maneuvers during the commissioning period.

Spacecraft bus commissioning included bus component activation, verification/characterization of the Radio Frequency (RF) communication, attitude control, onboard navigation, thermal control, and power systems, and included maneuvers to achieve mission orbit and attitude. Over the same time span, *payload commissioning* focused on initial activation and low voltage checkout of each sensor, boom deployments, gradual power up of high voltage instruments, and coordination of activities across the constellation. Almost all commissioning activities were completed at least four (4) times across the MMS constellation, although there were a few activities that were performed on a subset of observatories. Ground system commissioning included testing to identify and resolve network and multi-facility interface issues, which could not be tested prior to launch.

Planning for MMS commissioning addressed several critical activities and required coordination across multiple organizations, facilities, and resources including terrestrial

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and space communication networks. Mission planning responsibilities were performed by four (4) groups: (1) MMS program planners, responsible for building the long term (strategic) and day to day (tactical) schedule for payload commissioning coordinated with spacecraft activities, maneuvers, and ground contacts; (2) the Mission Operations Center (MOC), responsible for developing the tools necessary for S/C deck operations; the (3) Payload Operations Center (POC), responsible for planning the details of activities to be performed on the payload during each contact; and (4) Instrument Team Facilities (ITFs), responsible for providing instrument and investigation specific activity plans and instructions.

As the commissioning process proceeded from planning to execution, several challenges developed. The baseline commissioning plan quickly grew in complexity prior to launch as the amount of effort to commission four (4) spacecraft, the strict sequencing of operations to avoid instrument operational conflicts, and other factors had to be accommodated by the plan. Once under way, the need to adapt the schedule to deal with anomalies and investigate science targets of opportunity, the uncertainties posed by the limitations of ground emulation hardware, and delayed delivery of some instrument inputs began to require more instrument concurrent operations and last minute scheduling. However, thanks to solid preparation, commissioning was able to proceed with minimal impact from these potential disruptions.

2. COMMISSIONING BACKGROUND

The Science

The MMS Mission is an international, multi-institutional effort funded by NASA under the Solar-Terrestrial Probes program to "enable an understanding of **magnetic reconnection** in the boundary layers of the Earth's magnetosphere, which is formed by its interaction with the solar wind." [1] **Magnetic reconnection** occurs when the magnetic fields embedded in collision less plasmas become interconnected, converting magnetic field energy into the kinetic energy of the plasma ions and electrons [2]. In order to determine that magnetic reconnection is occurring, concurrent, three-dimensional maps of particle distribution functions, electric and magnetic fields, and plasma waves need to be made [3]. These measurement requirements flow directly into the mission configuration. The requirement for concurrent, three-dimensional (3D) measurements at varying temporal scales drives the use of a four (4) spacecraft tetrahedron; and the requirement for particle, and fields and waves measurements drives the instrument configuration of the observatories. Observations are separated into two (2) distinct science phases. Phase 1a observations occur on the dayside with crossings into the magnetosheath, while Phase 2 observations will occur in the magnetotail. A commissioning phase (Phase 0) occurred prior to Phase 1a, and a transitional phase (Phase 2a) between Phases 1a and 2b.

Each MMS observatory orbits in a 1.2 x 12_{Re} orbit for Phase 1 while maintaining a minimum quality tetrahedron throughout the science Region of Interest (ROI). Tetrahedron quality is based on the six (6) tetrahedron side lengths and the total volume within the tetrahedron. The tetrahedron is re-sized (ranging from approximately 160 to 10 km spacing for Phase 1, 400 to 25 km for Phase 2b) and re-constituted numerous times throughout the mission requiring precise locational knowledge.

During the operational phases, MMS collects high-resolution data in the science ROI where reconnection is likely to occur, and lower resolution data outside the ROI. Within the ROI, medium resolution "survey" data are automatically downlinked for evaluation. Data are automatically tagged with quality measures, but humans perform a Scientist in the Loop (SITL) evaluation and ultimately determine what high-resolution data from a particular ROI will be downlinked. "Burst" activity data (the highest resolution data) not selected for downlink are automatically marked available for reuse by this process; "burst" activity data downlinked are automatically marked for reuse once they have been successfully downlinked.

The Observatories

Each MMS observatory is functionally identical. Attitude determination and control is provided by a complement of the Danish Technical University's four (4)-head star sensor and an Adcole Digital Sun Sensor, supplemented with ground-based attitude determination software. Due to the timelines for formation maneuver execution and the requirement on interspacecraft time knowledge, MMS flies an onboard orbit determination system, supplied by Navigator, a specialized Global Positioning System (GPS) receiver with weak signal acquisition, a high-resolution and accuracy accelerometer from Zin Technologies, and the Goddard Enhanced Onboard Navigation System (GEONS), an extended Kalman filter-based orbit estimator. A complement of twelve (12)-thrusters (banks of four (4)-lbf radial thrusters on two side panels and two (2) 1-lbf axial thrusters on the top and bottom decks) execute both attitude and orbit maneuvers. Maneuver control can be executed open loop or via an onboard delta-V or delta-H controller developed for MMS to enable execution of precision maneuvers on a spinning spacecraft with flexible body motion. The spacecraft bus was built in-house at NASA's Goddard Space Flight Center (GSFC).

The observatories include separate "S/C" and payload decks. The S/C deck (Figure 1) includes the power; communications; thermal management; S/C processor; solid state recorder; and guidance, navigation and control subsystems. The S/C deck also includes the payload's magnetic booms and one of the Energetic Particle Detector (EPD) components. Communications modes include high data rate communications to the Deep Space Network (DSN), and lower data rate to the Near Earth Network (NEN) and Space Network (SN), with all contacts at S-band.

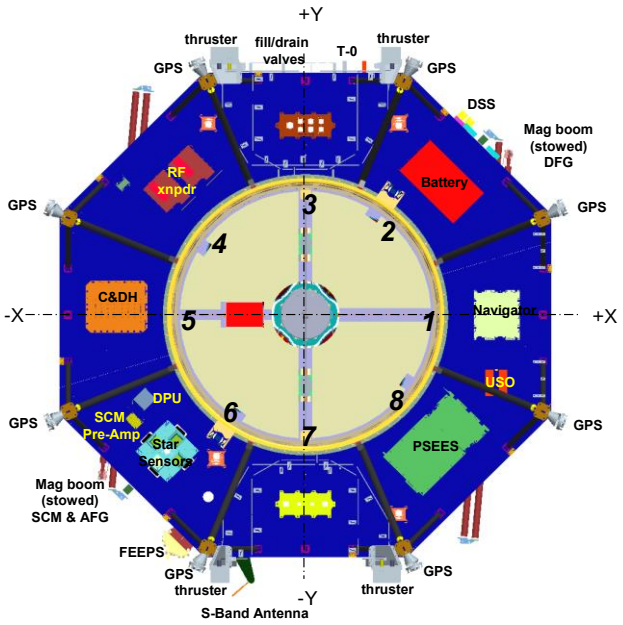

Figure 1. S/C Deck

The payload deck (Figure 2) contains the remainder of the instruments needed to make the required measurements. Each MMS payload deck contains six (6) major subsystems including instruments, observatory electrical potential management, and data processing/recording components. The six major subsystems are referred to as "investigations", several of which consist of multiple instruments, processing units, or other components. The investigations are: (1) Fields Suite - 3D electric and magnetic field sensors; (2) Fast Plasma Investigation (FPI) – full sky, thirty-two (32) energy step electron and ion sensors (10 eV – 30 keV); (3) Energetic Particle Detectors (EPD) – all-sky ion and electron energetic particle sensors (20-500 keV); (4) Hot Plasma Composition Analyzer (HPCA) – 3D ion energy distributions of H^+, He^{++}, He^+, O^+, and background measurement; (5) Active Spacecraft Potential Controller (ASPOC) - to keep the observatory electrical potential within 4 V of the ambient environment, enabling consistency of measurements; and (6) Central Instrument Data Processor (CIDP) – controls S/C access to payload and stores science data for future analysis [4].

More importantly from a commissioning perspective, a total of twenty-six (26) payload components (per S/C) required commissioning activities as follows: Fields (four spin-plane double probes [SDPs], two (2) Axial Double Probes [ADP] with two (2) receiving elements, two (2) Electron Drift Instruments [EDIs], an Analog Flux Gate [AFG] Magnetometer, a Digital Flux Gate Magnetometer [DFG], and a Search Coil Magnetometer [SCM]), FPI (four Dual Electron Spectrometers [DES], and four Dual Ion Sensors [DIS]), and an Instrument Data Processing Unit (IDPU), EPD (two Fly's Eye Energetic Particles Sensors [FEEPS] and an Energetic Ion Spectrometer [EIS]), ASPOC (two (2) each with four (4) emitters), HPCA (1), and CIDP (1). The Fields investigation receiving elements, SDP, and ADP required one (1) or more deployment step prior to reaching the operational state.

The Commissioning Team

The subsystems were commissioned by teams comprised of personnel from two (2) continents, five (5) states, and five (5) time zones. Early commissioning activity (Low Voltage [LV] check out, High Voltage [HV] check out of one (1)

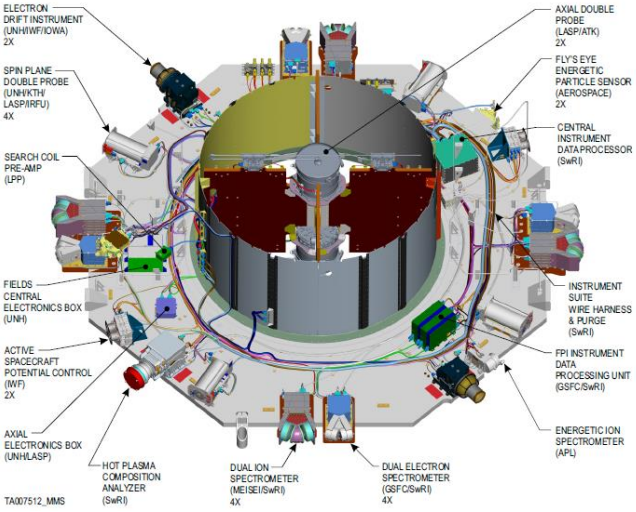

Figure 2. Payload Deck

instrument, and deployments) were performed on-site at University of Colorado/Laboratory for Atmospheric and Space Physics (CU/LASP), but later activities were coordinated remotely. The team consisted of:

- NASA Goddard – Mission Management, S/C Integrator, Mission Planning, MOC, Flight Dynamics Operations Area (FDOA), and the FPI ITF
- CU/LASP – Payload Operations Center (POC), Daily Planning and Payload Commissioning Execution
- Southwest Research Institute – IS integrator, IS Systems Engineers (ISSE), CIDP ITF, and HPCA ITF
- University of New Hampshire – Fields ITF including EDI and Fields deployables
- Johns Hopkins University/Applied Physics Laboratory – EIS ITF
- Aerospace Corp. – FEEPS ITF
- Institut für Weltraumforschung of the Austrian Academy of Sciences – ASPOC ITF

Commissioning Roles

MMS defined the following roles for commissioning:

- Executive Planner – Coordinate across all the stakeholders (Project Management, Guidance, Navigation, and Control [GNC], Propulsion, Thermal, Power, RF Communications, Command & Data Handling, POC, ITFs, and the three communication networks) to establish a master schedule that incorporates S/C activities (such a maneuvers and bus calibrations) and IS activities.

- Flight Director (FD) – Overall S/C operation, determines when payload commanding is permitted within a communications contact.

- Product Development Lead (PDL) – Subject matter experts for the S/C subsystems. They monitor responses and provide GO/NO GO direction to the FD as activities are performed.

- POC Planner – Assimilate master schedule information and produce individual activity plans that account for S/C and IS state, constraints (e.g., orbital location), and commanding requested by ITFs.

- POC FD – Overall responsibility for the IS with a focus on safely and efficiently completing the scheduled activities and responding to anomalies.

- POC Flight Controller (FC) – Voice of the POC to coordinate between the MOC and the ITFs, the FC follows the scheduled activities scripts.

- POC Command Controller (CC) – Execute the commands and scripts that control the activities under direction of the POC FC & POC FD.

- ITF – Subject matter experts for the instruments. They monitor instrument responses and provide GO/NO GO direction to the POC as activities are performed.

- IS Systems Engineer (ISSEs) – Represent integrated IS concerns and (usually) act as subject matter experts for the CIDP. For critical activities such as deployments, ISSEs provide GO/NO GO direction for the CIDP ITF and the IS as a whole.

3. COMMISSIONING PLANNING

Commissioning Constraints

With its large complement of instrument sensors, precision maneuvers, and four observatories, MMS proved unique among its spacecraft peers. Early on the commissioning team sought lessons learned from other multi-spacecraft missions. *Cluster*, operated by the European Space Operations Center (ESOC) in Darmstadt, Germany, offered insights into the human resource limitations and specifics about MMS predecessor instruments flying on *Cluster*. In addition, ESOC offered insights into their methods for planning maneuvers. Experience from the Time History of Events and Macroscale Interactions during Substorms (*THEMIS*) and the *Van Allen Probes* (formerly known as the Radiation Belt Storm Probes [*RBSP*]) was sought and found to be minimally applicable, as neither mission had as many sensors as each MMS observatory, nor the need to execute precision maneuvers to achieve the correct attitude and orbital placement.

Based on the feedback from *Cluster* and experience from operating other spacecraft from GSFC, the following list of scheduling rules were instituted to mitigate the impact of commissioning on the human element, maintain safe instrument operations, and work within cost constraints. In the following lists, an (S) represents a soft constraint that could be broken if needed; an (H) represents a hard constraint that involved mission safety; and a (~) represents a hard constraint depending on the ITF team-attributes. Human factors constraints included:

- Plan the entire schedule for six (6) days ON/ one (1) day OFF per week to allow for one (1) contingency day per week (S)

- Keep similar activities for an investigation in the same relative time slots each day, and if more than one (1) event needs to be executed, keep them in same twelve (12)-hour shift to maintain human element. (S)

- If the time slot for a set of activities for an investigation has to change to a different shift, allow at least two (2) days between shift changes to allow human factors adjustment to time change. (~)

- Schedule no more than four (4) consecutive days on the same activity to avoid team burn-out; if one must perform an activity set for longer than four (4) days, the schedule should allow for an extra day off before re-starting activities with that group of personnel. (S)

- Follow a 1-1-2 pattern for each new activity to give the ITF time to work any anomalies or quirks that arise. [Notionally, this translates to: perform the activity on S/C #1; wait a day then perform same activity on S/C #2; wait a day, then perform the activity on S/C #3 & #4 on the last day. (S)]

Cost constraints on the mission led to requirements for minimal network scheduling changes and consolidated travel periods for the ITFs during commissioning. The onboard navigation system needed a calibration period and would not be used operationally until after completing all the deployments, which led to a need for early orbit radiometric tracking data from the contacts with the networks. The S/C communication system supported only Doppler from DSN and NEN, and both range and Doppler from the SN. However, DSN provided higher data rate and was schedulable around apogee in the science Region of Interest. In addition, the flight dynamics team needed two (2) perigee transits between maneuvers to estimate the orbit in order to plan the next delta-V maneuver. All of these contributors led to the following additional set of rules:

- Develop patterned contact schedules (see description below) to avoid the cost of ad hoc contact schedules. (H)

- Consolidate Activities for an investigation as close as possible in calendar days, given the instrument constraints and human factors rules, to minimize travel costs. (H)

- Restrict IS activations to DSN contacts to obtain higher real time telemetry rate. (H)

- Allow adequate time to downlink data via DSN on each spacecraft every day, at least one (1) hour per spacecraft (solved with contact patterns) (H).

- Throughout the maneuvering period prior to GEONS calibration schedule a round-robin sequence of shorter-duration SN contacts throughout the four (4) hours before and after perigee to obtain radiometric tracking in the most dynamic region of the orbit. (H)

- Separate consecutive large delta-V maneuvers on the same S/C by at least forty-eight (48) hours prior to GEONS calibration. (H)

The DSN contact pattern needed to fulfill several parameters. It had to be identified and implemented by specific rules for use by the multi-mission network scheduler, such as the time duration following perigee to start contacts. The patterns also had to provide flexibility for the activity planning and had to limit late-breaking changes to the contact schedule in case of a contingency. The patterned contact schedule used the first three weeks consisted of a round-robin of 2-hour contacts on each observatory starting with MMS-2, centering the four observatories around apogee in reverse numerical order to meet maneuver requirements for the perigee-raising campaign. The contacts changed to an A-day/B-day pattern starting at week four in order to:

- Provide four (4)-hour focus contacts on two observatories each day

- Provide adequate contact time on each observatory for data downlink

- Provide geometric diversity in locations over two consecutive days to accomplish radiometric tracking considerations

Besides the human factors and contact limitations already mentioned, the remaining constraints for execution fell into six categories:

1. Earliest time after launch to activate a sensor (to allow for outgassing);
2. Orbital location and attitude spin axis pointing and spin rate;
3. Operation exclusion window around shadows (power limits);
4. Operation exclusion window around maneuvers (to avoid plasma contamination);
5. Interval and frequency of an activity, and the duration after completing the previous activity before starting the next activity;
6. S/C environmental conditions, such as thermal and electrical potential, required to begin an activity.

Communication

To enhance communication among all the stakeholders, there was a clear early need to establish a Commissioning Working Group (WG) consisting of a member from each ITF knowledgeable about the instrument operations, the ISSEs, Mission Systems Engineers, and the commissioning planning team. The WG held planning telecons every fortnight in order to gather inputs on the commissioning operations for each sensor, to answer questions related to operations and resolve issues, and to educate the science team on the imposed constraints such as:

- Real time telemetry allocation

- Data delays for the different telemetry virtual channels

- Implications of the S/C lunar and solar eclipses

In addition, the Commissioning team held splinter discussions at each semi-annual Science Working Team meeting to discuss items of general interest to the whole audience and specific items that benefit from face-to-face interchanges, such as the nuances associated with sensitive high voltage operations.

For commissioning execution, the WG morphed into two meetings: a daily Tactical Planning meeting and a weekly Strategic Planning meeting. The Tactical meeting covered the upcoming three to five days with participation from the ISSEs, POC, MOC, FDOA, as well as any interested ITF. The Strategic Planning meeting covered a sliding multi-week period to focus on longer-range planning and special topics, with additional participation from the ITFs and S/C PDLs.

Commissioning Procedure Development

While the Integration and Test effort offered a preliminary view of the procedures needed to activate the instruments, most procedures migrated from I&T needed significant changes for commissioning. In addition, each Activity for each sensor had a set of constraints that were either mandatory for instrument safety or highly desired in order to achieve the best results. The Commissioning WG defined a template for Activity Definition Forms (ADF) to provide descriptions of the activation and deployment activities as well as configuration updates and configuration and software loads. The ADF documented constraints and outlined steps for command and telemetry evaluation and included the following:

1. the duration of each step,
2. the frequency of execution,
3. the commands and telemetry, and
4. the instrument end state with an indication of whether the instrument could be safely operated via ATS around maneuvers and shadows after procedure completion.

The ADFs served as input to Colorado System Test and Operations Language (CSTOL) [5] procedure development performed by both the ITFs and the POC. If an ITF delivered the CSTOL procedure, then the POC performed the syntax verification only; otherwise, the POC defined the CSTOL and performed the syntax verification. Each procedure was tested on the IS FlatSat prior to use operationally. Figure 3 shows a flow diagram for the CSTOL development process. A similar process was followed with the S/C subsystems: each S/C PDL provided inputs in a template to describe the activities needed to commission their subsystem with associated duration, commands, telemetry, and other parameters. The mission operations team developed System Test and Operations Language (STOL) procedures from these templates and validated them on the S/C Flatsat or the software-based. Mission Training Simulator prior to execution. Information for the IS activities were documented on the IS Commissioning Plan Wiki maintained by the POC.

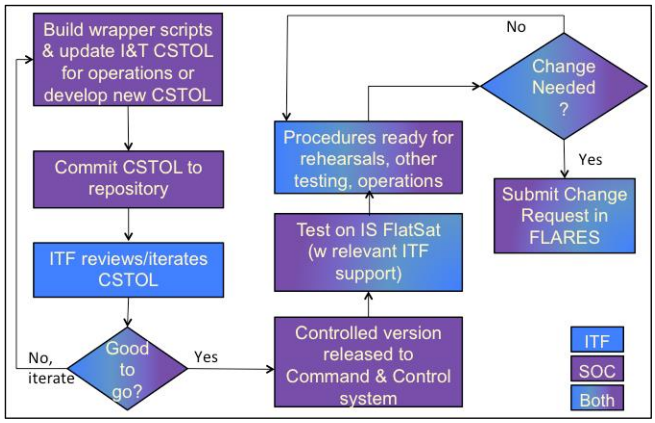

Figure 3. Process flow for developing CSTOL procedures for MMS commissioning

Commissioning Activities

Among the IS and the SC, there were eight hundred and forty-eight (848) activities defined prior to launch including an initial flight software load for EDI, and CIDP command sequence loads that repeated several times during commissioning. Table 1summarizes the number of activities per sensor and per S/C as well as the total estimated duration needed to execute the procedures. Table 2 and Table 3 list the activity categories and number of unique activities for the IS and S/C, respectively. These activities were repeated on each observatory, and for many, they needed to be repeated at different intervals or after achieving certain observatory configurations.

Table 1. Pre-Launch Commissioning Activity Summary

	# of Activities	Total Duration	Realtime Duration
CIDP	36	31:20:00	31:20:00
ASPOC	128	0:00:00	200:23:20
EIS	36	44:56:00	59:08:00
FEEPS	20	17:04:00	12:00:00
FIELDS	107	279:29:00	215:20:00
FIELDS/EDI	164	152:00:00	152:00:00
FPI	78	154:30:00	106:30:00
HPCA	42	104:18:00	103:33:00
IS	13	130:00:00	130:00:00
SC	224	831:38:00	84:18:00
TOTAL	**848**	**1745:15:00**	**1094:32:20**
SC #1	207	441:04:30	220:02:20
SC #2	207	442:54:30	223:52:20
SC #3	205	438:54:30	219:52:20
SC #4	205	438:54:30	219:52:20
SC-ALL	24	323:47:00	130:45:00

Table 2. Instrument Suite Commissioning Activity Categories

Activity Type	Number
Low Voltage (LV)	16
High Voltage (HV)	64
Deployments	14
Instrument Suite Level (IS)	13
Care and Feeding	18

Table 3. Spacecraft Commissioning Activity Categories

Activity Type	Number
Powering the CIDP and IS	6
Table and Real Time Sequence Loads	5
Oscillator and Clock Configuration	3
Navigation Hardware and Software	4
ACS Sensors & Calibration	9
RF Communications	13
Thermal & Power	10

Planning Process

The overall flow for the commissioning plan was based on WG expertise combined with the information in the populated templates.

- The first three (3) weeks after launch focused on S/C commissioning and IS LV commissioning, as well as

the early mission maneuvers to raise perigee, deploy the magnetometer booms, and achieve the mission science attitude spin axis target.

- The following four (4) weeks focused on the SDP and ADP boom deployments and associated spin adjustment maneuvers, and initial HV activation.

- The energy balance constraints mandated a five (5)-week shadow season, which limited the availability of instruments to those that needed the heat from their operation to survive the eclipses. A primary goal was to complete all deployments of booms and to bring up one of each sensor on at least one S/C prior to the shadow season to allow the science team time to evaluate data from all of the sensors.

- HV operations continued after shadow season along with maneuvers to achieve the tetrahedral formation at the initial scale size of 160 km.

- After completing all HV Activation, the focus shifted to the interference and cross-calibration campaigns, followed by SITL, the Burst Data Management system, and observatory preparations for operations.

Commissioning had to complete prior to achieving the orbital orientation for commencing Phase 1 science operations (apogee vector at 1800 Geocentric Solar Ecliptic time), which occurred September 1, 2015, based on the nominal launch date.

Initially, a spreadsheet was developed to plan the activities for each day with color-coding used to identify the different observatories and types of activities. Each MMS S/C was assigned a color during I&T that carried over into operations (MMS-1: yellow, MMS-2: blue, MMS-3: green, MMS-4: purple). Similarly, colors were assigned to different types of activities: S/C: orange; maneuvers: maroon; deployments: green; LV: blue; HV: red; shadows: dark gray; meetings: light blue. A notional identification of the DSN and SN contacts, the significant orbital locations (apogee, ROI entry, etc.), and the time from perigee provided a template onto which each activity was placed at the approximate time for execution. The scheduling process started by placing all of the shadows and maneuvers into the timeline as events. After the events, the activities were laid in according to their constraints, with ordering as described above.

The schedule determined how quickly commissioning could be executed. The benefit of this exercise was that it provided a useful indicator to the science team of the critical path leading to Phase 1 operations, helped to illustrate the complexity of the planning process, and set expectations for the level of effort needed during Phase 0. A favorable outcome was that the science team re-evaluated their initial inputs for activities and constraints and in many cases restructured their activities into reduced durations. Fitting all of these updated activities into patterned contacts proved to be a particularly useful approach. While it provided a realizable flexibility to readily identify specific times for re-scheduling an activity in the future, it also lengthened the overall duration of Phase 0. Figure 4a shows a sample day of the spreadsheet for Orbit 4.

Orbit 4	Hrs. From	S/C ID	S/C Activities	IS Activities
PER	0.0			
	0.5			
	1.0			
	1.5			SHADOW - 30 MIN
5 Re	2.0			
2.5 Mb	2.5			
	3.0			
	3.5			
	4.0	2	SPIN ADJ to 2.5RPM #2	
	4.5	2		
9Re	5.0	2	CIDP_ACTUATOR_PWR #2	FLD 003 Motor & HOP Checkout #2
	5.5	2		
50%	6.0	1	CIDP 0002 ADP Deploy #1	
	6.5	1		ADP 001 RECEIVING ELEMENT DEPLOY #1
	7.0	1		
	7.5	1		
	8.0	4	CIDP 0002 ADP Deploy #4	
	8.5	4		ADP 001 RECEIVING ELEMENT DEPLOY #4
	9.0	4		
	9.5	4		
	10.0	3	SPIN ADJ to 2.5RPM #3	
	10.5	3	CIDP_ACTUATOR_PWR #3	FLD 003 Motor & HOP Checkout #3
	11.0	3		
	11.5	3		
AP	12.0	2		
	12.5	2	FLD 002 MAG BOOM DEPLOY #2	
	13.0	2		
	13.5	2		
	14.0	1	FLD 002 MAG BOOM DEPLOY #1	
	14.5	1		
	15.0	1	CIDP_ACTUATOR_PWR #1	FLD 003 Motor & HOP Checkout #1
	15.5	1		
	16.0	4	FLD 002 MAG BOOM DEPLOY #4	
	16.5	4		
	17.0	4	CIDP_ACTUATOR_PWR #4	FLD 003 Motor & HOP Checkout #4
50%	17.5	4		
	18.0	3		
9Re	18.5	3	FLD 002 MAG BOOM DEPLOY #3	
	19.0	3		
	19.5	3		
	20.0		INIT THERM CAPAC #4	
	20.5			
2.5 Mb	21.0		INIT THERM CAPAC #3	
5 Re	21.5			
	22.0		INIT THERM CAPAC #2	
	22.5			
	23.0		INIT THERM CAPAC #1	
PER	23.5			

Figure 4a. Orbit 4 Example from Commissioning Master Plan Spreadsheet

There is great risk in maintaining a 'set' of all the different activities for each spacecraft and trying to update the whole schedule without error when the waterfall effect of an anomaly or even a missed contact disrupts the plan. While it may be possible to accomplish these types of rapid operational updates, the process is ripe for mistakes given that the collection of constraints for all of the activities cannot be easily enforced in a spreadsheet program. The conclusion was that a better scheduling tool was needed to act as a constraints warehouse capable of checking for constraint violations within the schedule. The team Activity Control Tool (tACT), developed by Hammers Company for previous missions at GSFC, was updated for MMS to handle multiple spacecraft. tACT ingests an Events file containing the network contact times and orbital events for each spacecraft and provides a means of defining an Activity and applying constraints based on any of the ingested Events or other Activities defined in the tool. The user develops a Gantt chart-like view using JavaScript Object Notation (JSON) language to define the attributes. The previously established color-coding was carried over

into tACT for consistency in providing a visual interpretation for the MMS community. Figure 4b shows the tACT complement to the Figure 4a spreadsheet for Orbit 4.

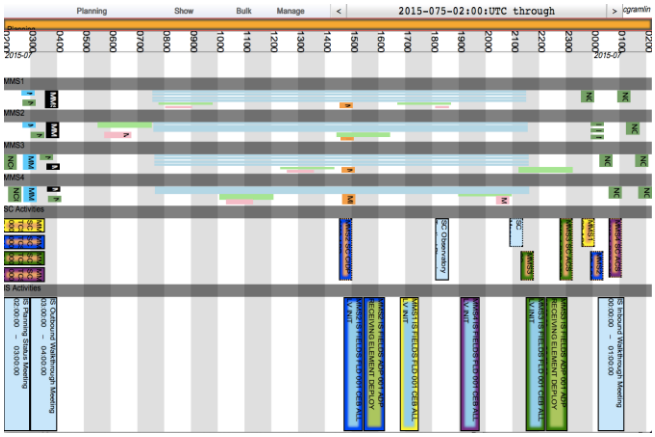

Figure 4b. Orbit 4 Example from tACT Plan

4. COMMISSIONING EXECUTION

Preparation for Commissioning

In addition the planning described in Section 3, several other types of preparation were conducted. These are described below.

Over the course of I&T, the POC participation was slowly incorporated into the testing. For example, each observatory completed a lengthy thermal/vacuum test. During each such test, a Mission Rehearsal Test (MRT) that integrated POC commanding in place of the I&T commanding systems was conducted. This test provided an opportunity for the POC to exercise its systems and to practice operational procedures such as mode changes, validate interconnects, command and telemetry databases, and other necessary infrastructure.

Far in advance of launch, each ITF generated activity definitions. As mentioned previously, associated with each activity were one or more CSTOL scripts. These scripts were used to encapsulate and make routine the execution of the activity. Each script would be executed on the POC IS FlatSat for validation. Minimally, the scripts were verified to load successfully and be free of syntax errors. Most operational aspects could also be checked as the IS FlatSat includes relatively high fidelity instrument simulators. Some aspects of the execution cannot be thoroughly confirmed due to limitation in the IS FlatSat. For example, the IS FlatSat has no deployables, so although the switches in the CIDP that activate the deployables can be exercised, no feedback indicating the success/failure or progress of a deployment will be received.

In January 2015, only a couple of months prior to launch, a detailed training session was conducted at LASP where the ITFs, POC, MOC, and scientists were able to learn about instrument subsystems other than their own, along with POC and MOC expectations and needs so that a unified commissioning team could be established. This was a critical and extremely effective interchange that resulted in a shared view of the commissioning process among stakeholders. In addition, participants were able to develop mental models of observatory operation that were very helpful for thinking about subsystem interactions and preventing potential interferences or conflicts in commissioning planning and execution.

Commissioning Day in the Life

Each MMS Phase 0 orbit had duration slightly less than 24 hours. The high data rate DSN contacts occurred in the 8-hour windows inbound and outbound near apogee. Most IS commissioning operations were generally not compatible with the higher radiation environment in the periapsis region. Thus, the 8-hour period around perigee focused on SN contacts for S/C operations, health and safety, and radiometric tracking data.

Each contact would typically be dedicated to a single investigation, although occasionally shorter activities for multiple investigations were able to be grouped together within a single contact. Activities were combined more as commissioning progressed and full instrument suite testing was performed for interference and cross-calibration efforts.

Ultimately, careful preparation and solid coordination between the mission planners, POC, ITFs, and ISSEs proved vital to maintaining such a tight schedule. Once the master schedule had been fed into tACT it needed to be broken into manageable parts that would allow the operations team to prepare for a given activity or set of activities. On a near daily basis, the tACT schedule was extracted and converted into an activity plan that laid out the detailed schedule for the next 14 orbits. The activity plan combined a graphical representation of each orbit with ground contacts, shadows, L-shell crossings, etc. overlaid as well as a summary of the activities to be executed on each DSN contact. This was provided to the IS commissioning team and served as a simple and effective tool to communicate the commissioning plan to the ITFs, ISSEs, and POC commissioning team.

With a clear view of the near-term activities, the POC planning team would begin assembling the CSTOL scripts and ensuring that everything was ready to execute on a given contact. This usually started with revalidation of the CSTOL scripts against the IS FlatSat in a more flight-like configuration. Some scripts were well vetted prior to launch and were rerun only for familiarity for the console teams. Others were developed much closer to launch or evolved as commissioning proceeded and these required careful testing and often updating to ensure they were ready for the flight assets. Additionally, as commissioning progressed and each observatory moved closer to its nominal operations configuration, some of the "standard" activities needed modifications or were found to no longer be valid. All of

this made pre-execution FlatSat testing a necessary and meaningful exercise.

While having an activity definition, CSTOL scripts, and a scheduled DSN contact were necessary prerequisites, validating that a particular activity was ready for execution required putting those pieces together in context. The MMS Real Time Request (RTR) web-based form was the repository for capturing all the information that could impact a planned activity during the specific contact for which it was scheduled. RTRs consisted of:

- Purpose of the activity
- Applicable flight rules
- Notifications to be communicated to the MOC
- CSTOL execution steps
- Stored commands with the potential to impact the activity
- Scheduled contact information
- Contingencies
- ITF/ISSE/SOC approvals
- Operator execution notes

This form gathered all the information applicable to a commissioning activity in one place, allowing the POC planning team to verify that the activity could be executed as planned. While tACT provided orbital, environmental and scheduling constraint checking, the tACT tool is not able to check what is executing from stored command sequences or what other instruments might be in an active state during a planned activity. The POC planners were responsible for verifying those types of restrictions and communicated that verification in the RTR. The RTR also summarized how to carry out any planned contingencies for an activity, listing script names or commands the operators might need to send in the event of a failed deployment or anomalous behavior during an instrument checkout.

Once all testing and constraint validation was complete, the RTR would be reviewed by the ITF, ISSE and POC FD. The teams would vet the execution plan for an activity and provide notes, additional contingencies, clarifications, etc. as necessary. Once all parties were comfortable that an RTR had captured all the necessary details they provided an approval signature, confirming that they were in agreement the finalized plan for a given activity.

As previously mentioned, the sheer size of the commissioning team, as well as the geographic distance between the teams' "home bases" presented coordination challenges from the start. In order to minimize these challenges during phase 0 the POC established a planning cycle that allowed time for all parties to review and approve RTRs in advance of the planned DSN contact. RTRs were generated on a 4-orbit cycle, as outlined in Figure 5.

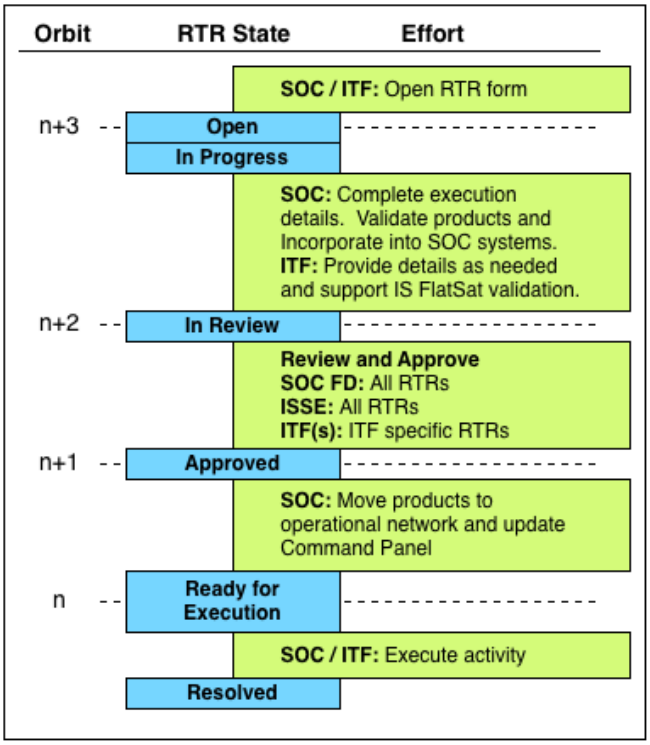

Figure 5. RTR Process

RTR status was reviewed each day at the POC planning meeting. RTRs for the next three orbits would have been generated by this point and would be in varying stages of completion as determined by the days remaining to execution. Activities planned for the upcoming orbit would be approved by the end of the planning meeting. Questions about pending RTRs would also be addressed, including timelines on CSTOL script delivery, altered contingencies or execution instructions as a result of instrument anomalies, or simply clarification on a given section of an activity.

The POC daily planning meeting served as the main status meeting for the IS commissioning team and was the prime forum for communication between the ITFs and the POC. The MOC & Mission Planning team routinely participated as well, providing the entire group with a great deal of insight into spacecraft activities that might impact the commissioning timeline. Having one centralized meeting where all parties had a voice made it much easier to inform ITFs of potential impacts to their commissioning schedule due to anomalies or to coordinate multi-instrument activities. It also gave the POC a chance to check in with all the ITFs at the same time about script development, activity definitions, or planned anomaly troubleshooting.

One of the major challenges faced by the POC was establishing a working knowledge of a commissioning activity in order to execute it. With the large number of deployments, command-intense software loads, and other

complex commissioning activities, it was crucial that the team performing a given activity be familiar with both its nominal flow and how to identify and react to problems that may arise. To that end, the first hour of each shift was spent walking through the activities planned for the coming 12 hours. These walkthroughs were led by the POC Planner and benefited from the participation of the on-shift ITF, ISSE, POC FD, FC, and CC. At a minimum, walkthroughs reviewed:

1. The CSTOL script or scripts to be executed
2. Possible contingencies and responses
3. Any limit violations expected during the activity
4. Any timing constraints or restrictions due to stored commands executing during the contact
5. The order activities should be executed on a contact if there was more than one

Holding these walkthroughs once per shift easily brought the on-console team up to speed without overburdening them with learning the minutiae of every planned commissioning activity.

Boom deployments were deemed critical activities and as such highly detailed walkthroughs were held for these. In the walkthroughs, the ITFs presented technical background on the activity and contingency flowcharts were reviewed extensively so that the whole team knew where the potential stopping points were. The MOC operators also participated in these walkthroughs as there was often a good deal of interaction between the MOC and the POC planned for the activity. These detailed walkthroughs were held a few days in advance when all of the crew members who would execute them on each observatory could participate. This also allowed the FC and CC who would be on console the time to run through the CSTOL scripts on the flatsat before they did it in flight. Having the entire team participate in these walkthroughs was extremely beneficial and this training made the entire team more knowledgeable about the activity.

Transition to Nominal Ops

A key factor was the incremental method used to ease the way into operations. Prior to entering the shadow season at the end of the second month of commissioning, an FPI activity to test an operational Orbit in the Life (OITL) (FPI.010.2) served as the initial segue into operations,. This was the first activity necessitating each ITF to consider other instrument's states and configurations and the first point at which multiple IS activities were coordinated using the S/C Absolute Time Sequence (ATS) mechanism. Participation was limited, since each sensor had not been fully activated and calibrated at that time. After executing FPI.010.2 the first time on MMS3, a target of opportunity arose during the shadow season when MMS aligned with the Van Allen Probes (VAP); this again brought the multi-discipline IS team together to execute for common science goals. Given the power limitations due to a long shadow period immediately preceding, the VAP Alignment was a limited case involving only two (2) spacecraft and a subset of instruments.

Following the post-shadow season, the pressing need to bring one (1) observatory to full operational readiness drove the planning. Once each sensor was activated at full level on MMS-1, FPI.010.2 was executed via ATS, followed by full-time pseudo-nominal operations. Pseudo-nominal referred to the fact that interference observations were still possible and the SITL process, while not in full operation, was able to be integrated in gracefully incremented steps. Each successive observatory was brought up in that manner, and the SITL process evolved, preparing for the four (4) observatory fleet.

With four (4) observatory SITL processing underway, the team was able to execute specialized tests for cross-calibration and interference identification. Following this cross-calibration campaign, the fleet went into full SITL operations, allowing the complete science team to participate and to debug the SITL process (which is intended to enable quick turn-around on science meta-data evaluation and to guide the science selections in the ROI of the previous orbit.) The science team also spent the last two (2) weeks prior to the transition to Phase 1 preparing their instruments by generating final software loads and tuning parameters. In this manner, the operational paradigm grew incrementally over the last several months of commissioning, providing science team engagement and education in preparation for Phase 1 operations.

Towards the end of commissioning a transitional period was planned to hand over day-to-day operations from the ITFs and ISSEs to the POC. Although the ITFs continued to participate by defining activity requests, many of these requests became sufficiently repetitive that they no longer required ITF participation in their execution. In contrast, major activities such as updates to flight software or operational configurations continue to include ITF participation.

One significant exception to ITF operation is the routine update of CIDP command sequences. The CIDP includes a capability for instruments to define command sequences that can be executed on board. CIDP command sequence updates will be required routinely (about monthly) throughout the mission. This would represent a significant cost burden if the ITFs, ISSEs, CIDP, and POC personnel were all required.

To minimize this involvement, a variety of tools were created to ease the operational burden on the POC such that participation from non-POC personnel was eliminated from most of the command sequence update process. The definition of command sequence updates are prepared by the ITFs and provided to the POC. The CIDP ITF produced

a general-purpose tool to automatically generate the CSTOL upload products from the raw data provided by the ITFs. Together with the POC, the CIDP ITF generated a CIPD command sequence upload process that encapsulates the expert knowledge of CIDP personnel such that the POC can execute these same processes over and over without routine CIDP ITF or ISSE participation. Figure 6 shows the high level view of the upload process (note the complexity, the details are purposely obscured).

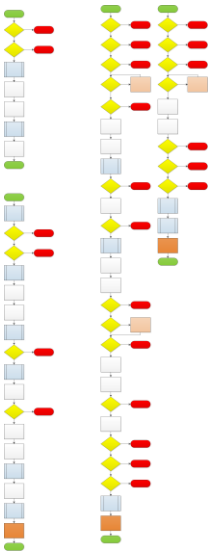

Figure 6. CIDP Command Sequence Upload Process (diagrammatic View)

The POC's steps have been minimized to the following:

1. Run the CSTOL generator tool against the raw command sequence files provided by the ITFs to produce the upload and commit CSTOL procedures for each observatory.

2. Execute the upload procedure on each observatory.

3. Execute the commit procedure on each observatory.

4. Execute the reconfigure procedure on each observatory.

By breaking the process into these large steps, recovery from difficulties is simpler. If the upload cannot be completed due to unexpected loss of signal, for example, a simple abort command can be issued for an in progress upload when contact is restored and the upload procedure can be rescheduled for a subsequent contact.

5. LESSONS LEARNED

Four S/C = Production

The commissioning plan was developed on the presumption that each test would require the same estimated time duration, regardless of repetition, since many activities involved a long series of commanding or wait-states Given the constraints on each activity and the rules listed in Section 3, on paper, the commissioning schedule consumed virtually all the calendar time allotted. In practice, repeating an activity more than once allowed everyone to become more familiar with the process. By the third or fourth execution of a commissioning activity, the total time to complete the activity was reduced significantly. MMS had an additional benefit, as each S/C had multiple copies of several instruments or required multiple executions of the same procedure on the same component (e.g., ASPOC). This proved to be an amplifier for decreasing execution time, and provided plenty of opportunity to fine tune the procedures and eliminate unneeded or wasted effort and time. However, some activities grew in execution time and often the DSN contacts were shorter than the minimum requested. Therefore, having allocated the original time estimates for an activity for every instance provided the schedule with contingency opportunities. This method of developing the original schedule also provided opportunity for additional activities not previously considered. In general, commissioning was completed several weeks ahead of schedule. The lesson should be to budget and schedule for the worst case, but be prepared to take advantage of early completion to perform opportunistic activities and begin operation early. Given a fleet of uniform design with more than four S/C, planning for reduced commissioning time after the second or third run of an activity would be reasonable from a planning perspective without adding significant risk.

"Test as you Fly"

To the extent the program budget made possible, the MMS development team incorporated a "test as you fly" approach to operations. Early in I&T a representative of the POC was embedded within the IS test team to provide operational experience and knowledge continuity. Significant effort also went into mission simulation operations, both nominal and anomalous, and every attempt was made to develop scripts for I&T that could be easily transitioned to flight procedures. The team also performed testing from scattered locations in order to verify the dispersed communications protocols necessary for flight commissioning. The attempt to 'test as you fly' was generally successful, but there were a few places where the approach fell short. Both successes and shortcomings are described in the following paragraphs.

There were several successful aspects to the MMS team's "test as you fly implementation." Including POC employees on the I&T team was very helpful in developing an institutional resource with IS operational experience, improving the quality of the scripts, and easing the transition from ground to flight procedures. In a like manner, the implementation of high quality mission simulations helped to prepare the commissioning team for the commissioning activities, the pace at which they were conducted, and the limits on the flexibility to rearrange activities. Of particular value was the launch and early orbit simulation, which included a number of simulated mission

anomalies. This simulation gave a realistic appreciation of the "feel" of flight and allowed the teams to test their approach to anomaly resolution, resulting in useful changes to procedures as well as a more successful commissioning activity. The commissioning phase of the mission was materially improved by these aspects of "test as you fly" ground operations.

There were several areas in which the "test as you fly" preparation was inadequate. The most serious from a budget/schedule standpoint was the amount of effort necessary to translate ground scripts into flight procedures. The ITF I&T effort used a ground software system called Ground Support Equipment Operating System (GSEOS), while the flight operational ground systems are the Operations and Science Instrument Support Command and Control (OASIS-CC) at the POC and the Advanced Spacecraft Integration and System Test (ASIST) at the MOC, which uses STOL. Addressing the differences between these ground and test systems had a non-zero cost. Both ground systems used by the instrument suite implemented a CSTOL variant, with the GSEOS implementation reasonably close to that of OASIS-CC. However, many of the I&T scripts for the IS had not been structured in a way that met flight operational coding standards. This required that the I&T scripts be rewritten for use in a flight environment. The lesson learned is that, if at all possible, the I&T development should use the flight command and telemetry (C&T) system as well as flight coding approaches. Even if a common C&T system is not used, a flight-centric coding standard should be established and followed prior to beginning I&T, and I&T work products destined for operations should be reviewed by operations personnel as part of the routine development process for I&T. If this is not done, then extra work will be required to transition I&T scripts to flight.

The most serious area of "test as you fly" shortcomings from a technical standpoint was the inability to reproduce the CFDP response delays inherent in operation with DSN and the ground station. During I&T, the CFDP files were closed generally within a 20-40 seconds. In flight, they would remain open 3-10 minutes (not seen in ground testing) and this resulted in a number of operational challenges including unexpectedly high processor usage, delays in data transmission, and increasingly complicated ground based data management. The operational difficulties eventually culminated in a new software load. The lesson learned was to ensure that future ground systems incorporate timing based upon flight norms.

The final "test as you fly" lesson exposed shortcomings found in the configuration of the mission "FlatSats". There are three FlatSats available for mission use, one at NASA/GSFC, a second at CU/LASP, and a third more limited test bed for CIDP-centric testing. The NASA/GSFC FlatSat has a complete S/C bus configuration including a communication card along with an engineering model (EM) CIDP and FPI IDPU (central processing unit) that connects to a ground segment telemetry system equivalent to the operational one, particularly as regards CFDP processing. However, instruments are computer-based simulations with moderate to low fidelity; they produce an appropriate volume of data, but the data lacks the periodicity, size, and internal structure of instrument produced data. The CU/LASP FlatSat has no S/C hardware but has an EM CIDP and a complete set of IS hardware with medium to high fidelity. These instrument simulators typically run their flight software, and thus produce data of much higher correspondence to operation, although a robust science simulation mechanism is typically not included. The software test bed for the IS consists of an EM CIDP and a special test equipment (STE) that simulates the instruments, S/C, and ground segment. Thus, there is no end-to-end, full fidelity FlatSat available. As a result, we must deal with a variety of "exceptions" when we test scripts, and are unable to fully ground test some aspects of system operation. The lesson learned is to generate a fully capable, high fidelity FlatSat for mission use.

Complexity vs. Flexibility

Commissioning a science observatory with one or two instruments is a complex and intricate task. Multiplying the number of observatories by four, and the number of instruments by 10, gave MMS a level of complexity that had to be offset by other factors in order to commission successfully. The primary offsetting factor for MMS was flexibility: There were times when MMS had adequate flexibility resulting in simplification and efficiency; there were other times where the lack of flexibility resulted in significant inefficiency; and there were times when no amount of flexibility could have made it easier.

One area of great flexibility was provided by MMS instrument specific command panels. These command panels included a set of pre-defined and pre-validated operational procedures that were developed during the planning phase and expanded as the mission progressed to incorporated lessons learned. While most operational sequences were created uniquely and vetted well in advance (24 hours or more) of an observatory contact, there were occasions when quick changes were required (often within a contact.) The existence of the instrument command panels allowed quick processing of operational sequence changes, or entirely new sequences that could invoke the existing procedures found in the control panels. The flexibility provided by the captured operational experience contained in those panels thus mitigated the complexity of late breaking changes, minimizing impacts to the overall commissioning schedule.

The as-developed commissioning plan had a high level of complex integration. As long as all of the operations went well, and all of the development efforts for the succeeding operations were on time, the system worked. However, the complexity left no room for error. As expected, there were times when instrument anomalies or missed passes resulted in the need to rearrange the sequence of operations. Some

rearrangement was as simple as swapping a sequence of operations between two observatories. Inevitably however, there were times when a RF contact could not be used for commissioning activity, either because of strict sequencing constraints or because a substitute procedure had not been developed. If a set of completed procedures had been ready for execution, and if the execution sequence order could have been made more flexible, a more efficient use of RF time could have been achieved. This is an example of a case where no compensating flexibility was available to offset the mission complexity. Fortunately, there was enough extra time in the commissioning schedule that the complexity caused no ultimate problem.

The MMS commissioning team discovered how truly complex MMS operations could be when a science opportunity arose towards the end of the eclipse season for a coordinated observing campaign with the Van Allen probe mission. (This opportunity was not included in the baseline commissioning plan.) It took a great deal of planning, procedure development, and engineering calculation to implement the joint campaign while ensuring that all of the instruments on the two observatories involved were ready to take quality science data and that the power margins were adequate. It also required developing the appropriate absolute time sequence (ATS) uploads on relatively short notice. The sheer complexity of the job, occurring relatively early in the mission, resulted in an extremely difficult period of effort for the POC, MOC, ITF, and ISSEs. The lesson is that, sometimes, operating a complex mission is going to be difficult no matter what compensating provisions are included.

Commissioning Team Shift Scheduling

Because the average length of an MMS orbit during Phase 0 was just under 24 hours, the commissioning teams had to choose between a shift schedule that followed a 24 hour day or one that defined the orbit as the standard day. Following a 24-hour day allowed crews a routine that they could plan for consistently throughout commissioning. The day shift crew could maintain a normal sleep-wake schedule and continue to interact with others in their organization during standard business hours. The night shift could adapt to a set of core work hours that wouldn't change over the course of the 6-month commissioning phase. Defining a day to follow the length of an orbit required crews to shift their sleep-wake times routinely and could cause confusion as to when shifts started on "transition" days. However there were clear benefits to activity execution in this mode.

The observatory commissioning team kept their shift times consistent throughout all of Phase 0. Although maneuvers required a small crew to support at any time of day or night, planning activities and Command Authorization Meetings (CAM) were performed during local day shift. Similarly, S/C bus activities occurred at any time, were often passive activities, included little real time commanding, and were subject to offline data analysis. Because of this, there was no driving need for the observatory crew to follow the orbit.

The POC's decision to align crew shifts with the MMS orbit provided significant benefits to the IS commissioning plan with minimal impact to the crews themselves. While this approach was more challenging to the humans on shift the benefits to the overall commissioning flow far outweighed the inconveniences. The POC shift handovers occurred near perigee and apogee each orbit. Because of the ground contact schedule and the need to execute the majority of the IS commissioning activities over DSN sites, this schedule guaranteed that one handover per day would occur during a quiet part of the orbit. The POC understood that, with the command intense activities planned for all instruments, trying to fit in a handover briefing while executing a realtime activity would introduce many opportunities for error. The added distraction of translating a large amount of information to an incoming crew member could easily cause mistakes in communication on console or the overlooking of anomalous indications in telemetry.

Organizing crew shifts to follow the orbit allowed the POC to take full advantage of the gap in DSN contacts during that part of the orbit. Without DSN contacts to execute commissioning activities the POC, ITFs and ISSEs were not needed on console. The ISSEs also realized the advantages of this schedule and aligned their shift splits with apogee/perigee as well. This provided the ideal time to schedule the daily IS planning meeting and activity walkthroughs and ensured that all teams were able to participate. This did present some difficulties coordinating with the MOC mission planners as there was a great deal of overlap between the observatory Tactical and IS Planning meetings. ITFs and ISSEs were often on console during these meetings and couldn't always participate as fully as they wanted to. To bridge this gap one member of the POC planning team would attend the observatory Tactical meeting and serve as the voice of the IS when needed. As the local time of perigee evolved, the time of the POC Planning meeting and the Tactical Planning meeting began to align and the commissioning team combined these two meetings starting after the shadow season. This did still present attendance problems at times, but since the commissioning schedule post-shadow was more relaxed it was less of an issue to work around.

6. CONCLUSIONS

MMS was a complex and challenging mission to commission. With careful attention to detail in the commissioning planning process complex, multi-observatory missions can be successfully commissioned on schedule and within budget. To date, MMS successfully completed the variations in formation separation over the first two months of Phase 1A, settling on separation scale sizing for the remainder of the Phase. The mission continues to provide remarkable science results and has not encountered any major anomalies among the fleet.

ACKNOWLEDGEMENTS

The authors wish to thank NASA Goddard for the opportunity to build this exciting fleet of observatories. We would also like to thank the entire MMS team involved in commissioning for their hard work and dedication that made MMS commissioning so successful and gave us many experiences we wanted to share. Finally, we would like to thank Martin Wasiewicz for his careful review of this paper.

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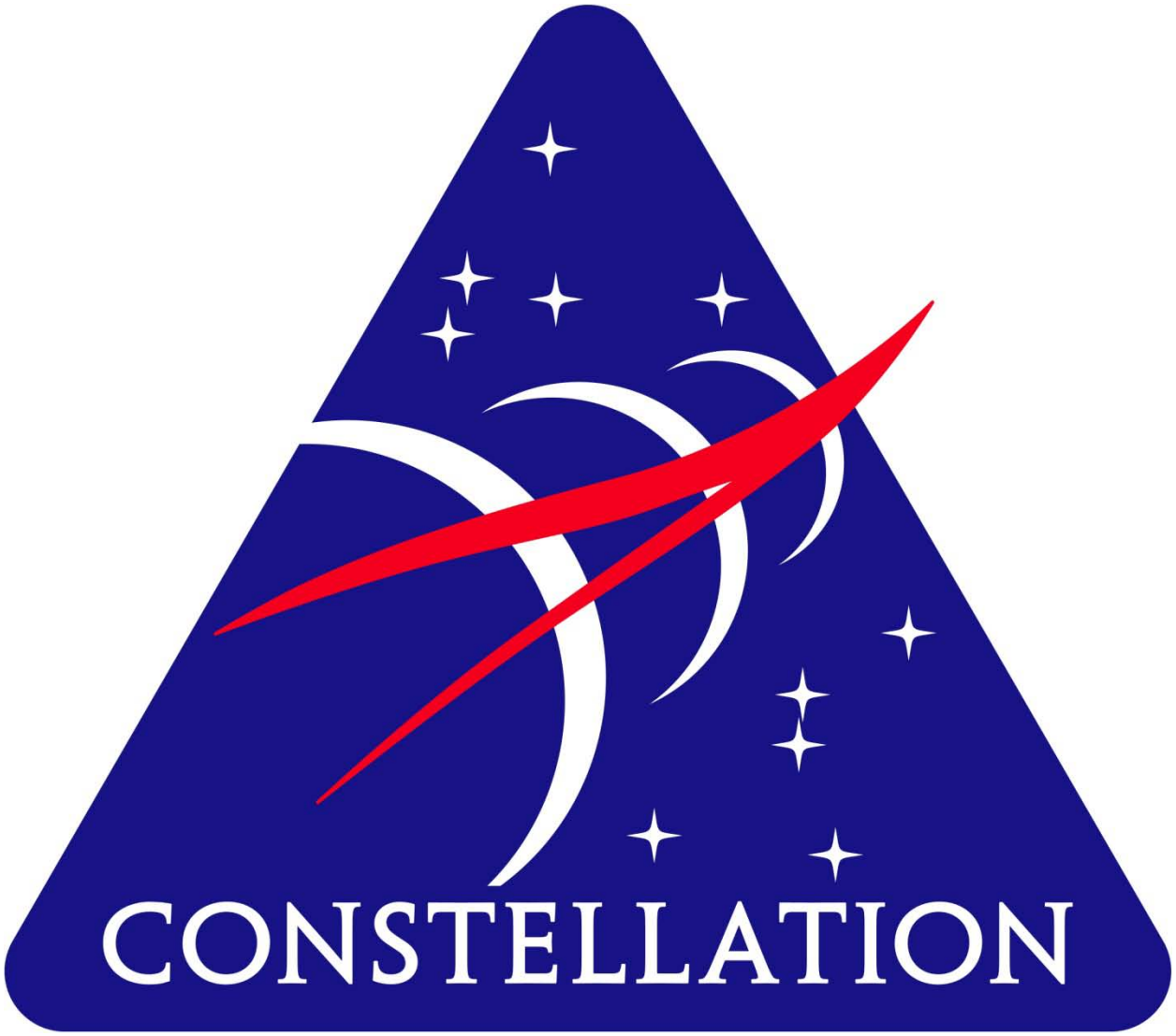
Constellation Program

Lessons Learned

Volume II
Detailed Lessons Learned



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Volume II

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FORWARD

The Constellation Program, as a national-level undertaking, had multiple purposes. These can and will be described from many points of view.

To us Constellation was born of the charred debris, scattered in the Piney Woods of East Texas that were reverently collected as the last remains of that delicate machine Columbia, she that failed to preserve the lives of our friends and colleagues due to our own very human errors. The painful acknowledgement of those errors became foundational principles for what later emerged as the nation's new space exploration program: Constellation.

Those of us who worked in the program were bound by a common belief that America's future lies in the Final Frontier; indeed that America must lead the way there. We joyfully dedicated our working lives and careers to building the ships that would sail those treacherous seas. We had prepared ourselves for this challenge, having learned from the best and honed our skills in the unique arena of human space flight. We were driven by the hope that America would one day step beyond the known, and were blessed when the national will bent toward our dreams for a moment. It was a privilege and an honor to have a hand in this endeavor. Perhaps our greatest shared joy and satisfaction came from the recognition that amid the inherent tumult of a program of this size and scope, we bore the challenges with teammates of superior skill and dedication. We understood that another generation would explore using what we had conceived and built. We rejoiced at our successes, but also knew faults and failures. This, the summation of what we have learned, is our final expression of that cherished hope.

To our families, we beg your forgiveness for the long hours away, and too many distracted conversations. Thank you for indulging our passion.

And, to our generational forebears in human space flight, our hope is that our efforts honor you.

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PREFACE TO VOLUME II

The prior document (Volume I) provides an executive summary of the lessons learned from the Constellation Program. This companion document, Volume II, expands on this information and provides more detailed analyses for those seeking further background, insight, and information. It contains new subjects that were not covered in Volume I.

In this volume, Section 1.0 introduces our approach in preparing and organizing the content to enable rapid topical location and assimilation of lessons. Section 2.0 describes the contextual framework in which the Constellation Program was formulated and functioned; this is necessary to understand most of the lessons. Section 2.0 supplies an expansion of the briefer contextual description provided in Volume I. As noted in Volume I, context of a former program may seem irrelevant in the heady days of new program formulation. However, readers should take some time to understand the context. Many of the lessons would be different in another context, so readers should reflect on the similarities and differences in their current circumstances. Section 3.0 summarizes key findings, which appear in Volume I, that were developed from significant lessons learned at the program level, and provides a link between the key findings and the topical arrangement of lessons learned in this volume. Readers can use the key findings in Section 3.0 to peruse for particular topics, and will find more supporting detail and analyses in Section 4.0 in a topical format arranged according to traditional NASA program disciplines. The Appendices (A and B) provide insight from the project view of lessons learned.

The reader will no doubt recognize some very similar themes from previous lessons learned, blue-ribbon committee reviews, National Academy reviews, and advisory panel reviews for this and other large-scale human space flight programs; including Apollo, Space Shuttle, Shuttle/*Mir*, and the International Space Station. This could represent an inability to learn lessons from previous generations; however, it is more likely that similar challenges persist in the Agency structure and approach to program formulation, budget advocacy, and management.

Prior lessons learned also drove planning for and formulation of Constellation; the reader may observe attempts, both successful and unsuccessful, to avoid pitfalls encountered by previous programs, and reflect on the outcomes and recommendations.

Perhaps the greatest value of these Constellation lessons learned can be found in viewing them in context with those previous efforts to guide and advise the Agency and its stakeholders.

1.0 INTRODUCTION

"On the actual day of battle, naked truths may be picked up for the asking; by the following morning they have begun to get into their uniforms."--Gen. Sir Ian Hamilton

These lessons learned are part of a suite of hardware, software, test results, designs, knowledge base, and documentation that comprises the legacy of the Constellation Program.

The context, summary information, and lessons learned are presented in a factual format, as known and described at the time. While our opinions might be discernable in the context, we have avoided all but factually sustainable statements. Statements should not be viewed as being either positive or negative; their value lies in what we did and what we learned that is worthy of passing on.

The lessons include both "dos" and "don'ts." In many cases, one person's "do" can be viewed as another person's "don't"; therefore, we have attempted to capture both perspectives when applicable and useful.

While Volume I summarizes the views of those who managed the program, *this Volume II* encompasses the views at the working level, describing how the program challenges manifested *in day-to-day activities.* Here we see themes that were perhaps hinted at, but not completely addressed, in Volume I: unintended consequences of policies that worked well at higher levels but lacked proper implementation at the working level; long-term effects of the "generation gap" in human space flight development, the need to demonstrate early successes at the expense of thorough planning, and the consequences of problems and challenges not yet addressed because other problems and challenges were more immediate or manifest.

Not all lessons learned have the benefit of being operationally vetted, since the program was cancelled shortly after Preliminary Design Review. We avoid making statements about operational consequences (with the exception of testing and test flights that did occur), but we do attempt to provide insight into how operational thinking influenced design and testing.

The lessons have been formatted with a description, along with supporting information, a succinct statement of the lesson learned, and recommendations for future programs and projects that may be placed in similar circumstances.

2.0 CONTEXT — "WHERE YOU STAND DEPENDS ON WHERE YOU SIT"

2.1 A Brief Description of the Program

NASA formed the Constellation Program in 2005 to achieve the objectives of maintaining American presence in low-Earth orbit, returning to the moon for purposes of establishing an outpost, and laying the foundation to explore Mars and beyond in the first half of the 21st century. The Constellation Program's heritage rested on the successes and lessons learned from NASA's previous human space flight programs: Mercury, Gemini, Apollo, Space Shuttle, and the International Space Station (ISS).

Following the loss of *Columbia*, NASA established the *Columbia* Accident Investigation Board (CAIB) to perform an in-depth review of the Space Shuttle Program. As a result of this review, the CAIB concluded that it was in the best interest of the U.S. to develop a replacement for the Space Shuttle. The CAIB concluded that it should be possible, using past and future investments in technology, to develop the basis for a system "significantly improved over one designed 40 years earlier, for carrying humans to orbit and enabling their work in space."

In January 2004, The White House issued a new exploration initiative to return humans to the Moon by 2020 in preparation for human exploration of Mars and beyond. As part of this initiative, NASA would continue to use the Space Shuttle to fulfill its obligation to complete assembly of the ISS and then retire the Space Shuttle by 2010. NASA would also build and fly a new Crew Exploration Vehicle (since named *Orion*) by 2014. In 2005, Congress expressly endorsed the President's exploration initiative and authorized NASA to "…establish a program to develop a sustained human presence on the moon, including a robust precursor program to promote exploration, science, commerce and U.S. preeminence in space, and as a stepping-stone to future exploration of Mars and other destinations."

In response to the Presidential direction, in 2004 the Agency formed the Exploration Systems Mission Directorate (ESMD) at NASA Headquarters to oversee development of exploration programs. The Constellation Systems Division was initiated to oversee human exploration mission development.

In May 2005, the NASA Administrator commissioned the Exploration Systems Architecture Study (ESAS), a 60-day study to perform the tasks of defining the top-level requirements and configurations for crew and cargo launch systems to support exploration objectives. The study concluded that the launch vehicles should be derived from existing technologies, leveraging the lessons learned from past programs. The ESAS recommended an architecture that formed the basis of the Constellation Program.

Since exploration of the moon and beyond was the overarching goal of the Constellation Program, all elements were designed to perform lunar missions, while also being capable of performing missions to the ISS. The Program was phased as a stepwise capability buildup

largely based on Space Shuttle heritage components. The Initial Capability (IC) comprised elements necessary to service the ISS by 2015 with crew rotations, included the *Orion* Crew Exploration Vehicle, the *Ares* I Crew Launch Vehicle, and the supporting ground and mission infrastructure that would enable these missions. The Constellation Lunar Capability (LC) added the *Ares* V Cargo Launch Vehicle, the *Altair* Lunar Lander, and spacesuits designed for partial-gravity exploration. Lunar outpost elements and capabilities were to follow, including mobility elements such as rovers, permanent or semipermanent habitats, and power and communication elements to support a sustained exploration presence.

The Constellation Program was managed at the Johnson Space Center (JSC) with the following seven "hardware development" project offices:

- Crew Exploration Vehicle Project (the *Orion* spacecraft), at JSC
- Exploration Launch Projects (the *Ares* I and *Ares* V launch vehicles), at the Marshall Space Flight Center (MSFC)
- Ground Operations Project (development of launch and recovery facilities) at the Kennedy Space Center (KSC)
- Mission Operations Project (development of flight and mission control facilities) at JSC
- Extravehicular Activity (EVA) Systems Project (spacesuit and tool development) at JSC
- Lunar Lander Project (the *Altair* lunar descent and ascent module) at JSC
- Lunar Surface Systems Pre-project (advanced planning for lunar habitats and surface support systems) at JSC

Orion, *Ares* I, Ground Operations, Mission Operations, and EVA comprised the IC projects. *Ares* V, the *Altair* and Lunar Surface Systems, and upgrades to the IC to meet lunar interfaces and requirements comprised the LC projects.

By 2010, all elements of the IC had achieved Preliminary Design Review (PDR), and test flights were under way, with the successful launches of *Ares* I-X and the *Orion* Pad Abort-1 tests. The White House announced cancellation of the program on Feb. 1, 2010, on the seventh anniversary of the loss of *Columbia* and her crew.

According to the NASA Authorization Act of 2010 (PL 111-267, Oct. 11, 2010), elements of the Constellation Program will continue in NASA's current planning. The *Orion* vehicle is redesigned as the multipurpose crewed vechicle (MPCV) and will likely enable crew launch on a variety of launch vehicles. The Space Launch System (SLS), intended as the vehicle to launch crews and cargo beyond low-Earth orbit (LEO), has various configurations under consideration including options based on Space Shuttle and *Ares* heritage designs and hardware. The Ground Operations infrastructure at the Kennedy Space Center, developed for Constellation, will be adapted to the SLS and new commercial launch capabilities.

2.2 The Program Environment — Key to Understanding the Lessons Learned

2.2.1 Program Scope

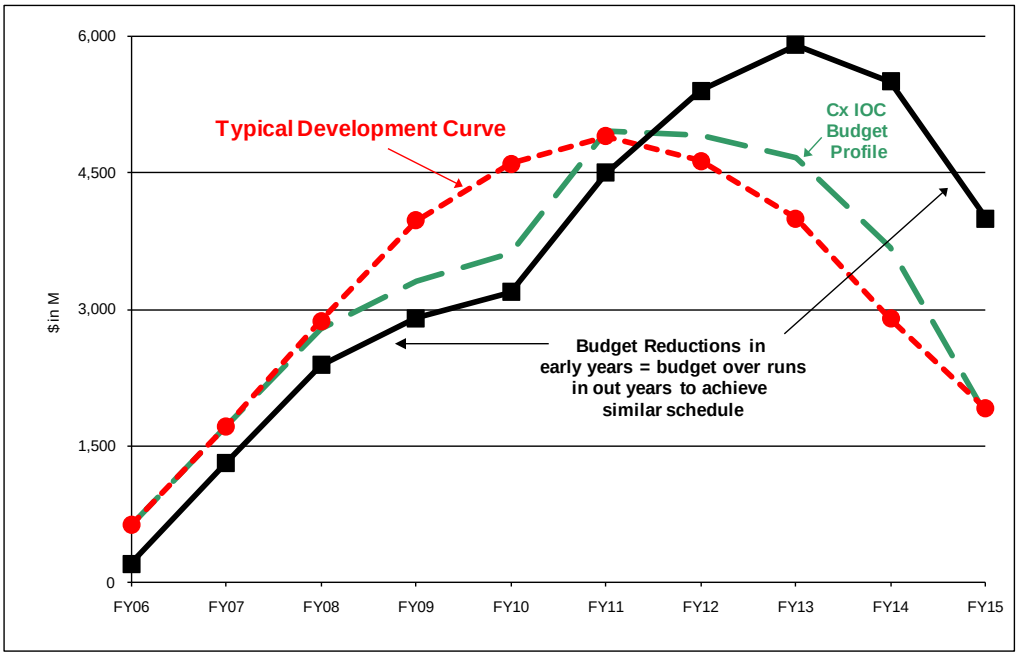
The Constellation Program was conceived as a multi-decadal undertaking, with the primary goal of enabling human exploration beyond LEO. It was to serve as the Space Shuttle successor not only in function, but also in utilization of facilities and workforce. It was to provide the primary mode of delivery of crews to the ISS, enable the construction and operation of an outpost on the moon, and enable human exploration of Mars. As the Agency flagship program, the effort spanned all 10 NASA centers and multiple large-scale acquisitions. It required modernizing an infrastructure designed and sized largely for the Apollo Program in the 1960s. Moreover, it required leading a workforce generationally removed from the previous human spacecraft launch and entry development challenges.

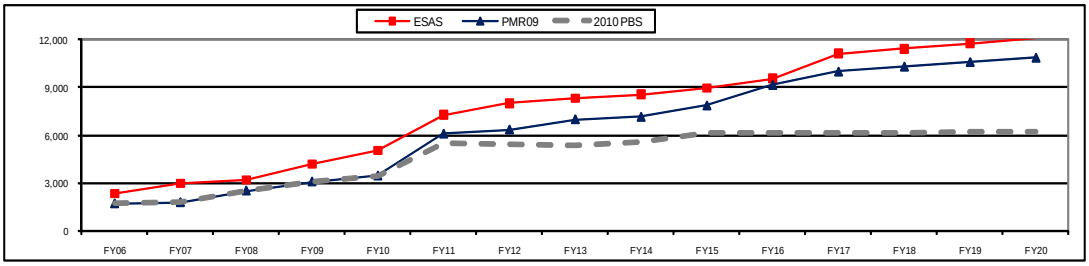
While the near-term focus of the program was providing crew transport to the ISS via the IC, the capability to go beyond LEO drove many technical and programmatic decisions. These decisions were suboptimal when viewed with only near-term objectives in mind, while they were necessary to support the LC phases of the program. They, in some cases, also increased risk to the IC through incorporation of newer technologies with less flight heritage. The need for commonality to decrease life-cycle cost and complexity drove many decisions. For example, the *Ares* I design used a five-segment, solid-chemical first stage along with the J2-X upper-stage engine. Other simpler, less-costly designs could have been used to optimize for *Ares* I alone, but in context with the *Ares* V development, these elements lowered the overall program design complexity, risk, and cost.

Optimization for the long-term program drove not only design decisions, but also infrastructure needs, standards, organizational structure, units of measure (SI [international system of units]), data architecture, etc., that would not have been necessary for the IC alone. The primary objective of stepping beyond LEO with the LC was optimized at the expense of having an IC that was more costly and complex than necessary as a stand-alone development.

2.2.2 Program Funding

Funding for the Constellation Program was inconsistent and unreliable from its initial formulation through its cancellation. Indeed, this inconsistency became the chronic constraint that aggravated all other constraints. Figure 1 illustrates this persistent problem. The program experienced a 10% budget cut prior to PDR. In addition, the funding “profile” (how the money is allocated on a yearly basis) was far less than optimal for a development project. Typical development projects swell in funding as they enter the design development phases. Constellation had to adjust its work to accommodate a funding “notch” in fiscal year (FY)10 as a result of Agency funding limitations due to Space Shuttle retirement. While Constellation was expected to transport crews to and from the ISS soon after Space Shuttle retirement, the funding ramp-up needed for development was not available until *after* the Space Shuttle retired. This, of course, put pressure on program content, schedule, and rationale for the ISS crew rotation mission (Initial Operational Capability [IOC]).





RY$ In M	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	Total
ESAS	2,333	2,976	3,195	4,202	5,034	7,273	7,994	8,324	8,558	8,948	9,547	11,107	11,422	11,744	12,073	114730
PMR09	1707	1779	2514	3085	3454	6085	6346	6991	7145	7856	9145	9983	10294	10582	10854	97820
2010 PBS	1707	1779	2514	3085	3454	5524	5444	5376	5570	6153	6161	6170	6178	6186	6195	71496
PMR09 vs. ESAS Delta	(626)	(1197)	(681)	(1117)	(1580)	(1188)	(1648)	(1333)	(1413)	(1092)	(402)	(1124)	(1128)	(1162)	(1219)	(16910)
Passback vs. ESAS Delta	(626)	(1197)	(681)	(1117)	(1580)	(1749)	(2550)	(2948)	(2988)	(2795)	(3386)	(4937)	(5244)	(5558)	(5878)	(43234)

Fig. 1: Constellation budget profiles before and after budget reductions (ESAS=Exploration System Architecture Study, the initial program budget baseline; PMR=Program Manager's Recommendation based on "marks" passed down by the Office of Management and Budget [OMB] and NASA Headquarters [HQ]; PBS=President's Budget Submittal)

Figure 2 illustrates the result of budget pressure on major schedule milestones (PDR, Critical Design Review [CDR], IOC, and human lunar return [HLR]). IOC moved 2 years (2012 to 2014) due to the first budget cut. The program was able to recapture 1 year of that loss by replanning (at greater risk). Subsequent budget cuts pushed IOC further, into 2015. The program was required to hold the IOC schedule commitment to 2015, since this was the "no later than" date that had been committed to the U.S. Congress.

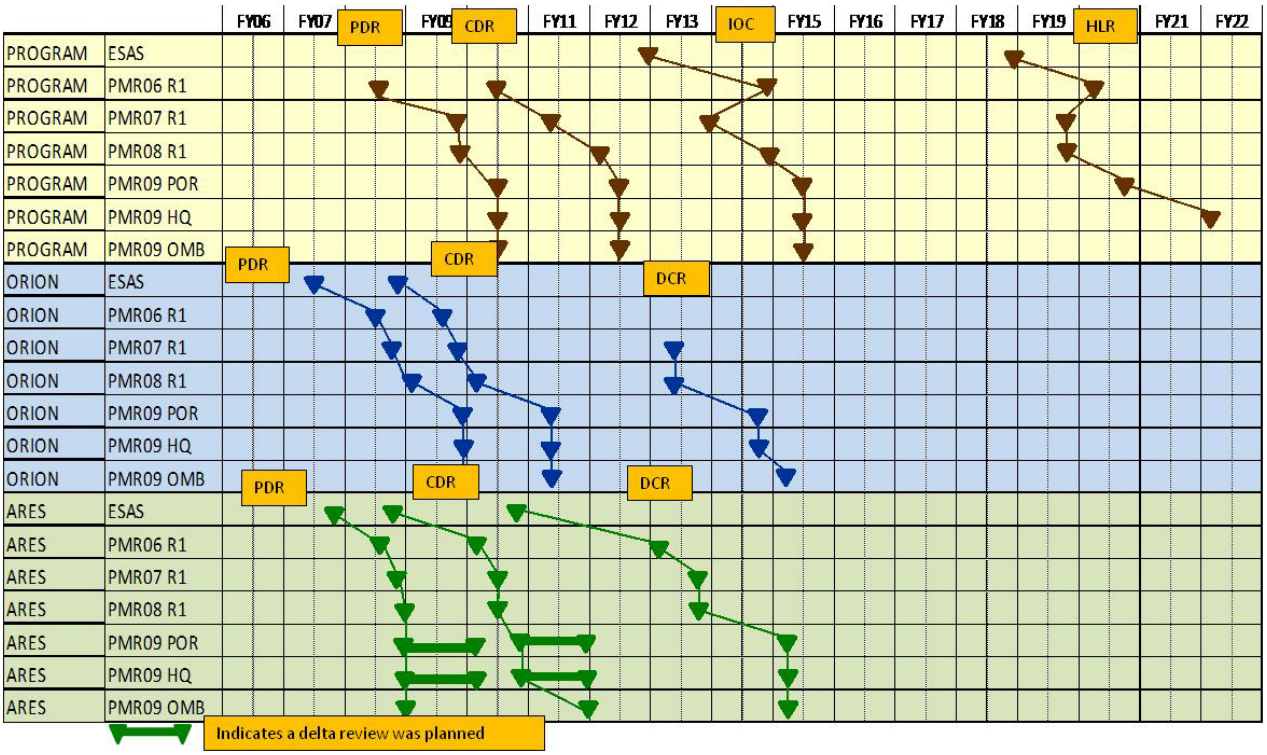


Fig. 2: Consequences of funding cuts on Constellation major milestones

The phasing of the program exacerbated the funding challenges, in a “rob Peter to pay Paul” fashion. The viability of the lunar program phase was under constant threat, as it was the only souce to supplement shortfalls in the IC when schedule slips had been exhausted (see effect of the fixed-base costs, below). The lunar phase of the program (e.g., HLR in Fig. 2) bore the brunt of the cuts that could be accommodated in out-years and was pushed even further than the IOC milestones. This is illustrated in Fig. 2 (observe that IOC was “held” in 2015 while HLR slipped almost 2 years).

Constellation was planned with adequate budget reserves, although these reserves were not phased to be most useful to the program (i.e., much of the reserve was phased later in the program schedule rather than earlier). An unfortunately prevalent perspective on program reserves in the federal government is that reserves are seen as “over-funding” that can be depleted to address other issues, or drawn back to the Treasury if unused within an FY. Agency reserves (i.e., allowance for program adjustment [APA] funds) had been eliminated long ago. Constellation reserves were intially planned to fund risk mitigation efforts. Reserves were rapidly depleted due to the combined effects of budget cuts, Agency “taxes,” and efforts to hold schedule without sacrificing content. Subsequently, risk mitigations were reduced and then eliminated, leaving little recourse to resolve the typical technical challenges that crop up in a design of this magnitude and complexity. Risk accrued as a result.

The large acquisitions for design and construction of the major components of the program were planned, sized, and budgeted early in the program, as neccessitated to meet schedule objectives.

The prime contractors' costs typically ramped up in accordance with plan. These costs were comprised of both "fixed-base" elements (work force, test facilities, etc.), and variable elements. As the program dealt with subsequent budget cuts, the fixed-base elements were extremely difficult to reduce; cuts tended to be absorbed within variable elements (e.g., deferred hardware buys). This led to a number of problems: schedule risk increased as more activities crept onto the critical path; planned activities were deferred to reduce risk, thus delaying risk mitigation strategies and increasing overall risk; we faced an exercise in diminished returns, in which fewer and fewer items remained in the variable elements of the budget to defer to the next round of reductions.

With the retirement of the Space Shuttle Program looming, there was great pressure to assimilate as much of the shuttle-heritage "fixed-base" (e.g., work force, infrastructure, and industrial base) from that program as possible, per direction NASA received in two Authorization Acts (2005, 2008). While the operational requirements and sustaining budget planned for Constellation were smaller than those of the Space Shuttle Program, nearly every component, building, fleet, process, and cadre of workers had its advocacy group to sustain it. Because of the phasing of the Constellation Program, much of the infrastructure was not needed for the IC but would be needed for the LC. This created an Agency-wide phasing challenge for these assets: Should NASA retire/mothball the asset, or sustain it for many years unused?

The tight coupling of the Space Shuttle retirement to the buildup of the Constellation IC, along with the necessity to plan the IC and the LC with a large degree of commonality, made sense strategically when the plan was developed, but only if all schedule and funding assumptions held. The rationale did not withstand subsequent budget pressure and consequential schedule slips.

The Constellation Program hardware development budget was also, in an absolute sense, large at the Agency level and not yet operational (as Space Shuttle and ISS were), so it was often perceived as the only source for unexpected expenses that cropped up in the Agency. Indeed, expenses were charged to the program that did not benefit the program. This is not atypical for flagship programs in governmental developments.

Cash flow disruptions, resulting from Congressional continuing resolutions (CRs), had been an occasional source of funding problems for the Agency in the past. These became annual events During Constellation's lifetime, and many times lasted well into the new FY. While these are experienced government-wide, they are particularly onerous on developmental programs in early stages when funding levels are increasing toward their peak. A typical program "ramp-up" is nearly impossible during a CR. These funding shortfalls, which sent annual "square-waves" of additional replanning through the program, projects, and contractor communities, were never fully attenuated through the remainder of the FY.

The Constellation Program content, constituted by the elements of the program architecture, along with their associated performance requirements were held as a higher priority than schedule performance by the Agency leadership; therefore, in the budget environment framed above,

schedules slipped, risks accrued, and reserves were depleted before serious consideration was given to descope program content.

2.2.3 The Mosaic of NASA Participation

As Constellation was the flagship program for the Agency, project and program work was distributed across the Agency to support the concept of maintaining "10 Healthy Centers" (Fig. 3). This distribution was planned at the Agency level. The concept was not sufficiently defined to satisfy either centers or the program in light of the Space Shuttle retirement. Details of the implementation were left to the program to sort out in consultation with center management. This resulted in a persistent tension between what was most efficient for the program vs. what was best for a particular NASA center to sustain or grow its current role. The nationwide team was probably larger than necessary, but it also covered "unused capacity" at some centers. The large teams at multiple locations led to instances of overlapping or unclear roles and responsibilities. Decisions taken to perform tasks "in-house" using an on-site work force at a center vs. contracting the task out were often made at the center or project level, and were not optimized for overall program benefit.



Fig. 3: The Constellation distributed team

The involvement of all 10 NASA centers exposed cultural differences that had to be managed by a management team whose members were geographically removed. Each center had different requirements, procedures, and processes that were documented at various levels of

detail and constraint. While the apportionment of responsibility was useful to each center, the Agency had not completed effort to assure that the requirements, procedures, and processes were consistent, non-duplicative, and noncontradictory. This placed a particular burden on the contractor community since it was charged with identification and compliance with duplicative and sometimes contradictory requirements. The mismatch of design and construction standards among centers, along with demands from the "insight" work force at each center, was a worrisome burden for contractors, constantly threatening their ability to meet schedule milestones and cost thresholds. The NASA use of an independent technical authority provided yet another source of direction and, thus confusion, to the contractor community. Although official direction can only flow to contractors via the Contracting Officer (CO), informal discussions and decisions coming from the program and separately from the technical authority sometimes made it difficult for contractors to distinguish a final decision from an interim decision.

The industrial base used by the Space Shuttle Program and, to a lesser extent, the ISS Program was managed by a separate mission directorate at NASA HQ. Overlapping strategic interests among the three programs (e.g., facility usage, floor space, test stands) had to be resolved at the highest levels in the Agency (between mission directorates).

The position of an Agency flagship program carried benefits as well. The program had access to the entire Agency knowledge base, along with skills and infrastructure. The program was viewed as a high priority at all centers, since it represented a path to a sustainable and growing role in most areas of expertise. Engagement of nontraditional human space flight centers allowed the program to tap into unique skills, approaches, and facilities. Contractors benefited from NASA technical depth and expertise, along with access to unique facilities (e.g., engine test stands, large vacuum chambers). The early test flights, *Ares* I-X and *Orion* Pad Abort-1, demonstrated the benefits of multicenter teams. These projects were successful early pathfinders in identifying and resolving the problems that could arise from a conflict of cultures in design, test, and manufacturing.

2.2.4 The Generation Gap in Human Space Flight

The work force that supported Constellation was not only geographically distributed; it was also bifurcated in crucial experience level. Since NASA human space flight developments have occurred on 20- to 30-year cycles, most of the Constellation work force was generationally removed from the previous human spacecraft development, particularly the launch and entry development challenges. The Space Shuttle design was performed in the mid 1970s and tested in the late 1970s and early 1980s, prior to the birth of many of the engineers working on Constellation. ISS design and development (which relied on the Space Shuttle for launch and entry of crew and equipment) took place in the late 1980s and into the mid 1990s. The Constellation Program was replete with ISS experience; however, only senior engineers and leaders in the Constellation Program had been involved in the early development stages and knew the pitfalls and travails in starting up a national-scale program. Most of the work force was

well versed in operating human spacecraft either via Shuttle, the ISS, or both, but only partially aware of how early design compromises affected those very operations.

The Agency took extraordinary steps to deepen the design skills of the work force. The critical thinking necessary to perform systems engineering (SE) design—which was emphasized in formal and informal training, lessons-learned briefings, leadership postings, work force discussions, and work rotations—became a focus at the level of the NASA Administrator. Opportunities for testing smaller development projects early were created to enhance work force experience.

To reach back and capture launch and return vehicle development experience, the Constellation Program created a ready resource known as SAGES [Shuttle and Apollo Generation Expert Services]. This contract provided a simple pathway by which to enlist the aid of retired experts from the NASA past (e.g., George Mueller, Chris Kraft, Glynn Lunney, Dick Kohrs, etc.). Beyond review and advice, SAGES was created to transfer knowledge through mentoring. It was based on relationships between Apollo- and Shuttle-era program managers and discipline experts and the Constellation team. It provided mentors on an as-needed, targeted basis in areas ranging from technical design and analysis disciplines, to ground and flight operations, and to program management.

A perspective drawn from past programs is invaluable in many ways. To individuals, it provides resiliency in the face of challenge, particularly if the challenge has been met before, albeit under different circumstances. To organizations, it lends strength and stability to the organization by having key personnel with this type of resiliency willing to mentor those who do not.

2.2.5 The Size of the Trade Space

An inherent characteristic of the early design phases in a large-scale development is the scope of the “trade space” within which designers and managers can make choices. Fundamental choices at this stage have very long-term consequences. Choices of fuels, engines, outer mold-lines, volumes, materials, etc. have a vast number and sequence of “touch points” in an existing and future infrastructure. In the case of Constellation, these touch points ranged from ground infrastructure already in place from earlier programs, to the lunar and martian surfaces. During maturation of a program, a trade space stabilizes and shrinks as choices are made and designs solidify. As we approach testing and operations, that trade space narrows. While new design work can occur in mature, operational programs, akin to those of ISS or Shuttle, the trade space is typically very limited and choices are few.

Due to the scope of the trade space for Constellation, early choices and decisions were very often brought into question when new knowldege was introduced, as new or overlooked touch points were discovered, or when budget and schedule constraints limited preferred choices. For a work force most adapted to the very limited trade space available in operational programs such as Shuttle and ISS, this cycle of working through options (and changing options as constraints change) can look like churn, indecision, and lack of leadership. And for a leadership team most focussed on socialization of major decisions with Agency mangagement, insufficient attention to this perception leads to frustration at the working level.

This difference in perception is manifest in many of the lessons learned that follow. Here are a few perspectives that illustrate these contrasting points of view. While some may be in opposition, each view is relevant because it affected daily operations and interactions in the work force.

On decision making:

Younger engineer: *"This [changing of decisions] could have been avoided by having a daily tag-up [meeting] as was done….on the ISS Program."*

Older engineer: *"ISS took much longer to get to PDR….with lots of upheaval getting there. It wasn't until around CDR that daily tags chaired by a strong leader were added to improve progress and accountability."*

Younger engineer*: "The program revisits the same decisions over and over. There seems to be no accountability for sticking with decisions that have been made."*

Older engineer*: "[Space Station] Freedom had three program managers in 4 years. The architecture was constantly changing, from power-tower to a single truss; from solar dymanic power to combined SD [solar dynamics] and PV [photovoltaic] power and back again to SD and back to finally PV. Then segments were cut from the truss, creating the shadowing that we deal with operationally today. And, it took years to get to the 20-kHz power architecture."*

2.2.6 Phasing of Project/Program Start-up

Two of the primary projects, the *Orion* Crew Exploration Vehicle and the *Ares* Crew Launch Vehicle, were begun well in advance of the Constellation Program.[1] This enabled rapid start-up and early results from each of these projects. They functioned for some time without an integration function between them, which led to an eventual Program Integration (PI) function that was very lean by historical norms.[2] This rapid start-up enabled rapid contract competition. However, these contracts were not fully scoped for the physical and analytical integration that was necessary. They were focussed on the IC, since trade studies had not been performed that would optimize an integrated architecture. These factors led to costly contract changes when the appropriate level of integration for a complete architecture was better understood.

This approach also provided an additional integration challenge; namely, the projects had formed requirements, budgets, design approaches, acquisition strategies, etc., that needed to be integrated retroactively. The late addition of integrating functions had a long-term effect that was not fully resolved by the end of the program. Strategies that were in a collective self-interest for the program were extraordinarily difficult to implement due to the cost of contract changes.

[1] The most logical approach to starting up a new program is to first understand the "big picture" before decomposing that end state into smaller and smaller elements. This is why it is ideal to first start up a program office with its integration products, then to start up project offices to accomplish the hardware development. This was not the case in the Constellation Program.

[2] A typical large space flight program historically uses approximately 10% to 15% of its budget for PI. The Constellation Program was relatively lean, spending 5% to 7.5% on these functions.

Examples of these include unit policy (SI vs. heritage English units of design and construction), data architecture, and facilities management. Boards and panels had been formed prior to the program office, which meant these boards and panels had different structures and responsibilities. Integration of these into a program board and panel structure confounded decision making. Moreover, integrated analyses by the program uncovered technical issues that could have been caught earlier (and been resolved in a more efficient manner) if the start-up timing had been different.[3]

Incentives on contracts were developed primarily to benefit each project rather than the overall program. Missing were incentives for contractors to participate in technical solutions that benefit the integrated program. This drove results that were less than optimum, and sometimes not mutually compatible.

2.2.7 Starting Well vs. Demonstrating Early Success

Many of the following detailed lessons learned describe the repurcussions of starting projects before the program is started. The start-up phasing described above was primarily driven by the Agency's need to demonstrate early successes to secure political support.

Experiences from the early stages of ISS may also have contributed to the push for early success. The ISS Program had its roots in the prior Space Station *Freedom* Program, a program that suffered "fits and starts" in the effort to "start well" and proceed to PDR as it underwent several major descopes and redesigns. While it formed in a different political and programmatic environment, it experienced many of the same funding and work force challenges as the Constellation Program did. Consolidation, under the ISS Program in the mid 1990s, alleviated some but not all of the start-up issues.

Much of this was in the minds of the Constellation organizers, who believed that the political will would not be sustained through a *Freedom*-like start-up. Again, we see the perspectives from the work force on this issue:

Program office integration engineer: *"The projects started way ahead of us, so we were always in catch-up mode. They had prime contracts on board, so every integration issue we found was a real headache."*

Project office engineer 1: "*We had to get up and running fast and get our test plans in place. We needed to have some early test successes to keep support for the project. The program office added layers of requirements and reviews. They just didn't get that we were moving and couldn't make changes without big cost and schedule hits."*

[3] An example of this was what became known as the "thrust oscillation" issue. Integrated analyses indicated that unacceptably large thrust oscillations from the *Ares* I first-stage burn could be transmitted through the stack to the flight crew in the *Orion* vehicle during launch. Design changes were implemented in the PDR time frame to mechanically dampen the oscillations and sufficiently isolate the crew. We can speculate that earlier identification could have resulted in simpler, lower cost changes.

Project office engineer 2: *"The program was trying to get in our knickers. They wanted to tell us how to design the vehicle. We had a schedule to meet, so this didn't go down too well."*

Ground operations engineer: "*We were at the tail end. Projects made changes and didn't tell us. They didn't know the change would impact the ground ops hardware. It cost us big time to make late changes."*

Program control analyst: *"The project procurements were way ahead of the program, and so changes cost big bucks. We didn't have much flexibility with reserve dollars, but every change we processed to integrate the project hardware and software came down to painful cost and schedule choices."*

3.0 KEY FINDINGS

Given the challenges described in Section 2.0, the following is a brief listing of the key findings distilled from the Constellation Program. Explanatory information, as well as further detail, can be found in Section 4.0.

The character of these lessons is worth noting. The reader will observe that very few technical issues arose that could not be solved in relatively short order; indeed, the most difficult and most persistent challenges involved cost, schedule, communication, and organization. The reader will no doubt recognize this pattern from previous large-program lessons learned. While the Agency is renowned for technical prowess, senior managers in flagship programs can be faced with a multitude of nontechnical challenges for which they have far less training or preparation. In this respect, lessons learned can be an invaluable source of insight.

3.1 Robust vs. Optimal Planning — The Only Certainty Is that the Funding Will Not Match the Plan

Driving Events

Section 2.1 describes the context and driving events for the funding and planning challenges faced by the Constellation Program. Constellation found itself in a grounds-up re-plan at least annually.

Lessons Learned

The reality is that Agency flagship programs like Constellation must be robustly planned (e.g., “elastic”) vs. optimally planned (“inelastic”). Absent a national imperative akin to the race to the moon, funding will not arrive as planned. Flagship programs are highly visible and stand alone in the national-level budget debates. They are not part of a budget portfolio and, therefore, cannot look elsewhere for funding.

A flagship program will never experience complete alignment of the budget with the plan, either in net or in phasing. Consequently, flagship programs should resist the urge to optimally plan each budget line item.

Recommendations

Plan for Continuing Resolutions CRs for the first quarter of each FY until and unless Congressional processes change substantially.

Decouple programs/projects as much as possible in strategic, programmatic, and technical aspects.

Proactively determine sensitivities and breakpoints in budgets, and communicate these to stakeholders *a priori*. Establish expectations for funding reductions in advance. This is the best hope to influence budget decisions.

Develop scenario(s) to accommodate 5% to 10% funding shortfalls in any given FY. Understand the major drivers to cost and options available (i.e., "knobs to turn") when unexpected challenges appear.

Supporting Lessons Learned from Section 4.0: 4.2.4, 4.2.5, 4.5.1, 4.9.4

3.2 Schedule Creep and the Fixed Base — The Law of Diminishing Returns

Driving Events

As discussed in Section 2.2, the Constellation Program dealt with funding cuts primarily with schedule slips rather than content reductions (due to NASA Administrator direction). Variable costs are early targets, since they can be deferred (while adding program risk). The fixed-base costs — both within the Agency and for the contractors — become proportionally larger, making schedule slips less and less effective in addressing cost cuts.

Lessons Learned

Each schedule slip resulted in longer periods for which Constellation was expected to maintain the Agency's Human Space Flight "fixed base" along with the industrial fixed base from its suite of acquisitions. This had the effect of reducing the overall cost savings being sought from the initiating event — the funding cut. A vicious cycle was established that only grew more severe during the life of the program as more and more time supporting the fixed base was added to the program lifetime. Ultimately, there could be no resolution without addressing content reductions.

Recommendations

Understand the inherent limitations of schedule slippage to resolve funding shortfalls, since accrual of the fixed-base portion of the budget erodes the buying power in the out-year funding. Reduction of program content warrants consideration under these circumstances.

Supporting Lessons Learned from Section 4.0: 4.2.4, 4.2.5

3.3 Tailoring and the Design and Construction Standards — Drinking from a Fire Hose

Driving Events

The involvement of 10 NASA centers (described in Section 2.2.3, Mosaic of NASA Participation), along with the overabundance and overly prescriptive nature of design and construction standards led to an avalanche of "shall" requirements on the Constellation contractors. While Constellation was allowed broad latitude to tailor requirements, tailoring required rationale and negotiation with the requirement "holder." The sheer number of direct and embedded requirements made the task of tailoring intractable.

The following illustrates the extent of the problem: The *Orion* prime contract alone levied design and construction (D&C) specifications from: 34 NASA standards, 10 Johnson (Space Center) Program Requirement (JPR) documents, 11 JSC technical standards, 3 NASA Program Directives (NPDs), 6 NASA Program Requirements (NPRs), and 11 KSC standards. This included the following particularly prescriptive examples:

- NASA STD 8739.3, Soldered Electrical Connections – a 93-page document with 391 "shall" statements inclusive of room temperature/relative humidity and 1077 lumens of light per square meter or 100 foot candles on the work surface.
- NASA STD 8739.4, Crimping/Cables/Harnesses/Wiring – a 66-page document containing 391 "shall" statements requiring (a) a Snell far-vision chart 20/50; (b) a near-vision Jaeger1 at 355.6mm; and (c) reduced Snell 20/20 or equivalent. Requires color vision testing and specifies temperature/humidity and lighting.
- NASA STD 8719.9, Standard for Lifting Devices – a 126-page document containing 996 "shall" statements covering the use of overhead devices as well as powered and motorized devices; approves the use of manufacturer's procedures and instructs on how to set the parking brakes on mobile and motorized units.

All of the major aerospace contractors, who build systems for multiple government customers (Department of Defense [DoD], National Security Agency [NSA], NASA, etc.), have certified internal processes and suppliers that meet both national and international standards. The set of NASA requirements is often redundant to this.

Lessons Learned

The massive quantity of D&C standards defies tailoring for even a large program such as Constellation. Major aerospace contractors have sufficient processes such that the NASA D&C standards are of questionable value. This is a major driver of program fixed costs.

Recommendations

NASA should assume the burden of "meets or exceeds" evaluations instead of making the contractor prove that it meets NASA requirements. NASA should implement this by establishing an experienced team to audit contractor internal processes at the NASA document level. This process should not burden the contractor with defending the adequacy of each individual requirement. For the most part, the aerospace contractor community is well versed in the appropriate manufacturing and safety measures required to develop space hardware. NASA should build on that expertise.

Currently, this topic (Affordability/Innovation) is the subject of discussion among the Chief Engineer Office, the Chief Health and Medical Office, and Safety and Mission Assurance (S&MA) leadership. A team has been tasked with describing a process and timeline for transforming the Agency approach to Technical Authority requirements and standards. This initiative should establish clear criteria for mandatory ("shall") requirements. It should also revalidate the current Agency requirements base with the goal of significantly reducing the total

number. Most requirements should become guidelines or best practices, and should take into account the pros and cons of the DoD experience with reduction of requirements.

Supporting Lessons Learned from Section 4.0: 4.2.4, 4.2.5, 4.2.6

3.4 Tailoring Process Simplification — The Law of Unexpected Consequences

Driving Events

One of the many findings of the CAIB was that NASA had institutionalized the waiver and deviation process for requirements such that permanent or semipermanent waivers and deviations to requirements were the accepted norm. The CAIB, as well as other committees and panels studying the NASA human space flight culture, questioned the quality and validity of requirements that need permanent waivers or deviations to remain extant. Consequently, the need to establish a waiver or deviation developed an understandable cultural taint in the work force. Training after the *Columbia* accident reenforced this aversion. Indeed, important NASA stakeholders (e.g., Congress, the Aerospace Safety Advisory Panel, members of the public) were keen to maintain visibility on the NASA use of waivers.

Meanwhile, the Agency did not grapple with the plethora of requirements that drove the practical need for waivers and deviations to requirements. While the Agency approach to requirements was redesigned with the introduction of the independent Technical Authority, the actual number and scope of requirements was not addressed.

This left the Constellation Program in a quandary. It was allowed broad latitude in tailoring requirements to its needs. However, the Agency decided that the program would use deviations and waivers to document tailoring outcomes. Cultural consequences were not evaluated. Moreover, the process for permanent deviations and waivers was formalized by the Agency. Discussions of tailoring were driven down to the level at which they were most productive — to those most familiar with design and implementation; however, waivers and deviations required higher visibility within the Agency to agree on. This cultural inconsistency, coupled with the sheer number of requirements addressed in the previous lesson, made the tailoring process nearly insurmountable.

Lessons Learned

While the use of waivers and deviations was intended to simplify the tailoring process of requirements for the Constellation Program, cultural consequences were not addressed. This had the unintended consequence of confounding the tailoring process rather than assisting it.

Recommendations

Tailoring of requirements is necessary and should not carry a cultural stigma. The process should be revised to remedy the negative implication.

Supporting Lessons Learned from Section 4.0: 4.2.3

3.5 Risk-informed Design — Risk as a Commodity

Driving Events

The broad scope of the Constellation Program permitted some greatly effective experimentation in the design process. The traditional aerospace design process (i.e., "rule-based" approach), wherein the vehicle is designed strictly to requirements (and, by implication, all requirements are equal or nearly so), was used on most elements. Progress in analytical techniques allowed the application of reliability to supersede redundancy in design, strengthening the use of design for minimum risk (DFMR). Two elements used a risk-based approach that resulted in overall better designs.

The *Orion* vehicle was designed initially using the rule-based approach. In meeting all of the requirements, the vehicle was overly constrained and too heavy, and it also had performance challenges. To "close the architecture," the project implemented a revised design process that prioritized mission-critical, reliability, and safety requirements. A "zero-based" vehicle was designed that met only these requirements. All other design features required justification based on ability to reduce risk, i.e., risk as a commodity, using standard risk assessment tools (e.g., probabilistic risk assessment, hazard analysis, and failure modes and effects analysis) along with the beneficial use of other design commodities (e.g., power, mass, budget). The ability of the *Orion* vehicle to minimize LOC (loss of crew) probability, along with meeting of performance and mass constraints, was improved through application of this process.

The *Altair* vehicle pioneered a similar approach, uniquely applied *a priori*. The Risk Informed Design process used an analysis-based approach to design the absolute minimum vehicle necessary to perform the mission and then added design features by proven value in increasing vehicle reliability and safety. This resulted in more robust design solutions that either eliminated or better controlled hazards.

Lessons Learned

Risk Informed Design (i.e., treating risk as a commodity in design) was a breakthrough for both *Orion* and *Altair*, resulting in designs that "closed" and were safer and more reliable than a rule-based design approach could yield.

Recommendations

A rule-based design approach can remove accountability to understand the implications of design choices. Employ risk-informed design methodology *a priori* to focus design on overall mission success rather than compliance with "design rules."

Supporting Lessons Learned from Section 4.0: 4.8.1, A.3

3.6 In-house Tasks — Sustaining the NASA Institutional Base vs. Affordably Supporting the Programs — Getting from "or" to "and"

Driving Events

Driving events for this lesson are described in Section 2.2.3 under "Mosaic of NASA Participation."

While the Constellation Program attempted to distribute work in logical packages, the competing needs of "10 Healthy Centers," the scope of the program, and phasing considerations (e.g., placement of work in the post-shuttle era) drove instances of incoherent distribution, resulting in muddling of roles, responsibility, and authority.

An example of the *Orion* Launch Abort System (LAS) development further illustrates the wide distribution of roles and responsibilities. This development was a subsystem of *Orion* and is not an extreme example, but it is typical of the rest of the program. Primary responsibilities were divided as follows:

- JSC: *Orion* project management, lead for crew module and vehicle integration, prime contractor oversight and independent analysis
- MSFC: LAS prime contractor oversight and independent analysis
- Langley Research Center: Lead for LAS integration, prime contractor oversight, and independent analysis
- Glenn Research Center: Flight Test Article and pathfinder production for Service Module (SM) and Spacecraft Adapter
- Dryden Flight Research Center: Lead for Abort Flight Test integration and operations

When everybody is responsible for everything, nobody is responsible for anything.

Furthermore, the relatively low cost of most in-house tasks can be deceiving. While sometimes low in cost, the price of confused roles, responsibility, and authority (RR&A) can lead to major headaches, and can flow into the contractor infrastructure. These roles are often coupled with the desire for modernization of associated host-center facilities, which can drive larger costs.

Lessons Learned

Task assignments for in-house work are strategic drivers within the Agency; they are more than a series of make-buy or in-house vs. contractor decisions. Clear RR&As must be a priority. In spite of the relative low cost, the distribution and RR&A for in-house tasks are deserving of management focus to avoid confusion and overlapping roles down the line.

Recommendations

Target in-house tasks for items that will mutually benefit programs (e.g., unique expertise) and centers (e.g., institutional sustainment). Due diligence will be needed to achieve this balance of benefit to the program *and* benefit to the NASA institution. Achieving balance will bring value to

the program as well as provide strategic support for the NASA institution, equipping the Agency to accomplish future programs and missions.

Affordability, institutional benefit, and coherence of RR&A should be three additional strategic considerations in these decisions. Or, simply stated, "Make sure the gain is worth the pain."

Supporting Lessons Learned from Section 4.0: A.5

3.7 Roles, Responsibility, and Authority — a Non-thermodynamic Application of Entropy

Driving Events

The clarity of RR&A for the Constellation Program was degraded by the combined effects of the wide distribution of program responsibilities via the "10 Healthy Centers" policy, multi-decadal phasing of program development in IC and LC, and assumption of traditionally understood roles from the space shuttle heritage component development as described in Section 2.2.

The Program undertook a number of steps to improve this, including conducting work force surveys and holding regular management retreats. Perhaps the most successful effort was the Program Excellence Team (PET), which was a council of program deputies who frequently met face-to-face and via teleconferencing to work through specific issues related to RR&A.

Lessons Learned

There is no formula or checklist for clear RR&A in an Agency-wide, flagship program. The specific approach on organizational structure taken by Constellation in this regard is addressed in Appendix A, in the paper on formulation of the program. Projects housed at centers where previous or similar work took or takes place will tend to assume these heritage roles, in spite of contrary direction.

Two early test flights provide examples of how strong leadership and meeting imminent schedule milestones can drive improvements in RR&A and decision-making.[4] The *Ares* I-X test flight and the *Orion* Pad Abort-1 test flight were both pathfinders in how to function and succeed within the broad scope and far-flung Constellation organization. Both were developed as the program relationships were forming, using distributed teams and hardware developments. While they were initially hampered by the same factors described in this section, these teams were able to focus on the most important elements and succeed in meeting all of their test flight objectives.

RR&A can be improved by functional examination, by either combining like tasks or separating functions by need. During development of the Integrated Master Schedule (IMS), implementation was hindered by the conflicting needs of the product/task providers and the schedule assessment

[4] See also Lesson Learned 4.11 for more benefits of test flights.

team. When these functions were separated, the IMS development quickly gained focus and results improved.

Risk management was challenged because it was separated functionally from cost threat management. When broader aspects of risk (e.g., cost threats, safety, etc.) were included, the results from the system improved.[5]

RR&A for the IC was relatively clear and in daily operation. Roles for the LC, while defined at a top level, were best developed for projects that had "follow-on" content from the IC.

The program was also contemplating the roles the International Partners might take. This formulation is described in Section 4.9.

Recommendations

While it is a good start to define RR&A, periodic examination is required for large-scope, distributed programs. Attention to the effects of heritage RR&A and phasing are particularly important. RR&A should also be planned to adapt to the program phase(s).

Creating a dedicated team of decision makers (e.g., the council of deputies) to critically review and address RR&A can be very effective.

Use of annual employee surveys provides a helpful metric toward gauging the effectiveness of measures taken to address RR&A issues.

Supporting Lessons Learned from Section 4.0: 4.1.1, 4.2.6, 4.4.1, 4.4.2, B.1

3.8 Decision Making — Only as Efficient as Roles, Responsibilities, and Authority Are Clear and Understood

Driving Events

The clarity and effectiveness of the decision-making processes for the Constellation Program were driven by the same events as summarized above in Section 3.7 and as described in more detail in Section 2.2.

The start-up phasing (late start of the program relative to the projects) previously described also confounded decision making. Projects made unilateral changes without considering integrated effects. For example, *Ares* made changes to the "stack height" that impacted the *Orion* and Ground Operations designs; *Orion* deleted a test flight it found unnecessary without understanding the integrated effects. Once the program integration function was operational, decisions were better coordinated but opportunities for early-phase, lower-cost changes were lost.

[5] NB: Risk management systems quickly degrade to "issues tracking" unless adequate reserves are maintained to address and retire risks at the appropriate time. Lacking this, risks become accepted *de facto.*

The mature decision-making structure affecting Constellation Program decisions is partially illustrated in Fig. 4. Not shown are other organizations having a significant influence on the decisions made: center institutional processes (e.g., Engineering Review Boards, Program Management Councils, facility boards), the Technical Authority (which provides the appeals route for technical decisions), or the internal decision processes for the prime contractors.

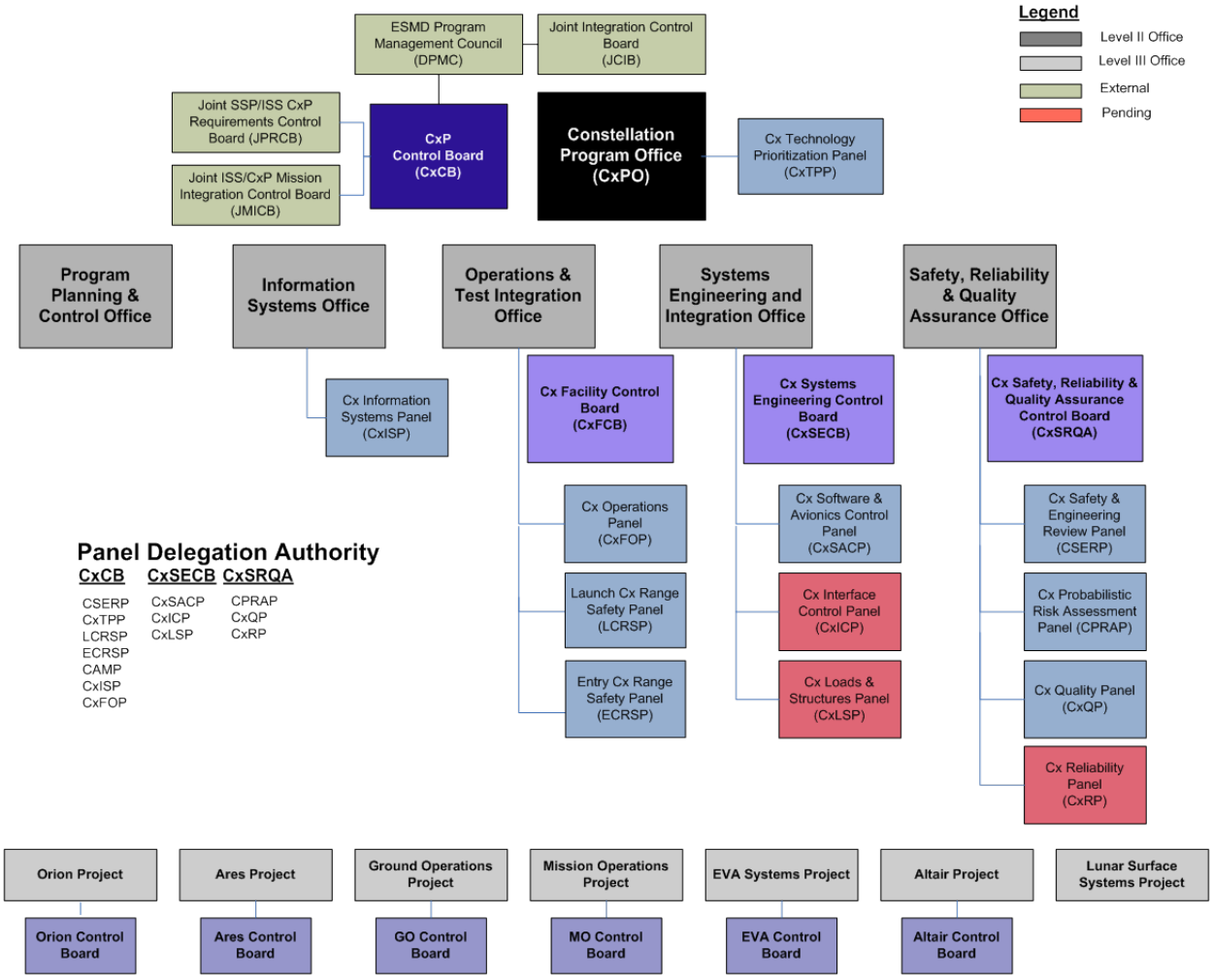


Fig. 4: Illustration of the Constellation Program decision-making board and panel structure. Note what is not shown: center institutional decision-making bodies, Technical Authority (the appeals process), or the prime contractors internal processes. (ESMD=Exploration Systems Mission Directorate, SSP=Space Shuttle Program, ISS=International Space Station)

Lessons Learned

In spite of constant attention from senior management, the decision-making process remained a persistent issue that only marginally improved over time. In a program of this scope, attempts to balance timely decision making at the appropriate levels, consider strategic and tactical viewpoints, and clearly delineate accountability for execution, while keeping all stakeholders

informed and included, often left someone dissatisfied. The need to maintain the multi-decadal focus was sometimes misunderstood, particularly in projects with immediate, near-term needs.

The need to make decisions regarding NASA center infrastructure that would or would not support Constellation over time was particularly nettlesome, bringing in communities that seldom dealt with program management. These decisions typically necessitated involvement at the Agency level and required extra time and staffing. Major infrastructure changes drew interest and attention from Congress as well, so it was necessary for many entities outside the program to be well informed.

Recommendations

A good start is important to define the decision process; however, constant vigilance is required for large-scope, distributed programs. Invest the time and energy to define a comprehensive decision process that includes all affected parties (Technical Authority, center management, and contractors). Impediments will arise by not anticipating key stakeholder interests.

Attention to the effects of project phasing, particularly for decisions intended to last decades or affect center infrastructure, is very important.

Supporting Lessons Learned from Section 4.0: 4.1.2, 4.1.3, 4.1.4, 4.1.5, 4.4.1, B.1

3.9 Organization is Organic — You Will Never Get It Right, But You Can Make It Better

Driving Events

The organizational structure for the Constellation Program evolved over time. Initially the organization was set up in a model derived from the Apollo Program – an integration function comprised of Systems Engineering and Integration (SE&I); Test and Evaluation (T&E); Operations; Program Planning and Control (PP&C); and Safety, Reliability and Quality Assurance (SR&QA),[6] along with individual projects including *Ares, Orion*, Ground Operations, Mission Operations, and EVA. An Advanced Projects Office was also included to begin formulation of the lunar projects, including the lander and surface systems. Significant changes within the next year included the following:

- Establishment of mission managers for the *Ares* I-X and I-Y flight tests to enable the focus needed for integration.
- Establishment of the Lunar Lander Project (*Altair*) and the Lunar Surface Systems Project, and dissolution of the Advanced Projects Office in response to the completion of early formulation activities for these projects and no immediate need for succeeding early formulation activities beyond the lunar missions.

[6] J. L. Rhatigan, J. M. Hanley, and M. S. Geyer, *Formulation of NASA's Constellation Program*, NASA-SP-2007-563, October 2007.

In the following year, other organizational refinements were implemented:

- Combination of the T&E Office with SE&I, since the T&E role had become entangled with that of SE&I and the *Ares* I-X and I-Y mission managers.
- Establishment of the Program Architect to balance the maturation of the Constellation architecture (LC) with near-term (IC) systems development.

In the subsequent year, further organizational refinements were implemented:

- SE&I was reorganized to transform its focus from requirements definition to design integration following completion of the Program Systems Definition Review (SDR).
- The Information Systems Office was formed in response to the focus needed in development and implementation of a program-wide data architecture.

The preceding listing is illustrative, rather than comprehensive, to communicate that the Program adapted the organization over time to both emergent issues and task completion.

Lessons Learned

Organizations should be treated as organic entities that are evolving and adapting to circumstances over time. Needed adaptation can be anticipated according to schedule milestones; the work force and organization should be focused on achieving the next key milestone, not on continuing to operate in the mode that achieved the last key milestone. Key milestones such as design reviews mark natural breakpoints in organizational strategies, and indeed the organizational scheme warrants assessment as part of a key milestone review. Consider that as the Constellation Program moved from requirements definition to development, the needed changes were not uniformly recognized, so the organization was slow to adapt after the SDR to prepare for PDR. Rather than preemptively assessing the organizational model, the program leadership reacted to issues associated with progressing to PDR as these issues emerged. The post-PDR organizational adaptation to CDR objectives was accomplished more quickly since it was anticipated.

Recommendations

Revisit the organization at key milestone reviews to address the changing nature of the work ahead to achieve the next milestone. This should be documented in a revision of the Program Plan and be briefed to senior Agency management at the appropriate milestone briefing. Senior Agency management must be enlisted to mitigate social impacts across NASA centers due to the ebb and flow of assigned work.

Supporting Lessons Learned from Section 4.0: 4.1.4, 4.1.5, 4.4.1, A.5, B.1, B.2

3.10 Communication Among a Distributed Team — Interpersonal Networks and Information Systems Can Improve Decision Making

Driving Events

As discussed in Section 2.2, Constellation's widespread 10-center team created a true communications challenge. While countless assessments and prevailing programmatic wisdom indicate that a small, centrally located team is the most efficient way to build a complex element, Constellation did not have that luxury. This posed many RR&A and decision-making issues, as described above (4.7, 4.8, 4.9), as well as integration challenges. Well-understood RR&A and clear decision-making processes reduce the communication "overhead" for the program team. Beyond that, any and all efforts to improve communications and data management (DM) are beneficial. Constellation used the following to enhance communication and DM over and above holding regular face-to-face meetings:

- A council of project and program deputies, mentioned in 4.7, was formed to resolve issues related to roles, decision making, and communications. The council was formed in early 2007 to tackle issues already apparent in RR&A associated with the formation of the Program Office. This council became an informal communication network; members spent time with each other and gained trust by sharing perspectives and working through problems of mutual interest.
- "Communities of Practice" were formed to foster discussions in particular technical areas and to aid information flow.
- Information technology (IT) tools and applications (teleconferencing, WebEx [Cisco, San Jose, CA], LifeSize® [LifeSize® Communications Inc., Austin, TX], ICE/Windchill [PTC, Needham, Mass.], etc.) were extensively used to enhance the flow of information.
- A data-centric (vs. document-centric) approach to program integration was implemented that enabled linking of configuration-controlled record-level data and automated integration of data direct from authoritative sources, thus eliminating error-prone manual copying of data.

Lessons Learned

This thorny issue was a classic case of "the devil is in the details." Overall RR&As were clear enough, as everyone understood the integrating responsibility of the Program Office with respect to constituent projects; however, translation of this overall understanding into day-to-day practice was needed to address the real issues that cropped up daily.

As such, frequent meetings of the council of deputies were necessary, which gave the informal network an ideal opportunity to form. IT tools, including teleconferencing and WebEx, allowed many virtual meetings to be interspersed with face-to-face meetings, thereby greatly increasing productivity of the group. Over time, as the relationships between group members grew stronger and the team's norms of behavior became more ingrained in team members, more and more of the group's work could be accomplished via these virtual meetings, further increasing productivity.

The council of deputies is only one example; integration groups for each of various engineering disciplines also benefitted from the improved IT collaboration tools over the previous generation, allowing significant improvements in the utility of virtual team meetings.

Due to the late start of the program relative to the start of the projects, incompatible data systems were the norm, so the program had to use a mostly manual approach to integrate data. This often involved use of non-authoritative copies of data, which resulted in decisions being made using out-of-date and inaccurate information (e.g., out-of-date IMS, 40% discrepancy rates in risks). Once a program-wide data systems architecture was established, promising results with core data sets were observed, thus reducing discrepancy rates and communication overhead in support of improved decision making.

Recommendations

Large-scope, geographically dispersed programs can benefit from interpersonal networks established across organizational boundaries.

Affordable, state-of-the-art IT tools can facilitate communications across time and space. They should be available as early and as broadly as feasible.

A large program should be diligent in anticipating the formal and informal networks that will emerge or intentionally be formed, and ensure that these networks have access to the IT tools that will enable these networks to work most productively.

Program-wide data systems architecture for data integration should be used *a priori*; and projects should use software tools that enable data integration and interoperability with published interfaces and, where practical, should also use common software tools.

A data-centric (vs. document-centric) approach for DM should be established at the beginning of the program, with clear and common data requirements between all levels and organizations of the program using formal agreements (e.g., data requirements documents [DRDs]) that include requirements for electronic data.

Supporting Lessons Learned from Section 4.0: 4.1.1, 4.3.1, 4.3.2, 4.3.3, A.5, B.2

3.11 Flight Tests – Learning by Doing

Driving Events

The value of flight tests in program development is undisputed; however, they are inherently resource intensive – which is to say, expensive. As such, they are typically reserved as risk mitigation for significant technical risks and demonstrations of critical capabilities. For the Constellation Program IC, flight tests were primarily focused in two areas: *Ares* launch vehicle ascent performance and *Orion* LAS performance.

Ares I-X was the first test flight in a planned series that would culminate in human rating of the vehicle. It was designed as a crewless development flight test to demonstrate first-stage ascent performance. *Ares* I-X successfully flew in October 2009, achieving all test objectives. One of the primary purposes of *Ares* I-X was to acquire flight data early enough to influence and impact the design and development of *Ares* I. The *Ares* I-X attributes were sufficiently similar to those

of *Ares* I to meet the test flight objectives. The test provided enough data for partial validation of models and processes used in the *Ares* I design, and allowed the test data to improve *Ares* I design and development.

For the *Orion* LAS, a series of flight tests was planned to certify safety and performance in the most challenging launch and flight regimes. The first flight test (Pad Abort-1) demonstrated LAS performance and Crew Module landing systems performance in a pad abort scenario. Launched in May 2010, Pad Abort-1, the second Constellation flight test, achieved all flight test objectives. A primary purpose of the flight, akin to that of *Ares* I-X, was to acquire flight data early enough to influence and impact the design and development of the *Orion* LAS and Crew Module landing and recovery systems. The test provided sufficient data to partially validate models and processes used in the *Orion* design, improving *Orion* design and development.

The *Ares* I-X and Pad Abort-1 efforts were largely independent activities. As such, comparing the two flight test activities reveals fundamental similarities that may characterize successful flight tests and provide insight for future program success.

Lessons Learned

Both flight tests were very successful, achieving all flight test objectives and returning a wealth of technical data early enough in the development cycle to inform design; however, the key lessons learned involved nontechnical returns from the flight tests. In both cases, these complex flight tests stressed the needed organizational constructs and drove clarity into RR&A and the decision-making structures. Had these issues been revealed later and addressed nearer to the first full-system flight (e.g., the planned *Orion*-1 mission), significant delays and an increased risk posture would have resulted.

Furthermore, nontraditional approaches can be tried during a flight test, particularly a crewless flight test. For instance, *Ares* I-X employed large structural margins in the mass and dynamics simulators used to emulate the upper-stage and *Orion* hardware; and it used a “ping-test” approach to determine the dynamic characteristics for guidance of the stack rather than a much more expensive and time-consuming structural ground test of the stack. This approach worked very well and, after its successful demonstration on *Ares* I-X, the Program was examining the cost savings vs. risk of adopting this approach for future flights.

Finally it is noteworthy that when cancelled, the Program was in the process of revising the development strategy for the IC to rely more heavily on flight tests, thus saving time and budget by reducing ground tests in response to the increased confidence in the analytical models and simulations that resulted from *Ares* I-X and Pad Abort-1 flight tests.

Recommendations

Plan a series of flight tests to demonstrate key system capabilities and mitigate major technical risks. Ensure that some of the flight tests occur early enough in the development cycle (i.e., PDR time frame) to return data in time to inform the system design. Flight tests have the additional

benefit of providing opportunities to test alternative approaches and discover efficiencies for overall organizational performance.

Supporting Lessons Learned from Section 4.0: 4.2.6, 4.7.5, 4.8.1

4.0 DETAILED LESSONS LEARNED

Section 4.0 comprises the detailed lessons learned. They are arranged in traditional program management and engineering disciplines. The reader should note that many of the lessons cover new topics, i.e., those not addressed in the executive summary lessons learned. Also note that most of these lessons are linked to the Key Findings as supporting information for those seeking further information on a particular topic.

Below is a listing of topical areas contained in Section 4. New topics, not addressed in Section 3.0, are indicated in italics.

- Roles, Responsibilities, Authority, and Decision Making
- Requirements
- *Data Management*
- *Integrated Master Schedule*
- *Earned Value Management (EVM)*
- *Joint Confidence Level*
- *Construction of Facilities*
- Risk Management
- Design and Development
- *International Partnerships*

4.1 Roles, Responsibilities, Authority, and Decision Making

To effectively integrate a multi-element, geographically dispersed human space flight program, roles and responsibilities should be defined early in the start-up process. This should include not only the program and its projects, but also the agency and centers involved. Lack of clarity in this area leads to team tension, inefficient decision making, and wasted efforts. Moreover, as program objectives change with program maturity (Phases A to E), RR&As should be reevaluated and adjusted for relevance to current program milestones and objectives.

4.1.1 Ensure the Decision-making Process Is Aligned with Program, Project, and Center Roles, Responsibilities, and Authority

Supports Key Finding: 3.8

Driving Events

As described in Section 2.0 and Key Finding 3.8, the program decision processes were perceived as duplicative and sometimes inconsistent. Arguably the most important of the factors described in Section 2.2 was the highly constrained budget environment. Budget cuts led to rapidly diminishing reserves. This drove the necessity to retain the remaining reserves at the program level, thus severely restricting decision authority at the project level. Budget cuts drove many revisits to prior decisions in search of remediation. In any decision-making structure, lack of reserves to implement risk reduction, changes, or schedule slips to accommodate reduced funding, etc. compromise the ability of a program to make progress (e.g., reevaluating decisions due to changed circumstances).

Further, the need to hold reserves at a high level directly subverted the best practice, described in 4.1.2, of pushing functions and decisions to the knowledge base (project or lower levels of the program). Lacking resources, boards can solve problems within their scope but often cannot implement the solutions. Rather, the decision must be pushed up through myriad boards to the top, seeking resolution.

The mosaic of NASA participation (Section 2.2.3) and program/project phasing (Section 2.2.6) resulted in a similar mosaic (and phasing) of institutional boards and panels, each with their own style of vetting technical recommendations. These existing institutional processes and procedures were, in some cases, duplicative or contradictory, and were not always clearly linked to program processes that were subsequently established in an effort to implement standardization.

As a result of *CAIB* recommendations,[7] NASA was in the process of adopting a new governance structure between the institution (i.e., center engineering and program support), Technical Authorities and the Mission Directorates. Constellation was the first program to adopt this new governance structure. While intended to alleviate instances of safety compromises in the face of extreme budget and/or schedule pressures, the new structure added further confusion to decision making at the working-level. As the first major program to operate under these new rules, Constellation had both the benefit (increased safety) and the difficulty (less clarity to decisions) associated with blazing a new trail.

These all contributed to inconsistencies, both apparent and real, in management direction. While projects were under program direction, center boards and the Technical Authority were not under program direction. It became very difficult to converge on a consistent approach once decisions were made by any of these. Further, when an issue arose, there was often confusion

[7] NASA 2003. National Aeronautics and Space Administration. *Columbia Accident Investigation Board — Report*, Volumes I-VI. August 2003.

about the "entry point" in the decision-making process and who had the ultimate authority. The variety of institutional processes and lack of physical collocation only added to the muddled situation.

While the Deputy-led Program Excellence Team (Section 4.1.2) addressed many of the program-to-project issues, the larger issue of institutional authority vs. program authority was not sufficiently resolved. The frustration at this, which was borne by the working-level engineers seeking resolution, was expressed in the bumpy path to PDR.

For specific task areas, the program and projects conducted multiple Lean Six Sigma[8] (L6S) events that identified and eliminated thousands of wasted steps. However, much of this "churn" may have been avoided to begin with by establishing a clear program decision-making path with buy-in from all affected institutional organizations.

Lessons Learned

- Boards without resources (budget and reserves) to implement decisions have limited effectiveness.
- Clear lines of authority among the program, projects, and institutions were addressed at the macro level but were not delineated or communicated well to the working level, resulting in tension and inefficiency. The operating model was already in place and was difficult to change.
- The program and institutional/center processes were not well aligned, resulting in inefficient decision making.
- Programmatic decisions on facility construction and modification funding (and the legal necessity not to intermix facility funding) were neither fully understood nor articulated at all levels and institutions (see Section 4.6).
- The need to involve the broadest range of personnel from many centers created a complex communications environment and resulted in frequent revisits of decisions.
- The arrangement of having program managers, deputy program managers, and associate program managers who matrix from different centers enhanced communications, dissemination of information, and team building.
- The concept of the associate program manager (APM) at the centers to facilitate communication between the program and the center was good, but the role of the APM was in some cases unclear and confusing with regard to the projects at that center.
- Communities of Practice (Section 4.1.5) were effective at bridging some of the complexities created by the multiple decision-approval chains.

[8] L6S is an industry standard approach that combines the statistical analysis of Six Sigma to improve quality with the tools and methods of the Lean methodology, which evaluates processes with a focus on speed and efficiency.

Recommendations

As discussed in Section 2.2, maintain a budget that includes enough reserves for boards to implement necessary decisions.

Create a Control Board flow diagram that documents control board, panel, and working group (WG) relationships and hierarchy. Minimize panels and working groups and clearly define what types of decisions can be made by each. Include relationships that fall outside of the strict program hierarchy (e.g., an institutional Engineering Review Board, Technical Authority, etc.). Publicize these clearly stated authority chains, and hold centers and projects accountable to them.

For widely spread, flagship-scale programs, create a Program Formulation Task Team that includes agency and center representation to integrate a new program structure within existing agency and center structures. Proactively discuss and document what is meant by locating a project at a center initially, then continue the discussion to the task level with the personnel responsible for delivering the product. Clearly defined roles and responsibilities need to be explicitly defined in a Memorandum of Understanding (MOU).

The roles of program-level Technical Authorities and the technical review process must be clearly established and understood by the program, projects, and institutions. As with the technical side of the institution, make the administrative functions (e.g., financial organizations) answerable to the program into which they provide matrix support.

Use methods such as L6S to regularly review processes and organizational structure for duplication and waste.

4.1.2 Establish a Cross-level Senior Management Team to Clarify and Improve Roles and Responsibilities

Supports Key Findings: 3.7, 3.10

Driving Events

A “best-practice” embraced by the Constellation Program was to push functions and decisions to the lowest possible organizational level, since that is where knowledge resides. This included pushing some roles down to the projects that traditionally had been held at the program level. The desire to implement this best practice led to challenges in RR&A that were exacerbated by the program environment.

As described in Section 2.0, the major projects were established prior to the Program; hence, each entity had its own integration organization, structure, and processes developed independently of the other. The far-flung organization, funding pressures, generation gap in human space flight, and size of the trade-space described in Section 2.0 also contributed to the magnitude of these driving events.

Lessons Learned

In an effort to identify and address areas of tension or inefficiency in RR&A, the Constellation Program chartered the PET to focus on areas for improvement. The PET was a council of deputies, with membership drawn from the program office and project deputies, as well as the Program Chief Engineer (a matrix position from the Technical Authority). This senior leadership team had the latitude to clarify, delete, or modify RR&A and associated processes to achieve better internal operations. Examples of functional areas discussed included Program and project roles and responsibilities for design integration, interface requirements, design and construction standards, schedule management, and vehicle stack integration.

An example was the delegation of vehicle "stack integration" to the *Ares* project. This is traditionally a program-level role; however, the bulk of the expertise required to perform the analysis resided in the project and delegation eliminated some duplicative efforts. The PET was tasked with clarifying RR&A that had arisen over the performance of the "traditional role" vs. the "new role" in stack integration. After clarifying these roles, the PET oversaw implementation so that the task could proceed more efficiently.

The team met primarily through off-site face-to-face meetings, which proved critical to enabling discussion of difficult and sensitive topics. Thorough and frank discussions resulted in more clarity and improved RR&A, which were documented and disseminated across the program in agreements. Documentation of agreements was instrumental in forming a better integration effort across the various levels of the program.

To quantify the degree of success in the implementation of these agreements, the program used the 4-D survey system© (©2010: 4-D Imaging Systems Inc., Oak Ridge, TN) to measure vertical and horizontal team satisfaction in recognized areas for improvement on an annual basis. These progress reports were published program-wide. The surveys indicated that the RR&A areas that had received management attention improved over time. As the program matured, the surveys provided new areas in RR&A that needed attention. While the PET was initially formed as an ad hoc group, it became the resident forum for RR&A improvements.

An added, and extremely important, benefit is that the personal bonds established in this team created a strong sense of trust and teamwork among the members; these relationships later enabled the rapid solution of many problems beyond the PET charter.

Recommendations

A senior-level management team, spanning projects, program, and institutions, is a key element to clarify and improve roles and responsibilities. It should be established from the start of a multi-element human space flight program. This team should meet face-to-face on a regular basis throughout the life cycle of the program and use a quantifiable process to measure success and identify areas for improvement.

4.1.3 Balance Decision Making with the Obligation to Air Dissenting Opinions

Supports Key Finding: 3.8

Driving Events

While decision making was addressed in the prior recommendation, another aspect is worthy of further discussion due to its cultural implications. A finding of the CAIB report (footnote 7) was that NASA culture inhibited frank discussion of dissenting technical opinions. Indeed, this was attributed as one cause of the *Columbia* accident. As a result, the management and work force, particularly at the space flight centers, were robustly trained to allay this cultural inhibition.

Perceptions in the work force indicated that the program was not entirely successful in finding a balance between decision making (as manifest in progress) and the need to find consensus and air dissenting opinions.

Program management was diligent in seeking consensus to assure that all valid stakeholder needs, opinions, and relevant factors were considered in making decisions. The continuously shifting budget situation drove priority changes that, in turn, caused decisions to be reopened. Some working-level personnel perceived this as a management weakness, an inability to "make decisions stick," and as kowtowing to dissention. What looked like dithering at the working level was, in fact, diligence in identifying cost impacts and seeking cost avoidance for otherwise meritorious or technically necessary changes.

Other factors contributed to this perception, including the program/project phasing (Section 2.2.6), the generation gap in human space flight (Section 2.2.4), and the size of the trade space (Section 2.2.5) in an early-development program. And, for a leadership team most focussed on socialization of major decisions with Agency mangagement, insufficient attention to this perception led to frustration at the working level.

One example was the Integrated Stack Technical Interchange Meeting (TIM), at which the Program sought to synchronize technical baseline requirements for all of the projects involved in the *Ares* I launch vehicle "stack." The event was intended to include all relevant decision makers in a 2-week, face-to-face period to allow necessary coordination. The outcome was intended as an update to the Constellation Architecture Requirements Document (CARD). While many hard decisions were made and implemented into requirements changes as a result of the TIM, the formal closure of some of these decisions dragged out over a much longer period of time as additional cost or technical issues arose. While this can be attributed to many of the reasons elaborated in Section 4.1.2, the perception of weak leadership, a "back-door" appeals route, and lack of accountability was only reinforced.

On the other hand, Section 3.11 addressed the successful *Ares* I-X test flight. That organization was permitted, indeed supported, to operate with somewhat autonomous authority and was able to ignore many of the drivers described in Section 2.2 due to its ambitious requirements and tight schedule constraints. The flight test leadership stressed the needed organizational constructs

and drove clarity into RR&A and the decision-making structure. Many of these were passed on and implemented into the larger program.

Lessons Learned

Dissenting opinion plays a critical role in any healthy organization. A thorough, thoughtful, and well-understood process must be used for raising, addressing, and resolving dissenting opinions. Otherwise, anyone with a strong opinion can bring progress to a halt.

Program management needs be diligent in socializing decisions not only to Agency management but also to the working level, particularly in early program stages when the trade space is most broad and decisions are often revisited. Accountability, and the perception of such, is critical to morale at the working level.

Recommendations

Establish, communicate, and enforce the open decision-making model and process, including the airing of dissenting opinions. Assure "buy-in" of decisions not only at the Agency level, but also the working level. Do not permit "back-door" appeals as these engender mistrust and frustration.

4.1.4 Implement Communities of Practice to Resolve Integrated Issues

Supports Key Findings: 3.8, 3.9

Driving Events

System Integration Groups (SIGs) were initially established to define and allocate requirements among projects. They were intended to actively include subject matter experts (SMEs) from the projects and contractors, while being led out of the program office. However, due to the pace of the formulation activities, program (Level 2) and project (Level 3) personnel focused on their own level of products, so the vertical integration of the team never completely gelled. In addition, the role of SIGs with respect to program oversight was not clearly defined or communicated.[9] This resulted in tension between the project-level system leads and the program SIGs over roles and responsibilities, and was a recurring topic at PET meetings.

Conflict around SIG vs. project subsystem lead roles continued until the Program matured, after which significant integrated issues arose that had multiple program, project, and institutional stakeholders. These issues *required* program and project personnel to work better together to find solutions. The Program performed a "reset" by transforming SIGs into communities of practice (CoP), which were defined as groups of technical discipline experts from program,

[9] Former ISS personnel, who had oversight authority in that program, staffed many of the SIGs. However, Constellation emphasized pushing authority down to the projects (4.1.1). This change in culture was neither immediately recognized by Program management nor made clear in articulation of RR&A between the Program and the projects.

project, and institutional engineering organizations that serve as the authoritative resource for resolving technical integration issues within a specific area of responsibility (e.g., electrical power). These CoPs were directly consulted in technical discussions and decisions made by the new Constellation System Integration Panel (CxSIP) the focus of which was to provide technical integration decisions and recommendations for the Program.

Some examples of integrated issues that were addressed include: launch tower clearance, thrust oscillation, power quality specifications, launch probability, and Human System Integration Requirements interpretations.

Lessons Learned

Communities of Practice proved effective at resolving cross-cutting integrated issues. They helped improve communication within the program/project organization and between centers. The three primary lessons learned in relation to CoPs are identified below.

- They were effective at solving hard problems. Consolidation of program and project technical positions was enabled. Stakeholder buy-in was enhanced since recognized experts in each area were able to achieve integrated solutions.
- They fostered collaboration of the best expertise from across the Agency, industry, and academia. This enabled resolution of complicated technical issues and advanced the volume of knowledge in some disciplines.
- Influence leadership was key to overcoming organizational boundary concerns. *CoPs worked better through leadership facilitation* than direction. This allowed flexibility to resolve issues at the most appropriate point, which could be a program board, a project panel, or an other integration forum.

Recommendations

Communities of Practice should be implemented early with the focus of facilitating integrated issue resolution. Although the pace of formulating a program or a project will encourage organizations to withdraw to focus on their own highest priorities, management and processes should be put in place to incentivize cross-level discussion and decision. Attention should be given to leadership, which is key in determining whether the CoP approach will work within a particular discipline. Specifically, influence leadership is a must, and facilitation rather than direction is needed to allow flexibility. Roles and responsibilities among WGs, panels, and the CoPs should be defined. Management should consistently engage the CoPs directly when solving problems and seek their input when making decisions.

4.1.5 Implement a Strong Technical Integration Function

Supports Key Findings: 3.8, 3.9

Driving Events

Driving events are the same circumstances described in Sections 4.1.1 and 4.1.3; however, aspects of leadership merit a separate discussion. In a program of such breadth, leadership may be strong in some areas and not in others.

Lessons Learned

Pushing traditional program integration roles (Section 4.1.1) to the lowest feasible technical level, coupled with elevating all meager funding reserves to the program level, created significant stressors to the RR&A in resolving technical issues. (Section 4.1.2 describes the forces that drove all reserves to be managed by the program manager rather than at lower levels.) Communities of Practice (see Section 4.1.4) helped, but could not resolve, the fundamental lack of integrated technical leadership.

The Standing Review Board (SRB), which was charged with oversight of the program, found that the program was deficient in technical integration and recommended that a Technical Deputy be appointed to alleviate this issue. Program management was evaluating the implementation of this recommendation at the time of Program cancellation.

The cultural implications of this are partially addressed in Section 2.2.5. A strong and prevalent belief resided at the working level that program leadership was consumed with political, budget, and schedule issues, and that insufficient attention was applied to the many technical integration issues. Moreover, no one was delegated the authority to clear the backlog of technical decisions that lingered. A yearning for leadership, particularly in the program (Level 2) integration function, was a prevalent theme around the water coolers.

The Program took steps in strengthening technical integration by refocusing the SE&I office toward design integration, and creating a CxSIP that served as a clearinghouse for key integration issues.

As noted in Key Finding 3.9, it is critical for an organization to recognize its weaknesses and adapt as its functions change over the life cycle of the program. Once these changes occur, it is just as critical to fully communicate to the working level why these changes have been made.

Recommendations

In a program of the size and scope of Constellation, authority, responsibility, and accountability should be delegated to a clearly defined technical integration function to assist the program manager in efficient resolution of technical issues. It is best to consolidate this responsibility earlier, rather than later, to avoid morale issues related to inattentive leadership.

4.2 Requirements

A long-term trend in the aerospace industry has been the proliferation of requirements and specifications. The forcing function for this has been attributed to the well-intentioned desire to "regulate" good behavior and practices. Failures involving loss of life and loss of mission (LOM) understandably drive care and detail into specifications. NASA has been no exception to this trend.

As noted in Section 2.2.3, the different cultures that have developed at each NASA center have driven 10 different sets and approaches to D&C standards and specifications. Although the Agency has been systematically trying to establish Agency-wide D&C standards, there are still a multitude of center-specific standards in practice. The collective effect on the contract environment (and cost) is illustrated in the lessons in this section.

Notably, this effect drives the size and scope of the contractor work force. Each requirement in each standard and each specification must be verified.[10] This task comprises a large part of the fixed-base costs, addressed in Key Finding 3.2 that can greatly hinder the flexibility of a program to respond to changing circumstances.

Recommendations in this section call for a balanced, measured approach in application of "shall" statements to contracts.

4.2.1 Reduce Agency Requirements Levied on Contractors

Supports Key Findings: 3.2, 3.3, 3.4

Driving Events

The procedural and policy directives (NPRs and NPDs) for the Agency contain tens of thousands of programmatic requirements and standards. While many Agency requirements properly address the outcomes sought ("what to do"), the vast majority attempt to incorporate and standardize best practices ("how to do") to maximize the likelihood of achieving those outcomes. Each NASA center layers its own set of requirements and standards on the set that exists for the Agency, as described in Section 2.2.3.

These requirements drive cost in large ways. Contractors must verify every requirement, and the program must ensure that every requirement is auditable. NASA represents a small portion of the overall contracted effort for most aerospace contractors. DoD, which typically represents the largest source of work, maintains its own set of standards and specifications, most of which are duplicative of NASA standards and specifications. There are costs associated with retraining portions of a contractor work force to use a different process for the relatively small portion of NASA work. Risks of errors are introduced because of switching processes for similar tasks

[10] A requirement is an individual "shall" statement within a document that may contain hundreds of individual "shalls."

between contracts. This drives costs up and lowers safety. Costs are associated with documenting a requirement and assessing the impact of a potential requirement. Finally, potentially hundreds of labor-hours of debate are spent just to tailor a single requirement.[11] Confusion ensues when the contractors are expected to sort through and understand the differing NASA requirements among NASA centers.

Design and construction standards were the greatest challenge due to their sheer number and scope at the designer level. Over prescription is very costly and time consuming because it severely limits the ability of the designer to balance risks, and often results in suboptimal outcomes for the intended system.

One example would be standards for lifting hardware. Each NASA center has a standard for this, and the various standards are not identical. This necessitates a contractor dealing with multiple centers to, depending on the locale, know, understand, train, and staff to implement multiple ways of lifting hardware. This approach increases both risk and cost.

Since D&C standards are usually written by the functional discipline experts, it is only natural for them to set standards that minimize risks in their particular area. But, sometimes adherence to these drive unwise system design decisions that actually *increase* risk overall and lead to a generally poorer design. It can also drain resources from the project to do the "perfect" design rather than the "good-enough" design. Many of the design and construction standards are also written to cover a wide array of products and do not necessarily fit any one product well.

It is important to acknowledge that experienced contractors are also motivated to apply best practices and document them as corporate processes, if they do not already use Voluntary Consensus Standards.

The NASA Administrator stated that for Constellation, "all requirements need to fight their way on to the table." Agency senior leadership embraced this approach (the Office of Chief Engineer [OCE] and Office of Safety and Mission Assurance [OSMA] in particular). However, reality proved to be that Constellation had to fight the working-level "requirement holders" over each requirement, and the burden was on the Program to document agreements regarding applicability and tailoring. On program cancellation, the number and scope of Agency NPRs and NPDs had not decreased.[12] Constellation did negotiate dramatic reductions in the number of applicable requirements and tailored the remaining documents into significantly fewer requirements.

[11] While the projects were allowed to do substantial project-specific tailoring, the process was time consuming and costly. It was not uncommon to have running dialogues of weeks to months for the applicability or meets/exceeds evaluation of a single requirement within a document containing hundreds of requirements. Often this was outside of the purview of the project manager, since the requirement "owners" or institutional representatives would defend the need for the requirement. In some cases, resolution had to take place at senior management levels.

[12] As of this writing, focus has been renewed at the Agency level to dramatically decrease the number of requirements within NPR 7120.5—a major parent document for programs and projects. The authors hope this renewed focus is managed to a successful conclusion and is promulgated to other Agency documents.

While this was a great help, the numbers were still too high. The biggest challenge was the sheer volume of “shalls.”

Lessons Learned

The “blanket approach” to requirements used by the Agency is untenable. While minimizing requirements on contractors was a priority for the Constellation Program, the resulting requirement base was, and still is, excessive. This drove a large portion of the contractor fixed-base costs.

This is a problem not imposed from outside the Agency, but is purely within the scope of the Agency to remedy.

Recommendations

Proactively address the issue of requirement over prescription in traditional acquisitions that are driven by Agency- (and multiple center-) level requirements and standards. Establish clear criteria for mandatory requirements at the “shall” level and revalidate the current Agency requirement base. The Agency, led by OCE and OSMA, must establish a process that will:

- Identify the criteria that must be met before “shalls” can be used in any Agency-level document.
- Capture best practices as “shoulds” in these documents to provide guidance for providers who do not have extensive space flight experience or documented standards.
- Reduce verification documentation and closure overhead by identifying criteria that can allow the “signature warranty” provider and process sampling by the customer to suffice for verification of targeted “shalls.”
- Review all Agency-level requirements documents with the intent of reducing the number of “shalls” by 75% to 90%.
- Reintroduce the use of NPGs to provide flexibility in managing NASA contractors to reduce the cost of leveraging valuable experience.
- In parallel, address the proliferation of center-level, non-unique documents with the same criteria.

4.2.2 Minimize Programmatic Requirements

Supports Key Findings: 3.2, 3.3, 3.4

Driving Events

The Constellation Program also fell victim to the Agency trend described above (Section 4.2.1), by generating requirements documents that were not wholly driven by Agency needs. Contributing factors include:

- A “system of systems” was being built that would span decades to develop and was intended to be used for generations. The program needed to ensure that the systems would integrate

well downstream, without needing to have the trailing systems fix the problems left by the early developments. However, after the scope of the program was reduced, the Program was slow to reassess and reduce the scope of the requirements.

- The program team bore the scars of the *Columbia* accident and lengthy ISS development and integration. Team members needed to avoid the mistakes that had cost so much.
- The Program was driven to reduce life-cycle cost. From a life-cycle cost perspective, having standard processes and requirements span across multiple systems seemed to be the most effective approach.
- There were perceived deficiencies in existing standards such as MIL-STD-1540 when applied to human-rated elements intended to operate reliably for decades with minimal logistical support capacity.

The Program was also guilty of writing requirements where guidelines or other less-prescriptive communication would have provided more flexibility. Although it was recognized that "one size does not fit all" when it comes to requirements, it was believed that through simple tailoring and allocating processes, the burden of requirements would be minimal. This proved to be incorrect.

An additional contributing factor was the use of requirements to define "design solutions" well above the designer level. Unfortunately, this practice began with ESAS and was evident all the way up to Level 0 (at NASA HQ).

The program, in particular SE&I and T&E, were in catch-up mode (see Sections 2.2.6 and 2.2.7), having started late with respect to the projects and their associated contracts. SE&I staffed up very quickly and began pumping out requirements and plans at rapid pace. Although program-level boards attempted to keep the number of requirements to a minimum, individuals and institutions applied continual pressure to add more requirements to address perceived deficiencies or noncompliances.

There were, however, attempts to reduce the number of requirements and their cost impacts. One example was the successful Safety, Reliability, & Quality Assurance Requirements Technical Forum. All projects were requested to work with their contractors to identify candidate requirements having significant cost or that were not enhancing mission assurance. Because the program had seen that many of the cost impacts were driven by misinterpretation of requirements, the projects/ primes also provided their understanding of the intent of a costly requirement. Over 3 days, with the participation of 90 empowered project and contractor staff, the team deleted 43 requirements, reduced the scope of 52 requirements, and modified 56 requirements to provide more clarity or flexibility in implementation. Program representatives also emphasized a willingness to engage in further tailoring and project representatives left with a better understanding of previously misinterpreted requirements.

Lessons Learned

Even programs committed to ensuring the implementation of a small, cost-effective requirement base can end up with much more than expected.

A repeated theme in debates on requirements revolved around the competing needs of minimizing life-cycle cost (particularly the need for operability) vs. near-term cost impacts in an ever-dwindling budget situation. Programs should carefully evaluate whether "consistency across the program" is necessary, and target for such consistency where it brings true value.

Recommendations

Challenge all self-generated program-level requirements to provide lower-level implementers as much flexibility as possible. Do this early and more than once, particularly in de-scope situations.

4.2.3 Separate Tailoring of Requirements from the Waiver/Deviation Process

Supports Key Finding: 3.4

Driving Events

With the advent of Constellation, the Agency OCE revised the Agency tailoring process. This activity occurred in parallel with Constellation requirements development, creating confusion within the work force. Notably, this even included definition of terms.

As explained in Key Finding 3.4, unintended consequences arose when Constellation applied the Agency requirements tailoring process.

Within the DoD (the U.S. Air Force in particular), the acquisition community has long had proven configuration management (CM) processes for the application of deviations and waivers that could be traced to MIL-STD-480, MIL-STD-973, and MIL-HDBK-61. *These are used primarily for noncompliances during production and delivery.* Likewise, tailoring was a separate CM process that was selectively used within the acquisition community, mainly in the early stages of program start-up, i.e., Phases A and B. Any higher-level document (i.e., MIL-STD, MIL-SPEC, etc.) that was authorized for tailoring could be tailored by a program in part or entirety. The document owner is always consulted if the document is tailored. If the entire document is tailored, the tailored version is "owned" by the organization and typically given a unique identifier that associates the document to an organization or a program. Deviations and waivers are given the proper attention and scrutiny with the approval level limited to the program director in his/her role as chairperson of the configuration control board. Approval of deviations/waivers is not delegated to lower-level boards/panels. Deviations/waivers are tracked and maintained until they are closed. No "permanent" deviations/waivers are allowed. Furthermore, the traditional definitions of deviations and waivers and tailoring are used as follows:

Deviation – A specific written authorization, granted prior to the manufacture of an item to depart from a particular requirement(s) of the current approved configuration documentation of an item for a specific number of units or a specified period of time.

Waiver – A written authorization to accept an item that, during manufacture or after having been submitted for government inspection or acceptance, is found to depart from specified

requirements but nevertheless is considered suitable for use "as is" or after repair by an approved method.

Tailoring – The process used to adjust or seek relief from a proscribed requirement to accommodate the needs of a specific task or activity (i.e., program or project specific).

NASA, in an attempt to standardize the tailoring concept across all centers, decided to use deviation/waiver definitions, processes, and documentation to tailor outcomes. This brought several unintended consequences that made tailoring problematic. These included: formalizing the concept of permanent deviations or waivers, the use of waiver documents for tailoring, and dealing with the cultural aversion to waivers explained in Section 3.4. In addition, the program desire to delegate tailoring to the lowest level (where the knowledge resides) conflicted with the higher-level visibility required for a waiver.

Lessons Learned

Some may argue that NASA can make the work force more comfortable with the fact that waivers are only form of paperwork to ensure proper documentation. However, the cultural taint is not only a NASA-internal problem. Outside stakeholders (Congress, the Aerospace Advisory Panel [ASAP], National Academies, etc.) have preconceptions about the waiver process. Repeated reviews with ASAP can attest to that fact. Processing waiver paperwork unnecessarily complicates tailoring. And, as seen in the two prior lessons, the amount of tailoring required is massive for a program akin to Constellation. This is also a large driver of fixed costs in the contractor base.

Recommendations

Reduce the cost of the requirements tailoring process by returning the definitions of deviations and waivers to their traditional role (akin to the DoD process) of temporarily dealing with nonconformances during production.

Tailoring should not carry a cultural stigma. Allow tailoring to be documented by the simplest method possible.

4.2.4 Reduce Cost by Maximizing the Use of Industry Standards

Supports Key Finding: 3.1, 3.2, 3.3

Driving Events

The Constellation Program, supported by the Technical Authorities, went to great effort to evaluate contractor (industry) standards. It is important to recognize that experienced contractors are also interested in applying best practices. They document them as corporate

processes, if they do not already use Voluntary Consensus Standards (VCS). While NASA has embraced the use of VCS,[13] the Agency has been slow in its implementation of these standards.

As noted earlier, major contracts were competed prior to program office formation, so the opportunity to perform program-wide analysis of appropriate standards was missed.

Lessons Learned

Contractor-based standards that are compliant with VCS were found to be mostly consistent with Agency standards. The exceptions that were not already fully compliant could be easily assessed at lower cost to programs and NASA.

Recommendations

NASA should maximize the use of contractor standards deemed "good enough" by Agency technical experts and only levy specific requirements to fill significant gaps. This would be best done on an Agency-wide basis to minimize impact on new programs. However, until this is done, programs and projects should consider performing this assessment before contracts are let.

4.2.5 Use Industry Standards for Data Management

Supports Key Findings: 3.1, 3.2, 3.3

Driving Events

Akin to the prior recommendation (4.2.4), this recommendation specifically addresses DM standards. Many of the data systems at the projects and within program integration offices were chosen prior to Constellation start and before the Program had identified requirements for data interoperability. A data system always requires some cost for interoperability, and the variables for that cost depend heavily on standardization. Most data systems used by the projects and program offices did not support or adhere to industry standards for data interoperability (e.g., Web services); and since many of them were closed-source systems, it was both difficult and expensive for the Program to achieve its DM goals. In addition, the Program spent significant effort developing various new standards rather than using existing industry standards or working with appropriate governing bodies to evolve those standards (if needed).

[13] The OMB Circular requires that agencies report their use of standards on either a "categorical" or a "transactional" basis. Those agencies that report on a categorical basis are not required to list each instance in which a government-unique standard is used in lieu of a private-sector standard in procurement actions. However, such agencies are required to have a system in place to ensure that government-unique standards are developed only when suitable private-sector standards are unavailable for use. At present, only the DoD and NASA consistently report on a categorical basis. For all agencies, in those cases in which government-unique standards are required because private-sector standards do not exist, use of the government-unique standard is not subject to reporting. From *The Thirteenth Annual Report on Federal Agency Use of Voluntary Consensus Standards and Conformity Assessment*, NISTIR-7718.

Lessons Learned

Developing independent, program-specific standards has many challenges that can be mitigated by using existing standards and working with appropriate governing organizations to evolve those standards to address specific needs (NASA Standards, Federal Standards, or International Standards).

Recommendations

Industry standards for DM should be adopted and promoted in compliance with the National Technology Transfer and Advancement Act. These standards should be made explicit, and named as dependencies with the purchase or development of systems and services supporting agency data. Furthermore, contracts and MOUs should be used to enable the adoption of specific criteria.

Program standards (including data interoperability) should be based on industry standards (e.g., American National Standards Institute, International Organization for Standardization [ISO], World Wide Web Consortium, and Organization for the Advancement of Structured Information). These rules for DM operations should be mapped to project or center standards, and levied on NASA projects and contractors as early as possible in the life cycle of a program.

Procurement of data systems should take into account the ability of those systems to support the standards or to be modified by NASA to become compliant. Deviation from program standards should be addressed via a named governing board in charge of waivers, enforcement, and data architecture. It is also essential that data systems reflect an architectural framework rather than defining one. An enterprise framework for data or data systems is necessary for global adoption, governance, and standardization across the agency to reduce costs, improve integration efficiencies, and provide effective traceability.

4.2.6 Anchor Integration Verification Requirements

Supports Key Findings: 3.3, 3.7, 3.11

Driving Events

As described in Section 2.2.6, the phasing of Program start behind the project starts led to many out-of-phase functions. One out-of-phase function was the development of system integration verification requirements prior to the establishment of certification criteria. This resulted in verification requirements that were not properly anchored to the performance and mission certifications. Another result was the integrated test and evaluation needs for certification, above and beyond requirements compliance verification, were not well understood across the stakeholder community.

Verification is the work done to create sufficient evidence to determine that, on delivery, the system will meet specified performance requirements and include required capabilities that will accomplish the design reference mission (DRM) in all applicable natural and induced

environments. Verification should, but frequently does not, include the work necessary to validate that component procurements, acceptance testing, manufacturing process controls, and assembly checkout will consistently deliver flaw-free products.

Nevertheless, verification work alone does not produce sufficient evidence to certify the system because it does not include all of the work necessary to validate that the behavior of the system is sufficiently well described and understood, that well-understood operating rules and procedures can accomplish operational missions within design constraints, and that the system is suitable for its intended purpose. Verification is a one-time-only "snapshot" of requirements compliance, while certification is the living, sustained, "as-certified baseline" definition of what the system is and what its capabilities and constraints are. The organization responsible for "sustainment" sustains the system certification, of which verification data make up only a historical portion.

Lessons Learned

The lack of a strong relationship between the verification requirements and the certification criteria did not allow for effective assessment of impacts resulting from reductions of verification events. Verification events, such as flight and ground test, were reduced without consistently assessing the impacts against baseline certification criteria, which resulted in increased risk postures. These reductions in test events were typically driven by cost and schedule constraints.

RR&A were not well defined. As a result, the T&E integration effort was less than effective. The appropriate, integration-level verification products were being developed, but products needed for interface and integration T&E were out of sync with the various project production schedules (likely resulting in cost and schedule impacts).

Integration-level verification needs were not identified and communicated in time to negotiate and acquire the deliverables necessary to support integration T&E events. The program and projects were not in sync with regard to integration software, analyses, and simulator delivery dates; and the integration effort required to resolve known disconnects across the independent planning for each of the stakeholders was not completed prior to the PDR.

Recommendations

Define the human-rating integration performance and mission certifications early in the program to influence development of integrated system verification requirements. Integration certification and verification deliverables should be defined no later than the PDR to effectively negotiate with multiple stakeholders. Example integration deliverables include: models, analyses, software loads, simulators, facility assets to support integrated testing, and stakeholder verification test results required to update integrated models and analyses.

Decision makers must take corrective action when the satisfaction of verification requirements is the sole or overriding consideration when building and implementing the T&E campaign. This frequently happens for two reasons. First, the understanding that verification is only a subset of a necessary and sufficient T&E campaign is not widely held; in other words, too few people fully understand and appreciate the difference between verification and certification. Second,

verification is a contract artifact, and "closure" of specifications "checks a box" for contract Statement of Work (SOW) closure, therefore management frequently emphasizes that T&E work must be linked to a driving requirement – sometimes even making policy or building processes that allow only work that can be linked to specification closure, considering any other T&E work to be "out of scope." Similarly, tracking only closure of specified requirement "shalls", as opposed to tracking the completion of all the T&E campaign work requirements can result in unbalanced emphasis on verification over other certification work.

4.3 Data Management

This section addresses DM and data systems for managing, defining, building, and operating large space systems. Proactive and systematic DM is key to enabling review and management of the overall integrated vehicle and program (e.g., integrate authoritative requirements with computer-aided design [CAD] models with Parts List with Problem Reports), mitigating risks and reducing costs associated with DM.

Lack of data integration leads to cost and risk increases due to use of non-authoritative/out-of-date data, miscommunication of data, and missing data. Key to DM is the use of a data-centric approach, as distinct from a document-centric approach, that involves managing electronic data effectively for data consistency and integration with: 1) structured format (e.g., XML [extensible markup language] or database) accessible at the field level (e.g., specific shall statements, not the whole requirements document); 2) searchable form (e.g., full text and field/value-based queries); and 3) linkable format that requires a unique identifier and machine/programmatic accessibility from external systems.

As discussed in Section 4.2.5, many data systems were chosen by the projects and program offices prior to Constellation start and/or before the Program had identified requirements for data interoperability. In many cases, these data systems did not support or adhere to industry standards for data interoperability.

In addition to the recommendations in this section, the reader will note that lack of DM drove problems in other systems, such as the IMS (Section 4.4), EVM (Section 4.5), and risk management (RM) (Section 4.8).

4.3.1 Use a Program-wide Data Systems Architecture

Supports Key Finding: 3.10

Driving Events

The Program did not have a data system architecture deployed across all of the projects to support integrated DM at its inception. For example, no support was given to link authoritative data sets such as: Requirements (component must sustain X impact), CAD models (component model), Parts List (components and subcomponents), and Problems (specific problem with component).

Projects and centers used a diverse mix of existing and new data systems with diversity of data formats (as described in Section 4.2.5), and limited or no support for interoperability. As a result, the Program used a manual approach for data integration that resulted in decisions being made using out-of-date and sometimes inaccurate information (e.g. out-of-date IMS, 40% discrepancy rates in risks). In addition, the lack of common software tools led to

- Additional cost and time expended to build/maintain multiple systems for similar data (e.g., shadow document and product structures).
- Increased cost and time to find and integrate data.
- Limited capability for efficient trending/data mining.

Program-wide data systems architecture was developed, deployed, and used 4½ years into the Program, with promising results for some core data sets.

Lessons Learned

Program-wide data systems architecture is needed to mitigate DM risks. The architecture should show clear traceability to the program DM requirements, and should specify an approach for automated data integration (aka “mash-ups”), which is a common practice in industry and a best practice in government.

The approach should

- Identify program data owners and their data responsibilities for key data sets (e.g., integration office manages requirements, safety office manages problem reports).
- Manage a definitive list of authoritative systems (tools) for authoritative data sets (e.g., requirements, risks, hazards).
- Ensure that new tools comply with program integration requirements for data integration using Web services (with fields and formats defined in DRDs using a data-centric approach).
- Implement updates or workarounds (e.g., a cache for a system that lacks integration capabilities) for legacy tools that do not meet requirements.
- Manage data interoperability agreements between system owners.
- Adequately address information security constraints from inception.
- Consider selecting or migrating to common open-source or source-available software tools that can be readily modified to align with the architecture.

Recommendations

A program-wide data systems architecture for data integration should be used with data owner identification and responsibilities, a managed list of authoritative data sources (tools), managed requirements for data integration using Web services, and managed data interoperability agreements between system owners. Projects should use software tools that enable data integration and interoperability with published interfaces and, where practical, common software tools.

4.3.2 Establish a Data-centric (vs. Document-centric) Approach

Supports Key Finding: 3.10

Driving Events

Constellation projects were established before the Program (as described in Section 2.2.6), and used numerous legacy processes and data systems that did not support data integration. Once the Program was established, data integration became critical for overall SE, Program management, and sustaining support, yet no clear and common data requirements existed to support data integration between levels and organizations (e.g., program-to-project, project-to-project). This resulted in misunderstandings (since groups had to translate between data produced in different formats), significant manual rework of data products that took time and introduced errors, and use of out-of-date and incomplete data for decision making (that resulted in increased cost). For example, different groups came to meetings with different conclusions based on different data, and argued which data were authoritative to attempt to reach agreement.

Lessons Learned

A data-centric, model-based approach to DM needs to be established at program inception, with all levels of management involved in implementation of the approach. Without this, the program incurs increased integration costs, additional risk from underspecified data requirements, and manual DM using documents.

To implement this approach, clear and common DRDs for specific data that are focused on sustaining engineering efforts should be developed for internal NASA and NASA-to-contractor data exchange, including the following:

- Requirements for defined attributes (fields, values, metadata, etc.)
- Electronic data formats for computerized data integration (e.g., XML)
- The NASA data systems where the data are to be delivered
- The delivery mechanism (Website upload vs. system-to-system integration push after every change)

A data-centric approach such as this enables linking of configuration-controlled, record-level data and automated integration of data direct from authoritative sources, eliminating error-prone manual copying of data. With this approach, CM can be done at the level of individual fields and data sets rather than of whole documents.

Recommendations

A data-centric (vs. document-centric) approach for DM should be established at the beginning of the program, with clear and common data requirements between all levels and organizations of the program using formal agreements (e.g., DRDs) that include requirements for electronic data. Key to this is to have a management structure for the approach that interfaces with key stakeholders (projects, program offices, and prime contractors).

4.3.3 Establish a Model-based Systems Engineering Approach

Supports Key Finding: 3.10

Driving Events

A comprehensive and clearly articulated Model-based Systems Engineering (MBSE) process was not established at the beginning of the Program and was not effectively communicated to the project offices until the *Altair* lunar lander office was initiated. As a result, consistent models were not established throughout the Program; and, when improvements were offered later in the program life cycle, there was little desire or funding provided to enhance the SE process. Resulting issues include: Program and project offices had operational concepts with substantial synchronization issues; SE practices were sidestepped to accommodate schedule pressure and avoid perceived costs (e.g., system functional analyses were not consistently performed or prematurely terminated); and the architecture was not ultimately traced to DRM objectives.

Lessons Learned

The benefits of using MBSE on the *Altair* design are articulated in Appendix A.2. Its use resulted in streamlined engineering requirements development and validation by developing integrated products among the Requirements, Design, and Operations communities.

Establishing requirement traceability to program figures-of-merit and mission and operational capabilities with proper functional analysis was an important step in ensuring requirement quality and completeness in the *Altair* implementation of MBSE. The definition of MBSE requirements and process standards as well as up-front education and broader work force experience greatly assisted the *Altair* project in the paradigm shift associated with MBSE. *Altair* successfully established traceability of the MBSE process to decision gates and design review criteria, and identified organizational responsibilities to implement the MBSE process. Configuration DM processes to efficiently and affordably manage the MBSE models and the corresponding data, in addition to managing documents generated from the models, were also key factors in the success of *Altair* and also provided a common focal point for SMEs.

Recommendations

Model-based Systems Engineering processes, with the ability to govern integration activities, should be established during program formulation to create an integrated set of models that all projects will use. Adoption of MBSE industry-wide standards integrated with NASA standards and policies is essential to MBSE success and should be strongly supported by program leadership throughout all organizations. MBSE training should be provided to model developers and SMEs to ensure consistent model development and traceability up to program decision criteria.

4.4 Schedule and Resource Management

This section outlines the primary lessons learned for the program IMS and EVM. This section should be read in context with the DM limitations described in Section 4.3. Lack of a consistent DM structure greatly hindered the development of an IMS and an earned value system.

4.4.1 Define Objectives and Uses for the Integrated Master Schedule *a priori*

Supports Key Findings: 3.7, 3.8, 3.9

Driving Events

Program development of an IMS was hindered by a number of factors. Primary among these was a lack of a common DM structure, described in Section 4.3. The late start of the Program with respect to the projects (Section 2.2.6) was also a contributing factor. Finally, the lack of clarity as to the purpose and use of the IMS delayed its implementation and use further.

Lessons Learned

Projects and program viewed the purpose of the IMS in fundamentally different ways, for high-level reporting vs. supporting detailed analysis, respectively. The Program did not explicitly define, or internally agree on, the purpose of the IMS. Lack of a single, clearly communicated vision from the Program resulted in the Program calling for multiple sets of data from the projects in various formats. Some projects objected to the increased effort being levied on them when the value of the end product was unclear and, in some cases, counterproductive. This lack of mutual understanding and intent, exacerbated by poor communication, led to development delays. The IMS architecture drove cases in which the Joint Confidence Level (JCL) analysis efforts (Section 4.5), detailed tracking of SE flows, and calculating an analytical critical path were mutually exclusive. When the Program set and communicated the clear goal of achieving a cross-program, analytical, critical path in the IMS, cooperation improved and implementation became easier.

Recommendations

The objectives and uses of the program IMS should be defined and clearly communicated prior to scheduling development activities, as these will drive the DM structure and cost to support the IMS.

4.4.2 A Bigger Schedule Is Not Necessarily a More Useful Schedule

Supports Key Findings: 3.7, 3.9

Driving Events

Due to the lack of clarity of purpose and conflicting opinions on purpose, the IMS development team, working with project counterparts, attempted to develop an IMS that included many activities at Levels 4 and 5 (e.g., contractor and subcontractor activities). As a result, the IMS

contained a huge data set that was difficult to maintain and use effectively. The value of the resulting schedule was questionable.

The Program also developed a high-level Program summary schedule that incorporated all key Program events on about 3 pages. This high-level schedule included an assessed critical path, which was developed by considering project-calculated critical paths, risk areas, and key technical and programmatic integration points. This summary schedule reflected the Program content in a more manageable package, and proved to be a much better management tool.

Lessons Learned

For large, multi-project NASA programs, a summary schedule approach with assessed critical path and key integration points can provide a more useful management tool with lower development and maintenance costs in comparison to a highly data-intensive schedule database.

Recommendations

Assess the depth and amount of information necessary to effectively manage the program. Consider that a summary schedule integrated from project detailed schedules may comprise the fidelity useful for program management at a lower overall cost.

4.4.3 Test Earned Value Management Systems in Phase B for Required Implementation in Phase C

Supports Key Findings: 3.1, 3.2

Driving Events

NPR 7120.5D requires the use of EVM in Phase C of developmental programs such as Constellation. While EVM is taught in NASA program/project management training, the NASA work force does not have extensive experience on its purpose and best use through successful application. Moreover, with the exception of the Jet Propulsion Laboratory, NASA centers do not have validated EVM systems in place.

In early 2009, the Program began to implement earned value reporting at Monthly Program Reviews (MPRs) in preparation for Phase C readiness (post PDR). Problems in understanding, readiness, data discrepancies, and perceptions of the value added from EVM were encountered.

While on-line and on-site training was available, this proved inadequate. One-on-one training was implemented to assure that all managers responsible for EVM reporting were able to manage the systems. This type of training encourages questions and creates a relaxed, open atmosphere for learning and will prevent planning errors that corrupt EVM data and damage EVM system credibility.

Lessons Learned

Early implementation of EVM in Phase B was difficult because of unrealistic expectations and insufficient training among the Constellation Program and project management team. One-on-one training was the most effective technique in the EVM training effort.

Recommendations

Programs should plan to provide EVM status at the MPR in Phase B and indicate this via the program plan. The EVM team should schedule "one-on-one" EVM training with managers very early in the program. This is necessary to have all managers engaged in dialogue prompted by EVM usage for cost control, schedule management, and corrective actions planning.

Note the following cautions in application of EVM described in Section 4.5.3.

4.4.4 Use Standardized Data for Earned Value Management and Cost Accounting

Supports Key Finding: 3.10

Driving Events

Due to the start-up phasing described in Section 2.2.6, the involvement of every NASA center (and associated contractors) described in Section 2.2.3, and the lack of an adequate data system architecture (Section 4.3), the earned value system was very difficult to implement. Not all processes were documented among the Program, projects, and centers, and no standardized reporting formats or templates were used NASA wide. Additionally, inconsistent rates and full-time equivalent conversion factors were applied by each center and project as well as the Program to calculate budgets and performance. These inconsistencies made reconciliation of products a Herculean task.

Further, cost accrual personnel were using a completely different financial system than that used by the earned-value community. This was primarily driven by the need to interface with heritage systems at NASA centers (i.e., NASA cost accounting is center oriented). This difference consumed much time and effort in reconciliation, and was particularly onerous because of the constant need to re-plan as budgets were cut. There was also no valid system in place to manage or track procurement costs (a major portion of the Program budget).

Lessons Learned

When the program and its projects do not have standardized data, integration and data quality suffer. Budget estimates and performance calculations are never truly consistent due to use of inconsistent data.

Recommendations

Data gathering and reconciliation needs to be accurate and consistent in concert with Recommendation 4.3.1.

4.4.5 Rigorous Baseline Control May Not Be Possible during Early Phases or Rapid Budget Changes

Supports Key Findings: 3.1, 3.2

Driving Events

As described in Section 2.2.2, the Program encountered inconsistent and unreliable funding through its lifetime. Budget changes directly affected the major schedule milestones and the ability of the Program to maintain schedule integrity during rapid budget changes. The effort to establish a working baseline in Phase B to execute early use of EVM was extremely difficult in this environment. In addition, the processes used for baseline CM (e.g., baseline change requests and a baseline change log) were still in development and not ready to track the numerous changes.

Moreover, the broad trade-space described in Section 2.2.5 is a natural driver of uncertainties in an early-phase program.

Lessons Learned

Phase B EVM requires a rigorous CM system in place to allow for the program formulation turbulence inherent in this phase. Without a well-documented and current baseline, quality EVM data generation is problematic.

Recommendations

Although the baseline is still being established during the formulation phase, an initial baseline change control log and baseline change documentation should be developed to trace budget and funding changes and communicate those changes regularly. Logs should be developed to enable the staff to have an historical trace.

4.5 Joint Confidence Level

This section outlines the primary lessons learned for the JCL, which is a methodology pioneered by Constellation at the behest of NASA HQ that can be used by a program to provide confidence levels for the achievement of program objectives based on budget and schedule information. It attempts to predict the confidence in success given a budget phased against schedule milestones. NASA HQ set a 65% confidence level for Constellation.

This topic is technical in nature, and the interested reader is encouraged to review the complete report on the Constellation development and usage of this technique.[14]

[14] Kuo, F. and Wilson, S. ”Joint Confidence Level Requirement: Policy and Issues.” NASA TM-2011-216154.

4.5.1 The Current Joint Confidence Level Budget and Schedule Reserve Requirements Are Untenable

Supports Key Findings: 3.1, 3.2

Driving Events

Requirements have been documented in NPD 1000.5 and NPR 7120.5 directing programs to budget to a 70% joint cost and schedule confidence level. Although the Constellation Program was permitted latitude to plan to a 65% JCL, analyses showed that this requirement, when coupled with the inherent uncertainties in large-scale, tightly coupled programs associated with human space flight, drives the need for high budget and schedule reserves. This is driven from the fundamental nature of portfolio management. There is a beneficial effect to cost confidence provided by portfolio diversification because cost and budgets are fungible; program managers can transfer money from a project in surplus to another in shortage. However, extending the requirement to include schedule, as in JCL, reverses the benefits of the portfolio effect. This is because, unlike money, one cannot transfer time from a project that has been completed early to one that is late.

The budget status of the program is described in Section 2.2.1 as is the first key finding, 3.1.The current 65% JCL demands budget and schedule reserves that are untenable for most projects and programs. The Agency and government budgeting process (along with many historical examples) precludes the types of reserves necessary to maintain this level of confidence.

Lessons Learned

To meet the 65% JCL requirement, budget and schedule reserves of 30% to 50% are needed for a typical, tightly coupled human space flight program. Using the minimum 30% reserve requirement and the approximate $24B budgeted for IOC, this translates to a reserve of **$7.2B for IOC alone**.

For the entire Constellation Program through FY20, the budget was approximately $100B (including $12B in reserves). Using the minimum 30% on program content ($88B) renders **$26.4B** that would have had to be set aside for reserves for the full program. This is more than double the actual reserves held, and does not include the required schedule reserve of 30%. Clearly, this amount of funding is excessively large with respect to the overall NASA funding and would not be allowed to sit idle in the Constellation budget in light of other Agency needs.

Recommendations

Implement an approach to stipulate requirements for cost confidence alone, but still enforce an emphasis on schedule uncertainty as an inherent element within cost estimates. This approach is described in more detail in the citation above.

4.5.2 The Joint Confidence Level Methodology Is a Useful Decision Support Tool

Supports Key Findings: 3.1, 3.2

Driving Events

The implications of a JCL target requirement notwithstanding, the analysis provided invaluable insight into the health of programs and projects and served as a vital portal into schedule, cost, and technical issues. The most significant contribution of JCL is its ability to provide information to program managers about the *comprehensive* impact of risks to schedule and cost, focusing on key issues at the macro level. It has proven to be a valuable management tool that merges the risk, cost, and schedule stance and also captures the dynamics of the interrelationships.

For the Constellation Program, the JCL process generated new strategic dialogue and understanding among program and project stakeholders — and even within the project control team. Analytical cooperation, as well as traceability, understandable methodology, identifiable input sources, and analytically rigorous results, are all hallmarks of successful JCL in action.

Lessons Learned

JCL analysis is highly useful in providing information to program managers about the comprehensive impact of risks to schedule and cost, thus enabling focus on key issues that most greatly effect the plan.

Recommendations

Continue to encourage (or require) programs to conduct JCL analysis to drive out the most relevant issues and focus on those that have the greatest impact.

4.6 Construction of Facilities

Management of facilities construction and modification has inherent complexities that were not fully appreciated at the outset of the Program. Since Constellation was the first major NASA development requiring new and modified facilities at multiple locations in many years, oversight skills were initially lacking. As described in Section 2.2, the Program was inheriting much of the vast space shuttle infrastructure, and was viewed as a source to solve pent-up facility maintenance demands. Moreover, management of facility construction is not a subject typically covered in program management training, so much of the management team was unfamiliar with some of the unique challenges. These include the following:

- *Facility use*. Some specialized facilities relied on the space shuttle (and, hence, Constellation) as the single, or nearly single, user. Centers desired to retain capabilities, but had difficulty either finding other users or justifying the costs to a single program (or both). Some facilities were nearly duplicated at centers, so securing a program commitment for usage was competitive and highly sought. Once the commitment was secured by a particular venue, cost estimates tended to increase.

- *Construction of facilities (CoF) funding*. Congress requires higher visibility for funding for new facilities, and funds must be managed separately from other program funds, reducing flexibility. Conversion of CoF funds to research and development (R&D) funds (and vice versa) is extremely difficult. Increased Congressional visibility increases visibility at NASA HQ and resident centers, necessitating additional reviews.
- *Center infrastructure*. Since most facilities reside at NASA centers, senior center management expected to be a part of the decision chain, regardless of funding source.
- *Cost control*. While not flight hardware, CoF is fraught with historical cost overruns and overestimations. This creates additional management difficulties in a budget that is highly visible and inflexible.
- *Facility development in parallel with hardware development*. New and modified facilities for use by Constellation were under design in parallel with hardware design in many cases. In some instances, hardware design changes drove changes in facility designs. The inflexibility of the CoF process made this a particular challenge.

To avoid these issues in future programs, flagship programs should establish an experienced facility team, conduct independent cost estimation on construction projects, and develop a facilities construction planning process that will guide selection and development of facilities and ensure due diligence is performed.

4.6.1 Establish Program-level Facilities Expertise during Program Formulation

Supports Key Finding: 3.1

Driving Events

The Constellation Program experienced all of the issues related to construction of facilities listed above. Moreover, there were multiple CoF projects under way at several NASA centers. Most of the issues resulted from one or more of the following:

- Inadequate front-end planning (FEP) and due diligence
- Poorly defined, immature, and changing facility requirements
- Vehicle requirements changes that affected ongoing CoF (since the vehicle designs were immature at the time that CoF had to begin)
- Limited funding and no contingency
- Lack of CoF experience in programs and projects
- Complexities and confusion in determining which parts of the project required CoF vs. R&D funding
- Late engagement of center facility expertise

Lessons Learned

The program and projects must have CoF expertise in their construction of technical facilities (manufacturing, test and operations facilities).

Recommendations

Establish a small, experienced facilities team early at the formulation of the program. This team should include facility cost estimators and facility development experts, as described below. This team oversees facility selection and development as well as aids in determining and tracking program facility use according to the facility planning process described below.

4.6.2 Develop a Facilities Planning Process

Supports Key Findings: 3.1, 3.7

Driving Events

Most facilities issues experienced by the Program could be linked to inadequate FEP, in part driven by the late Program start relative to projects (Section 2.2 6).

Moreover, the starting state of the facility was not necessarily understood for the facilities that were being modified. That is, the facility condition report was not detailed enough to accurately identify all problems, and estimates were based on the building only and not on unique vehicle requirements. Initial proposed budgets for some facilities did not account for the immaturity of the facility requirements. Facility requirements were often immature at the time at which the facility project needed to begin. Since CoF must start years before vehicle design requirements are solidified, vehicle design requirements were changing that would impact a facility that was already under construction. Some projects did not have project management plans. Trade studies and cost estimates often did not consider full life-cycle costs.

Lessons Learned

Appropriate due diligence should be followed in selecting and developing facilities needed to support the program. The program documented the CoF processes once these unique aspects were understood.

Recommendations

During program formulation, develop a facility selection and development process that is consistent with NASA processes, laws, and regulations, and that reflects the organization of the program. This FEP process must have built-in flexibility so it can be tailored for the unique facility complexities. The process should ensure appropriate due diligence is done throughout the development cycle: from initial trade studies through construction and commissioning. Project milestones should be linked to the existing budget processes to provide the most current and accurate facility cost estimate available. The process should ensure that environmental impacts, energy efficiency, and historic preservation are considered in development. The process should lay out roles and responsibilities regarding who is developing the various due diligence products. It should clearly define the role of the centers, the projects, the program, and other stakeholders that should be involved. Milestone approval requirements should be clearly defined (Reference:

CxP 70700 Constellation Program, Constellation Management Plan, Annex 10 Facility Planning Process.)

4.6.3 Accommodate the Unique Risks Inherent in Construction of Research and Development Facilities

Supports Key Findings: 3.1, 3.7

Driving Events

Many of the facilities that are needed to support a new program are technically complex (unlike an office building); therefore, these projects have significant technical risks. In Constellation, the Reverberant Acoustic Test Facility at the Plum Brook Station Space Environment Test facility and the Stennis Space Center A-3 rocket test stand had requirements that were beyond any facility in existence. These one-of-a-kind facilities led to technical risks that required technology development and testing to mitigate them. Technical risks can lead to additional cost or schedule risks; these technical risks should thus be accounted for in CoF budgets and schedules. Accounting for these risks also requires flexibility in budgeting and schedule.

A related factor is the immaturity in the requirements for a facility in a development program such as Constellation. Facilities, such as those to support testing, manufacturing, or operations, are required early in the program life cycle. Often the manufacturing, testing, and operations requirements are being developed at the time the facility construction must start, which leads to unavoidable changes to the construction (driving costs up).

In other cases, significant new requirements are levied on a facility. For example, after construction start, the Program required the Mechanical Vibration Facility to accommodate not only the IC hardware, but also LC hardware – namely *Altair* vibration testing.

The existing agency CoF process supports building administrative-type facilities that have low technical risks. To accommodate the challenges of building an R&D facility, a program must have large reserves set aside for the CoF projects and the flexibility to change funding levels without requiring an Operating Plan change, separate management, or Congressional approval. With the current CoF system, once a program sets aside reserves in the CoF account, it cannot reclaim that funding for R&D accounts should the facility reserve not be required. Changing Congressional operating plans just to manage risk in a facility development project is not good fiscal practice.

Lessons Learned

Construction of facilities processes should be modified to better accommodate R&D facility development and provide funding flexibility.

Recommendations

Modify existing CoF process to address the risk associated with the building of R&D facilities. Flexibility could be provided that allows the recapture of a CoF budget that has been used for

construction or to increase funding due to construction changes. A second tool for gaining limited flexibility is for the program to group construction projects at a geographic location into a larger project. Grouping would allow the program the flexibility to move funds from one subproject to another at the same location without requiring an operating plan change. For example, the numerous construction projects required at Michoud Assembly Facility (MAF) for the upper stage could be strategically grouped so that money could be transferred from one CoF project at MAF to another.

4.7 Risk Management

The Constellation Program implemented an integrated RM process compliant with NPR 8000.4, Continuous Risk Management, and consistent with experience on the ISS Program and SSP. Successful RM faced significant challenges, as described in Section 2.2. Chief among these was the dwindling budget reserve that in large measure consumed program flexibility to address risks. Risks were diligently tracked and reported, but many lingered and, indeed, accrued due to budget limitations.

As with Section 4.4, this section should be read in context with the DM limitations described in Section 4.3. Implementation of RM was partially hindered early in the Program by the lack of a common, requirements-driven data system. An integrated RM process for systems that must interact physically or operationally is essential to discovering, characterizing, and reducing integrated risks. To support these activities, it is important to maximize similarity in common standards for defining, comparing, and tracking risks. Using a common risk database can substantially improve the effectiveness of this activity by providing common reports, fields, definitions, evaluation criteria, and electronic sharing capability.

4.7.1 Ensure Risk Management Is Embedded in the Design Process

Supports Key Finding: 3.5

Driving Events

The complexity, size, and limited budget described in Section 2.2 were circumstances that engendered a difficult RM environment. While a rigorous RM system was implemented, using the best assets and knowledge of the Agency, management processes can develop a life of their own, yielding a myopic view and confusion about the value of the process vs. the product. The Program was most successful with RM when risks were identified, analyzed, and brought to resolution as part of the design process rather than independent of the design process.

Lessons Learned

This team-centered risk identification process worked especially well as part of the Integrated Design Analysis Cycle (IDAC) process. IDAC provided a venue for iteratively improving analysis tools, integrating analysis disciplines, and investigating design decisions and operational assumptions. It brought stakeholders from the directorate, Program, projects, and elements together on a regular basis to define assumptions, perform integrative analysis, interpret results, and draw conclusions. IDAC organized the design process and enabled systematic risk identification. As a result, many key technical issues were identified during early design cycles rather than later. Examples include: achieving acceptable probabilities for LOC/LOM, structural loads on *Orion* and *Altair* during trans-lunar injection, first-stage thrust oscillations, and mass growth during design maturation. This supported early action to reduce or eliminate risks, and enhanced integrated understanding of design and performance.

The Program experience illustrated that many risks require multiple design cycles to be fully addressed via research, analysis, option development, and, ultimately, testing.

Recommendations

Implement common risk standards, risk system, risk training, and joint risk review process on programs and projects that have significant interdependencies. Put this system in place early in development to ensure that architecture and mission-driving risks are understood early in the design process. Embed the RM process with the IDAC process to ensure maximum impact on the design.

4.7.2 Good Risk Management Relies on Open Communication

Supports Key Findings: 3.7, 3.8, 3.10

Driving Events

Several communication issues hindered implementation of an RM and tracking process. First, the purpose and use of the RM system was not well understood throughout the Program and projects. Some viewed the database of risks as too large and cumbersome; others viewed it as

a centralized tool to capture all risks, with simple processes to limit what was seen based on user need. Second, projects were reluctant to provide detailed risk insight because they viewed such insight as micromanagement. The Program needed broad risk insight due to the small and dwindling reserve level; projects viewed the level of insight needed as a lack of trust. Third, cultural issues were at play. While some centers saw a high number of potential risks as a good thing (folks are paying attention), others saw it as a bad thing (there is something terribly wrong if all these risks exist). These thorny issues hindered discussion and resolution of Program risks.

Lessons Learned

As with the IMS (Section 4.4.1), the purpose and use of the RM system was neither fully communicated nor embraced by all key stakeholders This led to distrust and a feeling by some parties that the risk system was overly burdensome and of limited value.

Recommendations

In establishing RR&A for programs and projects, the amount of insight necessary at each level for proper RM should be established and communicated *a priori*. Expectations of any risk system should be established early; do not assume they are understood because the system was used on a prior program.

4.7.3 Early and Robust Probabilistic Risk Assessment Enables Risk-informed Design

Supports Key Finding: 3.5

Driving Events

The Program built early probabilistic risk assessments (PRAs) to inform early design studies. As described in Key Finding 3.5, two projects used risk-informed design to great benefit. This was enabled by having a PRA available so that trade studies could proceed that weighed options for risk reduction.

Lessons Learned

The two projects (*Orion* and *Altair*) were able to use a risk-informed design process to improve mission success probabilities and reduce mass. These analyses relied on having early PRA available, and could not have proceeded successfully without this analysis capability in place.

Recommendations

Risk-informed design (treating risk as a commodity) can only be performed if good PRA data are available. Assure that an early and robust PRA is established to support risk-informed design.

4.7.4 Divide and Conquer to Address Complex Risks

Supports Key Finding: None

Driving Events

Complexities and interdependencies in design and, thus, risks drove complexity in solving those risks. Appropriately delegating aspects of risk mitigation to address complex risks arose as a management challenge during early design.

Lessons Learned

Division of risk mitigation was most effective if portions were defined within the scope of, and delegated to, individual teams. For instance, design risk for the liquid oxygen/hydrogen common bulkhead was broken down into many child risks that could be managed by individual teams. Each child risk contained a portion of the detailed mitigation plan developed to address every aspect of the overarching issue related to manufacture and production of the common bulkhead stage. This risk illustrated that it can be helpful to establish parent and child risks for complex or integrated issues. This approach makes work more manageable while retaining an integrated understanding of the risk and strong risk communication between stakeholders. The parent risk established a context, while the child risks focused on mitigation of specific risk aspects.

While the establishment of parent and child risks was found to be very helpful in managing complex integrated risks, it was also found that care should be taken to limit the establishment of "parent risks" to cases in which there is a unique higher-level mitigation activity. Simply establishing parents for all risks that are common across systems and elements inserts unneeded complexity into the risk process and clutters up the risk system. In the case of mass growth, for example, the Program did not track an integrative parent risk because it was felt that mitigations for potential mass growth would simply reflect standard SE practice. Risks were established on those systems that had mass issues, such as *Orion*. These teams conducted additional analysis and design activities to achieve their mass targets.

Recommendations

Use parent-child risk relationships to document where multiple stakeholders are performing significant mitigation responsibilities for the same integrated risk. However, limit the parent-child structures to risks with unique and significant mitigation contributions to avoid overpopulation of the risks system with less important risks.

4.7.5 Link Test Planning to Risk Mitigation

Supports Key Finding: 3.11

Driving Events

Choosing how best to test, and how many tests are needed, prior to human space flight is a debate explored more fully in Section 4.9. Testing is expensive in hardware development, and is

most often first on the chopping block when budgets are squeezed. It is therefore necessary to develop a solid and compelling rationale for testing, or elements of testing, to form cogent program and project plans.

Lessons Learned

To better focus limited test resources, the Program developed a Risk Informed Test (RIT) approach that was aimed at identifying the most significant operational and developmental risk drivers and ensuring that tests appropriately explored these through analysis, ground test, and flight test. RIT relied on evaluating both qualitative and quantitative systems safety assessment, historical failure history, historical test and verification experience, and expert elicitation to help identify test priorities, test fidelity, and frequency.

A qualitative approach such as RIT, which collects what is known about failure modes and the effectiveness of analysis and test to mitigate and understand these risks, can be very helpful when informing these decisions.

Recommendations

While more testing provides greater assurance of safety and maturity growth, there are clearly cost and schedule limits on how much testing can be done. An approach such as RIT can be helpful in discerning the best test approaches.

4.8 Design and Development

4.8.1 Ensure a Common Understanding for Implementation of Human Space Flight System Certification

Supports Key Finding: 3.11

Driving Event

As the Program matured, the Agency was unable to clarify requirements to govern the first flight of humans on a new spacecraft.[15] This was, in part, due to the generation gap in human space flight discussed in Section 2.2.4. The space shuttle was designed in the mid 1970s, and tested in the late 1970s and early 1980s. Few, if any, senior leaders in the Agency had dealt with the issues surrounding vehicle certification for human space flight, particularly for vehicle launch and reentry.

The NASA human-rating criterion[16] is stated as: “Given that the human [space flight] system is designed for human [space flight], it is accepted that the objective is to fly humans when risks to

[15] Such requirements exist for payloads and reflect varying levels of test of new commercial flight vehicles based on the level of government insight and importance of the payload.
[16] NESC-RP-10-00619. “Readiness for First Crewed Flight.” April 12, 2011.

the crew safety have been mitigated to the point where the need or benefit is worth the residual risks."

This criterion, while sensible and easy to understand in principle, is extremely difficult to implement as certification guidance. It is instead left to program management to interpret into a design, development, analysis, and test plan that leads to certification for human space flight. And, while program staffs are skilled in this, the breadth of interpretation leaves a program extremely vulnerable in the face of budget challenges once that plan is formulated. Moreover, as some have observed,[17] the current strategy does not adequately address "unknown-unknowns," or the unexpected things the hardware can "tell" the designers during test.

Section 2.2.1 described the budget challenges faced by the Program during its tenure. A primary target during multiple rounds of budget cuts was the test program leading to human certification. This test program became difficult to defend in the face of myriad interpretations of what it should take to certify for human space flight. The definition of "residual risk" was widely debated and never clearly understood, such that any critic could challenge the test plan. The interested reader is referred to a summary accounting of changes to the certification test plan during the life of the Program, cited in footnote 17, below.

The Constellation Program was advancing with necessary tasks that would define the certification requirements for a human space flight system. The integrated certification plan was not complete as required for the PDR in February 2010. This delay was due to the interpretation challenges noted above, along with the mismatch between the project procurement contract requirements vs. the integrated requirements produced by the Program SE&I organization (see Section 2.2.6). After PDR, work on the plan was halted as more cost/schedule-friendly variant strategies were studied. While an operational certification plan was not completed, a number of lessons learned were identified that addressed several inefficiencies that originated from these driving events.

Lessons Learned

A cogent, integrated test plan cannot withstand budget challenges if the underlying requirements and rationale (certification criterion, residual risk) are left open to broad interpretation.

The definition of "certification" (in terms of content and in relation to content definitions of terms such as "verification" and "validation") at the element and integrated hardware/system level were unclear (see Section 4.2.6). The Master Integration and Verification Plan (MIVP) was released at the Systems Requirements Review (SRR) but did not adequately define the certification process or the plan. It provided a high-level definition to Program elements but not to the level of detail necessary for certification planning (e.g., defining the role of the Systems Acceptance Review, Design Certification Review, and Certification of Flight Readiness in the overall certification plan). MIVP Revision A was released for the PDR and included an updated certification plan.

[17] Noriega, C. et al. "First Crewed Flight: Rationale, Considerations and Challenges from the Constellation Experience." In preparation as a NASA TM.

Work should be performed early in the life cycle of a program to develop an integration and test strategy (including flight tests) as a companion to design definitions, starting with system concept development and maturing with the design through certification completion. The early availability of this strategy would enable timely contribution of key driving test and evaluation figures of merit to support making better-informed decisions, such as the "what and when" of procurement content. Based on this information, "right to left" integration can occur to identify key integration points driving (hardware, software, data objects, etc.) product deliveries and critical paths through the certification campaign. The integration and test strategy should accompany design descriptions and be controlled in the same manner. The strategy should be used as a planning benchmark to provide a clearer and considerably more valid basis of content, cost, and schedule estimation.

Recommendations

The Agency should interpret its current certification criterion to a level such that a program plan for design, analysis, and test can be clearly seen to either meet or not meet that criterion, particularly in the face of budget pressures.

Programs should

- Clearly define what "certification" means prior to awarding contracts.
- Clearly define the test and evaluation roles and responsibilities prior to awarding contracts.
- Develop an integration and test strategy for accomplishing certification concurrently (and to a comparable extent and fidelity) with initial system concept development.

4.8.2 Embed Human-rating Certification in the Core Processes/Tools of the Program

Supports Key Finding: None

Driving Events

The Constellation Program was the first program to implement NPR 8705.2B, which was approved coincident with the Program SDR. A draft human-rating certification package (HRCP) was developed for the SDR. The NPR 8705.2A and B versions both require implementation of a safety process; one key difference between them is that Version B places more emphasis on performing the analysis to drive the design vs. using a rule-based approach to drive the failure tolerance for catastrophic events, which is the emphasis in Version A. Since the NPR was approved after contracts were put in place, needed NPR data had to be accommodated with the currently planned contract deliverables. Some potential gaps existed for the new NPR-required specific design assessment data.

The Constellation human-rating approach was to embed human rating into Program standard procedures. This placed responsibility for compliance with the designers rather than establishing a separate process. It also leveraged the NASA human space flight heritage and culture for implementation of these procedures.

A team, which was staffed by technical experts responsible for ensuring the satisfaction of the NPR requirements, project representatives responsible for ensuring project compliance, technical authorities, and astronauts, was responsible for ensuring that the evidence provided met the intent of the NPR requirements.

The team demonstrated to human-ratings stakeholders that the required content was covered (and augmented, if necessary) within the Program products. The HRCP provided pointers (via hyperlinks) to the evidence contained within the planned Program documentation. The Program used the requirements software tool to demonstrate compliance with NPR technical requirements. Fault tolerance and the use of the hazards database is a key area in which this type of negotiation with stakeholders is necessary.

Lessons Learned

Build human-rating precepts into the program teams along with standard processes and tools. Do not establish human-rating activities as a separate process unto itself.

Recommendations

For future human-rated procurements, include the process-related requirements from the NPR, including access to all human-rating data in the contract SOW.

Establish a team with the implementers and technical experts to develop the HRCP. Include the technical authorities and astronaut crew on that team to assure the certification package content satisfies the NPR.

4.8.3 Use Risk-informed Design at the Outset of a Project

This lesson learned is addressed in whole in Key Finding 3.5.

4.8.4 Address Units of Measure Early

Supports Key Findings: 3.1, 3.2

Driving Events

NASA has attempted to move the Agency and its supporting contractor infrastructure from use of English units of measure to the more widely used and accepted SI units of measure. Most notably, the ISS Program attempted this in the late 1980s and early 1990s, particularly since the International Partners use SI units. The ISS Program abandoned the effort when costs of implementation became prohibitive. Human space flight programs have lagged in this effort, primarily due to the reliance on heritage infrastructure that was built in English units (e.g., launch pads, test stands, transport ships and crawlers, railcars, etc.). NASA science missions have enjoyed the best success at this conversion, since they are less reliant on heritage infrastructure.

The Agency attempted to implement SI units once again, using the Constellation Program as leverage to incentivize the change. The CARD established SI as “primary units of measure,”

stating: “All Level 1, 2, and 3 integrated analyses, performance and verification systems will be completed in SI units.” However, the CARD allowed “English units” for Level 4/5 (contractor and subcontractor) if justified. The CARD was ambiguous on “operational data.” Yet as of 2007, the Program was not compliant – there was a units “Tower of Babel” in presentations and analysis. This was primarily due to a lingering heritage infrastructure issue that drove a similarly unacceptable cost overhead for implementation. The risk of a units-produced error was clear and present.

A directive was approved in late 2007 that reinforced the use of SI units and provided details on where and how to use a “hybrid” units system based on proven practice in robotic missions. It also addressed the primary constraint that “flying” in SI units requires testing in SI units (i.e. “fly like you test”).

Lessons Learned

While the Program and projects were willing to implement this new directive, cost estimates provided by the major contractors (who were well into design due to early contract starts) were very high, approaching $370M.[18] Funding was unavailable, even at a low level, to start implementation and negotiate the contractor costs. Ultimately, due to these funding limitations, the Program had no choice but to issue a new directive in June 2009 that specified U.S. customary (English) units across the Program.

Recommendations

Establish adequately specific units requirements *a priori*, including a well-thought-out and executable implementation approach that addresses heritage infrastructure and contractor conversion costs. Unless SI units are specified prior to acquisition, the cost to change will be prohibitive.

Assign a champion to enforce implementation at all levels until use of SI units is standardized in the human space flight community.

4.8.5 Design for Operability to Reduce Life-cycle Cost

Supports Key Finding: 3.1

Driving Events

One of the many observations of the CAIB was that the space shuttle was expensive to operate. The need to use Apollo-era infrastructure, along with early design compromises that saved then-year dollars as opposed to out-year dollars, led to an expensive operational program. During formulation, Constellation was challenged to design in lower operational costs while using and upgrading the shuttle-era (and, in some instances, Apollo-era) infrastructure and “fixed-base” (see Section 2.2). All involved recognized that program sustainability depended on lower life cycle and,

[18] Notably, these costs were primarily due to changes in documentation, rather than hardware.

thus, operational costs. Moreover, lower spending on IC operational costs would allow the development of the LC to proceed.

An example concept was the “clean pad” approach, which recognized that every attachment, umbilical, structure, etc. on the launch pad that touched the vehicle drove an interface that needed a design, an ICD, operational requirements, procedures and launch constraints, and a team of operators. This, in turn, drove operational costs and complexity. Designers were challenged to drive interfaces to an absolute minimum to achieve the “cleanest” pad possible.

Another launch-related concept for the LC was to shorten the time between launches of the crew vehicle (*Ares* I) and the cargo vehicle (*Ares* V) to drive minimal launch preparations into designs. A target of 1.5 hours between launches challenged designers to reduce both launch preparation and processing times.

An activity was initiated, during the SRR in late 2006, to formalize these “stretch requirements” for inclusion into the CARD. Teams from the operations centers (JSC, KSC) brainstormed an initial set of candidates that would help the Ground Operations and Mission Operations projects to reduce their costs to operate the integrated program systems. The teams developed a set of proposed requirements that were assessed by the projects and elements for cost and schedule impact. Roughly half of the proposed requirements were implemented into Revision A of the CARD. Those that were not implemented as requirements became a set of Constellation Program “design guidelines” that were scored for their implementation progress at subsequent Program milestone reviews.

Many of the design guideline items found their way into the architecture where there was performance or schedule margin to accommodate them. Some examples of these design changes for operability include the use of a single common fuel for all *Ares* reaction control systems (hydrazine), non-pyrotechnic separation systems for all flight-to-ground umbilicals, and locating all vehicle-to-ground pad interfaces within the tower-facing arc of the flight system.

Several initial stretch requirements were deleted from Program specifications during the season of SDRs. The most significant of these deletions was the requirement for meeting targeted operation cost caps, by system, at full-operational capability. Others were tailored or ameliorated based on budgetary and performance limits of the architecture.

The most successful of the stretch requirements dealt with minimizing the critical path of integrated launch operations processing. An integrated WG was established to estimate and track the impact of vehicle and infrastructure design changes to the targeted 45-day vehicle processing flow. By the time of Program PDR, the architecture was showing the capability to meet this aggressive timeline requirement. While working this ongoing assessment, strong working relationships between the Ground Operations Project team and the vehicle design elements were established in which the common goal was developed and shared.

The Program recognized that the stretch requirements were only able to address the operations phases of the life cycle (post-handover from the contractor). To attack life-cycle cost challenges

inherent in production and sustaining engineering, the Program established an operability "czar" to focus on the fixed and recurring costs of the flight elements.

Lessons Learned

Design for operability must be a driving metric in the initial architectural trades, particularly for programs planned with significant operational lifetimes. Operability requirements imposed after the major architectural decisions are made must compete for budget and performance margins that, in the case of Constellation, were extremely limited.

Operability must be defined uniformly across all program and project elements. Ground Operations saw operability as a measure of cost/complexity to perform launch system integration and checkout; *Ares* saw it through the lens of the ease of maintenance of its designs; Mission Operations aligned it as being associated with operational robustness and flexibility of in-space elements; *Orion* assessed it as the reliability and robustness of its subsystems. While these definitions had some overlap, they often led to competing interpretations of the intent.

Focus on design for launch site operability improvement provides some cost-reduction benefit, but is only a small contributor to the total life-cycle cost of complex space systems. Operability improvement is further constrained by incorporation of legacy systems and infrastructure.

Many stretch requirements were defined with both "threshold" and "objective" values. Threshold requirements were minimum targets to be met with objective requirements as goals to continue to work toward as systems matured. In practice, while projects did do assessments to reach the objectives, many objectives were not implemented because the needed contract changes were cost prohibitive.

Recommendations

Programs should establish an initial cost model, which includes operability, and maintain that model as systems evolve from SRR through PDR to CDR. Consider using the best practices of "design-to-price" and "cost as an independent variable" as implemented in DoD acquisitions.

Use of "stretch requirements" that incorporate both "threshold" and "objective" specifications can be maximally effective if they are included up front in acquisitions or procurements through performance incentives for contractors. Programs should consider these measures to assist contractors in focusing on design innovations that provide operability improvements of significant life-cycle cost drivers.

4.8.6 Simulate Processes Early (Run a "Virtual" Mission)

Supports Key Finding: None

Driving Event

The Program freshly developed mission integration and certificate of flight readiness (CoFR) processes needed to be assessed for efficiency and productivity. Typically, these processes are "shaken out" during early missions or mission preplanning. Since the technology was available, the Program undertook an early mission simulation, prior to PDR, that included prelaunch, in-flight, and post-flight planning and operations.

An ISS crew rotation mission was chosen. The first simulation was termed Virtual Mission-1 (VM1), and a second simulation, VM2, was planned prior to Program cancellation.

Lessons Learned

Gaps and areas of improvement were discovered in the mission processes and, in one case, an *Orion* vehicle design deficiency was discovered.

Process improvements: Several critical mission milestones that had schedule or assignment disconnects were identified. An example was the Mate Review: There was some difference of opinion among the *Ares* project, Ground Operations Project, and ATK [Alliant Techsystems, Inc., Minneapolis, Minn.) (the *Ares* first-stage contractor) as to who was responsible for the stacked first stage. While *Ares* assumed responsibility for VM1, the issue remained open and the plan was to simulate this activity during VM2 to resolve it. The VM1 team also identified schedule disconnects with the Mission Control Center and Constellation Training Facility reconfiguration. Other mission milestones needed processing improvements. For example, the CoFR was a manual process that was very labor intensive. VM1 helped confirm that mission stakeholders needed a continuous status capability that could be provided by a software tool (e.g., the CoFR dashboard).

Design improvements: The management team challenged the virtual team during VM1 with an ISS control moment gyroscope (CMG) failure such that a new CMG would need to be processed quickly for launch in the *Orion* SM. The VM1 team identified the need to access the SM unpressurized cargo later than planned (L-270). The command module (CM)/SM stack had to be accessed before leaving the KSC operations and checkout (O&C) building because no ground support equipment existed to access the SM in the KSC Multipurpose Processing Facility. For VM1, the team was able to load the CMG later in the flow because the CM/SM stack was still in the O&C and the Ground Operations team worked around the clock. Another simulated emergency, which coincided with an SM redesign study to accommodate unpressurized cargo, resulted in several new *Orion* recommendations for the SM design (e.g., overhead mounting using a lunar propellant tank mounting point, radiator removal). This underscored the concept that design decisions made early in the program can drive operational capabilities later.

Recommendations

The virtual mission is an excellent vehicle with which to exercise planned mission management processes. In the case of VM1, the team refined many of the processes and began developing needed software tools.

Additional virtual missions are recommended with lessons learned from VM1. A virtual mission simulation to exercise an initial (non-operational) ISS rendezvous flight would be very helpful in identifying and resolving any process problems that might be present in the longer mission management template planned for these initial flights.

4.8.7 Focus the Certificate of Flight Readiness Process

Supports Key Finding: None

Driving Event

Perceptions that the current human space flight CoFR process was inefficient and needlessly burdensome led the Program manager to charter a CoFR L6S composed of representatives from all Program organizations, as well as the ISS and Space Shuttle Programs, and an external senior advisor.[19] The L6S team charter was to develop a CoFR process that was "integrated, efficient, and streamlined."

Lessons Learned

The existing Program CoFR (flight preparation processes) was people, meeting, and paper intensive. The CoFR lean event led to a philosophy of a continuous (anytime) status capability that was to be facilitated by a CoFR tool (the CoFR "dashboard"). In addition, the process was redesigned to be product focused vs. organizationally focused. That is, for a group to be integral to the CoFR process, it must provide a concrete product such as an assessment or a report that contributes to certification. This eliminated several "checkers checking the checkers" that have been added to the CoFR process over the years. A similar activity regarding WGs revealed inefficiencies with unchartered WGs using precious resources.

Recommendations

Continue to use L6S or similar methodologies to assess process efficiency and effectiveness. Continue to use applications/dashboards, "roll-ups," etc. to get a continuous status of not only CoFR but of any work process that spans a considerable time duration. This should be done in lieu of infrequent and large status events, and to avoid the generation and use of paper products for such events. This is not only inefficient and time consuming, but leads to "stale" information.

[19] The ISS and Space Shuttle Programs were included because the Constellation CoFR process had been largely based on prior program experiences.

The full set of recommendations was implemented in CxP 70175, the Constellation Program Certification of Flight Readiness Process Plan (CPP).[20]

4.9 International Partnership Development

These lessons learned related to international partnership development are focused specifically on topics relevant to NASA and Constellation internal program planning and development. Two recent and very relevant documents provide broad consensus views of international partnership lessons learned. The first of these, "International Space Station Lessons Learned as Applied to Exploration,"[21] was developed by the ISS partnership to provide timely guidance in planning the Constellation Program. These lessons learned were widely shared and frequently discussed in the activities described below. The second, "The ISECG [International Space Exploration Coordination Group] Reference Architecture for Human Lunar Exploration—Summary Report"[22] contains consensus lessons learned from the perspective of all international agencies involved in the development of the ISS. Both of these documents are valuable tools for planning; however, since they are consensus-based documents, they do not provide a view internal to the Agency.

As Constellation was forming, the ISS International Partners expressed an interest in continuing to pursue human space flight challenges to expand frontiers together with NASA. As Constellation represented the next step in human space exploration, consulting International Partners could have been an important step in strengthening our existing partnerships. It also brought us the opportunity for expanding international partnerships to additional space agencies beyond the ISS partnership. It is widely recognized that international agreements enhanced the sustainability of the ISS and, thus, could do so for future human space flight efforts.

However, NASA policy and federal regulations restricted the scope of potential international partnership opportunities available for the Constellation Program to projects and hardware not designated as critical path items (see Lessons Learned below). As a practical matter, export control regulations exclude international partnerships on launch vehicle development and any shared technologies that are defense related. Thus, the focal point for potential partnership opportunities occurred during the later phases of the Program—namely, the lunar exploration (LC) phase.

[20] Although this document was not baselined prior to Program cancellation, a full draft was produced in support of the Program PDR and may be found as an official record within that review.
[21] ISS Multilateral Coordination Board. *International Space Station Lessons Learned as Applied to Exploration*. 2009.
[22] International Space Exploration Coordination Group. *The ISECG Reference Architecture for Human Lunar Exploration—Summary Report*. July 2010.

The primary mechanism for discussion of partnership opportunities was the ISECG, which was comprised of 14 space agencies from around the world.[23] ISECG discussions were led by the NASA HQ Exploration Systems Mission Directorate and supported by personnel in the Program.

4.9.1 Engage Potential Partners Early in the Program Life Cycle

Supports Key Finding: None

Driving Events

The Program prepared its first *integrated* lunar-phase budget estimate in 2008. It was at this time that initial concept designs and potential architectures were mature enough to frame an integrated discussion. This integrated framework provided enough knowledge to initiate understanding and planning of the scope and roles that potential partners could take.

A small team of Constellation personnel began activities within the ISECG to explore potential avenues that could lead to partnerships and build relationships that would be key to this understanding. This team had the following objectives:

- To understand national priorities. An understanding of the national priorities of each agency, with respect to human exploration, was critical to gauge whether, when, and to what extent a partnership opportunity might evolve.
- To develop a realistic planning framework. A realistic understanding of the extent and nature of potential or contemplated contributions from each agency was necessary for the Program to plan a viable architectural framework.
- To inform the NASA budget process with realistic assumptions. This understanding allowed the development of a set of budget assumptions based on current and projected international states of affair based on national priorities.
- To build a sustainable framework for the lunar phase of the Program. As the sustainability of the ISS was achieved via international partnerships, the team envisioned a lunar partnership that would anchor a long-term program within participating agencies and governments.

Understandably, each of the agencies with ISS partnership experience viewed future opportunities in the context of ISS participation. The ISS was nearing the “assembly complete” milestone, and agencies were readying for full utilization of the ISS research capabilities. Moreover, much of the Partner hardware on ISS was deployed in later program phases; so large budget expenditures

[23] In alphabetical order: ASI [Agenzia Spaziale Italiana] (Italy); BNSC [British National Space Centre], now UKSA [United Kingdom Space Agency] (United Kingdom); CNES [Centre National d’Études Spatiales] (France); CNSA [China National Space Administration] (China); CSA [Canadian Space Agency] (Canada); CSIRO [Commonwealth Scientific and Industrial Research Organization] (Australia); DLR [Deutches Zentrum für Luft- und Raumfahrt] (Germany); ESA [European Space Agency]; ISRO [Indian Space Research Organisation] (India); JAXA [Japanese Aerospace Exploration Agency] (Japan); KARI [Korea Aerospace Research Institute] (Republic of Korea); NASA (U.S.); NSAU [National Space Agency of Ukraine] (Ukraine); and Roscosmos (Russia). “Space agencies” refers to government organizations that are responsible for space activities.

had been recently spent and/or committed. Full utilization of agency investments in ISS was a high priority and was just being realized. Non-ISS partners involved in ISECG were either seeking ISS participation (e.g., South Korea) or contemplating space stations of their own (e.g., China). Recent global economic challenges had left most agencies challenged to meet ISS commitments and left little to no room in governmental budget planning to accommodate lunar exploration on an equivalent scale.

Lessons Learned

NASA led two major WGs—an objective WG and an architecture WG—that sought to develop realistic plans in light of the national constraints described above. Results of these efforts were quite striking as they greatly influenced NASA internal and external planning for lunar exploration. Prior to these interactions, NASA had envisioned a lunar outpost as a base from which to explore the moon; something akin to a "space station on the moon." In working with potential partners, the international group conceived a new architectural plan that was much more flexible and responsive to national priorities and budget realities. This is described in more detail below (Section 4.9.2).

Recommendations

Include potential International Partners in architectural discussions as early as possible to achieve realistic planning.

4.9.2 Develop a Common Understanding of Goals and Objectives to Inform the Architecture

Supports Key Finding: None

Driving Events

After conducting initial formative architectural discussions via ISECG, it became apparent that an understanding of national goals and objectives was needed to drive formulation of architectural scenarios. NASA proposed a WG within the ISECG to develop this understanding. This group, which was formed in early 2009, was chartered to pursue a common understanding of agency objectives for human lunar exploration.

NASA had spent the previous 2 years working with a series of external and internal groups to develop a set of objectives for lunar exploration. These objectives spanned scientific, technological, economic, cooperative, and educational objectives that could be made possible, and provided benefit via human lunar exploration. While not yet prioritized, these objectives had been used to drive the initial NASA architectural concept of an "outpost," described above. An outpost from which to explore was believed to satisfy the largest number of NASA objectives. Therefore, NASA was able to articulate goals and objectives for human lunar exploration towards a common international set.

Lessons Learned

Timing was important here. In 2006,[24] NASA led an initial effort to develop exploration themes and objectives in collaboration with the international community as well as other stakeholders,[25] collecting nearly 200 potential objectives. The apparent similar motivation and rationale for exploration by worldwide space agencies led to the development of the Global Exploration Strategy (GES) framework document and the creation of ISECG. This document articulates five exploration themes shared by participating space agencies. However, meaningful consensus beyond these five themes was not attainable because no other agency at that time had done enough preparation with national stakeholders to engage in discussion to sufficient depth.

By 2009, ESA had conducted a series of workshops with external stakeholders to understand lunar exploration objectives and was also in a position to discuss commonality among interested parties. ESA member agencies (ASI, CNES, UKSA, DLR) had participated in the stakeholder reviews and, thus, were able to provide input to discussions based on the particular interests and capabilities of their agency. CSA was conducting a similar review of exploration objectives. JAXA was in the midst of a national review of lunar objectives and was able to provide insight from a series of external stakeholder discussions during 2009. Other agencies, while not having conducted formal national reviews by 2009, wished to participate in the formulation of a common set of objectives for human lunar exploration. The time was ripe for a group of nine agencies to embark on discussions.

The WG collected more than 600 national objectives ranging from broad, large-scope statements to detailed, investigation-level statements. It became clear that a distillation of these was necessary to achieve an understanding of where commonality among agencies would lie. Something between the five GES themes and these 600 national objectives, traceable to each, was necessary to define the level of commonality achievable at this early, pre-program stage. The WG agreed these statements should be called goals and also agreed on a definition. NASA led the development by providing a set of 10 summary-level statements of goals. These goals were traceable to the full set of NASA stakeholder-articulated objectives as well as the five GES themes articulated by ISECG.[26] This set of goals provided a framework within which to discuss commonality. Other agencies followed the NASA lead by providing summary statements of their own. It was from these statements that a common set of 15 goals for human lunar exploration was developed. ISECG endorsed these in late 2009, and they became the drivers for the architectural work to follow.

From the NASA perspective, these goals achieved the international commonality necessary to frame architectural concepts and became an important step forward. Moreover, these common goals did not provide sufficient support to the concept of a permanent outpost on the moon that

[24] NASA. [Online] 2006. http://www.nasa.gov/exploration/news/GES_FAQ.html.
[25] NASA. [Online] 2006. http://www.nasa.gov/exploration/home/why_moon_objectives.html.
[26] Rhatigan, J., Matsumoto, K., Carey, W., Hipkin, V., Kim, H-D., *Developing a Common Set of Human Lunar Exploration Goals and Objectives*, IAC-10.B3.1.11, Sept. 2010.

NASA had espoused. This drove NASA to engage the ISECG agencies in the architectural discussions described below.

Meaningful architectural discussion could be held with a common understanding of goals and objectives in hand. NASA learned that development of common goals and objectives depends on sufficient stakeholder engagement by participating agencies. Most importantly, the common goals allowed NASA to perceive that an "outpost" architecture was not necessary to achieve most agencies goals (see next lesson learned).

Recommendations

Before engaging in architecture discussions, develop a common understanding of goals and objectives among interested agencies. This common understanding will drive the architecture.

4.9.3 Develop an Architectural Framework for Discussion of Partnership Opportunities

Supports Key Finding: None

Driving Events

An architectural WG was chartered by ISECG, at the behest of NASA, shortly after ISECG was chartered. In our view, this WG struggled in its early efforts because there was no common understanding of, or framework for, its discussion. Early efforts focused on developing common international standards and interfaces; but without an architectural framework, these discussions faltered.[27]

In 2008, NASA announced its intent to build an outpost for human exploration of the moon. During the 2009 ISECG discussions and, in particular, the formulation of the common set of human lunar exploration goals (Section 4.9.2), NASA learned that most agencies would not be able to endorse this type of architecture in the near term, and possibly never.

There were several compelling reasons for this. First, as discussed in Section 4.9.1, agency budgets were highly constrained due to both ISS commitments and the stalled global economy. Commitments in the foreseeable future would be limited by budget realities. Second, most of the ISS partner agencies envisioned expanded roles for themselves in the next major international undertaking.[28] Third, the ISS experience had led to an understandable aversion among partner

[27] NASA may have been inhibited by its previous experience with ISS, in which NASA determined an architecture and invited other agencies to contribute elements. NASA may have tacitly assumed that the next program would proceed in the same way; i.e., along the "outpost" path. This is explored in greater depth in the next lesson learned.

[28] While partner agencies had taken on dependent roles in the ISS Program, that experience had developed extensive new capabilities within these agencies, and they no longer saw themselves as dependent on NASA to provide the same level of leadership and integration expertise.

agencies to a high degree of dependency on NASA.[29] This high degree of dependency on NASA, exacerbated by the delay imposed by the loss of *Columbia,* drove a desire to seek a participatory role unlike the "ISS on the moon" concept proposed in the NASA outpost vision. Fourth, and perhaps most importantly, because of the development of the common goals described above, an outpost was not necessary to achieve common goals. Indeed, these goals called for a much different architectural approach.

Via the ISECG, NASA sought to lead the development of an architectural framework, later called the Reference Architecture. Through a series of workshops, 10 agencies participated in its development. The architectural framework was endorsed by ISECG in June 2010.

This architecture is described in detail elsewhere.[30] Key elements of the Reference Architecture that were important to NASA include the following:

- It represented a flexible, phased approach for lunar exploration that demonstrated the importance of agencies working together early in program formulation. Neither a lunar outpost nor a series of Apollo-style missions, the Reference Architecture reflected anticipated global realities and challenges while enabling significant scientific and exploration accomplishments.
- It would accommodate innovations in technologies, international priorities, and programmatic constraints over time.
- It enabled opportunities for multiple partnerships coupled with a phased deployment for partners at varying levels of maturity. Thus, it was much more attractive to ISECG agencies.
- It could use launch vehicle assets from many agencies, not just those able to launch humans.
- It was composed of largely independent phases, employing an international range of human-rated and robotic assets over time to explore the moon. These could be started, paused, and/or restarted over time, depending on budget resources.

The Reference Architecture strategy provided continuous human and/or robotic science and exploration activity, spanning multiple locations on the moon, starting from at least 1 year before the first flight crew arrives.

Lessons Learned

The development of an architecture framework, in collaboration with potential International Partners, resulted in a highly viable architecture for NASA. It was much more responsive to both NASA and international community goals and objectives than the initial outpost concept. It was flexible and could accommodate programmatic and budget changes over time. Early engagement of the international community resulted in a much more robust concept for collaborative human

[29] International modules were deployed late in the assembly sequence of ISS and could only be launched by the space shuttle. Partner astronauts were transported to and from the ISS by either the NASA space shuttle or the Roscosmos Soyuz.
[30] International Space Exploration Coordination Group. *The ISECG Reference Architecture for Human Lunar Exploration—Summary Report*. July 2010.

exploration of the moon. Indeed, this method provides a cooperative framework for any human exploration endeavor in the solar system.

Recommendations

Partnership discussion should be founded on a common architectural understanding, informed by national priorities, budget realities, and common goals and objectives.

4.9.4 Build On Current and Past Successes, But Beware of Past Paradigms

Supports Key Finding: None

Driving Events

Much of the NASA senior leadership engaged in the ISECG activities had spent large parts of their careers on the ISS Program, and were experienced in dealing with the very successful ISS partnership. This provided an invaluable experience base from which to build future partnerships. It also led to some initial limitations in what NASA was able to envision as a future with international partners. The following discussion, while not exhaustive, illustrates some of these hazards.

Lessons Learned

Stability: Perhaps the greatest benefit of the ISS international partnership is the stability it has provided over more than 20 years for the governments and agencies involved in it. Having interdependency among nations obligated long-term funding support among partners and led to a stable program that was sustained through unprecedented political change. Of course, this benefit was not lost on those planning the future program. Stability was a primary reason, along with the benefit of sharing resources, that the Constellation Program sought partnerships.

Maturity: NASA had engaged the ISS partnership at a time, in the mid 1980s, when most other space agencies were in a developmental mode of operation. One attractive reason to join NASA in the ISS partnership was to use the partnership as a mechanism to develop a skill base and learn from NASA. After Roscosmos joined the ISS partnership in the mid 1990s, the benefit was doubled for other agencies—to learn from the two organizations capable of launching humans into space. CSA, ESA (along with its member-state agencies), and JAXA all developed substantial space-faring capabilities over the length of the ISS partnership.

By 2009, and with a fully active ISECG, it was clear those agencies participating in ISS viewed themselves as mature space-faring agencies, no longer in need of the strong leadership role NASA provides on ISS. Indeed, many of these agencies were contemplating the costs and benefits of continued reliance on NASA and Roscosmos vs. developing their own human launch capabilities. And yet for some time, many within NASA assumed the Agency would take the same role it does currently on ISS. The ISECG members expressed the desire for NASA to continue to lead, but in a different way.

This new style of leadership required an internal challenge to NASA: to define a leadership role that recognized current global capabilities and strengths rather than leaning on past paradigms. Being open to this new way of leading resulted in collaborative definitions of goals, objectives, and a robust and flexible architecture described in the previous lessons learned (4.9.3). While the small community of NASA employees engaged with ISECG quickly adapted this style, it represented a cultural change within the Agency. It was not fully articulated and adapted within the broader community in the short time before the Constellation Program was cancelled.

Limiting Opportunities: The programmatic decision, described in the opening to Section 4.9, limited partnership discussions to noncritical path items. This policy resulted in partnership discussions on only the later lunar exploration phase of the Program. It also created offense with long-term and loyal International Partners, that NASA would not discuss future partnerships in the initial planning of its new exploration program.

In retrospect, we can pose a number of questions that challenge this policy. We do not know the answers, and perhaps never will, but the questions concerning this policy are relevant to planning any subsequent human space flight program.

- Did it come about under the ISS paradigm? Did it too strongly reflect past knowledge of global space-faring capability rather than current capabilities?
- Did it weigh too strongly the problems that might arise from “critical path” partnerships at the expense of benefits? Could more have been done to avoid offending long-term international partners?
- Could stability have been added to the Program by allowing “critical path” partnerships on near-term development elements?

Granted, these are retrospective questions and could be viewed as unfairly challenging what was widely believed to be a wise policy at the time. We offer these as food for thought to planners of the next program.

Nevertheless, the Program did not achieve the benefit of stability that an international partnership can provide. NASA may have been hindered by both the late recognition of the contemporary views other space agencies held of themselves and the policy limiting partnership opportunities to noncritical-path items.

Recommendations

Do not “manage to the last program.” Welcome participation by mature international partners in early program formulation and seek roles for less mature partners that are consistent with their capabilities and long-term interests.

5.0 KNOWLEDGE CAPTURE AND CONTRIBUTORS

The entire Constellation Program team contributed to these lessons learned, in both the content of Volume I Executive Summary and that of Volume II.

An executive review committee assisted in synthesizing the lessons learned. This committee was comprised of: Bob Ess (*Ares* I-X Mission Manager), Jeff Hanley (Program Manager 2005-2010), Deborah Neubek (Chief of Staff—Technical), Charlie Stegemoeller (Deputy Program Manager and former Program, Planning and Control Director), Dale Thomas (Program Manager and former Deputy Program Manager), and Teresa Vanhooser (*Ares* Project Manager).

Dale Thomas, Deb Neubek, and Jennifer Rhatigan synthesized and structured these contributions into the Lessons Learned documents (Vol. I and Vol. II).

The Program and its projects conducted knowledge-capture activities throughout its duration. These included many L6S events, a multitude of technical reports, conference papers, and final lessons learned activities. All formal program documents, reports, review materials, lessons learned reports, etc. will be archived with NARA and made available in the ESMD ICE system.[31] Those lessons learned that are deemed key risks are being fully documented via text and video interviews as knowledge-based risks (KBRs). In addition, hundreds of lessons learned are being entered into the NASA Engineering Network's Lessons Learned Database (NEN LLDB). To make finding all of these materials easier, the ICE system will include a Constellation Program Knowledge Management Webpage that will link to the various topics.

Current URLs for these resources are below:

Exploration Systems Risk and Knowledge Management Portal:
https://ice.exploration.nasa.gov/ice/site/km
NASA Engineering Network (Click on the Lessons Learned Tab): https://nen.nasa.gov/web/nen
Public NASA Engineering Network Lessons Learned: http://llis.nasa.gov/llis/search/home.jsp

In addition to the hundreds of Constellation team members who contributed to the content of this report, the following played a significant role in synthesizing that data in the development of these lessons learned:

Jose Amador, Kathy Andrews, Bill Arceneaux, David Bell, Joe Caram, Sean Carter, R. H. Coates, John Connolly, Alan Dickey, Dave Hall, Linda Ham, Fred Kuo, Kathy Laurini, Burt Laws, Jon Lenius, Charlie Mallini, Deb Neubek, Carlos Noriega, Ned Penley, Jennifer Rhatigan, Doug Sander, Beto Sanchez, Debbie Stapleton, John Turner, and Keith Williams.

[31] In researching lessons learned from previous programs, primarily the Apollo and Space Shuttle Programs, a number of key documents were scanned into electronic form for wide distribution within the Program and archived in the Constellation database. These documents are available to interested readers as well.

APPENDIX A. *ALTAIR* TOP LESSONS LEARNED

1. Consider an In-house Skunkworks®-like Team to Initialize New Projects

Supports Key Finding: 3.1

Driving Events

A study was performed in late 2006 to identify options for initiating the development of a lunar lander to meet the Human Lunar Return requirements in the National Space Exploration Policy. That study determined insufficient budget was available to execute a lunar lander development project using a standard NPR 7120.5 process with contractors performing pre-phase A and Phase A/B studies. The Lunar Lander Project Office (LLPO) was formed to implement a more streamlined and efficient path through the project formulation phase. Key tenets of the approach included the following:

- NASA Administrator buy-in to the approach and broad latitude to deviate from NASA policies, as needed
- A small, handpicked team made up of spacecraft and subsystem design experts from across the Agency
- A set of guiding principles that included a small set of hard requirements and a clear goal of developing a spacecraft specification based on an in-depth understanding of every additional requirement levied
- Project start-up by collocating the multicenter team in a single facility for the first 2 months of the project, which maintained that cohesiveness with regular, short-term collocated meetings

Lessons Learned

A small, focused multidisciplinary in-house NASA team is a very effective way to initiate new projects. The small team was able to provide *Altair* project insight to impact integrated lunar-phase Constellation activities at very low relative cost.

Recommendations

New projects should begin with a small, focused team that uses the LLPO/*Altair* experience as a basis for initial project formulation.

2. Use Models-based Systems Engineering

Supports Key Finding: None; supports recommendation 4.3.3

Driving Events

The Constellation Program initiated the requirements development process by determining the capabilities needed from each of the systems in the architecture to accomplish the mission, and levied requirements through various documents, including the CARD. As a project within a large

program, it is the responsibility of the project to implement a more detailed assessment of the mission to validate requirements levied on it from the program and determine whether these requirements are necessary and achievable, as well as to scrutinize the mission for latent requirements. The *Altair* project used MBSE as the approach to requirements development. MBSE focuses on building data models that clearly depict the operational flow of the mission. These hierarchical models manage the complexity of the mission and functional allocations. They make excellent integration products for a group review between different organizations for consistency in assumptions. The operational models can then be analyzed to determine the functionality the vehicle must possess to enable these operations. These models are kept in the requirements database for the program, and cross-references between the vehicle functions and mission phases in which the functions are used serve as validation of the function. Further, linkages between functions and requirements that enforce them on the design provide complete traceability from requirements to the concept of operations. Finally, by assigning durations to the activities within the operational models, activities can be simulated to provide a complete timeline of the mission from the same models that are being used to establish vehicle functionality. By developing these common products, a single model set becomes the authoritative source for the requirements, functionality, and operations, thereby improving the quality of the requirements, integrating the various organizations within the projects, and minimizing disconnects.

Lessons Learned

Model-based Systems Engineering streamlines requirements development and validation by cultivating integrated products among the Requirements, Design, and Operations communities.

Recommendations

Model-based Systems Engineering should be used to provide an integrated set of products on which architecture, element, system, and subsystem requirements can be sequentially decomposed.

3. Start Risk-informed Design during Conceptual Design

Supports Key Finding: 3.5

Driving Events

The initial lunar design analysis cycle (LDAC-1) for the *Altair* lunar lander provided a spacecraft with “minimum functionality.” Minimum function was defined to mean that the lander was designed to meet the primary key driving requirements, not the complete set of Level II Lander requirements. Primarily, it meant that the vehicle and its subsystems were designed with zero fault-tolerance and with no consideration for contingency operations. It was understood that this design did not represent a flyable vehicle; rather, this provided a theoretical vehicle that could perform a lander mission if everything worked with 100% reliability, obviously an unrealistic design point. However, during LDAC-2, the risks that could result in LOC failures were identified and prioritized, and specific vehicle, subsystem, and component trade studies were performed to

identify the amount of reliability improvement needed as a function of mass of the alternatives. The resulting vehicle concept was referred to as the Increased Safety vehicle. This process was repeated during LDAC-3 for the LOM risks to provide the Enhanced Mission Success vehicle. A risk assessment tool was developed using component failure data to quantify risk associated with subsystem and component alternatives. This included reliability data from the space shuttle and ISS databases, the lander operational timeline to define mission phases and component operating times, and a vehicle preliminary hazard assessment to determine which components could lead to a LOC. The term "risk-informed design" is used because the design decisions were literally "informed" by the quantified risk information instead of using a rule-based decision process. This gave the project team much greater insight into risk drivers at an early stage of project development.

Lessons Learned

A risk-informed design process provides the project with early, in-depth insight into risk drivers so that safety, reliability, and capability functions can be systematically added to a minimum function design baseline. This allows a more complete understanding of integrated effects on other primary constraints, such as spacecraft mass.

Recommendations

A risk-informed design process should be used early in the project formulation phase to achieve efficient design and understand major design drivers.

4. Involve Industry during Phase A

Supports Key Finding: None

Driving Events

One of the early tenets of the LLPO was to solicit input from industry throughout the project formulation phase. In June 2008, a little over 1 year after the LLPO was created, the office awarded broad area announcement (BAA) contracts to five companies: three major traditional aerospace companies and two small, independent companies.

The BAA had two primary objectives. The first asked the companies to review the government LDAC-1 minimum-function lunar lander conceptual design and plans for implementing risk-informed design, and to provide suggested alternative design concepts. The second asked companies to provide recommendations for the roles and responsibilities of government and industry for lunar lander development. A process was then set up whereby the companies that participated in the BAA and other entities meeting International Traffic in Arms [ITAR] export control regulations could continually obtain updates on the government design.

This two-way interaction was extremely valuable to both government and industry. It provided the government some important alternative perspectives and industry with information that helped focus internal investment funding. The input from industry also helped shape the roles of

the government and industry that were incorporated into the *Altair* acquisition strategy. As the *Altair* project proceeded into Phase A concept exploration and refinement, and while preparing for the SRR, this two-way interaction developed a process whereby multiple contractors would be integrated into the *Altair* team to support the work.

This process was the basis of a BAA contract that was in preparation for release at the time Constellation was cancelled. This process would have maintained government leadership of the design until a prime contractor was selected for flight vehicle development, enabling the government team to develop a better Request for Proposals (RFP) solicitation and allow all contractors greater insight into the information that the government was using to shape the requirements.[32]

Lessons Learned

Industry should be brought into the formulation process of a project early to ensure the NASA project team is aware of alternative ideas and perspectives, and help the contractor community better understand the basis of the requirements.

Recommendations

While the acquisition model that *Altair* was developing may not be appropriate for widespread application, the primary recommendation is that the project team should explore unique and creative ways for incorporating the industry community into the project as early as possible.

5. Making Multicenter Teams Work

Supports Key Findings: 3.6, 3.9, 3.10

Driving Events

When *Altair* began as the LLPO, it collocated approximately 35 people in a single, small building at JSC for a period of 8 weeks. This period allowed the team to get through most of the "forming, storming, norming," and begin performing as a high-performance team before returning to home centers and organizations. The project maintained team cohesiveness by planning a travel budget that allowed a significant part of the team to get back together for a minimum of 3 to 4 days once a quarter to work together. These periodic collocations were rotated through the centers; and, to the extent possible, the team stayed in the same hotels, dined together, and spent time socializing. This approach ensured that the personal relationships that were initially formed were maintained, and that as new members joined the team, they were more quickly assimilated. The interpersonal bonds were tested as inter-center institutional competition for roles and responsibilities emerged; however, the strength of the team prevented impacts to progress.

[32] The Altair approach to NASA and industry collaboration was specifically cited as a good model by two contractors responding to the Heavy Lift and Propulsion Technology Request for Information (HLPT RFI).

Lessons Learned

Diversity provided by a multicenter team is worth extra management effort. While teleconferences and Internet-assisted virtual meetings are required, the key to operating with a multicenter team is to periodically bring the team together to work in a single location. Regular collocations/face-to-face meetings with a significant portion of the team, including all key system, subsystem, and discipline leads, are essential to maintain team cohesiveness when using multicenter teams.

Recommendations

Specific considerations that enabled the LLPO/*Altair* multicenter team to be highly effective included: 1) leadership of key portions of the spacecraft design and analysis was assigned to different centers; 2) initial and subsequent collocations all included social events designed to allow people to get to know each other; 3) collocations were scheduled, to the maximum extent possible, to avoid conflicts with family vacations—i.e., consideration was given to when K-12 school breaks; and 4) collocation meetings were well planned to make maximum use of the time together.

6. Design during Pre-phase A and Early Phase A

Supports Key Finding: None

Driving Events

One of the key initial tasks for the LLPO was to develop a preliminary in-house design within 6 to 9 months, with emphasis on performing significant design; i.e., focus on the "D" in DAC [design analysis cycle]. The design work allowed the team to validate and identify weaknesses in the parametric modeling. A few notable examples, as follows can illustrate this point:

- The mass of the landing legs could not be easily scaled from the Apollo lunar module due to the dramatic size difference between it and the hydrogen-fueled *Altair*. By performing detailed analysis to determine the required size for stability at the bounding landing site terrains and then developing and analyzing a design, we were able to improve mass confidence.
- As the team used the design and began identifying assembly, integration, and test during both development and operations, it identified the Constellation Program decision, which was made early in LDAC-2 to increase the descent module diameter to take advantage of the 10-m *Ares* V shroud, had significant implications for transportation and thermal-vacuum propulsion system testing. That assessment found the *Altair* descent module could not be transported in the NASA Guppy aircraft (the largest available) but would require barge transportation. The barge would require an icebreaker to clear a path through Lake Erie during winter to perform an acceptance test of each descent module propulsion system in the Plumbrook Station B2 test facility.

These examples represent some of the more dramatic items that were revealed by allowing the NASA in-house team to perform significant design work during the project-formulation phase.

Lessons Learned

Design work during pre-phase A and early Phase A can identify important issues that cannot be determined until a design concept is of sufficient maturity to evaluate a more complete set of development, test, and evaluation considerations.

Recommendations

A design concept should be developed, as early as possible in the project formulation phase, to allow a more complete understand of programmatic implications. The concept needs to be more than an artist rendering or a parametric design. It needs to have engineering design analysis substantiating it so that a design team is made of SMEs with the experience to foresee potential issues during later project phases.

APPENDIX B. GROUND OPERATIONS TOP LESSONS LEARNED

This Appendix contains the top lessons learned from the Constellation Ground Operations Project. These are linked to main volume key findings as applicable.

1. Clearly Define Roles and Responsibilities within the Program/Project

Supports Key Findings: 3.7, 3.8, 3.9

Driving Events

As discussed in the main volume, the late start of the Program relative to that of the projects led to unclear RR&A. Many WGs were solving the same issues in parallel with other WGs across the Program (e.g., logistics). Furthermore, requirements and expectations were unclear due to lack of formal documentation. Some examples are provided for illustration:

- Both the *Ares* project and Ground Operations Project believed they were responsible for the processing timeline for operations at KSC because both had CARD requirements that were to be verified via the KSC processing timeline. Therefore, both organizations developed and maintained what each considered the "Constellation Program Ground Operations Timeline." These timelines were not consistent; each required a significant effort to maintain. Resolution of discrepancies therefore required lengthy discussion.
- Management of integrated and stand-alone flight hardware testing at KSC (which involved/ impacted multiple projects) was not actively controlled at the Program. There was no consistent definition of which flight hardware testing was going to be performed at KSC.
- While there was sufficient participation by the projects to define what testing was required within the launch vehicle and the spacecraft during development of integrated test objectives by the Flight Element Integrated Test WG, there was very little (if any) analysis of the integrated system to determine testing between the elements and the effects of testing on one element with the others (e.g., integrated vehicle test, end-to-end testing).
- Maturing requirements caused significant rework and delays. For example, vehicle changes drove costly changes to already designed and fabricated ground systems. Different organizations were working to different vehicle configurations and technical baselines at the same time.

Lessons Learned

Unclear accountability led to duplication of effort among projects. Integration of multiple projects must remain the responsibility of the overarching program and not be delegated to one (or more) supporting projects. The specific responsibilities of each of the projects must be clearly defined and socialized among and between all stakeholders to minimize confusion and inefficiency across the program.

Engineering analysis of the integrated launch vehicle and spacecraft must be performed and used to define integrated test objective details for testing at KSC. Program baseline synchronization activities should be done periodically and often to assure that all are using the same baseline.

Recommendations

The program should clearly define roles and responsibilities of the individual projects as soon as possible and reinforce those roles regularly, revisiting as necessary. WGs involving multiple projects should be chartered at the program level with clearly defined roles and responsibilities to avoid duplication of effort and maintain clear accountability.

Maintain at the program level complete responsibility for performing analytical integration for the entire launch vehicle and spacecraft, and determining test objectives/requirements for the overall integrated vehicle.

Synchronize vehicle and ground system design to the same baseline. Program synchronization with all systems (mission systems, EVA, etc.) should be performed quarterly, at a minimum, to ensure goals and objectives are met. No metal should be cut until simulation models and schedules are coordinated.

2. Streamline Processes to Improve Communication Across Program/Projects

Supports Key Findings: 3.9, 3.10

Driving Events

Two different processes were levied for records management for the Ground Operations Project: the KSC Business Records Template, governed by NPD 1441.1D; and the program "catalog" (i.e., access database) with many additional attributes for program records.[33] This resulted in an unstructured change management process that drove costs and schedules. Because of change management process immaturity, unfunded requirements were levied on the Ground Operations Project and costs were not adequately quantified. The Program created change processes (Change Requests, Document Change Notices [DCNs]) to expedite and document changes. The DCN, for instance, was intended to push through Program-level changes quickly. Instead, the change processes merged into one cumbersome process that required weeks or months before changes could be instituted.

During change evaluations, multiple document revisions appeared during the evaluation period. This caused confusion and wasted technical resources. While the Program had an approved formal Technical Coordination Meeting process, its application varied between Change Package Managers (e.g., virtual, email only, telephone only). As it was difficult to give direction to Change Package Engineers, complaints were often elicited from them.

[33] Similar situations existed at each NASA center supporting the Constellation Program.

An organization-wide common process and tool for agreements regarding exchange of hardware, software, data, etc. was not implemented until late in the Program lifetime. The Constellation Program bilateral exchange agreement (BEA) tool was useful and user friendly with very responsive developers; however, there was much controversy over the use of the term “bilateral exchange agreement” (originated for agreements between countries). Further issues involved the process itself, where the confusion was over whether a BEA needs to be approved prior to inclusion in the schedule and enforcement of the agreement (e.g., at what point and by whose authority is a providing organization directed that due dates cannot change).

Lessons Learned

The use of new and/or different processes can add churn and reduce effective communications. It is best to adopt known and proven processes for change management and standardization of agreements within a program. Better processes and communication will eliminate confusion and frustration on agreements.

Recommendations

Develop and document a robust change management process from inception that precludes levy of unfunded requirements.

The Agency should develop NASA-wide processes for records management. Implement this at the start of any new program, with continuous monitoring for any new additional requirements or improvements.

Create one change control process that can be used to make changes to project/program-level documents (minimize the number of change control processes). This will eliminate unnecessary overlap and confusion in the change control process. Both vehicle and ground should proceed from an agreed baseline such that all stakeholders are expeditiously notified when changes occur.

Establish clear and concise processes up front pertaining to agreements.

3. Use a Consistent Financial Approach to Ensure Emphasis on Life-cycle Costs

Supports Key Finding: None

Driving Events

The acquisition strategy did not address program life-cycle supportability due to the late start of the Program relative to that of the projects (Section 2.2.6). Each prime contractor defined life-cycle supportability strategies that were inconsistent across projects. This resulted in different expectations for maintenance concepts, and support infrastructure required at the launch site.

Further, the involvement of all NASA centers (Section 2.2.3) and multiple contractors introduced confusion, since each center/contractor used somewhat different definitions for general accounting terms (e.g., WYE [work year equivalent]) to characterize work content.

Program requirements (formats, actions) tended to focus on cost data, while the Ground Operations Project focused more on obligations (which are more representative of work/content in process). This difference in focus impacted the timely receipt of funding. Program shifts/adjustments mandated on project cost could not be reconciled/traced to NOA [new obligation authority]/ obligations. Projects performed a thorough bottom-up estimate, significantly focusing on obligations; but the same emphasis on cost is not undertaken, which leads to suboptimal communication with stakeholders.

Liens were captured as cost threats in the same manner as potential risk impacts.

Lessons Learned

Supportability strategies and concepts for flight and ground systems must be defined early in the program, as part of the acquisition strategy, and incorporated into the RFPs to influence designs and have a positive effect on program life-cycle costs.

The Agency, program, and projects depend on the information provided to make prudent decisions. Consistent and well-defined terminology between all levels and projects, as well as an understanding of these definitions, would increase accuracy and efficiency in providing the data and enhance analysis. Clear definitions and consistency should be used in reporting WYE numbers. A properly developed and used work breakdown structure (WBS) will enhance efficiency, minimize errors, and lead to better analysis of work content as related to budget and schedule.

An increased emphasis on NOA/obligation requirements by the program would lead to a better understanding of the work/content being undertaken in relation to monetary requirements and schedule. An increased emphasis on cost requirements by the project would lead to a better ability to communicate with external stakeholders by providing a more thorough and complete understanding of technical work and milestones accomplished in relation to budget and schedule.

The Program mixed potential risk impacts with liens/shortfalls. This turned the risk system into a budget tool, which did not allow analysis of potential cost threats vs. unfunded mandates.

Recommendations

Develop an acquisition strategy early in the program that includes life-cycle supportability strategies and concepts prior to release of RFPs. Include strategies and concepts in the RFPs and ensure that if contract negotiations make any changes to one contract they are changed the same way in all the contracts, as applicable. Ensure that guidance conferences emphasize the need to keep supportability, logistics, and maintenance concepts the same.

Clearly define all important financial terms across the Agency and assure consistent use. Develop and use WBSs at a level at which financial actuals are received, characterize the work content (regardless of center), and reflect the planning and execution structures (e.g., by phase, etc.).

Program PPBE and phasing plan requirements should include NOA/obligation requests, as appropriate. Project stakeholders supporting PPBE and phasing plans should forecast cost requirements more thoroughly.

Capture true risk-related cost threats as such, separating liens (i.e., change request impacts) or remove liens from the risk system. Financial impacts, as part of a change process, should be addressed on approval rather than driven into the risk system.

4. Improve Interface Product Integration

Supports Key Finding: Supports the data management recommendations, Section 4.3

Driving Events

The following are examples of difficulties encountered in negotiating Interface Control Documents/ Interface Requirements Documents (ICDs/IRDs):

- Flexibility was not permitted in product templates for inclusion of data as tables or figures in lieu of verbiage, thus introducing confusion.
- The same requirements were allocated to multiple ground and/or vehicle elements, creating confusion.
- Required drawing exchanges were not defined early in development work for the interfaces.
- It was difficult to navigate and search interface data in the chosen document format.
- It was difficult to obtain quick updates of approved interface data or to easily communicate interface data to designers or new employees.
- Interface change impacts were not well balanced between projects. The *Ares* project was often able to implement requirements changes without showing detailed rationale illustrating that several concepts had been explored.

Lessons Learned

Flexibility in product templates (ICD/IRD), tailored for each interface, can improve the outcome of the interface.

Real dimensional measurements are needed in the ICDs to control the design on both sides of the interface properly.

A single neutral party should manage the project-to-project interfaces. Each project should be responsible for bringing forward full and consistent change packages to the Interface Manager for discussion prior to implementation.

Recommendations

Allow the interface team to define the most effective template (this may be unique for each interface). Organize interfaces by project, and allow projects to sub-allocate requirements.

A Website site navigable by a graphical representation of the vehicle and ground should be used to specify all data for each interface, with requirements generated from a requirements database.

Define standard drawing/model exchanges early on in the development work for the interface. Use a controlled-access Website to specify all data for each interface (similar to system used by shuttle). Provide easy navigation to interface data: requirements, drawings, etc.

Provide real dimensional measurements in the ICDs.

Each project should have an office dedicated to interface management. The project-to-project interface requirements baseline should be controlled by a neutral board/unbiased interface management group, and not at the project-to-project level.

5. Address Logistics and Supportability in a Consistent Manner

Supports Key Finding: None

Driving Events

As discussed in the main volume, projects initiated contracts prior to formation of the Program. These organizations were not mature enough to adequately specify logistics and supportability requirements. Logistics tools for the *Orion* and *Ares* projects were developed independently from the Ground Operations Project with the end result being different final products. The Ground Operations Project participated in the WGs for both *Orion* and *Ares*. It became evident, in working with the contractors, that the supportability requirements and direction levied on the contractors was not the same. This caused both groups to rework some products to allow them to interface with each other.

A comparison was done between the Program supportability plan and the project supportability plan to map requirements between documents. Gaps and disconnects were uncovered between the plans.

Lessons Learned

Critical logistics data items such as source maintainability and recoverability code charts need to be common across projects to facilitate parts transfer.

Ensuring continuity between parent-child documents is important to prevent confusion about requirements.

Mismatched logistics requirements included in projects RFPs caused rework later while trying to align acquisition/performance guidance between projects.

Additional supportability requirements that affect life-cycle costs need to be defined in program-level requirements documentation. Life-cycle costs are affected by supportability factors such as

commonality and interchangeability. If these factors are not stated as requirements, the design organization is not compelled to incorporate revisions or suggestions (guidance) into the design.

Recommendations

Identify essential logistics infrastructure data items that need to be common across projects, and specify data items in a program requirements document.

Ensure that the program-level supportability plan is used as a parent document when creating project-level plans, and routinely perform a gap analysis between the parent-child documents.

Develop a standard set of supportability requirements to be applied to all projects prior to contract initiation.

Performance requirements can be traded against other logistics and supportability requirements for the system so the program will have a more accurate assessment of life-cycle costs vs. system performance.

APPENDIX C. ACRONYMS

APA	allowance for program adjustment
APM	associate program manager
ASAP	Aerospace Advisory Panel
ASI	Agenzia Spaziale Italiana
BAA	broad area announcement
BEA	bilateral exchange agreement
CAD	computer-aided design
CAIB	*Columbia* Accident Investigation Board
CARD	Constellation Architecture Requirements Document
CDR	Critical Design Review
CM	configuration management
CMG	control moment gyroscope
CNES	Centre National d'Études Spatiales
CO	Contracting Officer
CoF	construction of facilities
CoFR	certificate of flight readiness
CoP	community of practice
CR	continuing resolution
CSA	Canadian Space Agency
CxSIP	Constellation System Integration Panel
D&C	design and construction
DAC	design analysis cycle
DCN	Document Change Notice
DES	discrete event simulation
DFMR	design for minimum risk
DLR	Deutches Zentrum für Luft- und Raumfahrt

DM	data management
DoD	Department of Defense
DRM	design reference mission
DRD	data requirements documents
ESA	European Space Agency
ESAS	Exploration Systems Architecture Study
ESMD	Exploration Systems Mission Directorate
EVA	extravehicular activity
EVM	earned value management
FEP	front-end planning
FY	fiscal year
GES	Global Exploration Strategy
HLPT RFI	Heavy Lift and Propulsion Technology Request for Information
HLR	human lunar return
HQ	Headquarters [ie, NASA Headquarters]
HRCP	human-rating certification packet
IC	Initial Capability
ICD	Interface Control Document
IDAC	Integrated Design Analysis Cycle
IMS	Integrated Master Schedule
IOC	Initial Operational Capability
IRD	Interface Requirements Document
ISECG	International Space Exploration Coordination Group
ISO	International Organization for Standardization
ISS	International Space Station
IT	information technology
ITAR	International Traffic in Arms
JAXA	Japanese Aerospace Exploration Agency

JCL	Joint Confidence Level
JPR	Johnson (Space Center) Program Requirement
JSC	Johnson Space Center
KBR	knowledge-based risk
KSC	Kennedy Space Center
L6S	Lean Six Sigma
LAS	Launch Abort System
LC	Lunar Capability
LDAC	lunar design analysis cycle
LEO	low-Earth orbit
LLPO	Lunar Lander Project Office
LMI	Logistics Management Information
LOC	loss of crew
LOM	loss of mission
MAF	Michoud Assembly Facility
MBSE	Model-based Systems Engineering
MIVP	Master Integration and Verification Plan
MOU	Memorandum of Understanding
MPCV	multipurpose crewed vehicle
MPR	Monthly Program Review
MSFC	Marshall Space Flight Center
NOA	new obligation authority
NPD	NASA Program Directive
NPR	NASA Program Requirement
NSA	National Security Agency
O&C	operations and checkout
OCE	Office of Chief Engineer
OMB	Office of Management and Budget

OSMA	Office of Safety and Mission Assurance
PBS	President's Budget Submittal
PDR	Preliminary Design Review
PET	Program Excellence Team
PI	Program Integration
PMR	Program Manager's Recommendation
PP&C	Program Planning and Control
PPBE	planning, programming, budgeting, and execution
PRA	probabilistic risk assessment
PV	photovoltaic
R&D	research and development
RFP	Request for Proposals
RIT	Risk Informed Test
RM	risk management
RR&A	roles, responsibility, and authority
S&MA	Safety and Mission Assurance
SAGES	Shuttle and Apollo Generation Expert Services
SD	storage device
SDR	Systems Definition Review
SE	systems engineering
SE&I	Systems Engineering and Integration
SI	international system of units
SIG	System Integration Group
SLS	Space Launch System
SM	service module
SME	subject matter expert
SOW	Statement of Work
SR&QA	Safety, Reliability, and Quality Assurance

SRB	Standing Review Board
SRR	Systems Requirements Review
SSP	Space Shuttle Program
T&E	Test and Evaluation
TIM	Technical Interchange Meeting
UKSA	United Kingdom Space Agency
VCS	Voluntary Consensus Standards
VM1	Virtual Mission-1
WBS	work breakdown structure
WG	working group
WYE	work year equivalent
XML	extensible markup language

DEEP SPACE CLIMATE OBSERVATORY





DSCOVR Contamination Lessons Learned

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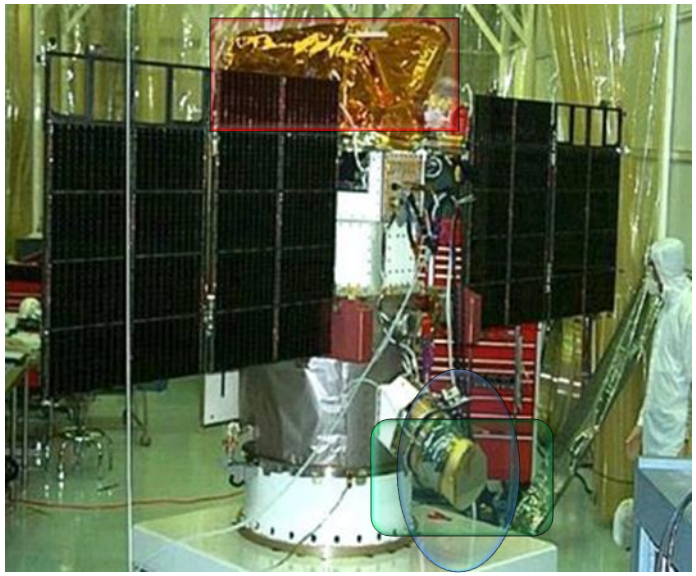
Background: Triana to DSCOVR

- Triana was developed in the late 1990's as a quick-build small explorer carrying five instruments on a NASA-based mission.
- Primary mission was Earth science via a visible-band camera and infrared radiometer. Space weather (magnetometer, electron spectrometer, Faraday cup) was secondary science.
- Observatory was slated for L1 orbit, oriented to permanent Earth and sun views.
- Manifested for a shuttle. Later removed from manifest to accommodate ISS build.
- Placed into storage after completing thermal vacuum test in Fall 2001
- Briefly removed from storage on two occasions. Permanently removed from storage in 2012 to become a NOAA-based mission.
- NOAA and NASA rededicate the spacecraft as DSCOVR. Space weather to be DSCOVRs primary mission.
- Spacecraft dismantled to box level for component testing.
- Repeated environmental tests.
- Launched on a Space X Falcon 9 in February 2015.

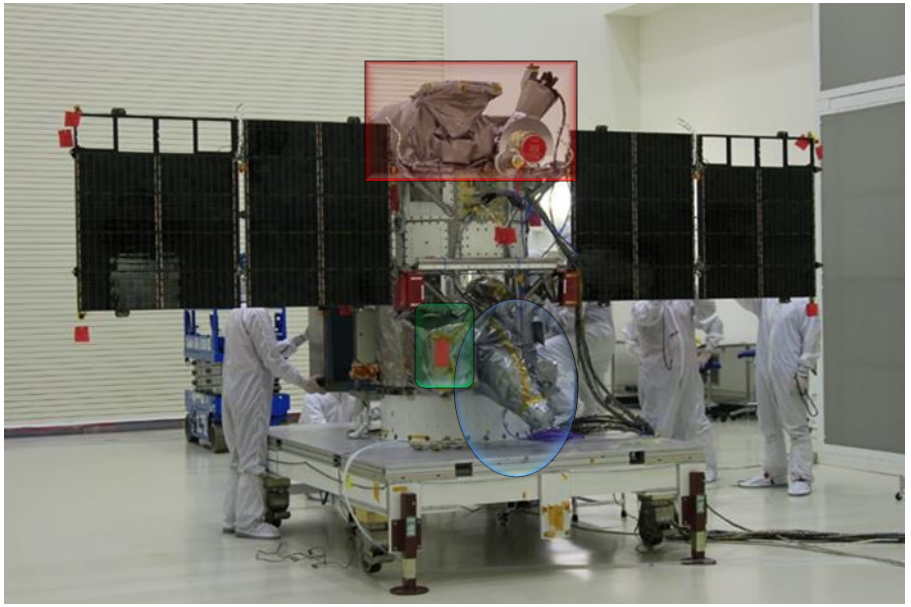
Then and Now: Changes Made

Triana in 2001



Magnetometer placed on angled cone at end of boom

Electron Spectrometer moved from boom to spacecraft bus



Camera and radiometer MLI outer layers changed from ITO-coated Kapton to Germanium-coated Black Kapton (GBK)

DSCOVR in 2015

Storage of Hardware and Information



- Triana was double bagged and placed in a metal container. Container was placed in a cleanroom and purged with nitrogen.
- Some GSE was dispersed to functional groups
- Most GSE was boxed and placed in warehouse storage.
- Documents and drawings that were in configuration management control were maintained well. Background information under personal or vendor control was sometimes lost.



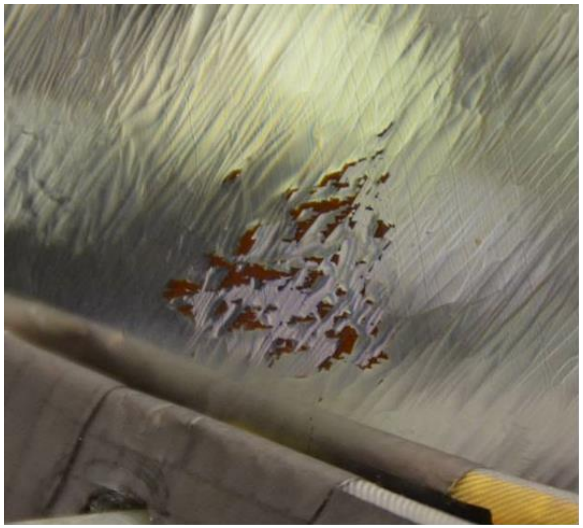
- CC group retained all bakeout data and reports from Triana
- In future, request data stored by vendors as deliverables

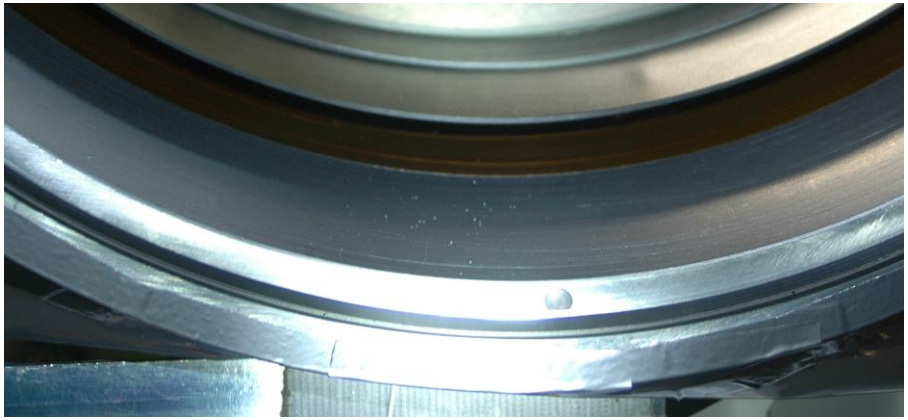
Unpacking

- Needed to evaluate materials list for limited-life items
  - Lubricants were biggest concern
  - All were considered still usable
- Needed to review parts list for items with known problems as reported through industry alerts
  - Some electronics parts had been flagged a few years earlier
  - Flight battery determined to be unusable. Changed to a new Lithium Ion battery, which required some mechanical modifications to the bus
  - Thermal control surfaces looked fairly good upon first look
    - Some dark spots seen on Silver Teflon and GBK surfaces. Measured within thermal specification
    - White paint still within thermal specifications and adhering well
    - Conductivity of surfaces needed to be evaluated
- Boom removed, deployed and inspected
  - Saw some slight splintering on fiberglass struts
  - Mild paint wear was touched up with Z306
  - No major work needed. Were able to re-install and fly
- All mechanisms thoroughly tested

Thermal Control Surfaces

- Most thermal control surfaces degraded quickly with handling
  - NS43C paint powdered throughout I&T; repaired with Z93C55
  - Germanium flaked from some tape surfaces
  - High temperature MLI frayed at edges; backed with SS mesh to strengthen
  - Phosphoric-acid etched nickel inside radiometer began flaking. Stripped and recoated with Z306
  - ITO conductivity questioned, noticeable cracks seen on some surfaces. ITO Kapton outer layer replaced with GBK layer
  - All produced conductive particles, which were a problem for the high-voltage Faraday Cup
- Root cause not clear: time alone, too dry for too long or a combination





Budgets and Modeling

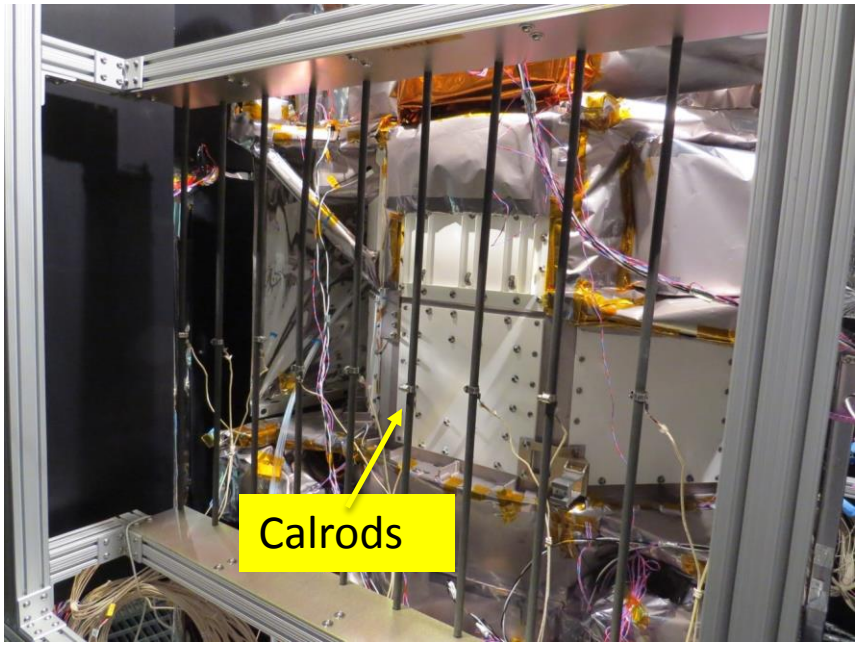
- Needed to take a fresh look at the contamination budget and verification methods.
  - A new approach may have developed in intervening years.
  - For DSCOVR, budget was only slightly modified to reflect better understanding of instrument sensitivities.
  - Needed to upgrade magnetic cleanliness procedures
- Updated all contamination models
  - Knowledge of thruster plume shape and behavior advanced while Triana/DSCOVR sat in storage
    - Thruster plume shape in model changed from cone to tear drop
    - Better and more complete information on exit gas properties
  - Thruster plume model was no longer considered valid and needed to be redone
  - On-orbit molecular transport model still valid. Only needed update to account for move of spectrometer and magnetometer
  - Need to know assumptions and parameters to evaluate the models. Data retention from Triana days was key.

Purge

- GSE-disconnect purges on camera, radiometer, faraday cup, electron spectrometer
- Purge would have been easier to use as a T-0 disconnect
  - Drag-on system designed for shuttle
  - Purge connection points had aged poorly and were difficult to replace
  - Redesign would have been difficult and expensive
  - Electron spectrometer had no instrument purge port and would still need drag-on line
- Purge panels required updates in order to be used for DSCOVR
  - Pressure relief valves now needed
  - Filter models obsolete, new versions were smaller
  - Switched to newer set of purge panels rather than update old panels

Bakeouts and Thermal Vacuum Test

- Diffusion caused outgassing rates to rise to pre-bakeout levels
  - Solar array took 3 days to return to pre-storage outgassing rates
  - Known phenomenon that was seen consistently throughout program
  - Needed to build that time into test estimates
- During storage preparations, some internal thermocouple wires were snipped too short, removing labels and complicating test preparations and data collection.



- Used three-step process to prepare new calrods for first use with DSCOVR
  - Placed in highbay and run hot to burn off worst volatile species
  - Placed in chamber and run hot with hot walls, no QCM
  - Run in chamber with QCM to certify outgassing rate

- Should certify calrods at 100% power to allow for contingency during test.

Environments and Bagging

- Know your environmental limitations and emergency access procedures
  - Lost power in B7/10/15 complex for 2 days after 2012 derecho storm
    - Temperature went to 80°F, humidity to 70%
    - Purge remained operational
    - No evidence of condensation seen
    - Limited emergency access stickers to project personnel at the time
- By end of program bagging had become a long process
  - Needed to cutout, then individually bag star tracker, solar array harnesses, mag boom to distribute weight evenly
  - Needed to triple bag for move to/from mag test site and for moves around ASO since observatory was being moved via forklift
  - Needed a cart with nitrogen bottle and purge panel to keep purge active during forklift moves
  - Extra bagging required close eye on internal bag temperature and dew points
  - Placed temperature and RH monitors in bags to track changes



First NASA Mission on Falcon 9



- DSCOVR launched on a Space X Falcon 9
- Instituted magnetic, particulate and molecular cleanliness requirements.
- Fairing was cleaned to an acceptable level
- "Diving boards" used to access observatory for closeouts
- Purge gas certified to Grade B. Purge operated well throughout Falcon 9 operations. Disconnected ~16hours prior to launch during final closeouts.
- Magnetic controls successful: flight magnetometer sees very little background noise.
- Contamination controls successful: camera and radiometer are operating well.



EOSDIS
NASA'S EARTH OBSERVING SYSTEM
DATA AND INFORMATION SYSTEM

Earthdata Search UX Lessons Learned

ESIP 2019

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5 Lessons Learned

- You can’t please everyone
- Golden paths simplify complexities
- UX is often dictated by underlying systems
- Screen real estate is expensive
- Nothing beats live user testing

You can’t please everyone

- Users have opinions, and they often don’t align
- Users are all coming from different places, literally and figuratively
- Recommendation:
  - Design to the 80% rule
  - Industry standards
  - Add multiple paths/options, but don’t over-complicate things

Golden paths simplify complexities

- Workflows make complicated processes easier
- EDSC assumes a user follows a general search > discovery > configure > download process
- EDSC doesn't *force* a specific workflow
- Recommendation:
  - Encourage users to go down a golden path by making that path easy to follow
  - Allow users to escape at each step if necessary

UX dictated by underlying systems

- Interacting with legacy systems is usually required, but never fun
- User expectations have *dramatically* changed with the proliferation of cutting edge tech
- Recommendation:
  - Move as much as you can to modern systems
  - Decouple live tasks/actions from slow endpoints

Screen real estate is expensive

- Exposing all data and metadata does not work
- Users can become paralyzed with too many options to choose from
- Constrained panels do not work
- Recommendation:
  - Understand what your users need at each point of your application

Nothing beats live user testing

- No design survives first contact with the user
- Spectrum of understanding always amazes
- Product teams can be susceptible to confirmation bias
- Recommendation:
  - Find opportunities to put your application in front of a user *who has never used it before* and watch them try to complete a task.

Lessons Applied

- EDSC Governance Group discusses, product team makes final decision.
- End-to-End Services brings discovery and customization closer than ever.
- Actively moving information from Legacy Services calls to tags and scheduled background tasks.
- Reverting back to (better) vertical panels

Questions?

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Maryland Hawk Corporation

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Stinger Ghaffarian Technologies

Valador

EOSDIS

EMU Lessons Learned Database

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USRP Fall 2011

Date: 09 Dec. 2011

EMU Lessons Learned Database

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As manned space exploration takes on the task of traveling beyond low Earth orbit, many problems arise that must be solved in order to make the journey possible. One major task is protecting humans from the harsh space environment. The current method of protecting astronauts during Extravehicular Activity (EVA) is through use of the specially designed Extravehicular Mobility Unit (EMU). As more rigorous EVA conditions need to be endured at new destinations, the suit will need to be tailored and improved in order to accommodate the astronaut. The Objective behind the EMU Lessons Learned Database(LLD) is to be able to create a tool which will assist in the development of next-generation EMUs, along with maintenance and improvement of the current EMU, by compiling data from Failure Investigation and Analysis Reports (FIARs) which have information on past suit failures. FIARs use a system of codes that give more information on the aspects of the failure, but if one is unfamiliar with the EMU they will be unable to decipher the information. A goal of the EMU LLD is to not only compile the information, but to present it in a user-friendly, organized, searchable database accessible to all familiarity levels with the EMU; both newcomers and veterans alike. The EMU LLD originally started as an Excel database, which allowed easy navigation and analysis of the data through pivot charts. Creating an entry requires access to the Problem Reporting And Corrective Action database (PRACA), which contains the original FIAR data for all hardware. FIAR data are then transferred to, defined, and formatted in the LLD. Work is being done to create a web-based version of the LLD in order to increase accessibility to all of Johnson Space Center (JSC), which includes converting entries from Excel to the HTML format. FIARs related to the EMU have been completed in the Excel version, and now focus has shifted to expanding FIAR data in the LLD to include EVA tools and support hardware such as the Pistol Grip Tool (PGT) and the Battery Charger Module (BCM), while adding any recently closed EMU-related FIARs.

Nomenclature

EVA	=	Extravehicular Activity
EMU	=	Extravehicular Mobility Unit
EMU LLD	=	EMU Lessons Learned Database
BCM	=	Battery Charger Module
EHIP	=	EVA Helmet Interchangeable Portable Lights
REBA	=	Rechargeable EVA Battery Assembly
SPCE	=	Service Performance Checkout Equipment
SAFER	=	Simplified Aid For EVA Rescue
PGT	=	Pistol Grip Tool
PRACA	=	Problem Reporting and Corrective Action Database
FIAR	=	Failure Investigation and Analysis Report
JSC	=	Johnson Space Center

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I. Introduction

Manned spaceflight first began with the successful orbit of Soviet Cosmonaut Yuri Gagarin on April 12th, 1961[1], ushering in a bold new age of exploration on the grand frontier of space. On February 20th, 1962, Astronaut John Glenn became the first American to successfully orbit the Earth as part of the Mercury project[2]. Through 1965, both nations proved that man could be put in orbit and brought back safely, but the question remained of how a human would fare in the space environment. The question was answered in 1965, when Alexei Leonov and Ed White II became the first Soviet and American, respectively, to perform a spacewalk, or EVA[3, 4]. Since then, EVA has become a crucial routine function during space missions, from repairing the Hubble Space Telescope[5], to assembling the International Space Station[6]. Spacesuits and tools used have changed drastically since that time, improving in order to maximize the amount of time an astronaut can spend on an EVA, and to meet the required tasks. The EMU has become the main spacesuit of choice for EVA since debuting in 1983 on STS-6[7].

In a twenty-nine year period, many changes have been made and lessons have been learned in regards to design and maintenance of the EMU and EVA support hardware. Every time a failure occurred, a FIAR was filled out in order to document the nature of the failure, and the corrective action taken. FIARs are kept in a database known as PRACA which contains all of the information from the FIAR, along with the original scanned document. While the information is available, it is unorganized and the codes used to describe the failure are undefined or obsolete, and thus, based on the amount of time someone has worked with the EMU, the data can be hard to interpret. The objective of the EMU LLD is to compile information from EMU and EVA tool FIARs in an organized user-friendly interface which accommodates all familiarity levels with the EMU, and allows analysis, on a large and small scale, of past failures to aid in any future EMU or EVA tool design.

II. EMU LLD Work History

The EMU LLD was started by Jake Baker in 2009. It was developed in Excel with the intent of compiling data from FIARs related specifically to EMU hardware. Original work included establishing a format for the database, along with entering the first EMU Hardware entries. In 2010 work was started by Samantha McCue to create a web-based version of the database in order to expand accessibility to the EMU LLD throughout JSC. Web-database work included coming up with a design for the website, keeping user-friendliness in mind, along with coding the features, and finally transferring entries from the Excel version of the LLD, to the website.

III. EMU LLD Structure

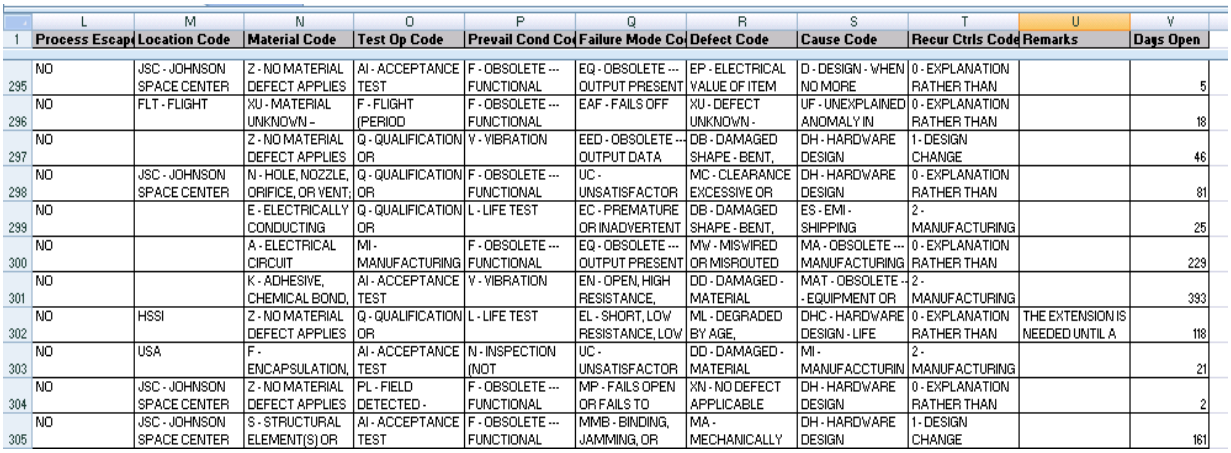
The Excel database is made up of the "Text" "All" and "Parts" pages, each with specific information. The "Parts" page contains more information about the specific components in the hardware that experienced failure; including the serial/lot number, the report number, and the date of the failure. The "All" page has more in-depth information from the FIAR, including the PRACA trend codes. The trend codes were originally used as a system to quickly give information regarding the failure. Codes were in place to describe the operation in place when the failure occurred, where it happened, what happened, and what part was affected among some examples. The "All" page includes most of the original information off of the FIAR along with dates. The "Text" page contains simplified information on the components, the failure and corrective action, using both text and a graphical representation to organize the data. Every entry in the database has data on each page of the excel sheet, including the related FIAR number, which overall gives a very detailed view in to the nature of the failure which is easily understood, and easy to navigate.

A. Parts

The text page contains fields for the FIAR number, which is assigned to every FIAR based on the location and chronological order of the FIAR, the part number which specifies the hardware that failed, and then the serial/lot number which specifies the exact piece of hardware which failed, or production lot in the case of a production-based error.

1	Report No.	NSTS Part No	Nomenclature	Serial/Lot N	Detect Date
375		EV032676-1	EMU LITHIUM ION BATTERY CHARGER	5002	
376	JSCEP0233	EV032676-1	EMU LITHIUM ION BATTERY CHARGER	1004	1/27/2006
377		EV032676-2	EMU LITHIUM ION BATTERY CHARGER	1006	
378	JSCEP0232	EV032656-1	BATTERY, LITHIUM ION ASSY	1010	2/2/2006
379	JSCEP0235	EV032676-2	EMU LITHIUM ION BATTERY CHARGER	1005	2/8/2006
380		EV032676-2	EMU LITHIUM ION BATTERY CHARGER	1006	
381		EV832986-1	LCD DISPLAY MODULE	N/A	

Figure 1. "Parts" Page. *Contains specific information on components involved in failure*

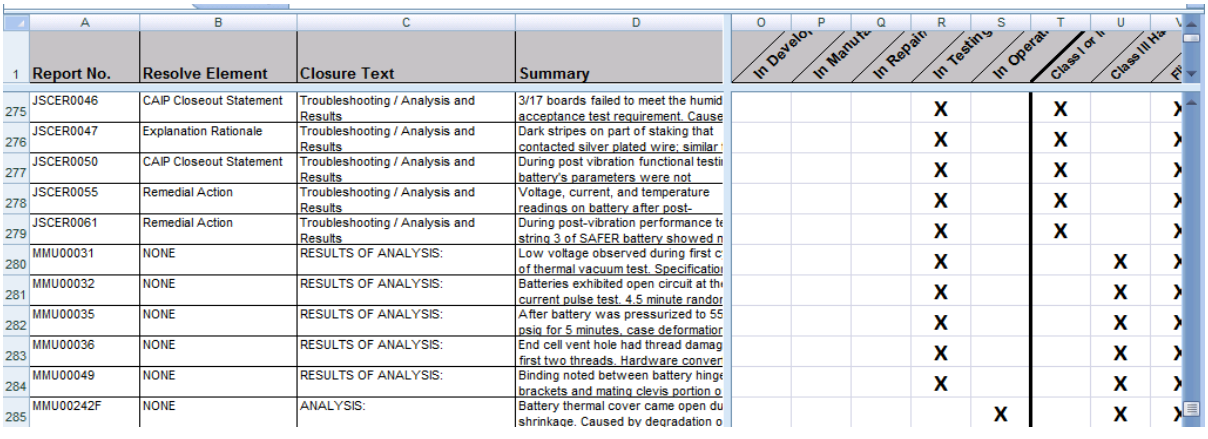


	L	M	N	O	P	Q	R	S	T	U	V
1	Process Escape	Location Code	Material Code	Test Op Code	Prevail Cond Co	Failure Mode Co	Defect Code	Cause Code	Recur Ctrls Code	Remarks	Days Open
295	NO	JSC - JOHNSON SPACE CENTER	Z - NO MATERIAL DEFECT APPLIES	AI - ACCEPTANCE TEST	F - OBSOLETE --- FUNCTIONAL	EQ - OBSOLETE --- OUTPUT PRESENT	EP - ELECTRICAL VALUE OF ITEM	D - DESIGN - WHEN NO MORE	0 - EXPLANATION RATHER THAN		5
296	NO	FLT - FLIGHT	XU - MATERIAL UNKNOWN -	F - FLIGHT (PERIOD	F - OBSOLETE --- FUNCTIONAL	EAF - FAILS OFF	XU - DEFECT UNKNOWN -	UF - UNEXPLAINED ANOMALY IN	0 - EXPLANATION RATHER THAN		18
297	NO		Z - NO MATERIAL DEFECT APPLIES	Q - QUALIFICATION OR	V - VIBRATION	EED - OBSOLETE --- OUTPUT DATA	DB - DAMAGED SHAPE - BENT,	DH - HARDWARE DESIGN	1 - DESIGN CHANGE		46
298	NO	JSC - JOHNSON SPACE CENTER	N - HOLE, NOZZLE, ORIFICE, OR VENT;	Q - QUALIFICATION OR	F - OBSOLETE --- FUNCTIONAL	UC - UNSATISFACTOR	MC - CLEARANCE EXCESSIVE OR	DH - HARDWARE DESIGN	0 - EXPLANATION RATHER THAN		81
299	NO		E - ELECTRICALLY CONDUCTING	Q - QUALIFICATION OR	L - LIFE TEST	EC - PREMATURE OR INADVERTENT	DB - DAMAGED SHAPE - BENT,	ES - EMI - SHIPPING	2 - MANUFACTURING		25
300	NO		A - ELECTRICAL CIRCUIT	MI - MANUFACTURING	F - OBSOLETE --- FUNCTIONAL	EQ - OBSOLETE --- OUTPUT PRESENT	MW - MISWIRED OR MISROUTED	MA - OBSOLETE --- MANUFACTURING	0 - EXPLANATION RATHER THAN		229
301	NO		K - ADHESIVE, CHEMICAL BOND,	AI - ACCEPTANCE TEST	V - VIBRATION	EN - OPEN, HIGH RESISTANCE,	DD - DAMAGED - MATERIAL	MAT - OBSOLETE --- EQUIPMENT OR	2 - MANUFACTURING		393
302	NO	HSSI	Z - NO MATERIAL DEFECT APPLIES	Q - QUALIFICATION OR	L - LIFE TEST	EL - SHORT, LOW RESISTANCE, LOW	ML - DEGRADED BY AGE,	DHC - HARDWARE DESIGN - LIFE	0 - EXPLANATION RATHER THAN	THE EXTENSION IS NEEDED UNTIL A	118
303	NO	USA	F - ENCAPSULATION,	AI - ACCEPTANCE TEST	N - INSPECTION (NOT	UC - UNSATISFACTOR	DD - DAMAGED - MATERIAL	MI - MANUFACCTURIN	2 - MANUFACTURING		21
304	NO	JSC - JOHNSON SPACE CENTER	Z - NO MATERIAL DEFECT APPLIES	PL - FIELD DETECTED -	F - OBSOLETE --- FUNCTIONAL	MP - FAILS OPEN OR FAILS TO	XN - NO DEFECT APPLICABLE	DH - HARDWARE DESIGN	0 - EXPLANATION RATHER THAN		2
305	NO	JSC - JOHNSON SPACE CENTER	S - STRUCTURAL ELEMENT(S) OR	AI - ACCEPTANCE TEST	F - OBSOLETE --- FUNCTIONAL	MMB - BINDING, JAMMING, OR	MA - MECHANICALLY	DH - HARDWARE DESIGN	1 - DESIGN CHANGE		161

Figure 2. **"All" Page.** *Contains trend codes from PRACA. Shown "expanded"*

B. All

The "All" page contains information from the FIAR such as the FIAR number, title of the problem, a short description of the problem, the dates, the criticality, and trend codes. The title of the problem and the description give a short summary of the failure that occurred, whereas criticality relates to the potential outcome of the failure, broken down in to "Crit 1," "Crit 2," and "Crit 3." Crit 1 failures result in the loss of life, or vehicle, "Crit 2" failures result in a loss of mission, and "Crit 3" contains all other failures. Criticality has letter codes that can be added to the crit classification which signify levels of redundancy or other special circumstances. Finally, the trend codes are taken from PRACA and expanded out from their original form in order to define their meaning. The trend codes are undefined in PRACA and on the original FIAR documents, originally needing a PRACA code table to look up the meaning. In the EMU LLD these codes are defined so that no further documentation is required, allowing all information in the database to be easily interpreted for all familiarity levels.



	A	B	C	D	O	P	Q	R	S	T	U	V
1	Report No.	Resolve Element	Closure Text	Summary	In Develo	In Manufa	In Repair	In Testing	In Operat	Class I or I	Class III Ha	Fl
275	JSCER0046	CAIP Closeout Statement	Troubleshooting / Analysis and Results	3/17 boards failed to meet the humid acceptance test requirement. Cause				X		X		X
276	JSCER0047	Explanation Rationale	Troubleshooting / Analysis and Results	Dark stripes on part of staking that contacted silver plated wire; similar				X		X		X
277	JSCER0050	CAIP Closeout Statement	Troubleshooting / Analysis and Results	During post vibration functional testi battery's parameters were not				X		X		X
278	JSCER0055	Remedial Action	Troubleshooting / Analysis and Results	Voltage, current, and temperature readings on battery after post-				X		X		X
279	JSCER0061	Remedial Action	Troubleshooting / Analysis and Results	During post-vibration performance te string 3 of SAFER battery showed n				X		X		X
280	MMU00031	NONE	RESULTS OF ANALYSIS:	Low voltage observed during first c of thermal vacuum test. Specificatio				X			X	X
281	MMU00032	NONE	RESULTS OF ANALYSIS:	Batteries exhibited open circuit at th current pulse test. 4.5 minute randor				X			X	X
282	MMU00035	NONE	RESULTS OF ANALYSIS:	After battery was pressurized to 55 psig for 5 minutes, case deformatior				X			X	X
283	MMU00036	NONE	RESULTS OF ANALYSIS:	End cell vent hole had thread damag first two threads. Hardware conver				X			X	X
284	MMU00049	NONE	RESULTS OF ANALYSIS:	Binding noted between battery hinge brackets and mating clevis portion o				X			X	X
285	MMU00242F	NONE	ANALYSIS:	Battery thermal cover came open du shrinkage. Caused by degradation o					X		X	X

Figure 3. **"Text" Page.** *Information split with written and visual information*

C. Text

The text page is the result of combining all of the data from "All" and "Parts" to a single page in a written and visual representation. Component information is broken down by system, and component, to the specific

K	L	M	N
Found	**Class**	**Failure**	**Solution**
In Operation	Class I or II, Flight Crew/Ground	Electrical Anomaly	No Action (see details)
In Operation	Class I or II, Flight Crew/Ground	Expected wear, Expired Hardware,	Procedure Change
In Testing/Processing	Class I or II, Flight Crew/Ground	Design Error	Replaced Hardware
In Operation	Class III, Flight Crew/Ground	Unknown	No Action (see details)
In Testing/Processing	Class I or II, Flight Crew/Ground	Excessive Load, Expected Wear	Procedure Change, Train/Notify
In Testing/Processing	Class I or II, Flight Crew/Ground	Design Error	No Action (see details)
In Testing/Processing	Class I or II, Flight Crew/Ground	Human Error, Manufacturing Error,	Procedure Change, Manufacturing
In Manufacturing	Class I or II, Flight Crew/Ground	Manufacturing Error, Design Error,	Design New Hardware, Replaced
In	Class I or II, Flight	Manufacturing Error,	Repaired Hardware,

Figure 4. "Bucket Categories." *Also represented visually.*

item that caused the failure. The page has unique elements in the "Bucket Categories" on the right portion, which allow visual overview of problems to identify trends and see where and how problems occurred, and what action was taken to correct the problem.

The Closure Text from the FIAR is also located on this page, which gives in-depth information on topics such as the Troubleshooting and Analysis process, the Root Cause, and the Corrective Action taken.

A summary is written for every entry and included on this page, which is kept under 400 words, and includes the problem, the cause of the problem, and the corrective action. The summary grants the ability to get an overview of the FIAR in a few sentences, and is an important part to every entry.

The last 4 categories, in Figure 4, correspond to the "Bucket Categories" which are graphed on the adjacent side of the spreadsheet. These include information on the process in which the failure occurred, for example, testing, manufacturing, or repair; classification of the hardware, divided in to Class I or II and Class III; the cause of failure, such as incorrect handling or errors in design; and corrective action taken, such as repairing hardware, or updating the firmware or software. The visual representation gives an organizing factor to the information, where a column could be sorted through to find FIARs related to the desired category, instead of having to sort through the different textual fields.

D. Creating An Entry

FIAR data come from the PRACA online resource, also available as a Microsoft Access database, which allows FIARs to be searched and sorted through in multiple categories such as: System, date, part number, and part name. Hardware is typically added in groups for better organization in the database. The process for adding hardware can be broken down in to a sequence of steps:



Figure 5. PRACA. *Contains transcriptions of FIARs*

1. Transfer the Parts List information from PRACA in to the "Parts" tab
2. Transfer the dates, problem title, and description from PRACA to the "All" page.
3. Transfer the criticality over from PRACA; "expand" the code by inserting the definition from the PRACA code tables after a hyphen following the number code.
4. Transfer over the Location and Trend Codes from PRACA; "expand" the code by inserting the definition from the PRACA code tables after a hyphen following the code.
5. Transfer resolving element, dates, component information and class to "Text" page.
6. Format the Closure Text in chronological order; space out to make it easier to read. Transfer Closure text.
7. Use the Problem Description and the Closure Text in order to write a concise summary which covers the failure, the cause, and corrective action in fewer than 400 words.
8. From the information gathered, classify the failure in the "Bucket Categories"; mark the applicable boxes in the graph and record the category in the corresponding text box.

Each entry utilizes the information from PRACA, although the formatting and organization is unique to the EMU LLD which allows greater control over the data for desired analysis.

IV. EVA Tools Expansion

The EMU LLD was originally started for compilation and organization of EMU related FIARs. Upon completion of EMU hardware entries in the Excel database, the website was in development, and work was shifted to transfer entries from the excel version to the web database. The decision was made to improve the EMU LLD and extend the coverage it provides by adding EVA tools and support hardware such as the PGT and the BCM. A total of 606 entries have been added to the database related to EVA tools, taking the total of entries in the EMU LLD from 2360 to 2966. Of these new entries the hardware added includes:

- EMU and EVA Tool Batteries (PGT, REBA, EHIP, SAFER)
- PGT Hardware
- SAFER Hardware
- Wireless Video System
- SPCE (Fluid Pumping Unit, Power Supply Assembly)
- Retractable Equipment Tethers (RET)
- BCM
- Battery Stowage Assembly (BSA)

The format and organization remains the same as with EMU hardware, although a new "Bucket Category" was added to solutions/failures in order to accommodate the hardware: "*Update Software/Firmware*" and "*Unexpected Output*".

Update Software/Firmware was added to the Solution "Bucket Categories" after analysis of BCM failures showed that corrective action included updating the firmware for a multitude of errors which either had software anomalies or other errors that led to a fault in the software.

Unexpected Output was added to failure "Bucket Categories" to accommodate hardware testing which did not have any failure, but had out of specification readings. Usually the specifications or procedures were changed in order to accommodate the out of spec readings if everything performed nominally (See: Figure 6.).

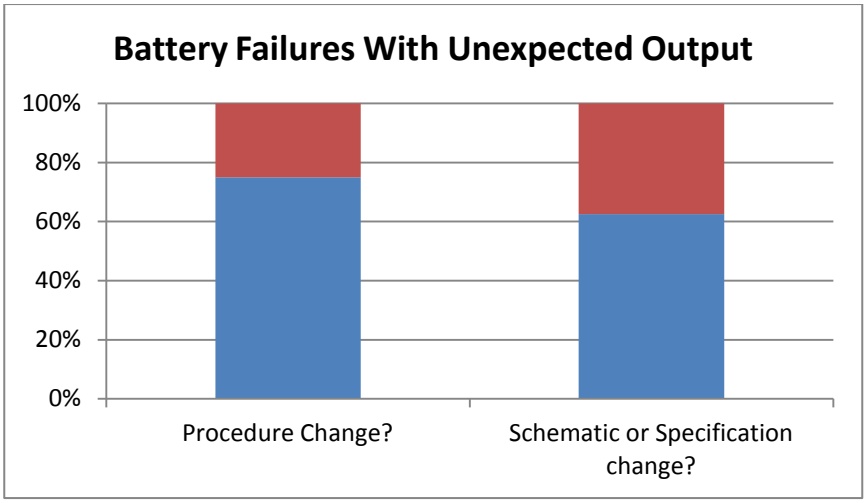


Figure 6. Battery Hardware with Unexpected Output Failure.
Percentage of hardware experiencing unexpected output failure that had the specified corrective action.

V. Conclusion

Since summer of 2009 plenty of work has been done on the EMU LLD, and in its current state, it supports analysis and navigation in the organized Excel interface for the EMU. With the work done this past semester, the EMU LLD now extends coverage to EVA tools and support hardware, for the same purpose in aiding with future

design and current maintenance. With some of the oldest FIARs in the database dating back to the 1970s, the history of EVA tools and the EMU can be carefully analyzed for over three decades of information. The EMU LLD is a valuable tool for development, and will increase in usefulness and accessibility with further development of the website portion in the future.

A. Forward Work

Although much work has been done on the EMU LLD to this point, there is still work to be done for it to reach completion. There are still entries that need to be transferred to the website portion, as only 32% have been moved over from the Excel database. Although, now that hardware FIARs have been entered up to the most recent closures, more focus can be shifted to transferring the entries in the system. As work is being done to convert entries to the correct format for the web database, newer, more recently closed FIARs can be added to the Excel portion. FIARs are added to PRACA periodically as they are closed, and need to be entered in to the EMU LLD for any relevant hardware.

Improvement of the website portion of the database is always a possibility for work. Adding increased functionality such as photographic elements for hardware entries, as well as general aesthetics, and as feedback is taken from the community, the interactive elements of the site can be built upon to make the experience easier for the user. Another possible element, to improve the efficiency of adding new entries, would be a "Direct Entry Addition" system. As of right now, the only way to add entries to the web database is to take data from PRACA to the Excel spreadsheet, from the Excel Spreadsheet to an individual .csv (Comma Separated Value) file for each entry, and finally upload the .csv file to the server containing the web database. The implementation of a feature on the webpage, accessible through administrative permissions, which would allow one to simply fill in fields for text entries, choose from drop down menus for "Bucket Categories," check off the visual "Bucket Categories," and directly enter FIARs to the web database, would make the ability to keep the database up to date after completion a much simpler task. The feature could be coded in to the web database through HTML or possibly port the database to another language such as Java or PHP, which allow greater ability, at the cost of being more time consuming to learn.

Acknowledgments

K.M. Matthews would like to say thanks to mentors Scott Cupples and Lori Crocker for the enormous amount of support and guidance given in the development of the EMU LLD, as well as providing an excellent learning experience here at JSC. The previous interns for their work on starting and improving the EMU LLD. K.M. Matthews would also like to recognize Brian Johnson for creating the concept of the EMU LLD. K.M. Matthews would also like to extend thanks to the XA Chief Engineering and Systems Engineering & Integration office for project support and help in development of professional skills. K.M. Matthews would also like to thank Glenn Lutz and the entire XA division for the opportunity to work in and experience the community. And finally, K.M. Matthews would like to thank Undergraduate Student Research Program (USRP) coordinators Diego Rodriguez and Dr. Adams for granting the opportunity to work at JSC and discover the many great things planned in manned spaceflight.

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[5]NASA, "STS-61" *NASA Space Shuttle Launch Archives* [online archive], URL: http://science.ksc.nasa.gov/shuttle/missions/sts-61/mission-sts-61.html [cited 09 December 2011].

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[7]NASA "STS-6" *NASA Space Shuttle Missions Archive* [online archive], URL: http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-6.html [cited 09 December 2011].

JFCC Space Conference Abstract

Human Spaceflight Conjunction Assessment Lessons Learned

In June of 1999, the International Space Station (ISS) attempted a maneuver to avoid a high risk conjunction with a piece of a Russian Soyuz rocket body. The maneuver failed. Although the object missed the ISS and no harm was done to the vehicle or crew, this incident is considered a failure and an example of a breakdown in situational awareness.

In July of 2009, just after the docking of STS-127, the ISS and Space Shuttle mated stack maneuvered to avoid a high risk conjunction from an unknown debris object. This incident is considered a successful use of situational awareness to protect two human spaceflight vehicles and crews.

This paper will compare and contrast these two incidents in human spaceflight conjunction assessment history. Early in the ISS flight program, many lessons were learned regarding conjunction assessment and utilizing conjunction notifications. Through this growing process, there is today a highly successful program of conjunction assessment to protect human spaceflight vehicles and crews. This paper will explain the background behind these two incidents, as well as lessons learned which can be applied to future conjunction assessment activities.

Human Spaceflight Conjunction Assessment

Lessons Learned

26 Jan 2011

NASA/JSC – Jason T. Smith

Agenda

- Background
- Object 1844
- Lessons Learned
- Object 84180
- Take-Aways



Background

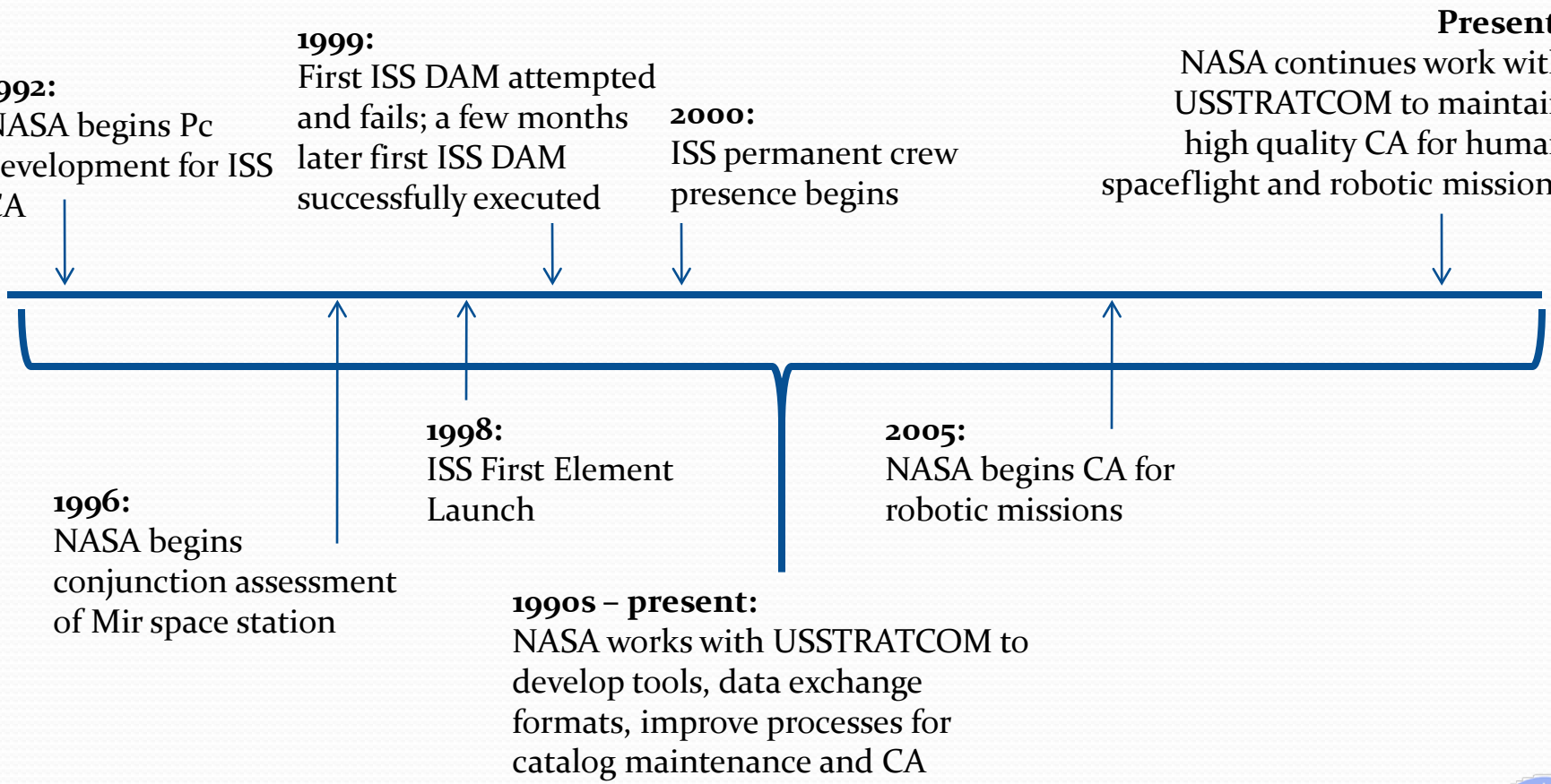
- Since First Element Launch in Nov 1998, the International Space Station (ISS) has had a continuous conjunction assessment team – on-call 24/7/365.
- During this time there have been over 700 conjunction notifications[1].
- Many lessons learned over the 12+ years of ISS operations.
- Examine an example of early conjunction incident (1999).
- Explain some lessons learned from this incident.
- See how these lessons are applied to a more recent conjunction example (2009).

[1] Taken from *NASA Human Spaceflight Conjunction Assessment: Recent Conjunctions of Interest*. Ansley Browns, CSM Workshop, Oct 20, 2010

Acronyms

- DAM – Debris Avoidance Maneuver
- OSA – Orbital Safety Analyst (JSpOC team member responsible for predicting conjunctions for NASA)
- TCA – Time of Closest Approach
- TOPO – Trajectory Operations Officer (Houston Flight Control Team member responsible for conjunction assessment and collision avoidance)

Conjunction Assessment History[2]

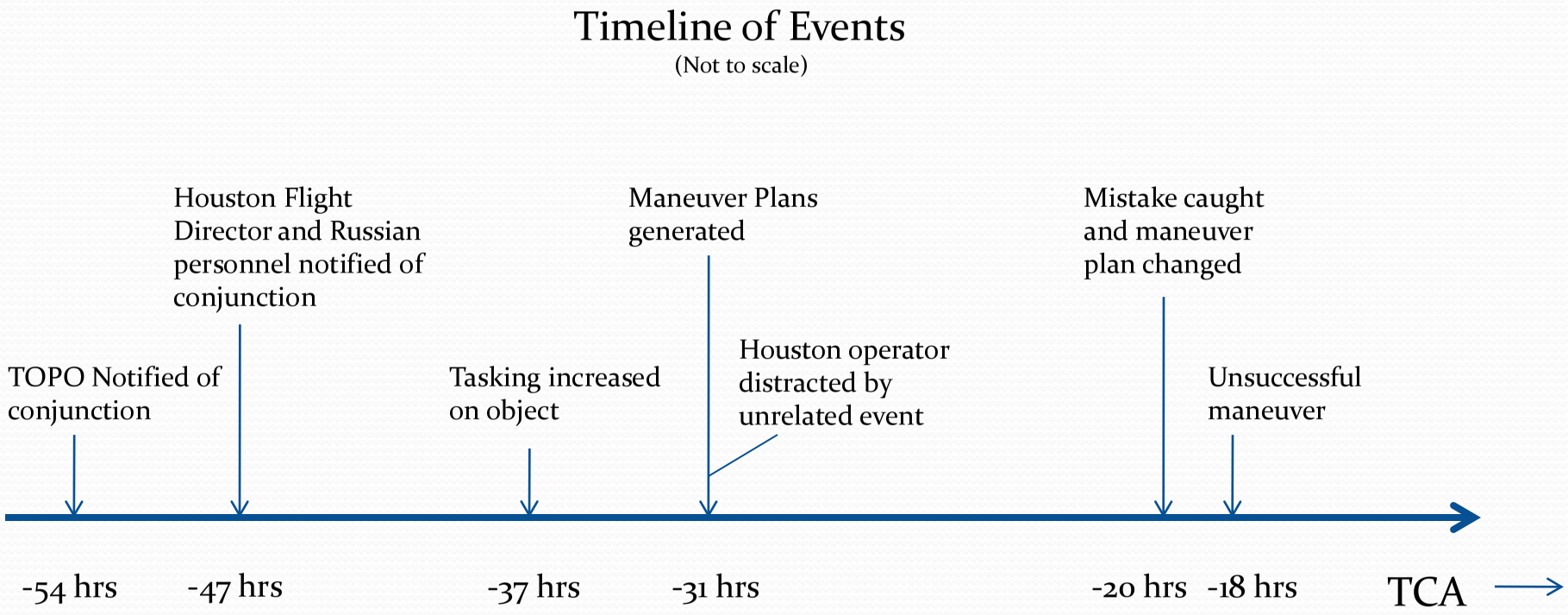


[2] Adapted from *NASA Human Spaceflight Conjunction Assessment: Recent Conjunctions of Interest*. Ansley Browns, CSM Workshop, Oct 20, 2010

Object 1844

- TOPO notified of ISS conjunction with Object 1844 on June 11, 1999.
- The following page presents a timeline of events as they transpired over ~1.5 days following notification of the conjunction.
- Following the timeline are some additional comments on the situation and the outcome.

Object 1844 (con't)



Object 1844 (con't)

- Maneuver execution needed to take place 18 hours or more before TCA due to constraint of flying over Russian ground sites immediately following the burn (this is no longer a constraint).
- Throughout the event there was confusion between TOPO and OSA of what differential correction span to use.
  - Multiple solutions were delivered with no resolution as to what the correct solution should be.
  - At the time, the OSA position was filled with military personnel, making consistent operations difficult due to frequent military rotations.

Object 1844 (con't)

- Distraction resulted in TOPO applying wrong time-tag to a vector sent to OSA for post-burn conjunction screening.
  - This was a manual data entry procedure.
  - Incorrect vector produced false negative screening results. The error was eventually corrected but required a late change in the burn plan.
- Russian command error resulted in loss of attitude control prior to the start of the DAM and hence failure of the burn.
  - Contributing factor to the command error was the late change in the burn plan.
  - Attitude control was regained on the last Russian ground site pass of the day with ~14-28 hours of electrical power remaining.
  - Ironically, post-event reconstruction showed low risk from the conjunction.

Lessons Learned

- Notify people early, get everyone working toward the same goal and have an agreed-to timeline.
- If required, increase tasking early. Waiting reduces the effectiveness.
- When operators are separated by great distances, it is important to understand as much as possible about what the other is doing so as to facilitate questions and discussion.
  - Following this event, the OSA position was moved to contractor personnel, allowing for more retention of experienced operators.
- Automate critical data entry as much as possible. Where automation is not possible, get two sets of eyes on the data.



Object 84180

- Shuttle launched on July 15, 2009 for STS-127 mission.
- TOPO notified of ISS conjunction with Object 84180 on July 16, 2009.
  - First notification ~44 hours prior to TCA – less time than the previous example.
  - Notification came in the middle of Shuttle rendezvous profile (~26 hours prior to docking).
- TCA ~15.5 hours after docking (during crew sleep).
  - Maneuver would need to be performed before sleep.



Object 84180 (con't)

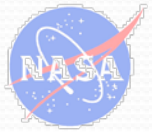
- Within 2 hours, ISS, Shuttle, and International teams are briefed on the situation.
- Immediately following notification, discussions began about when to do a DAM if it became necessary and which vehicle would do it (Shuttle post-docking).
- Several discussions with OSA about increasing tracking and what resources are available.
- Some tracking passes were missed, but the situation was discussed and resolved.
- Post docking perturbations made the conjunction higher risk, so maneuver was executed successfully by Shuttle.

Take-Aways

- Have a plan – don't wait until you are over your head to start swimming.
- Be flexible – every event is unique, so understand when to deviate from the plan.
- Communicate – the easiest path to failure is a breakdown in communication.
- Automate – relying on manual data entry for critical operations should be avoided where possible.
- Don't automate too much – automating data entry is good, automating decision making is not.
- Weigh all the risks – sometimes doing a maneuver is more risky for the vehicle than the conjunction. Don't forget the big picture.



Questions?

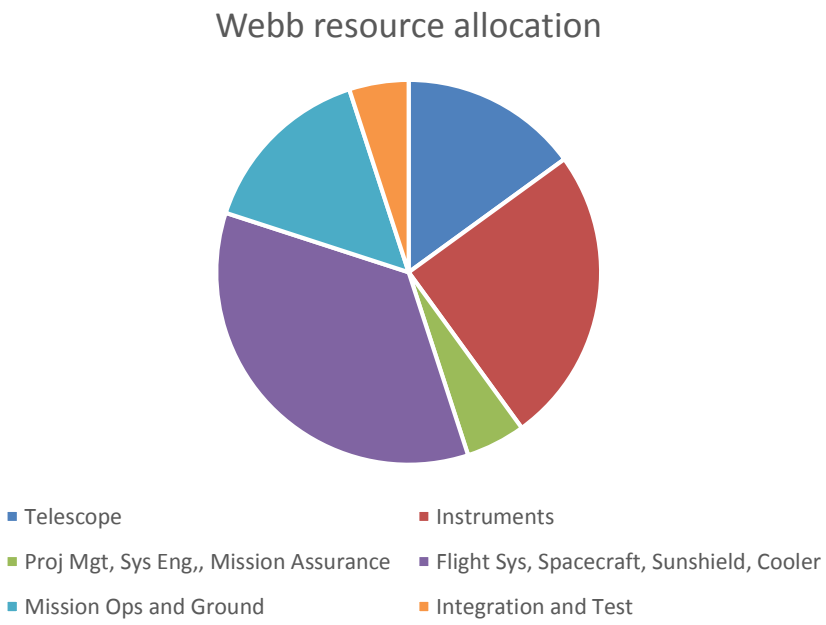


JWST Lessons Learned

Lee Feinberg
JWST OTE Manager (NASA Goddard)
J. Arenberg (NGAS), P. Lightsey (Ball Aerospace), D. Yanatsis (Harris Corportation)

Introduction

- While there is a lot of focus on how a few key parameters like aperture size and pixel count drive costs of large space telescopes, the JWST experience suggests that a lot more insight is needed to understand and control costs
  - Next level of detail to aperture size is how long does it take to design, fabricate, test etc. and this can be very dependent on specific requirements.
  - A smaller mirror is not necessarily cheaper!
  - Other large programs like Chandra backup this experience
- From experience on JWST, no single area drove costs, no silver bullet
- As can be seen below, the cost resources are spread across all of the WBS elements suggesting there is no single metric that can alone be correlated to costs.



JWST lessons learned

- In thinking about what actually drove things on JWST, there are five major areas that are critical to evaluate early in the program in order to control future large telescope costs:
  - 1. System complexity (multiple difficult first of a kind challenges simultaneously, design complexity and iterations, etc.)
  - 2. Critical path and marching army driven by technical considerations (like being cryo, long manufacturing times)
  - 3. Verification challenges (modeling, facilities, test approach)
  - 4. Programmatic constraints (funding/phasing, reserves, replans)
  - 5. Early integration and test considerations (practice, pathfinders, modularity)
- Many of these factors interact: system complexity can drive critical path, phasing constraints can drive critical path, etc.
- The rest of this presentation will discuss how each of these areas impacted JWST and how we can mitigate these issues on future telescopes (eg, LUVOIR)

1. System Complexity

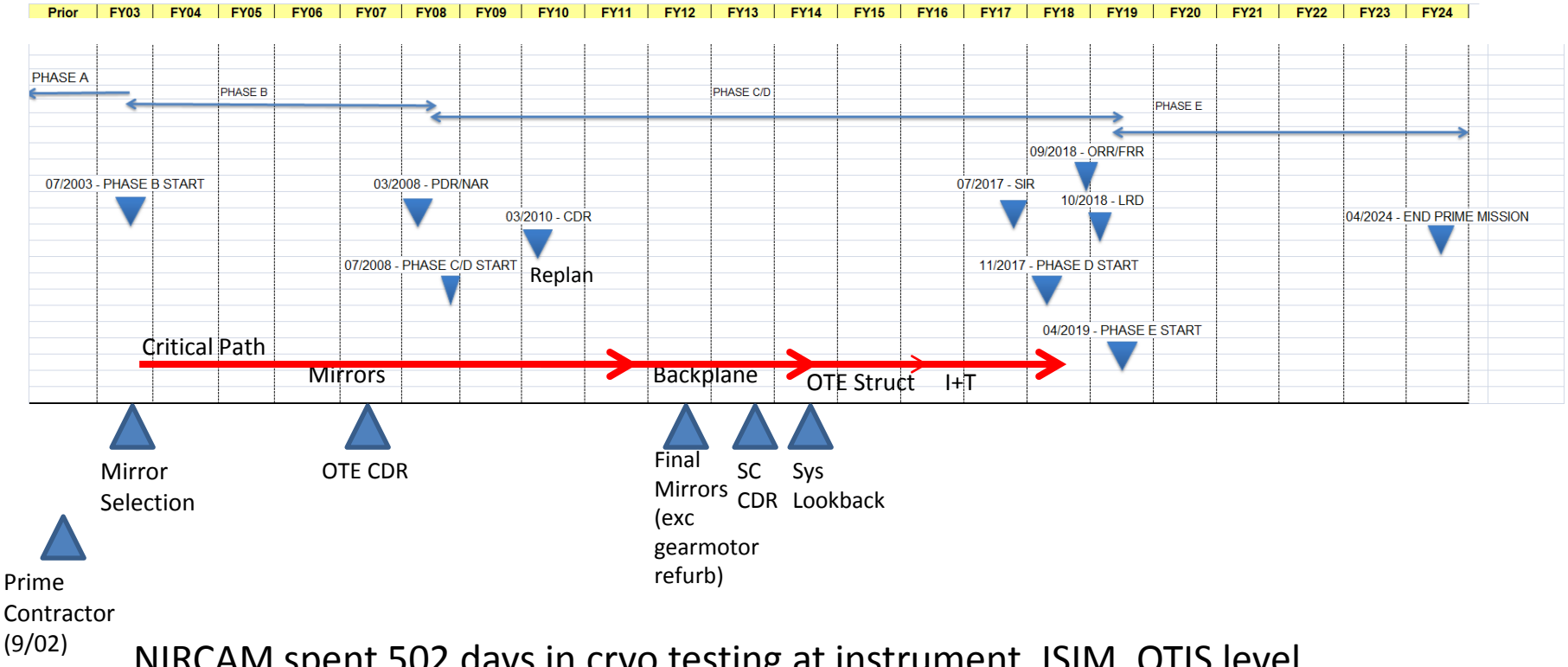
- **There were several system complexity factors that all had to be solved simultaneously leading to many design iterations, complex modeling, many system trades**
  - Cryogenic (50K) with tight performance requirements: lots of complex flexures, bond and joint complexity including cryo strength, cryo polishing while still 10's of nanometer error budgets for mirrors and stability
  - Low system margins (mass and volume) and associated programmatics
  - Lightweight structures that have to be tested in 1-g (mirrors, backplane, sunshield)
  - Large deployments, large number of single point failures, cryo shock
  - Optical quality, stability, sensitivity including MIR (thermal) and NIR (particulate)
  - Large FOV's in SI's
  - Large number of technology areas (10) – though early investment meant this was not a large driver
- Lessons Learned
  - **Focus on the minimum number of complex challenges that are needed to do the core science.**
  - **Don't architect by committee – architect by logic**
  - **Avoid short term decisions based on fiscal profiles (always consider lifecycle impacts)**

2. Critical Path and Marching Army

- A really key issue for any program is the cost associated with fixed marching army over time cost = FTE x time (schedule)

- Schedule: JWST marching army is on board for 18 years
- Marching Army on a program like this is large
- For JWST, funding constraints meant that critical path ran through telescope and instruments for over a decade which prevented starting other areas earlier
  - While aperture size was a factor in the mirror time, the funding constraint was actually a bigger issue as it stretched things out
- In addition, facilitization was needed which ate into the same resources needed for design
- Cryo and being passive/thermal drove design times, test times on instruments and telescope
- Lesson Learned
  - **Prioritize schedule time and need for early resources, including: facilitization, mirror and structure fabrication times, design iterations, etc**
  - **Use heritage to save tame and reduce risk, avoid recreating the wheel when you can. Use a bigger picture strategy to design programs as a continuum.**
  - **Combining cryo and performance together is challenging.**

As-run Schedule

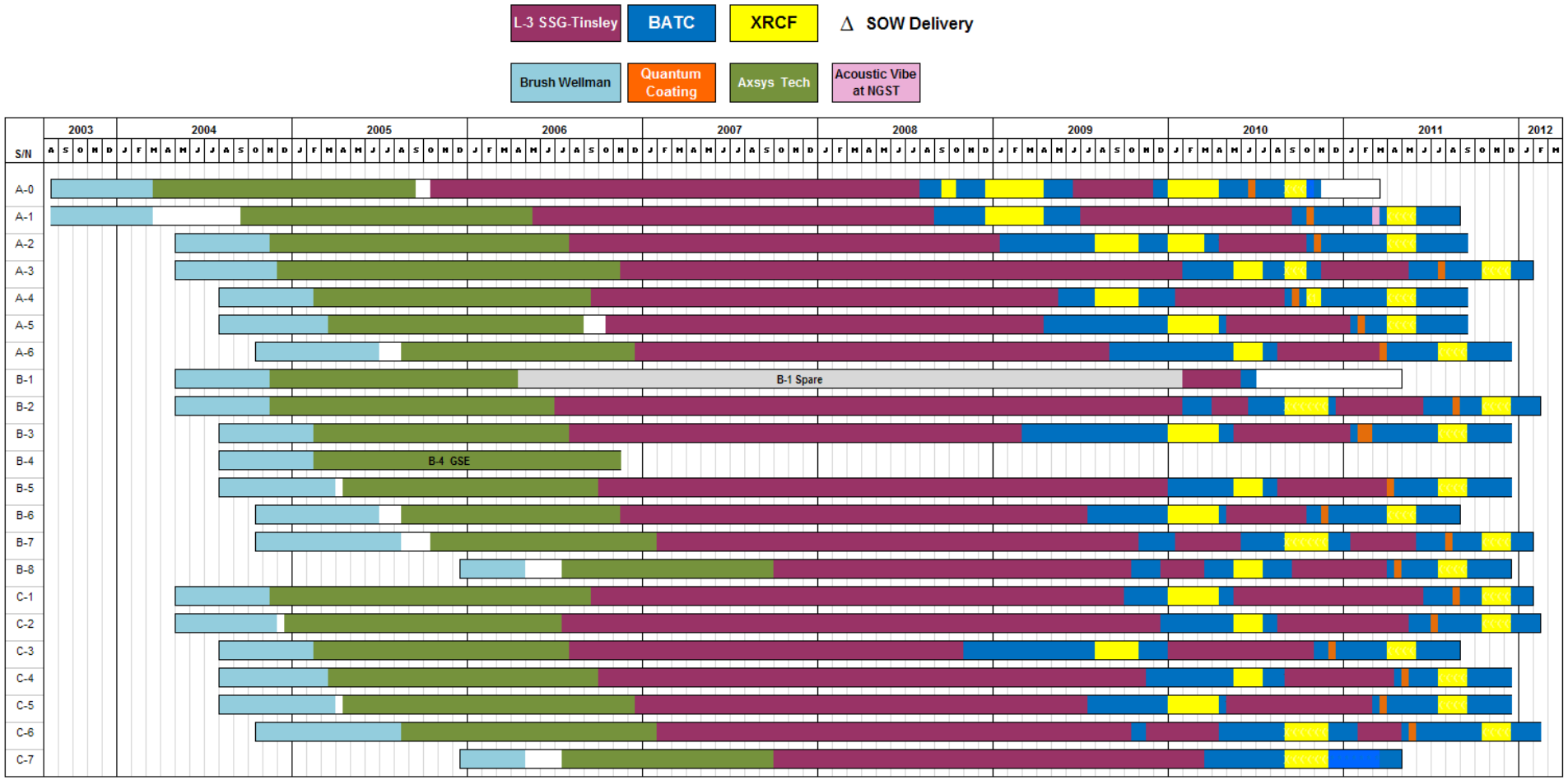


NIRCAM spent 502 days in cryo testing at instrument, ISIM, OTIS level

Mirrors took 8 years to fabricate which was driven primarily by Beryllium polishing time (Beryllium was selected because of it's cryo and performance properties)

As-run Mirror Schedule

Beryllium Chosen for Cryo Performance Took a Long Time Complete - Using up Reserve in the Early Years (opportunity cost) and stretching out marching army



Beryllium Blanks

Axsys driven by machine time, stress control for Beryllium

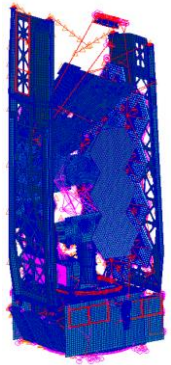
Tinsley driven by grind and polish time and stress control of beryllium, metrology
Economies of scale helped later mirrors

Cryo Testing, metrology, actuators

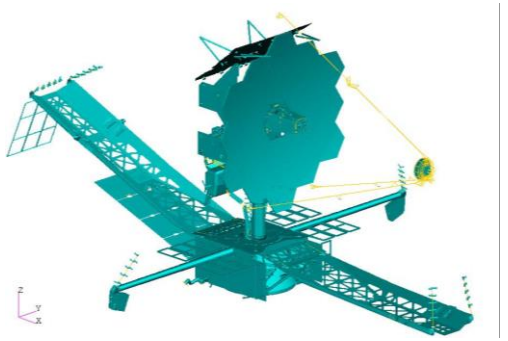
3a. Verification Of JWST On-Orbit Performance Using Analytical Models

- **JWST is a passively stable lightweight cryo system and relies on model validation**
- **Validation:**
  - **Prove what is mathematically modeled is what was actually built**
  - **Prove interfaces are modeled correctly**
- **Building and validating models required substantial manpower, time, validation testing**
- **Correlated models, such as those on right, are used to predict/verify on-orbit performance of:**
  - **Thermal Performance**
  - **Optical Thermal Stability**
  - **Dynamics**
  - **Stray Light**
- **Tests at high levels of assembly conducted to verify "workmanship" and behavior of critical interfaces**
- Lesson Learned
  - **Use robust designs and active controls to minimize the reliance on complex high fidelity models**
    - **Architect the system to avoid reliance on complex modeling**
  - **Avoid complicated modeling challenges like cryo with lightweight where you can't solve it easily with robustness (cryo joints)**

Structural Dynamics Models



Stowed

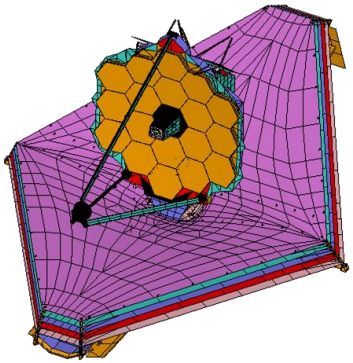


Deployed

Thermal Models



Stowed

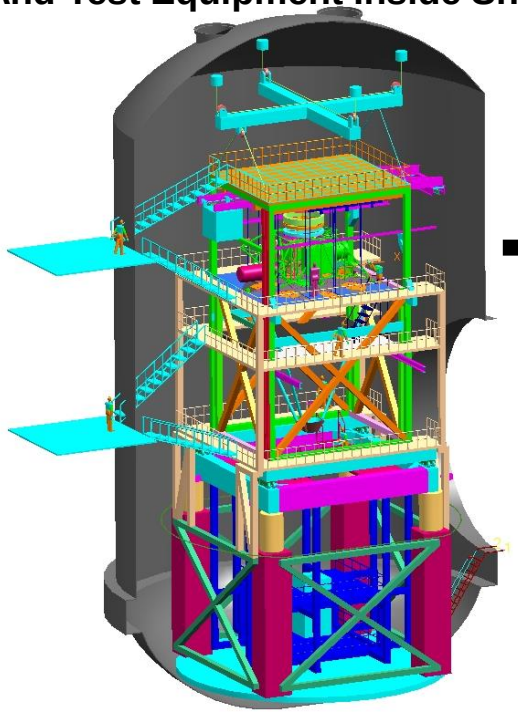


Deployed

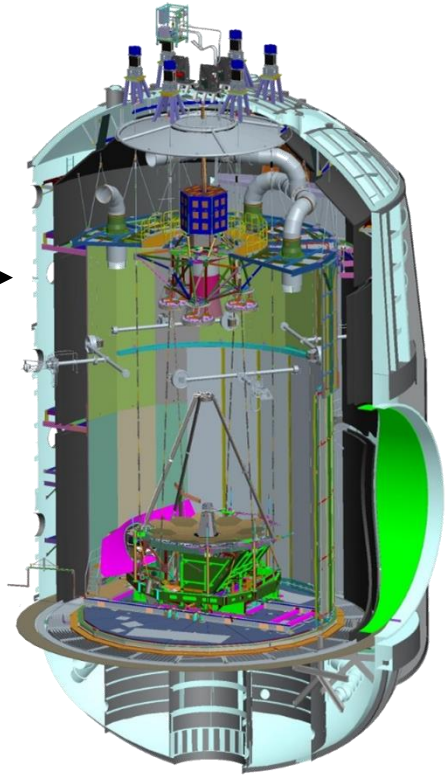
3b. Verification: System Testing

There were several iterations of the verification architecture as we got smarter on what needed to be verified and how best to do it

Original "Cup Down" Configuration Included Large Metrology Tower And Test Equipment Inside Shrouds



Current "Cup Up" Configuration Eliminates Tower and changed many of the alignment test approaches



Lessons Learned:

- **Think about verification during the architecture phase**
- Consider facilities, test strategies, necessary degrees of freedom
- Use active controls as your friend.
- Measure what you need to measure

4. Programmatics/Phasing

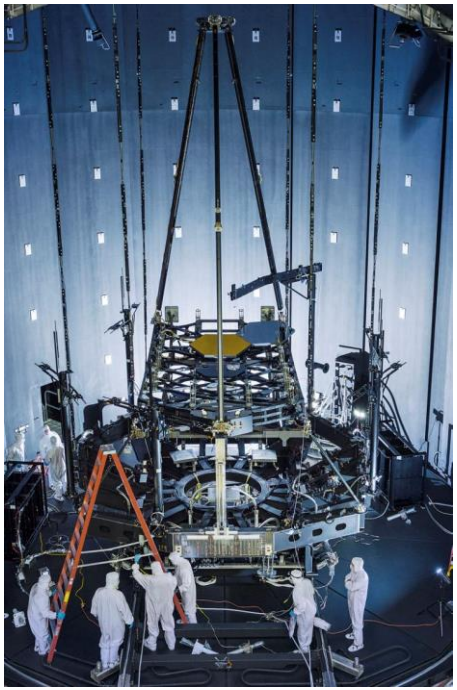
- JWST had single digit reserves for many of the early years
  - Lack of early year reserves was the number 1 issue presented by at Mission PDR
- Had to push out work (spacecraft, mirrors, etc) due to lack of reserves
- Need for early year money for facilitization, technology maturity and complex design challenges needs to be factored against available phasing
- Lesson Learned
  - Consider facilitization time and cost as opportunity cost
  - Pick long lead items (eg, mirror and structure materials and temperatures) that don't require long design, fabrication times (eg, material removal times, economies of scale, test time)

5. Integration and testing

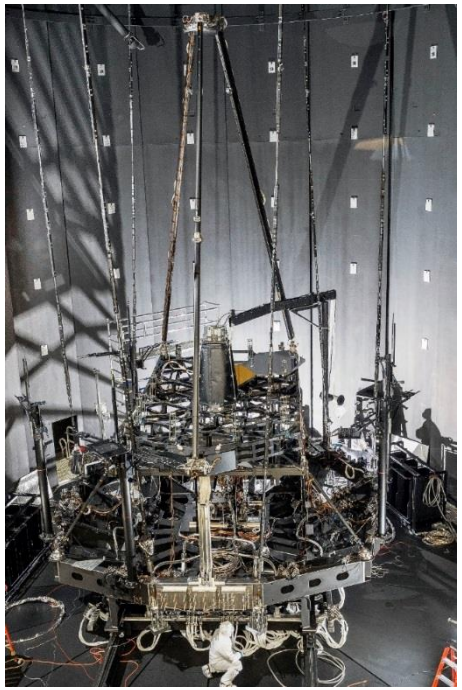
- Due to volume and mass constraints, some aspects of JWST are not modular:
  - Instruments installed in a sequence – doesn't allow for easy late detector swapping without removing instruments
  - Sunshield takes a long time to unfold and stow – workmanship take a long time to deal with
- Some areas of JWST had detailed pathfinders which allowed for practice and GSE checkout and greatly reduced risk, other areas did not have full scale high fidelity simulations leading to late schedule impacts
- Lesson Learned
  - Build high fidelity pathfinders to vet out integration and test processes, ground support equipment, and allow for practice
  - Strive for modularity in the design and the simplest possible interfaces including swap out of key risk items late in flow

OTIS Risk Reduction at JSC

3 Pathfinder Tests/Rehearsals in JSC Chamber to test the test equipment and ready the test team – this was highly successful! Same approach should be taken on large deployables.



Optical Ground Support Equipment (OGSE) #1: Prove-out optical GSE. Featured Cryo Optical Test on Pathfinder OTE w/ 2 Spare PMSA's and Spare Secondary



OGSE #2: 2nd Cryo Optical Test but w/ Flight Aft Optics System and AOS Source Plate Assembly. Full check-out of optical GSE and measurement schemes



Thermal Pathfinder: Verified all thermal environment/boundary conditions (e.g., sunshield layer 5 thermal simulator, ISIM radiator sinks)

Conclusions/Closing Thoughts

- To minimize costs, we need an approach that addresses the key items identified
  - Faster critical path
  - System complexity
  - Verification Approach
  - Programmatic constraints/phasing up front
  - Early integration and test considerations (practice, pathfinders, modularity)
- Several next generation architectures are taking these recommendations in consideration:
  - Not combining cryo and UV-optical
  - Leveraging heritage where it makes
  - Thinking about verification and adding in enough active controls
  - Lots of other examples
- A well thought out architecture addressing the items identified here, can make a large impact on reducing total mission cost
- The only silver bullet to controlling cost is an early and continuous disciplined, informed, systematic approach to every aspect of the program and from all layers of the program

KSC Human Factors Lessons Learned



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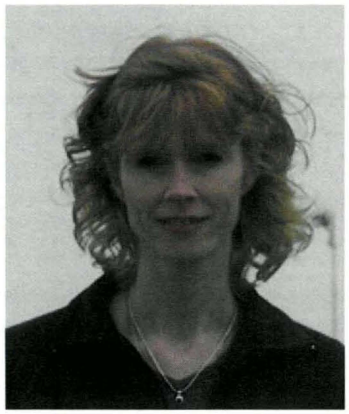
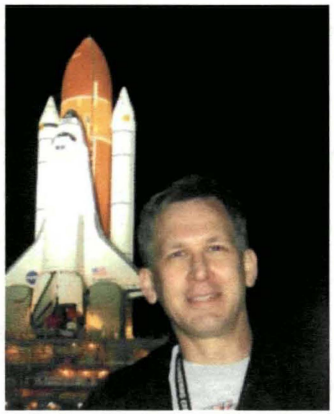


Darcy Miller



Tim Barth Ph.D.



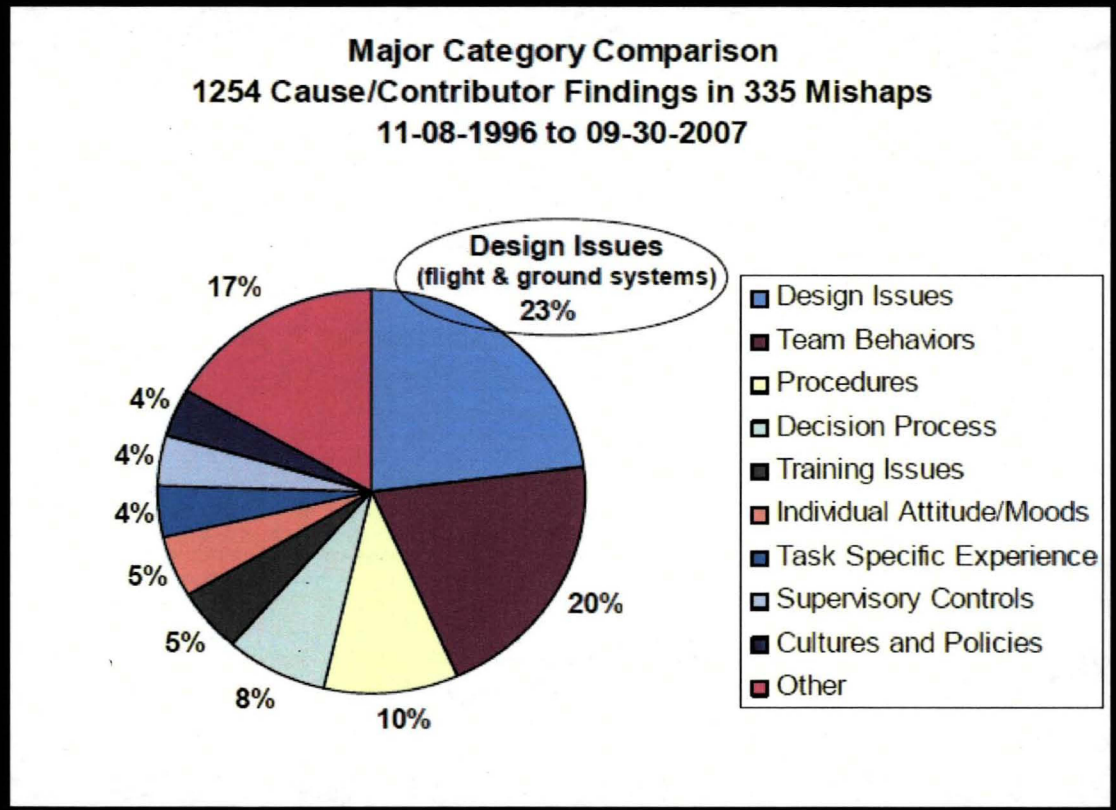
Barbara Kanki Ph.D.

Agenda

- Importance of Human Factors for Ground Processing
- Human Factors Lessons Learned
- Accomplishments from Lessons Learned
- Recommendations

The Importance of Ground Human Factors for Ground Processing

Shuttle Ground Operations Mishap Data



Courtesy of USA Industrial and Human Engineering

The Importance of Ground Human Factors for Ground Processing

Mishaps in Ground Operations

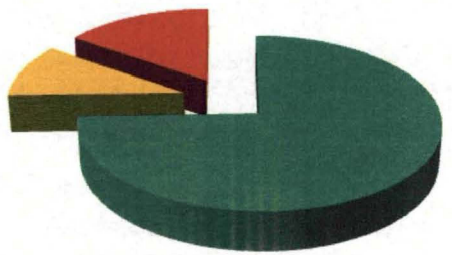
- For 11 NASA/KSC mishap investigation boards in FY06 and FY07:
  - Several million dollars in direct costs (includes civil service board member labor and travel, board procurement costs, and estimated hardware damage costs)
  - Plus additional direct costs such as contractor labor for amelioration, contractor labor for investigation boards, corrective actions (new procedures, training, etc.)
  - Plus indirect costs
  - Plus schedule impacts
  - Plus personnel injuries

Human Factors
Lessons Learned

Summary of Lessons Learned Metrics

- Lessons Learned Entry: 1801 Human Factors Engineering; Acceptance, Implementation, and Verification as a System.
- Lessons Learned Entry: 1831 Human Engineering should be considered a Systems Engineering and Integration function
- Lessons Learned Entry: 2136 1-G Human Factors for Optimal Processing and Operability of Constellation Ground Systems
- Lessons Learned Entry 5200: Synchronization of Vehicle Development with Ground Systems Development
- Lessons Learned Entry 5376 No clear communication between the Apollo program and the Shuttle program
- Lessons Learned Entry 5377 The use of human factors and the Space Flight Awareness (SFA) in the Apollo development
- Lessons Learned Entry 5378 Improved Quick Disconnect (QD) Interface Through – Visual Indicators and Labeling Lessons Learned Entry 5416 Kennedy Space Center (KSC) Ground Support Equipment (GSE) Human Factors Engineering Pathfinder
- Lessons Learned Entry 5480 Human Factors Review in the Critical Review Board (CRB)

44 recommendations implemented
6 partially implemented
9 have not been implemented



Human Factors Accomplishments from Lessons Learned

- The Human Factors Engineering Analysis (HFEA) Tool
- Orion Time line HF Analysis
- Mockup Analysis
- Assessing Human Factors using Motion Capture
- Biomechanical Analysis of Installing Avionics Boxes
- Spacecraft Requirements for Ground Processing

A 1

The Human Factors Engineering Analysis (HFEA) Tool

The Human Factors Engineering Analysis (HFEA) Tool

- KSC Design Engineering;
  - Define the human factors Level 5 requirements from the FAA HFDS for each CxP GOP subsystems (Over 40 Subsystems)
  - Develop a process for developing these requirements and improve the design for ground operations

Examples of subsystems:

- Crew Access Arm
- Breathing Air
- Cold Gas Helium
- Crew Module Ammonia
- Environmental Control
- Electrical Ground Support Equipment
- Hypergol
- LO2
- LH2
- GHE
- Ignition Overpressure/Sound
- Vehicle Access Arms
- Umbilicals

HFEA Process

Human factors engineering analysis was required to be performed by qualified human factors engineers

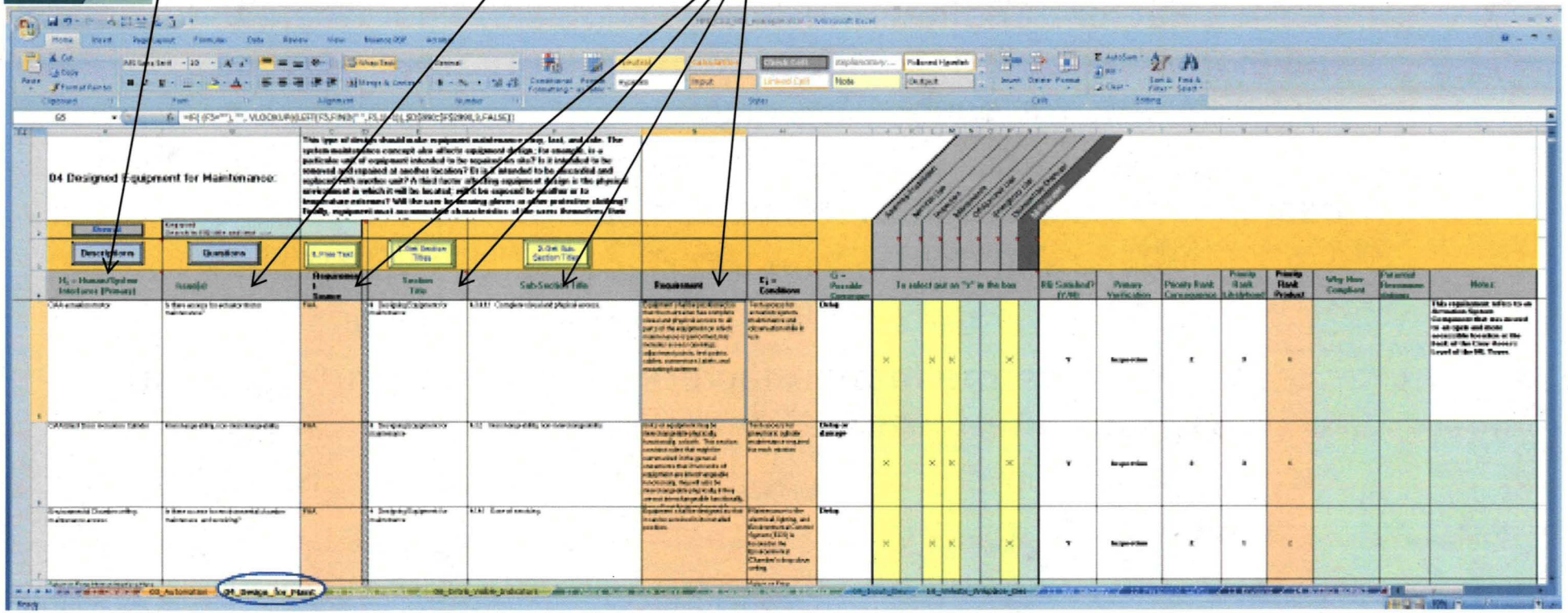
- Human Factors Engineering Analysis (HFEA) Tool was used to develop a dedicated subset of requirements from FAA requirements for each subsystem
- Meetings were held between the human factors engineers, lead design engineers, and systems engineers:
  - To understand the human interfaces of the subsystem
  - To understand the task at these interfaces
  - To determine the human factors considerations/issues with these task interfaces
  - To get agreement on the allocation of requirement on these task interface issues
  - And to derive human engineered design solutions for these requirements

HFEAT

Human/System Interface

Issues

Requirement (Source, Title, Sub Section, and requirement words)

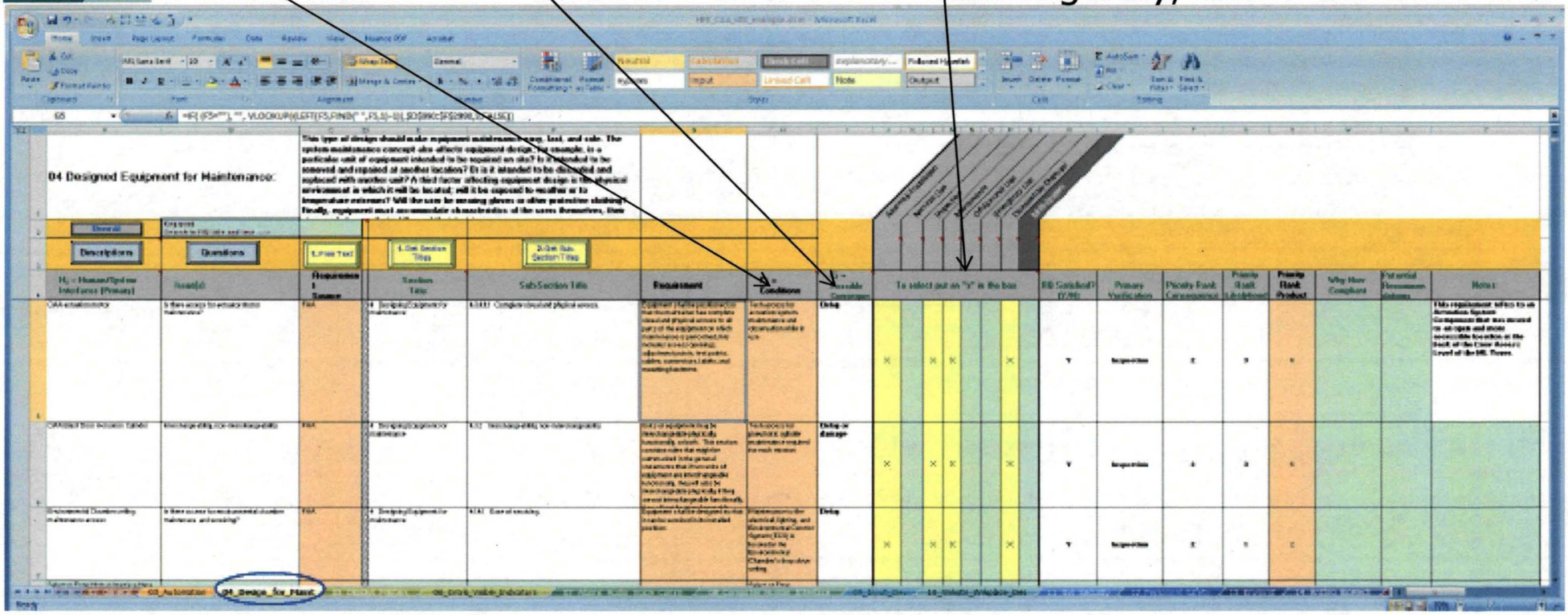


HFEAT

Conditions

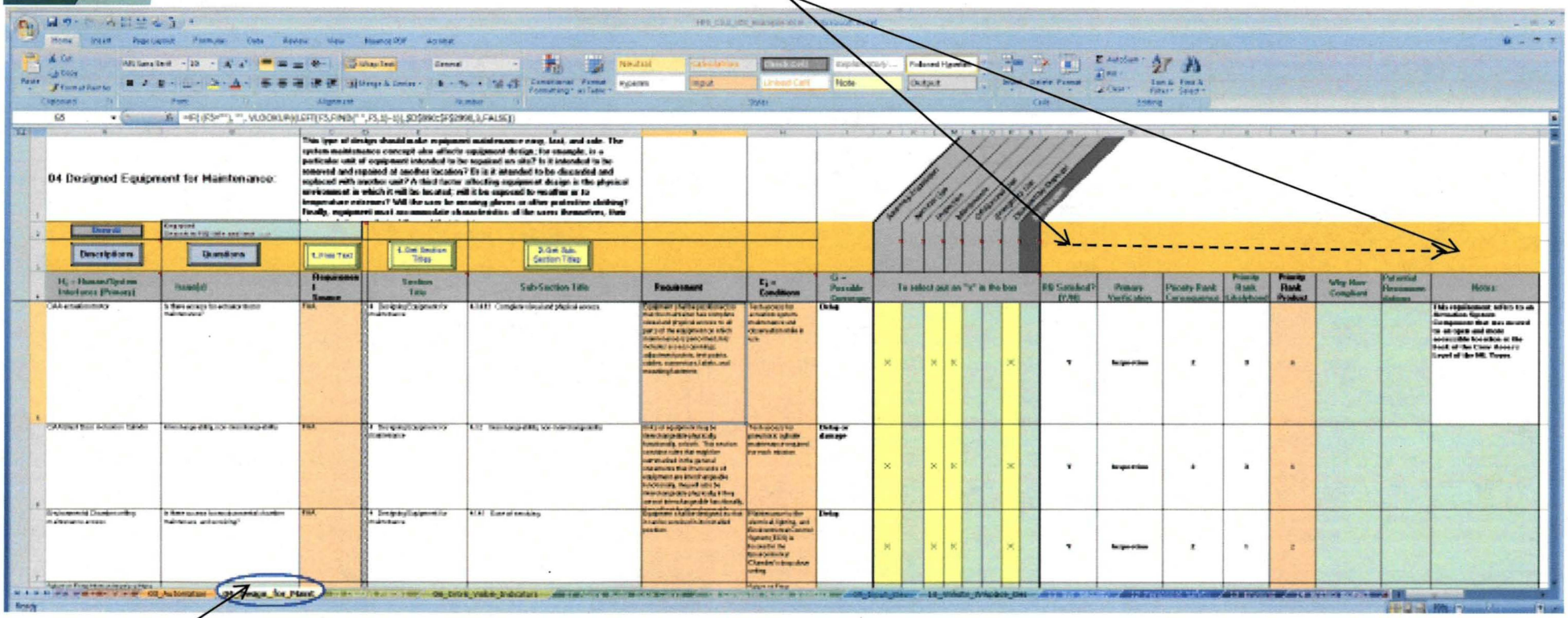
Consequences

Type of processing, Assembly, Nominal, inspection, Emergency, etc.



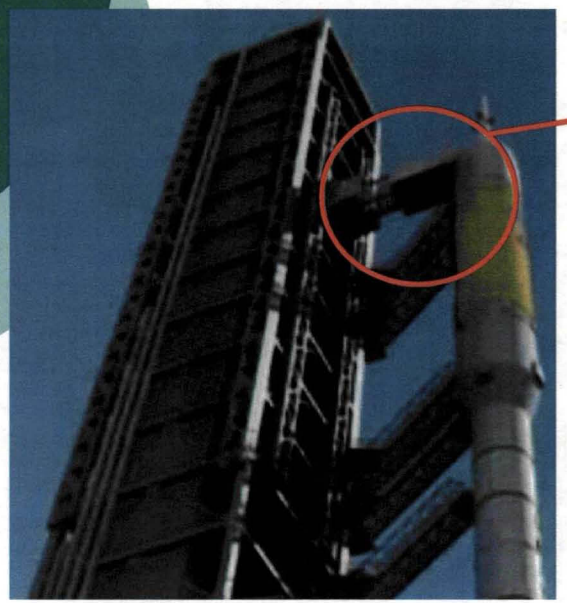
HFEAT

Requirement Satisfied, Verification, Consequence, Likelihood, Priority Rank, Why Non-Compliant, Recommendation, Notes.

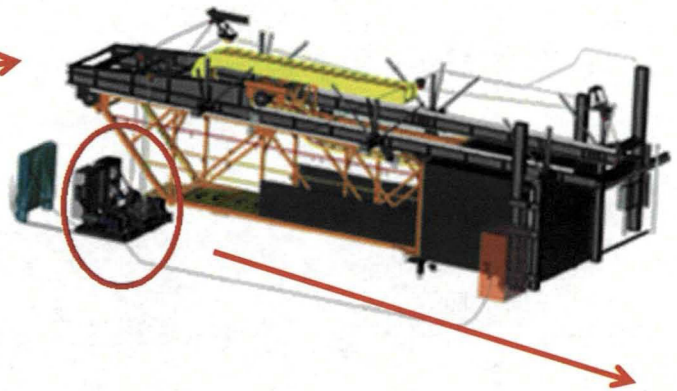


Example Actuator Motor

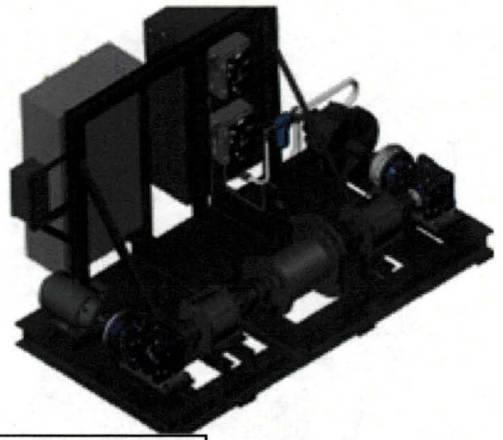
Mobile Launcher



Crew Access Arm



Actuator Motor

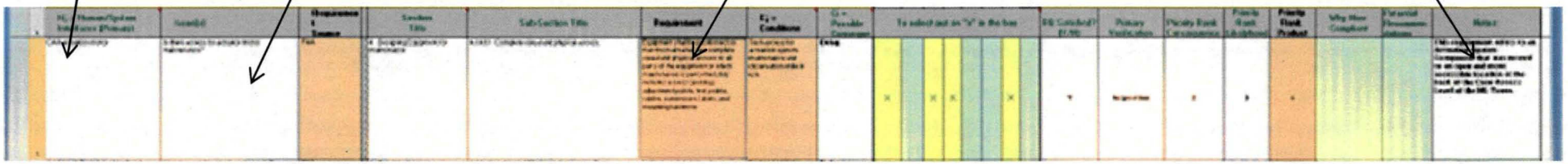


Actuator Motor

Access for maintenance

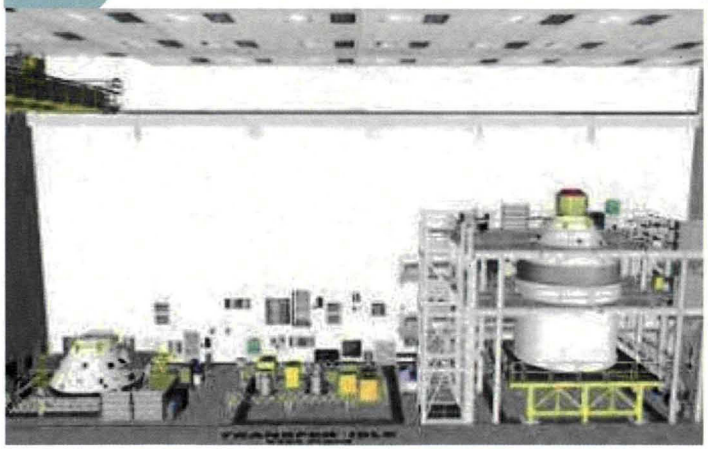
Complete visual and physical access

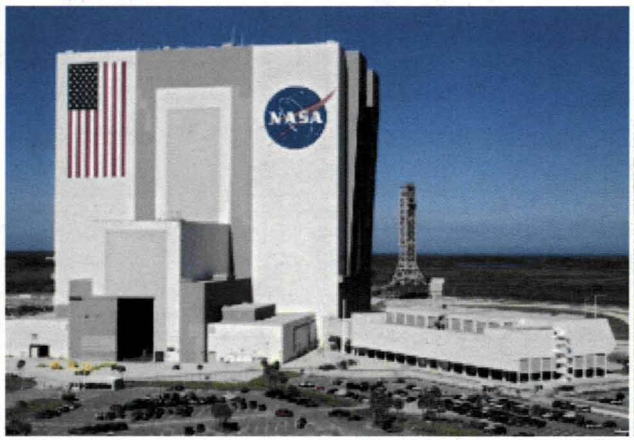
Move the motor



A 2

Orion Time line HF Analysis







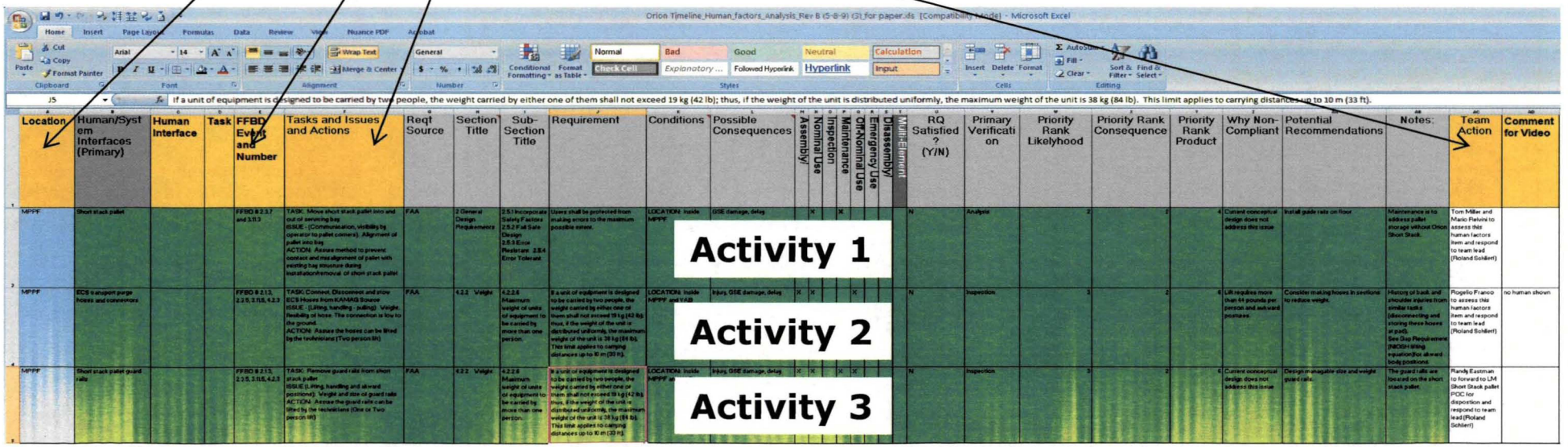
Orion Time line HF Analysis

- Orion vehicle goes through several areas and stages of processing before its launched at the Kennedy Space Center
  - In order to have efficient and effective processing, all of the activities need have a human factors engineering analysis
  - Corresponding Human factors requirements and design solutions needed to be defined

- Areas of Processing
  - MPPF (Crew module and Service module)
  - Vehicle Integration Building (VAB) (Crew module/Service module to Launch Vehicle and Ground Support Equipment
  - Launch Pad

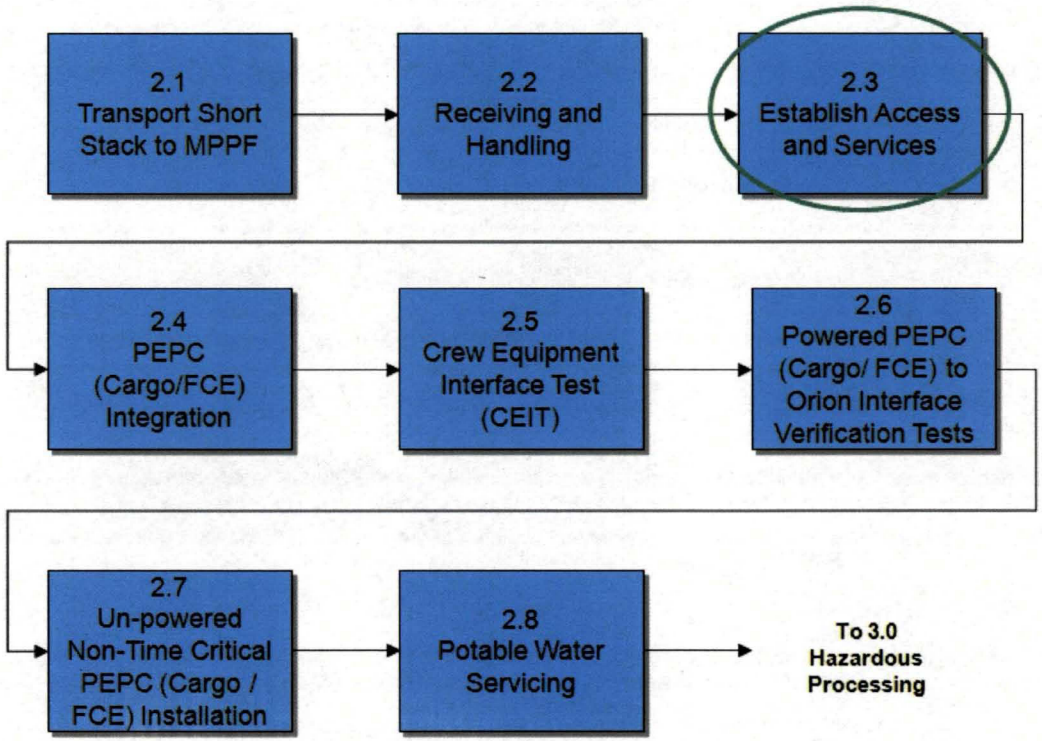
Modification of HFEAT for Timeline Analysis

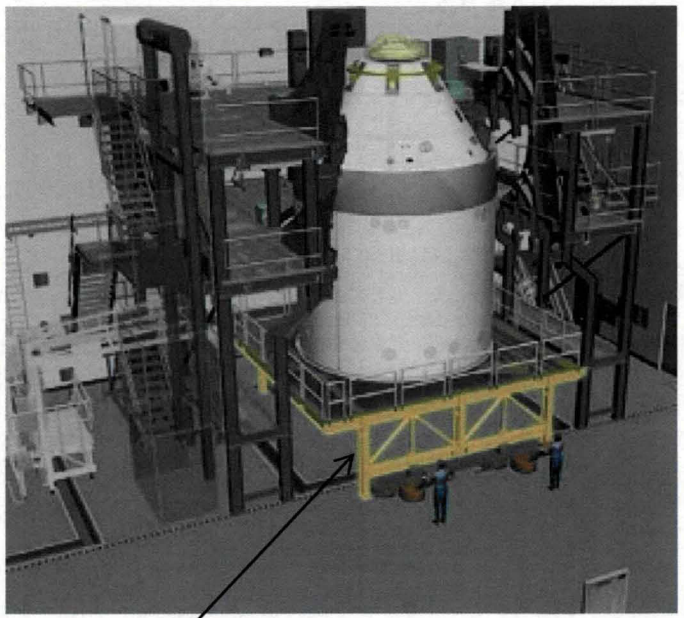
- The HFEAT was modified to analyze the task in a timeline, and additional input columns were added.
  - Location
  - FFBD Event and Number
  - Tasks, Issues and Actions
  - Team Actions



Example of Establishing Access in MPPF

Functional flow block diagram at MPPF



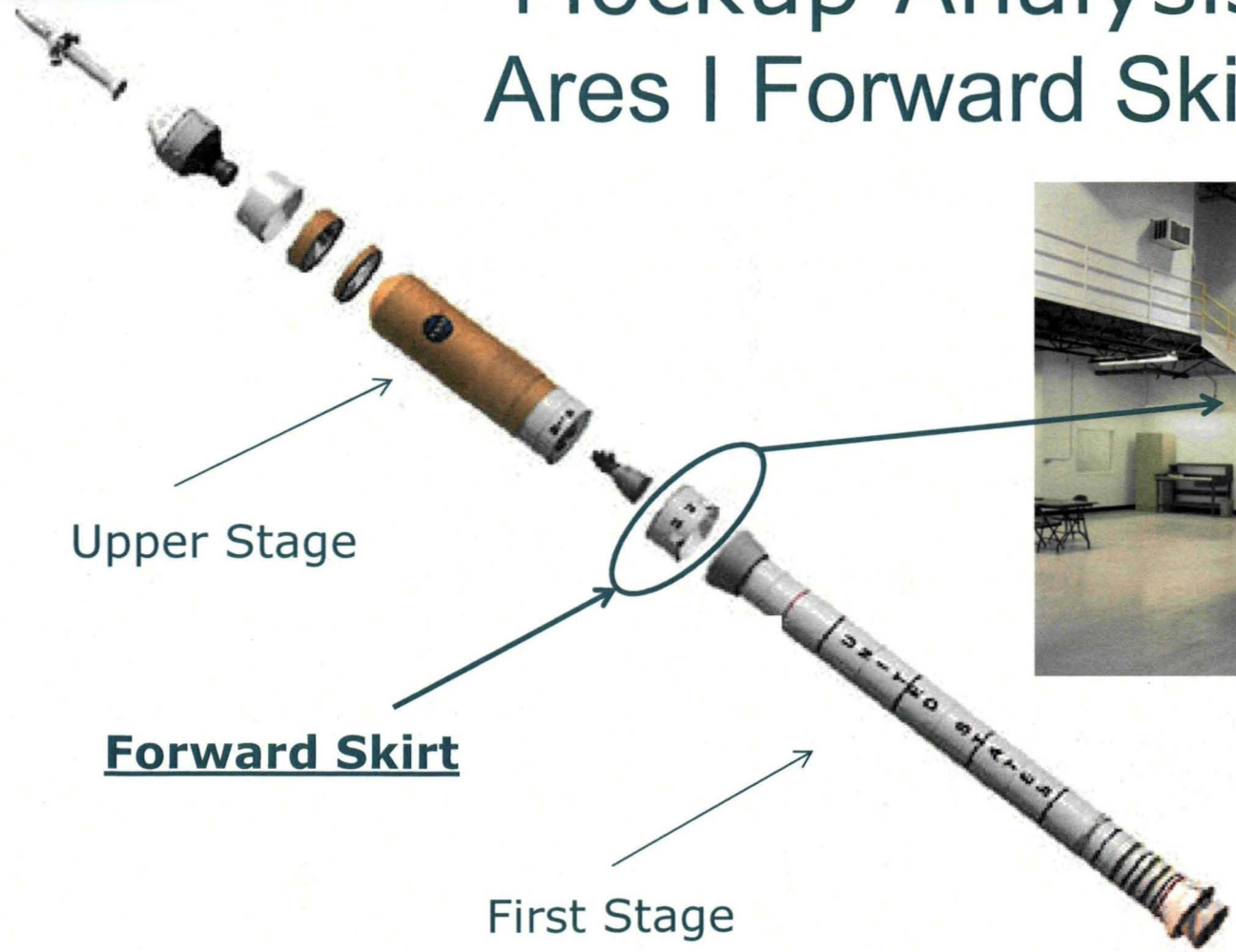


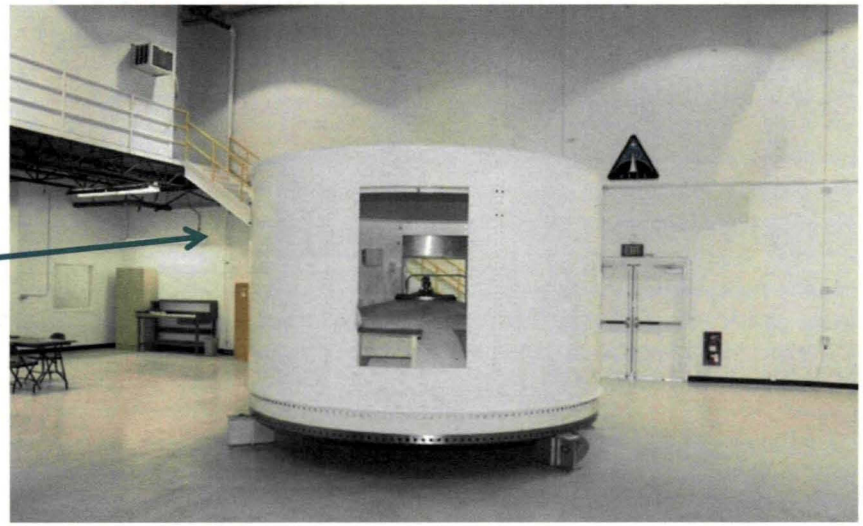
Short stack pallet



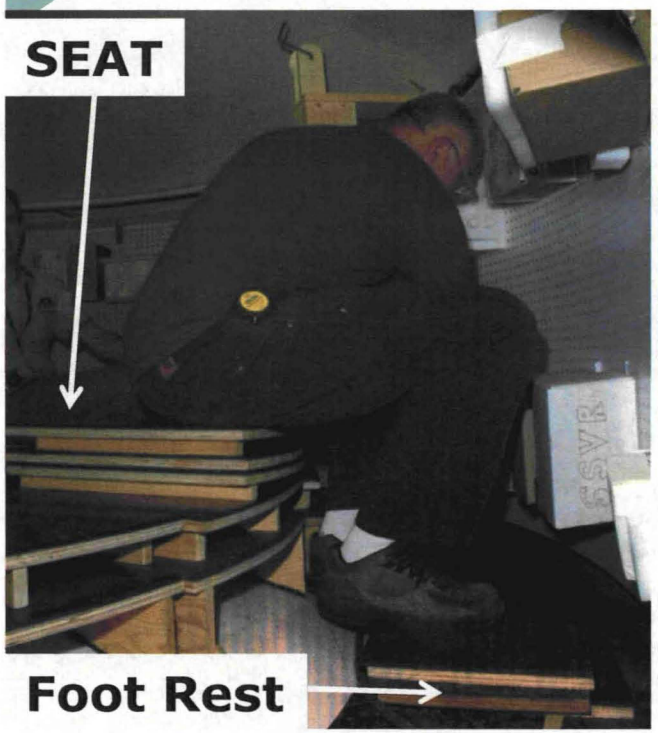
A 3

Mockup Analysis
Ares I Forward Skirt





Example Ground Support Equipment



- There is little that can be done to change these cramped dimensions in rocket design, so adjustments were made to:
  - the ground support equipment
  - box placement locations and heights
- The ground support equipment acts as a seat, and foot rest.
- Ground support equipment installed to:
  - protect the technician from injury
  - protect the flight hardware from damage

Avionics Boxes

- The analysis determined the best locations of avionics boxes based on the technicians location capabilities and:
  - Box weight
  - Tool access
  - Hand volumes
  - Cable routes



Hatch





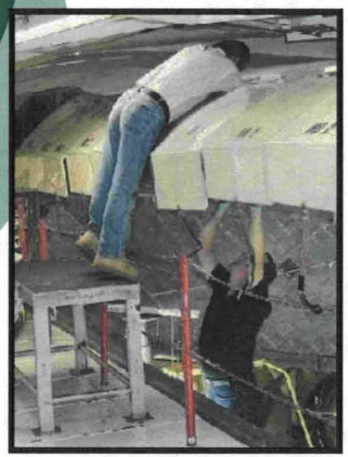




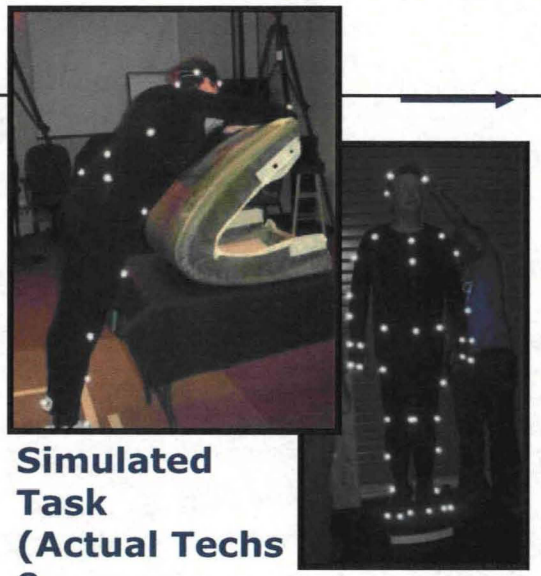
A 4

Assessing Human Factors using Motion Capture

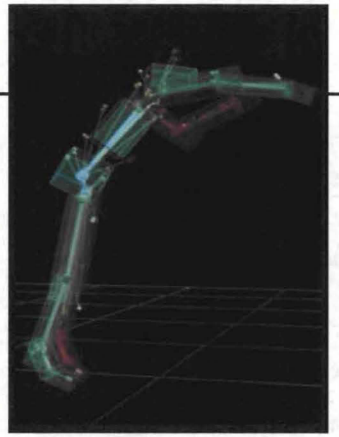
KSC Human Engineering Modeling and Performance Laboratory (HEMAP) Motion Capture to CAD to HF Analysis Process



Real-time Task



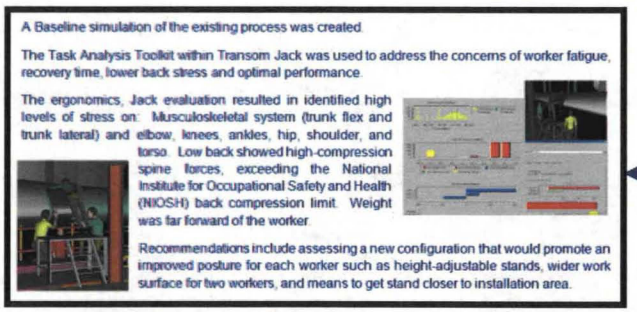
Simulated Task (Actual Techs & Biomechanical Data)



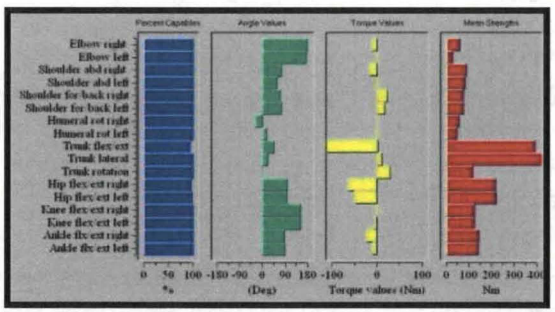
Motion Capture



Simulations



Human Factors Analyses/Recommendations



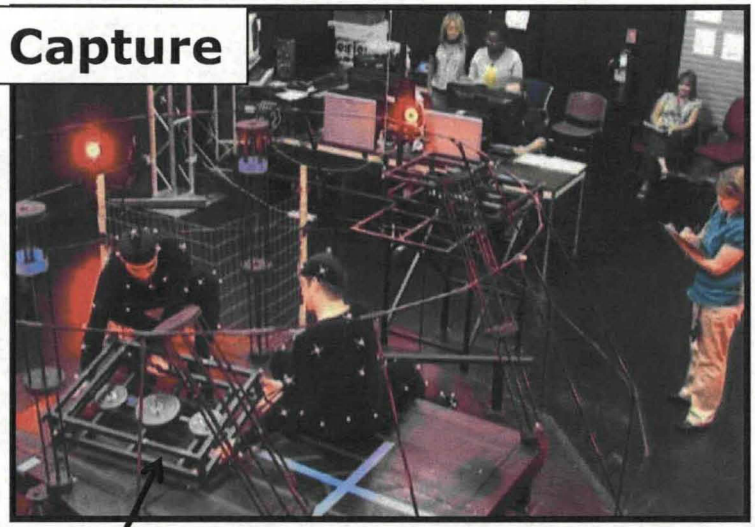
Ergonomic Analysis Output/Indicators

HEMAP supports multiple person/object tracking plus live ergonomic analyses

Orion Seat R&R

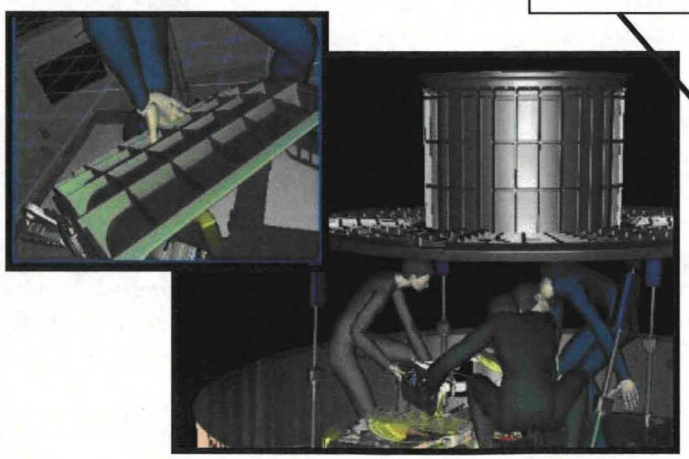


Motion Capture

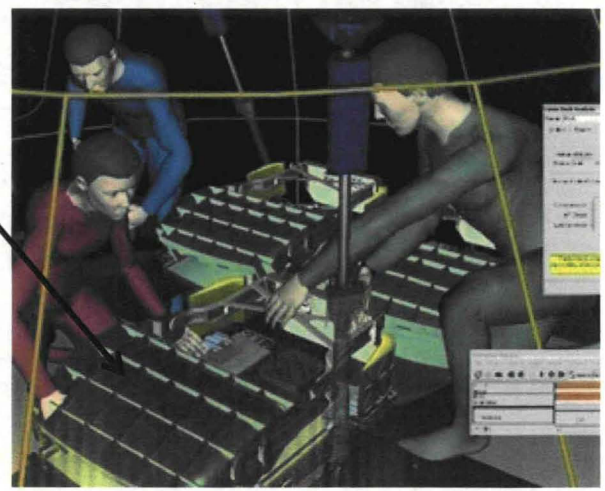


CAD Models with Human Models

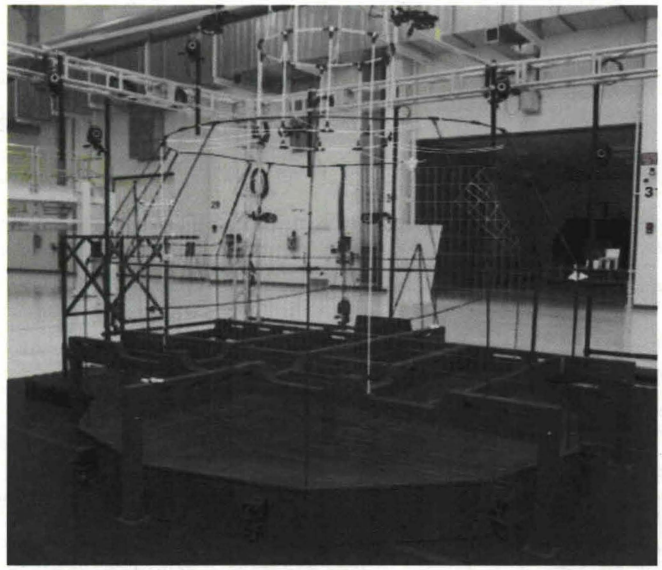


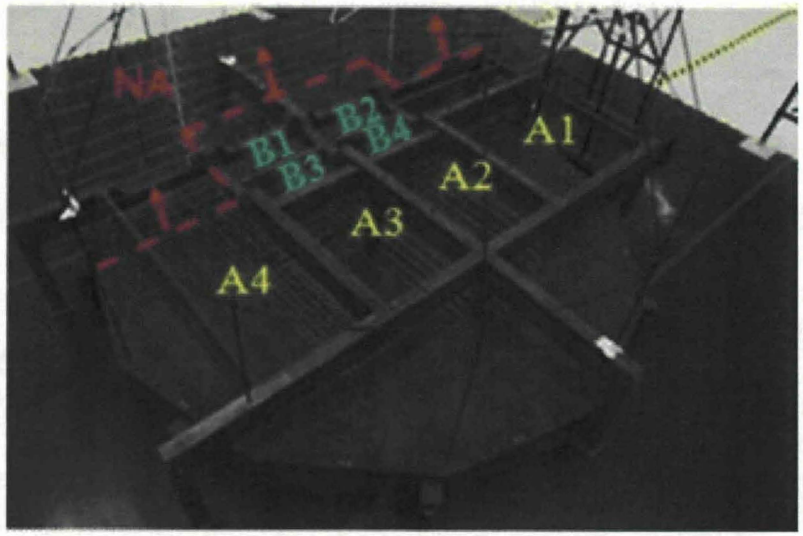


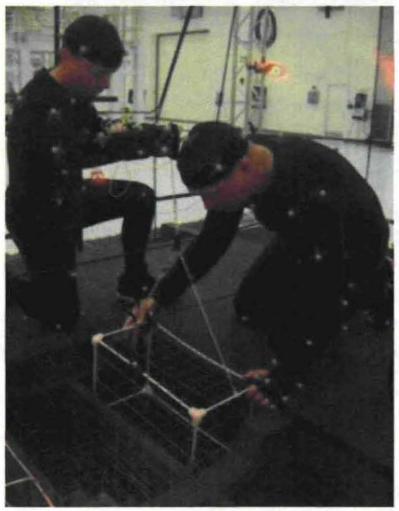
SEAT

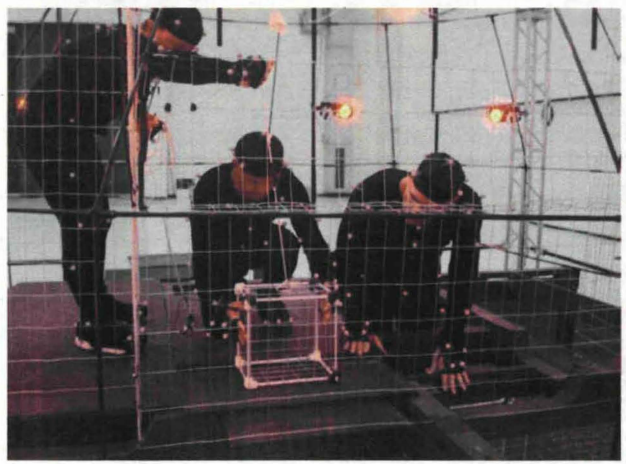


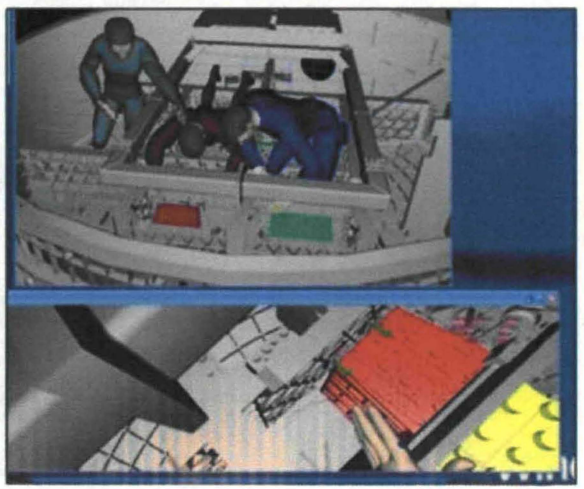
Orion Avionics Box Installation



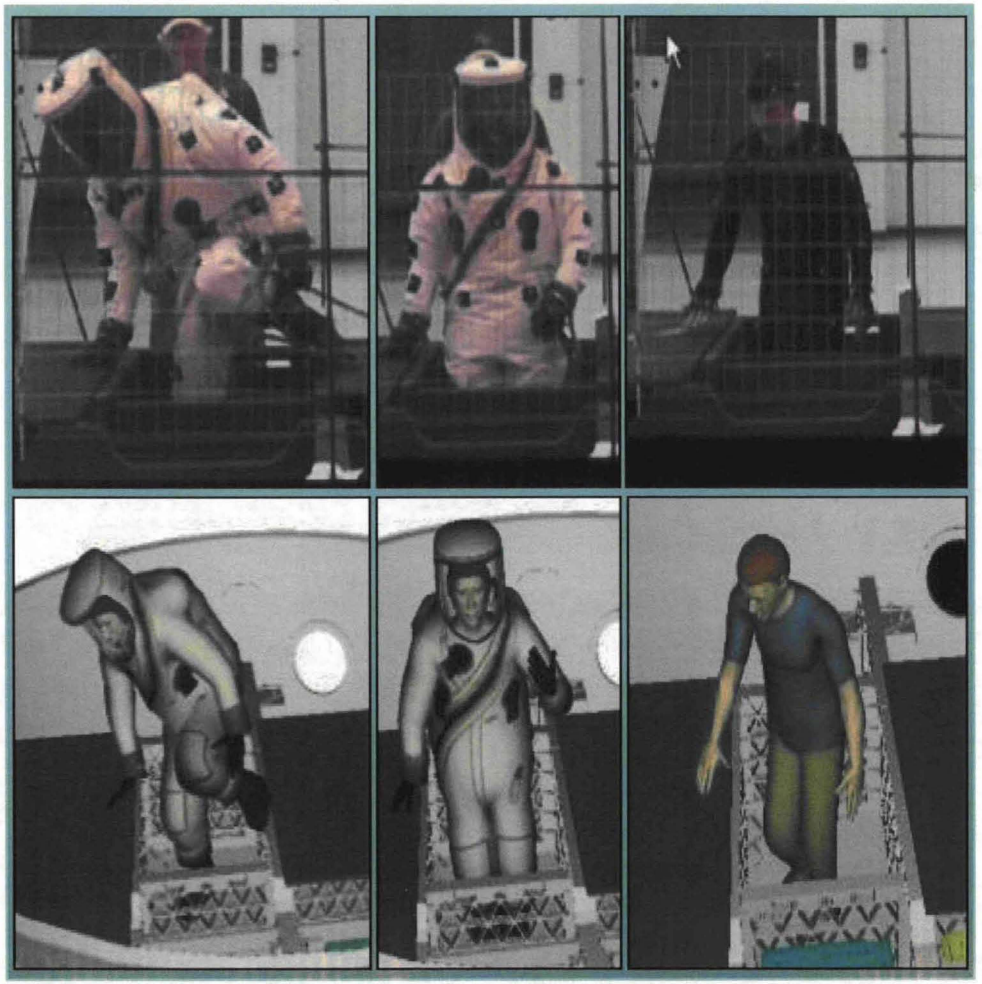








Self-Contained Atmospheric Protective Ensemble
SCAPE Suit



Markers placed on SCAPE suits to create actual life size and motion of suits

HEMAP Most Recent Accomplishments

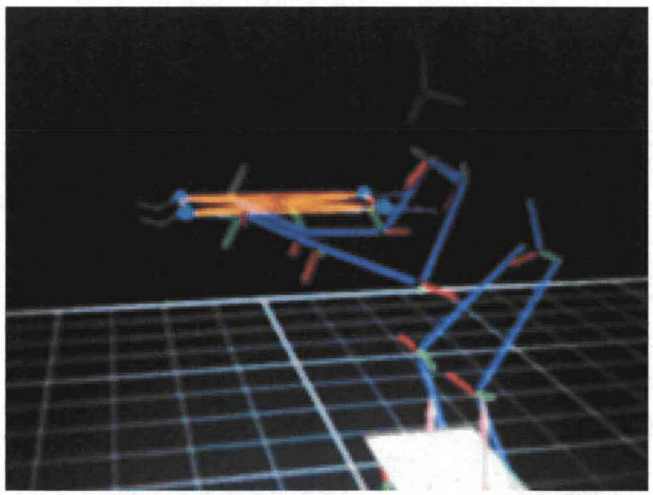
- Interactive virtual collaboration of motion capture data among KSC and MSFC
  - The web sharing of motion capture tasks within the shared virtual environment provides real-time ability to update designs based on actual human-system interfaces being evaluated.

HEMAP Most Recent Accomplishments

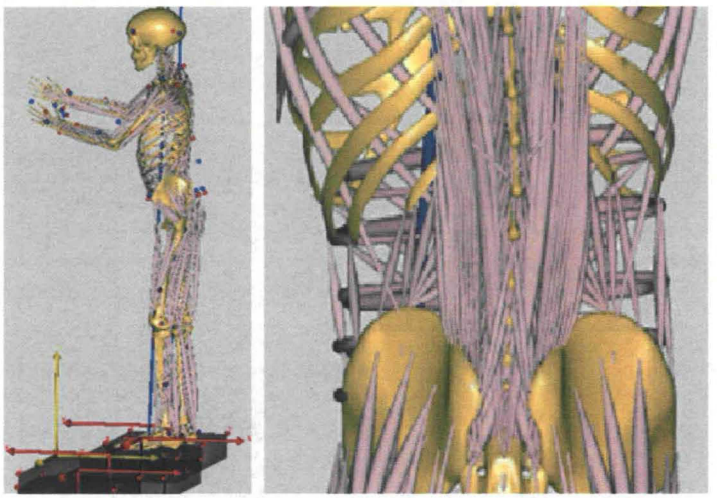
- Incorporation of wearable Head-Mounted Displays (HMDs):
  - Negates need for physical mockups.
  - Familiarization/training benefits
  - Collaborative web sharing of models and live motion tracking among NASA centers
  - Immersing the HMD wearers in simple physical mockups

A 5

Biomechanical Analysis of Installing Avionics Boxes

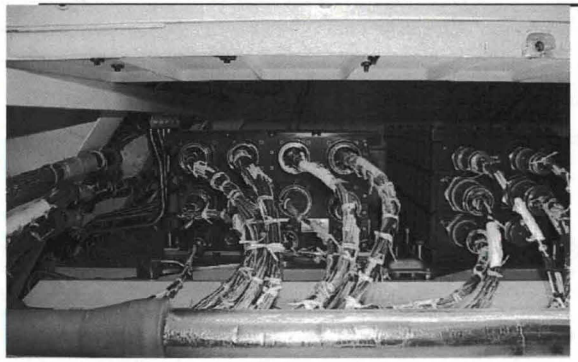


Placing Box Accurately

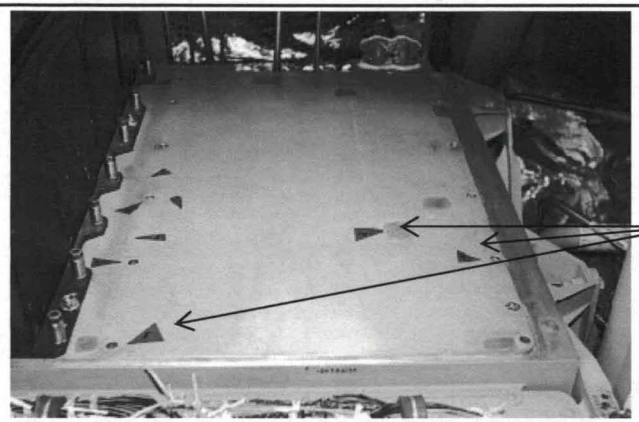


L5/S1 spinal stress

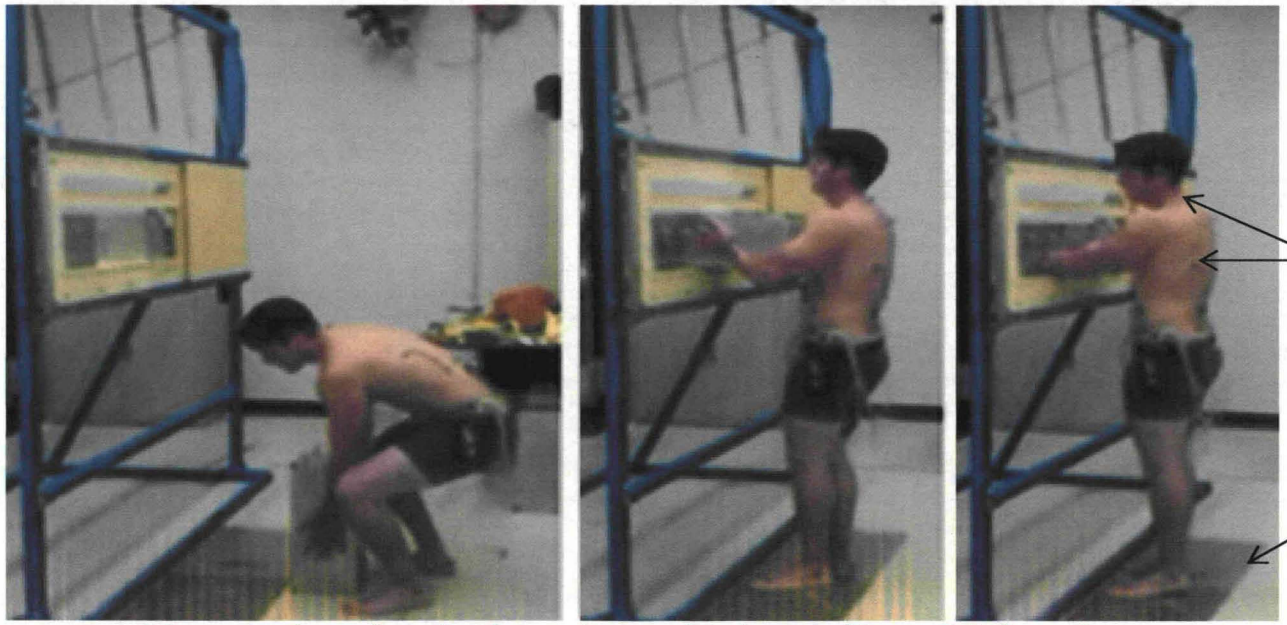
Biomechanical Analysis of Avionics Box Installation



Box in restricted space



Cold plate damage



EMG and reflective markers

Force Plate

Biomechanics Laboratory University of Miami

A 6

Development of Human Factors Engineering Requirements for Ground Task Design for a NASA Flight Program

Janis Connolly
Charles, Jr. H. Dischinger
Keith V. Holubec
Barry Tillman

Development of Human Factors Engineering Requirements for Application to Ground Task Design for a NASA Flight Program

- The National Aeronautics and Space Administration (NASA) has long employed human factors requirements for development of flight systems.
- NASA-STD-3000 does not include human factors design requirements for ground tasks, and therefore, programs have not been required to develop human factors requirements for ground crew tasks.
- The result has been that ground crews have had to develop complicated strategies for accomplishment of ground assembly and maintenance of flight systems.
- The Constellation Program (the execution program for the Exploration Vision) has accepted the responsibility, imposed by the NASA Administrator, to find ways to reduce ground operations costs. One of the ways the Program is doing this is through the application of human factors design requirements for the ground processing to flight systems.

Human Systems Integration Requirements (HSIR)

1.2 SCOPE AND PRECEDENCE

The requirements in this document are applicable to the Constellation Systems, including but not limited to Orion, Ares I, Ares V, Altair, Mission Systems (MS), Ground Operations (GO), Extravehicular Activity (EVA), and Flight Crew Equipment (FCE)

The requirements in this document address the needs of the flight crew during all phases of flight. These requirements also address the needs of ground personnel during pre-flight preparation, maintenance, and post-flight activities on the flight vehicles where there is a common interface with the flight crew

Human Systems Integration Requirements (HSIR)

3.9 GROUND MAINTENANCE AND ASSEMBLY

This section addresses tasks to be performed by NASA and its launch site contractors in accomplishment of launch site processing and ground maintenance. Launch site processing includes vehicle assembly (e.g., Ares I + Orion) activities that occur within the Outer Mold Line of the Launch Stack, Launch Stack physical integration (e.g., umbilical integration), and launch preparation (e.g., propellant loading). Ground maintenance includes corrective and preventive maintenance activities associated with Line Replaceable Unit (LRU) removal and replacement. These requirements do not apply to unplanned repair at the launch site, build activities at the manufacturing site, or potential build up at the launch site prior to system integration (for example, build up of the Orion). The requirements in this section apply only to those aspects of design that are under direct control of the vehicle developers, but not to the design of external Ground Support Equipment (GSE) and test systems. These requirements do not apply to any powered portable equipment that is intended for flight.

NASA-STD-3001, VOLUME 2

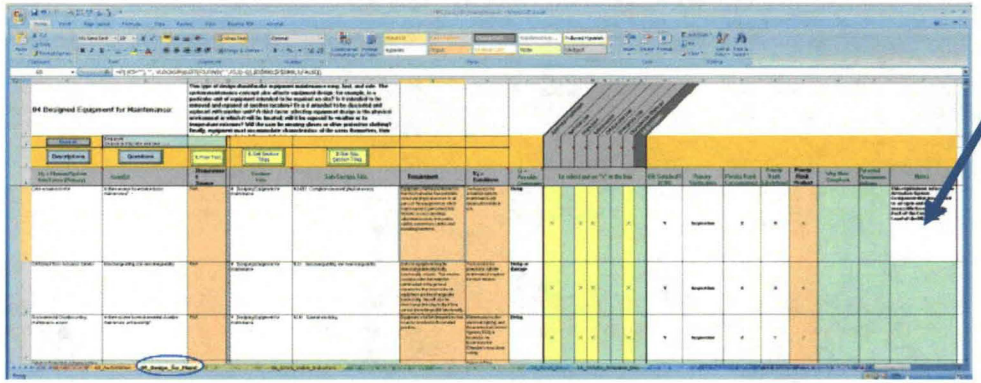
Section 13, Ground Maintenance and Assembly, will address the requirements for the configuration of interfaces that are common to both flight crew and ground personnel. This section is currently marked reserved and will be developed during Fiscal Year 2010.

https://standards.nasa.gov/documents/viewdoc/3315785/3315785

- Pro E Manikin
- KSC Design Visualization
- KSC Display/Control Screens

A 7

Pro E Manikin



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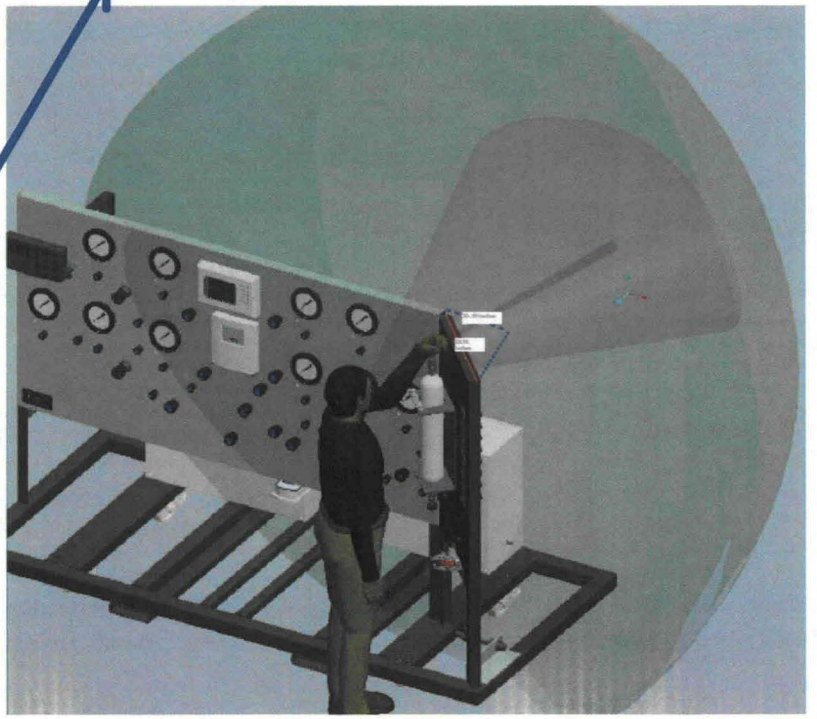

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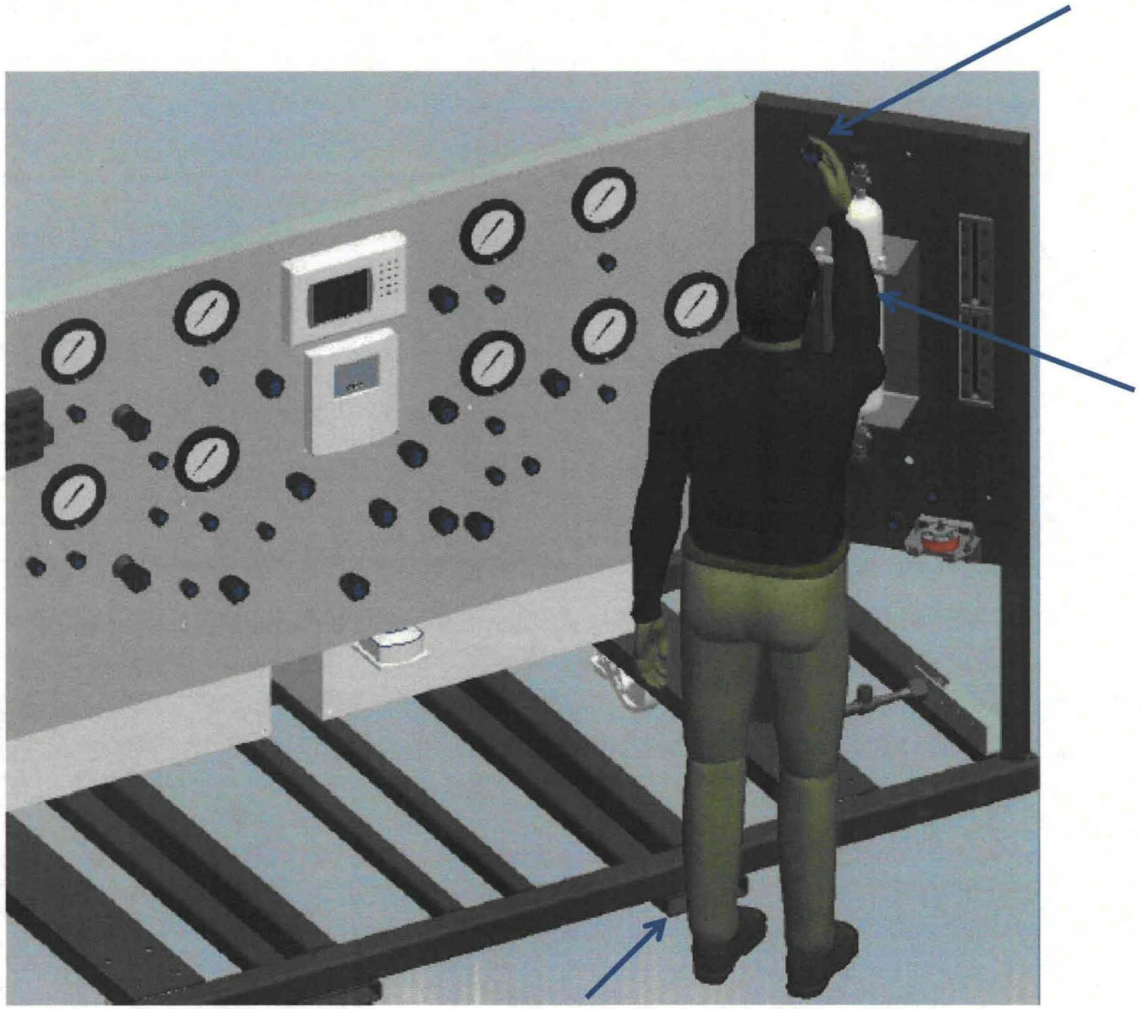

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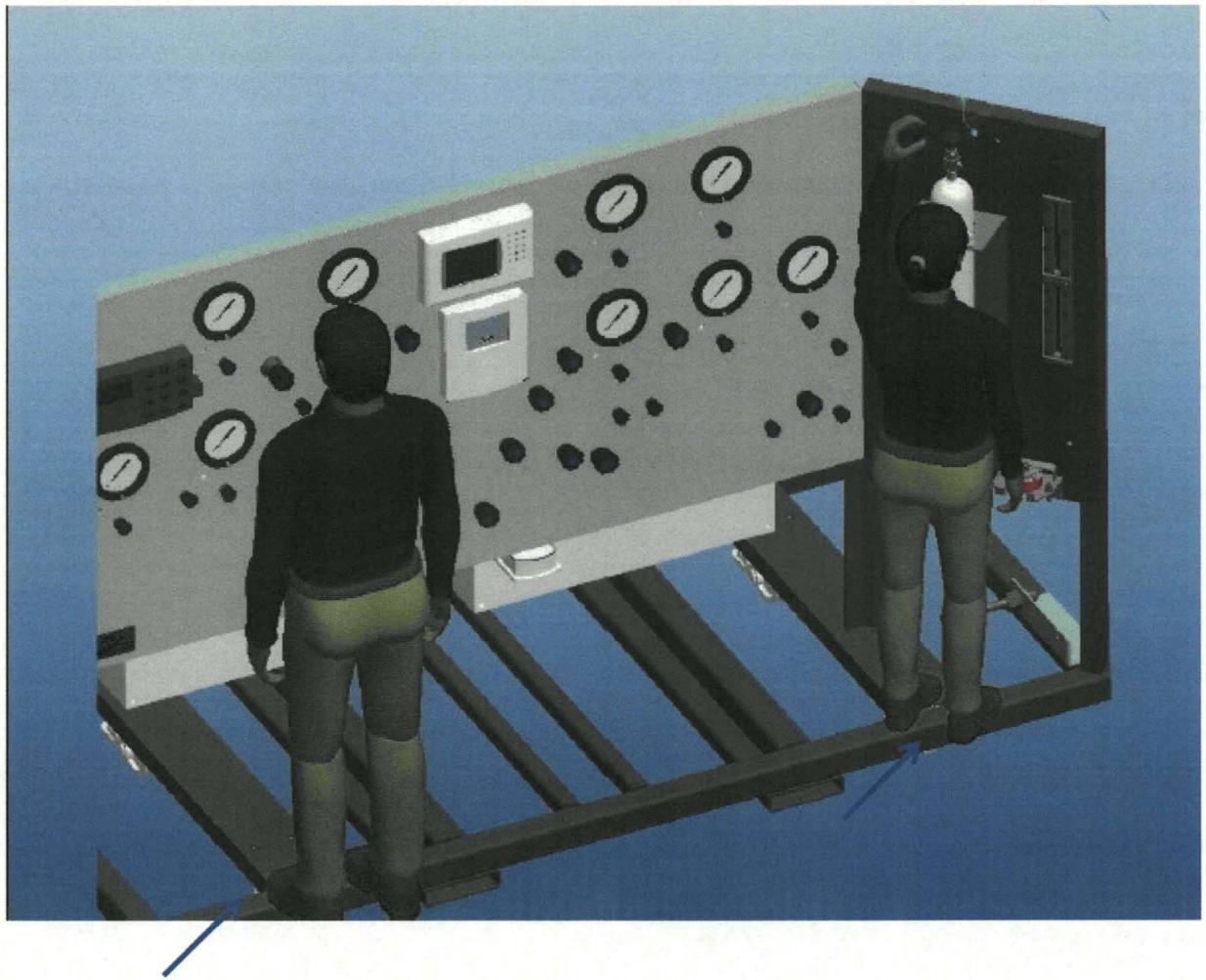

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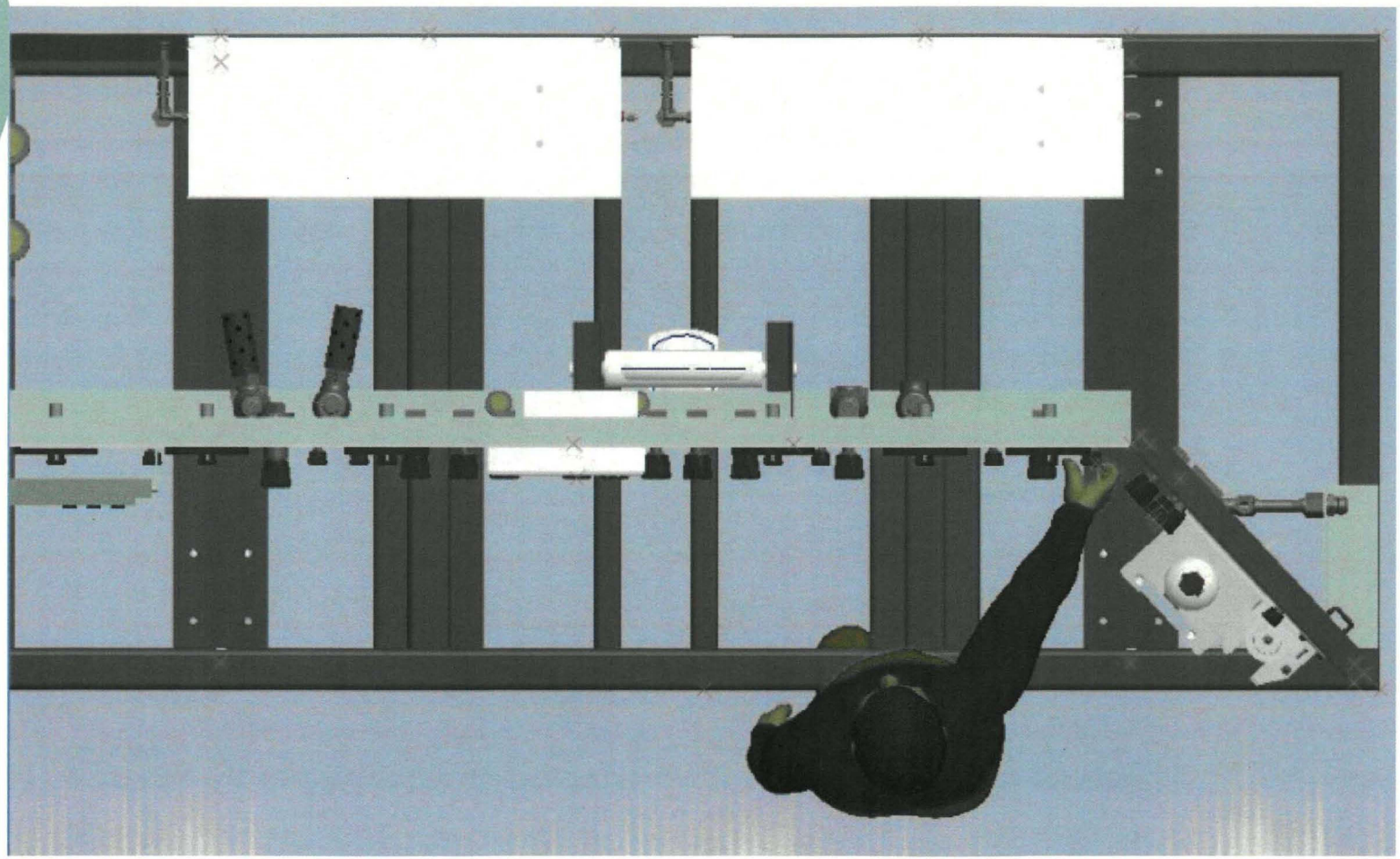
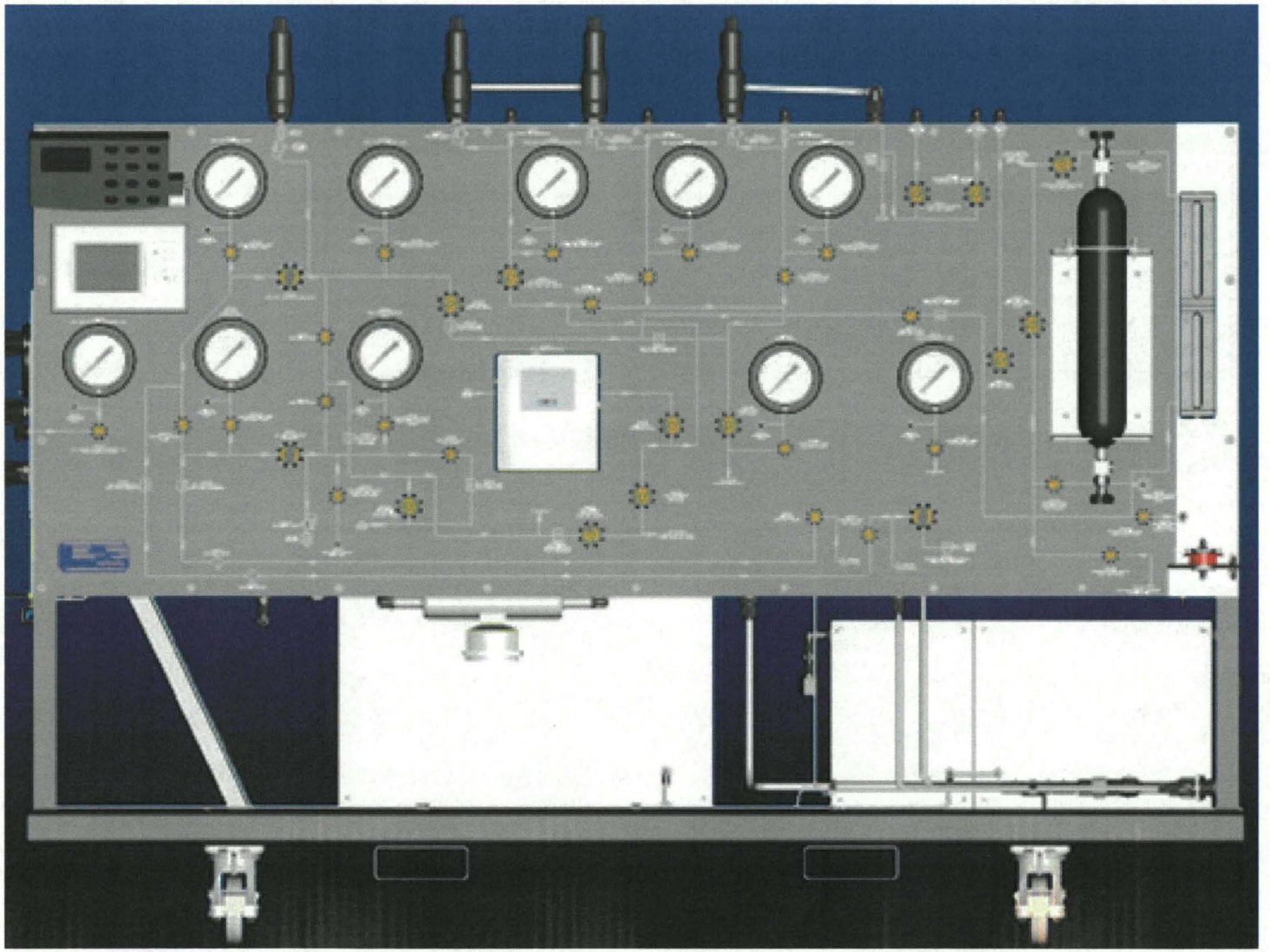


Solution



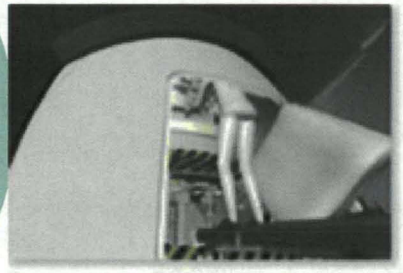
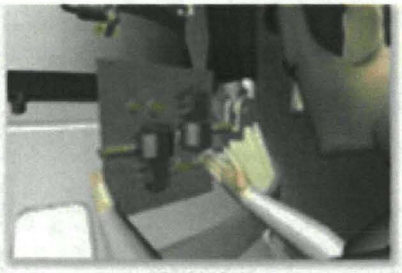
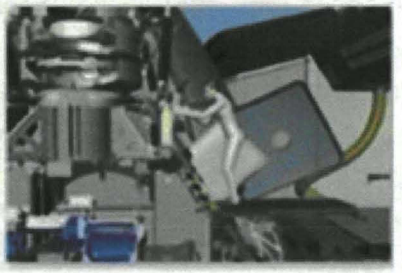
A 8

KSC Design Visualization

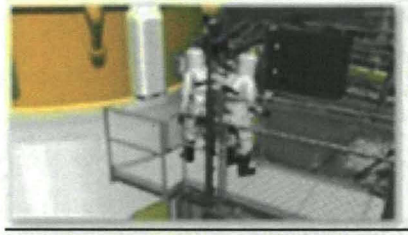
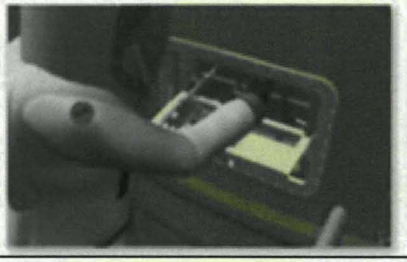
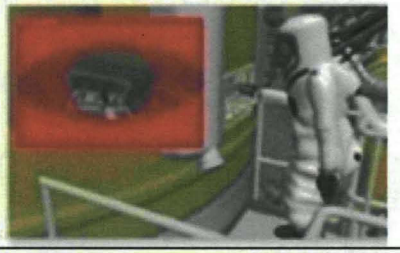
Simulation-Based Human Factors Kennedy Space Center has the capability to analyze human factors.

These factors include sight lines, visibility, reach, motion, joint loading, repetition, calories and any additional impediments caused by safety or life support systems.

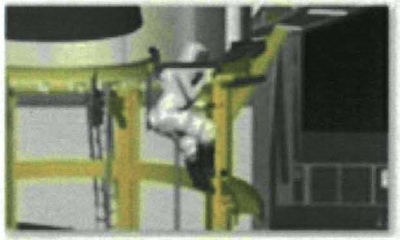
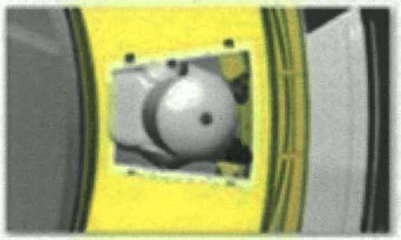
KSC Design Visualization

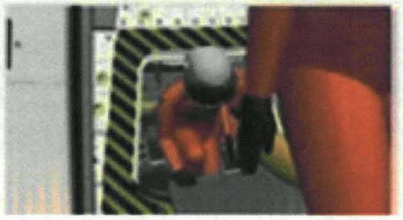
LAS safe and arm access at PAD

SCAPE fueling

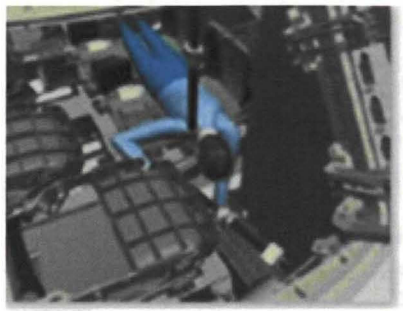
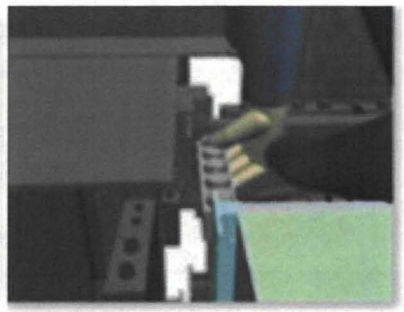




SCAPE access

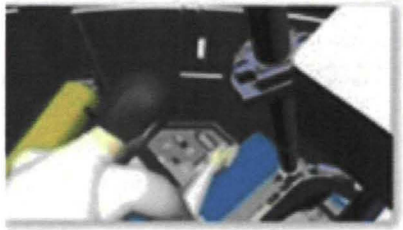
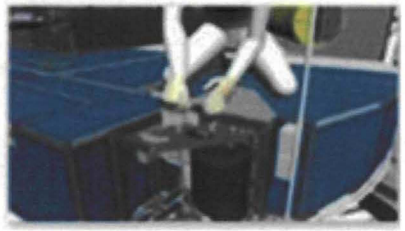




Astronaut emergency egress

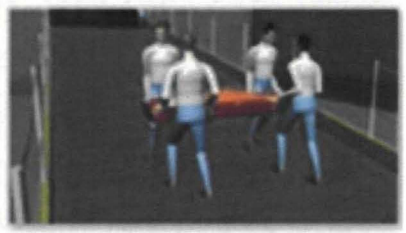
KSC Design Visualization

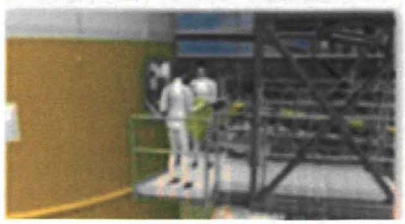
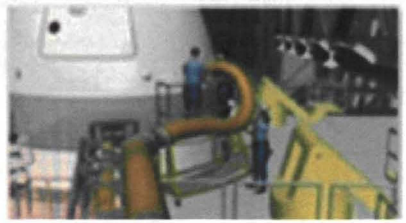
Pryo access

Water filter access

Astronaut egress post flight

Access arm assessment

A 9

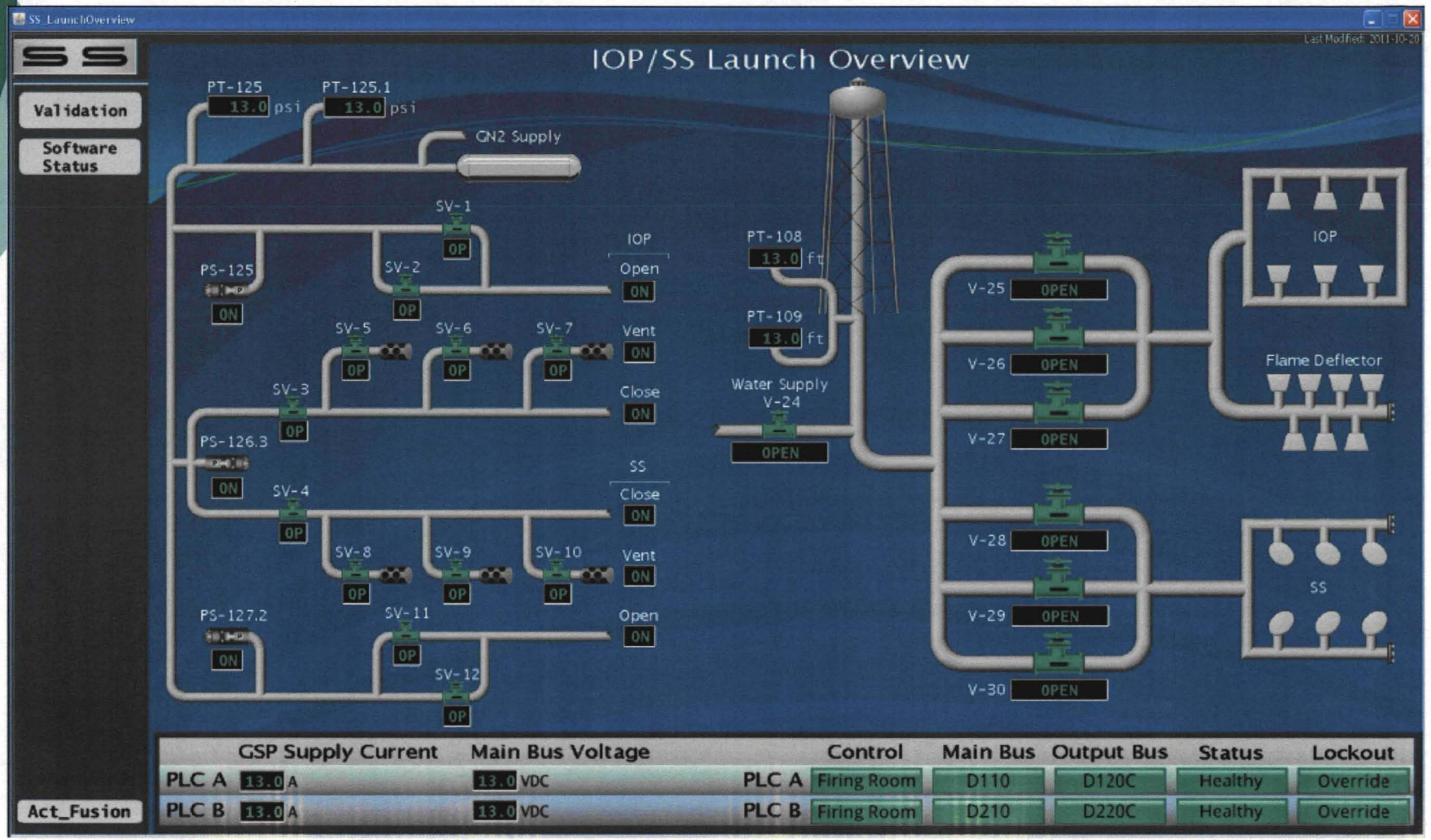
KSC Display/Control Screens

A 9

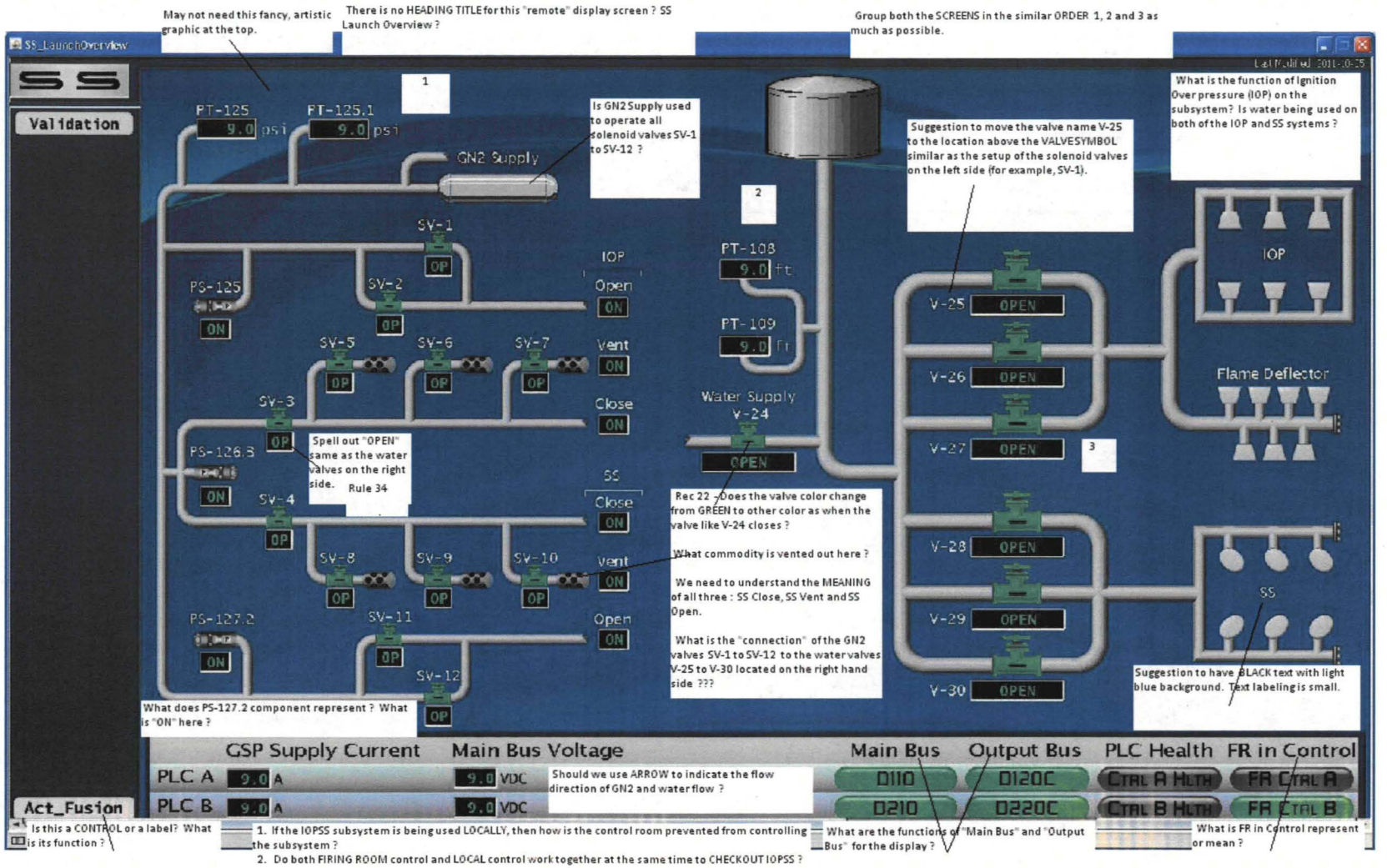
Local and Remote(LCS)

- Human Machine Interface (HMI) Programming Guidelines, (KGCS) local screen guidelines document
- Ground Elements Integrated Launch Operations Application Software Implementation Standards (ILOA) human factors section for local and remote screen design.
- Screens currently under development
  - GSP (Ground Special Power)
  - ECS (Environmental Control System)
  - CMASS (Crew Module Ammonia Servicing System)
  - FLDS (Fire Detection)
  - LH2/LO2
  - IOPSS (Ignition Overpressure Sound Suppression)

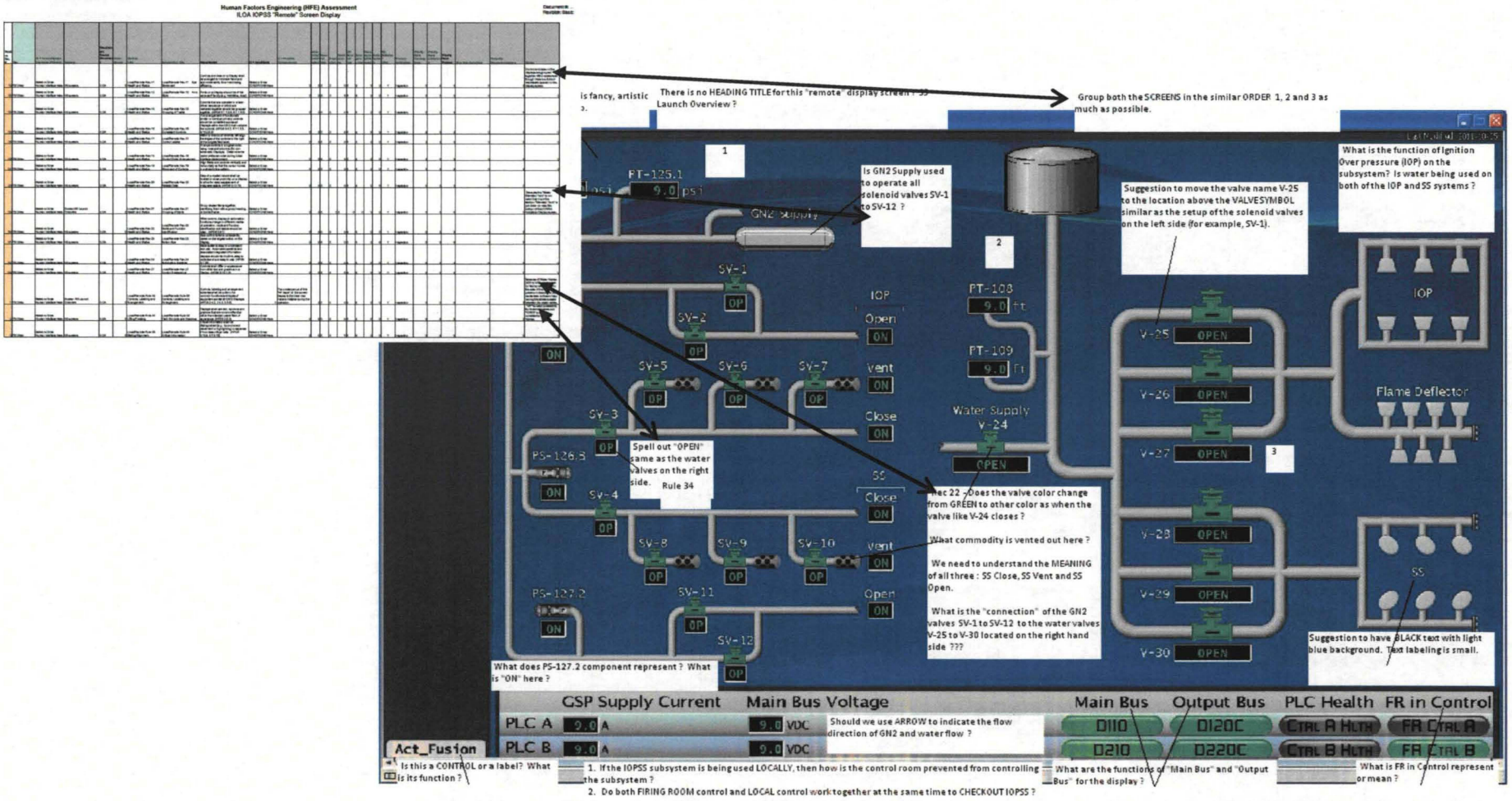
IOPSS Screen Shot



Screen Shot With HFEA Notes



Screen Shot With HFEA Notes



HFEA Report

Human Factors Engineering (HFE) Assessment
ILOA IOPSS "Remote" Screen Display

Document #: ...
Revision: Basic

Requirement Key #	Tab	HE = Human/System Interface (Primary?)	Issue(s)	Regulation and Practice Document(s)	Shall / Should	Section Title	Rule/Section Title	Requirement	CI = Check/Book	C = Possible Comments/Issues	Rate design initial (after)	Need/ risk Use	Scope (Risk)	Mental wkld.	HR Hand-held Use	Glove (gen. Use)	Glasses (work Spec)	Shall Guide	SD Satisfied ? (YES)	Priority (w/Rationale)	Priority Rank Comments	Priority Rank Likelihood	Priority Rank Product	Who Not Consulted	Picker/Set Resolution/Status	Notes
19	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rev.11 Health and Status	Local/Remote-Rev.11 Eye Movement	Controls and data on a Display shall be arranged to minimize hand and eye movements, thus maximizing efficiency.	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		Control and data on the displays are grouped together within areas even though there is a limit of real estate (space) on the display screen.
20	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rev.12 Health and Status	Local/Remote-Rev.12 Font Style	Fonts on a Display should be of the sans-serif family (e.g. Helvetica, Arial).	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		
22	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rev.15 Health and Status	Local/Remote-Rev.15 Grouping of Tasks	Controls that are operated in a task-driven sequence or which are operated together should be grouped together. (HFDS 6.5.1.3.3, 6.5.1.3.5)	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		
24	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rev.18 Health and Status	Local/Remote-Rev.18 Consistent Controls	The arrangement of functionally similar or identical primary controls should be consistent across all Displays within the CWC that contain the controls. (HFDS 6.4.2, 6.1.1.3.5, 6.14.2.6.3)	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		
25	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rev.17 Health and Status	Local/Remote-Rev.17 Control Labels	Within a column of controls, left-align the edges of the controls to the right of the longest field label.	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		
26	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rev.16 Health and Status	Local/Remote-Rev.16 Control Order Arrangement	Arrange controls in a logical order, using rows and columns (for non-schematic Displays). Determine the users' preferred order during initial interface development.	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		
27	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rev.19 Health and Status	Local/Remote-Rev.19 Movement of Controls	Align fields and controls vertically and horizontally so that the cursor moves in a straight line pattern.	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		
28	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rev.20 Health and Status	Local/Remote-Rev.20 Related Data	Data of a related nature shall be located in close proximity on a Display to allow for easy assessment of integrated status. (HFDS 6.12.10)	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		
29	18 Other	Reject or Note Human Interface Here	Screen XII Launch Overview	ILOA		Local/Remote-Rev.21 Health and Status	Local/Remote-Rev.21 Grouping of Items	Group related items together, identifying them with a group heading or border/frame.	Reject or Note CONDITION# Here		0	0	X		EX		0	0	0	0	Y	Inspection		0	0	0		Because the "Water Elevated Tank" is not used that much the section "Elevated Tank" is put down on near the bottom of the IOPSS Validation Display screen.
30	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rev.22 Health and Status	Local/Remote-Rev.22 Mode and Function Identification	When control, display or automation functions change in different modes of operation, mode and function identification and status should be clear. (HFDS 6.6.1)	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		
31	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rev.23 Health and Status	Local/Remote-Rev.23 Action Area	Size control buttons consistently, based on the largest button on the Display.	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		
32	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rev.24 Health and Status	Local/Remote-Rev.24 Automation Systems	Make systems easy to understand and use. Automated systems and associated integrated information displays should be intuitive, easy to understand and easy to use. (HFDS 6.1.10)	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		
34	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rev.27 Health and Status	Local/Remote-Rev.27 Control Appearance	Controls shall differ in appearance from other text and graphics in a Display. (HFDS 6.13.1.2)	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		
1	18 Other	Reject or Note Human Interface Here	Screen XII Launch Overview	ILOA		Local/Remote-Rule-03 Controls, Labeling and Arrangement	Local/Remote-Rule-03 Controls, Labeling and Arrangement	Controls, labeling and arrangement schemes shall be uniform for common functions and types of equipment across all CWC Displays. (HFDS 2.4.2, 2.4.3, 3.6.6)		The consequence of this "HF Issue" of the screen display is the User may make a mistake during the Operation.	0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		Because of Water Valves (V05 to V06) are stacked by having valve labels to the side of the valve position indicator this will cause less confusion than having the labels located between the water valves.
2	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rule-04 Utility/Plumbing	Local/Remote-Rule-04 Text, Symbols and Graphics	Displays shall use text, symbols and graphics that are commonly/familiar within the intended users' field of experience. (HFDS 2.6.1)	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		"OPP" is used consistently for Solenoid Valves and "CPRP" is used consistently for Water Valves.
3	18 Other	Reject or Note Human Interface Here	All screens	ILOA		Local/Remote-Rule-05 Valving/Alignment	Local/Remote-Rule-05 Critical Information	Critical information shall be distinguished (e.g., by prominent placement or highlighting) to separate it from time-critical data. (HFDS 6.12.9, 6.1.3.13)	Reject or Note CONDITION# Here		0	0	X	X		EX	X		0	0	Y	Inspection		0	0	0		



RECOMMENDATIONS

Recommendations to Agency

- Continue to develop Human Factors requirements and processes at All levels.
- Continue to develop human factors tools, motion capture and other mockups and human modeling.
- Continue the Human factors collaborations between centers for our missions and programs, tools, requirements, and processes.
- Continue to revisit and improve upon these lessons from the past. And develop new lessons as we go through these incremental developments.

Thanks to all the folks at KSC and across the NASA Agency for their efforts towards the human factors achievements for spacecraft ground processing.

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Lessons Learned Briefing
PLSS 2.0

Joe McMann

June 25, 2012

Preliminary Thoughts

- My preparation of this presentation prompted many questions which had not occurred to me during the May 31, 2012, briefing
  - Some questions are not specific to the PLSS 2.0 manufacturing and test topic, but I didn't want to lose them
- Answers provided today will influence the final, written report to be provided after this briefing

Lessons Learned Briefing

- Made up of five components:
  - Comments on what I saw and heard during the briefing, related to my own experience
    - Including questions that I failed to ask earlier
  - Possible risks and some thoughts on how to mitigate them (may revisit some topics from above)
  - Thoughts on what needs to be done to have a complete EVA system (may revisit above comments)
  - Some comments on CTSD – ADV – 780 “Development Specification for the Advanced EMU (AEMU) Portable Life Support System (PLSS)”
  - Random comments

Briefing Material

- Overview – Carly Watts
  - Team – Unbelievable depth
    - Specialists for everything!
    - Very heavy on analysis; maybe short on design
    - Where is manufacturing support on the team?
      - Usually called manufacturing engineering
  - System/Component advancements
    - New technology items just about across the board
      - Up side: if they work as advertised, the system is a step function forward
      - Down side: significant problems with any one can pace the whole system

Briefing Material

- Overview – Carly Watts (cont'd)
  - Project Roadmap
    - Shows a luxuriously-paced schedule – e.g., three iterations after PLSS 2.0 to get a DTO item
    - No tie-in of CWCS 2.0 to PLSS 2.0 shown
      - This is a critical subsystem
      - Need to find problems as soon as possible
    - No tie-in of suit to PLSS 2.0 configuration shown
      - Crew evals with hi-fi mockups
    - Should maybe have an accelerated schedule in your "hip pocket" if funding gets tight, and you need an earlier DTO

Briefing Material

- Overview – Carly Watts (cont'd)
  - PLSS 1.0 findings
    - SWME backpressure valve; RCA pneumatic valve identified as areas for improvement – more on these later
    - Good to see the importance recognized of knowing the configuration, and how it relates to PLSS 2.0
      - Keep that philosophy throughout the program

Briefing Material

- Overview – Carly Watts (cont'd)
  - PLSS 2.0 Development
    - It may be not feasible, but if you could evaluate realistic airlock and suit port interfaces with PLSS 2.0, it could save time later

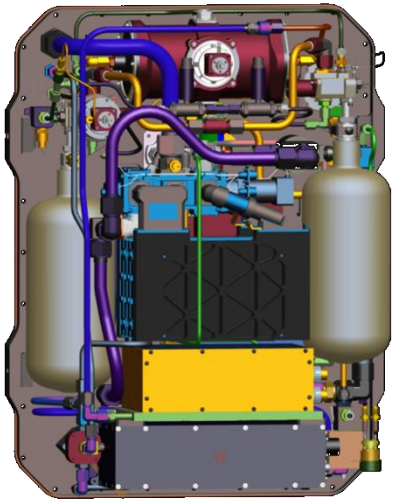
Potential Risks/Possible Mitigation Actions

- Risk
  - **Problems with manufacturing final version (post-PLSS 2.0)**
    - **E.g., accommodation of structural loads**
  - **Difficulty of coordinating "long distance" with Glenn on CWCS/PLSS 2.0 testing at JSC**
  - **Out-year funding problems and/or accelerated schedule**
  - **Problems in integration of suit, PAS, PLSS, Suit-port**
    - **Current plan seems to push integration out pretty far**
- Mitigation
  - **Incorporate Manufacturing Engineering for later versions (see next slide)**
  - **Have Glenn rep. on site for critical testing, starting with CWCS 2.0**
  - **Have "hip-pocket" schedule for getting to DTO configuration faster**
  - **Early evaluations of integrated system – hi-fi mockups; table-top CWCS/controls & displays mockup**

Risk Mitigation

Management

PLSS Hardware



Power, Avionics & Software

Design & Analysis

Manufacturing Engineering

Suggested Addition

Briefing Material

- Test Objectives – Carly Watts
  - PLSS level test objectives
    - Glad to see you plan to run to failure – define that green squatcheloid!
    - Good review comment on demonstrating rapid turnaround – need to explore all the possible ways you can use (and abuse) the system
    - The metabolic simulations need to mimic how humans actually react, e.g., I think that you can hit the RCA with a 3000 btu CO2 load rapidly, but the corresponding water load may lag

Briefing Material

- Test Objectives – Carly Watts (cont'd)
  - PAS
    - Default modes and any manual backups need to be demonstrated – totally automatic makes me nervous
  - Vehicular Interfaces
    - Try to determine what the promising options are for vehicle power supplies
      - Try to simulate expected ripple, impedances, etc.
      - We got some unwelcome surprises in Shuttle
  - Lack of dynamic testing requirements leaves a hole…

Briefing Material

- Test Objectives – Carly Watts (cont'd)
  - I didn't find anything specifically related to crew-operated controls and displays

Risk Mitigation

- Risk
  - Undesirable Reaction of RCA to early hi-CO2/low H2O
    - Sweat rate is reaction to increase in body core temp
  - Crew non-acceptance of controls and displays
    - Don't see much evidence of manual backup – does crew agree with current concept?
  - Vehicular power interface incompatibility
  - Packaging problems due to incorporation of system accommodation of dynamic environmental loads, e.g., brackets, line supports.
- Mitigation
  - Incorporate a profile with early high (~700w) CO2 with low H20 – mimic human performance
  - Have crew evaluate C&D hi-fi mockups/table-top simulator
  - Get over/under voltage; impedance; and ripple requirements out there ASAP
  - Look at worst combination of Dragon and Progress loads and see effects on design.

Briefing Material

- PLSS Components – Colin Campbell
  - POR/SOR
    - Good to be using Monel from the start
    - Are seats Vespel?
    - Identical design should be a benefit
    - Statement made that POR/SOR may be orientation sensitive
      - This could be a risk area for dynamic testing
    - What happens if/when stepper motor fails?
      - Fails to change position
      - Fails open/Fails closed
  - Test article pressure vessel
    - Carbon overwrapped Al bottle – has JSC structures bought off on the bottle vis-à-vis static fatigue failure mode?
    - Arde cryoformed SS planned for flight bottle – Unaged?

Risk Mitigation

- Risk
  - Soft seat design incompatible with oxygen
  - POR/SOR may be damaged by dynamic loads, if orientation sensitive
  - Static-fatigue failure of test pressure vessel
  - Stress-corrosion sensitivity of flight cryoformed SS bottle
    - Aged material has higher strength than unaged, but is stress corrosion sensitive
- Mitigation
  - Use Vespel as early as possible
  - Impose dynamic loads (worst-case Dragon/Progress) and assess results
  - Have JSC structures validate safety
  - Assure unaged material used for flight bottle

Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - Fan
    - Speed controlled by flow sensor feedback
    - 4.7 CFM – is this constant volumetric flow rate independent of pressure? Is this enough to wash out CO2 with representative helmet flow configurations at various met rates?
    - What happens if flow sensor feedback lost or out of spec high?

Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - Gas Sensor
    - Seems to be very different from straight IR absorption in the CO2 band
      - Do the sensors require reference cells, or are they calibration-free in operation?
    - Is the 5 second response time for the sensor alone, or in the system? Specs should probably be more relaxed at the system vs component level to avoid eliminating good sensors
    - How do these sensors work to control the RCA?
    - Even though the system operation would seem to be biased towards dry conditions, what happens if liquid water enters the sensor? Are there steps being taken to eliminate/alleviate this potential condition?
    - Having the ability to monitor water and Oxygen in addition to CO2 should be a very valuable engineering tool

Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - RCA
    - Vast potential improvement over Metox
    - RCA is perhaps the most significant "heavy-hitter" change to the PLSS schematic from previous systems
      - Goes one better than Metox – regeneration in place
      - Removes water – mixed blessing?
      - Has (theoretical) potential of exposing suit loop to vacuum
      - Interrupts flow to helmet
      - Depends on input from gas sensor(s?) for operation
      - Was not tested in all-up configuration in PLSS 1.0 tests
        - » No bypass valve
      - As I understand it, RCA will not work on Mars (4.3 mm ppCO2)
        - » What is the planned approach for Mars?
    - 1-3 minute cycle rate – why not simplify and go to fixed cycle rate?
    - What is overdesign margin on CO2 and H2O removal? What happens if water comes through?

Risk Mitigation

- Risk
  - Failure mode of exposing suit loop to vacuum during bed changeover
  - Flow interruption to helmet undesirable
  - Control system doesn't work, e.g., CO2 sensor failure or controller failure
  - Bypass valve (if incorporated) fails to operate
  - RCA doesn't work for Martian atmosphere
- Mitigation
  - Verify through FMEA and design features that this cannot happen, or takes several sequential failures
  - Verify through design/test that either flow interruption OK, or bypass valve makes it tolerable
  - 1) Assure default configuration gives automatic adequate cycling for high met rate; or 2) have manual select
  - Have manual override
  - Use something like Metox

Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - Liquid-to-gas HX
    - Glad to see drain ports (you never know…)
  - Vent Flow Sensor
    - This is small, but a "heavy hitter"
      - It controls fan speed
      - It may be orientation sensitive – therefore, may be sensitive to dynamic environmental input
      - Previous questions about effects of VFS failures – default configuration

Risk Mitigation

- Risk
  - Moisture condensation in HX (e.g., due to breakthrough of RCA)
  - Vent flow sensor damaged by dynamic loads
- Mitigation
  - For PLSS 2.0, check drains periodically. If water found, determine cause and if viable for flight, incorporate water trap
  - Impose worst case Dragon/Progress loads and assess results – take action if required

Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - Trace contaminant control
    - Are there no SOA active contaminant removal systems?
    - A powered system might save quite a bit of weight and volume

Risk Mitigation

- Risk
  - Channeling of charcoal contents due to dynamic environments
- Mitigation
  - Impose worst-case Dragon/Progess dynamic loads and assess results

Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - Feedwater Supply Assembly
    - Is heat seal method used a mechanical or RF Type?
    - Any thought given to redundant seals?

Risk Mitigation

- Risk
  - Water tank seal leaks
  - Gas bubble prevents full fill (translucent design would show condition)
- Mitigation
  - Incorporate redundant seal
    - (Problem – how to check it?)
  - Assure feedwater supplies compatible with degassed water, OR, incorporate gas separator for fill

Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - Water pump
    - Have subatmospheric tests of the PLSS 2.0 pump been performed, and if so, what were the results?
    - Positive displacement is good from a pumping standpoint; requires the relief valve to prevent overpressurization
      - Will relief valve be checked as part of pre-use checkout?
      - In any event, with all the electronic controls, why not have an automatic shutdown at, say, 20 psid?

Risk Mitigation

- Risk
  - Pump cavitation
  - Pump relief valve fails closed (or open)
- Mitigation
  - Increase water tank supply pressure, if required
    - (pressurization line/regulator required, OR stretched bladder)
  - Check before use; assure failure in use detected by CWCS – shutdown primary; go to aux.

Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - Avionics coldplate
    - Prudent to design, build and evaluate this, even if eventual plans are not to require it
    - Plans change….

Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - Battery
    - Suggest individual cell protection circuitry in Li ion battery in case of internal short/runaway
    - Batteries are black art…
    - For final battery, look at all technologies - lithium ion polymer, nickel-metal hydride and silver-zinc need to be researched, along with any other promising technologies

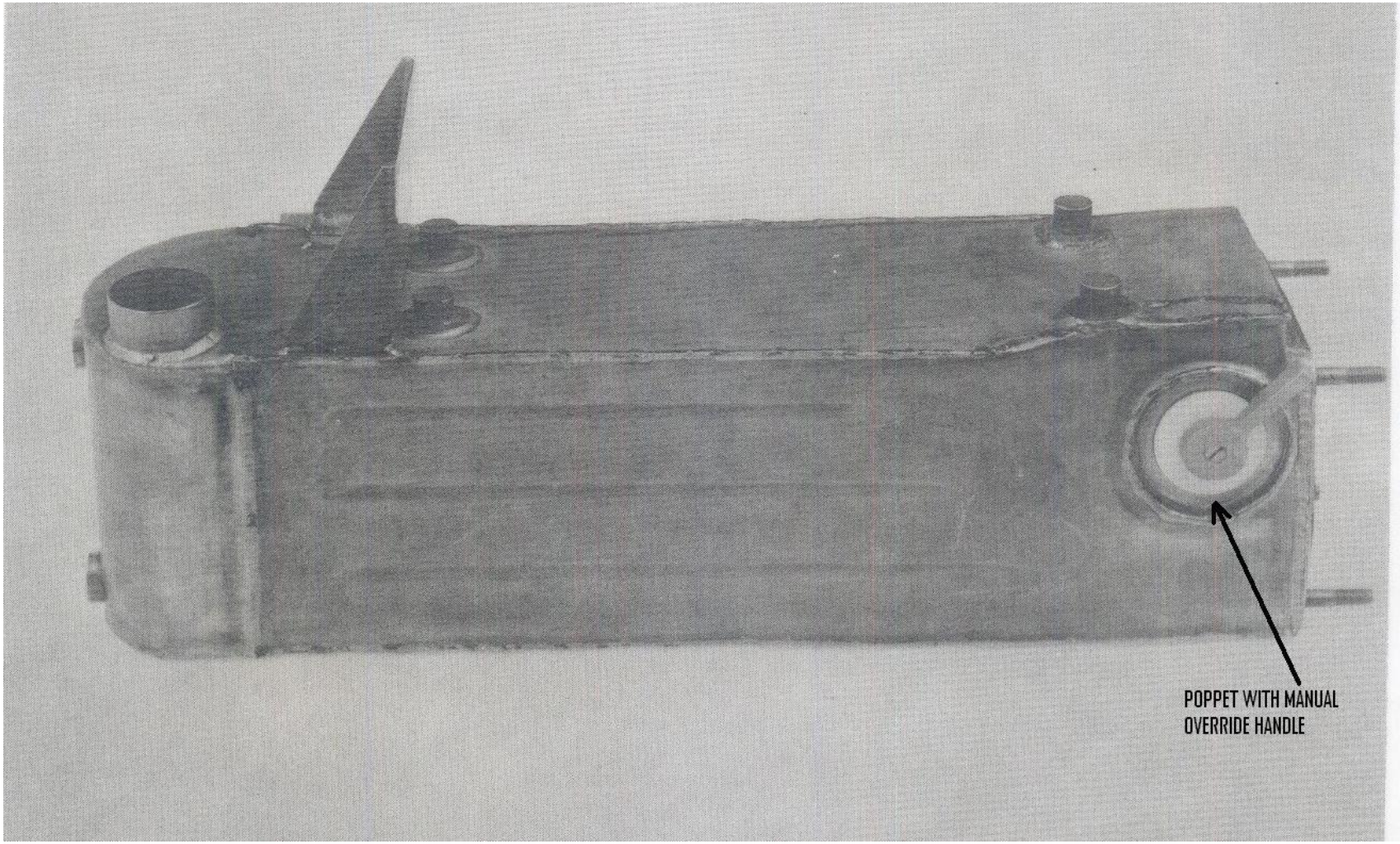
Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - SWME
    - Another "heavy hitter" in terms of new technology
    - Back-pressure controls had problems in the past
      - Apollo ECS 240 controller – had difficult problem statement: +/- 2 deg F. over wide range of equipment and environmental loads (IMU protection)
      - Gemini S/C and ELSS evaporators – Wax pellet (Vernatherm) expansion/contraction opened/closed steam valve – very coarse control
      - Extremely accurate control probably not required for spacesuit application
    - What happens to biocide upon evaporation of water?
    - What level of filtration is required?

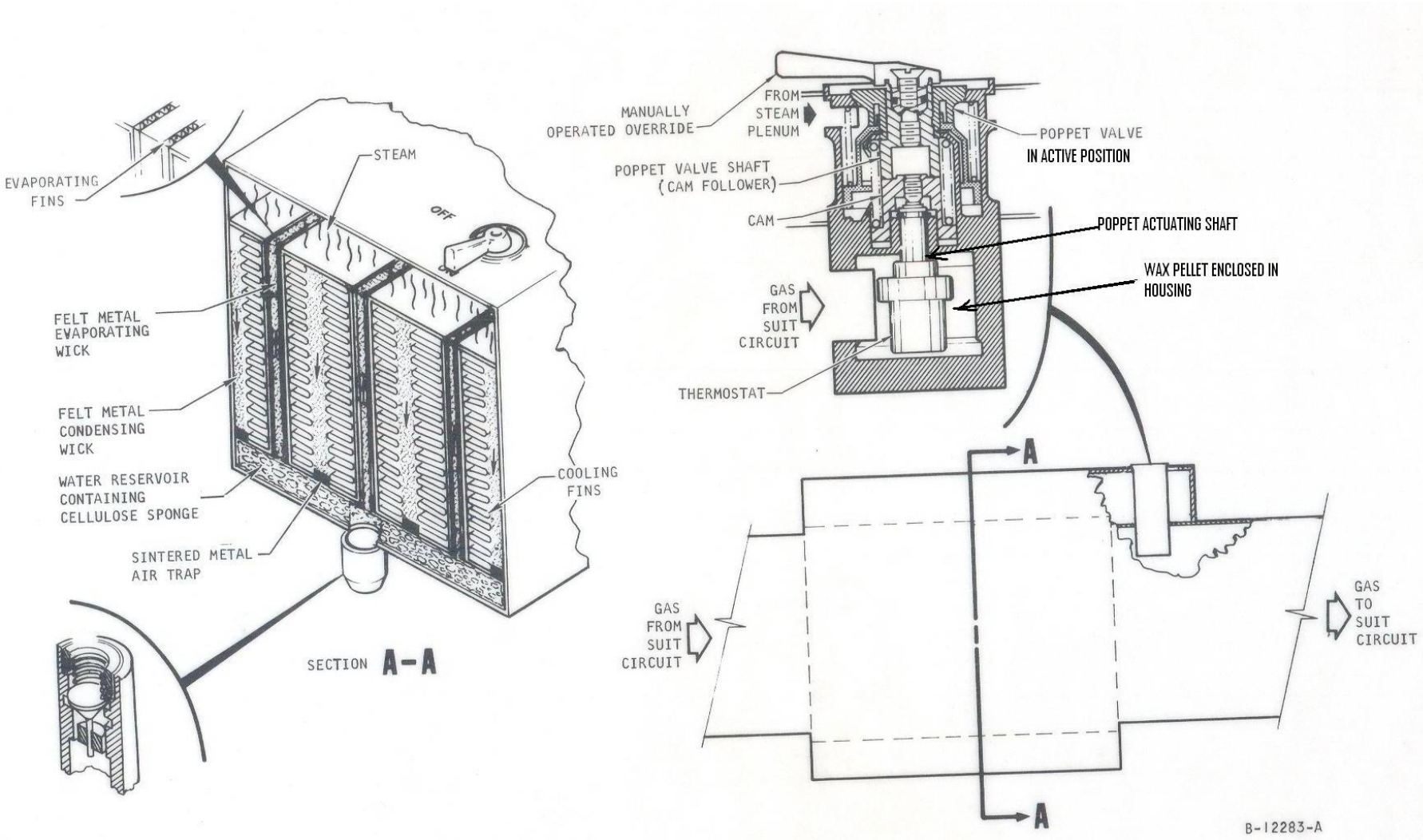
Risk Mitigation

- Risk
  - Biocide inhibits water boiling properties of HFM
  - Problems with back-pressure controller
- Mitigation
  - Test; if results show problem, investigate other biocides, e.g., silver ion
  - Investigate other means of back-pressure control (see next slides)

Gemini ELSS Heat Exchanger



Gemini ELSS Steam Control Valve



Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - Thermal control valve
    - Provides thermal control by varying flow (like Skylab) rather than by varying temperature (like Shuttle)
    - Skylab crews reported some cold spots, but nothing intolerable
    - Does CV have manual override?

Risk Mitigation

- Risk
  - Crew deems flow control (vs temp control) undesirable
  - Automatic control fails
- Mitigation
  - Re-plumb circuit a la Shuttle
  - Incorporate manual override

Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - Mini-ME
    - Looks like better packaging than full sized ME
    - Why not use same simplified controls on SWME?

Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - Positive Pressure Relief Valve
    - Needs to have fail-open flow < worst regulator low flow

Briefing Material

- PLSS Components – Colin Campbell (cont'd)
  - COTS/Other hardware
    - Need to have a good idea of what will be involved to make them compatible with oxygen

Briefing Material

- PAS – Scott Bleisath/Mike Lichter
  - CWCS
    - Significant change – adding the second “C”
      - Seven critical LSS controllers
    - “DCM” desktop – will it “look” like a prototype item for crew use?
    - Manual backup for critical control functions?
    - B/U plans for “long poles”?

Risk Mitigation

- Risk
  - Any problems with controllers
    - SWME
    - Fan
    - TCV
    - POR/SOR
    - RCA
    - Pump
- Mitigation
  - Have “hip-pocket” alternate paths
    - Vernatherm (mechanical)
    - Go to constant speed
    - Manual
    - Pneumatic (with var. settings)
    - Default setting (worst case)
    - Constant speed

Briefing Material

- Test Program – Carly Watts
  - Critical to have CWCS in PLSS 2.0 testing
  - Overall, CTSD-ADV-986 looks to be comprehensive
    - Have a rapid way to incorporate unplanned tests
      - Document the configuration, procedures and results, including unexpected findings

Briefing Material

- PLSS Development Lab – Dave Westheimer
  - Looks thorough – look forward to what will be required for oxygen use
    - Charging
    - Test panels
    - Isolation from nitrogen

Briefing Material

- Test Point Matrices – Carly Watts
  - Metabolic rate
    - Suggest a profile with a high (i.e., 700 W) spike at the end of the mission
      - Simulates difficulty in returning to habitat/vehicle at the end of EVA
  - Helmet CO2 washout
    - Suggest STS testing of helmet duct configurations, manned testing on treadmill, varying metabolic rates
  - Manned evaluation of controls and displays
    - Suited, pressurized - STS

Briefing Material

- Analysis – Bruce Conger
  - Extensive boundary testing
  - Separate manned tests of red. Tube LCG with and without TCU

Briefing Material

- Hazards/Controls – Colin Campbell
  - Make sure you have overvoltage protection on power supplies
  - Make sure there's no way to apply reverse polarity, OR have protection on the hardware

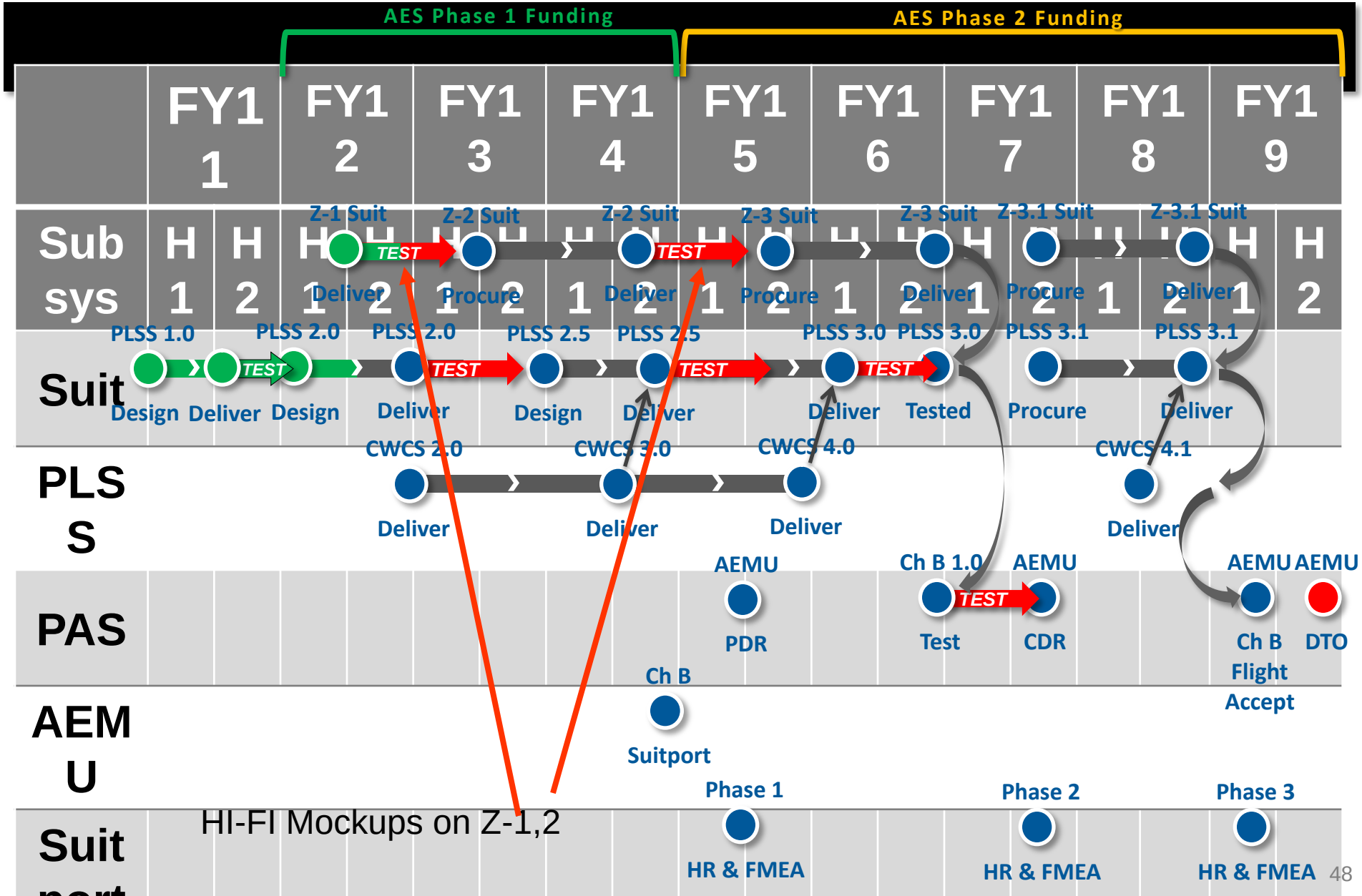
Briefing Material

- Test Operator Training and Forward Work – Carly Watts
  - Have tie-in process for oncoming team (overlap, briefing of new team by outgoing team)
  - Have a process for documenting, tracking, investigating and dispositioning anomalies

System-level considerations

- Early system-level evaluations
  - HI-FI mockups, or whatever you have
  - PLSS, C&D, Suit, Suit-Port
    - Also, any EVA accessories that people are thinking of – tools, carts, etc.
  - Multiple crew evaluations early on
- CO2 removal for Mars
  - What looks good, or at least, feasible?

AES Advanced EVA Project Roadmap



HI-FI Mockups on Z-1,2

System-level considerations

- If funding dries up and/or you get a chance for earlier DTO
  - Look at going from PLSS 2.0 to PLSS 3.1
    - Oxygen compatible; suitable for dynamic environments
  - Use same philosophy for suit, CWCS
- Try to get manned thermal vacuum testing with oxygen as early as possible
  - System level is where the tough problems come out

Comments on CTSD-ADV-780

- 3.2.1.1 Operating Life
  - Strongly suggest that during development, records of pressure cycles on all pressurized containers (e.g., bottles, water storage) be kept, along with powered time
    - History has shown that operational use may impose more cycles than planned
    - Similar concerned with powered-on time
    - May show that flight item requirements can be relaxed
- 3.2.1.4 Limited Life
  - Best case – no limited life; reality – be prepared for limited life items – be able to track

Comments on CTSD-ADV-780

- Table 3.2.5.1 Leakage rates
  - Worst case component leakages may exceed loop allowables
  - Suggest RMS approach for evaluating components
  - Otherwise, may have to “cherry-pick” components

Comments on CTSD-ADV-780

- Table 3.2.17.2-1 – Transient Metabolic Rates
  - Average inspired CO2 concentration dependent on helmet duct configuration, and results of human tests
  - Suggest parallel tests of helmet/duct configurations with subjects of various sizes
- 3.2.18 Impact Tolerance
  - I think we also had a requirement for an impact with a 0.020” radius corner (like a filing cabinet)
    - System just had to hold together; didn’t have to operate in spec

Comments on CTSD-ADV-780

- 3.5.2 VENTILATION FLOW (FN-323)
  - May be able to get by with less, if testing of helmet/vent duct indicates
- 3.5.10.3 FREE WATER TOLERANCE - sensors
  - Very prudent to allow for free water – it's likely to happen
- 3.5.10.4.4 RESPONSE TIME (CO_2 sensor)
  - Make sure system level response time allows for physical location of sensor
    - Don't tax sensor with needing to operate the same as it would as a component

Comments on CTSD-ADV-780

- 3.5.19 NEGATIVE PRESSURE RELIEF
  - Prudent to allow package space/accessibility for this in case it's needed
- 3.5.20.2 POSITIVE LOCKING AND CONFIRMATION (Purge Valve)
  - Suggest at least two separate and exclusive motions to open valve
- 3.6.7 THERMAL CONTROL VALVE
  - Suggest manual backup
  - Interested in crew response to flow variation vs temperature variation

Comments on CTSD-ADV-780

- 3.6.11 FEEDWATER QUANTITY
  - What is potential for a gas bubble forming when pressure decreases?
  - How do you deal with one, if it occurs?
- 3.6.18 OVER-PRESSURE PROTECTION for water loop
  - How is relief valve checked before use?

Comments on CTSD-ADV-780

- 4.1 VEHICLE INTERFACES
  - 4.1.1 POWER
    - Make sure that impedances and ripple are compatible with PLSS components
- 5.1.5 DYNAMIC LOADS
  - 5.1.5.1 RANDOM VIBRATION
    - Suggest looking at worst case combination of Dragon and Progress module launch/landing requirements

Random Comments

- Interfaces, Interfaces, Interfaces…
  - You've got 'em aplenty
    - With other pieces of hardware
    - With other centers
    - With unknown vehicles
  - The tie-in between the suit, PLSS, CWCS and suit port looks to be pushed downstream
- Get system-level testing done as soon as you can
  - You are working from the components outward
  - When you get to a system level, you find out how things REALLY work
  - This is where assumptions are verified or thrown out
  - Interfaces are really defined
- Suggest some residency by Glenn at JSC and vice versa
  - Communication tools are great, but nothing beats being on the spot
- The effects of dynamic environments on system design can be significant
  - Brackets, supports, etc. can complicate an otherwise clean design
  - Need to find these out as soon as possible
  - Design in margin

Random Comments

- The team is impressive
  - Lots of capable, motivated people
  - Seems to be short of manufacturing engineering
    - Probably should start involving them
- Schedule is laid-out; laid-back
  - Remember the other end of the spectrum: We went from a standing start from March 26, 1965 to the first USA EVA on June 3, 1965
  - Be prepared for acceleration, cutting back
  - Have ideas for system simplification in mind
- A lot of very new technology being pursued in parallel
  - Be open to back up/back out approaches

Concluding Remarks

- A lot of what I've said isn't directly applicable to PLSS 2.0
  - I didn't want to lose the thoughts
  - Use what seems to fit
- Most Important, enjoy today…this could be as good as it ever gets…

Lessons Learned from Recent Space Flight Assessments

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ABSTRACT

This paper highlights four space flight assessments, each with an important lesson. The first assessment points to the challenge of material substitution for weight saving. Space Shuttle's external tank stringers were changed from Al 2024 to Al 2090 without comprehensive analysis. Lack of understanding the low Short-Transverse (S-T) strength associated with Al 2090 led to widespread cracking. The second assessment addresses the failure to understand that time-dependent relationships and loading interactions of multiple disciplines can lead to non-conservative results. An aerodynamic test article of the Orion Multi-Purpose Crew Vehicle (MPCV) Launch Abort System (LAS) was analyzed for worst-case single discipline loads, showing positive structural margins. When disciplines were combined with time dependent loading, the analysis resulted in negative margins. The third assessment highlights the pitfalls of putting blind trust in historical architecture. The MPCV re-entry heat shield adopted the Apollo design approach despite fundamental differences between the two designs (e.g., the underlying substructure design, material differences, scale, and geometry). Manufacturing resulted in cracking along seams of the cured MPCV heat shield and produced lower mechanical properties of the Avcoat witness panels. Subsequently, the design was changed to a block architecture, which introduced unperceived technical, cost, and schedule risk. The fourth assessment shows how the lack of a comprehensive investigation of design modifications and inappropriate Finite Element Analyses (FEA) can lead to trouble. A mass reduction campaign eliminated highly critical internal struts on the ISS Node-1 pressurized module based on inadequate and uncorrelated FEA. High strains were noted and ignored as a modeling aberration. A system level high fidelity FEA discovered large plastic strains in the gussets of all four radial ports. These findings initiated a full-scale test campaign, new test correlated assembly-level FEA, and significant design modifications.

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INTRODUCTION

The true nature of the successes and shortcomings of a space flight becomes apparent as the flight design matures only after test flights, or as a result of operational failures or loss of mission. Assessments and analyses of each flight are of utmost importance as failures, mishaps, missteps, and shortcomings reveal lessons to be learned. Success of subsequent flights depends on not repeating these errors, mistakes, missteps, and poor decisions. Such learning lessons should be a top priority for space flight programs. To avoid repeating mistakes, engineers must pay attention to historic events and make sure the valuable lessons are recorded, learned, and assimilated. This paper presents lessons learned from four recent space flight assessments and highlights some of the shortcomings observed in thought processes, hardware configurations, analyses, and experimental methods.

Those who cannot learn from history are doomed to repeat it.

– George Santayana

Lesson Learned 1: 'Inconsequential' Design Changes Seldom Are:

The Space Shuttle External Tank (ET) consists of liquid hydrogen (LH2) tank, liquid oxygen (LOX) tank, and intertank (IT). LH2 and LOX propellants were the fuels for the Orbiter's three main engines. The ET also served as the structural backbone of the Space Transportation System (STS), providing for attachment of the Orbiter and the Solid Rocket Boosters (SRBs).

On November 5, 2010, the launch of Space Shuttle mission STS-133 was scrubbed after propellant loading, due to a gaseous hydrogen leak at the ground umbilical connection to the ET. During visual inspections following the scrub, an anomalous crack in the ET sprayed-on foam insulation (SOFI) was observed at the forward end of the IT near the interface of the LOX tank (Figure 1). Removal of the damaged foam revealed that an underlying aluminum hat-section stringer had cracked approximately 9 inches along each side, just inboard of the fasteners that attached the stringer "feet" to the IT forward flange chord[1-3] (Figures 1 and 2).

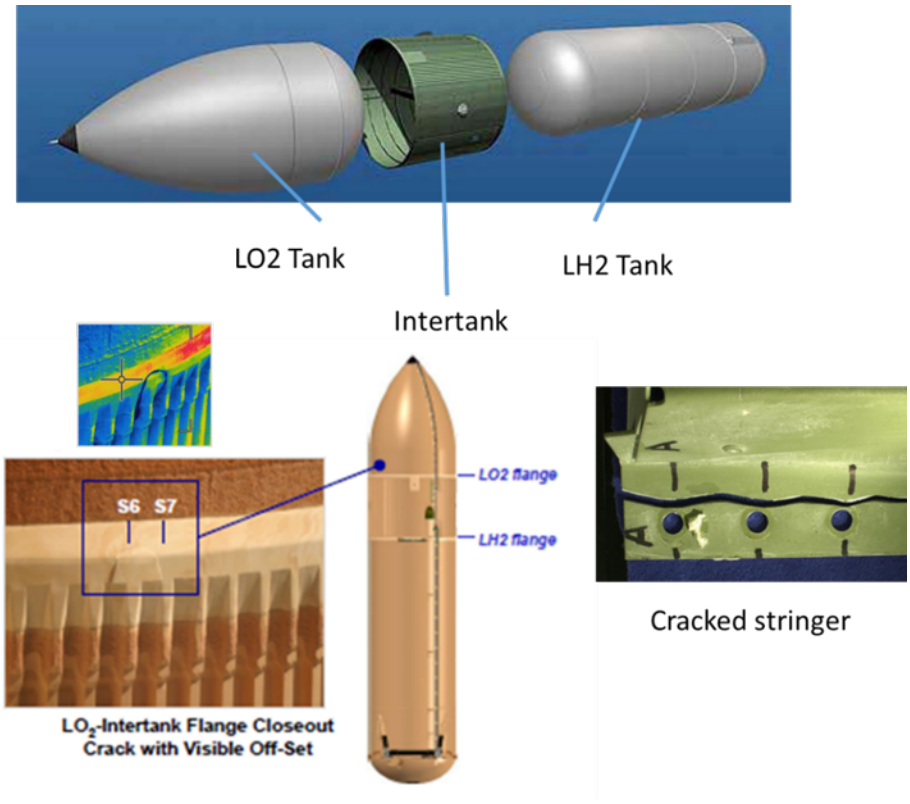


Figure 1. External Tank and Cracking near LO2 Tank-Intertank Interface

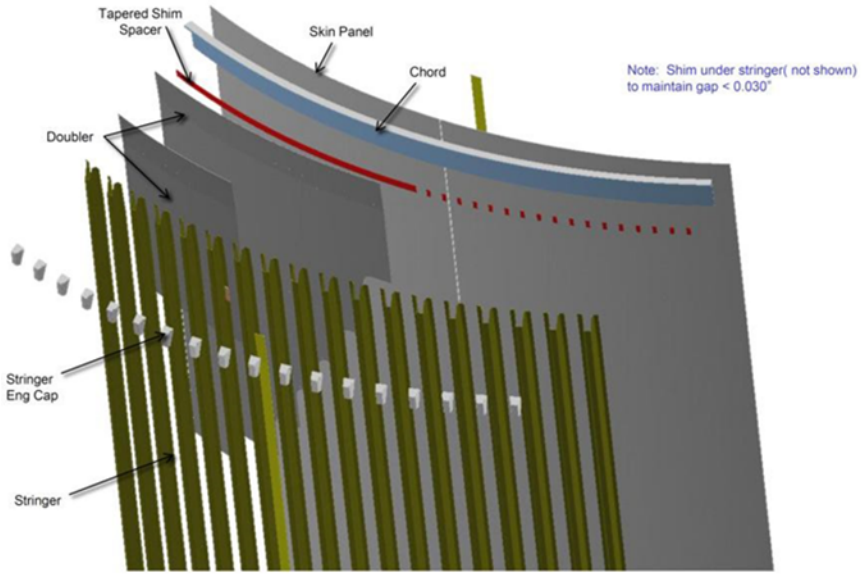


Figure 2. Representative IT panel with external hat stringers

Closer inspection of this region revealed that two hat-shaped stringers, Panel 2 - Stringers 6 and 7, had through-cracks along the stringer feet between the fasteners and the stringer sidewall. These two IT stringers were repaired at the launch pad, and a second tanking of ET-137 was performed with considerable added instrumentation which showed additional anomalies in the IT region. The vehicle was returned to the Vehicle Assembly Building (VAB) and a full 360-degree inspection was conducted. This inspection revealed three additional stringer cracks (Panel 6 - Stringers 6, 7 and 11). These stringers were repaired, and the vehicle was then rolled back to the launch pad. Various material and structural investigations and assessments were initiated to understand the root cause of the IT stringer cracking, to develop and assess repair options, and to develop flight rationale for STS-133.

The IT is an unpressurized, stiffened cylindrical structure that serves as the structural connection between the liquid propellant tanks. The IT also functions to receive and distribute all thrust loads from the SRBs. An assembly of eight curved panels are mechanically joined into a barrel with five internal ring frames to form the IT. Of the eight panels, two diametrically opposite panels are connected to the SRB box beam. The box beam reacts the majority of the SRB thrust loads. These two panels are thick plate, one piece panels, with integrally machined blade stiffeners and pocketed membrane areas[3]. The other six IT panels are manufactured from sheet metal skins with externally mounted, hat-section stringer stiffeners. These stringers are mechanically attached with rivets along most of their length and with specialty fasteners, such as GP Lockbolts and Hi-Loks, at the forward and aft ends where the stringers attach to flange chords. The hat-section stringers are fabricated from aluminum sheet using a combination of rolling and hot-forming processes. There are 18 stringers per panel, located on approximately 7-inch centers[1-3].

Over the history of the Space Shuttle Program, there were been two major revisions of the ET design to decrease structural weight. The general structural configuration of the IT remained unchanged throughout those changes. The last major evolution from Lightweight Tank (LWT) to the Super Lightweight Tank (SLWT) involved a widespread change of skin/stringer material from aluminum alloy Al-2024 to aluminum-lithium alloy Al-2090[2] to reduce mass.

The basic assumption made regarding the November 5th IT stringer cracking event, was that a rogue IT stringer existed, and after the ET tanking event, the strain in the stringer feet due to tanking alone was just below the failure strain. This premise led to the conclusion that a relatively high combined assembly and tanking strain level existed in the stringer feet between the fastener and the stringer sidewall. However, investigation determined the magnitude of the assembly strain not to be additive to the strain resulting from the operational loading events.

To better understand these effects and assess the influence of plasticity, elastic-plastic, large-deflection nonlinear thermomechanical stress analyses were performed for the IT external hat-shaped stringers[1]. Detailed 3D FE models were developed and analyzed to investigate the elastic-plastic response of the IT stringers and to assess the potential for local failure to develop in the stringer feet. The stringers were subject to assembly strains caused by initial installation on an IT panel. Transient thermal loading occurred in these stringers as the LOX tank was filled prior to launch. Other bounding mechanical loading events were present for pre-tanking, pre-launch, and flight-loading events. These extensive analytical and experimental investigations concluded that

these stringers failed due to the material short-transverse capability being less than and the stresses being greater than expected. Material studies documented that, "Alloy 2090 rolled products are known to have dramatically reduced material properties in specific directions relative to the rolling direction, especially in thin-sheet material. Short transverse and longitudinal (long transverse) properties are important for the initial stages of stringer crack propagation and for later stages of through-the-thickness cracking, repesctively"[4]. The greater than expected stresses were attributed to unexpectedly higher assembly-induced stresses that combined with stresses resulting from cryogenically induced deflections.

All five stringers in which cracks were found were repaired. The remaining Al-2090 stringers were reinforced with radius blocks at the LOX tank end of the stringers (see Figure 3). The SOFI at the LOX tank interface was removed prior to the mechanical installation of the radius blocks, and after all radius blocks were installed, the insulation was reapplied and trimmed to flight configuration. Significant analysis and test efforts concluded that the radius blocks were effective in restoring the structural capability and that they had no detrimental system level side effects.

The cracking did not occur on the previous flights as the original Al-2024 was a ductile material with homogeneous and near isotropic properties. In contrast, the Al-2090 was an orthotropic material with reduced material properties in specific directions (i.e., Short-Transverse, S-T). Documentation showed Material and Processing (M&P) engineers had previously warned against the use of this material in regions of large stresses but that message was lost/ignored over time.

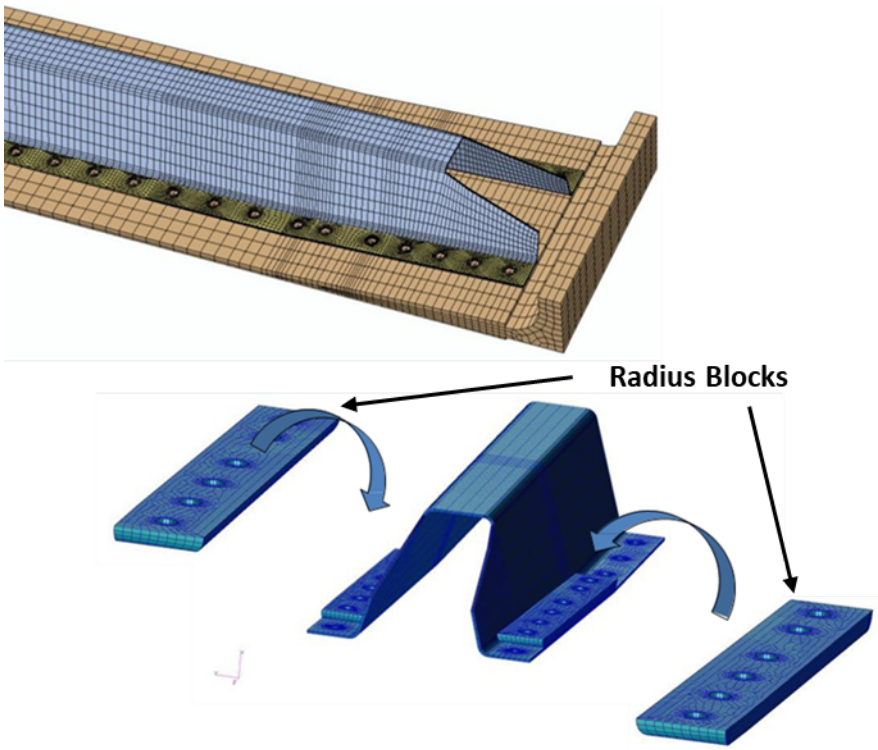


Figure 3. Hat stringer and radius blocks

Lessons: 1) Listen to discipline experts and follow their advice. 2) Avoid making material substitutions without a comprehensive study of all aspects of the hardware configuration and loadings.

Lesson Learned #2: Worst on Worst Is Not Always Worse:

In recent years, advanced multi-physics/multi-disciplinary analysis techniques and tools have become more widely used in the areas of structural design for aerospace vehicles. Advanced software packages now possess the ability to account for differing physical behaviors simultaneously within a simulation run. These methods usually come at a cost of increased model complexity, longer run times, and may require the inclusion of time dependent behavior in the analysis. Often advanced analysis, if performed, does not occur until after the designs have been partially developed and, in some cases, after the design is finalized and manufacturing has started. Results from these higher fidelity analyses may uncover design defects that were unanticipated or unaccounted for in the preliminary design/analysis process where traditional methods, using modified properties (i.e., material knockdowns) and/or simplified assumptions are the norm. It is vitally important for hardware design/analysis cycles to account correctly for multi-discipline environmental effects early in their development to reduce the possibility of significant design changes being required late in the process, when they tend to be much more expensive to correct.

An example of this type of issue occurred during the development and testing for aeroacoustic environments on the ORION/Multi-Purpose Crew Vehicle (MPCV) Launch Abort System (LAS). This testing, known as the 80-AS test series, was performed at Ames Research Center in 2009-2010. Panda et al.[5] provides details of the goals, procedures, and results of that testing.

The ORION/MPCV LAS system consists of an aerodynamic fairing assembly that protects the spacecraft from external aerodynamic and aeroacoustic loading during launch and ascent or abort. In the event of an abort, a set of solid rocket motors fire to pull the ORION Crew Module (CM) and crew away from the Space Launch System (SLS) stack. Control motors also provide attitude control. Figure 4 shows an illustration of the ORION/MPCV LAS.

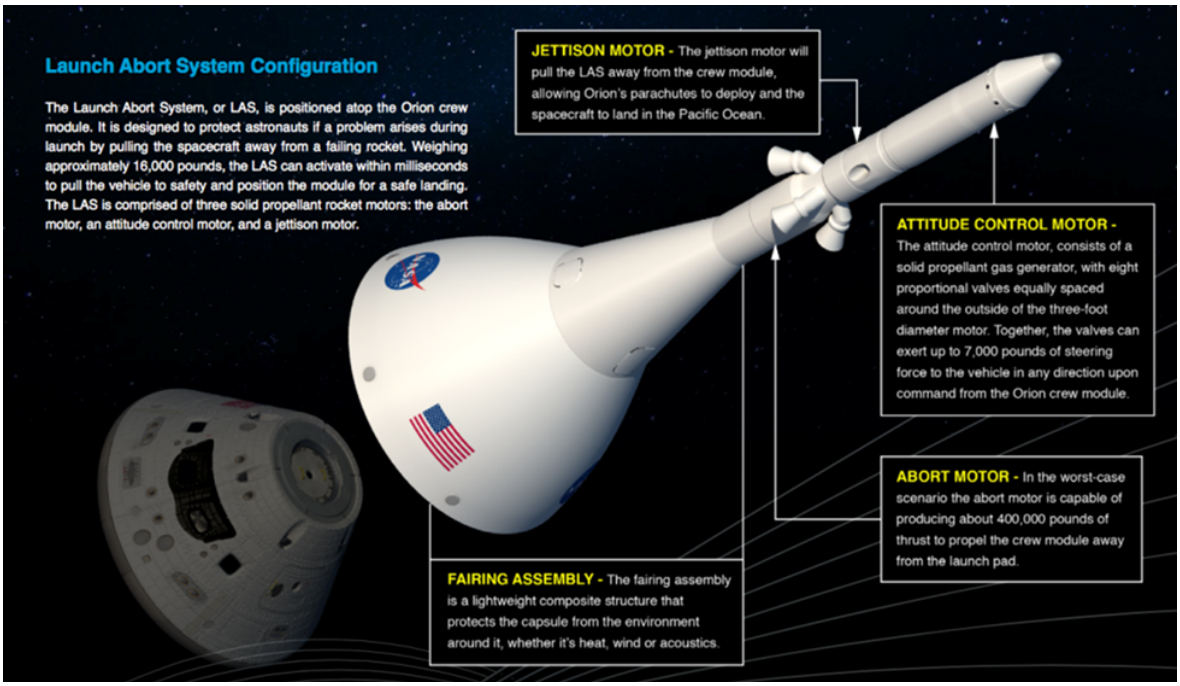


Figure 4. ORION Launch Abort System[6]

Thrust impingement and high acoustic loads produced by abort rocket motor exhaust onto the LAS fairing assembly during a launch abort were known design issues. The ORION program decided to conduct simulations and measurements of this acoustic environment by means of wind tunnel testing. This testing was performed in the 11-Foot Transonic Wind Tunnel facility at the Ames Research Center using a LAS model with simulated abort motor exhausts. A scale model of the LAS, shown in Figure 5, was developed to measure the magnitude of these acoustic loads in different flight regimes. This scale model included internal ducting for the routing of hot helium gas through the model allowing it to exit at the abort motor nozzle locations and impinge directly onto the fairing. Helium was selected due to the similarity of acoustic energy transmission properties at elevated temperature, compared to the actual abort motor exhaust. Tunnel airflow around the exterior of the model provided simulation of transonic aerodynamic pressures and flow effects.

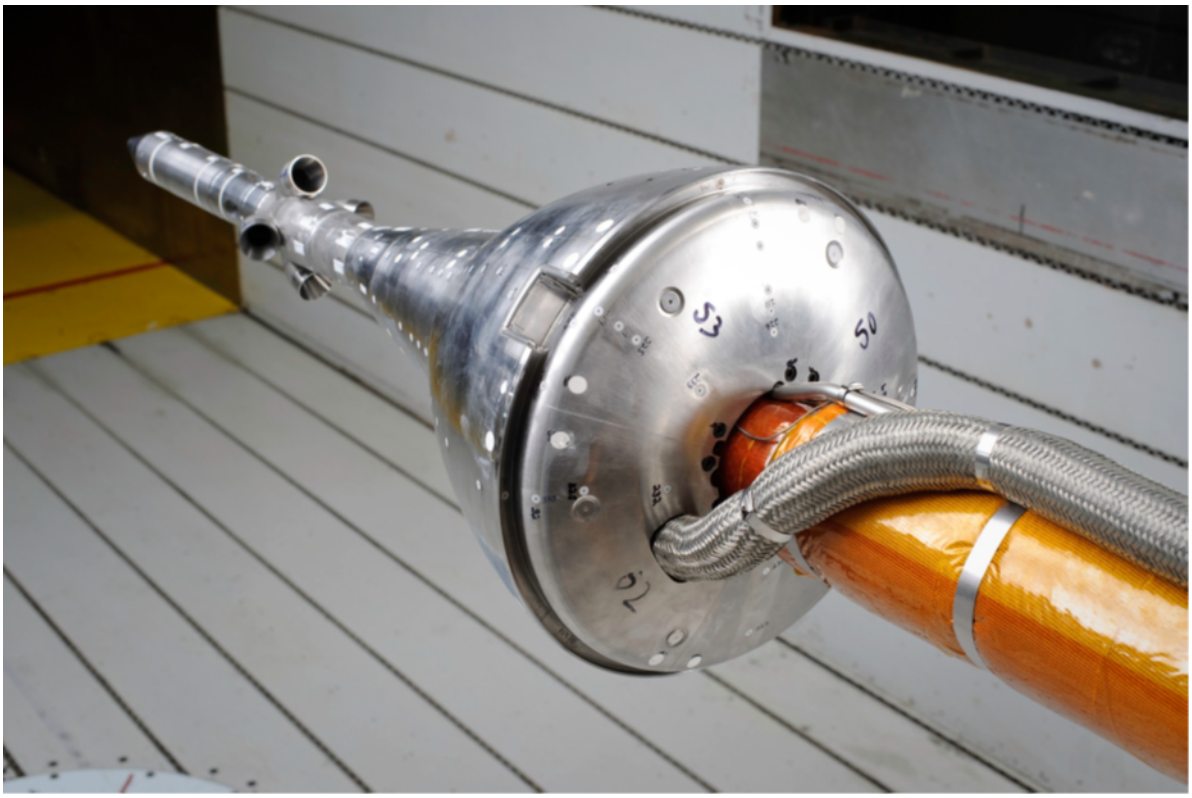


Figure 5. 80-AS Test Article Installed in ARC Transonic Wind Tunnel

The test article preliminary design used linear static analysis, performed in Parametric Technology Corp. (PTC) Pro-Mechanica, and accounted for the loads due to transonic airflow and pressure imparted by tunnel conditions. Steady state pressures, obtained from CFD flow simulation of various tunnel test conditions, were applied to the structural finite element model and were believed to account for worst-case structural loading and stresses.

Elevated temperature effects on the structure were accounted for in the following manner. Temperatures obtained from steady state thermal analyses, performed via a Thermal Desktop simulation, allowed determination of strength property knockdowns, using graphs of material temperature dependency from MMPDS[7], for the various materials used in fabrication. In this way, strength margins were determined using the stress values obtained via static analysis of pressure loads only, which were compared with reduced allowable strengths, based on the steady state temperature analysis of the test article. Differential thermal strain effects were not considered, and believed to be minimal at worst-case steady-state temperature conditions predicted by analysis.

The wind tunnel model design used precipitation hardened (PH) stainless steel, incorporating different heat treatments of 17-4 PH with differing CTE values over the temperature range. The nozzle assembly, representing the locations of the abort rocket motors, was fabricated from a chrome-based material to resist heat loading, also with differing CTE. Differing elastic moduli and CTE values at various temperature are outlined in Table 1.

Table 1: Mechanical and Thermal Properties at RT and Elevated Temp (MMPDS-04)

Material	E @ 70ºF ($x10^6$ psi)	E @800ºF ($x10^6$ psi)	CTE @70ºF ($x10^{-6}$ in/in/ºF)	CTE @ 800ºF ($x10^{-6}$ in/in/ºF)	Density (lb./in^2)
CoCr (Nozzle)	30.5	30.5	7.5	7.5	0.322
17-4 PH (H900)	28.5	23.37	5.8	6.5	0.282
17-4 PH (H1075)	28.5	23.37	6.2	6.8	0.283
17-4 PH (H1150)	28.5	23.37	6.2	7.2	0.284

Results from the preliminary sets of analyses showed positive margins for all parts based on the loading and stresses resulting from these steady state assumptions. Therefore, in order to meet schedule constraints for wind tunnel test times, the design was released for fabrication of components before final design reviews were completed.

In actuality, the test simulation environment was highly transient. As shown in Figure 6, as the test progressed, flow of the hot gas cycled on and off through numerous cycles over about thirty minutes (2010 seconds). In periods when hot gas was not flowing, the test article structure was effectively cooled by the tunnel airflow over the model exterior, and by room-temperature air flowing through the interior ducting and discharging through the nozzles. The model gradually heated up from the inside following these cycles. Over the first several cycles, exterior parts exposed to the tunnel airflow did not heat, but interior surfaces heated much more quickly. Differential thermal strain developed between structural parts and contributed significantly to the stress.

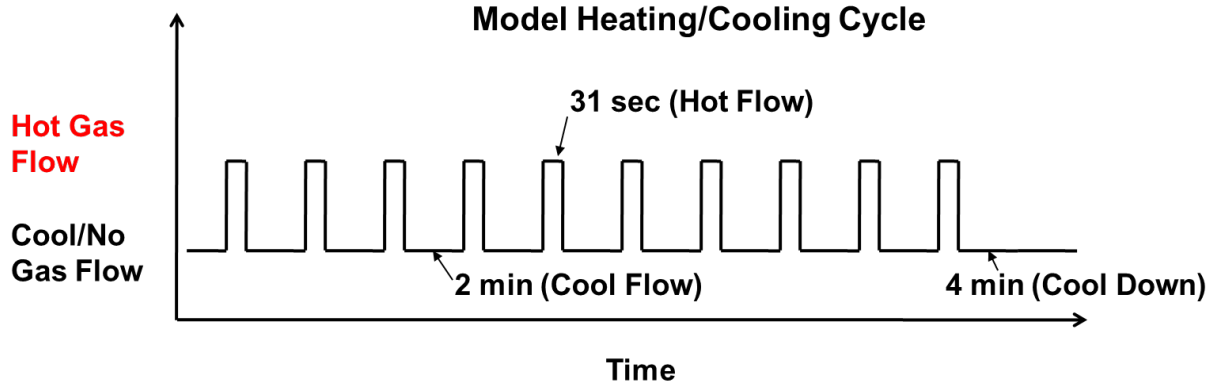


Figure 6. Gas Thermal Cycles

To ascertain if thermal transient response would be a safety issue, a new finite element model was constructed in MSC-NASTRAN to simulate the thermo-structural transient effects. A solid model composed of mostly CHEXA elements was used to predict both the transient temperatures and the thermo-structural stress results. Using the same mesh for both analyses allowed for easy transfer of nodal temperatures without a complicated mapping or interpolation of temperature data between dissimilar meshes. Details of the various components of this model are shown in Figure 7.

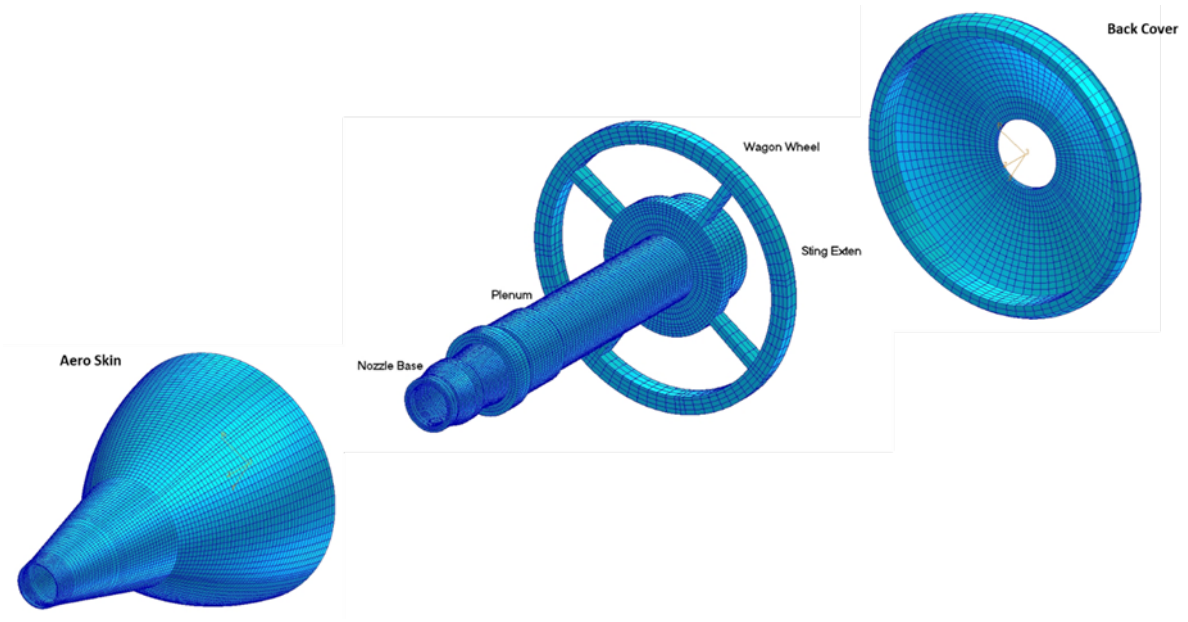


Figure 7. FE Mesh for Thermo-Structural Analyses

The first part of this new analysis sought to predict transient temperature throughout the test article structure over the entire thirty minutes of simulation. MSC-NASTRAN solution 159 (Transient Thermal) was used to generate a temperature profile at each second of the 2010-second tunnel test run. Convection boundary conditions were applied to the interior plenum surfaces exposed to the flow of hot and cold gas flow, and the exterior model surfaces exposed to both tunnel flow and the simulated exhaust plumes. Material conduction properties were applied to the solid portions of the model and contact resistance between mating parts was simulated with 1-D thermal contact elements. The results of this simulation showed significant thermal gradients in the structure, especially in the first few heating cycles as illustrated in the three plots of Figure 8.

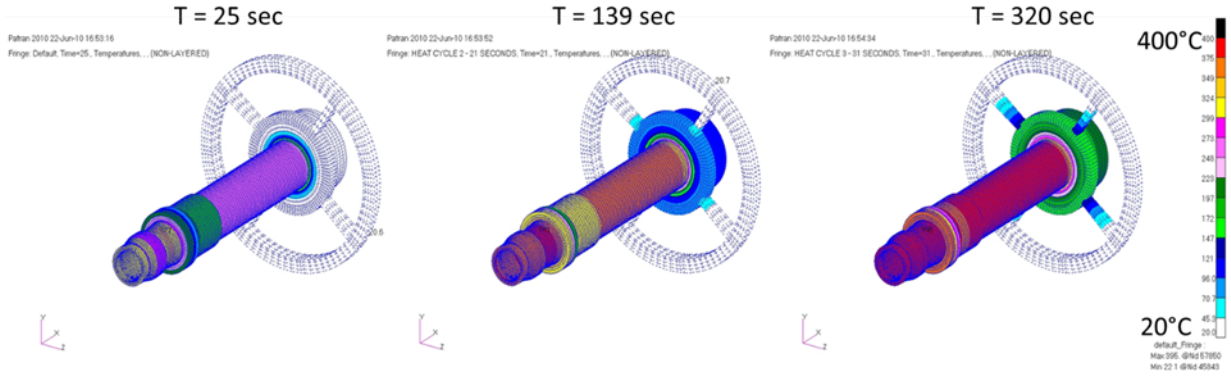


Figure 8. Temperature Distribution in Interior Components at Three Time Steps

Transient temperatures saved from each time step were used as temperature loading inputs for MSC-NASTRAN linear static analyses (Sol 101). Material property temperature dependency was accounted for in the material definitions. Structural effects of the transient thermal gradients were

combined directly with the external and internal pressure loading to give an overall thermo-structural response of the model hardware for each second of the simulation.

The simulation now allowed the model to gradually heat from the inside, following the heating/cooling cycles. Thermal strain now developed between structural parts. These more accurate results showed an increase in loads and stresses in the components of the test article, especially at joints, due to pressure effects combined with transient flow of heat. Stress levels were significantly higher in the first 3-4 transient cycles than had been predicted by steady state analyses, as is shown in Figure 9 and Table 2[8]. Figure 9 illustrates the peaking of stress in the early heating/cooling cycles resulting from thermal transient behavior.

Table 2. Von Mises Stress in Structural Components of 80-AS Model

Time (sec)	Nozzle Stress (ksi)	Plenum Stress (ksi)	Sting Stress (ksi)	Skin Stress (ksi)	Wagon Wheel Stress (ksi)	Back Cover Stress (ksi)
0.0	44.6	35.1	12.0	4.6	4.7	5.1
1.0	44.2	34.5	17.2	4.2	6.1	6.2
25.0	44.9	74.5	**77.3**	**53.0**	66.1	71.6
139.0	46.3	**82.6**	62.5	49.8	83.4	96.8
320.0	**47.0**	71.1	46.3	45.4	**85.4**	**103.4**
581.0	46.9	57.0	33.6	37.5	78.0	96.8
737.0	47.0	51.6	27.4	37.0	76.6	95.6
913.0	46.9	47.1	26.3	36.5	74.5	93.0
1131.0	47.0	43.7	25.3	36.2	72.8	90.0
1338.0	46.9	41.2	24.7	36.1	71.7	88.2
1557.0	46.9	40.4	24.2	36.0	70.5	86.4
1779.0	46.9	39.5	23.8	36.0	69.4	84.9
2010.0	46.8	38.9	23.4	36.1	68.3	83.6

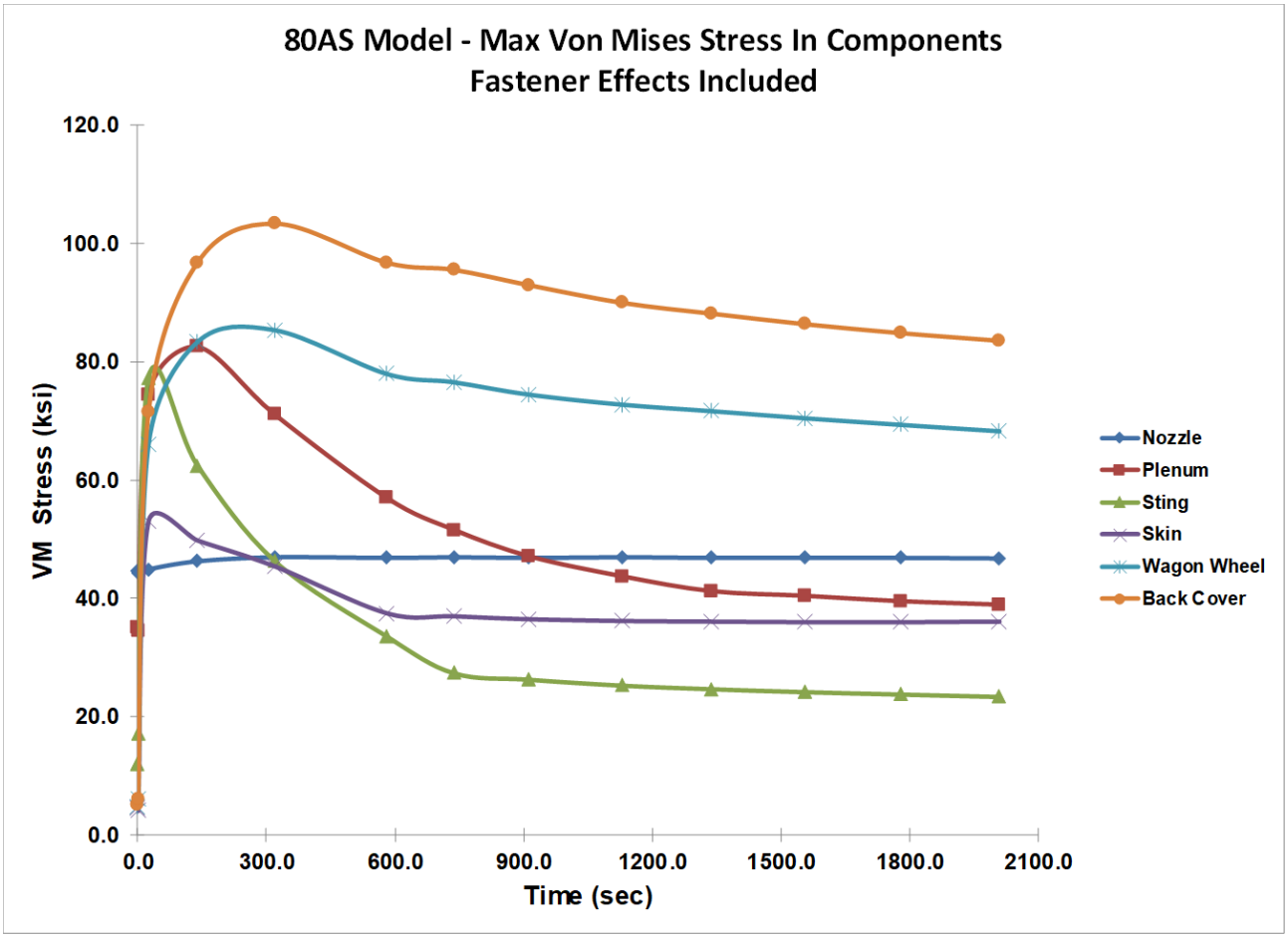


Figure 9. Stress Effects Resulting from Thermal Transients

Margins, which originally had shown positive, were now negative in many locations. However, much of the hardware was already fabricated - a result of starting manufacturing based on the results of the earlier steady state analysis. Test schedules in the ARC wind tunnel were set and did not allow sufficient time for hardware re-design or re-manufacture.

Based on results from the more detailed transient analysis, a plan was developed to perform detailed inspection of the test article throughout the test campaign after each data collection run. Locations of predicted high stress and negative margin were identified and an inspection plan was developed to check for onset of fatigue failure or overload in any components or fasteners. Using this analysis-based inspection process, the entire test series was completed successfully, without incident, and vital data for ORION LAS design was obtained.

This example demonstrates the need for engineers to be aware of how loading is applied and the need to capture its character and effects correctly. Loading from different disciplines, in this case thermal and mechanical acting together and affecting each other, must be accounted for properly. These interactions can be vital in understanding true behavior of a complex structure. The original analysis attempted to capture the thermal and mechanical aspects of the environment by using a

worst on worst assumption, but failed to understand how their time dependent relationship might affect the analysis result.

> *Lesson: Understanding the appropriate simulation of time-dependent environments in structural analysis is of utmost importance. Preconceived assumptions of how environments may or may not interact may produce inaccurate or non-conservative results.*

Lesson Learned #3: Heritage Does Not Mean It Works As It Did Previously:

A lesson that continues to be learned is the two-edged sword of both placing blind trust into historical architectures and the "grass is greener" syndrome. An example of this is the changing architecture of the NASA Orion Multi-Purpose Crew Vehicle (MPCV) re-entry heat shield. NASA's experience with the Apollo Program architecture[9] was the basis for the Orion heat shield design. That design entailed the bonding of a fiberglass and phenolic honeycomb onto a structural substrate followed by the manual injection of Avcoat 5026-39 into the individual cells of the honeycomb. This laborious process, shown being performed in Figure 10, introduces unique workmanship issues such as variability of technique of the numerous technicians responsible for the Apollo heat shield fabrication. For example, the speed and pressure applied during the injection process as well as the angle at which the tool is held can introduce process variability.

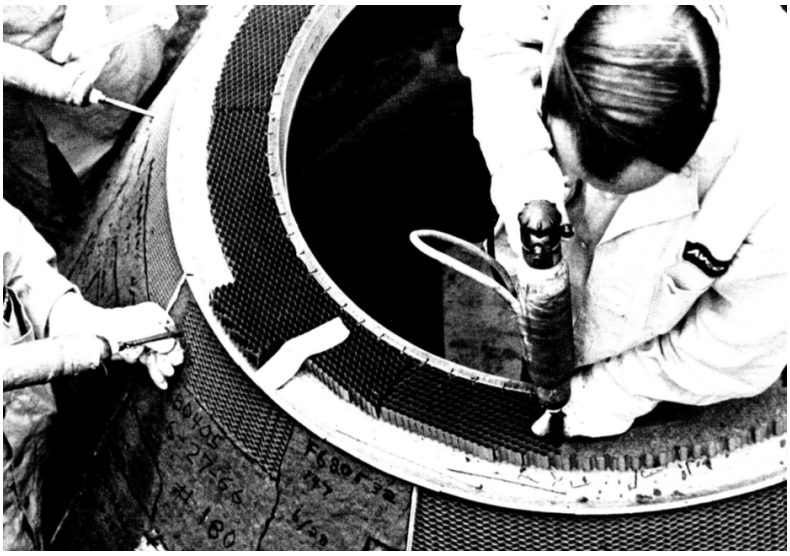


Figure 10. Manual injection of Avcoat 5026-39 into Apollo heat shield honeycomb[9]

By comparison, some five decades later, the heat shield fabrication on the Orion MPCV followed many of the same processes. The manual injection process, shown in Figure 11, was largely unchanged. This manual process involved injecting over 300,000 individual cells by hand to create a rough form of the ablative heat shield followed by non-destructive evaluation using X-ray.

Afterwards, the rough surface was machined down to a smooth, final flight profile per the drawing specifications.



Figure 11. Manual injection process implemented on Orion EFT-1 heat shield
(https://www.nasa.gov/content/partnerships-make-missions-possible)

However, even though the touch labor processes for these two heat shield designs, decades apart, were similar, fundamental differences existed between the heritage Apollo design and the Orion implementation, including:

- Apollo used a stainless steel plate and honeycomb substructure[9] whereas Orion used a composite substructure with a titanium backbone[10] (Figure 12)
- Material constituents used in the Apollo era Avcoat mixture were no longer available in the Orion era due to modern environmental regulations
- Differences in how requirements were levied, such as the use of average material properties during Apollo and A-basis properties for Orion and how design factors were levied on the thermally induced loads
- Apollo's heat shield diameter was 154 inches compared to Orion's diameter of 198 inches[10]

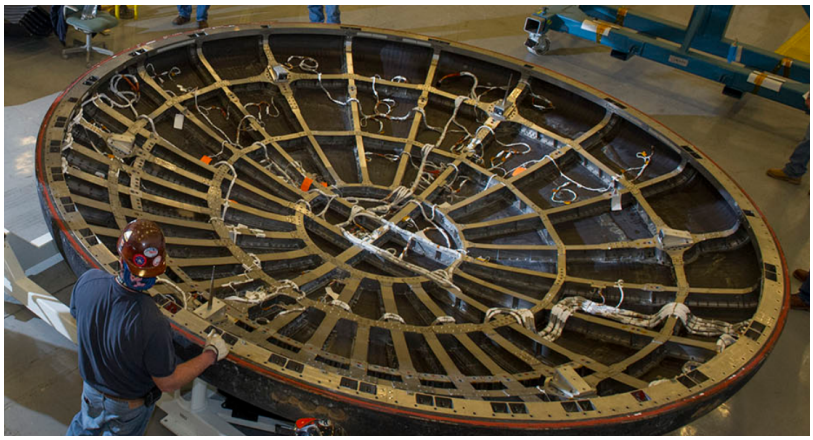


Figure 12. Orion Heatshield Substructure
(https://www.nasa.gov/centers/marshall/news/news/releases/2015/heat-shield-for-nasas-orion-continues-post-flight-journey-by-land.html)

The difference in structural design has certain implications for the thermo-mechanical response of the heat shield system. The mechanical stiffness of the Apollo steel sheet and honeycomb design is significantly different from Orion's quasi-isotropic composite laminate and titanium backbone system. The Apollo system provides for repeatable mechanical response (i.e., essentially isotropic-like bending response), but the circumferentially and radially stiffened Orion system allows for local bending between stiffeners.

The combined system coefficients of thermal expansion between the Orion and Apollo architectures differ greatly due to the materials selected as the backbone and substrate. The thermal properties of the architectures are just as varied as the mechanical properties, with drastically different thermal conductivities, specific heats, and mass densities. Despite these fundamental differences, the Avcoat ablative solution derived from Apollo was applied to the new Orion spacecraft.

During manufacturing, two significant issues were uncovered[10], namely the presence of cracking along some seams in the cured heat shield and Avcoat witness panels that were found to have lower mechanical strength than the specimens used in the population for development of material strength design allowables. An example of fabrication induced cracking is shown in Figure 13 for two locations on the heat shield. The image on the left shows locations of the cracks, most of which are aligned with the radial coordinate direction and are located in the unsupported regions between radial stiffeners.

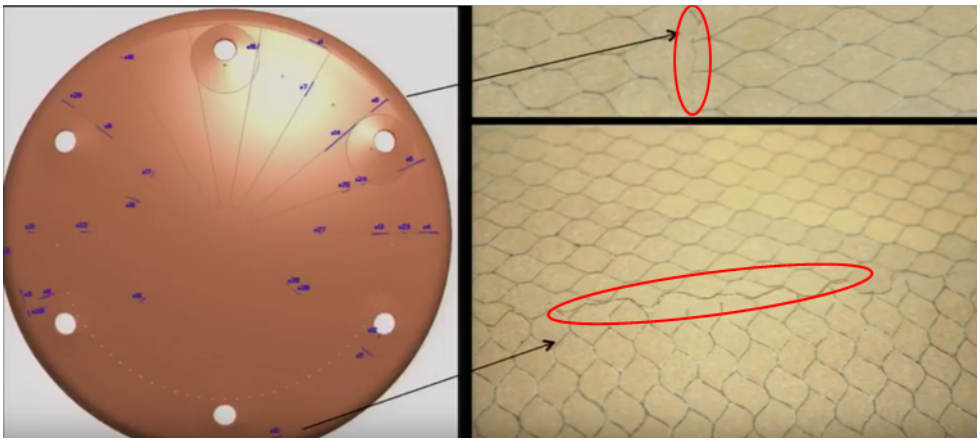


Figure 13. Typical EFT-1 Avcoat crack geometries[12]

The Apollo Program developed and implemented a repair process because Avcoat cracking was a known issue at the time. Indeed, all Apollo Command Module spacecraft had these repairs, as shown in Figure 14.



Figure 14. Apollo plug repair[12]

The issues associated with Avcoat cracking on Orion were corrected in the field using a repair process derived from original Apollo processes. While the repair process was recertified for the MPCV implementation, much of the heritage Apollo process remained intact.

The Orion Program conducted a root-cause analysis of these failures, but that analysis was inconclusive as to their source. Subsequently, the NASA Engineering and Safety Center embarked on a multi-year root cause analysis of both failures. It must be recognized that the Orion EFT-1 flight heatshield design was successful in completing its test flight using the repair procedure developed from the heritage Apollo design.

The over-reliance on the historical architecture without understanding how other parameters (e.g., underlying substructure, material changes, scale) can affect both the heat transfer and structural response of the combined substructure and ablator system, demonstrated an example of using blind trust in a heritage application.

The monolithic Apollo architecture was even recognized by the Apollo Program as having introduced technical and programmatic risks, but the Apollo experience was to move away from the block architecture of Mercury to the honeycomb design. The rationale at that time was that the honeycomb system provides a fail-safe design[9] compared to the block design, where loss of a single block could result in a catastrophic hazard.

Even with the fundamental thermal and structural differences, Orion probabilistic risk assessments[11]predicted a loss of vehicle risk of 1-in-160,000 of Avcoat cracking in flight due to the inherent fault tolerance of the honeycomb Avcoat design. The successful flight test of the EFT-1 vehicle showed the merits of this historical design. However, moving to the EM-1 design, the Orion Program determined that transitioning from the Apollo architecture and to a bonded block design would provide cost, schedule, weight, and technical performance benefits[10].

In this case of the "grass is greener" syndrome, the Orion Program assumed there would be tangible advantages, reversing the lessons learned from Mercury to Apollo, including

- Improved inspection with off-the-vehicle non-destructive evaluation (NDE) of fabricated blocks prior to attachment
- Improved acceptance criteria to reject low-strength blocks via acceptance testing
- No interface issues due to lack of seams
- Reduced schedule risk due to greater availability of the heat shield during the vehicle integration process flow
- Reduced cost due to less touch labor associated with individual filling of honeycomb cells

On the surface, the cost and schedule advantages could be rationale for change assuming the technical and flight safety risks were comparable between the architectures. By moving most fabrication off the vehicle and instead relying on the bonding of approximately 300 blocks, processing of the vehicle could be changed from a serial to a more parallel process. However, even though molded blocks are associated with lower manufacturing costs, they introduced additional work not originally anticipated.

Preliminary assessments used to rationalize the change in architecture did not account for unknown unknowns in the implementation. For example, new NDE techniques[10] had to be developed to reduce the risk of inadequate structural bonding between the blocks and structural substrate. Traditional NDE techniques were not capable of adequately detecting flaws due to the materials and geometric features, as shown in Figure 15. This new Terahertz inspection process proved to be a cost, schedule, and technical risk. The cost and schedule impacts were due to this being a new development taken on by the Orion Program when it was found the existing techniques were not suitable. The technical risk was associated with the use of materials during the NDE process that could have affected the flight performance of the Avcoat insulation blocks. Extensive testing was required to demonstrate that these NDE materials would not affect the ablative or mechanical performance of the Avcoat.

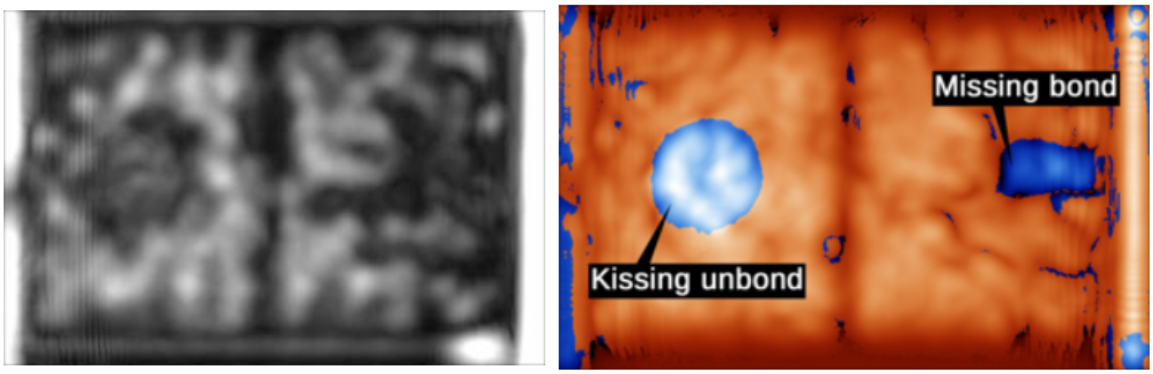


Figure 15. Improved NDE of Avcoat blocks[13]

Additionally, exhaustive test campaigns were conducted, due to the emergence of new failure modes associated with a block design that differed from the EFT-1 honeycomb architecture, namely crack propagation within Avcoat blocks or along bond line interfaces. A fracture-based approach has been targeted for heat shield certification to address some areas of structural integrity. The measurement of either within Avcoat fracture toughness or the toughness of adhesive bonds between Avcoat and the composite substrate has been a challenge, particularly at temperatures above the glass transition temperature of Avcoat.

Beyond the fracture testing currently being performed, significant efforts have been undertaken in the area of finite element analysis to assess the susceptibility to continued flaw growth due to undetected initial flaws either at adhesive bonds or within the material. This has led to development work for guidelines on how to discretize models, global-local methods to map data from the flight model to fracture models, and additional materials testing to validate models. These activities, which were not anticipated in the original decision to switch from the monolithic to block architecture, have impacted both the cost and schedule of the heat shield certification.

The "grass is greener" mentality was in full force in the decision to switch architectures from monolithic honeycomb to bonded blocks. The lessons learned by the Gemini and Apollo design teams were not followed. The technical team did not fully appreciate the differences in failure modes between a monolithic and block architecture, and how those failure modes could affect mission risk. These new design and certification challenges were not anticipated, and this has directly led to an increased amount of design certification to validate that the system has appropriate damage tolerance and flight safety.

The decision to change from the monolithic to block architecture was not taken lightly. Programmatically, there were perceived cost and schedule benefits to switching. Clearly, the manufacturing of blocks and subsequent manual bonding to the substrate is less labor intensive compared to manually injecting material into hundreds of thousands of cells, thus directly affecting both cost and schedule. Additionally, the block architecture releases the flight vehicle from flight processing flow constraints, providing flexibility of that integration flow. These are valid programmatic reasons for implementing a change, but the technical teams should have been more proactive in clearly outlining to program management the new schedule, cost, and technical challenges associated with an architecture change instead of optimistic projections. Whether or not

the "grass is greener" will only be understood after the Orion EM-1 and future missions are completed.

> *Lesson: Do not blindly trust historical architecture data before utilizing it for new designs, and do not move to newer architectures without fully understanding new failure modes that are introduced*

Lesson Learned #4: Inadequate Analyses May Still Give Answers; Perhaps Not Correct Ones (ISS Node Gusset Issue)

In preparation for launch of the first International Space Station (ISS) pressurized module, Node-1, high strains were observed in the radial port low-wall gussets[14]. Finite Element Analysis (FEA) had used Node-1 models with coarse 2D shell elements without running a mesh convergence check. These high strains were considered a modelling aberration that would improve once more detailed analysis was performed. It did not work out that way. In fact, the coarse elements had masked the strain gradients and true peaks in the region. The gussets had an E-beam weld area with low strength allowables, which made the situation worse. Figure 16 provides the gusset details.

A subsequent assembly level FEA of the Common Berthing Mechanism (CBM) utilized detailed Finite Element Models (FEM) of two pressurized elements on each side of the CBM and found an even higher strain peak in the gussets. The added stiffness in the assembly level FEA had made the problem worse. This finding put the Node-1 proof pressure campaign in jeopardy and presented safety and schedule risks to the first US element launch on STS-88. This issue became the focus of intense scrutiny by all stakeholders and the news media. A Blue Ribbon committee was formed with experts from Boeing, NASA, and the aerospace industry chartered to examine, review, advise, and suggest modifications and monitor progress towards a solution.

Preliminary investigations revealed the high gusset strains were the result of a pre-critical design review (CDR) mass-reduction campaign. The original Node-1 design had internal struts inter-connecting the four radial berthing ports to maintain Common Berthing Mechanism (CBM) deformations within the berthing allowable envelope. This design provided a stiffness balance when other pressurized elements were added to the ports. To save mass, these internal struts were eliminated. Global effects of the strut removal were not investigated thoroughly and the role of these struts in reducing the gusset strain was not realized.

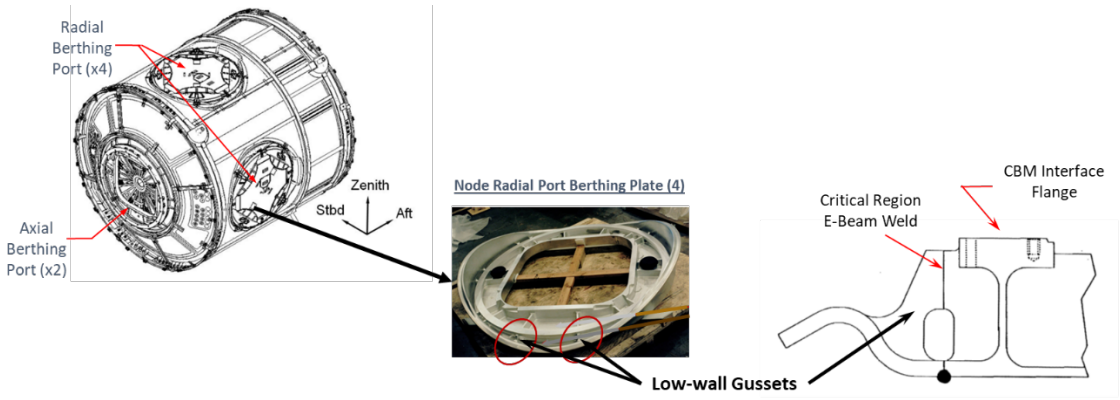


Figure 16. Radial Port Low-wall Gusset Details

Investigation

Detailed investigation campaign started with a study of the material properties. A coupon test campaign was launched at the Marshall Space Flight Center (MSFC) and the Langley Research Center (LaRC) test labs to generate as-built Al-2219 Electron-beam weld mechanical properties in order to ensure accuracy of the updated margins of safety. Additional mechanical testing was performed to assess stress creep behavior of the weld region. The gussets were loaded in the Short-Transverse (S-T) direction during Node pressurization, further exacerbating the problem because of the low ductility and percent strain-to-failure in that direction.

Detailed 2D Shell and 3D solid finite element models with optimized meshes (Figure 17) were developed to better understand gusset strains.

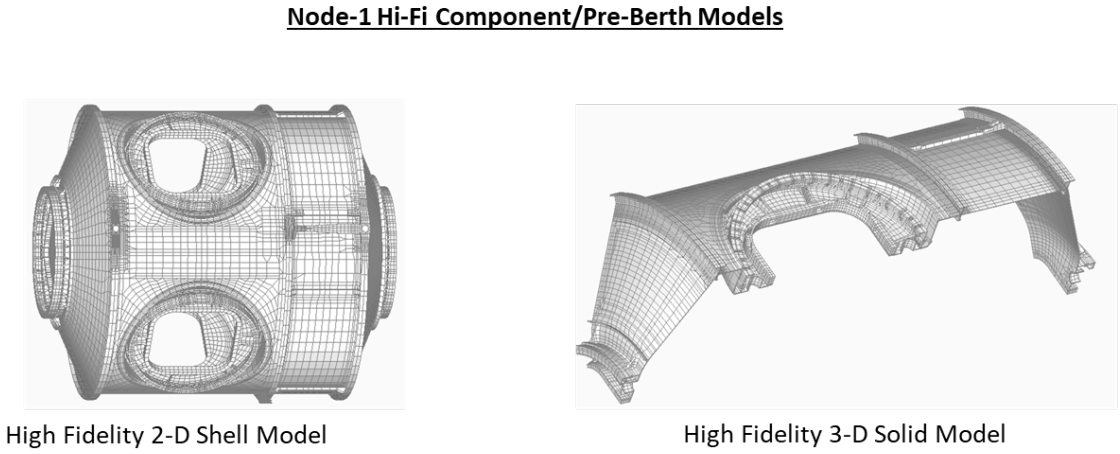


Figure 17. High Fidelity 2D and 3D Node Component Finite Element Models

A fully instrumented and outfitted Node Static Test Article (STA) was prepared for proof pressure testing (@22.5 psig) to validate the analysis predictions. Ten strategically located strain gages on each low-wall gusset provided real time strain measurements. Testing was halted prematurely at 20-psig when strains started a non-linear trend in low-wall gussets on each of the four radial ports, confirming model predictions. Strains continued to increase upon depressurization. A follow-on

proof pressure test was conducted on the Node-1 flight module with no internal secondary structure nor closeout pressure domes. This test was halted at 17-psig due to non-linear strain profiles, ellipsoidal deformation of the pressure shell, and post-test creep as seen on Node-STA. Refined analyses and full-scale testing proved the gusset issue was not an analytical aberration.

Solution

All Node-1 2D and 3D FE models were refined and correlated to the full-scale pressure test data. Twenty-five design solutions were proposed and each was analyzed via test-correlated FEA. Loading conditions included pre-berth (component level) and post-berthed (assembly level) loading with hatches open and closed (Figure 18). The new design solutions ranged from addition of external straps to re-installation of internal struts to off-load the gussets. Of the three final candidates, the most promising solution suggested eliminating the four low-wall gussets on each radial port and re-introduction of internal struts to stiffen the berthing plate and prevent excessive CBM and Hatch distortions.

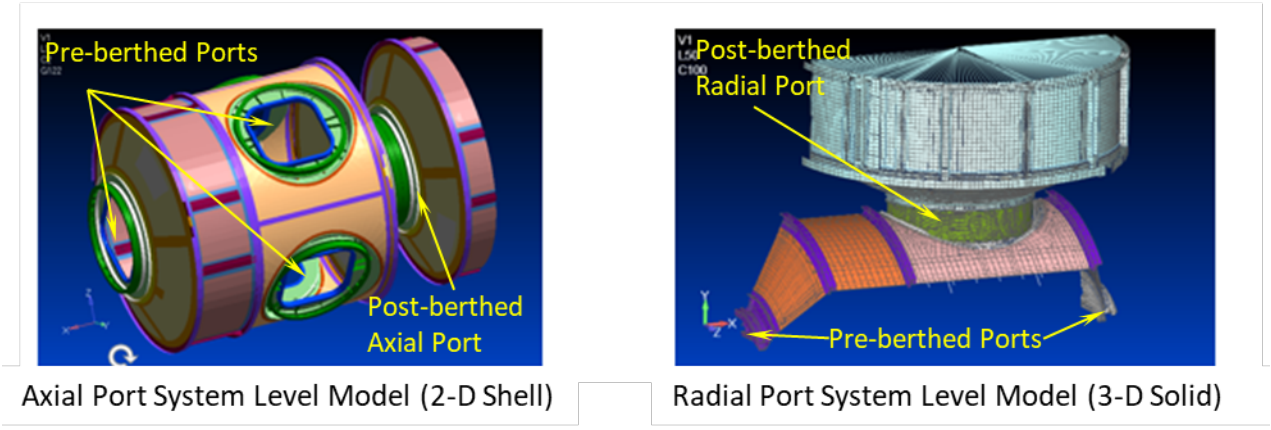


Figure 18. Hi –Fi System Level FEM (Pre-berth and post-berth configurations)

Removing the gussets posed a major concern. Node-STA and Node-1 gussets had experienced plastic strains during proof pressure test campaign. Removal of the gussets could relieve the berthing plate residual strains and result in four distorted berthing plates with the possibility of violating the CBM berthing envelope. Procedures were devised to measure residual strains and to systematically cut out the gussets with minimal distortion. Figure 19 highlights the gusset region before and after the modification.

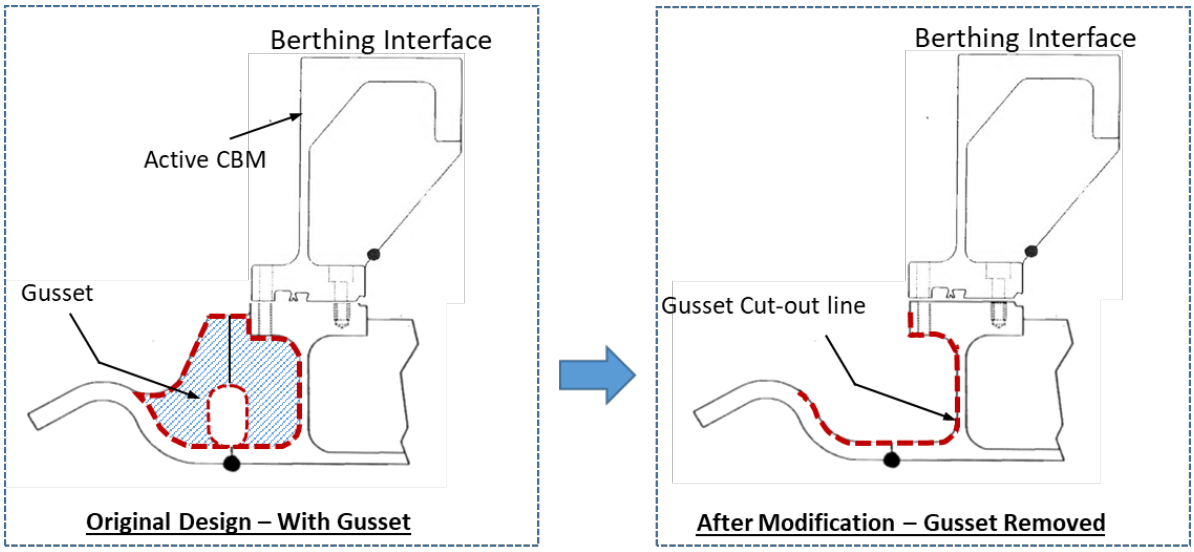
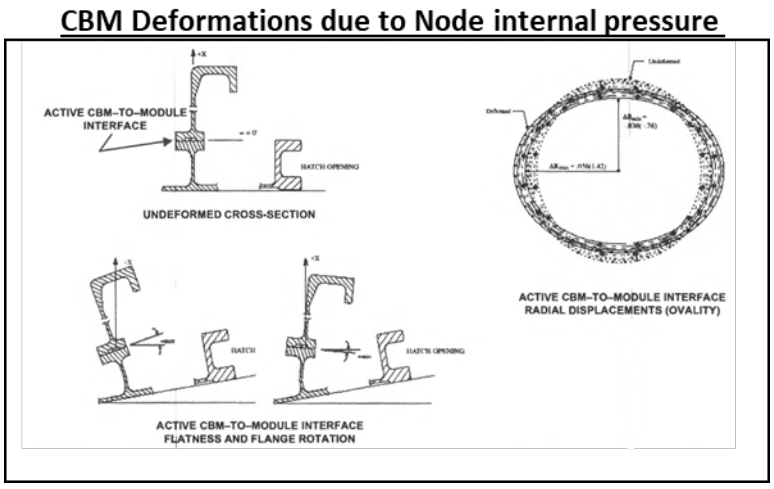
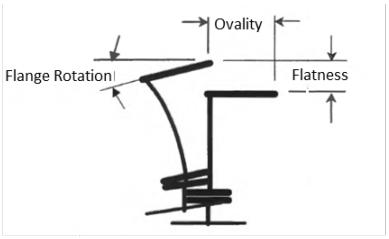
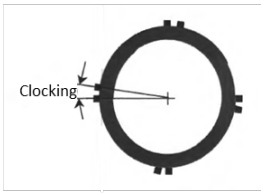


Figure 19. Radial Port Gusset before and after modification

Controlling the CBM and Hatch deflection with great precision is a key design requirement. Unfavorable distortions of the CBM flange at the Berthing Interface could potentially make the port unable to berth. It could impact the performance of automated berthing mechanisms, inability to seal the joint, compromise secondary internal seal installation, and negative structural margins of safety. Each deformation of the CBM ring, i.e., "ovality", Flange "surface flatness", out-of-plane "rotation", and tangential (clocking), must be within the prescribed envelope. Deformations are depicted in Figure 20.







	Deformations			
	Ovality	Flatness	Flange Rotation	Clocking
Capture Dynamics	✓	✓	✓	✓
Powered Bolt/Nut Acquisition	✓	✓	✓	✓
Sealing (ACBM/PCBM)		✓	✓	
ICVA Seal (ACBM/PCBM)	✓	✓	✓	✓
Structural Strength	✓	✓	✓	
CBM Static Fit (Interchangability)	✓	✓	✓	✓

Figure 20. Berthing interface deformations and their affect

New internal strut design must provide the ability of tuning the berthing plate stiffness to ensure the deformations do not violate the berthing envelope. This was accomplished by the addition of preloading features on the struts and then loading each strut to a specific preload. Strain gages were added on each strut to monitor the load on-ground as well as on-orbit as needed. Resulting design configuration included four pairs of titanium trusses, which inter-connected all four radial ports inside the Node and were preloaded to help distribute pressure loads throughout the shell. Figure 21 shows a sketch of the internal strut configurations.

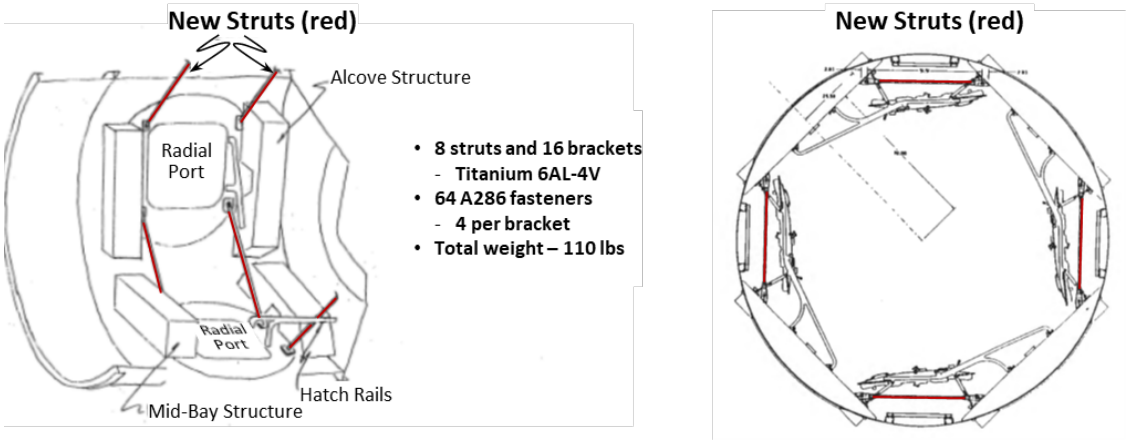


Figure 21. Node-1 Internal strut configuration

A summary of all the activities leading to final design modification is as follows:

1) Multiple high fidelity 2-D shell and 3-D solid Finite Element models created and correlated via full-scale proof test results.
2) Additional pressure tests on highly instrumented Node-STA and Node-1 performed to collect necessary data.
3) Coupon testing campaign to characterize gusset creep, residual strains, and elongation.
4) Machining approaches to cut the gussets with least structural impact due to weld and pressure induced residual stresses to minimize berthing flange distortions.
5) Hundreds of non-linear post-berthed assembly level analyses performed to characterize berthing plate response to stiffness changes affecting CBM berthing envelope.
6) Several internal strut design configurations to achieve the desired stiffness. Included strut design iterations, preload optimization/tuning calculations, and assembly planning.

With the modifications completed, Node-1 and Node-STA were successfully proof tested to the required 22.8-psig in pre-berth and post-berth CBM/vestibule configurations as well as with CBM bolt-out (fail-safe) configurations. (Note: For the Node-1 Proof Pressure Test, several major load-carrying pieces of internal secondary structure were included so that the overall deflection of the pressure shell would assume a similar cylindrical shape to the Node-1 STA). Test campaigns for the Node-STA continued and successfully achieved the combined pressure plus mechanical load conditions. To protect the proto-flight test article, the test factor of safety for the combined load was reduced to 1.05 x (pressure + mechanical) for an agreed upon conservative envelope of the specified transient dynamic interface loads on the radial ports. Node-1 was launched in December 1998 aboard STS-88 and has been operating flawlessly for over 21 years.

Lessons: 1) Poor meshing in Finite Element analyses can mask or hide underlying stress/strain profiles. Interpretation of FEA results requires due diligence. Do not ignore unfavorable results as a modeling aberration. 2)Any mass reduction campaign must include a thorough system level analysis to understand the local as well as global impact of stiffness changes.

CONCLUDING REMARKS

In this paper, four space flight assessments are presented and they each highlight important lessons to be learned. The first assessment recounted a substitution of metallic materials with another alloy to save weight, which on the face appeared to be inconsequential. While saving weight is every program manager's dream, before a substitution is implemented, a comprehensive analysis and evaluation of all aspects associated with the change needs to be performed to minimize unintended effects and avoid introduction of harmful consequences. The Al-2090 alloy selected as replacement material for External Tank stringers was a poor choice as it has low Short-Transverse (S-T) strength. Comprehensive analyses, testing and evaluation clearly demonstrated that the high stresses associated with fit-up and closing of gaps at the stringer feet produced cracks resulting from the low ST directional strength. The major lesson from this assessment is not to make design substitutions, especially to existing design configurations, without a comprehensive study of all aspects of the hardware configuration and loadings.

The second assessment outlined how combining worst-on-worst analyses from differing disciplines performed independently, may not be worst case when disciplines interact. In this case, separate thermal and mechanical analyses did not adequately capture the worst case of thermal-mechanical effects from a combined physics type analysis. Results from higher fidelity analyses may uncover design defects that were unanticipated or unaccounted for in the preliminary design/analysis process where traditional methods, using modified properties (knockdowns) and/or simplified assumptions are the norm. Hardware design/analysis cycles need to account correctly for multi-discipline environmental effects early in their development to reduce the possibility of significant design changes being required late in the process, when they tend to be much more expensive to -incorporate. The major lesson from this assessment is an understanding and correct simulation of all environments and their interactions in structural analysis is of utmost importance.

The third assessment outlines pitfalls of putting blind trust in performance of a historical architecture or design and then switching to a new hardware configuration, based on performance of the heritage design, and assuming that no new issues will arise due to the change. Fundamental differences existed between the heritage Apollo design and the Orion implementation, first using monolithic honeycomb approach and then changing to bonded blocks based on Avcoat material. The over-reliance on the historical architecture without understanding how other parameters (e.g., the underlying substructure, material changes, scale) could affect both the heat transfer and structural response of the combined substructure and ablator system demonstrated an example of using blind trust. A heritage design solution is no longer heritage if original assumptions or parameters are significantly changed.

The Orion Program determined that moving away from the Apollo architecture to a bonded block design would provide cost, schedule, weight, and technical performance benefits. On the surface, the cost and schedule advantages could be tangible rationale for change, assuming the technical and flight safety risks were comparable between the architectures. However, even though molded

blocks are associated with lower manufacturing costs, they introduced new failure modes and additional work not originally accounted for or anticipated. The "grass is greener" mentality could have influenced the decision to switch architectures and not follow the lessons learned by the Gemini and Apollo Programs.

The fourth assessment highlights the importance of Finite Element Modeling fidelity and the need for a comprehensive investigation of late-breaking design modifications. A mass-reduction campaign resulted in the removal of radial port internal struts on ISS Node-1 pressurized module. The verification analysis included only Node 1 component models with less than optimum mesh density. Observed localized strain peaks were discounted as modeling artifacts. Later, a system-level analysis with high fidelity (Hi-Fi) models revealed the strain peaks were real and even higher than originally predicted. Hi-Fi models included the CBM and pressurized element attached at the port, which added stiffness and drove the localized strain peaks at the radial port gussets. Struts had balanced the stiffness and helped unload the gussets. Resolution required a comprehensive test campaign, development of multiple higher fidelity 2-D shell and 3-D solid finite element models correlated to full-scale proof tests, a full set of system level models to predict all loading and stiffness scenarios, and structural modifications including return of internal struts. The lesson learned is, any FE model can give you an answer, but is it the right answer? Does the model have an optimized mesh density? Does it represent the assembled structure's stiffness? Are the loads and boundary conditions adequately understood and implemented?

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Lessons Learned in Building the Ares Projects

John P. (Phil) Sumrall

Since being established in 2005, the Ares Projects at Marshall Space Flight Center have been making steady progress designing, building, testing, and flying the next generation of exploration launch vehicles. Ares is committed to rebuilding crucial capabilities from the Apollo era that made the first human flights to the Moon possible, as well as incorporating the latest in computer technology and changes in management philosophy. One example of an Apollo-era practice has been giving NASA overall authority over vehicle integration activities, giving civil service engineers hands-on experience in developing rocket hardware. This knowledge and experience help make the agency a "smart buyer" of products and services. More modern practices have been added to the management tool belt to improve efficiency, cost effectiveness, and institutional knowledge, including knowledge management/capture to gain better insight into design and decision making; earned value management, where Ares won a NASA award for its practice and implementation; designing for operability; and Lean Six Sigma applications to identify and eliminate wasted time and effort. While it is important to learn technical lessons like how to fly and control unique rockets like the Ares I-X flight test vehicle, the Ares management team also has been learning important lessons about how to manage large, long-term projects.

National Aeronautics and Space Administration



Phil Sumrall

Advanced Planning Manager, Ares Projects

NASA Masters Forum

May 13, 2010

Lessons Learned in Building the Ares Projects

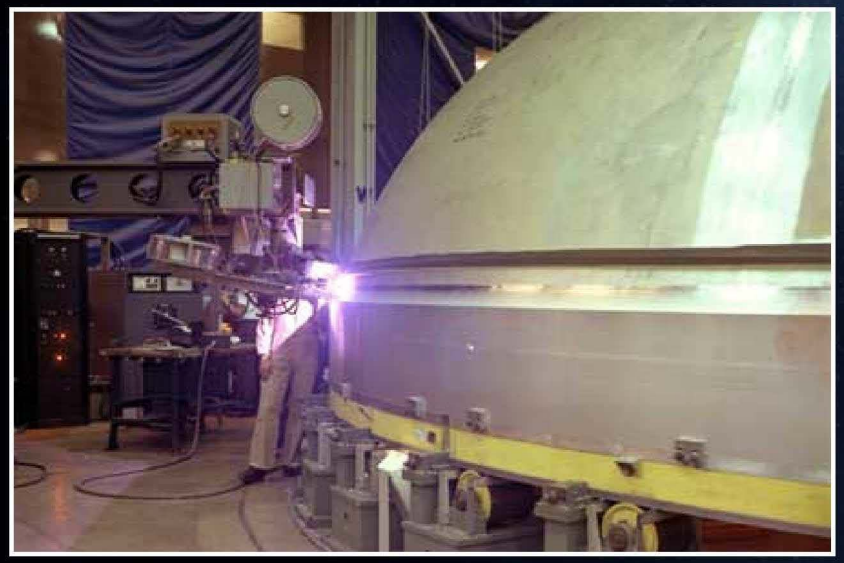
Agenda

- Rebuilding In-house Capabilities from the Apollo Era
- NASA Vehicle Integration Activities
- Making the Agency a “Smart Buyer”
- Anticipating Problems
- Knowledge Management / Capture
- Lean Six Sigma
- Design, Development, Processing, Flying, and Controlling New Launch Vehicles
- Q & A

Rebuilding In-house Capabilities from the Apollo Era







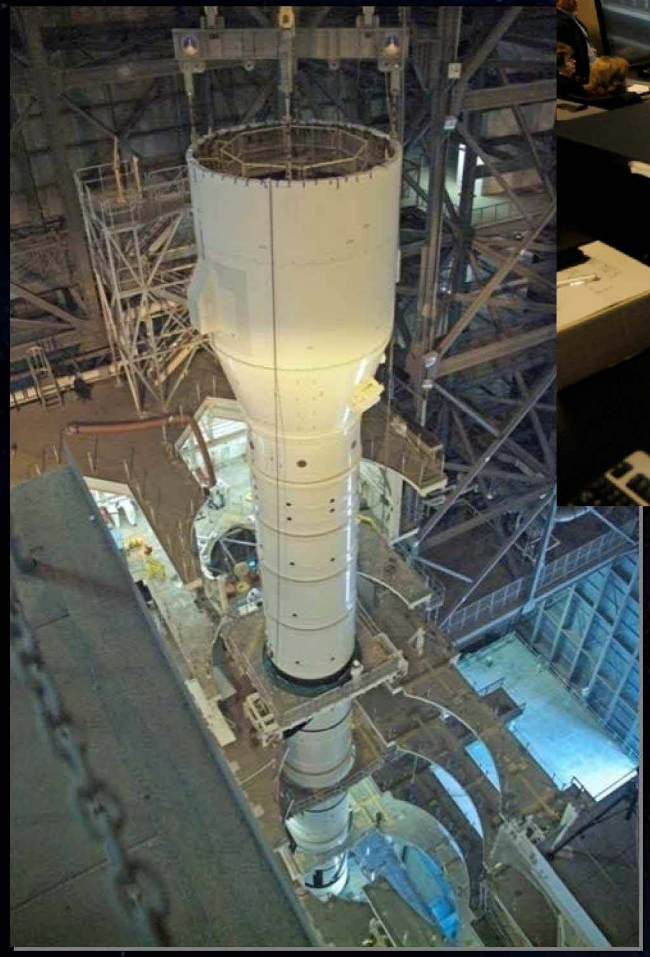


Establishing and Fixing Requirements Early

- Why is it advantageous to do this?
- How well are we doing it?
- What can be done to make it better?
- What could any project—not just Ares—learn from doing this?

NASA Vehicle Integration Activities





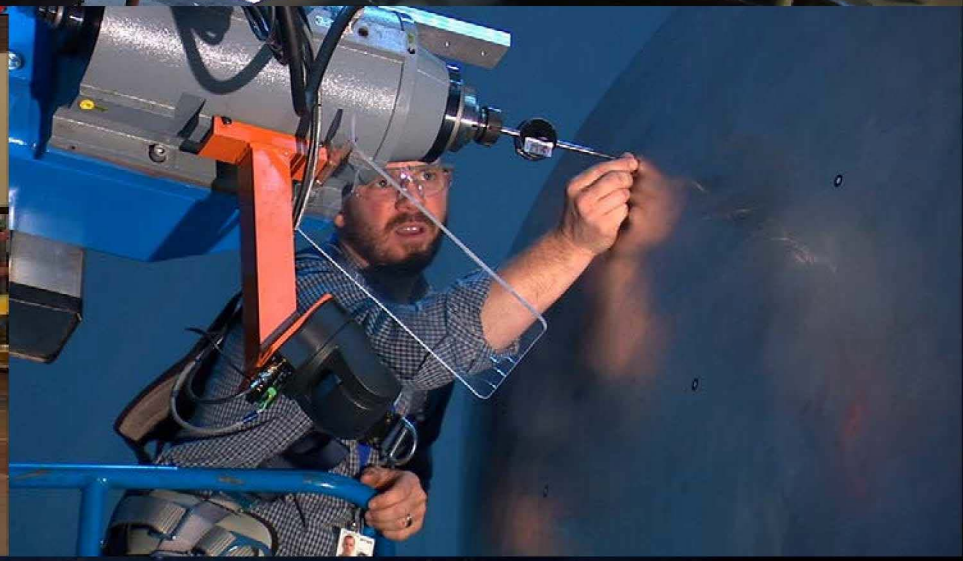


Hands-on Experience / Making the Agency a "Smart Buyer"

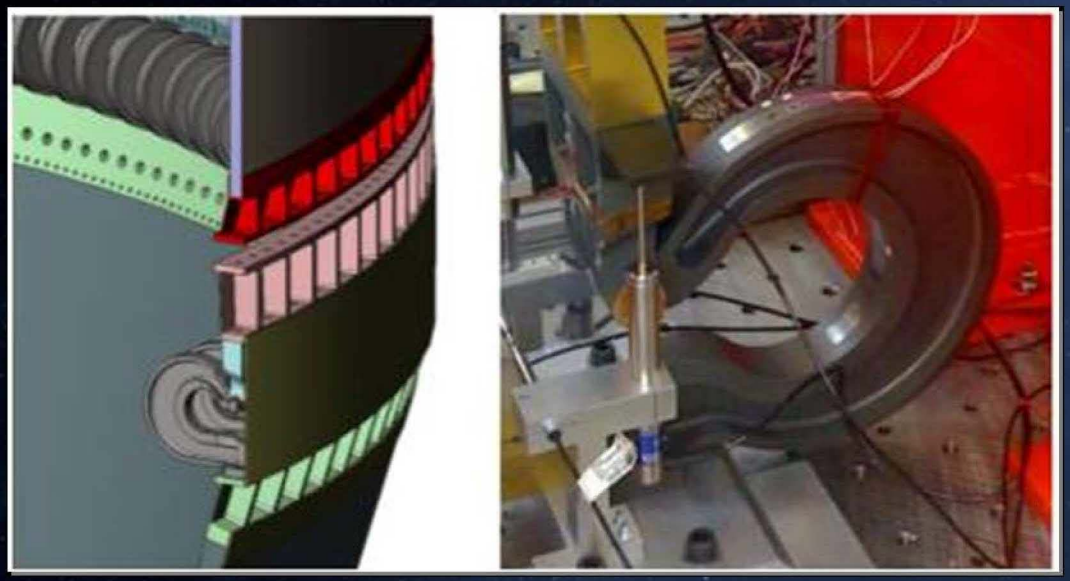








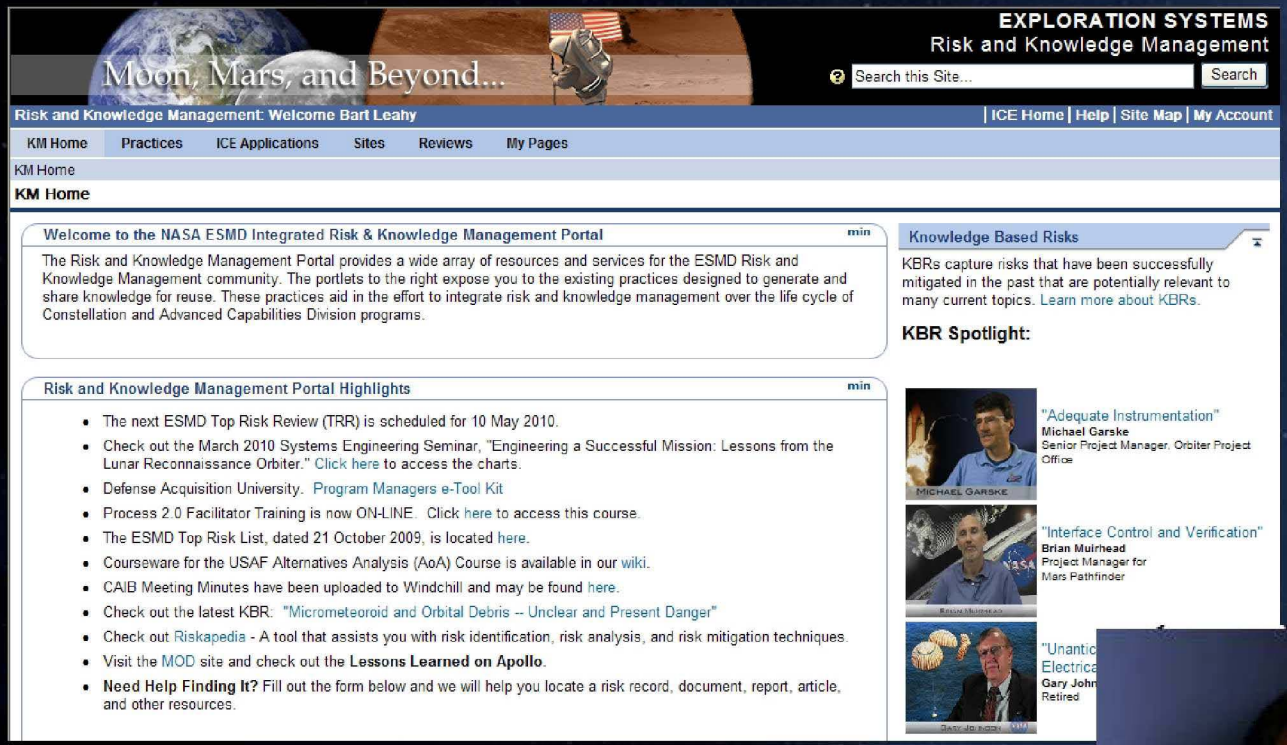
Anticipating Problems





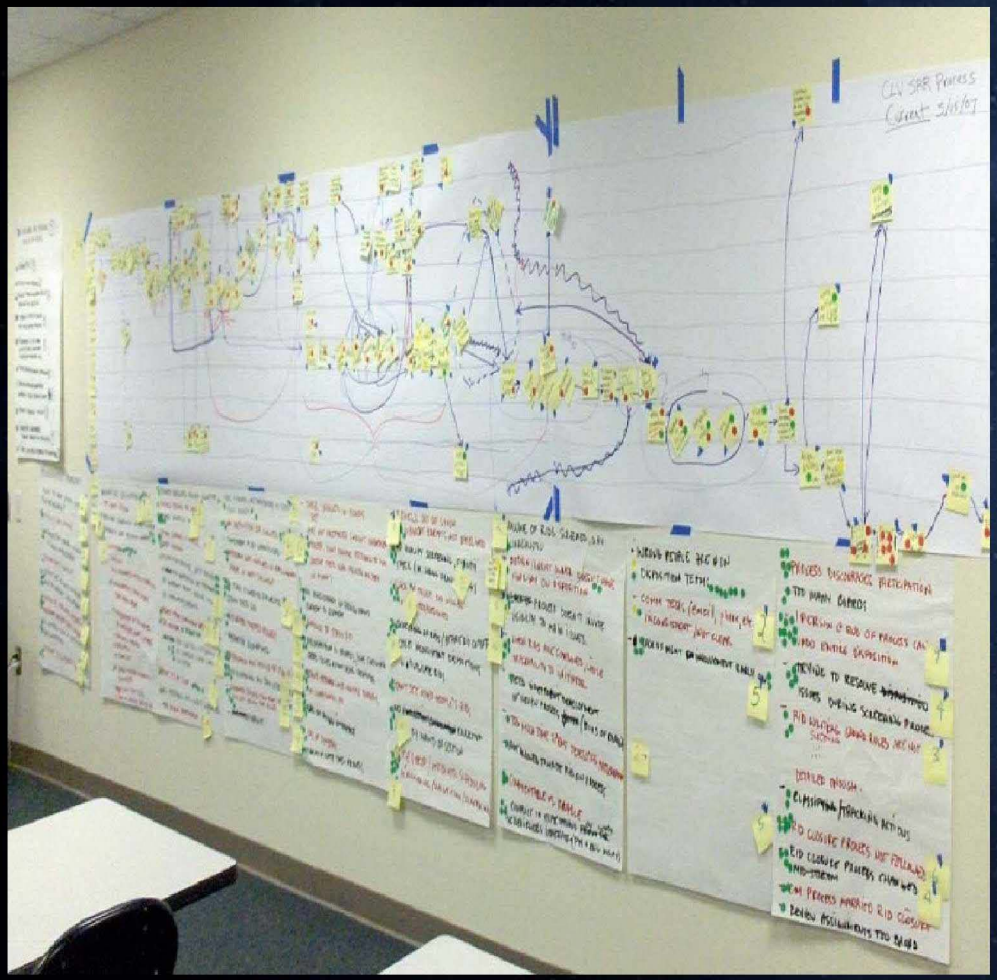


Knowledge Management / Capture





Lean Six Sigma





Design, Development, Processing, Flying, and Controlling New Launch Vehicles

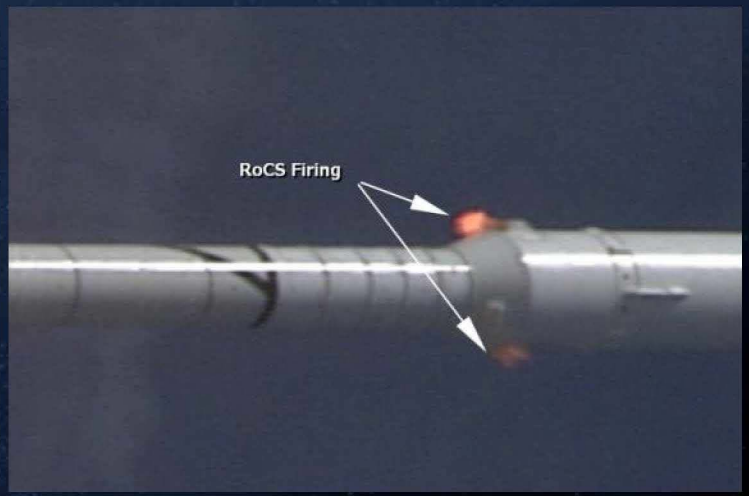













Q & A

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Lessons Learned in Engineering

J.C. Blair, R.S. Ryan, and L.A. Schutzenhofer
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LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS

AFSIG	Ascent Flight Integration Working Group
AIAA	American Institute of Aeronautics and Astronautics
ASME	American Society of Mechanical Engineers
AT	Alternate Turbopump
ATD	Alternate Turbopump Development
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CD	Compact Disk
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
cg or CG	Center of Gravity
CIL	Critical Items List
CM	Crew Module
CRES	Corrosion Resistant Steel
Cryo	Cryogenic
CSM	Command/Service Module
DAC	Design Analysis Cycle
DCR	Design Certification Review
DoD	Department of Defense
DOF	Degrees of Freedom

LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS (Continued)

DOLILU	Day of Launch I-Load Update
DOP	Detail Operating Procedure
EPA	Environmental Protection Association
ET	External Tank
F-1	Saturn First Stage Engine
FMEA	Failure Modes and Effects Analysis
g	Acceleration Due to Gravity (32 ft/sec)
GLOW	Gross Liftoff Weight
GH_2	Gaseous Hydrogen
GP–A	Gravity Probe–A (Redshift Experiment)
GVT	Ground Vibration Test
H-1	Saturn IB First Stage Engine
HCF	High Cycle Fatigue
HEX	Heat Exchanger
HP	Horse Power
HPFTP	(SSME) High Pressure Fuel Turbopump
HPOTP	(SSME) High Pressure Oxidizer Turbopump
ICD	Interface Control Document
ILoads	Parameters for First Stage Trajectory Guidance
IQ	Intelligence Quotient
IRD	Interface Requirements Document

ISS	International Space Station
Isp	Specific Impulse
ISPR	International Standard Payload Rack
ISS	International Space Station
IU	Instrument Unit
IUS	Inertial Upper Stage
J-2	Engine on Third Stage (SIV-B) of Saturn V
KSC	Kennedy Space Center
LAX	Los Angeles Airport
LCE	Loads Combination Equation
LCF	Low Cycle Fatigue
LES	Launch Escape System
LH_2	Liquid Hydrogen
LM	Lunar Module
LN_2	Gaseous Nitrogen
LOC	Loss of Crew
LOX	Liquid Oxygen
LOXAT	Liquid Oxygen Alternate Turbopump
LRU	Line Replaceable Unit
LWT	Light Weight Tank
Max q	Maximum Dynamic Pressure

MCC	Main Combustion Chamber
MF	Mass Fraction (measure of structural efficiency)
MIT	Massachusetts Institute of Technology
MLP	Mobile Launch Platform
MOV	Main Oxidizer Valve
MPS	Main Propulsion System
MSFC	Marshall Space Flight Center
MVGVT	Model Vehicle Ground Vibration Test
OAFPL	Over All Fluctuating Pressure Level
PDF	Probability Density Function
PDR	Preliminary Design Review
POGO	Thrust Structure Closed Loop Coupled Longitudinal Oscillation
POT	Potentiometer
PRA	Probabilistic Reliability Analysis
PRA	Probability Risk Assessment
PSD	Power Spectral Density
psf	Pounds per Square Foot
PWL	Power Level
P&W	Pratt and Whitney
PWR	Pratt Whitney Rocketdyne
q, Q	Dynamic Pressure

Qα, Qβ	Dynamic Pressure Times Angle of Attack or Side Slip Angle
RCS	Reaction Control System
RMS	Root Mean Square
RP-1	A Type of Hydrocarbon Rocket Fuel
RPM	Revolutions Per Minute
RSRM	Shuttle Redesigned Solid Rocket Motor
RSS	Root Sum Square
SAE	Society of Automotive Engineers
SAFE	Solar Array Flight Experiment
SAS	Solar Array System
S I	Saturn I
S-IC	First Stage of Saturn V
S-II	Second Stage of Saturn V
S-IVB	Third Stage of Saturn V
SLWT	Super Light Weight Tank
SM	Service Module
S&MA	Safety and Mission Assurance
SN	Stress Versus Number of Cycles
SOA	State of the Art
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor

SSME	Space Shuttle Main Engine
SSTO	Single Stage To Orbit
STS	Space Transportation System
TDRS	Tracking and Data Relay Satellite
TP	Technical Publication
TPS	Thermal Protection System
TRL	Technology Readiness Level
T/W	Thrust to Weight
VAB	Vehicle Assembly Building
VIPA	Vehicle Integrated Performance Analysis Team

CONTRACTOR REPORT

LESSONS LEARNED IN ENGINEERING

INTRODUCTION

This report is a compilation of Lessons Learned in approximately 55 years of engineering experience by each, of James C. Blair, Robert S. Ryan and Luke Schutzenhofer. The lessons are the basis of a course on Lessons Learned that has been taught at the Marshall Space Flight Center. The lessons are drawn from NASA Space Projects and are characterized in terms of generic lessons learned from the project experience, which are further distilled into overarching principles that can be applied to future projects.

Included are discussions of the overarching principles followed by a listing of the lessons associated with that principle. The Lesson with sub-lessons are stated along with a listing of the project problems the lesson is drawn from, then each problem is illustrated and discussed with conclusions drawn in terms of Lessons Learned. The purpose of this report is to provide principles learned from past aerospace experience to help achieve greater success in future programs, and Identify application of these principles to space systems design. The problems experienced provide insight into the engineering process and are examples of the subtleties one experiences performing engineering design, manufacturing and operations. A CD of a class taught on this subject is included, providing the illustrations used in this report, along with other related material.

How to avoid the mistakes of the past and how to train people in the essence of engineering are mandatory questions we face in aerospace engineering. Those who forget the lessons from the past are doomed to repeat them. Dr. Wernher von Braun has said that; “Crash programs fail because they are based on the theory that with nine women pregnant you can get a baby in a month.” Failure also occurs because we forget that physics rules and we try to bypass it in our designs.

NASA and DOD have a great heritage in Space Systems programs that have been very successful; however, they are pushing the limits of technology in order to defeat gravity, survive extreme environments, and meet their programmatic goals. In pushing the limits, we have to take risks, and in taking risks we naturally have problems.

The power density and the high efficiency requirements of space exploration lead to an unprecedented and challenging sensitivity of the system performance to the system parameters and their uncertainties, manufacturing practices, etc. which implies great risks and many potential problems. The experience we have had with these systems in the last six decades bears out these observations. NASA has lost astronauts three times, the first was the Apollo fire at KSC, the second was the loss of Challenger and its crew, and last the loss of Columbia and its crew. There are other failures that have led to loss of mission and many

other problems that have had major program impacts. DOD and the commercial side of space exploration have experienced problems of the same general categories discussed.

The goal of this report is to review the NASA programs, develop lessons learned, and from them derive basic principles that can be applied to future programs. While only those problems and systems worked on by the authors are included as examples, the lessons and principles are generic and can be applied in other technical and organizational arenas. The report concludes with a reiteration of the principles.

NASA Programs

We started out working with the Army Missile Command, on the Redstone and Jupiter missiles and their derivatives, which were eventually used in space exploration. The Saturn I was started as an Army project and then taken over by NASA. It was a vehicle that used current hardware and manufacturing processes in order to get an early heavy lift launch capability. The Saturn I first stage used the Jupiter manufacturing process and tank diameter for the center tank, and the Redstone tank diameter and manufacturing process for the clustered tanks. The first stage engines were H-1's produced by Rocketdyne, and the upper stage engines were RL-10's produced by Pratt & Whitney. After successfully launching the Saturn I vehicle we were transferred to the newly-formed NASA organization in 1960 and worked all the NASA programs including the potential new starts that did not materialize or were canceled before completion. Figure I-1 shows a partial list of the projects, and Figures I-1, I-2, I-3 & I-4 include pictures of some of the projects. Notice on Figure I-1 that a sketch of the Russian vehicles and the DOD vehicles are included. We had some small efforts on these systems. Bibliography provides details if the reader wants to explore further the various projects and their characteristics.

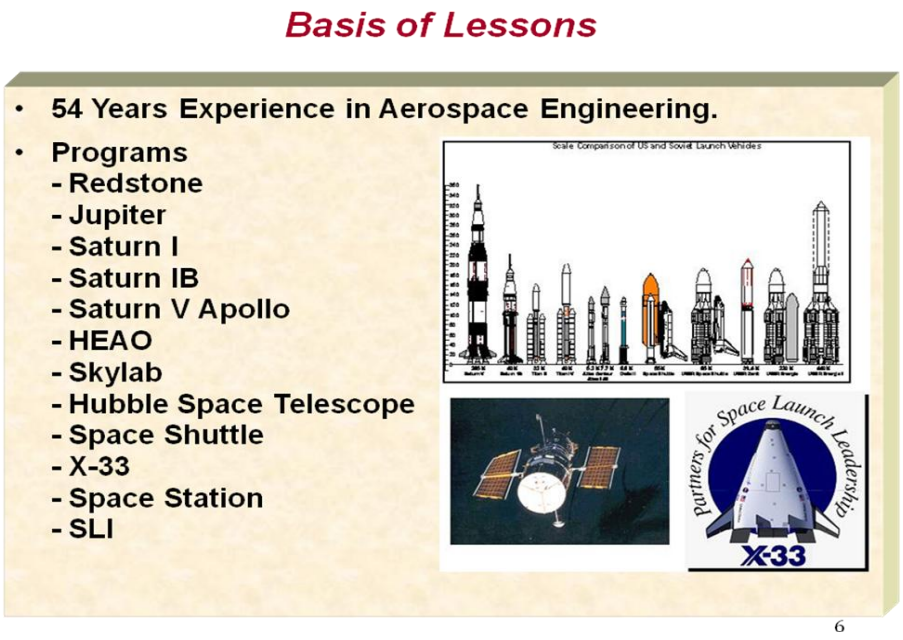


Figure I-1. Example Projects that Formed Basis of the Lessons



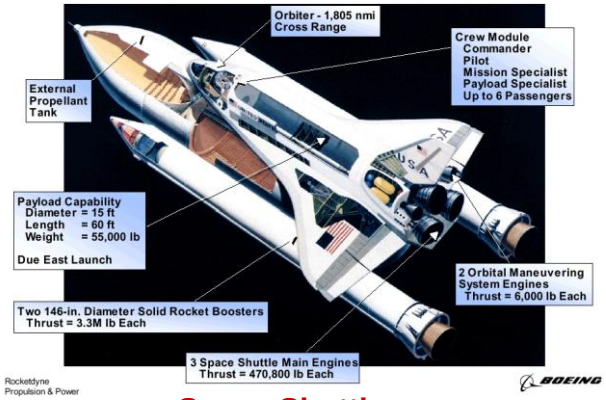




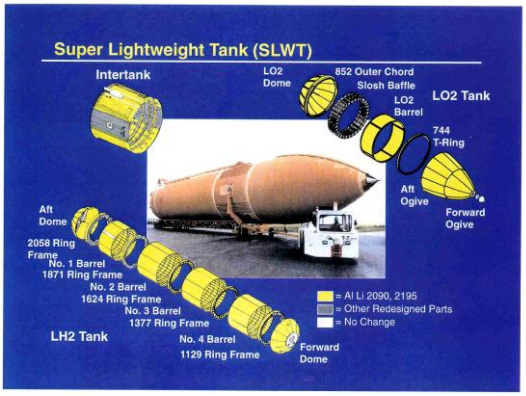




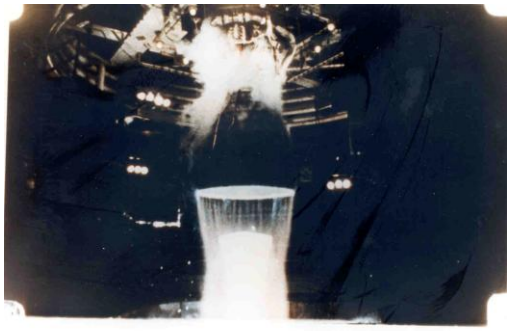
Figure I-2. Example Projects that Formed Basis of the Lessons –cont'd.



Space Shuttle



Super Lightweight ET



SSME



RSRM

Figure I-3. Example Projects that Formed Basis of the Lessons – cont'd.



Figure I-4. Example Projects that Formed Basis of the Lessons – cont'd.

Lessons Learned Process

The process used for developing and describing the "Lessons Learned" starts with the listing of various project experiences and problems from which we developed the lessons. We limited the projects and lessons to those that the authors had experience with. There are many other lessons in our collection which others have developed which are a rich source for the reader to explore. We next grouped the observations into generic and technical categories. We first subdivided the two categories into more definitive categories as shown on Figure I-5. Under these categories the observations were then grouped as lessons derived from the observations. Top level principles of design and management were distilled from these lessons.

Basis and Applicability of Lessons

- From our experience, which has been primarily in technical integration and flight mechanics, we have derived lessons and distilled principles that are general in nature and apply across all engineering.
- The general lessons and principles can be supported by examples from disciplines other than those of the authors' experience.

- In addition to these general lessons, there are also discipline-specific and component-specific lessons that are not addressed in this course. They are available from other sources such as the NASA and Center Lessons Learned databases, Lunar e-Library (Materials Division), etc.

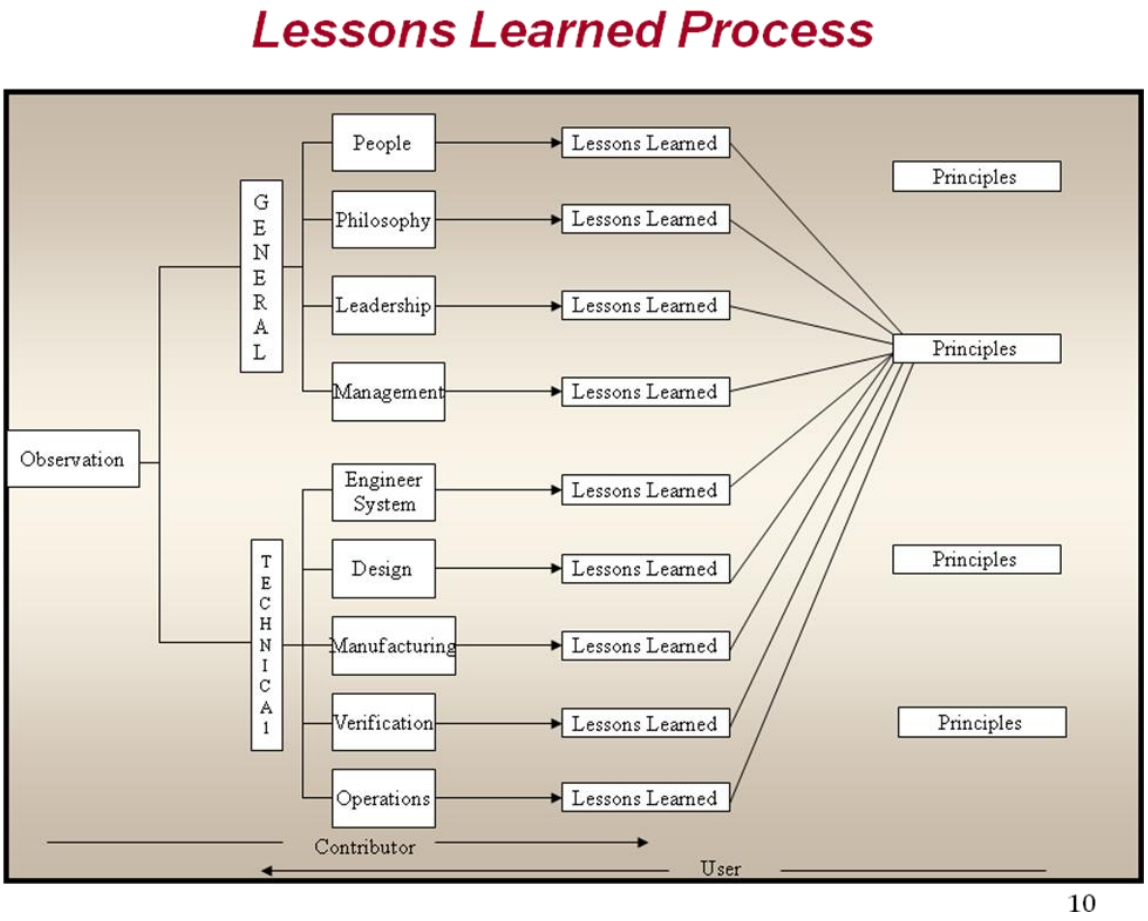


Figure I-5. Lessons Learned Process

The top level principles are listed below, with associated corollaries. Principle 1 deals with the importance of people. Most of everything we do depends on the judgment and decision making skills of our people. People are the most important resource an organization has. In fact, all infrastructures exist as an aid to the human personality and mind. Principle 2 deals with how the challenge of putting systems in space drives everything, including all analysis and test and the project design. Principle 3 deals with the system interactions and the fact that all the parts are interacting elements of the system. Communications is a key to understanding this systems aspect of a project or program. Principle 4 is fundamental in that everything is governed by the laws of physics. In a broad sense this also includes the basic principles of finance, organization, etc. Principle 5 deals with need for robustness and the understanding of sensitivities, uncertainties, risks and margins of the system.

Principle 6 says that we must design a product for its total life cycle, not just one phase. Principle 7 says that testing and verification are essential to developing a good product. Principle 8 deals with the need for critical thinking and having a culture that listens, thinks creatively and questions critically. Principle 9 goes back to the people and deals with the importance of leadership. Each of the principles will be discussed in more detail in the following sections of the report.

Lessons Learned Principles

I. **System success depends on the creativity, judgment, and decision-making skills of the people**
   - People are our most important resource

II. **Space systems are challenging, high performance systems**
   - High energy, high power density
   - Therefore, high sensitivity

III. **Everything acts as a system (whole)**
   - We design by compartmentalization and reintegration
   - Understanding interfaces and interactions is crucial
   - Requires pervasive communications

IV. **The system is governed by the laws of physics**
   - Reality can't be ignored
   - Look to the real performance of the hardware and software

V. **Robust design is based on our understanding of sensitivities, uncertainties, and margins**
   - Must consider sensitivities, uncertainties, margins, risks
   - Aim for robustness

VI. **Project success is determined by life cycle considerations**
   - Program constraints can result in a non-optimal design
   - Requirements can drive the design in unexpected ways
   - Early phases of project most influential on design
   - Design must consider full life cycle including manufacturing, verification, and operations

VII. **Testing and verification have an essential role in development**
   - We understand by testing
   - Must know limitations

VIII. **Anticipating and surfacing problems must be encouraged**
   - Critical thinking
   - Think out of the box
   - Listen

IX. **Leadership is the foundation**
   - Integrity
   - Outward focused
   - People centered

Another way of visualizing the lessons is shown Figure I-6 as a triad of Insights, Integration, and Individuals. *Insights* deal with principles, physics of the problem, critical thinking, creativity and discoveries. *Integration* deals with the system and subsystems, their uncertainties, sensitivities and trades, while the *Individuals* leg deals with leadership, people skills, communications etc. Only representative items are included. *Insights* are the basic principles that we see from the lessons and the discoveries they reveal. *Individuals* involve the individual skills and organizational characteristics. *Integration* covers the complex interactions which occur within complicated space systems and the process of making the total system perform successfully.

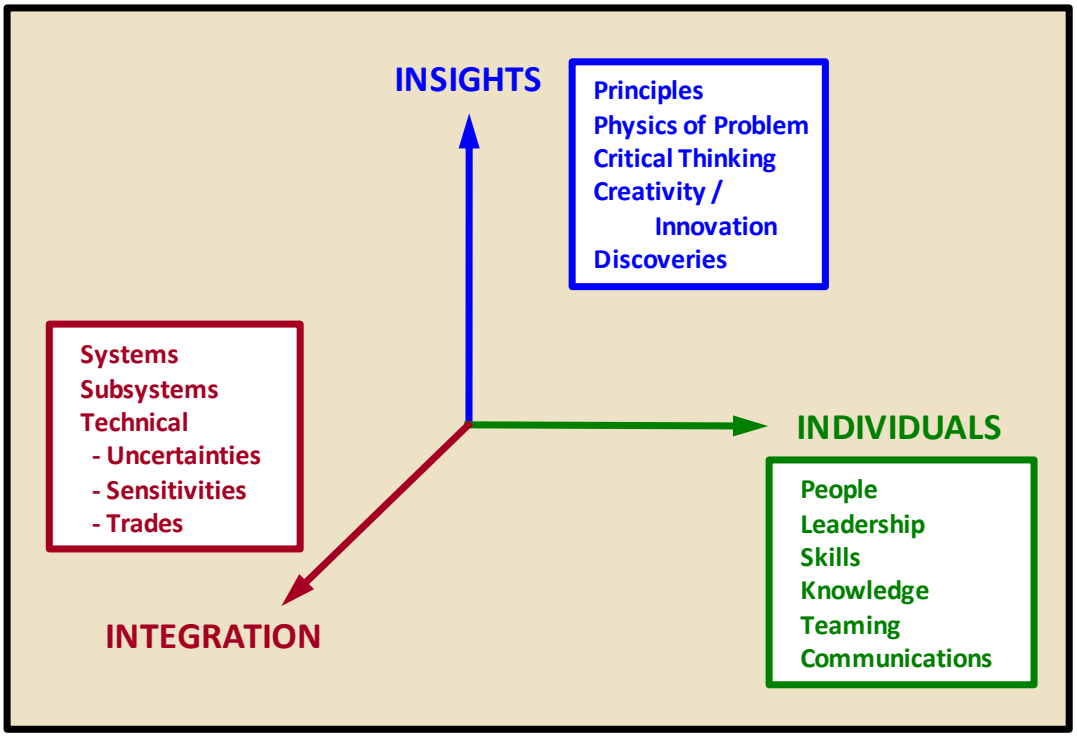


Figure I-6. A Triad of Principles and Lessons Concepts

We have grouped the twenty-seven Lessons Learned under the nine Principles discussed earlier. The Principles and the Lessons grouping becomes the outline for discussion for the rest of the report as shown below.

Listing of Principles with Supporting Lessons

I. **System success depends on the creativity, judgment, and decision-making skills of the people**

1. People Are the Prime Resource for Project Success
2. People Skills are Mandatory for Achieving Successful Products

II. **Space systems are challenging, high performance systems**

3. Demand for High Performance Leads to High Power Densities and High Sensitivities

III. **Everything acts as a system (whole)**

4. Systems and Technical Integration
5. Risk Management
6. All Design is a Paradox, a Balancing Act

IV. **The system is governed by the laws of physics**

7. Physics of the Problems Reigns Supreme
8. Engineering is a Logical Thought Process
9. Mathematics Is The Same!
10. Fundamentals of Launch Vehicle Design

V. **Robust design is based on our understanding of sensitivities, uncertainties, and margins**

11. Robustness
12. Understanding Sensitivities and Uncertainties is Mandatory
13. Margins Must Be Adequate

VI. **Project success is determined by life cycle considerations**

14. Design Space Constrained by Where You Are in the Life Cycle
15. Concept Selection and Design Process
16. Requirements Drive the Design
17. Designing for the –ilities and Cost

VII. **Testing and verification have an essential role in development**

18. Hardware and Data Have the Answers
19. Can Test Now or You Will Test Later
20. Independent Analysis, Test, and Design Keys to Success
21. All Analyses and Tests are Limited
22. Scaling is a Major Issue

VIII. **Anticipating and surfacing problems must be encouraged**

23. Must Hear and Understand All Technical and Programmatic Opinion
24. There are No Small Changes!
25. Expect the Unexpected

IX. **Leadership is the foundation**

26. Integrity
27. Focus Beyond Yourself

Discussion of Lessons Learned Principles

In the following sections we will divide the report by the Principles shown above. For each Principle, there will first be a discussion of the principle category in general, followed by a listing of the lessons supporting that principle, along with sub-categories of the lesson. Included will be a listing of the various problems/projects used to create the lesson. The format will be: The lesson with corollaries is stated along with a listing of the project problems the lesson is drawn from, then each problem is illustrated and discussed with conclusions drawn in terms of Lessons Learned.

Principle I: System Success Depends on the Creativity, Judgment, and Decision-Making Skills of the People

1. **People Are the Prime Resource for Project Success**
2. **People Skills are Mandatory for Achieving Successful Products**

What we have found is that of all the resources and skills required for project success, people are number one; everything else comes in second. We will discuss this category under the above two lessons:

Lesson 1: People Are the Prime Resource for Project Success

- ***People are the prime resource. Engineer's judgment and creativity are the key to quality engineering. All other resources are an aid to the human mind.***
  - **The complexity of the system requires applying judgment and innovation to the specific situation. Dogma, rules, or recipe cannot supplant this.**
  - **Tools enhance efficiency, but cannot replace judgment and creativity of the human mind.**
  - **Guidelines and criteria should be tailored or adapted to the particular project, to avoid a dogmatic approach, which unnecessarily constrains design solutions.**
  - **Many decision gates are not explicit, but are judgment based, requiring in-depth system knowledge and wisdom.**
  - **The level of penetration is an engineering judgment, determined by project characteristics, phase, sensitivity, and uncertainty.**
  - **Reward all expressions of creativity.**

The sub-topics of the general lesson that people are the prime resource state clearly that we cannot just depend on process and procedures to obtain a successful product; but, that the complexity of our space systems depends on the judgment and innovation of the people of the organization to create, build and manage a successful system. Dogma and rules, although they can guide and are necessary, can never replace this judgment and creativity of the human mind. In the end the human mind trumps. The same can be said of tools. We need process, procedures, criteria and guidelines but they should never be used to replace the creativity and the human judgment. We use these tools to aid in decision making but in the end most decisions are human judgments based on wisdom and understanding. One of the big questions design and operations of space systems raises continually is “When is enough good enough for the system.” Our tendency is to be risk aversive and add detail way beyond what is good enough. Human judgment and creativity should be applied in all aspects of space operations. The organization should reward all expressions of creativity of its people and not have an organization governed by fear of failure.

The complex technical and managerial problems we face depend on human judgment, creativity, and innovation for solutions. All our other tools are aids for the human mind in the performance of these tasks. Our job then is to bring out and develop these human resources. There are many examples that illustrate the value of human resources and how they have been rewarded. This creativity exists in many forms as illustrated next. The basic lesson is that we must reward all forms of creative actions of our people and start development of processes to remove inhibitors which suppress the creative actions of its people.

Creativity exists in several forms.

1. Technical expression
2. Artistic expression
3. Naming of hardware parts
4. Musical expression

Reward all forms of creativity expressed by the people.

Examples for Lesson 1 are:

- Rich Holman
- Honeywell Calendars
- Jupiter Propellant Sloshing Solution. "Beer Cans"
- Synthetic Wind Profile
- SSME LOX Pump Silicon Nitride Bearings
- Tethered Satellite Skip Rope Damper

Rich Holman

In the early Apollo days there was an engineer, Rich Holman, at McDonnell Douglas who drew cartoons of the Saturn IV B problems and the personalities involved in the problems. McDonnell Douglas thought the value of the cartoons was so great that they

published a selected group in a little booklet titled “Nicely Drawn by Rich Holman”. [Holman, Special document] We have selected two of these to illustrate the content and value. Figure 1-1 deals with a problem we had with the dynamic response of the engine gimbaling actuators. The actuators were coupling dynamically with the thrust structure creating an undesirable high response, which compromised the controllability of the vehicle. Rich summed up the physics of the problem by saying that it only hurts at resonance. The people involved that were not convinced were the recipients of the statement. The name of Eggleston on the badge is one of the SIVB Stage Program managers that were having trouble accepting the existence of the problem. Rich’s cartoons not only dealt with the physics of the problems but the human involvement as well. Figure 1-2 had to do with a control feedback potentiometer that was giving a problem. Getting rid of the potentiometer required the addition of additional elements that increased the complexity of the system. In those days the potentiometer was a series wound coil which the wiper arm moved across to create the signal. Each time the wiper arm encountered the next winding of the coil, the signal would jump in amplitude, creating a series of frequency pulses. The frequency of the pulses was introduced by the speed the arm was moving. This series of pulses was creating a dynamic problem. The quote; “But it does get rid of the feedback pot”, sums up the principle, that adding complexity creates additional problems. The cartoon illustrates this by the number and complex arrangement of parts in the base region of the SIV B Stage.

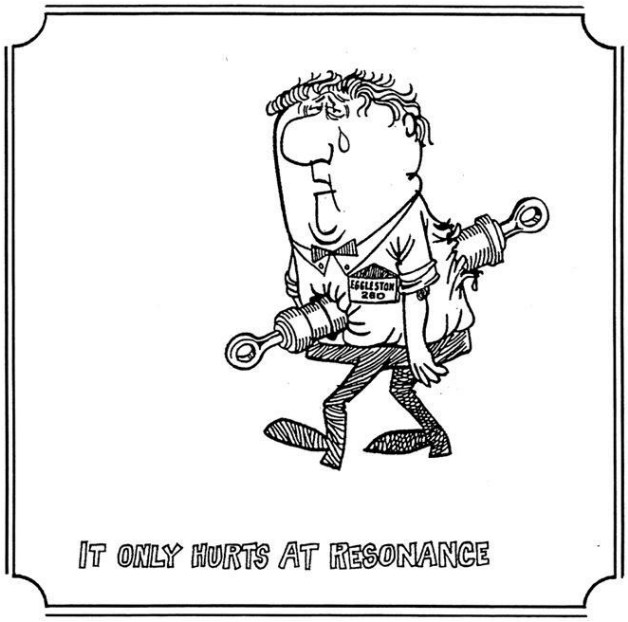


Figure 1-1. It Only Hurts At Resonance



Figure 1-2. But It Does Get Rid of That Feedback Pot

Honeywell Calendars

In this same time period Honeywell Corporation put out calendars with cartoons drawn by Bill Eddy that were of the same character as was Rich's. The cartoons were published by Minneapolis Honeywell in two books [Eddy, 1956] and [Eddy, 1962]. We have chosen three of these monthly calendar cartoons: Figure 1-3 is one of our favorites which illustrates that all details are important. It shows the importance understanding any anomaly before proceeding; as the bridge that doesn't connect because of the design error of a decimal point. Figure 1-4 shows the importance of capturing early and controlling requirements versus letting requirements grow and change uncontrolled. Space programs have been replete with large cost growth due to changing requirements. Figure 1-5 deals with the Alaskan oil pipeline where they were painting it from different ends and when they met the colors where different. (Not an actual happening) It illustrates the concept that one must stay with the specifications and requirements or push back on the system so that the design is consistent.

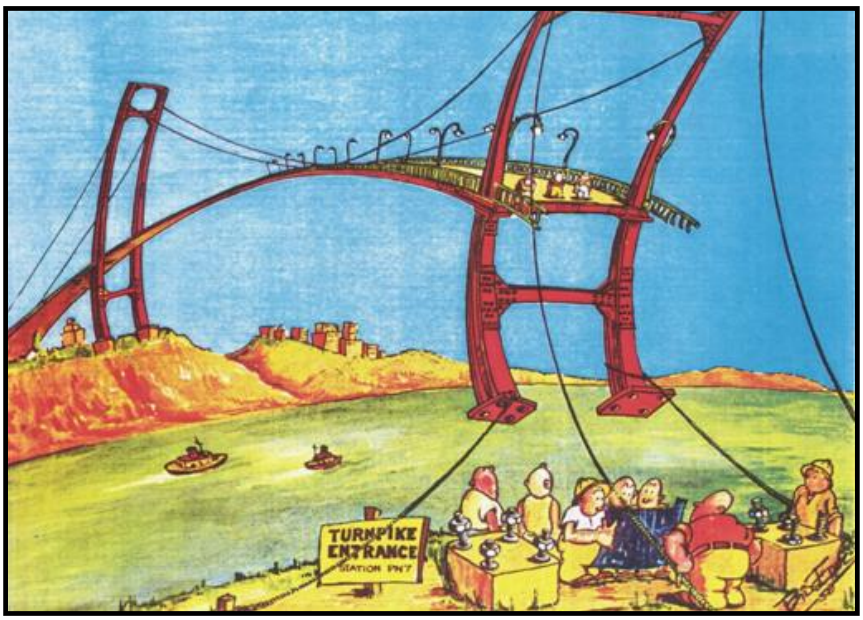


Figure 1-3. So That Decimal Point Indeed Was A Fly Speck

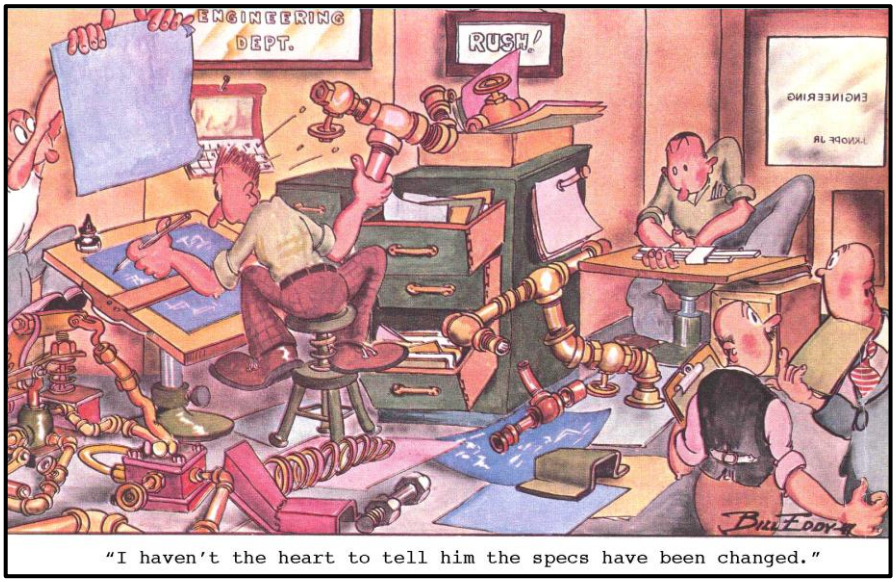


Figure 1-4. Changing Requirements

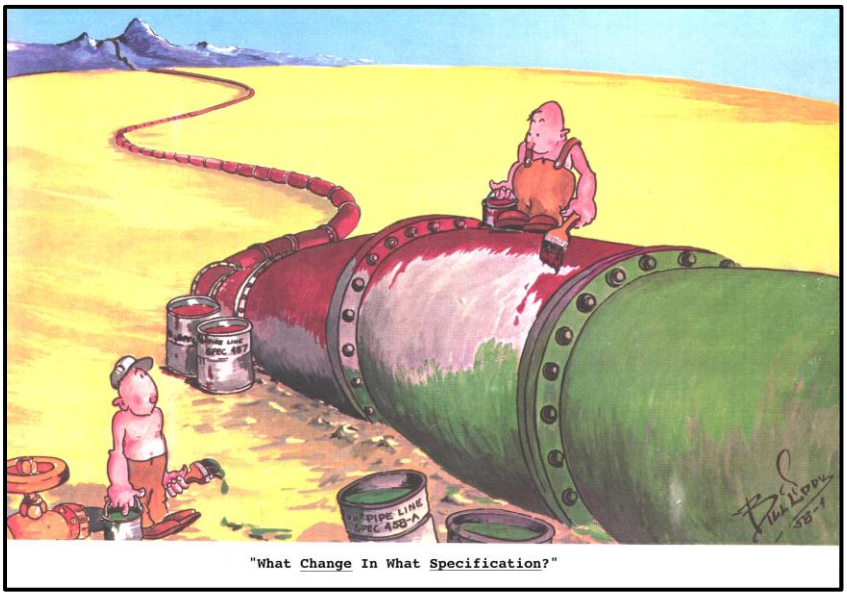


Figure 1-5. What Change in What Specifications?

Jupiter Propellant Sloshing Solution. "Beer Cans"

We lost the first Jupiter missile due to an engine plume recirculation problem burning the actuator control wires. The second Jupiter launch was lost due to propellant sloshing dynamics coupling with the control system. [Ryan, September 1996; Abramson, SP-106, 1967; Abramson, SP-8031, 1969].The control system was saturated and vehicle control was lost at max q. The first problem was fixed with the installation of a heat shield where the gas generator exhaust was dumped overboard; however the second problem required more work and engineering creativity. No analytical models existed for characterizing the dynamics of liquids in a tank, and this type of experimentation was an emerging technology. The problem became the instigator for a long term analytical and experimental technology development. Helmut Bauer at NASA and Norm Abramson at Southwest Research Institute were the leaders in this effort. [Bauer, 1964] However, this effort was downstream and we needed a quick solution so that Jupiter 3 could be launched on time. We took the Jupiter LOX tank and put it on an empty railroad car and filled it with water. We then bumped the railroad car against the spur railroad stop, exciting the liquid dynamics. A movie camera recorded the motion and we were able to derive an equivalent slosh mass and frequency to be used in a control feedback simulation. The question then was: “What is a fix for the problem?” so that we could launch the next vehicle. Someone said that when they were back on the farm and had to haul water in steel drums in a wagon, that they floated pieces of lumber on the surface to keep it from sloshing. Well, lumber would not work in a missile, but floating something would. The original design was a perforated cylinder truncated with cones and had a commode float inside to make it float. The entire surface was filled with these devices called

beer cans. We then put these in the tank on the railroad car and demonstrated that they would indeed suppress the sloshing. They were eventually flown on Jupiter. See Figure 1-6.

Later, through analysis and sub-scale testing, we developed the baffle approach making the perforated baffles a part of the ring stiffeners. See Figure 1-7. This approach was used on Saturn and saved weight by having the baffles also perform part of the stiffening required to prevent tank buckling etc. Shuttle used baffles attached to an inter-frame instead of the ring frames due to manufacturing and operational requirements.

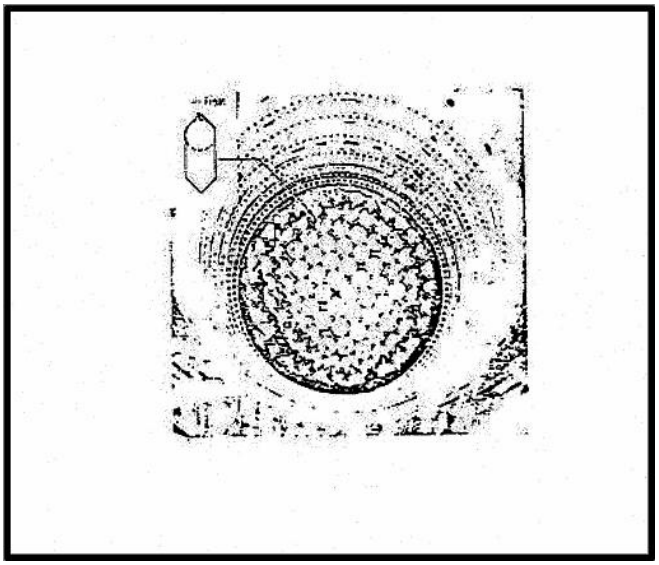


Figure 1-6. "Beer Cans" Flown on Early Jupiters

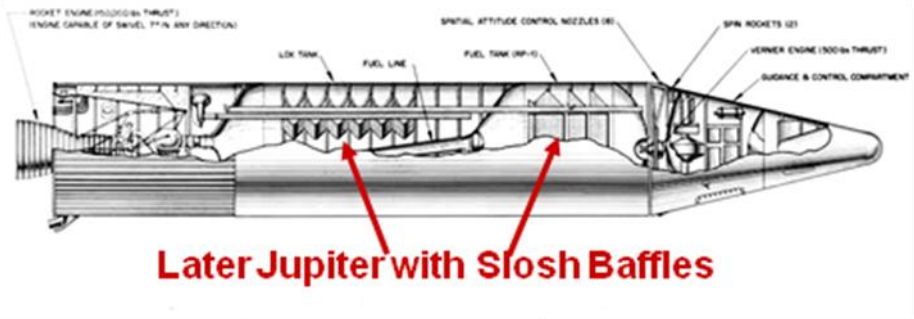


Figure 1-7. Later Jupiter Configuration with Slosh Baffles

Synthetic Wind Profile

Early in Saturn development, we were challenged with the problem of representing the atmospheric wind characteristics in a manner that would allow 6-degree of freedom control and vehicle dynamic simulations to provide time consistent 3-sigma response data for structural design. Two creative ideas were required to meet this goal. The first involved a way of taking each single parameter 3 sigma run of the 6-DOF response run and comparing it to a nominal run, extracting the differences for each response parameter. These deltas were then root-sum-squared (RSS'd) and added to the nominal, producing the 3-sigma design values. The problem was that this discrete value was needed in combination with all other parameters in the time consistent manner in order to have a balanced load set. Jud Lovingood came up with a way of taking the 3-sigma deltas and ratioing them with the nominal to generate a ratio for the input parameters, which then provided a 3-sigma time consistent response. [Lovingood, J.A. 1964] In addition we needed a way of having the wind characteristics modeled in a time consistent manner for a forcing function for the 6-DOF simulation. Helmut Horn, Jim Socggins, Bill Vaughn and Robert Ryan came up with the synthetic profile based on a 95% wind speed and RSS'd 99% wind shear and square waved wind gust. See Figure 1-8. This was used very successfully in the early design of Saturn. [Geissler, E.D. et.al.1970] The need arose to have a more realistic representation of the wind shear and gust, so a monthly set of detailed measurements were measured over a few years timeframe, that had the wind gust and shears correct to 50 meter lengths. Using these detailed Jimsphere wind profiles a Monte Carlo approach was used to verify that accelerometer feedback load relief was not effective. As a result Saturn V flew without load relief. (See Lesson 6) [Ryan,R.S. January 20-23,1969; Geissler, E.D. et.al. 1970] Since then a vector wind model and the Global Reference Atmosphere Model (GRAM) wind model have been developed for use in Shuttle and new programs.

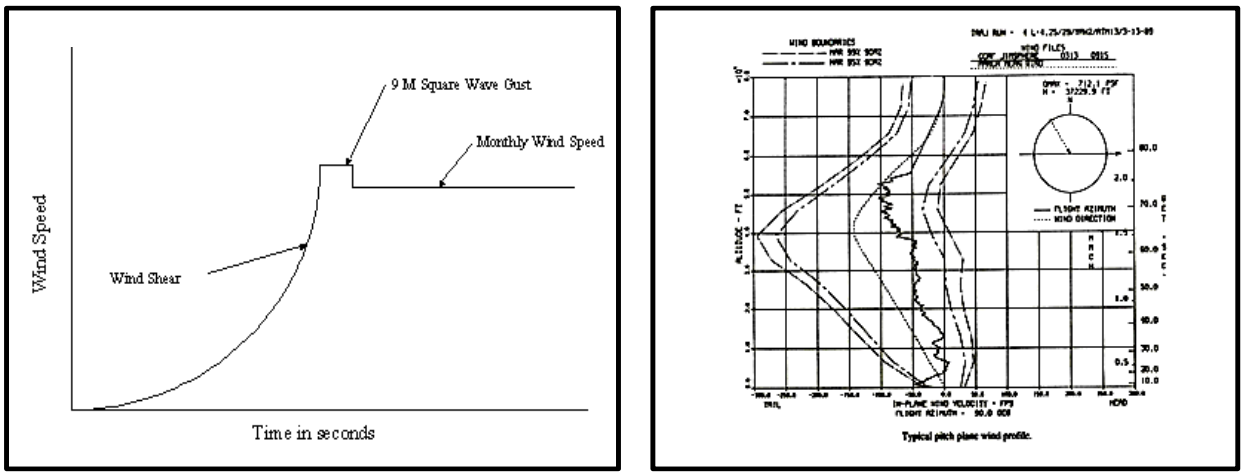


Figure 1-8. Synthetic and Measured Wind Profile Approach

The need for and the application of this approach is summarized as:

- Control and Loads response analysis requires time-consistent data.
- Question: How do I generate this time-consistent data from a root-sum-squared (RSS) peak value from perturbated individual response runs?
- The *A-Factor approach* ratios the individual perturbated peak values to the RSS'd value, to obtain parameter scaling factors, which will produce a time consistent run with the peak value matching the RSS'd. This produces a time-consistent data set for all response variables at a 1-sigma level

SSME LOX Pump Silicon Nitride Bearings

During Space Shuttle operational flights, liquid oxygen (LOX) pump bearings were a major problem, as were other elements such as turbine blades and welds. Bearings would wear out very quickly and along with other problems led to a requirement to refurbish the pumps after every one or two flights. Alternate turbopumps were proposed as a solution to these problems. The development of the alternate LOX turbopump was having major issues with the pump end bearings in that they would overheat and wear out in the first 50 seconds of run time. This problem was threatening continuation of the program, and needed a quick solution. A team was formed to find a solution to the problem. They tried everything with nothing working. Prior to this team's formation a MSFC engineer Dr. Robert Thom, was thinking out of the box and came up with use of Silicon Nitride (SiNi) ball bearings and had a technology program in place to test the bearings in a bearing tester. The team was near the deadline of program cancelation unless a solution was found, when we decided to try the new SiNi balls. [Gibson, Jannaf-1354] Silicon Nitride is a ceramic material. A manager of Pratt & Whitney was reluctant to try them and had said no one would put glass balls in his pump. A Pratt engineer took him into the shop and put a new ball bearing in a nylon sack and had him hit it with a large sledge hammer. The anvil and the hammer were dented, but the ball had no fracture under microscope inspection. As a result we started testing the balls in a pump and surprisingly there was no wear of the balls or the race. The results have been that pumps can fly 20 times with no bearing wear. See Figure 1-9. Currently, all space shuttle turbopumps have these SiNi bearings.

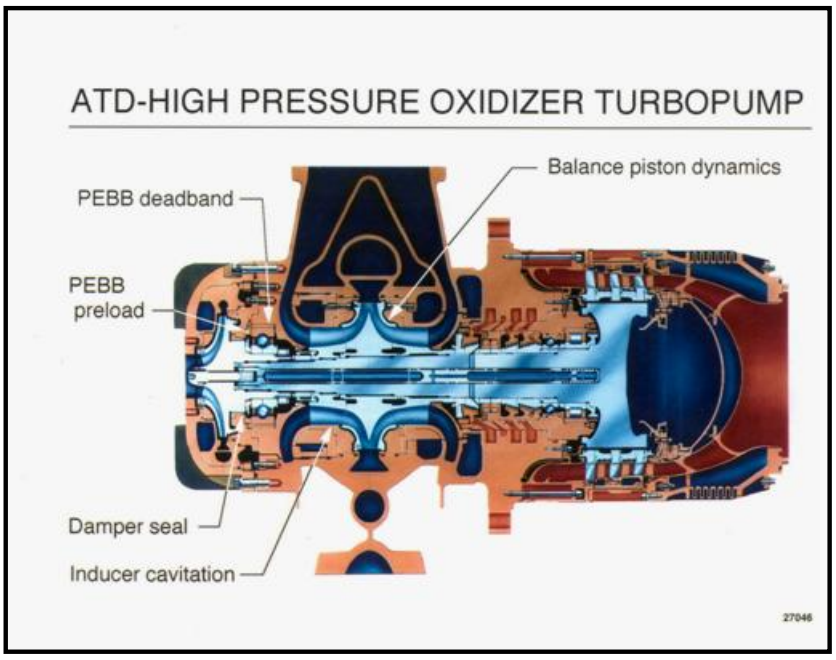


Figure 1-9. Alternate SSME LOX Pump with Silicon Nitride Ball Bearings

Tethered Satellite Skip Rope Damper

Tethered satellites have many technical features that are desirable. The can be used for power sources, orbit changes etc. However, implementing a Tethered Satellite had major design problems. As the satellite was deployed on a tether, the tether would set up dynamic oscillations (skip rope), which in the end could destroy the system. A team was formed to solve the problem through analysis and test. It was clear that some means of damping the oscillations was required. The approach was to install a damping system in the tether output ferrule using negator springs. As the tether dynamically moved, the dampers on the end of the cable attached to the eye through which the tether was deployed would move with the dynamic motion, thus damping the skip rope. After much testing the system was verified and flew very successfully on the first tether flight. See Figures 1-10 through 1-12 for details.

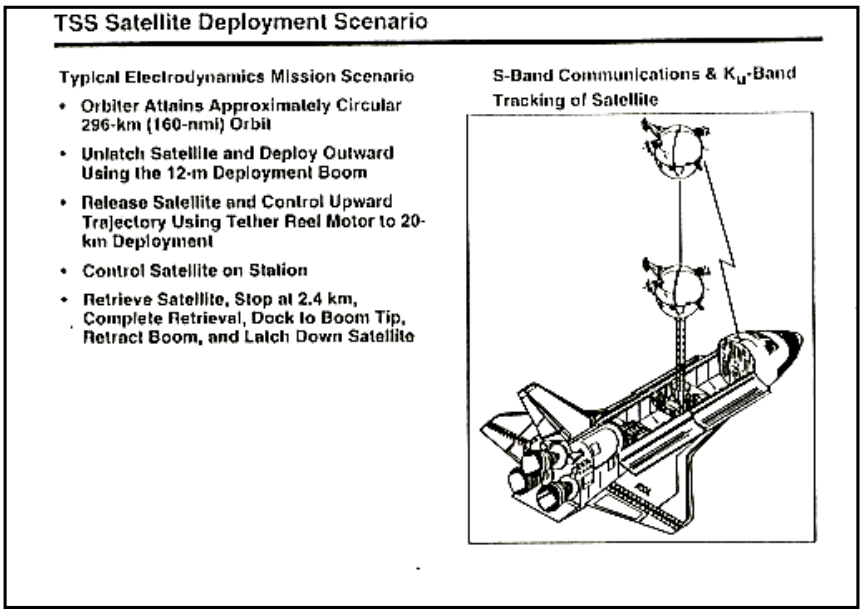


Figure 1-10. Tether Deployment Scenario

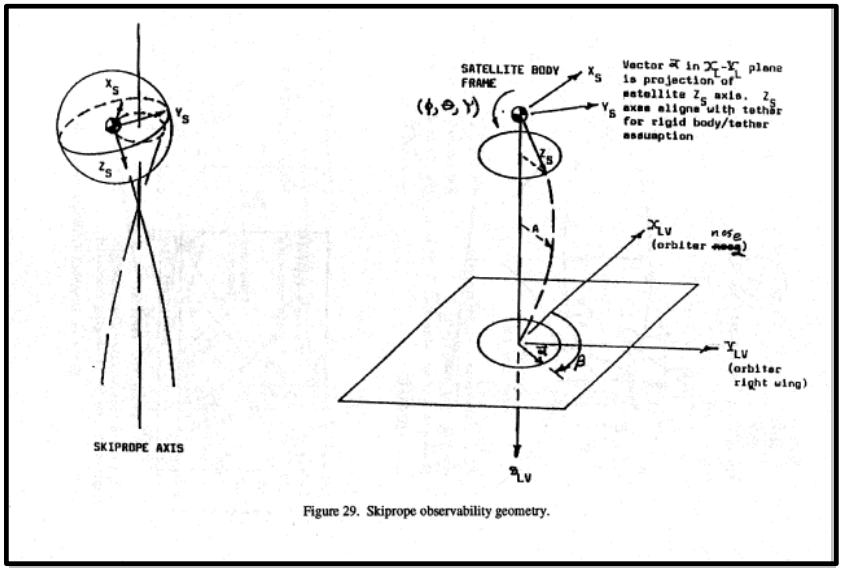
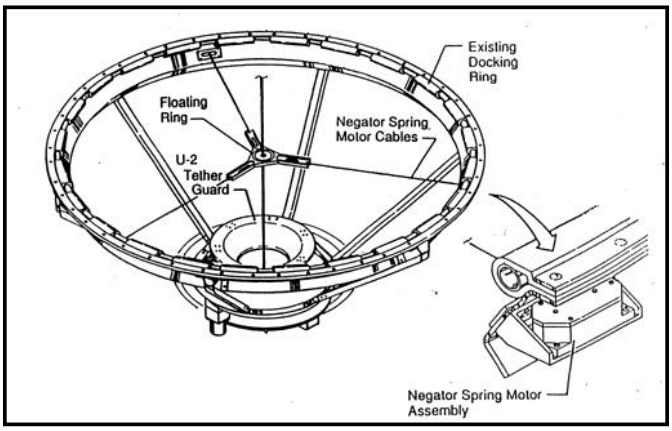


Figure 1-11. Tether Skip rope Characteristics



- **Tether skip-rope was stabilized using an innovative damper mechanism.**
- **The dampers were on the ends of motor cables attached to a floating ring through which the tether passed.**

Figure 1-12. Tether Skip Rope Damper

What we have illustrated with these examples is how innovation and creativity of the human mind has resulted in the solution to very complex problems. It is mandatory that the individual and the organization be provided the opportunity for the free expression of this creativity and employ both means for its development and rewards for its expression. [Mowery, D.M.,et.al.,1993]

- **A key message from Lesson 1:**

  ***Reward Judgment and Creativity*.**
  Dogma, rules, and recipes stifle Critical Thinking

Lesson 2. People Skills Are Mandatory For Achieving Successful Products

- ***Although engineering skills are essential, people skills are mandatory for achieving successful products.***
  - **Choose a strong leader with decision making capability who listens and encourages everybody to integrate.**
  - **Organization is the tool to accomplish the job; must provide leadership and motivation.**
  - **Encourage engineers to enhance their cooperative interactive skills as well as their technical skills.**
  - **Train engineers to be specialists with a system focus.**
  - **Reward specialists to participate in integration activities in order to formulate a world view of the total system.**
  - **Provide an open environment, which encourages innovation and stimulates communication.**

Since people are the prime resource in achieving project success, engineering skills are essential. However, that is not enough; people skills are mandatory for achieving success. There are a number of people skills, but the focus here will be on nurturing skills and developing skills associated with individual and organizational growth.

Nurturing skills requires strong leaders who can make correct judgments and decisions. They encourage everyone to interact and integrate (system focus), while keeping in the forefront the importance of technical skills. Leaders are mentors, teachers, and role models for technical integration and systems engineering. In those capacities, they advocate their views while inquiring the views of their reports. Everyone knows the leader's goal is the search for the best balanced design, technical solution, or truth, all with a system focus. They demonstrate the nurturing process through example while providing an open environment where innovation and communication are encouraged and the fear of failure is minimized. These leaders inspire and motivate everyone to accomplish their goals with passion.

An important aspect of people skills has to do with providing people a means for achieving personal and organizational growth. There are numerous subjects associated with individual and organizational growth. The select list below represents some that have been found to be beneficial. Each will be discussed briefly and references provided for further understanding.

Characteristics of Individual and Organizational Growth

A. The Principle of Attitude
B. Tree of Life
C. Senses Involvement
D. Aperiodic Reinforcement
E. Hierarchy of Needs
F. Law of Readiness
G. Must Lose to Gain
H. Expectancy Theory (Pygmalion Effect)
I. Follow-up and Feedback
J. Role Modeling
K. Guidance and Control Theory
L. Communication

A. The Principle of Attitude

The mind is one of the keys to growth. A person's attitude is the fuel of growth. Whitmore shows an interrelationship between the attitude of the mind, knowledge (technique) and experience (fitness). [Whitmore, 1997] Figure 2-1. The openness of the mind influences how our attitude changes, what we acquire, and the experience we achieve. Knowledge has

to do with the technique of the job while experience relates to the fitness to accomplish the job. If we think we have all the answers, we are not open to new knowledge or experience. Hunger for growth is important, as is humility. Humility means that we are trainable.

Closely related to the principle of attitude is *The Law of the Mind*. "Whatsoever a man thinketh, so is he." Earl Nightingale said it like this: "Whatsoever a person indelibly impresses on the mind will one day be expressed." He said that, "The mind will marshall the resources required to accomplish the goal." [Nightingale, 1990, 1997] Some have said that if it can't be done ethically, then it will be accomplished unethically. There is a warning implied: "Be careful what you impress on the mind."

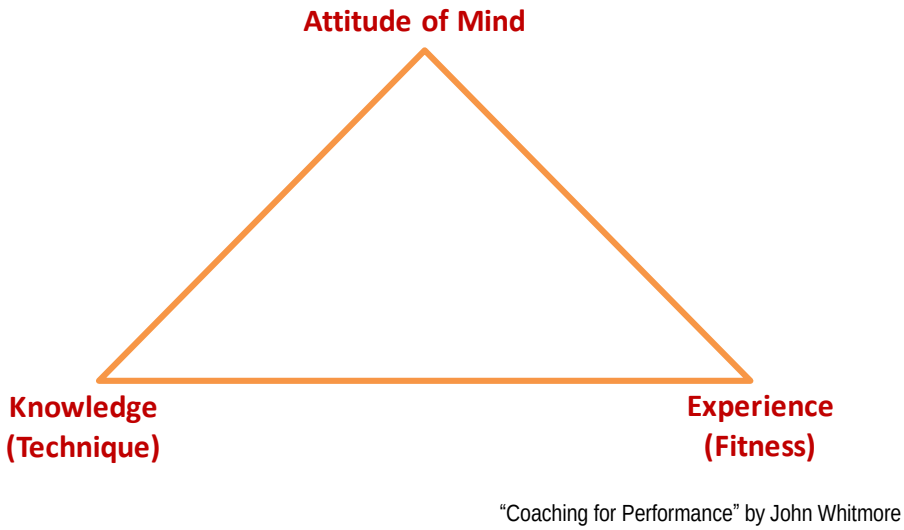


Figure 2-1. Principles of Attitude

B. Tree of Life

In all stages of our lives we have various diverse roles to accomplish. For the most part, this creates conflict because: 1. there are many; 2. they can be intense; 3. they can be time consuming: and 4. they can be conflicting. As a consequence, major frustration can be experienced. There is a need to identify and understand all our roles and then determine how to deal with them. [Covey et. al., 1994], provides some insights by relating our principles, mission, and roles to a tree, thus "Tree of Life." Figure 2-2 is an adaptation from Covey.

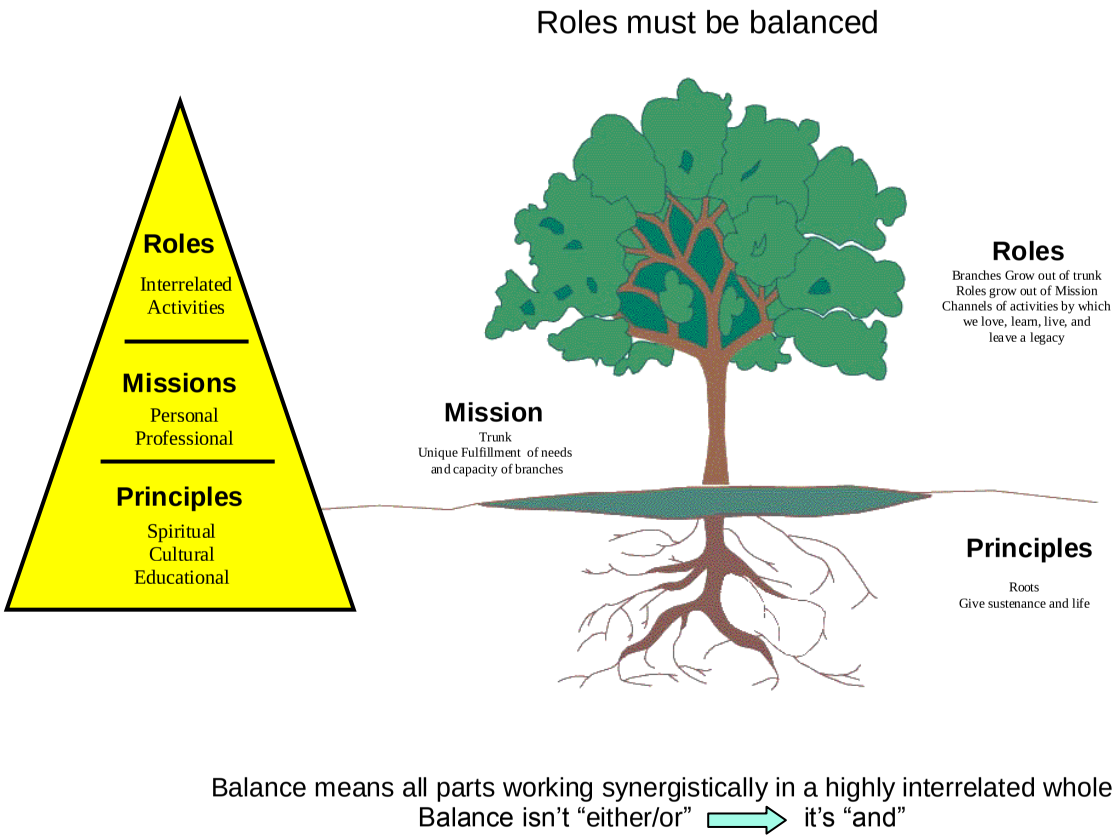


Figure 2-2. Tree of Life

When we look at the Tree of Life we see a growing life form that is strong, healthy, colorful, and pleasant to look at. The main elements of the tree are the roots, trunk, and the branches. The roots provide the necessary sustenance while the trunk fulfills the needs of the branches, i.e., food and strength. The branches grow out of the trunk. They provide nourishment for the system and aesthetic value. Each of these elements have specific functions, but for the tree to attain its strength and beauty these elements must work together to achieve balance. Balance is achieved when all parts work together achieving synergism to accomplish the strength and beauty of the highly interrelated whole tree.

The diversity of our roles at various stages of our lives can create conflict and frustration. If we make a comparison between key aspects of our lives and the tree of life, there are similarities that are helpful. For instance, see Figure 2-2. In this figure we have principles, missions, and roles. These are analogous to the elements of roots, trunk, and branches of the tree. The principles in our lives are spiritual, cultural, and educational. They are the foundations upon which we set achievable goals, determine our paths, and make decisions. Our mission in life is mainly related to the personal and professional life style and occupation we choose. Our mission determines the roles that we have to carry-out for our missions to be successful. When we consider our personal and professional roles there can be considerable diversity that can lead to frustration. There is a demand for our time, capability, participation in number of activities, complications, etc. To complicate matters, as we were

growing-up into adulthood, we learned to compartmentalize our activities;" I'll either do this or that." In consideration of the number of roles we have, if we continue to compartmentalize our roles it will lead to pain in personal relationships and retard personal growth. Like the "Tree", our roles are parts of a highly inter-related whole where balance is needed. Recall, balance in the tree is achieved when all parts work together. Our roles appear conflicting and unrelated because we have not figured out how to make everything work together. Balance is not "I'll either do this or do that." We will see that balance means "I'll do it all."

Our initial look will focus on how to achieve balance in executing the activities associated with our roles. At first when all the roles are considered, it may look like an insurmountable monumental time consuming effort that no one could accomplish. In fact, it turns out that most of our roles are "parts of an interrelated whole that work synergistically". After it is understood how the various roles play together and how they can be conditioned, our attitude relating to dealing with them will change and there will be a reduction in frustration. Instead of fighting the notion of all the "things" that must be done "now", accept it as a challenge. For instance, "my hobby will be conquering my roles." I'll interact with all those close to me, i.e., I'll let them know I have accepted the challenge and invite them to participate. They are now partners with me in my new hobby. Then as part of the challenge, put things in an appropriate perspective. Firstly, consider the time it takes to accomplish an activity. Sometimes deadlines are levied without any notion whatsoever regarding how long an activity will actually take. Also, if there is a real short- fuse deadline, make sure it is understood that the results will be a short-fuse result. Occasionally, everything can be dropped for a better than short-fuse result, but all of our activities can't run in the short-fuse timeline mode. Thus, the timeline of our activities must be understood and balanced. Secondly, consider the magnitude of the activities. Could it be that we can't tell what is important (big rocks) and what is not (sand pebbles)? When a set of activities is initiated, it might be difficult to determine what's important. The sensitivity of the outcome to the various activities has to be determined, i.e. what are the consequences of not doing a specific activity or reducing the level of effort. After the big rock activities are determined, what is their sequence? Thus the balance of the effort of the activities is determined. Now the important activities and their timelines are known and balanced.

At this point it will be observed that our hobby has activities where parts fit together into an interrelated whole that work synergistically. Now instead of doing this or that in a piecemeal frustrated fashion, all the balanced activities are being accomplished in a harmonious commanding fashion. I have taken charge of my roles!

C. Senses Involvement

When Bob Ryan was studying education, one professor emphasized the principle, *"The more senses you involve in the experience, the greater the learning retention."* (Touch, sight, sound, taste, and smell). Our experience in engineering has verified this principle. Engineers that see, touch, test as well as analyze hardware, in order to understand engineering design better, will produce better products. Learning and understanding is further enhanced if they have struck a weld, cut a line, made a dove tail joint etc. As a result we

worked hard to have our engineers in the plants where the hardware was being produced, tested etc. Ferguson at MIT recognized this, discussing it in great detail, emphasizing that educational Institutions must change their approach to teaching engineering, getting the students to where the hardware is being produced. [Ferguson, 1992]

D. Aperiodic Reinforcement

Aperiodic reinforcement, developed by Skinner and Watson, says that the learning retention is proportional to the lack of periodicity of the reinforcement. If the reward is given after every successful attempt the learning retention is short. If the reward is aperiodic, the knowledge of when the reward comes is unknown, hence the learner works harder for the reward and the learning retention is greater. Aperiodic reinforcement is a powerful tool in developing skills/ behavior. The lesson is clear, reward the effort but do so on an aperiodic basis for best results. [Skinner, 1972]

E. Hierarchy Of Needs

Understanding and fulfilling our needs are necessary elements that can improve motivation. The associated knowledge can be acquired by understanding Maslow's hierarchy of needs as is shown in Figure 2-3.



Fig 2-3. Maslow's Hierarchy

Dr. Abraham Maslow was born April 1, 1908 and died June 8, 1970, [Boeree, 2006] His contributions were primarily related to human behavior and motivation. In one of his early publications he conceptualized his basic theory where he delineated fundamental needs of man [Maslow, 1943]. Then in 1954 those needs were visualized in a hierarchy as shown above where the lower four needs are deficiency needs and the top need is a growth need [Maslow, 1954]. Within the deficiency needs, the lower level needs must be satisfied before going to the next level. If one of the deficiency needs is removed at some later time (I have no food), then we will act to relieve the deficiency (I have food).

In the years that followed, Maslow determined that there were additional growth needs [Maslow, 1971] and [Maslow and Lowery, 1998]. Thus, the hierarchy was expanded. While the expanded hierarchy is not shown in the figure, insight is provided below for understanding. The expanded list that follows is a summary of all of Maslow's needs in ascending order.

Deficiency Needs:

1. Physiological: food, water, bodily comforts, …
2. Safety: out of harm's way, …
3. Belonging: family, friends, …
4. Self-esteem: self-respect, respect of others, competent, …

Growth Needs

5. Cognitive: knowledge, understanding, searching, …
6. Aesthetic: symmetry, order, beauty, …
7. Self-actualization: to be the best we can be, …
8. Self-transcendence: help others realize their potential

Despite the fact that there is no scientific evidence to support Maslow's hierarchy, it is widely accepted based on anecdotal evidence. Further understanding of Maslow's conceptualization of human behavior and motivation can be found in [Boeree, 2006] and [Huitt, 2004]. While numerous insights can be investigated relating to human behavior and motivation, the focus will now be on self-esteem and self-actualization.

Self-esteem can be thought of as one's overall self-appraisal of their worth. It encompasses both beliefs and emotions and is reflected in behavior. In addition, it enables us to face the challenges in life and feel worthy of happiness. Maslow believed that we need the respect of others as well as self-respect. There are numerous activities that can be done to enhance self-esteem. Shown below is a short list which can be incorporated into our daily interactions with others.

1. Recognize, maintain, and enhance self-esteem
   - learn how to do it; show others by example
2. Listen actively and respond with empathy
   - I'm interested in what you have to say
3. Ask for help and encourage involvement
   - delegate instead of control; seek advice

4. Share thoughts, feelings, and rational
    - this is what I think; what do you think
5. Offer support without removing responsibility
    - help others achieve their goals; but, don't do it for them

In addition to the above, consider the following: spiritual activities, exercise, praising, achieving goals, dress style, integrity, generosity, good work ethics, education, being courteous, and so on.

Self-actualization is the desire for self-fulfillment; to strive to become actualized in what I am potentially, i.e., to become everything that I'm capable of becoming. In order for one to achieve their potential, time must be taken to understand one's self. Then take the appropriate actions to achieve your potential.

In learning organizations, provisions are in place to encourage personal growth. Listed below are some limited examples relating to what a learning organization should provide.

1. Define and clarify roles, goals, and values
2. Provide development opportunities
3. Provide coaching
4. Celebrate, recognize, and reward
5. Promote communication and trust (share information)

Delineated above are some ideas relating to understanding and fulfilling needs. These ideas are a snapshot aimed at providing an eye opener to achieve a highly motivated life style. Since everyone is different, each must find their own tailored needs. What are yours?

F. Law of Readiness

"The Law of Readiness" is essential to understand how individuals and organizations grow. [Thorndike, 1912] In essence it takes the meshing of the physical, the emotional, and the intellectual to create readiness. Until the blending occurs performance is not up to par. When they mesh performance is high and graceful. It takes time (patience), and experience (practice) to achieve readiness. When it happens it is obvious. You don't give up easily on people. Provide time for the "law of Readiness" to work. When coaching the 1955 Alabama Class "A" Basketball Championship Team Robert Ryan had a 6'7" center who was key to winning. John had a habit of rebounding the ball and then pulling it down to dribble or pass. We set up practice drills having him push the ball back to the goal or pass it out. Finally Ryan put a block over the goal so that the ball would bounce out for him to push back. After several weeks of this drill, Ryan was losing patience. John had no confidence and he couldn't get the hang of the principle. We worked one Friday and no progress was evident. Monday John came to practice performing the task with ease. Never again did he have to be reminded of the principle. Readiness works that way. Most of the time readiness appears to occur practically instantaneously but is built over a period of time. The authors have seen it work in areas of engineering, where all of a sudden everything fits. The process repeats as new skills are added.

G. Must Lose to Gain

Another principle of development, “Must Lose to Gain” is fundamental to growth. Figure 2-4 illustrates the principle using the trapeze artist. Growth implies first having a place of security from which to take off from. In this place one has social acceptance, equilibrium, control of one’s domain, good feelings, calmness, and status. To grow means turning lose and floating in uncertainty while reaching for the new. This turning loose is a leap of faith based on a challenge, encompassed with vulnerability, falling, and other undesirable risks. Leadership and management have the role of providing a safety net in case the employee falls so that they are not destroyed. Grasping the challenge means surrendering abilities, status, techniques, awards, becoming a nonconformist, many times risking financial security. A more disciplined life is implied along with commitment. In the end comes recognition, adventure, growth, power, but more importantly fulfillment. Growth always is anchored in choice; therefore “To grow means loss, and loss means mourning, so that newness can come in.”



Figure 2-4. Must Lose to Gain

When Robert Ryan went from being a dynamicist to a manager, giving up doing the analysis was very hard. Many times it would have been easier and quicker to accomplish the job himself, yet development of people meant turning loose and letting them do the job. When he moved to the position of deputy lab director the change was dramatic. Engineers, who felt free to come into his office before, now felt constrained. The furniture, the office size,

location, etc. was a turnoff to openness. After some times of frustration, he started going to the engineers instead of having them come to his office. This helped eliminate some of the feelings of isolation but never totally solved the problem. Other roles replaced the old roles and growth occurred. Growth always means loss [Tournier, 1966]. Recognition of the principle is very important. It explains why people are reluctant to give up the security, friends, etc. of the place to take on the adventure of discovering a new place. Choice is difficult because it means giving up something. Coaching and mentoring people will bring the coach and mentor in constant relationship with this principle as people are trying to grow by making choices.

H. Expectancy Theory (Pygmalion Effect)

People tend to learn/accomplish what you expect them to do. This is called the Pygmalion effect or principle. Let them know what you expect and believe they can do it. In general they will surprise you in what they accomplish. [Livingston, 1988]

I. Follow-up and Feedback Successive Refinement

Learning follows the principle of successive refinement. Figure 2-5 follows the *Learn, Commit, Do* spiral. Bob Guns shows the principle as five levels of learning. [Guns, 1996] They are acquisition, use, reflection, change and how. The process is repeated for each new learning activity. These principles and models strongly indicate that growth takes time. In other words you can't bypass nature. Many have said that on the average it takes 20 years to mature an engineer. Learning then requires commitment, action, then thinking about what happened and how, then making a change and repeating the process.

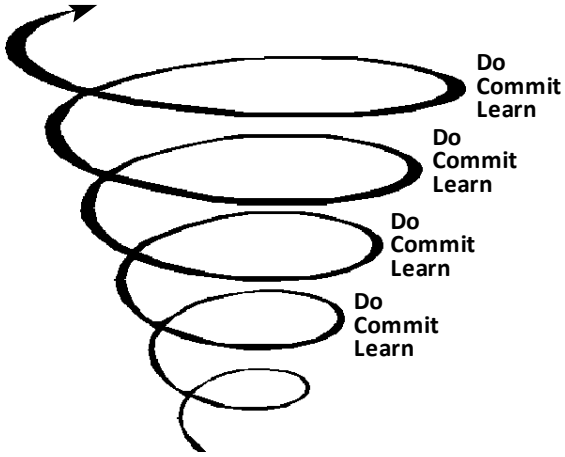


Figure 2-5. Model of Successive Refinement

Feedback is the principle involved in refinement. Feedback has four basic sources. The sources are: personal/self, mentor/coach, peer groups/others and supervisors. There are two types of feedback: To encourage and reinforce and to modify and correct. The latter can be unpleasant; but must be accomplished when the job being done is very critical or is detrimental to the individual. The general principle is to encourage and reinforce the positive

behavior. If this feedback is done properly the positive will, over time, supplant the negative. Cliff Wells when he was coaching basketball in Louisiana, said, “Praise 10 times for each time you criticize.”

There are many factors of feedback, as noted on Figure 2-6. It is a continuous process (real time) that involves a clear understanding of lags and the do loop shown on the figure. The do loop starts with mission/vision, then learns. Action is created from the learning. The act is then evaluated in terms of the vision providing new learning and action. The difference between the vision and current reality creates the “dynamic tension” fueling growth. The degree of follow-up is based on task complexity, consequence of failure, employee capability and the morale and development of the employee. Bob Guns lists 9 principles of feedback, shown on the figure**.** The bottom line is never attack the employee personally. The principles are clear without interpretation. In summary feedback is both positive (encouragement) and negative (criticism). Both are necessary; however, concentrate on the positive, eliminate the negative, as the old popular song goes.

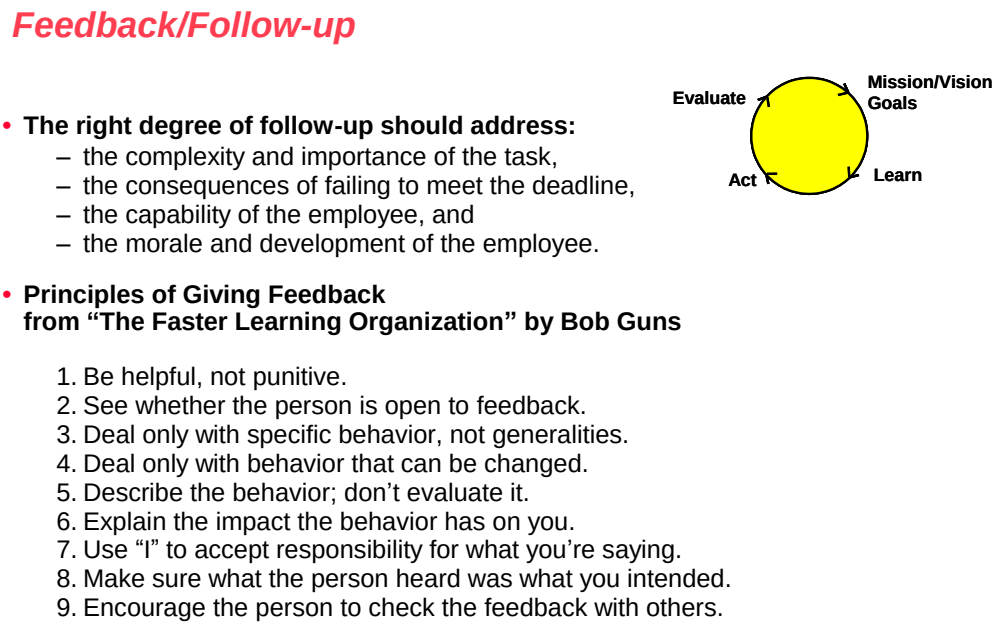


Figure 2-6. Feedback and Followup

J. Role Modeling

Role modeling is another way people develop. When Robert Ryan first married they shared a living room with a family who had two boys. Robert would sit and loop his leg over the chair arm. Jackie would try to mimic him but his legs were too short. One day he said, “I can’t do it.” Organizations need good role models both live and in their stories. There are

many stories at MSFC of role models used, which were unsuccessful since the role of the model did not fit the personality of the one mimicking. The role models must fit the person and the organization. Countless models exist on the positive side. Observe how people will dress, speak; etc. to mimic a role model. Many role models at MSFC and all organizations are Legends that influence way beyond their active employment time. Dr. Von Braun is a great example.

K. Guidance and Control Theory

The guidance and control theory of growth is based on the principle of the guidance and control of space vehicles. The control system handles the short term disturbances by correcting the vehicle attitude against a reestablished path attitude. (Some form of optimization) Guidance is concerned with keeping the vehicle on the path to the goal (orbit). The guidance gains get tighter the closer the vehicle gets to the target. During peak disturbances guidance usually is de-emphasized and control becomes one of relieving the disturbances versus maintaining the guidance-prescribed attitude. An example is load relief control during high winds and high dynamic pressure, where the vehicle is turned into the wind to reduce loads. This load relief control introduces drift away from the ideal trajectory, thus some performance loss, in order to reduce the loads. Maintaining attitude would probably break the vehicle or result in large increases in structural weight thus reducing how much payload can be put in orbit. People should be developed, managed in the same manner. Greenleaf says, “You need enough control to maintain order, but not so much that it kills the creativity and innovation of the organization’s people.” Successful growth personally and organizationally requires the maximum expression of creativity of its people. [Greenleaf, 1977]

L. Communication

Two descriptions have been useful in featuring specific aspects of technical communications as applied in the design process. The first is the *T-model* and the second is *communications in the design process*.

The T-model is shown in Figure 2-7 and is so named because of the horizontal and vertical components. It is a global model that focuses key features of technical integration. It delineates the system (horizontal) along with subsystems, design functions, or disciplines (vertical) while emphasizing the importance of formal and informal integration.

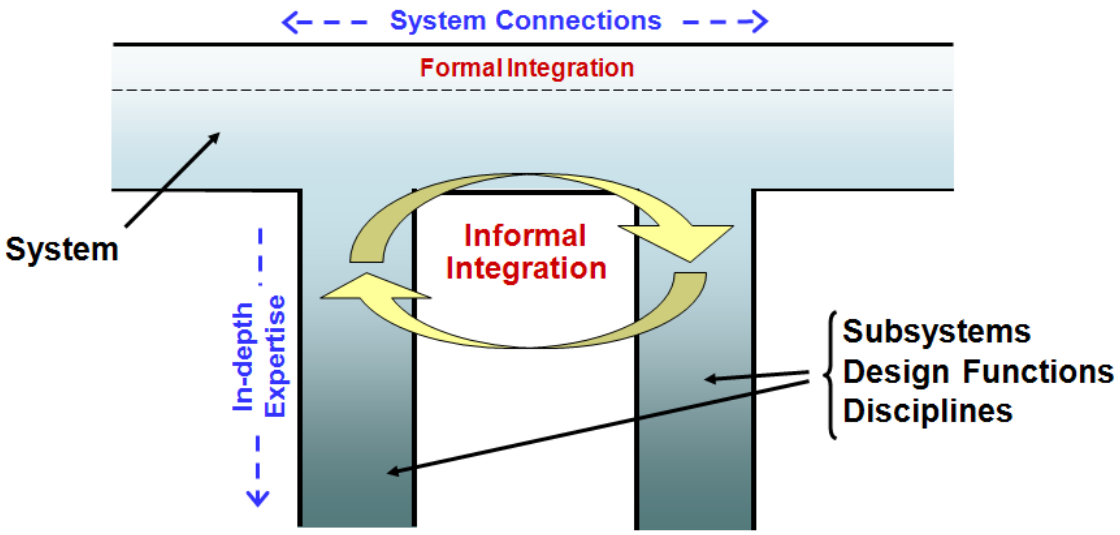


Figure 2-7. T- Model for Technical Integration

The horizontal portion of the "T" represents the System. The upper level (above the dashed line) of technical integration has been known by interchangeable names as system integration, formal integration, or top level integration. The leader and his office are the primary facilitators or operatives at this level of integration. The emphasis of this technical integration is primarily related to the systems aspects of the design process, i.e., technical management, certification of the system, etc. The primary focus is delivering the product with the proper balance of performance, cost, reliability, safety, operability, schedule, and TRL. Balance is achieved via managing and resolving conflict. All system related decisions and all system related technical conflicts are respectively made and resolved at this level. In addition, all system planning, control, and documentation is maintained at this level. Technical integration below the dashed crossbar is informal and is a key enabler for achieving a successful design. The vertical bars relate to subsystems, design functions, or discipline functions. There are a number of combinations of these (subsystems, design functions, or discipline functions) that require informal horizontal integration. The emphasis here is informal integration (communication) between and among subsystem, design function, or discipline while including the system. It can be hall-talk, phone calls, inter-office discussion, technical interchange meetings, etc. or other forms of communications. Since there are many vertical legs that affect each other, informal integration among these elements is critical. The functional organizations are the primary operatives of integration for discipline-to-discipline aspects of the design process, while the engineering design functions are the primary facilitators of integration for the subsystem-to-subsystem specific aspects of the design process. Recall, the vertical legs of the "T" also represent discipline activities (analyses, tests, simulations, etc.) associate with subsystems and design functions. They signify in-depth knowledge (in the vertical direction) but with a system perspective. This in-depth knowledge is required to be accurate and with the associated uncertainty defined.

A classical example of the T-Model is the game of basketball which is both a team and an individual emphasis sport. The vertical legs are the fundamentals of the game such as passing, shooting, dribbling, footwork, hand and finger position on the ball, screening,

blocking etc. Basketball is played with the ball being controlled with the finger tips not the cup of the hands. Footwork is first played on the ball of the feet and movement is by shifting without crossing the legs. In guarding an individual you in general don't slap down on the dribbler but slap up or to the side otherwise you get called for a foul. These are examples of informal interactions. The systems part is both formal and informal. The formal takes place by the team running patterns and then informal takes place by taking advantage and adapting to what the defense does such as the back door, or the pick and roll. The jump ball and out of bounds situation etc. are additional examples of formal activities.

Shown in Figure 2-8 is the second form of technical communication. The design process depicted in the figure is described in Lesson 4; the figure is used here to illustrate the need for extensive communication within the process. While the T-model description is global, this figure more specifically depicts technical communications as related to the compartmentalized design process. It shows the scope and variety of integrated communications needed. This can be seen by observing the interactivity among subsystems, design functions, and discipline functions; along, with their associated IxI and NxN diagrams (data flow). In addition, the V-diagram from Classical Systems Engineering indicates the need for system integration to provide discipline, planning, balancing the system design, etc. to support the design process. Furthermore, the main aspects of Safety and Mission Assurance are illustrated: Safety, Reliability, and Quality. The ultimate goal is to achieve a balanced design.

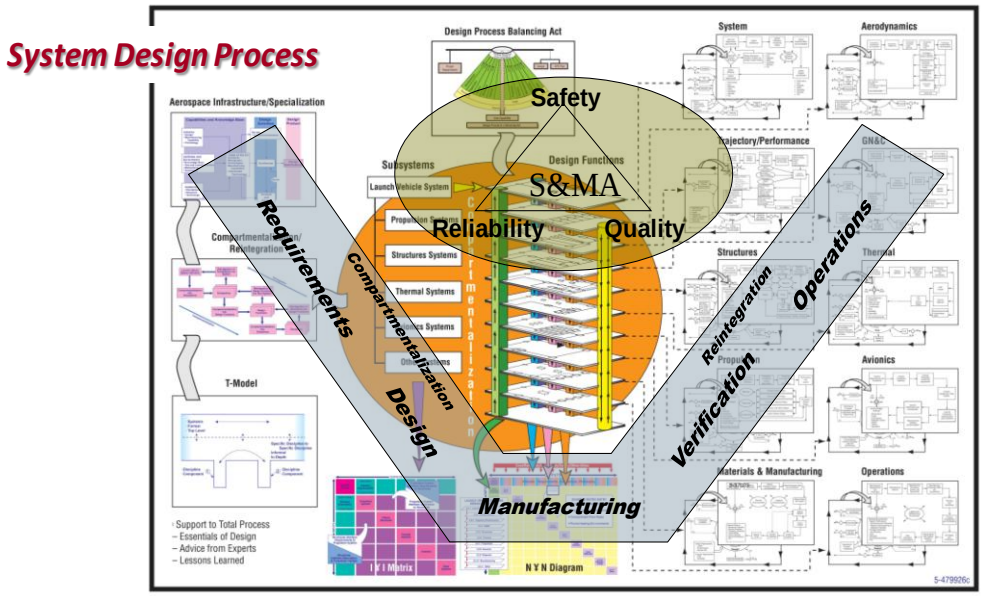


Figure 2-8. Communications in the Design Process

- **A key message from Lesson 2:**

  Apply Principles Related To: Nurturing Interactive Skills
  Balancing Our Roles, Needs, and Communication

Principle II: Space Systems Are Challenging, High Performance Systems

The physics of flying into space demand that maximum energy must be extracted from the chemical energy source. This transformation from potential energy to kinetic energy must be very efficient, pushing the limits of current technology. The same is true of the structural or dry mass of the system. Here the limit is pushed by current technology to make the structure very light, but very strong. In addition losses that occur in terms of how we fly the system must be stringently managed and controlled. In other words we can just barely make orbit with the technologies available today. These factors result in a requirement for high performance systems that drive large sensitivities and unwanted interactions.

Lesson 3: Demand for High Performance Leads to High Power Densities and High Sensitivities

- ***Demand For High Performance Leads To High Sensitivities and Power Densities***

- **High performance launch vehicles are required to deliver payloads to specific orbits. To accomplish this, they must overcome gravity and attain enough velocity to achieve a stable orbit.**

  - **Consequences:**
    Systems Pushed to the Limits:
    1. **Chemical Propulsion System Efficiency**
    2. **Structural Mass Efficiency**
    3. **Losses Minimized**

  - **Current Technology Just Barely Enables Us to Make Orbit**

Figure 3-1 shows this challenge in terms of engineering, costs, and project requirements. The physics of the problem dictates that engineering must design high power density systems, very efficient propulsion and structural systems, and manage all the losses efficiently and effectively. This must be balanced with cost and project requirements of operability etc. This results in a high risk system in comparison to all other known

transportation systems. Mission success is paramount, especially if manned flight is involved, dictating that the risks must be managed and mitigated in an effective manner. When risks are coupled with costs, this balancing the system becomes a very difficult and complex problem.



Figure 3-1. The Complexity of Managing High Risk Systems

Figure 3-2 puts the challenge in perspective by comparing the power density of common transportation engines with the Space Shuttle Main Engine (SSME). Plotted is horsepower per pound for an auto engine, Indy race car engine, small jet engine, large jet engine and the SSME. Notice that the car engine has a ratio of 0.54 while the SSME has a ratio of 879. If an average car engine was built to the same power density and efficiency as the SSME it would weigh about 1/4 of a pound. The structural efficiency required is also extreme. For example, if an aluminum Coke can was made at the same structural efficiency as the Space Shuttle External Propellant Tank, its skin would be 1/3 the thickness it is today.

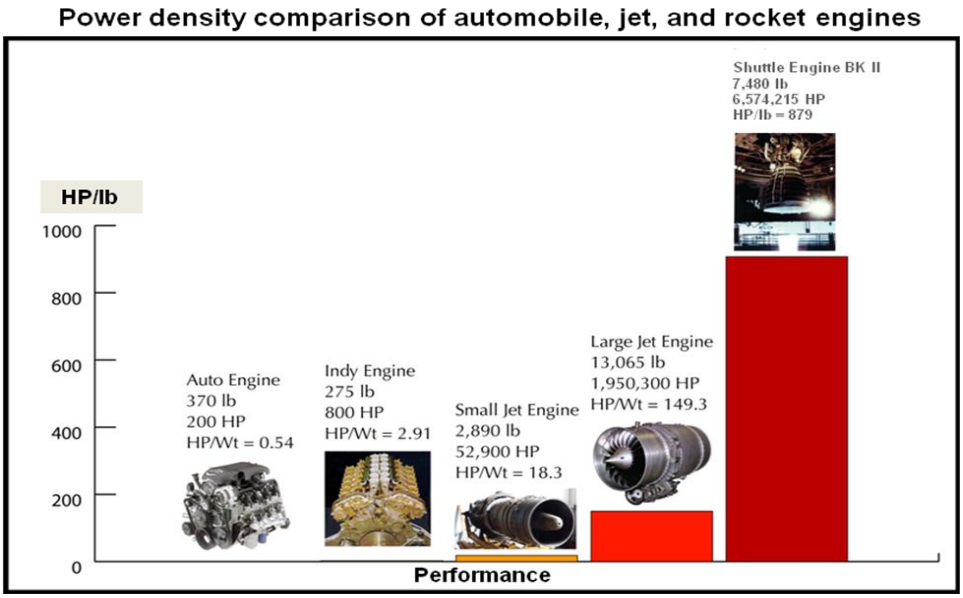
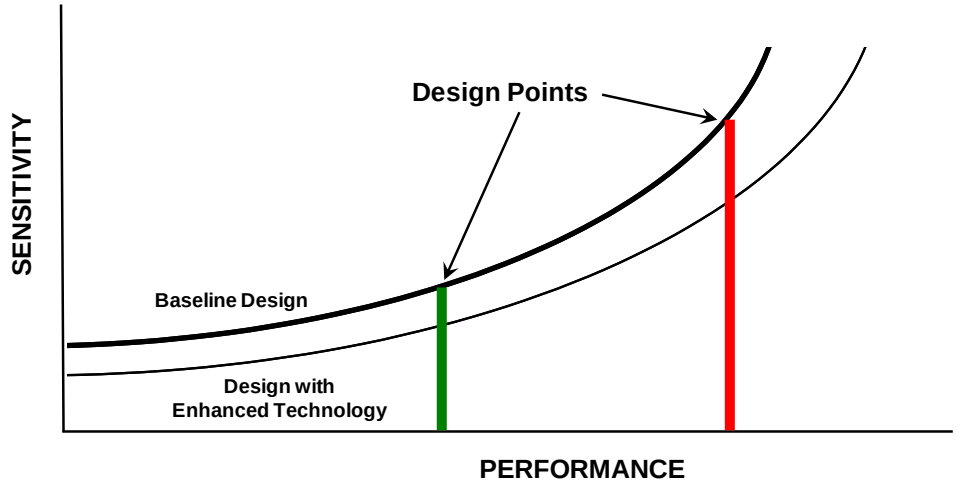


Figure 3-2. Power Density Comparison of Transportation Systems Engines

All of this high power density and high efficiency comes with a price as illustrated on Figure 3-3. This chart depicts a design principle that can be extracted from the history of space systems and says that the higher the performance requirements, the higher the sensitivity of the system to design and performance parameter uncertainties. This is a generic curve which represents a number of different physical systems. For example the structural SN Curve for fatigue is the inverse of this curve. A plot of vehicle dry weight versus dry weight margin will basically trace this generic curve. What this means then is that as we move out on the performance curve, our design, verification and operations challenges go up non-linearly with the increase in performance requirements. It means that great attention must be used to design, build, verify and operate these high performance systems. The complexity factor of these systems also makes it much more difficult to predict and understand the system induced interactions. Poole in his book, “Beyond Engineering: How Society Shapes Technology” says that the complexity factor leads to most of the failures and is very difficult to predict. [Poole, 1997] He also concludes that this results not only in a technical complexity, but in organizational complexity as well. There are many problems that occurred in the SSME that can be shown to be a direct result of the high performance requirement, which will be discussed later.

Sensitivity versus Performance

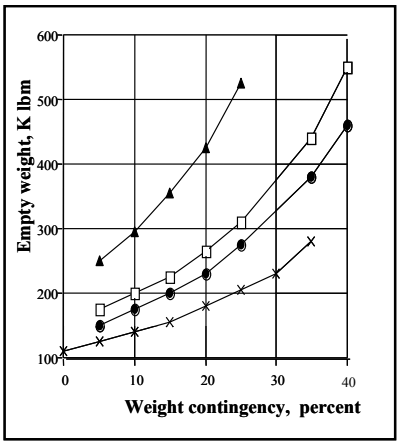


- **The higher the performance requirements the greater the system sensitivity to weight, cost, parameter uncertainties, manufacturing flaws, etc.**

Figure 3-3. Sensitivity Versus Performance Requirements

Figure 3-4 shows the sensitivity of a single-stage-to-orbit vehicle, where dry weight is plotted versus weight contingency in per cent. The same nonlinear trend is shown as for Figure 3-3.

Weight Contingency Sensitivity



Single Stage to Orbit launch vehicles are very sensitive to the technologies used and to the weight margins assigned.

- ▲ **Current AL material and SSME propulsion system**
- □ **Composite materials**
- ● **Combined cycle engines**
- x **Combination of composites and combined cycle engines**

Figure 3-4. Dry Weight Versus Weight Contingency in Percent

In conclusion, high performance requirements lead to high power densities and sensitivities, which require in-depth understanding and intricate balancing of the system to achieve success.

A key message from Lesson 3:

High Power Density Systems Require:

- ***In-depth Understanding***
- ***Intricate Balancing***

Principle III: Everything Acts As A System (Whole)

Overarching design and Technical Integration principles are summarized on the following list. They are the foundation and summary of what follows in this section, as well as in other sections.

- **Physics and other governing principles (cost, …) rule all design activities.**
- **Everything is a System composed of complex interacting parts that have a best balanced state. Attempting to operate out of that balanced state is very costly.**
- **The best balanced state is achieved by understanding sensitivities, uncertainties and margins → leads to the quantification of risk and design confidence.**
- **Present design practice of complex systems entails compartmentalization**
  - **Subsystems, design functions, and discipline functions.**
- **Overcoming complexity and balancing the design requires Technical Integration**
  - **Interactive activity among all participants in the design process**
  - **Compartmentalized parts are designed and reintegrated into a balanced and verified product**
- **Technical Integration is enabled through formal and informal communications following the T-Model philosophy. The in-depth elements must be accurate while operating in a system role.**
- **The innovation, creativity, and decision making skills of the people form the basis for successful design.**

Embodied in these principles is the idea that while we can easily identify complex systems as a whole entity; many are composed of complicated subsystems and parts that must be designed to robustly and interactively function to support the system life cycle needs.

This section contains three lessons:

4. System Engineering and Technical Integration is the Linchpin of Project Success
5. Risk Management
6. All Design is a Paradox, a Balancing Act

Lesson 4: System Engineering and Technical Integration Is the Linchpin of Project Success

System engineering and technical integration are concerned with validity of analyses, tests, and simulations; software and hardware integration; interfaces compatibilities; interactions; validation; … all of which are necessary for product success. Along with the basic lesson are the following corollaries:

- ***70 to 80% of all problems we encounter in design are caused by a breakdown in Systems or Technical Integration. Said differently, problems, in general, were not due to undiscovered or missing theory, but to the neglect of basic system principles.***

- ***Dick Kohrs said, "Systems Engineering is 95% communication and 5% engineering." Yet we must maintain very honed specialist skills or there is nothing of value to communicate or integrate.***

    - **Technical integration is crucial to the design process. Make every effort to encourage technical integration, and to assess that it is being done.**
    - **Communication is the key, the predominant part of technical integration.**
    - **The most effective integration communication is informal.**
    - **Understanding the physics of interactions is key to integration.**
    - **Continuously check requirements and their flow, their verification.**
    - **Continuously check assumptions.**

The above statements emphasize *basic system principles*. Yet while emphasizing the system aspects, we must maintain very honed specialist skills or there is nothing of value to integrate. These specialists are required to understand and quantify the validity of their results; in addition, to specifying the sensitivities, uncertainties, and margins associated with those results. General reference for this total section is [Blair, et. al., 2001].

An important element that overshadows the design process is Technical Integration. *Technical Integration* is an interactive activity among all members of the design community where the compartmentalized subsystem → parts are designed and then reintegrated into a balanced system design that can be verified and validated and will operate at acceptable risk. Every effort should be made to ensure that technical integration is being accomplished. As mentioned above, communication is a key factor in achieving technical integration and, as is evident, informal communication is a pervasive aspect of technical integration.

In the design of complex systems where there are high power densities, it is not only important to understand the physics but also associated interactions. In many situations the bleed off of a "slight" amount of energy can lead to instability. This is a situation where small differences can have as enormous impact. In addition, requirements can change as a result of maturing the design. Requirements, as well as, assumptions should be tracked and verified at each stage of a "design and analysis cycle" (DAC).

In order for the design process to work efficiently and take advantage of the state of the art (SOA) knowledge base, the STS must be compartmentalized into workable units after the mission and programmatic requirements are defined. The SOA information exists in three types of organizations: (1) Industry, (2) Government, and (3) Academia. The capabilities and knowledge bases of these three organizations represent the SOA and they capture standards, monographs, technologies, manufacturing processes, etc. This capability and knowledge base is a major resource for achieving successful designs where there are high power densities and extreme environments. Listed below are examples that illustrate the main points in the narrative associated with Lesson 4

- Characterization of Design Process/Technical Integration
- Shuttle First Flight Aerodynamic Anomaly

Characterization of the Design Process/Technical Integration

The purpose of this example is to provide an overview of the design process and illustrate technical integration. More detail about the design process can be found in [Blair, et. al., 2001]. The design process consists of various features and providing an explanation is analogous to "peeling an onion". An insight will be gained of the overall process. While understanding the process, the reader should understand where she/he fits and with whom they interact. Furthermore, the illustrations represent functions that are required to achieve the design and are not to be confused with organizational charts. Finally, functions and activities associated with the design process are independent of the organization and project.

Shown in Figure 4-1 below, is the project life cycle flow. It can be seen that it starts with the Mission Statement then goes to Requirements. The design process starts with defining Architectures and proceeds through Detail Design. Then the product is built, verified, and operated. From the initial design activities through Detail Design there are a number of cycles associated with DAC and verification tests. While the life cycle process is

as shown, there are cyclic layers as the design matures; the level of design detail increases as well as the supporting data associated with analysis, test and simulations.

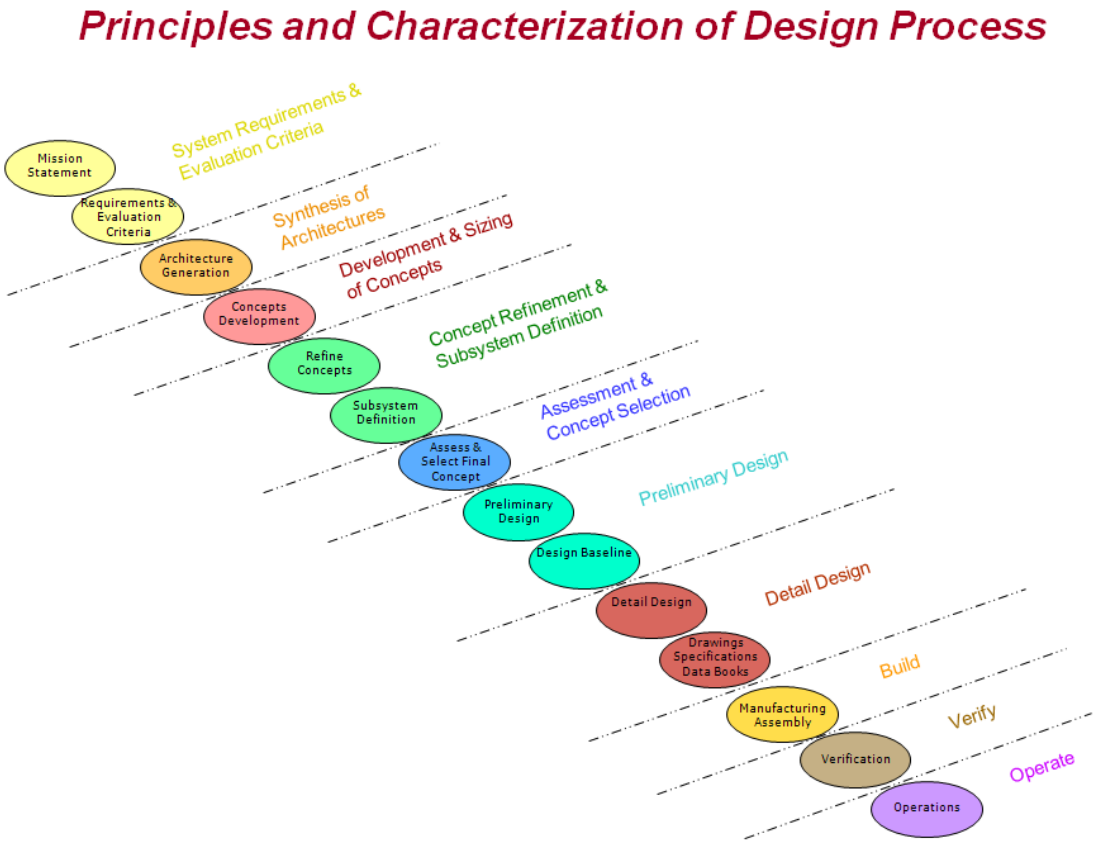


Figure 4-1. Project Life Cycle Flow

As noted in Figure 4-1, the mission statement and requirements definition precede all the design activities. Before anything can be designed, all of the requirements must be known. There have been projects in the past where the requirements were not adequately defined and the unintended consequences were significant cost over-runs. Initially, the top level requirements are defined, such as, orbit, payload definition, cost, schedule, safety, top operational requirements, etc. Then derived requirements have to be developed to fully accomplish the design of the system, subsystems, components, and parts. As the design continues requirements are continually defined, iterated, verified, and documented.

The central part of the life cycle, i.e., from Architectural Generation to and including Detail Design, is enabled by compartmentalization and reintegration, see Figure 4-2. While compartmentalization is necessary to accomplish a design, it does add complexity. The process starts with the initial launch vehicle definition and ends with the final total integrated system configuration. Firstly, the system is compartmentalized into subsystems (hardware pieces). This creates interfaces that have to be tracked via interface requirement documents (IRD) and interface control documents (ICD). Each subsystem is then compartmentalized into design functions that design the subsystem so that the attributes of the subsystem meet the derived requirements. To achieve the design, the design functions are

compartmentalized into disciplines. The disciplines provide design results determined from analysis, test and simulations.

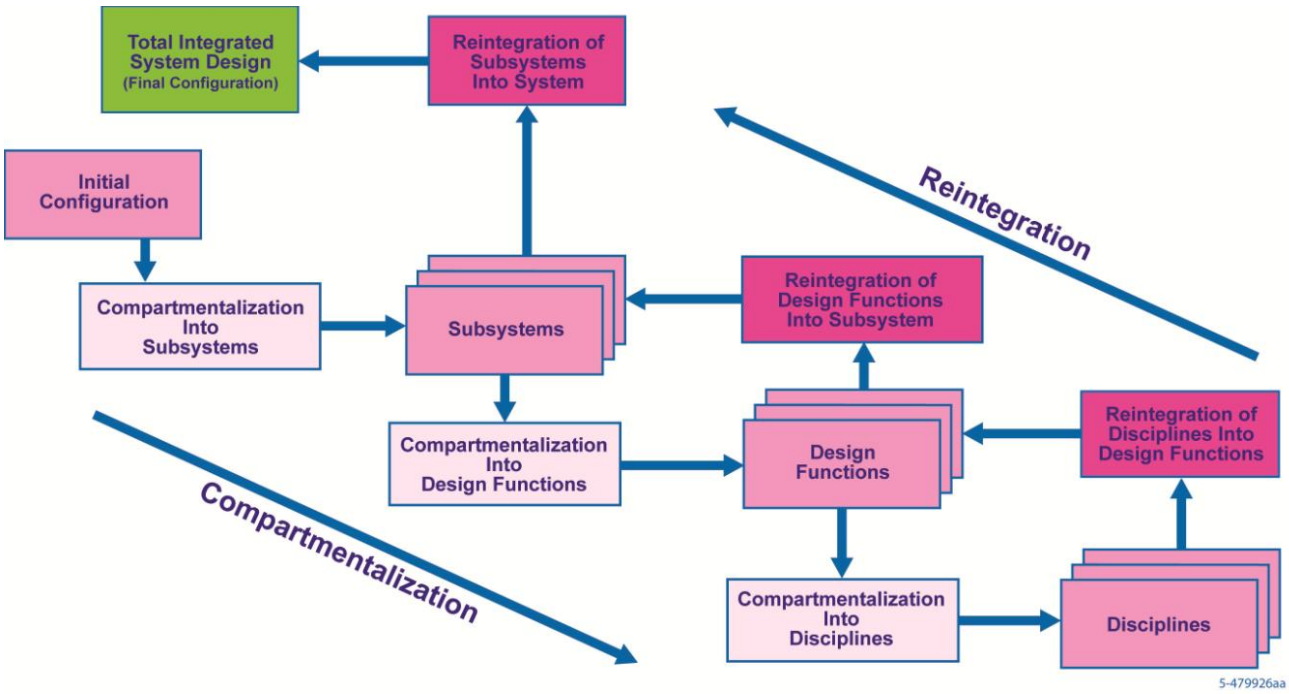


Figure 4-2. Compartmentalization and Reintegration

Thus the system is compartmentalized, now it must be reintegrated to obtain a totally integrated system design. Firstly, the disciplines are reintegrated. Adequate analyses, tests, and simulations are required to be accomplished. Then sensitivities, uncertainties, and margins need to be defined to provide information for risk assessment. Next the design functions are reintegrated. It must be assured that the attributes of the design meet the derived requirements. Furthermore, they are required to be verified. In addition, account of all interactions and nonlinearities has to be included. Finally, based on all knowledge of the design, a risk assessment is developed. This activity includes, at least, designers, disciplines, and S&MA. The final level of reintegration deals with subsystems and addresses interfaces. Specifically, the physical, functional, and informational flow across interfaces must be matched. Also interactions and nonlinearities related to the total system must be addressed. System integration and verification, operational constraints, and system risk are also considerations. A total integrated system design is achieved when compartmentalization and reintegration are completed.

Figure 4-3 provides additional insight in the compartmentalization process. The major activities and products associated with subsystems, design functions, and discipline functions are shown.

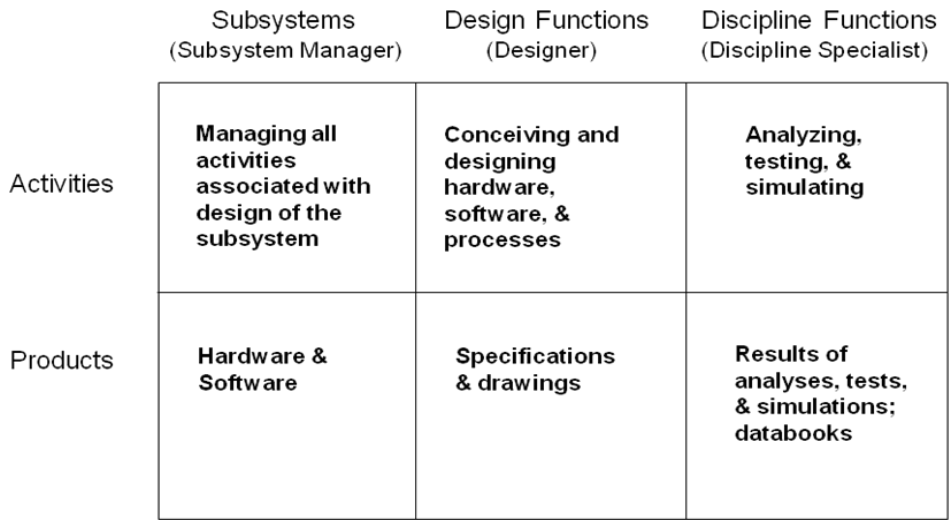


Figure 4-3. Compartmentalization Elements

Further insights, i.e., “peeling the onion”, into the design process can be gained in consideration of Figure 4-4. Shown here is an illustration of subsystems and design functions. Note; requirements flow down, design attributes flow up, and interfaces are created. In the middle of the figure is an example of a system and some of its subsystems. For example, follow the solid blocks; they go from the launch vehicle system to the propellant conditioning system. Each is designed by the design functions indicated with the dashed arrows. At the top left is the system set of design functions with the top design function being the launch vehicle system plane. It is responsible for all technical aspects of the system design. That includes classical system engineering, technical integration, hardware/software integration, etc. In addition, the system design plane orchestrates and integrates the design activities. In a similar fashion the top plane for each subsystem performs a similar activity.

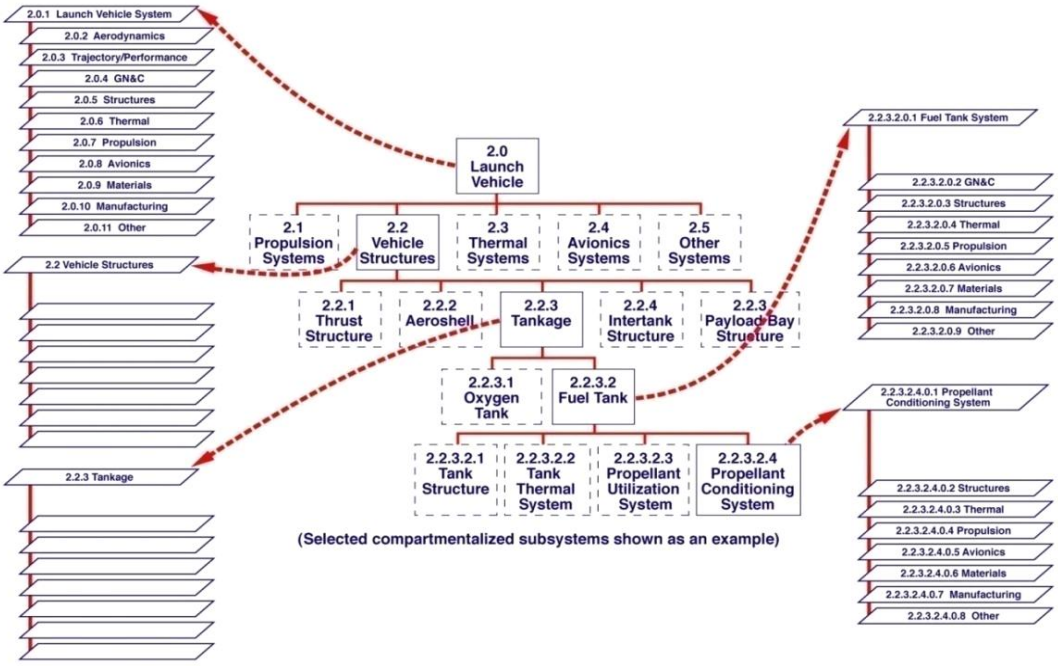


Figure 4-4. Typical Subsystems with Associated Design Functions

Technical integration of the system, design, and discipline functions are shown in Figure 4-5. The design functions are listed on the right of the figure. They provide the drawings, specifications and/or data books associated with each design function. For example, the aerodynamic design function provides the vehicle shape (outer mold line) and associated data books; trajectory/performance designs a balanced trajectory to achieve the target destination for the payload within all constraints, structures provides drawings and manufacturing specifications and so on. However, the system plane is responsible for all technical aspects of the system design. That includes classical system engineering, technical integration, hardware/software integration, etc. In addition, the system design plane orchestrates and integrates the design activities.

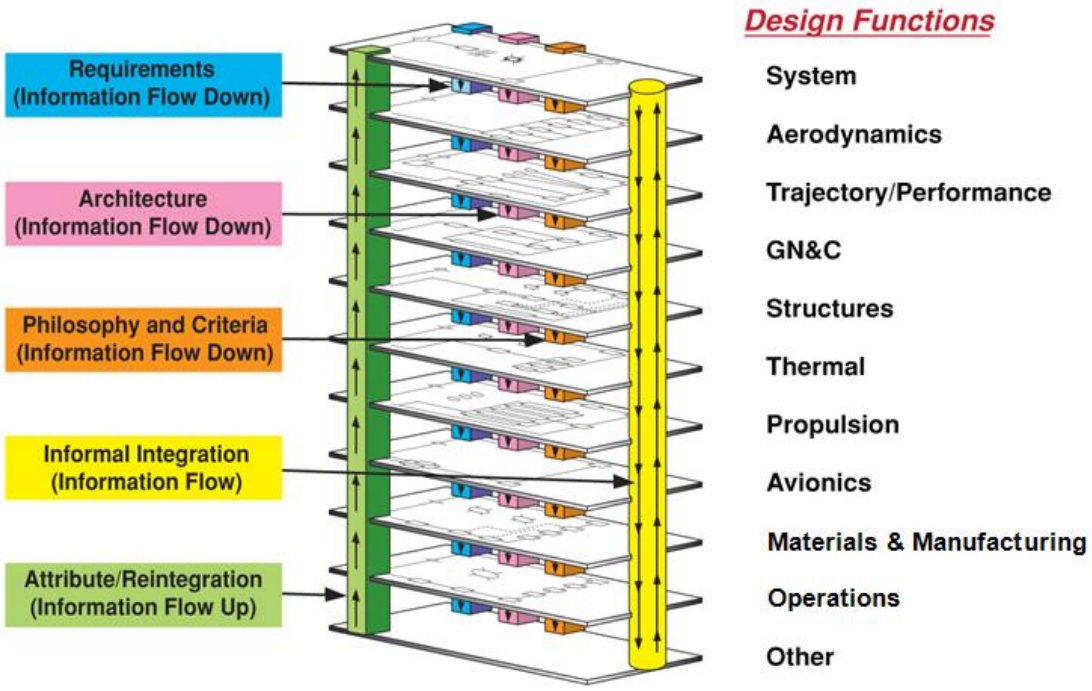


Figure 4-5. Technical Integration of System, Design, and Discipline Functions

The vertical conduits labeled requirements, architecture, and philosophy indicate formal flow of the associated information and they are controlled by the system. The system design is achieved in an iterative fashion via the design functions. Initially, a small group composed of representatives from each design function evolve a conceptual design(s) after a number of iterations. As the design matures through the DAC cycle process, the number of participants increases as well as the supporting data base. However the basic idea shown in Figure 4-5 remains in place but on a larger scale. The yellow conduit represents informal integration between the design functions and this is a key factor in achieving a balanced design. In addition, there is also significant informal integration within each design function. As the design converges, reintegration takes place and the converged attributes (green conduit) of the design formally flow to the system plane where they are eventually put under configuration control. If a balanced converged design with adequate margin can't be achieved, more iterations may be required or some system level requirements may have to be changed.

We have discussed the stack of design functions that are required to design a system or subsystem. Now consider the process that takes place within a design function (i.e., what happens on the design function planes). This is where the design functions are compartmentalized into discipline functions. As an example, consider the Structures design function shown in Figure 4-6. The block titled "Design" represents the structural designer on the CAD machine, who is responsible for taking the requirements, architecture, and philosophy from the Systems plane and synthesizing a structure that meets those requirements. In accomplishing this, he/she is supported by a number of discipline functions,

some of which are illustrated on the diagram. These include Natural Environments, Materials, Thermal, Control, Loads, and Stress. These discipline functions perform analysis, test, and simulation, and provide the necessary databases. Discipline functions also are the keepers of standards for their respective technical areas.

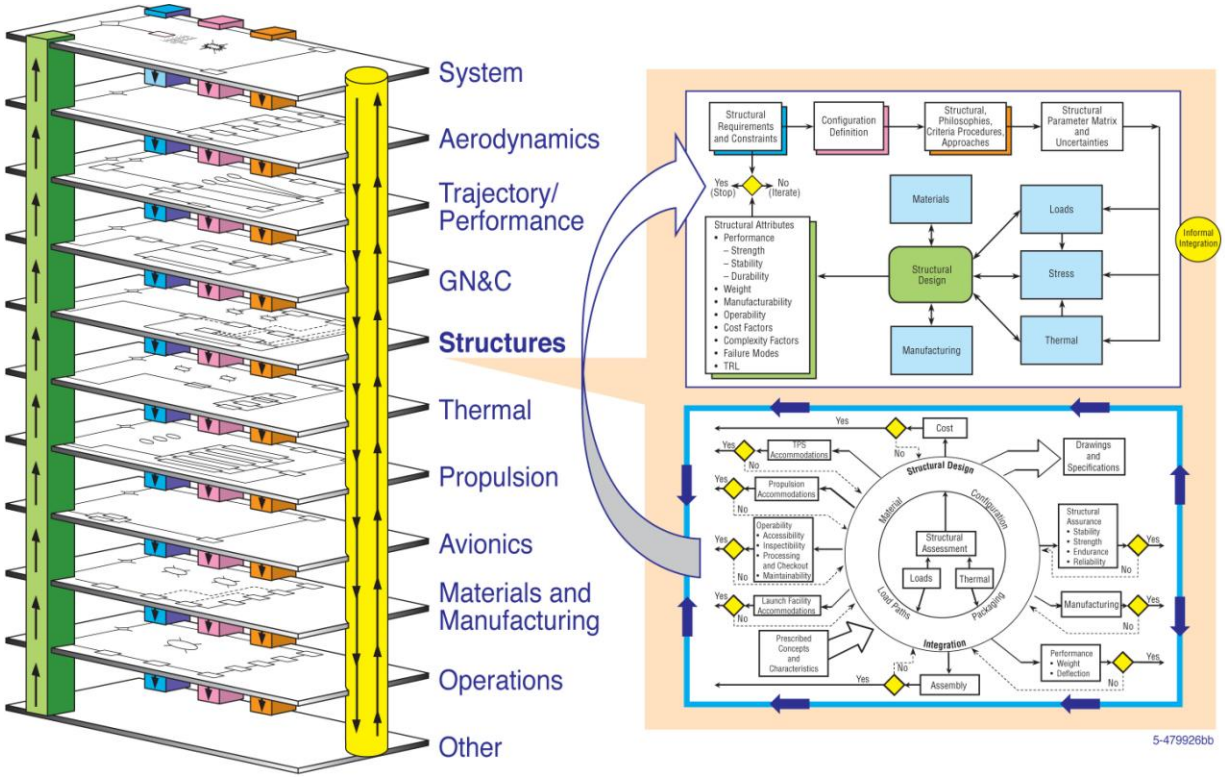


Figure 4-6. Structures Design Function with Discipline Functions and Decision Gates

The discipline functions provide the designer with information necessary to determine if the structural design will meet requirements. This is a very iterative process that requires extensive communication among the parties involved. Typically the designer hypothesizes a design (geometry, materials, etc.) from his/her experience base and imagination, informed by interactions with the discipline functions. The hypothesized design is analyzed to determine its attributes, which are compared with the requirements.

Note: The designer's activity can be thought of as an input/output process where the independent variables are the choices made by the designer (the *design variables*) and the dependent variables are the characteristics and qualities of the resulting design (the *design attributes*).

The goal, of course, is to have the attributes match the requirements. This is shown diagrammatically as a single decision gate on the Structures design function plane. However, since there are multiple requirements to be met, there are multiple gates that must be successfully passed. Examples of these gates are shown on the diagram below the

design function plane. They include attributes such as structural strength, endurance, and weight, accommodations of propulsion and thermal protection, and manufacturing and assembly compatibility. Notice that along with these measures the gates include cost and "-ilities" such as operability. When the design has been iterated to the point that its attributes successfully pass all the gates, the Structures design function can feed the structural design and its attributes up to the System plane, and output the drawings and specifications.

This process obviously does not occur in one pass, but requires many iterations and tradeoffs. Design inherently is a balancing and tradeoff process. To arrive at an acceptable design, there are multiple tradeoffs and iterations among the discipline functions and the design functions. We will not achieve a successful design unless there is intensive interaction and communication among all the participants. Iterations may also be required with the System plane, particularly if requirements relief or reallocation is required.

These highly-connected functions and activities involve flowing a great amount of information. How is all that information managed? Input-output matrices can be useful in identifying and providing locators for information needed by the various participants. Information flow among the subsystems can be envisioned on an "I x I" matrix where the subsystems are on the matrix diagonal, outputs from a subsystem are on the horizontal of that element, and inputs to the subsystem are on the vertical. Information flow among the design functions and the discipline functions is represented on an "N x N" matrix that has a similar layout. The matrices provide placeholders to identify and locate information that is required for the integration process. In some cases, the matrix information is formally identified, for example in subsystem interface control documents and design and analysis cycle data books.

Recall that *Technical Integration* is an interactive activity among all members of the design community where the compartmentalized subsystem → parts are designed and then reintegrated into a balanced system design that can be verified and validated and will operate at acceptable risk. The Technical Integration process is represented in Figure 4-7.

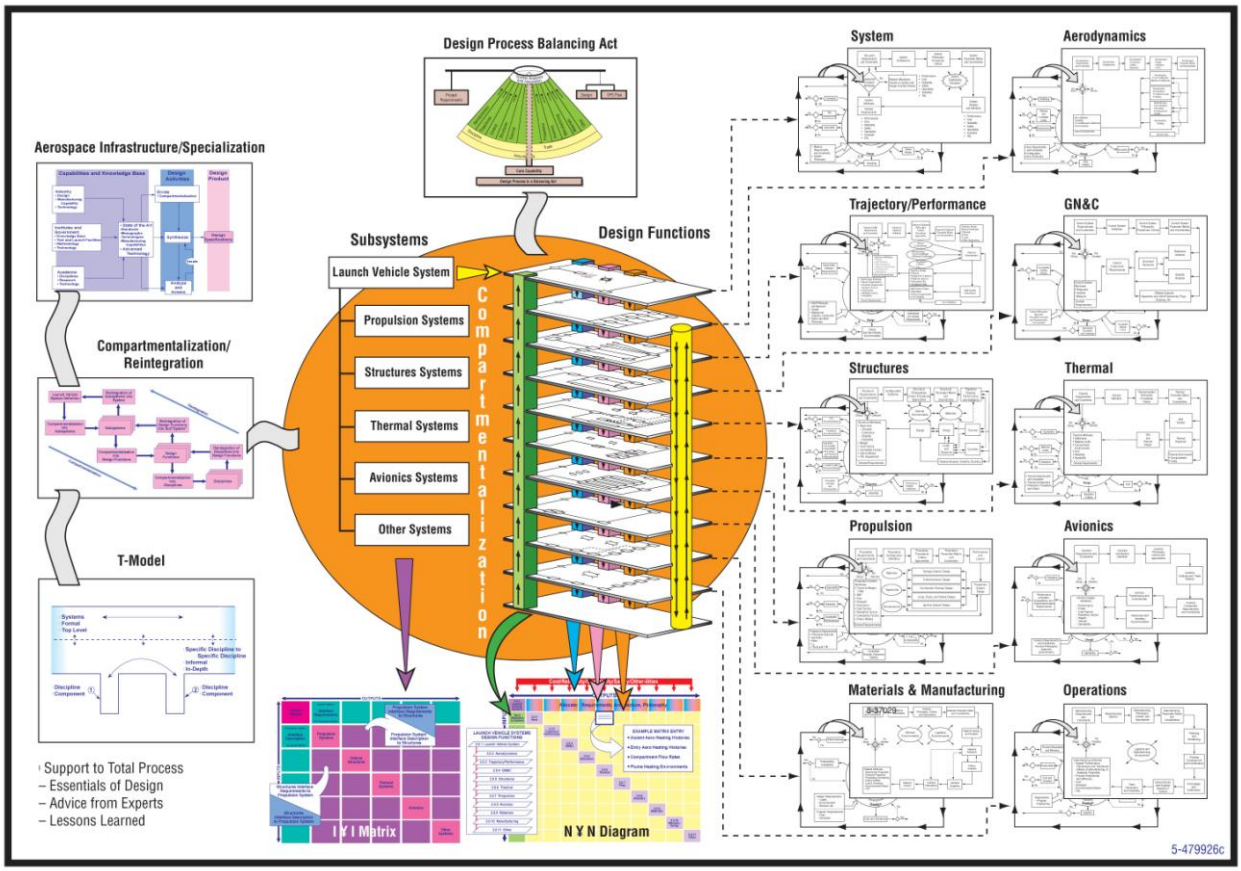


Figure 4-7. Technical Integration

There are two essential activities that overlay the Technical Integration process: Classical Systems Engineering and Safety and Mission Assurance (S&MA).

Classical Systems Engineering provides the framework, process control, and documentation for the Technical Integration process. (Figure 4-8) It is represented by the classical Systems Engineering "V" that follows the design life cycle from requirements through development and manufacturing, verification at component/subsystem level, then systems verification, certification, and operations.

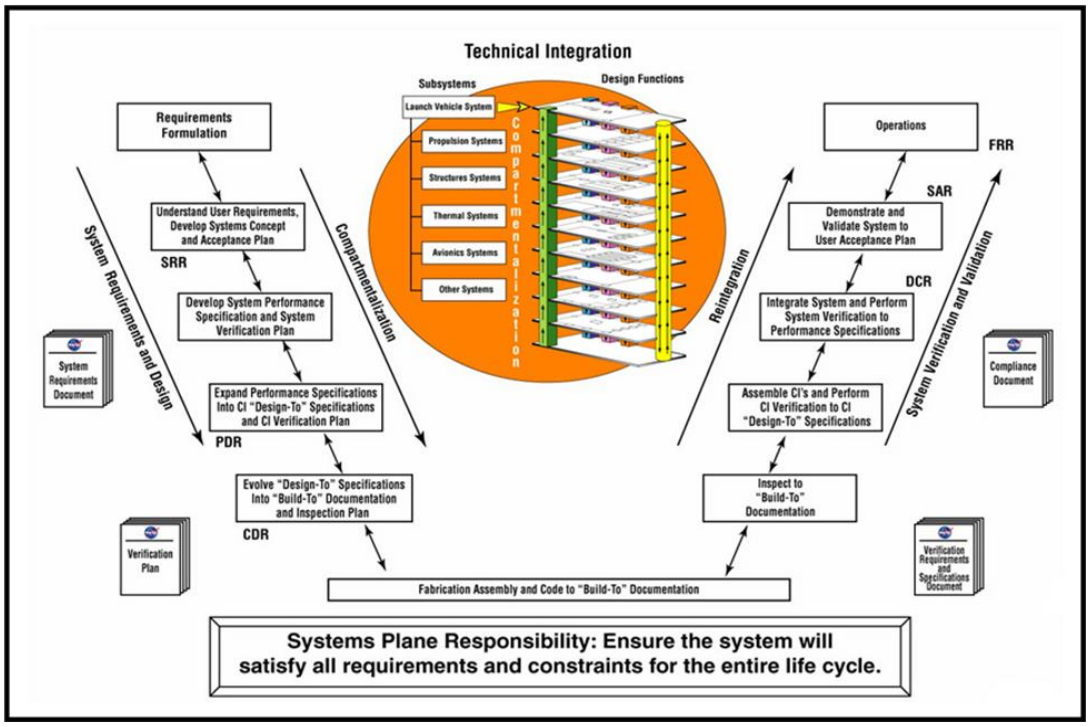


Figure 4-8. Classical Systems Engineering

Safety and Mission Assurance activities are an inherent part of the design activities. (Figure 4-9) S&MA has three main components: (1) System Safety deals with hazard identification, detection, and mitigation; (2) Reliability identifies failure modes and causes, along with their associated probabilities; (3) Quality addresses process control and verification of the as-built hardware and software.

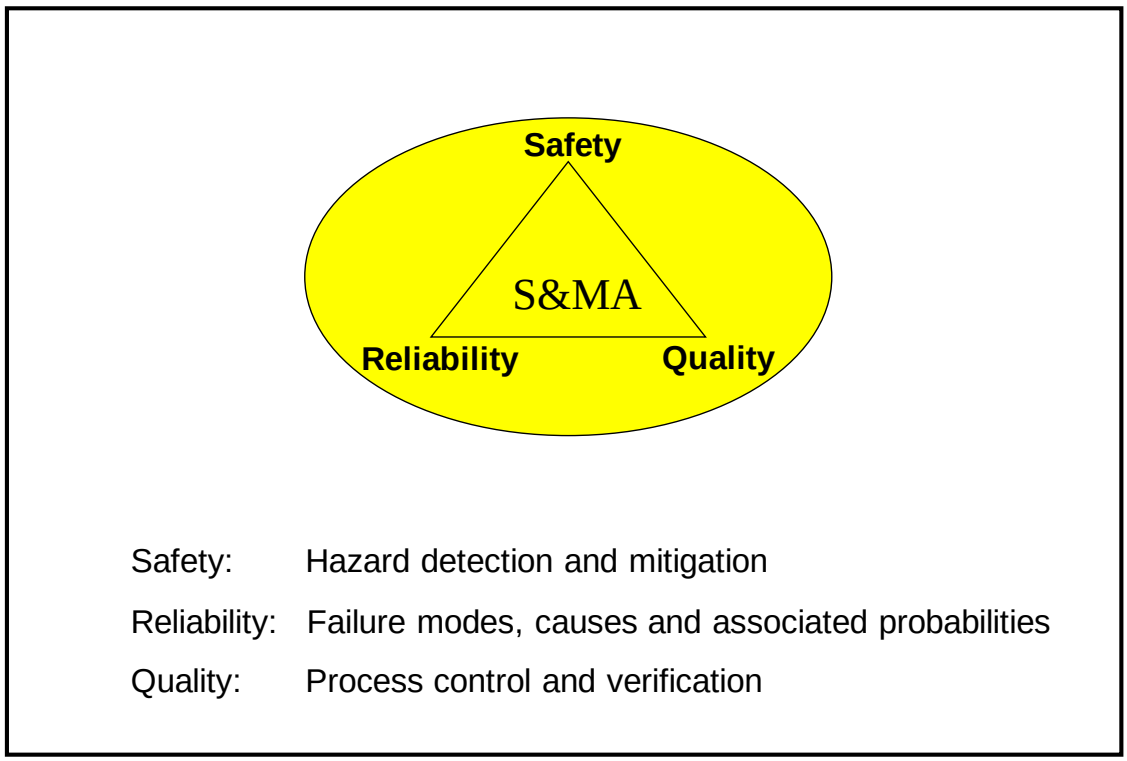


Figure 4-9. Safety and Mission Assurance

Overlaying Classical System Engineering and Safety and Mission Assurance onto the Technical Integration diagram then summarizes the Technical Execution of the Design as represented in Figure 4-10.

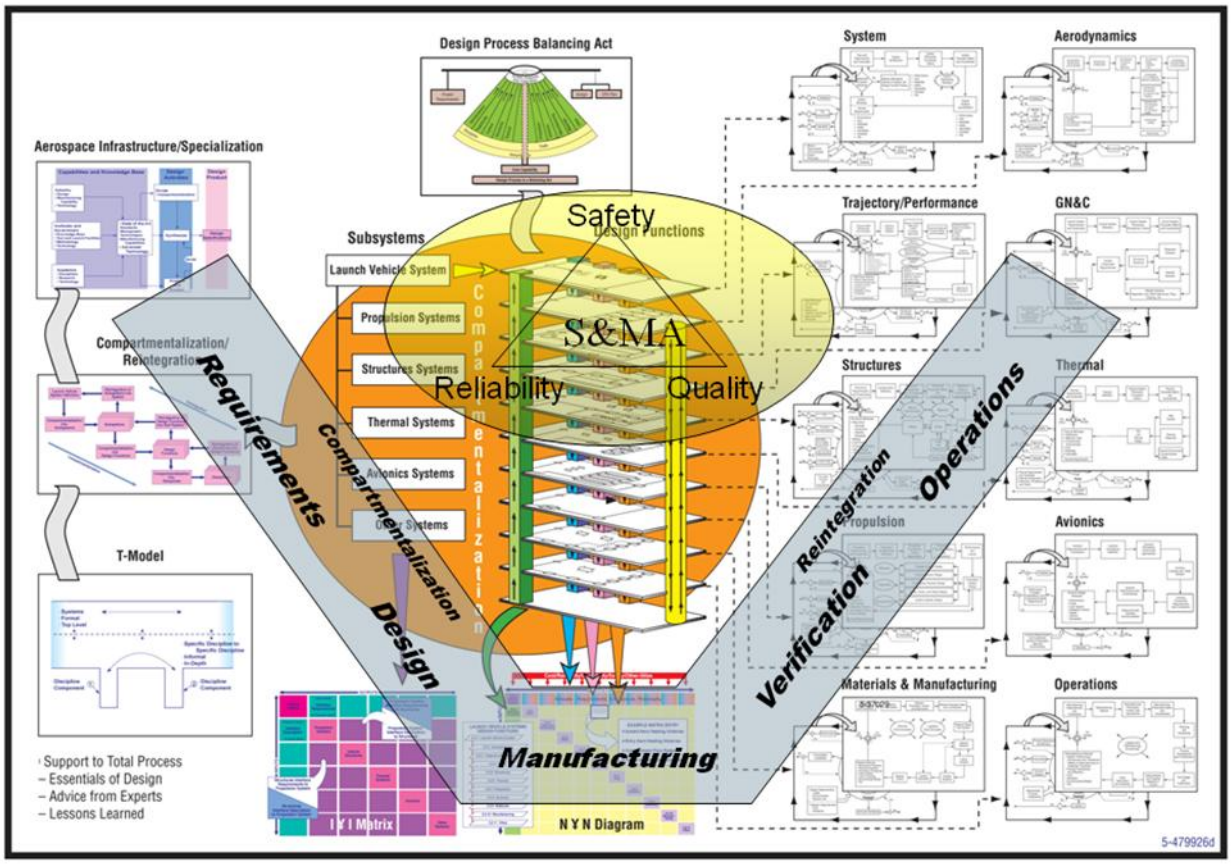


Figure 4-10. Technical Execution of Design

Achieving successful products clearly requires proper Technical Execution of Design. It also must have astute Project Management and be undergirded by the right Individual and Organizational Culture. This interactive triad of essential elements, illustrated on Figure 4-11, work together to produce products that successfully meet their objectives. These elements are addressed further in a separate report on Engineering Excellence.

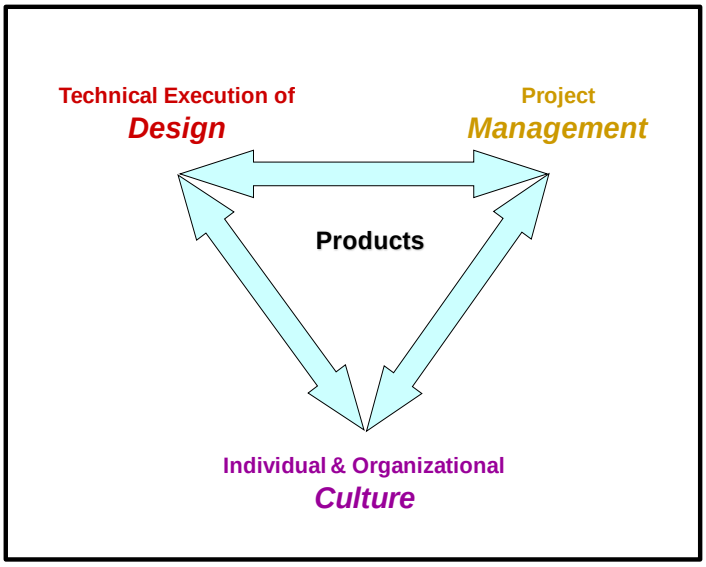


Figure 4-11. Elements of Product Success

Shuttle First Flight Aerodynamic Anomaly

The Space Shuttle is a high performance, intricately balanced launch system with complex interactions. These factors combined to generate a highly sensitive and hard to predict set of complex interactions. The first launch of shuttle STS-1 (Figure 4-12) produced several surprises.



Figure 4-12. STS-1 Space Shuttle Launch

The first was the liftoff SRM propulsion induced overpressure problem which yielded the RCS system attachment arms and produced large dynamic oscillations of the vehicle.

These phenomena will be discussed in a later lesson. The second surprise occurred during ascent when two anomalies occurred. First, the vehicle lofted significantly more than was predicted indicating that there was an unpredicted bias moment acting on the vehicle. The vehicle at SRB separation was approximately 10,000 feet higher than predicted. The second anomaly had to do with the orbiter wing loads. The trajectory had been designed to fly the vehicle conservatively at a predicted 65% of the design limit load; however, the strain gauges showed that the wing was experiencing up to 100% of the design limit load in some areas. The two effects were due to the same cause. In designing the vehicle, wind tunnel tests were required to develop the vehicles aerodynamic characteristics. In order to accomplish an adequate test, the propulsion system plumes, including the atmospheric effect on their shape, had to be simulated using a solid plume. Analytical techniques available to make the estimate of plume characteristics at that time were crude and thus gave an inaccurate answer. The plumes, in conjunction with the tunneling effect between the Orbiter wings and the External Tank and the Solid Rocket Boosters, altered the aerodynamic distribution on the Orbiter wing, creating the unpredicted moment and the increased loads on the Orbiter wings. Figure 4-13 illustrates the effect. Initially no one believed the strain gauge and aerodynamic pressure data, requiring that all the strain gauges be recalibrated. This recalibration showed that the strain gauges on the flight were accurate. Many thought that the pressure gauges were recessed too deep causing them to give inaccurate data; however after working the problem there was indeed a bias moment on the vehicle from the aerodynamic characteristics.

Space Shuttle Aerodynamics



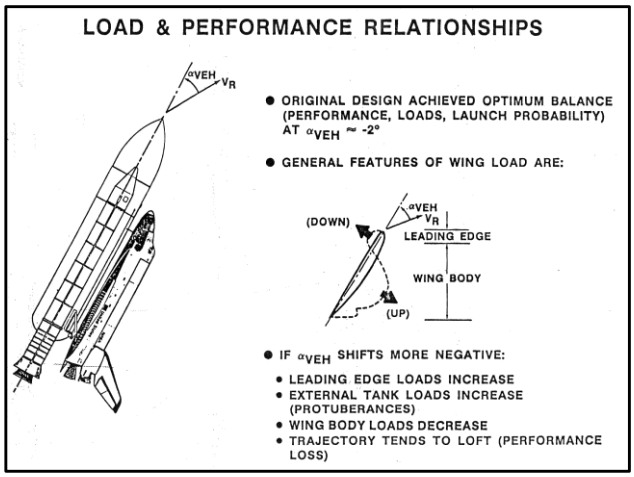


Figure 4-13. STS-1 Space Shuttle Aerodynamic Anomaly

The solution to the problem was complex. If the Orbiter wing was beefed up to handle the increased loads there would be a 5,000 pound payload loss and a schedule slip of the next launch by 2 years. An alternate fix involved flying the vehicle at a -6 degrees angle of

attack instead of the original -2 degrees at a payload penalty of 5,000 pounds. In addition the leading edge of the Orbiter wing had minor structural beef-up and the External Tank protuberances had to be requalified to the new loads. Even with these fixes the original total structural capability was not gained, requiring that a Day of Launch I-Load Update approach be added to the operational procedures to bias the trajectory to a wind profile measured 4 hours prior to launch. Figure 4-14 shows the original Q-alpha envelope and the reduced envelope that resulted from flying the vehicle in the new way. The above information is taken from presentations and notes of ASFIG meetings that the authors participated in and is summarized in [Chaffe, 1983].

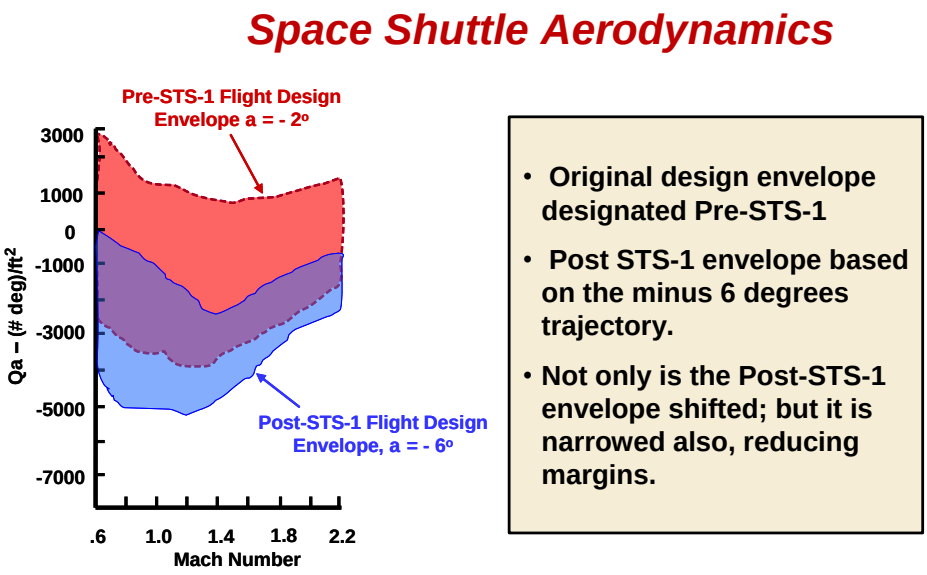


Figure 4-14. STS-1 Space Shuttle Aerodynamic Anomaly and Solution

The aerodynamic problem on the first Shuttle flight can be summarized by the following statements:

- Aerodynamic design distribution was missed as evidenced on the first Shuttle flight STS-1.
- The cause was not understanding the SRM and SSME plume effects and the base flow interaction along with the tunnel flow effects between the ET and Orbiter.
- Aerodynamics were predicted using wind tunnel test data where the plume shape and size was simulated using a solid plume.
- Sensitivity assessment using various size plume shapes would have revealed the problem.
- The Fix: Change the tilt program from –2 degrees to –6 degrees and beef-up the wing leading edge attachments and ET protuberances.
- The Cost: 5,000 pounds payload and in-flight wind constraints to launch. [Or, could have redesigned wing with 2 year schedule hit and 5,000 lbs increase in dry weight (5,000 equivalent payload loss)]

- **A key message from Lesson 4:**

  Our Organizations and Products are Highly Complex Systems. Technical Integration is the linchpin of their success. Definition of sensitivities and uncertainties is a fundamental activity of the design and operations of space systems.

Lesson 5: Risk Management

- **"Risk Management" Guides the Design with Confidence**
  - **Risk is assessed throughout all stages of the project life cycle**
  - **Risks are both developmental and operational**
    - **Technical [Safety (Personnel, Assets, and Environmental),**
    - **Performance (Requirements, Operations, and Supportability)],**
    - **Cost, And Schedule**
  - **Methods include: Risk Matrix and PRA**

One of the keys to success is assessing, understanding, and managing the various risks of the system. These risks are both technical and programmatic. The decision making process dictates that we make these decisions based on the total risks of the system. Technical risks deal essentially with potential failure modes and their probability of occurring as well as the severity of the failure. Programmatic risks of cost and schedule are similar in their approach. The technical risks also have a large impact on the programmatic risks and must include those impacts. Risk assessment and mitigation are major design activities that must be assessed throughout all stages of the project life cycle.

Risk Overview

Risk pertains to situations where there are undesirable and uncertain events that could be detrimental or have adverse consequences. In the development of space hardware, risk is concerned with the likelihood of occurrence of undesirable end states and the severity of resuling consequences. The first reference in the literature, see [Clemens, et. al., 2005], relating to the above risk definition is attributable to Blaise Pascal in1662.

Risk assessment and management guides the design through all stages of the design process. In the end, it provides confidence in the final design. Risk *assessment* pertains to the process of identifying and modeling potential risk scenarios, determining the associated probablility of a occurrence, the severity of the consequences, and actions required to reduce the risk to an acceptable level. Risk *management* is a process concerned with identifying, analyzing, planning, tracking, and controlling risk.

Concerns relating to risk occur during all stages of the design process. They pertain to technical , cost, and schedule risk. The main focuses of technical risk are *safety* (personnel, assets, and environmental) and *performance* (requirements, operations, and supportability). After a risk assessment is accepted it is usually prioritized by a project review team. The application of risk assessment and management enables the project to focus on the most pressing issues. In Figure 5-1 it can be seen that risk in one category can affect risk in other categories.

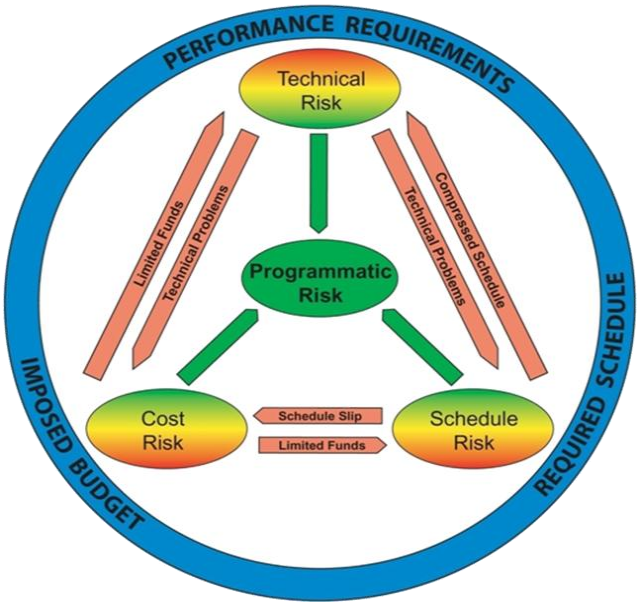


Figure 5-1 Relationships Among Risk Categories

The project's goal is to balance all risk categories and bring them to a level as low as practically possible.

Figure 5-2 provides a risk assessment taxonomy. It can be seen that there are two major legs associated with risk assessment. One method deals with risk matrix assessment and the other deals with probabilistic risk assessment (PRA).

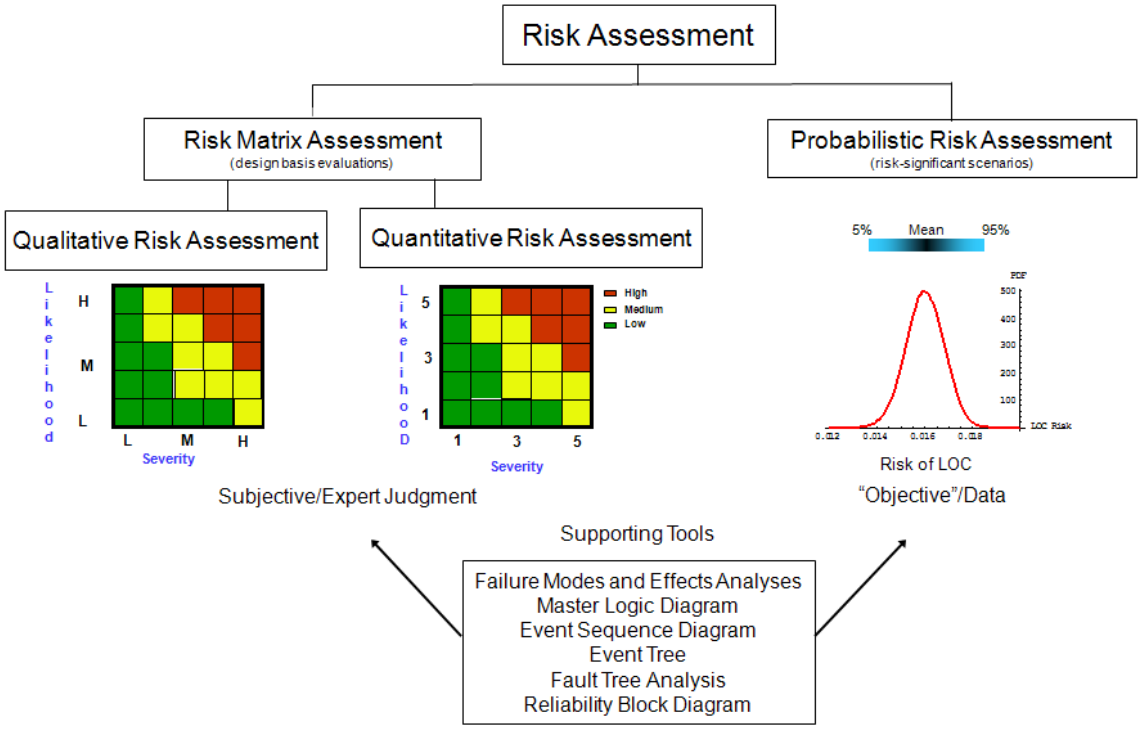


Figure 5-2. Risk Assessment Taxonomy

The risk matrix method usually applies to project levels 3, 4, and 5. The main purpose is to determine and assess undesirable events associated with technical (safety and performance), cost, and schedule and includes participation of engineering and S&MA. They determine the likelihood of an undesirable event and the corresponding severity. The risk assessment then goes to the project team where the priorities are determined. This methodology was established in the mid to late 1970's and continues to be refined to accommodate various applications.

PRA is a method that is usually applied to project levels 2, 3, and 4. This method is usually applied to assess events that have a low probability of occurrence, but with enormous consequences, for instance: loss of crew, loss of vehicle, or loss of mission. One of the distinguishing features of PRA is the determination of uncertainty associated with the risk level. As can be seen from the figure the results are represented by a probability density distribution. This methodology was developed in the early 1970's to assess risk associated with nuclear reactors. The first PRA for the Space Shuttle was completed in 1988 and the risk of loss of crew was 1/78 (current value is 1/80). In comparison the risk associated with the loss of crew of Ares-1 is 1/2000.

Examples:

- Space Shuttle SRM Ignition Overpressure
- Saturn V IU Rate Gyro Deflection

Listed above are two examples that illustrate risk. The discussion that follows will focus on these two examples.

Space Shuttle SRM Ignition Overpressure

During the ignition of a Space Shuttle solid rocket motor (SRM), the maximum rise rate of the internal total pressure is about 9000 psi/sec. When the SRM hot exhaust products (mass of exhaust gas) is suddenly injected (it takes ~ 0.5 seconds to reach a total mass flow of ~12,000 lbs/sec) into the confined volume of the Shuttle Mobile Launcher Platform (MLP), main deflector, exhaust trench and side deflector elements it produces an "overpressure wave" that is propagated back to the launch vehicle approximately as a hemispherical, high amplitude wave. The result is a transient high amplitude pressure distribution that vibrates the vehicle system.

Titan III flight tests about 1975 indicated high ignition overpressure (IOP) levels. In addition, tests at Marshall Space Flight Center Acoustic Model Test Facility also indicated high IOP levels; see [Jones, et. al., 1994]. Structural analysis indicated the response was acceptable and a decision was made to fly STS-I as is and to assess IOP effects after the first flight. On STS-1, there was a high amplitude overpressure wave that was developed that resulted in vibration responses on the Orbiter's wing, body flap, vertical tail, and crew cabin that exceeded predictions. In addition, struts on the Orbiter's reaction control system's oxidizer tank were buckled.

The first Space Shuttle flight was in April 1981 and the second flight was in November 1981. During this time an extensive effort was initiated not only to devise a means for abating the IOP but also implementing a design fix on the Space Shuttle MLP at KSC. During that period, 40 tests using a 6.4% Shuttle model, see Figure 5-3, were conducted and a design fix was established. Two types of fixes were finalized and these were used to reduce the IOP levels. One consisted of a water spray nozzle system where the water sprays were directed towards the SRB at two axial positions under each SRB for a total water discharge of 100,000 gpm for each SRB. Six nozzles were positioned ~ 22 inches below the SRM and two other nozzles were 140 inches below the SRB. These sprays function to provide a substantial mixing of the water with the SRM exhaust mass flow so as attenuate the IOP wave. The effectiveness of the water injection alone is shown in Figure 5-4. The second fix was a set of 12 inches deep water troughs that were placed completely across the large drift holes and they were filled with water. This fix was designed to act as barriers to block any reflected waves that developed below the MLP, see [Jones, et. al., 1994]. Figure 5-5 shows both the water spray and water trough fixes.



Figure 5-3. Acoustic Model Test Facility - 6.4% Shuttle Model

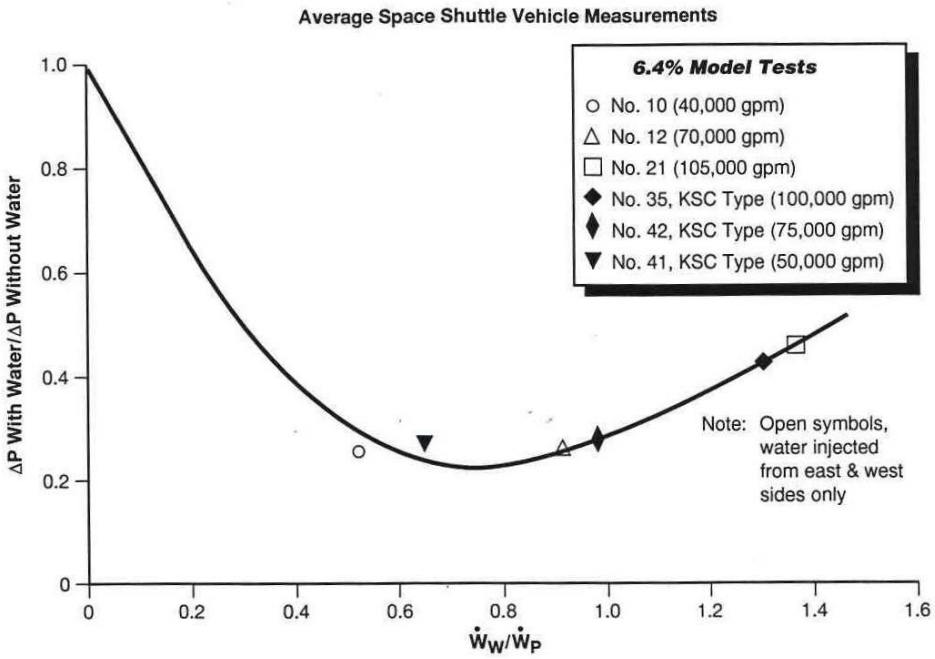


Figure 5-4. Effect of Water in Primary Side of SRB Hole on Positive Peak Overpressure

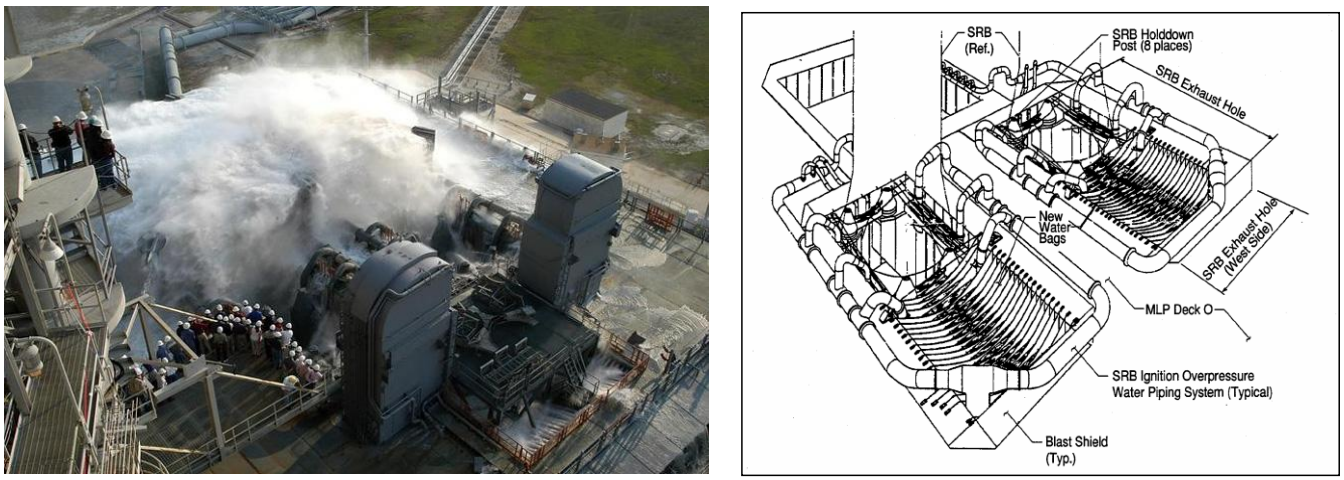


Figure 5-5. Water Spray System and MLP Water Troughs

The IOP suppression fix described above was implemented on STS-2 and all subsequent Shuttle flights. Figure 5-6 shows the comparison of the overpressure waveform at the Orbiter Base Heat Shield between STS-2 (with) and STS-1 (without) the IOP suppression fix.

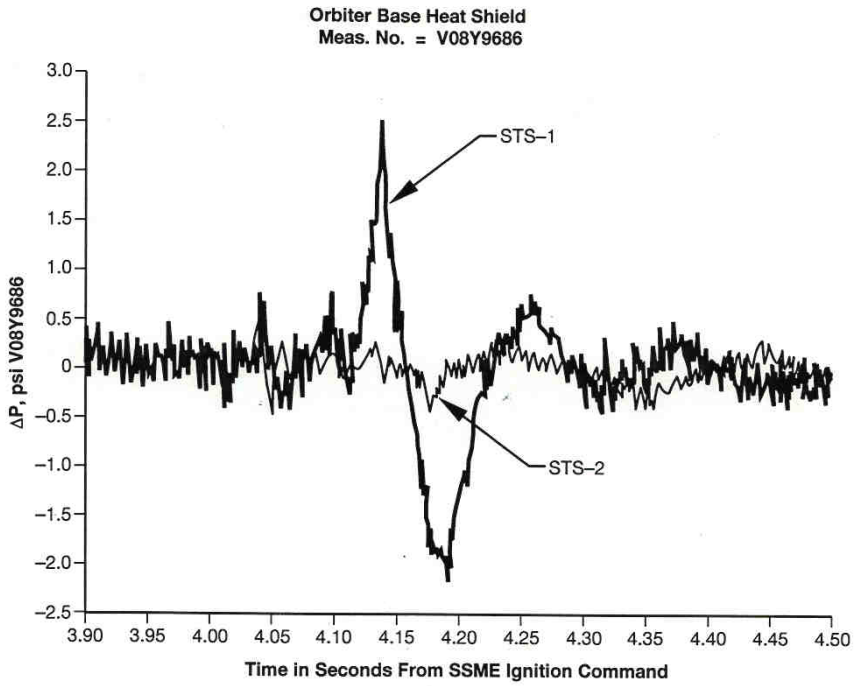


Figure 5-6. Comparison of the Overpressure Wave at the Orbiter Base Heat Shield Without Suppression (STS-1) and With Suppression (STS-2)

Also, shown in Figure 5-7 below, is the SRB IOP peak amplitude data indicating the effect of the fixes. This figure indicates the trend in the data, i.e., approximate mean values.

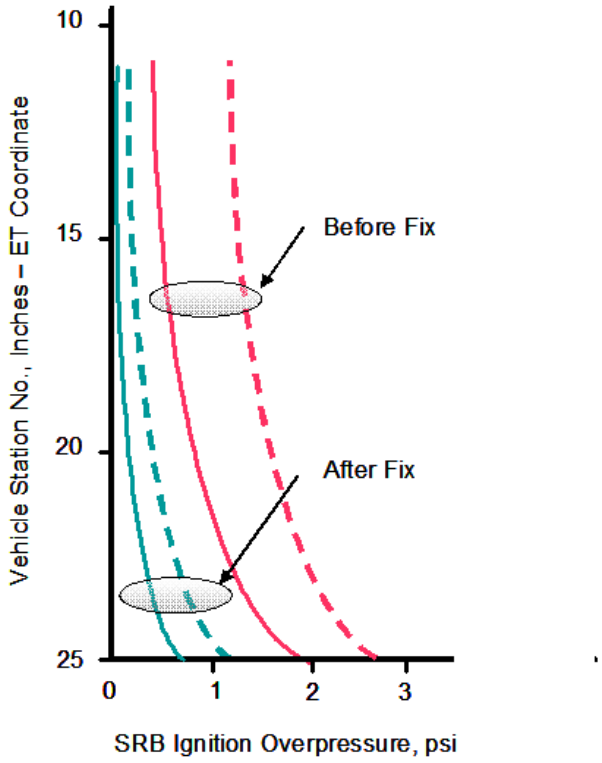


Figure 5-7. SRB Ignition Overpressure

In the figure there are two sets of data. One set pertains to IOP levels before the fix and the other set is after the fix. It can be seen that the maximum level on the Space Shuttle External Tank before the fix was about 2.0 psi. In the model test the levels were higher. These levels were higher because the solid rocket motor used in the model test was not an exact scale of the SRB and because of the scaling factors used. However, in the tests after the fix, the data indicates levels that would not seriously impact the vehicle loads. Also, the flight data after the fix substantiates the findings that the fixes would abate the IOP and it would no longer impact vehicle loads.

This is an example where the risk in the system was not correctly judged and had to be addressed after the first flight.

Saturn V IU Rate Gyro Deflection

During the development of Saturn/Apollo there were unknowns regarding the ability to model the dynamics associated with bending, controls, loads, aeroelasticity, etc. This resulted in risk regarding flight uncertainty. The design team recommended to the project office that a ground vibration test (GVT) be conducted to determine various unknowns and uncertainties to anchor the models. The project accepted the recommendation and a GVT was conducted. This test series uncovered a large deflection in the instrument unit (IU) at the location of a rate gyro.

In Figure 5-8 the instrument can be seen on the Saturn/Apollo along with approximate locations of rate gyros. It turned out that the load path of the Service Module (SM) and Lunar Module (LM) went through the forward portion of the Instrument Unit (IU) through the location of the rate gyro at the first bending mode frequency. The consequence of this situation was that as the vehicle flew a bending vibration sensed by the rate gyro would be sent to the control system and could couple in such a way that the vehicle would be dynamically unstable. [Ryan, et. al., TM-78037, 1980]

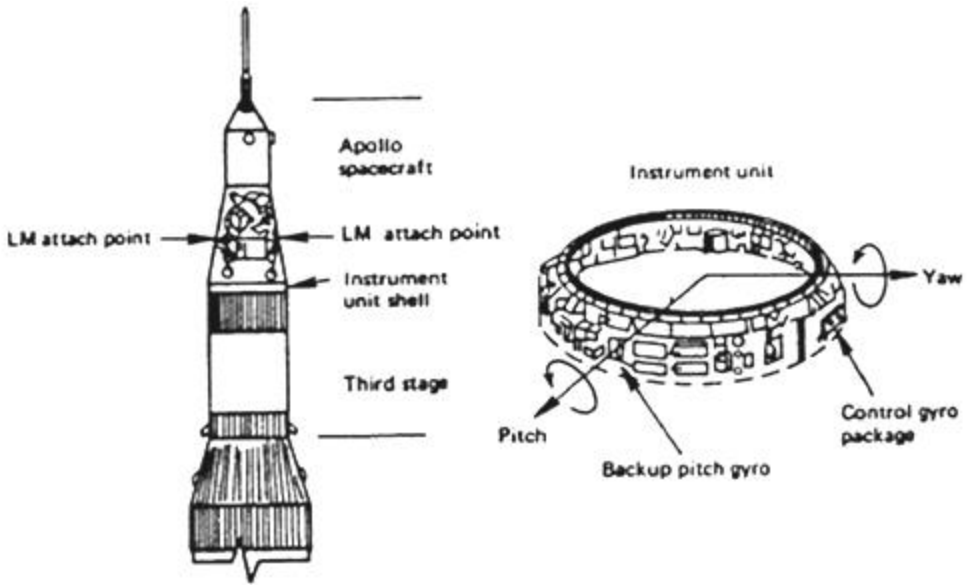


Figure 5-8. Saturn/Apollo – Instrument Unit

In Figure 5-9 is a schematic of a control rate gyro that shows its location along with an exaggerated view of the deflection. Also, the LM attach point (load path) can be seen with the control gyro located below it. In the deflected position shown, the control system would indicate that the vehicle was at an angle of attack as indicated when in fact it would not be at the sensed angle of attack. In addition, it would indicate that the vehicle would be vibrating as a rigid body at the bending frequency. The rate gyro was moved to a more benign location that reduced this effect by a factor of three and potential problem was eliminated.

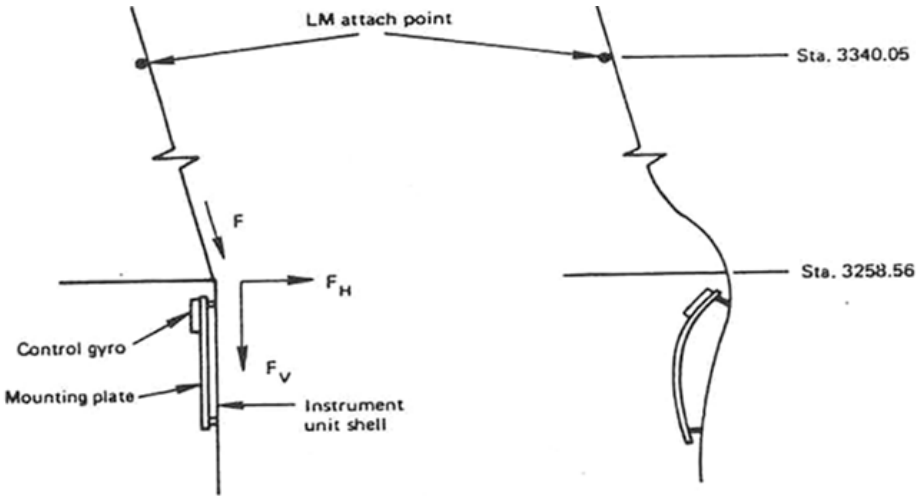


Figure 5-9. Schematic of Gyro Mounting and Local Deformation

This is an example where the risk was assessed and appropriate action was to reduce it to a level as low as possible, i.e., benign state.

From these examples it can be seen that risk must be continually assessed and managed throughout the project life cycle. Analysis and careful testing with all conditions simulated is best for quantifying risk; however, there can be "unknown unknowns." In that case, the unknown events should be *anticipated*! In many in-flight anomalies, there were usually indicators pointing to potential problems.

- **A key message from Lesson 5:**

  Risk must be continually assessed and managed throughout the project life cycle

Lesson 6: All Design is a Paradox, a Balancing Act

- ***All design is a paradox, a balancing act. Because of conflicting requirements, you must take some of what you don't want, to get some of what you do want.***

  - **All designs must achieve acceptable reliability for safety.**
  - **Within this constraint, balancing must occur:**
    - Among design and discipline functions (energy redistribution).
    - Among program requirements, the design, manufacturing, and operation plans.
    - Problems not cured in design must be compensated for in operational compromises and constraints (e.g. may lead to reduced probability of launch).

- **Among cost, schedule, and performance, with associated risks.**

- **The above attributes are linked; an improvement in one attribute typically produces a detriment in another.**
- **The balancing act requires open communication and key decision judgments.**

Lesson 6 deals with balancing the system among its set of conflicting requirements and performance metrics. We accomplish design in terms of the requirements/constraints using trade studies. Trade studies drive out the differences in design alternatives and illustrate the strongly coupled nature of space systems. Sensitivities are the guiding light for accomplishing trade studies. How well we accomplish this balancing act using trade studies determines product success. David Pye says,

"Any of these forms of energy is capable of producing changes, changes in things; more exactly, redistribution of matter…Now whenever a change is made by passage of energy and a result is left, this event takes place in a group of things. Things are always together. They do not exist separately… All you can do, and that only within limits, is to regulate the amounts of the various changes. This you do by design."

"The requirements for design conflict and cannot be reconciled. All design for devices are in some degree failure. The designer or his client has to choose to what degree and where the failures shall be."

"You must take some of what you don't want in order to get some of what you do want." [Pye, 1969]

Thus, design is paradoxical. As a consequence, we balance the system to the degree possible among conflicting requirements. Because of the demanding, high-performance nature of launch systems, this balancing act associated with their design is especially challenging. Balancing must occur within the performance attributes of the system, and there must be balancing among technical performance attributes, the -ilities, and the programmatic attributes of cost and schedule. There can be tradeoffs between payload delivery capability, vehicle robustness, launch probability, and operational complexity. Problems that can't be cured in design must be compensated for in operational compromises and constraints. Knowledge of system risks is necessary to make correct tradeoff and balance decisions. The balancing act requires open communication and key decision judgments.

Tradeoffs are made at essentially every level to achieve the desired balance. An example of performance based trade studies is shown in Figure 6-1. Each of the design functions shown has options that can be explored to meet its requirements, and can be traded within its own area. There are also trades among the design functions, as well as trades with the total system. An actual trade space would have many more options than just the few illustrated here.

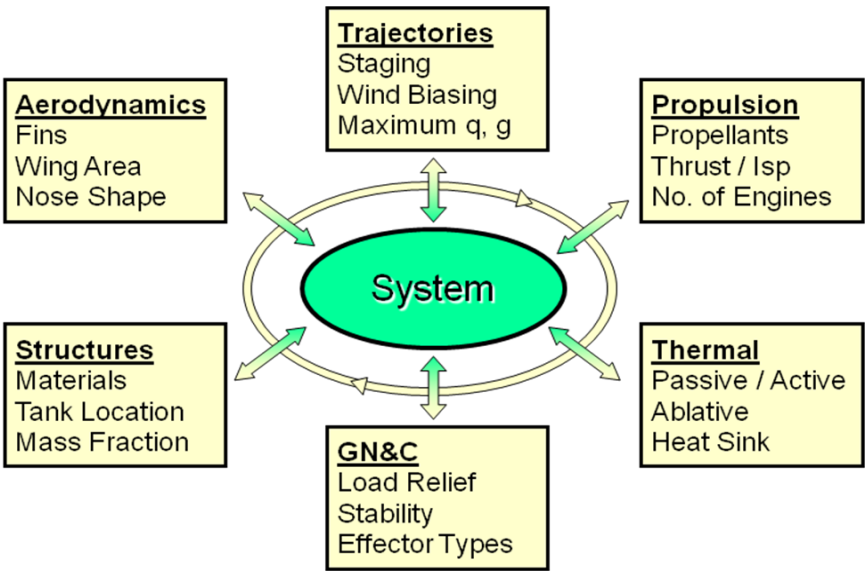


Figure 6-1. Example of Performance Based Trade Studies

Figure 6-2 illustrates the fact that the design process is a balancing act, seeking the best design balance point among all the many interacting elements. Balancing must occur among all technical and programmatic aspects of the project.

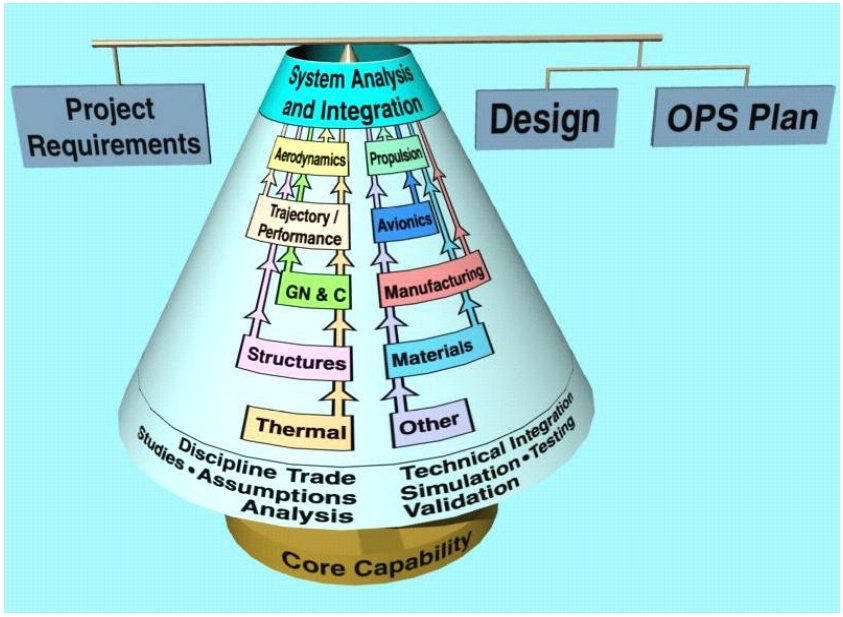


Figure 6-2. Design Process Balancing Act

Examples:

- Balancing Payload Performance, Trajectory, Control, Loads, Thermal
- Load Relief / Performance Trades
- Wind Biasing
- Saturn V Load Relief Trade
- Operations versus Vehicle Performance
- Solid Rocket Booster Water Impact / Recovery

Balancing Payload Performance, Trajectory, Control, Loads, Thermal

For the ascent phase of flight, there are a number of flight mechanics parameters that must be traded to achieve the best balance of payload mass to orbit, launch availability, operational complexity, and system robustness. They include trajectory, control, loads, and thermal environment (Figure 6-3). The basic trajectory is determined to maximize payload mass delivered to orbit. The control system orients the vehicle to follow the optimal trajectory. The more closely the vehicle can be controlled to the optimal trajectory, the more payload mass can be delivered to orbit from a flight-mechanics viewpoint. However, when the vehicle encounters winds, holding tightly to the optimal trajectory causes the aerodynamic loads to be relatively high. Higher aerodynamic loads require stronger, heavier structure, which reduces the payload mass delivery capability. We can relieve the wind-induced aerodynamic loads by turning the vehicle to reduce the angle of attack; however, this causes the trajectory to deviate from optimal. So there is a tradeoff required—a balancing act. Thermal environments can be affected by the flight path during the latter part of atmospheric ascent, so those considerations are also part of the balancing.

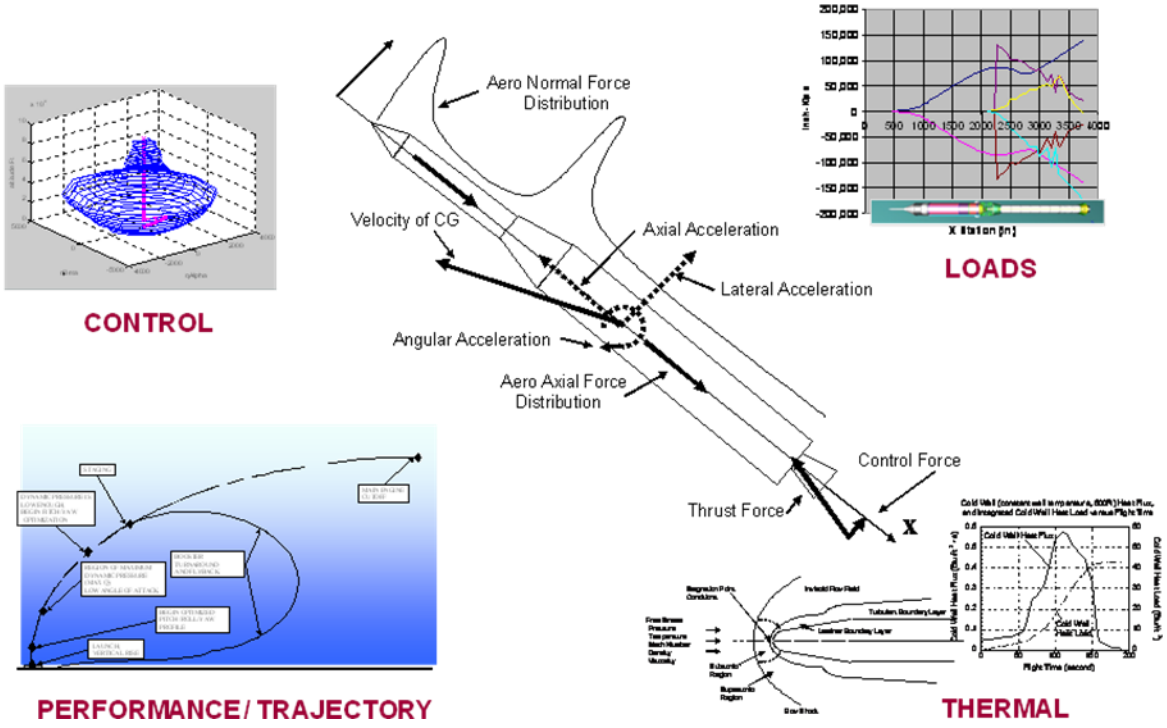


Figure 6-3. Balance Performance, Trajectory, Control, Loads, Thermal

One of the most highly tuned and balanced systems is the Space Shuttle. The Shuttle is a stage-and-a-half configuration with a winged, reusable Orbiter. This means that it is extremely sensitive and must be reevaluated after any change, however small. It must "thread the needle" through its many tight constraints. As a consequence, it is operationally expensive, requiring much continuing attention. [Chaffe, 1983]

Load Relief / Performance Trades

Typically, the best balanced system involves reducing the wind-induced aerodynamic loads to allow a lighter structure. There are three techniques commonly used to reduce these loads: wind biasing, load relief control, and modal suppression. Figure 6-4 summarizes the benefits and costs/disadvantages for each technique.

Method	Benefits	Costs/Disadvantages
Wind Biasing	**Lower rigid-body loads, thus lighter structure or more margin; Lower performance variations**	**Operational complexity and cost**
Load Relief Control	**Lower rigid-body loads, thus lighter structure or more margin**	**Path-deviation performance losses; Control system complexity; Added failure modes**
Modal Suppression	**Lower flex-body loads on forward section of vehicle, thus lighter structure or more margin**	**Control system complexity; Ground vibration tests for required modal accuracy**

Good vehicle design chooses the best balance of these options, considering benefits, costs, risks, and robustness.

Figure 6-4. Comparison of Load Reduction Methods

For wind biasing, the ascent trajectory/guidance profile is biased for an expected value of winds occurring over a specified time period (e.g., a month). If that expected wind were actually experienced during flight, there would be no wind-induced load on the vehicle. Of course, the actual wind always differs from the expected or predicted wind, so there will be wind loads caused by the difference between the actual and expected (biased) winds. Wind biasing allows the structure to be designed to withstand only the deviations from the expected wind, instead of the full range of winds possible for that time period. The disadvantage of wind biasing is operational complexity and cost. There will be more discussion of wind biasing later.

Configuring the control system to sense and reduce the wind-induced aerodynamic load is designated “load relief control”. Although controlling the vehicle to reduce the aerodynamic load generally entails deviating from the payload-optimized trajectory, using load relief control provides the most favorable net payload capability for many vehicle designs. However, it entails the addition of lateral accelerometer sensors and filtering, which adds failure modes and operational complexity.

Modal suppression is the use of the control system to actively damp some vibrational modes to reduce loads caused by modal tuning with wind gusts. This can reduce the loads on the forward section of flexible vehicles, thus allowing lighter structure or more margin. However, there is some system complexity introduced, and active modal control requires accurate knowledge of modal characteristics, which may entail ground vibration tests of the structure.

Good vehicle design chooses the best balance of these options, considering benefits, costs, risks, and robustness.

Wind Biasing

As discussed earlier, wind biasing is a means of relieving loads during ascent. The choice of what wind-biasing time period to use for design is a tradeoff decision. See Figure 6-5. For example, we can design for the expected (average) wind over a yearly, monthly, or daily (several hours) time period. In each case, the trajectory/guidance profile must be generated and loaded into the flight computer. Designing for a yearly wind bias would allow one profile to be used regardless of when the launch occurs during the year. This is operationally simple, but requires a strong vehicle, since the actual wind varies greatly during the year from the average annual wind. A monthly bias requires loading a profile for the specific month of launch, but reduces the design loads because wind variations within a month are smaller than within a year. Carrying the concept further, we can measure the wind on the day of launch and bias to that wind. Now the variability is much smaller, so the wind loads are reduced to those corresponding to only the wind variability within a few hours. The structure can then be lighter, but now there is a significant operational cost incurred on every flight, because on the day of launch the winds must be measured, the profiles must be generated, independently verified, and loaded into the flight computer. So a tradeoff decision is required. (Further details of day-of-launch biasing are given in Lesson 17.)

If one designs for wind biasing for a given time period, the vehicle will have to operate with biasing for that period or a shorter period. One approach is to design for a monthly mean, for example, and hold in reserve the possibility of operating with day-of-launch biasing. This retains margin that can be used to accommodate downstream payload performance problems, increase launch probability, or provide mission flexibility. Figure 6-5 illustrates this concept.

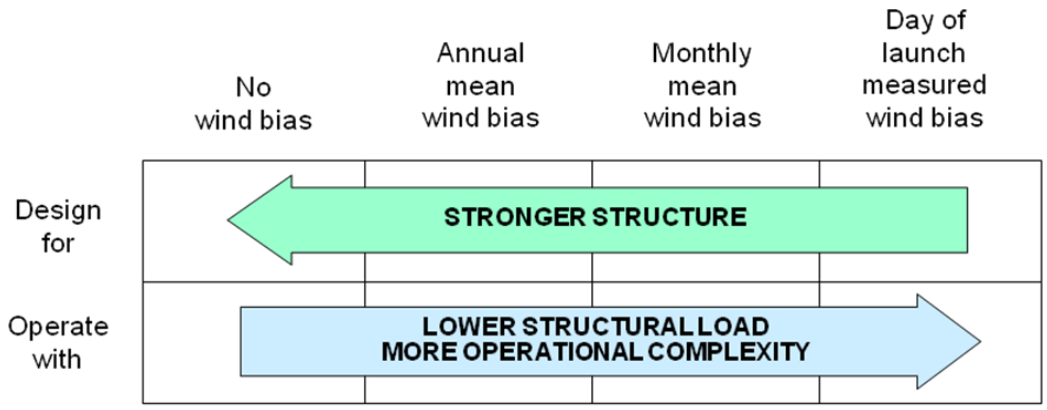


Figure 6-5. Wind Biasing Options and Effects

The approaches taken for Saturn V and Shuttle are illustrated on Figure 6-6. Saturn V was designed for no wind biasing, so it had a very strong structure. It was operated with monthly mean wind biasing, so there was margin provided by the difference between the "Design for" and the "Operate with" points. This margin in structural capability, along with margin in the propulsion system, provided mission flexibility that enabled carrying the Lunar Rover and launching Skylab, two applications that were not envisioned in the initial design.

Space Shuttle followed a different path. Being a stage-and-a-half vehicle, it required a relatively more efficient (lighter-weight) structure than did the three-stage Saturn vehicle. The initial intent was to design for monthly mean wind biasing. However, the effects of the unexpected first flight aerodynamic anomaly discussed in Lesson 4 meant that the as-built vehicle was not as strong as initially intended, and required day-of-launch wind biasing. Since there is no spread between the as-built point and the operate point, there is no margin benefit for Shuttle as was the case for Saturn.

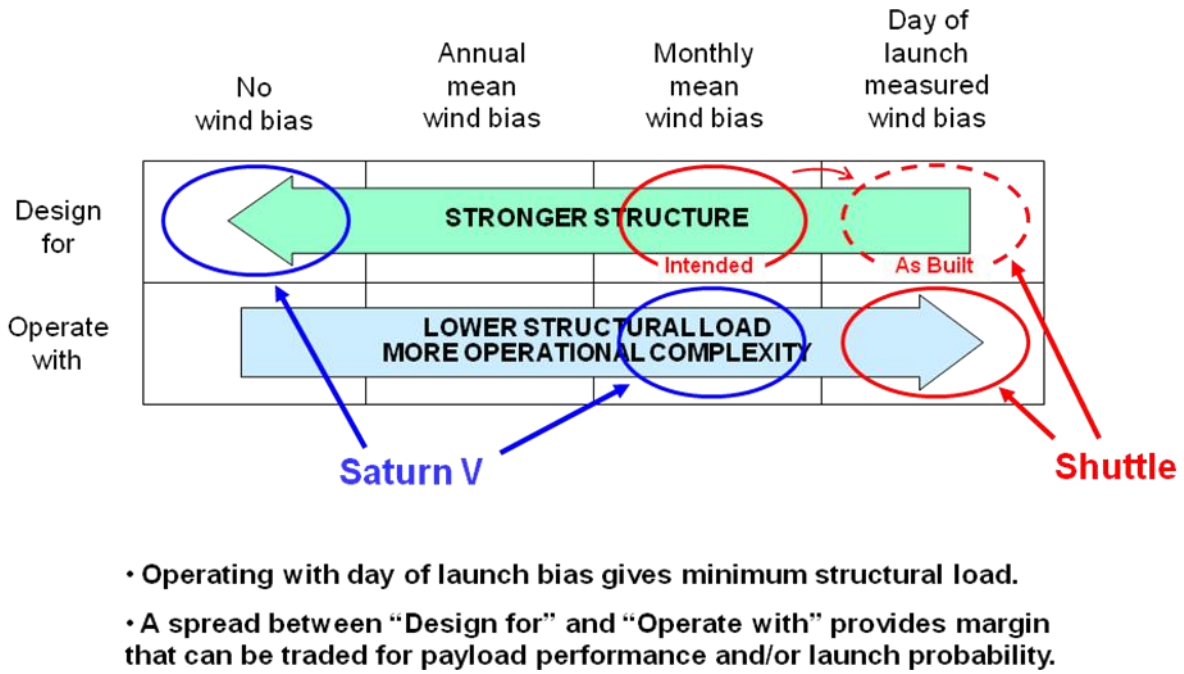


Figure 6-6. Comparison of Wind Biasing Approaches for Saturn V and Shuttle

Saturn V Load Relief Trade

On the Saturn V / Apollo vehicle, the usual trade study was done to determine potential benefits of using load relief control. Analysis that modeled the vehicle as a rigid body showed that there was sufficient reduction of basic aerodynamic loads to recommend using load relief control. However, when structural flexibility was included in the analysis, it was found that adding load relief control significantly *increased* the loads on the upper one-third of the vehicle, due to accentuated bending response to gusts. This detrimental effect on the upper third of the vehicle outweighed the beneficial effect of rigid-body load relief on the middle third of the vehicle, resulting in a decision to not use load relief on Saturn V. [Ryan, R. 1986, Geissler, E.D. 1970]. This example also illustrates the importance of employing sufficient fidelity in trade studies so as to avoid an erroneous conclusion.

Saturn used analog filtering technology in the flight control computer. Today's digital filtering technology would probably enable more effective compensating for flexibility components of the accelerometer signal, so as to take advantage of load relief control without the detrimental effects.

Operations versus Vehicle Performance

There is a tradeoff between maximum performance and maximum operational efficiency. If we design to optimize payload performance or other measures of physical performance of a vehicle, it is likely to be highly tuned and sensitive to parameter variations and perturbations. Such vehicles are not robust and require much effort and cost to operate

safely. Historically, we have designed for performance, then dealt with the risks and consequences of a performance-based design through operational procedures. This approach comes at a high cost in operations.

We should balance the vehicle performance to achieve robustness, reducing the risk and therefore the operational complexities.

Solid Rocket Booster Water Impact / Recovery

The decision to recover and reuse parts of the Shuttle Solid Rocket Boosters is an example of a different type of trade and balance activity. The overall decision involved many technical and cost factors, and eventually was based on a probabilistic prediction of the attrition rate. Ascent payload delivery capability was affected by the mass of the recovery system including parachutes. Reusing the SRB's entailed development of recovery methodology, on-board systems, recovery vessels and infrastructure, refurbishment and inspection process, etc. [Nevins, 1975]

One aspect of this development was the prediction of what damage can be expected upon water impact. There are several events related to water impact that produce major loads on the SRB, as illustrated on Figures 6-7 and 6-8: (1) the initial splashdown causes large loads on the nozzle and aft skirt, (2) the air cavity created by the splashdown collapses and the water slams the aft part of the case, (3) maximum depth penetration creates hydrostatic loads, (4) the SRB buoys up vertically, then slaps down horizontally, creating side-loads on the forward part of the case. Any of these events has the potential to damage the hardware.

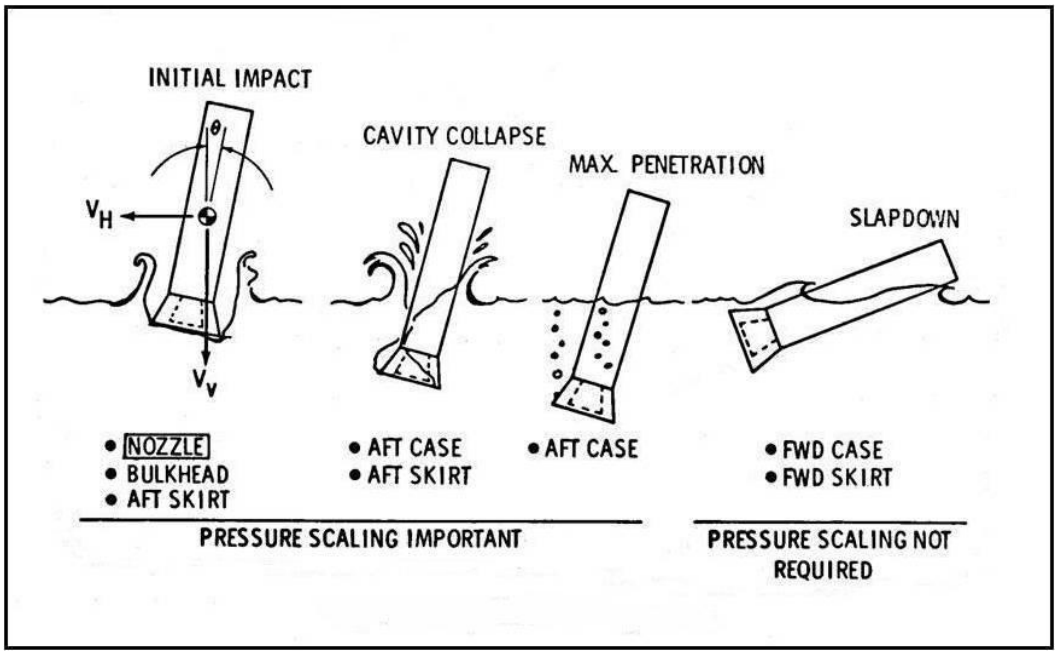


Figure 6-7. Significant Loading Events for SRB Water Impact

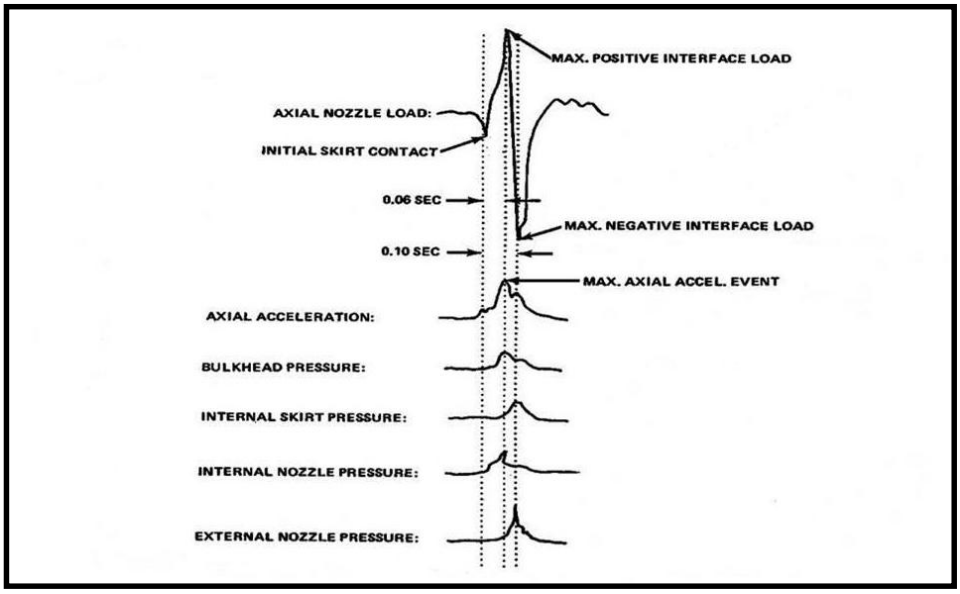


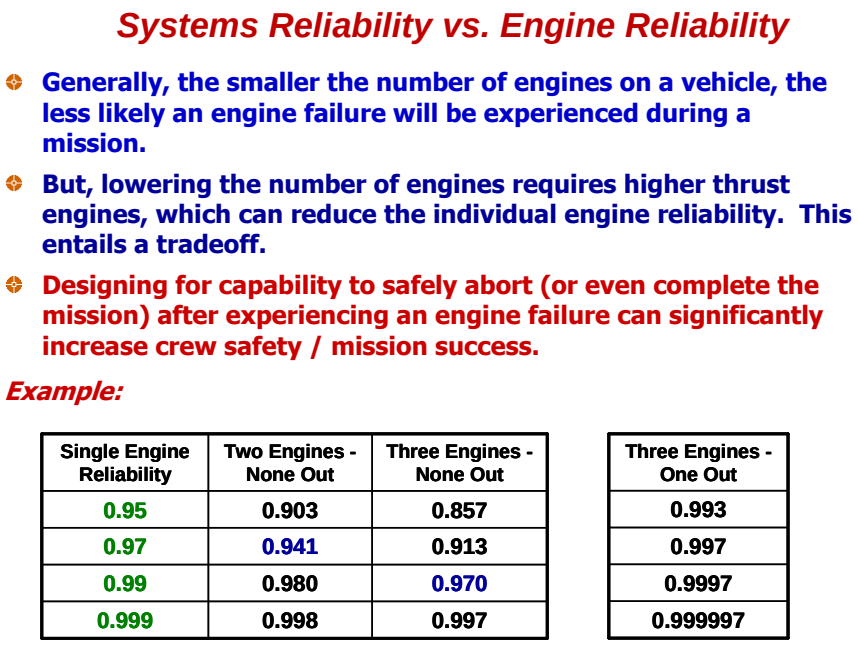
Figure 6-8. Typical Initial Water Impact Dynamic Events

There was a large amount of scale-model drop testing done during the development of the recovery system, along with some full-scale testing. There were trade-offs for parachute sizing and assessment of sea state probabilities, along with economic analyses to assess the cost benefit of recovering and reusing the hardware. The conclusion reached was that booster recovery and reuse would be cost effective if there were no more than 2% attrition of the hardware due to recovery damage. So there was a probabilistic balance-point, or target, for the recovery system design. The initial desire was to not modify the ascent SRB design for any recovery loading events, but to accept whatever attrition would occur. However, because the actual cavity-collapse loads were consistently higher than predicted, a design modification was made to strengthen the aft segment. While one pair of SRB's were lost because of a parachute triggering device malfunction, there have so far been no SRB's lost because of the probabilistically-defined variables such as sea states, parachute deployment conditions, etc. A major advantage of recovering the SRB's is the ability to inspect the recovered hardware and determine its post-use condition. This has proved important in determining actual margins (such as for thermal protection) and revealing incipient problems. [McCool, 1991]

Vehicle Reliability Versus Engine Reliability

Another act of balancing has to do with the trade of vehicle reliability versus engine reliability and the number of engines. Here we are trading engine reliability for vehicle reliability particularly in man-rated systems where we want engine out capability for abort. If each engine has the same reliability regardless of its size, the vehicle reliability is highest if the vehicle uses a single engine. But a single engine would imply high thrust, and high thrust engines tend to be more unreliable. Smaller engines have higher individual reliability, but the need for multiple small engines can reduce the overall vehicle reliability. This is illustrated by

on Figure 6-9. Reliability numbers in the figure are for illustration only and do not represent actual systems. As an additional consideration, a vehicle with multiple engines may be designed to allow engine-out capability as a safety measure for crew survivability or mission continuance. Airlines have dealt with this issue extensively and had difficulty for a number of years getting certification for twin engine versus four engine planes. They had to show a gain in engine reliability and the ability to fly on one engine to sell the approach.



Single Engine Reliability	Two Engines - None Out	Three Engines - None Out
0.95	0.903	0.857
0.97	0.941	0.913
0.99	0.980	0.970
0.999	0.998	0.997

Three Engines - One Out
0.993
0.997
0.9997
0.999997

Figure 6-9. Systems Reliability versus Number of Engines

X-33 Aerodynamics and Controllability

Balancing the X-33 single stage to orbit launch vehicle was a major challenge. X-33, being a single stage to orbit vehicle, had to balance between the ascent and reentry aerodynamic characteristics. Ascent controllability and loads had to be balanced with reentry and landing controllability. Solving this balancing act took 1,000 hours of wind tunnel tests in the MSFC tunnel. There was an approximate 9 months hit in the vehicle development schedule required to solve this design set of trades. [David, 2001]

The above examples have illustrated the multi-dimensional nature of balancing that is required for the design process. There is balancing among all aspects of the system: subsystems, design functions, disciplines, performance, the –ilities, flight phases, life-cycle costs, and more.

- **A key message from Lesson 6:**

  Balancing Required Among All Aspects of System:

  - Subsystems
  - Design Functions
  - Disciplines
  - Cost / Performance / -ilities
  - Flight Phases
  - Life-Cycle Expenditures

Principle IV: The System is Governed by the Laws of Physics

In this section we deal with the lessons associated with fundamental technical principles. In dealing with these principles, it is not implied that there are not other technical lessons; in fact most of the remaining lessons are of a technical nature. What we are doing here is dealing with four of the very high level technical lessons necessary for successful products. The four lessons for this principle are:

7. Physics of the Problems Reigns Supreme
8. Engineering is a Logical Thought Process
9. Mathematics is the Same!
10. Fundamentals of Launch Vehicle Design Deal with Balancing Efficiencies

Lesson 7. Physics of the Problems Reigns Supreme

- **The Physics (Mother Nature) of the problem reigns supreme (The God of Design). Either you bow down to Her or you will fall down.**

  "Mother Nature does not read our paper. If we don't follow her way, she lets us fall"

  - **Understanding the Physics is crucial.**
  - **Designing using unrealistic assumptions results in program failure.**
  - **Technologies must be fully verified before use. Verification as you fly increases risk and cost.**
  - **Independent analysis is a great approach to risk identification leading to subsequent mitigation.**
  - **The quality of the technical features determines project success.**

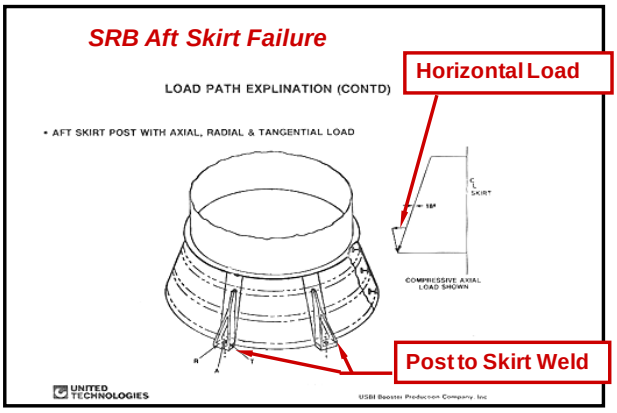
Designing a product optimistically--in other words, thinking that you can bypass “the physics of the problem”--will lead to failure. Physics will always win. As a result we must develop means of enhancing “Critical Thinking” in order to always fully understand the basic physics of the product. In addition as stated in the corollaries, we need to utilize other avenues to enhance our understanding. It is standard practice to assume unrealistic or too optimistic requirements. These must be challenged and brought into the realm of reality. The tendency is to baseline new technologies before they have are matured and verified. Technologies should be understood, matured and verified before incorporation in a product. Developing technologies in parallel with development and manufacturing is a high risk approach and is not prudent. Independent analysis and open inquiry are good techniques for assuring understanding of complex space systems. Lessons Learned should be brought to play in all phases of a products lifecycle. Finally “the quality of the technical features” determines the product success.

The following examples will be discussed to illustrate the lesson.

- SRB Aft Skirt Failure
- Skylab Loss Of Thermal Shield / Solar Array
- SSME Turbine Blade Cracking
- SSME Duct Bellows
- SRB Reentry Acoustics
- Heating Impacts

Space Shuttle Aft Skirt Failure

The Structural Test Article structural qualification of the High Performance Motor resulted in a failure of the SRB aft skirt at a safety factor of 1.28 (versus the required 1.4) in the hold-down post region. As a result the SRB Aft Skirt flew for many flights with a waiver before installation of a fix. The problem is a very complex load path situation that occurs due to the vehicle weight and SSME thrust-induced loads bending the vehicle over the outer SRB posts. The SRB skirt angle transfers these longitudinal loads into a lateral and longitudinal load situation causing the skirt skin to bend against the hold down post where it is welded to the hold-down post as shown on Figure 7-1. [Townsend, 1998]



- **The SSME thrust bends the vehicle over the 2 SRB Holddown posts, putting a compressive load into the skirt.**
- **The skirt flare angle creates a horizontal component of the thrust, pushing the post outward, putting a bending moment in the weld, which led to a test failure at a safety factor of 1.28 vs. the required 1.4**

Figure 7-1. SRB Aft Skirt Failure at the Holdown Post Weld Area

Figure 7-2 shows the magnitude and distribution of the stress introduced by the load. The figure below is a linear analysis that indicates the peaking of the stress but not its real amplitude. The actual stress of the weld was highly nonlinear and requires a nonlinear analysis and special materials characterization to understand the issue. As a result of the test failure of the SRB aft skirt, the Space Shuttle flew the skirt under waiver through flight 86. Flying with a waiver required constant monitoring of the loads on each flight, special inspections and special analysis in order to fly the system safely. This required approximately 5 equivalent full time engineers to accomplish. At that juncture in the program a fix was instituted, gaining back the margins and removing the waiver.

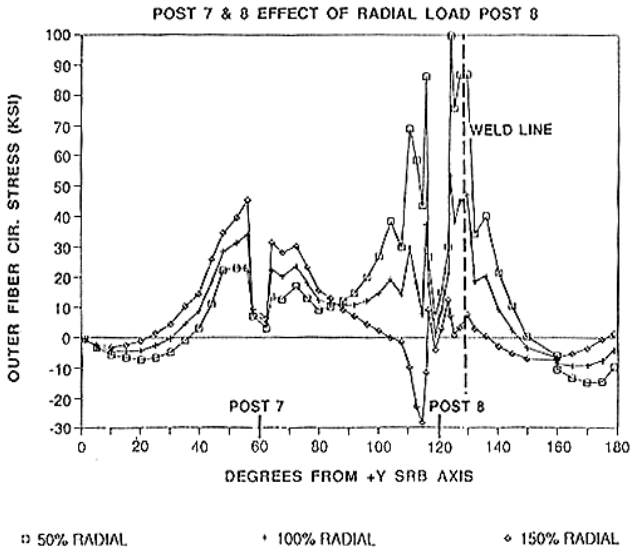


Figure 7-2. SRB Aft Skirt Stress Distribution

X-33 Shortfalls

X-33 was a scaled model technology demonstrator for a single-stage to orbit launch vehicle scaled at 40% of anticipated full size SSTO. The goal of the project was demonstration of the critical technologies -- mass fraction, metallic TPS, integral shape composite fuel tanks, aerospike main engines, coupled ascent and reentry aerodynamics and control systems, and simple low cost operations. Demonstration of TPS needed trajectories that reached a Mach number of at least 18. The mass fraction requirement needed to be demonstrated at approximately 0.9 in order to say you could extrapolate to full scale.

Major shortfalls were the following:

1. Weight growth precluded reaching orbit / Weight growth limited Mach number needed to verify TPS and didn't demonstrate acceptable mass fraction.
This shortcoming had to do with large mass growth to solve tank problems, aerodynamic problems, and was limiting the achievable Mach number to 12 or less. This was hampering the ability to verify the TPS. The same mass growth was pushing the mass fraction to around 0.85 making it nearly impossible to extrapolate the results to full scale.

2. Missed coupling of aerodynamics and control (Uncovered in wind tunnel testing).
During wind tunnel testing it was found that the ascent and reentry aerodynamic characteristics were in conflict requiring a reorientation and resizing of the canted fins. It took 1,000 hours of wind tunnel testing to reach a compromised solution that ended up with some undesirable reentry and landing response and higher loads and performance loss during ascent.

3. Composite integral fuel tank failure
The integral composite fuel tank failed during verification testing. See Lesson18 for details. This failure ended up with the cancellation of the X-33 program.

Gravity Probe A - Redshift

If a spinning object has internal energy dissipation, it will orient itself so that the spin is about the axis of *maximum* moment of inertia (e.g., a long cylindrical object will flip into a flat spin). The initial design of the GP-A spacecraft was spun about the axis of *minimum* moment of inertia, and it had internal fluid (ammonia for the thermal system) that would slosh. The problem was recognized before launch, and the internal components were repositioned to make the moment of inertia maximum about the spin axis. The mission was successful. Figure 7-3 illustrates the phenomenon where the figure on the left is spinning about its minimum axis, while the figure on the right is spinning about the maximum axis and is stable.

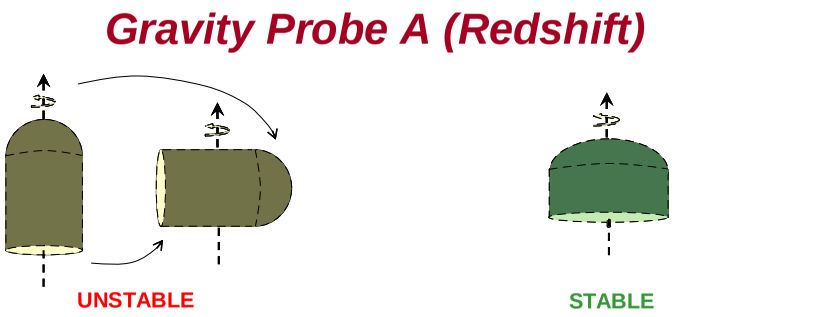


Figure 7-3. Model Illustrating Effects of Spinning About Minimum and Maximum Axes of Moment of Inertia.

Aerodynamic Venting Failures

There have been at least three similar venting incidents in the history of space flight. Two resulted in the loss of the vehicles and one crippled the payload. Those lost were the Atlas-Able-Pioneer (1959) and the Atlas-Centaur (1966). The one crippled was the Saturn Skylab (1973). The similarity in these incidents was that each had a shroud that came off during the transonic flight regime. In the first two incidences, the understanding of the flow physics was not known. Had it been known, the shrouds would have been designed so that they would have been under crush loads; however that was not the case. They were unknowingly designed so that during transonic flight the shroud load was a burst load that resulted in failure. These failures could have been prevented had the shrouds been adequately vented.

In the case of the Saturn Skylab an auxiliary tunnel was not adequately vented. The venting analysis was predicated on the assumption that the tunnel would be completely sealed at the aft end, but the aft end as manufactured was not sealed. The openings in the aft end were a result of lack of “technical integration.” The fact is this critical sealing requirement had not been communicated between aerodynamics, structural design, and manufacturing personnel, see [Lundin, 1973]. Furthermore, “system engineering” was not adequate. There was no dedicated project engineer and that resulted in lack of effective integration.

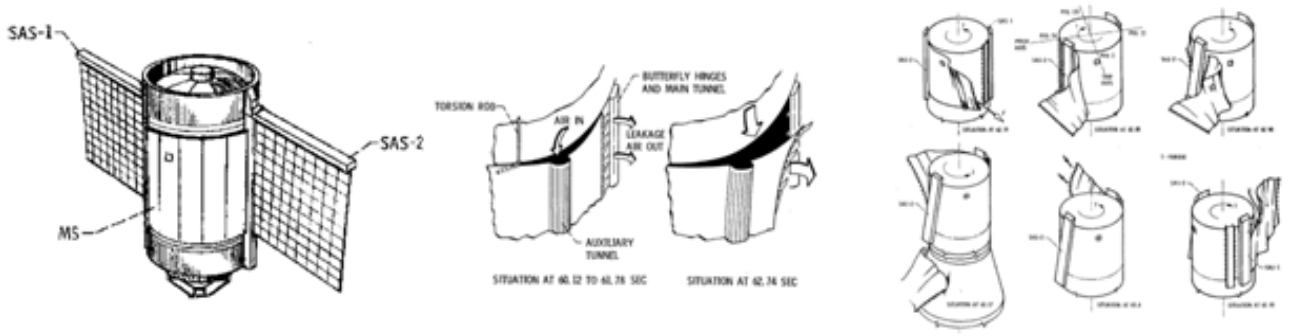
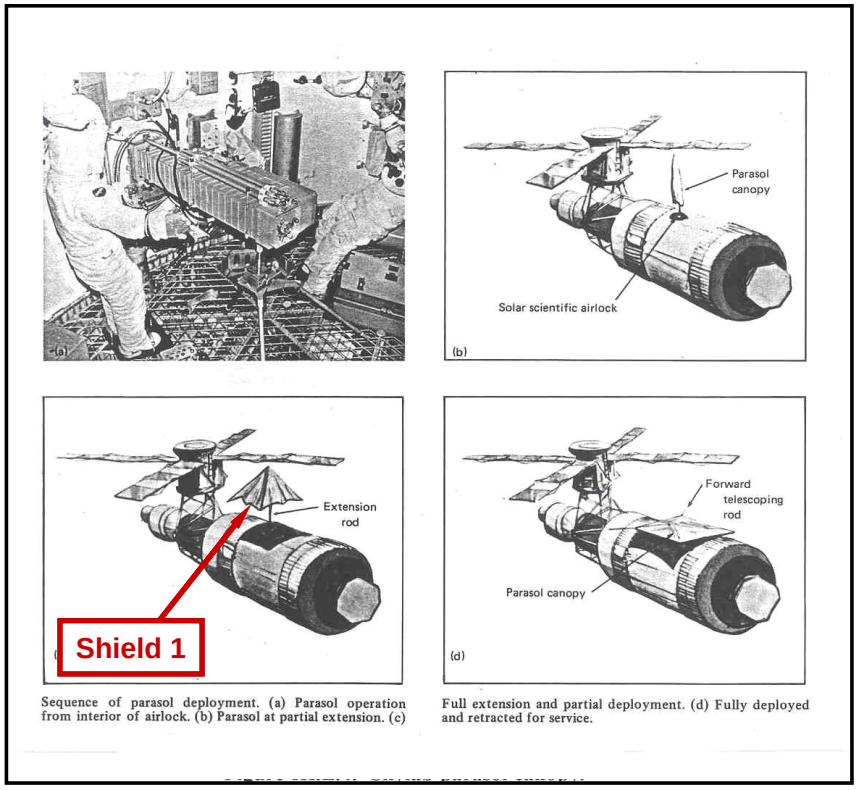


Figure 7-4. Saturn Skylab Solar Array System (SAS)

Shown in Figure 7-4 is the Skylab SAS. The first figure shows the system as it should have been deployed. In the middle figure, the destructive liftoff of the auxiliary tunnel as a result of the transonic flow induced burst load can be seen. The figure on the right shows the unwrapping of the micrometeoroid shield that was also a thermal shield. While the vehicle was not lost, the payload was crippled. However, eventually, a sun shield was added for thermal protection and the mission was saved. Saving the Skylab was a complex process that required two mission EVA activities. Ground and satellite pictures showed the damage and what had to be accomplished in order for the spacecraft to be operational. They showed that one of the solar arrays was destroyed and the other was jammed with parts from the failed structure. Also it showed that the thermal shield was destroyed resulting in high temperatures within the living quarters etc. The first crew carried cutters for unleashing the jammed solar array and a parasol that could be installed through a scientific lock. Unleashing the jammed solar array required an EVA activity for the crew that had some risks due to the dynamics of the release of the partially deployed array when the jamming strut was cut. These two activities were performed and the first crew then completed the science part of the mission after they had activated all the systems of the Skylab and the Apollo Telescope Mount. The temperature within the workshop was higher than desired by the crew so on the next flight a larger thermal shield was deployed. This required another EVA to first install the two long telescoping poles from the ATM along the workshop. Once they were installed then a new thermal shield was installed on the poles covering the shield from the previous flight and a much larger area of the workshop. This fixed the temperature problem. The only remaining issue was the limited power restoration ability of having only one solar panel instead of two. This was handled by mission event planning and then the remaining missions were very successful. See Figure 7-5 for the first fix and Figure 7-6 for a picture of the final configuration.

This in-flight anomaly was a result of failures in both technical integration and systems engineering. All the requirements were not communicated. In reference, [Augustine, 1983], there are fifty-two laws (Augustine's Laws). The forty-fifth law states, "One should expect that the expected can be prevented, but the unexpected should have been expected."



- **Inadequate venting of the Solar Array container during ascent destroyed one solar array and the Workshop insulation.**
- **On-orbit installation of thermal shields by the astronauts was required during first mission occupancy.**
- **Initially a parasol was deployed through a viewing port, with a larger shield deployed on the second mission.**

Figure 7-5. Skylab Initial Thermal Shield Deployment

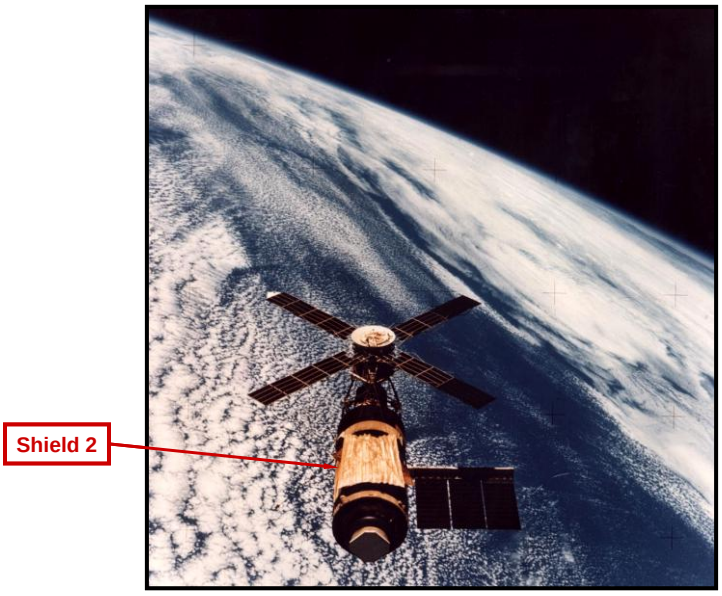


Figure 7-6. Final Skylab Configuration with Second Thermal Shield Deployed

SSME Fatigue Issues

The high performance of the SSME coupled with the high power density, discussed in the earlier section on the challenge of space travel, created many fracture and fatigue problems. [Ryan, et al, in Chaffe, 1983] The high pressure turbo pumps turbine blades is one classical example. There were two types of fatigue experienced in the SSME program: (1) Low cycle fatigue, (2) High cycle fatigue. The low cycle fatigue is introduced by the cycle between low and very high pressures and temperatures. At maximum operating conditions the temperature is 1800 R and at shutdown the pump is purged with low temperature gaseous nitrogen. The fuel pump with its preburner is about 3' long, weighs 750 pounds and rotates about 30,000RPM, generating 70,000 HP. Each turbine blade, about the size of a man's thumb, generates 550 HP. As the turbine spins, the driving gas is guided with vanes, which creates a fluctuating pressure on the each blade as it passes each vane. This introduces vibration in the blade that leads to high cycle fatigue.

The fix for the high cycle fatigue was to install a damper between the blade platform and the wheel it is mounted in. During the test where the failure occurred the gold plating used on the damper to eliminate hydrogen effects failed and the blade damper became ineffective. The fix involved disallowance of platings on the damper. No additional problems occurred with this blade during the tenure of the Rocketdyne pumps on Shuttle. Figure 7-7 shows the fuel pump blade; Figure 7-8 depicts the LOX pump blade that had a low cycle fatigue problem. The low cycle fatigue was caused by the thermal cycling the blade experienced in going from a very high operating temperature to ambient temperature during shutdown. The crack growth phenomenon was controlled though inspections, ground test hot fire history and the application of the 50% fleet leader rule. This rule says that no part can fly on a Shuttle mission that does not have twice the time on two identical parts in ground tests. This rule has been applied to all critical SSME parts and components.

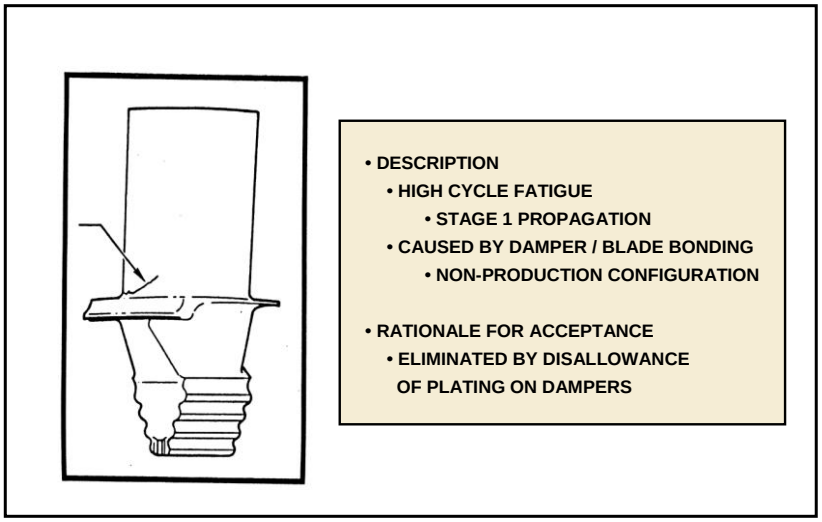


Figure 7-7. Fuel Pump Turbine Blade High Cycle Fatigue

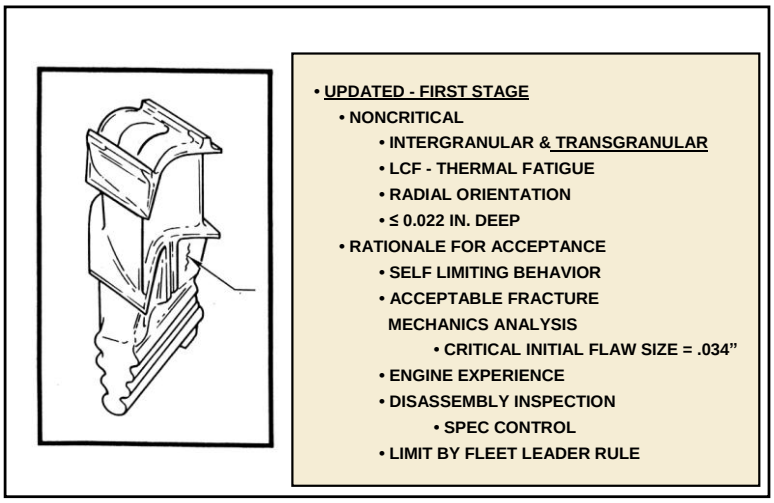


Figure 7-8. LOX Pump Turbine Blade Low Cycle Fatigue Problem

There have been many technologies tried, some with success, to solve the problem of a blade operating in such an extreme environment. Various materials, in conjunction with growing the blades as single and double crystals have been developed and used; however, operating in these extreme environments will always be a complex and daunting challenge. Sensitivities, uncertainties and risk are means whereby mitigation approaches such as the 50% fleet leader rule are developed to ensure mission success and flight safety.

Low Pressure Fuel Duct Bellows Failure

The low pressure fuel pump on the SSME is connected to the high pressure fuel pump by a duct that has three bellows, see Figure 7-9. This duct design enables the SSME to execute gimbal motion during static testing and ascent flight.

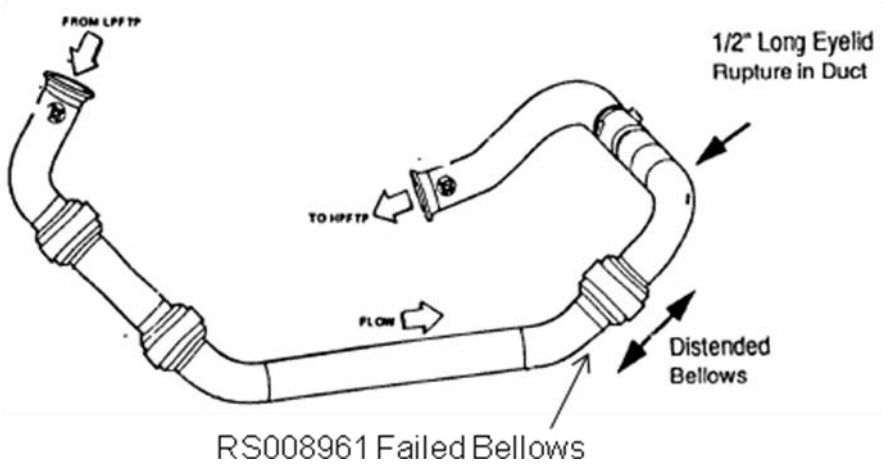


Figure 7-9. Bellows Flex Joint

The flex-joint is composed of a flexing bellows that is rigidly attached to the ducts on each side of the bellows. Internally this is accomplished using a gimbaling tripod as shown on Figure 7-10. The propellant flow across the gimbal causes it to vibrate, fatigue, and crack as indicated on the figure.

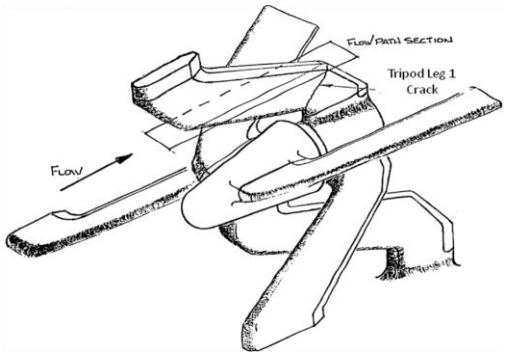


Figure 7-10. Flex Joint Internal Tripod Tie

During static testing of engine 2206, the RS008961 bellows failed due to a high cycle fatigue crack that initiated at the inner radius of tripod leg 1. When the tripod separated, it produced projectiles that traveled downstream and impacted the fuel duct wall causing a hydrogen leak, see Figure 7-11.

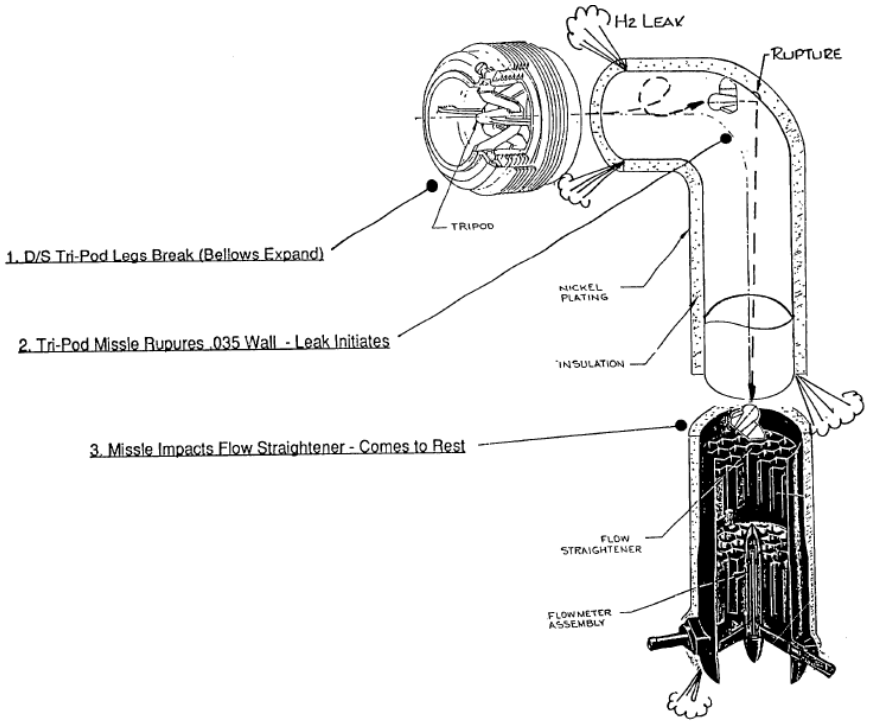


Figure 7-11. Bellows Failure and Duct Rupture

The test history associated with this duct was: 90 starts, 31,853 seconds, and 19.54 equivalent gimbal cycles. The fleet leader had 36,114 seconds of hot fire. Subsequent investigation revealed the fatigue cracking started at the inner dogleg radius as a consequence of missing a drawing requirement. This radius was found to be significantly smaller than specified by the drawings. At the failure location the cross-section was machined incorrectly to an area smaller than specified. Thus the failure was attributed to misinterpretation of drawings, inadequate manufacturing, and inspection procedures. The corrective actions included revising drawings to clarify dimensioning of the cross-sectional area and procedures were revised to inspect the tripod geometry during final assembly and subsequent welding. As a result of this and other failures of this type, the SSME and Shuttle project has adopted a 50% fleet leader rule for the engine parts as discussed previously. This approach has been very successful since there have been no SSME flight failures.

Solid Rocket Booster Reentry Acoustics

During reentry of the SRB after it boosts the Space Shuttle, its trajectory exhibits random characteristics with the angle of attack varying from 96 to 180 degrees and with the dynamic pressure varying from 360 to 1,020psf for a 95 percentile envelope at a reentry Mach number of 3.5. During the design phase, pressure fluctuations of 189dB were predicted on the nozzle extension and later verified in wind tunnel tests. It was initially thought that these high levels would have a severe effect on the SRB nozzle. To mitigate any adverse effects, the nozzle extension was severed at apogee. Shown in Figure 7-12 are wind tunnel results at a Mach number of 3.5 without the nozzle extension.

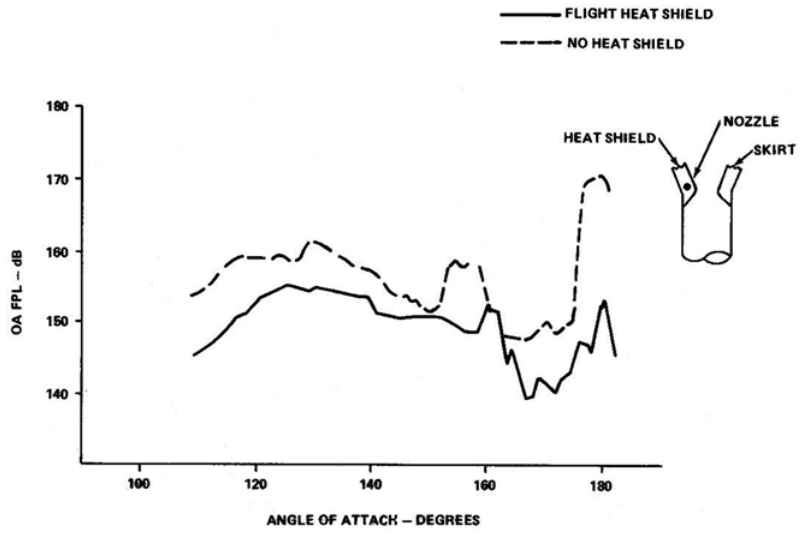


Figure 7-12. SRB Reentry Fluctuating Pressure Levels without Nozzle Extension

It can be seen that without a nozzle extension the overall fluctuating pressure levels (OAFPL) are significantly below 189dB. In addition, having a heat shield reduces the levels. A description of the reentry trajectory, wind tunnel testing, and scaling is provided in reference [Schutzenhofer et. al., 1979]

The effect of the having high OAFPL's on the system was not understood. It was decided to instrument the SRB with dynamic pressure transducers to measure the levels with the nozzle extension on. Shown on Figure 7-13 is the OAFPL on the nozzle extension through the reentry. These are root-mean-square (rms) values converted to decibels as function of time. The oscillatory variations are due to the oscillatory variations in angle of attack. It can be seen that there were high levels (>190dB) as predicted and measured in wind tunnel testing. However, there was no dynamic tuning with the structure or electrical/hydraulic components. Thus while the OAFPL's were high, their effect was benign and the project decided to sever the nozzle at different time during reentry.

In this case, the unknown aero-acoustic event was *anticipated!* The project implemented a fix to mitigate potential effects of the high fluctuating pressure levels. Even though the OAFPL's were high, the fix was eventually changed since the response of the structure and electrical/hydraulic components was benign.

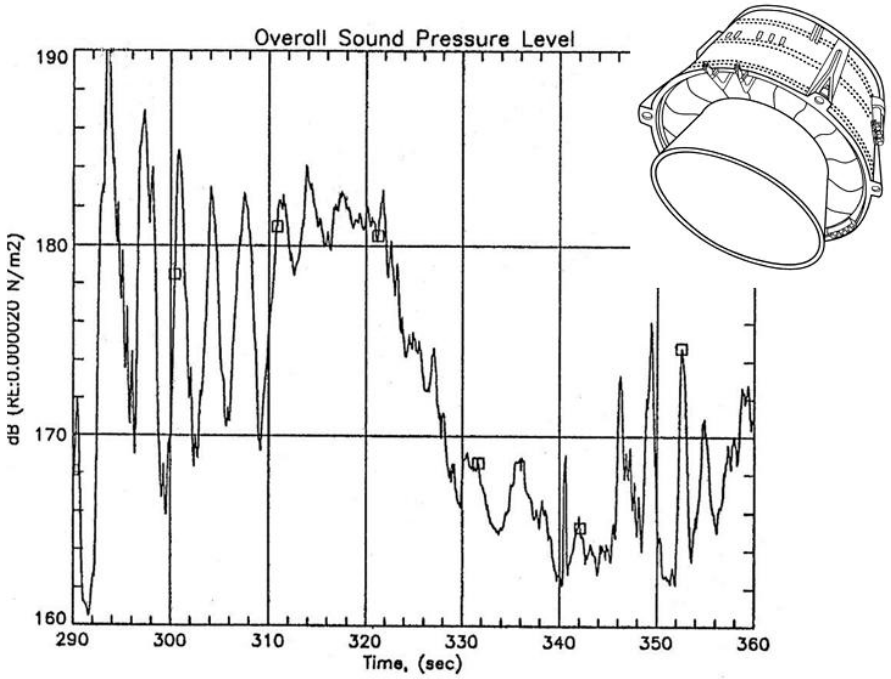


Figure 7-13. STS 6 Aft Nozzle OAFPL with Nozzle Extension

Plume / Base Flow Heating

During the first Jupiter flight there was an in-flight anomaly where burning in the base of the vehicle resulted in loss of vehicle. The root cause was entrainment and burning of gas discharged from the turbine of the Rocketdyne A-7 hydrocarbon engine.

Shown in Figure 7-14 is the Jupiter 1 in flight. The figure on the left is early in flight where the pressure in the base is lower than free stream static pressure (atmospheric pressure). The smaller stream of gas, seen in the base, is the fuel rich turbine exhaust flow.

The interaction of the base flow and the plume is benign. The figure on the right is prior to loss of vehicle at high altitude. In this situation the interaction of the plume and base flow is significant. The pressure in the base is higher than that of the free stream pressure. The turbine exhaust gas was unexpectedly entrained and recirculated in the base where the fuel rich gas ignited and burned in the base region resulting in loss of vehicle. A heat shield was added to mitigate effects of base burning.

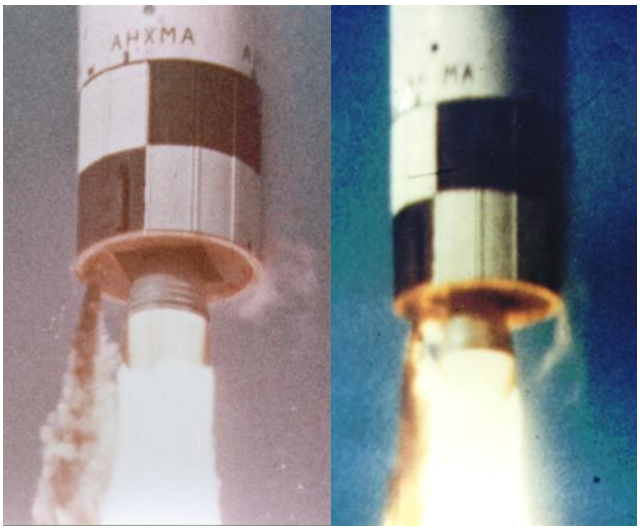


Figure 7-14. Jupiter 1 Base Flow

The illustration in Figure 7-15 shows a comparison of a flow field at low altitude to that of one at high altitude. It can be seen that at low altitude where the pressure in the base is lower than the free stream pressure, the flow is aspirated through the base area. However, at high altitude, where the free stream pressure is lower than the base pressure, the flow field in the base is reversed with hot gas from the plumes being recirculated increasing the thermal environment.



Figure 7-15. Plume Induced Base Flow Field

Other vehicles have also experienced significant plume induced separated flow. Shown on Figure 7-16 below are the plume flows for the Space Shuttle and Saturn Apollo. In the case of the Space Shuttle the plume flow was expected but the effects were under predicted. This resulted in unexpected loads that required fixes that cost 5000 pounds of payload. In the case of the Saturn, the plume size and shape were unexpected; however, there were no significant impacts to the vehicle.



Figure 7-16. Space Shuttle and Saturn Apollo Plume Flow

- **A key message from Lesson 7:**

Our Systems Are Governed by the Laws of Physics –

You Can't Wish It Away,

You Can't Analyze It Away,

You Can't Ignore It.

Lesson 8: Engineering is a Logical Thought Process

- **Engineering is a logical thought process, not a collection of computer codes. Learn to think; use the computer to enhance the thought process.**

Engineering is based on the laws and principles of physics; therefore, engineering and engineering design is a logical process that considers the various options available within the constraints of the applicable principles. The basic skill required is the ability to think in terms of the principles in a logical manner. Computers, tests, analysis are therefore tools that provide information for the human mind to accomplish the design. There are many examples in space history that can be used to illustrate the lesson. The SRB aft skirt problem was discussed previously; two will be discussed here.

The following examples will be discussed to illustrate the lesson:

- Saturn V Sloshing Computer Program.
- Space Station Node Gusset

Saturn V Sloshing Computer Program

During Saturn V development, propellant sloshing was a major concern. Tools for analyzing the interaction of the vehicle, the vehicle control system and propellant sloshing were in a state of development. While laboriously checking out the program to compute sloshing dynamics using computer priority, we kept making program changes due to errors found, which required new punched cards and card assembly. The computer operator finally asked Robert Ryan, “If you know the answer why are we running the program?” He replied, “If we didn’t know the answer we should not be running the program.” In other words we need to know the physics of the problem so that we can continuously check the computer program. Computer programs only give you what you ask them to. This check is made using simplified equations and back of the envelope calculations in terms of the basic physics of the problem. Helmut Horn, our early German supervisor, would make you go to the blackboard and show a simple model of the more complex model being discussed. He said that if you couldn’t explain it in simple terms you did not understand it. He wanted you to use that same model to check out the computer results or even someone else’s work or presentation.

ISS Node Load Paths and Common Berthing Mechanism Fretting

The ISS Node (Figure 8-1) had two major problems during development. The first had to do with the berthing ports gusset yielding during proof testing. The second was the galling of the common berthing mechanism during berthing simulations.

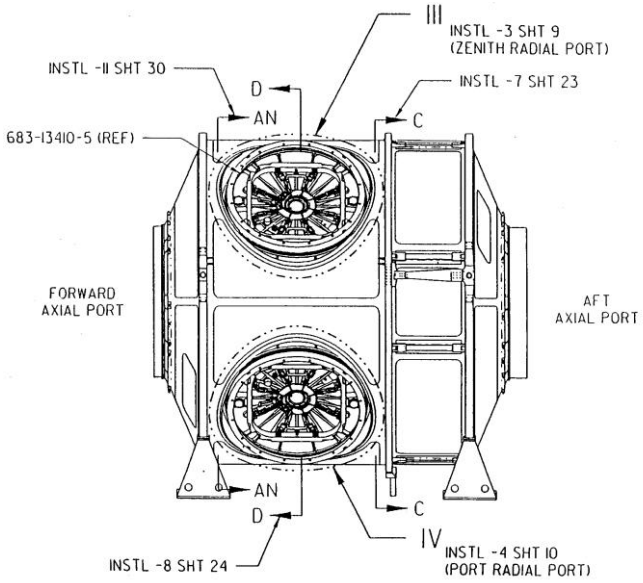


Figure 8-1. ISS Node Showing Berthing Ports and Gussets

The gusset yielding was found in the proof pressure testing and was a classic load paths problem created by trying to save weight and not understanding the primary load paths. The hoop stress was all dumped into the two gussets installed on the radial sides of the berthing port. Understanding load paths is critical to the design of structures. Pugh has written articles and has sections in his books on designing for load paths. [Pugh, 1991] Load paths are one of the basic physics of the design that must be adequately understood and designed for.

The berthing mechanism was tested extensively on the 5 degree of freedom motion simulator at MSFC's computational laboratory. During test the mechanism would gall due to the unpredictability of the contact angle. This was a result of the fact that the berthing was accomplished using the remote manipulator system (RMS) which had no unique position to bring in the second body because of the multiple joint angle possibilities. This contact angle depended on how the RMS captured the second body and its position relative to the station. The problem was solved once the total motion possibilities were clearly understood (initial conditions) and it has performed flawlessly during ISS missions. [Ryan's working papers]

- **A key message from Lesson 8:**

  Engineering is a Logical Thought Process
  Instead of Blindly Applying Processes and Codes
  - ***Think Critically***
  - ***Understand***
  - ***Explain***

Lesson 9: Mathematics is the Same!

- ***The mathematical expressions (describing equations) for our systems' physical processes are the same. The difference is in the dimensions (units) and boundary conditions.***

The following mathematical categories illustrate the lesson:

- Algebra and Geometry
- Ordinary Differential Equations
- Partial Differential Equations

The fact that mathematics can describe the physical phenomena of nature is astounding. In addition the fact that mathematics, using the same forms, can describe all of the various areas of physics is even more astounding. Of course algebra and geometry is basic to all; however, the use of ordinary and partial differential equations is also foundational. Since the same form of the differential equations describe all the various disciplines then we can make analogies between the various disciplines, by just changing coefficients and units. This was the basis for the analog computer that many of us grew up

using to solve our equations. This also means that we can think in disciplines other than our specialties using this transformation. The basic message then is that we must be proficient in the use of mathematics while at the same time understanding the difference in the phenomenon that is being observed. We can use the similarities to a great advantage but in the end "the physics of the problem rules".

- **A key message from Lesson 9:**

Learn the mathematics. It is the foundation of all analysis and modeling.

Lesson 10: Fundamentals of Launch Vehicle Design

- **Challenges of launch vehicle performance**
- **The fundamentals of launch vehicle design are:**
  - **Propulsion system efficiency**
  - **Structural (non-propellant mass) efficiency**
  - **Managing the losses**

The design of a launch vehicle is concerned with getting a payload to orbit in an effective and efficient manner. To design and operate a space launch vehicle one needs to understand the physical basics of the system. The essence of this lesson is the elements of that fundamental understanding: propulsion system efficiency, structural efficiency and managing the system losses. Overcoming gravity makes this a very challenging job as discussed in Lesson 3. To accomplish this task we must have highly efficient structures and propulsion systems and manage the losses in order to have a balanced system. The next section will discuss these fundamentals.

Figure 10-1 goes into more detail of the elements of the fundamentals of launch vehicle design. The discussion in Lesson 3 illustrated the complexity and challenge of space flight. Figure 10-1 summarizes the basic characteristics of the challenge. Emphasized is the fact that the technical, propulsion and structural efficiencies and managing the losses must be balanced and traded with the programmatics of cost, schedule and the -ilities. This balancing between the programmatics and the technical is a major challenge in that what we do to reduce cost and schedule greatly affects the technical. The process is further complicated by the fact that the technical requires that the design get all the performance possible in order to overcome gravity etc. Figure 10-1 depicts representative but not complete lists of the characteristics of the three fundamentals of launch vehicle design. Notice that for mass efficiency the three elements of mass fraction, packaging, thermal protection system are some of the things you can manage to get mass efficiency. Each though has many subsets; for example, mass fraction contains structural configuration, materials, loads etc. Propulsion systems deal with at least the engine cycle, Isp and engine thrust to weight ratio. Again each of these would have many sub parts. Managing the losses includes the generally known parts such as gravity losses and expands into environments, etc. A big effort is

dealing with uncertainties and interactions. Uncertainties must be clearly defined starting with an initial set. These uncertainties are then burned down as the lifecycle is moved towards operations. Interactions are very complicated and must be analyzed and controlled or the losses get very high. Interactions not understood are one of the major causes of problems in any launch vehicle system. The classic ones such as flutter, whirl, pogo etc. must be designed out of the system.

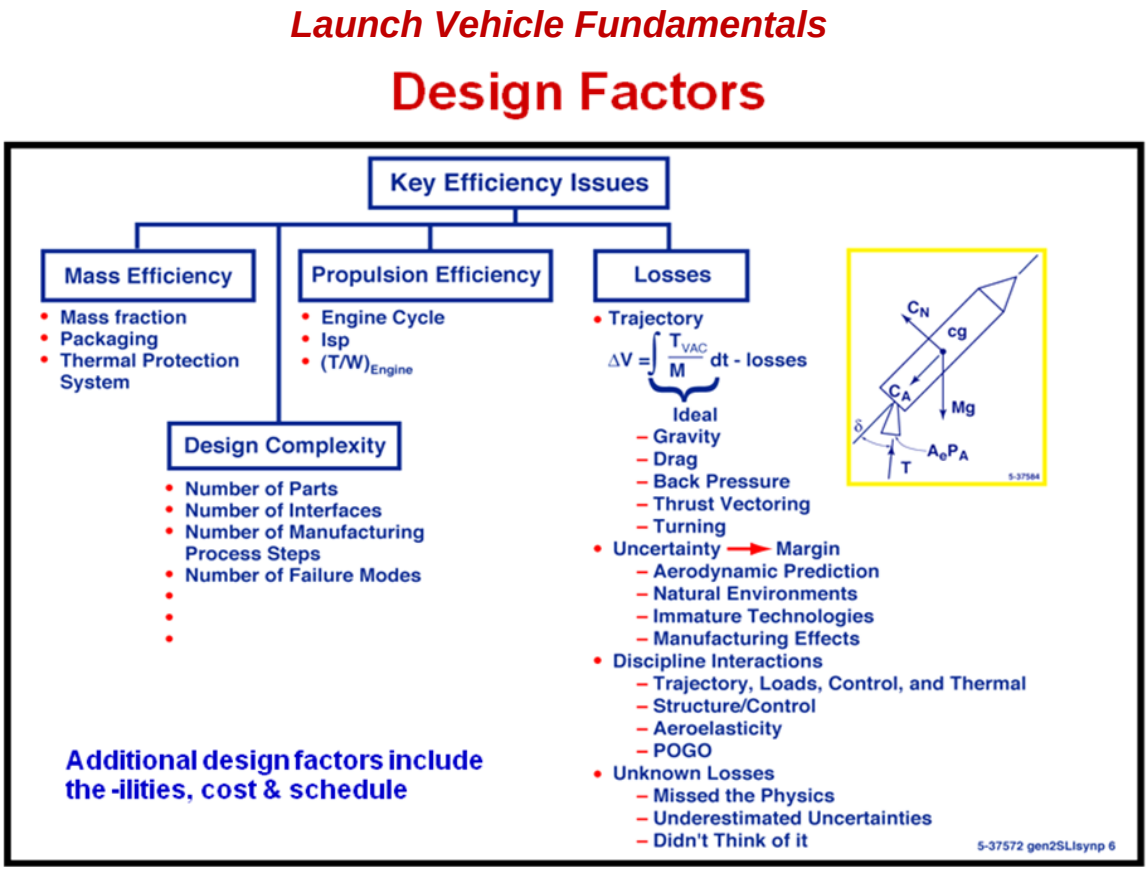


Figure 10-1. Balancing the Key Elements of Launch Vehicle Design

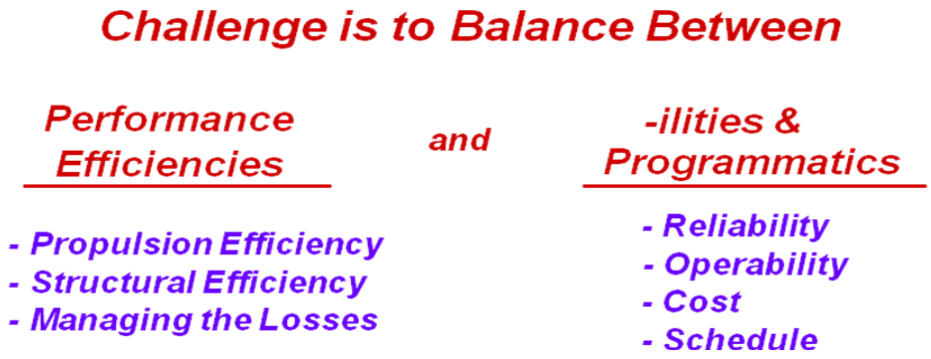
The following examples are used to illustrate the fundamentals of a launch vehicle design:

- Launch Vehicle Efficiencies
- Sensitivity Versus Performance
- Historical Mass Growth
- Typical Issues of Launch Vehicle Configurations

Launch Vehicle Efficiencies

The first example deals with the concept of balancing the efficiencies with the programmatics as shown on the list below. Early space system design was driven by performance and then assessed for the Illites/programmatic. When the illities/programatics is

placed on the design table with the first three principles, the balancing act of the design get very complicated. What is required is to develop functional relationships between the illities/programatics parameters and the design parameters of structures, propulsion etc. so that the design is a total system design. [Ryan, et al, 1977] For example if the system is not designed for cost in conjunction with the physical design one will never get minimum cost design. Accomplishing a total system design is one of the major challenges space systems design faces today. This will be further discussed in Lesson 17.



Sensitivity Versus Performance

One of the techniques we use to accomplish design is developing and quantifying the sensitivities of the system to the design parameter variations. Figure 10-2 shows the sensitivity of a single stage to orbit launch vehicle gross liftoff weight to the structural mass fraction and the propulsion system Isp. Notice that we have put two lines on the graph to bound the problem. The first is a limit on gross liftoff weight that was estimated based on efficient size for operations. The second is the practical limit on Isp. This limit is 453 out of a possible 460 seconds for a typical LOX hydrogen engine operating at a 6.0 mixture ratio.

As you can see there is only one design curve that lies well within the boundaries—that is for a mass fraction of .95, a value that is still unattainable. A 0.9 mass fraction has way too much sensitivity to Isp and is not practical as is 0.89. The message of this chart is that because of the sensitivities, a single stage launch vehicle is not practical using today's technologies. [Ryan's working papers]

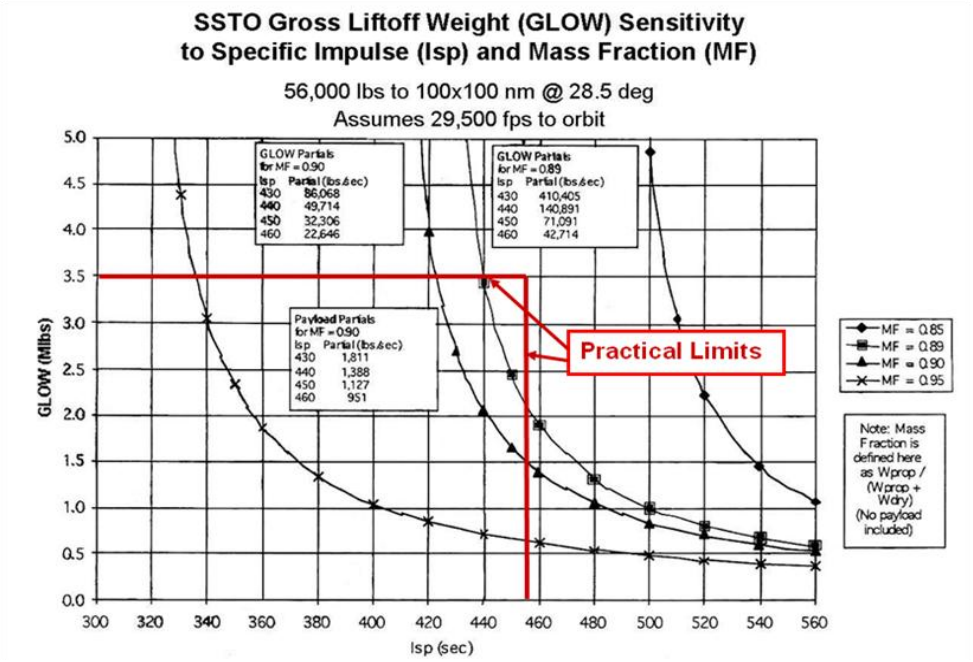


Figure 10-2. Effect of Isp and Mass Fraction Uncertainty Sensitivities on Vehicle Gross Liftoff Weight

Figure 10-3 shows the sensitivity of launch weight to launch weight margin assumed in initial design. Depicted using three different curves is the burn down of margin versus lifecycle. This plot is generic in nature and does not contain absolute values.

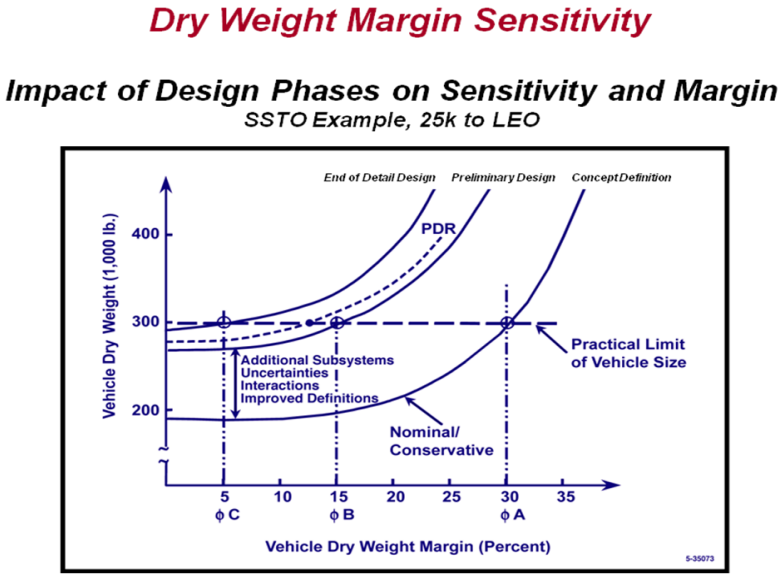


Figure 10-3. Launch Vehicle Dry weight Sensitivity to Dry Weight Margin

Historical Mass Growth

The reason we use dry mass margin initially is that history has shown that all space systems grow in mass as the lifecycle matures. The following list indicates factors in mass growth.

- Experience shows that space vehicles have mass growth
- Margins must be taken into account early in design process
- Technology exists to improve mass estimates
  - e.g. Vehicle Integrated Performance Analysis (VIPA)
- Categories where mass growth has to be taken into account
  - Vehicle dry mass (vehicle stages and payload)
  - Propellant reserve
- Primary causes for mass growth are
  - Improper definition of environments
  - Inadequate definition of subsystems
  - TRL not maturing as expected
  - Uncertainties not taken into account or controlled
  - Unknown unknowns

Figure 10-4 shows a data base of historical mass growth in various programs. [Alexander, et al, 2002] It is clear that initial design must account for this growth. The question then arises as to what is an acceptable mass growth margin and are there additional margins that should be used? A current practice for launch vehicles uses 15% on all new structure and 5% on all heritage hardware being used. In addition 15% performance margin is allocated to cover the losses discussed earlier and for program manger reserves for later unpredicted problems.

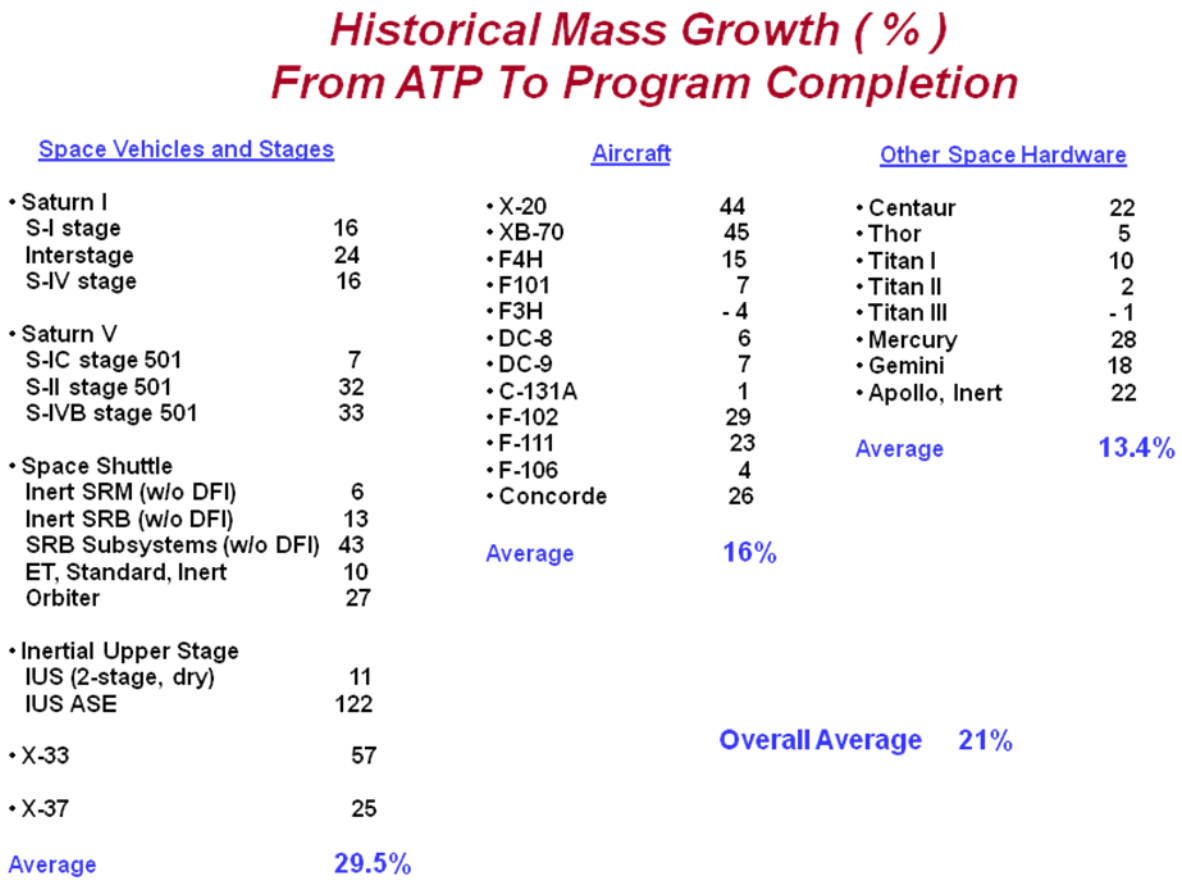


Figure 10-4. Historical Mass Growth of Space Systems

Typical Issues of Launch Vehicle Configurations

Depicted on Figure 10-5 is a list of other design complexities that can lead to weight increases and system complexities that must be understood and considered in design. Dynamic tuning of any multi-body configuration usually has large sensitivities of the dynamic response to events such as liftoff and gust response thus must be clearly understood and characterized. The same is true for all load paths and unsymmetrical geometries. Major interactions between subsystems, disciplines etc. are key drivers that are the source of many problems and therefore must also be characterized and designed out where possible. One principle is stated as: “The simpler the loads paths, in general, the more reliable the system.” TRL levels of each element should be verified before incorporation into a design. Designing for robustness is nearly always a plus. Depth of analysis is determined by the system complexity and sensitivities.

Typical Issues of Launch Vehicle Configurations

1. Static unsymmetrical coupling
2. Dynamic coupling (symmetrical and unsymmetrical)
3. Load paths
4. Subsystem and discipline interactions
5. Subsystem optimization / TRL
6. Analysis depth / iterations / verification
7. Operability
8. Flexibility / Robustness



Figure 10-5. Additional System Considerations for Launch Vehicle Design

- **A key message from Lesson 10:**

  Challenge is to balance between performance efficiencies and -ilities and programmatics

Principle V: Robust Design is Based on Our Understanding of Sensitivities, Uncertainties, and Margins

In the design of complex systems with high power densities there are always top level requirements, constraints, ground rules, and assumptions that set the stage for accomplishing the design. It is the designer's challenge to figure out how to strike balance among them. Included in the art of design is knowing how to apply sensitivities, uncertainties, and margins to achieve the best balanced design with confidence. Sensitivity analysis is a key tool to achieve the best balance among the design's attributes by assessing the changes in the attributes in term of changes in the design variables. This is accomplished by understanding the sensitivity factors (partial derivatives). It enables the designer to iteratively converge the design and involves the application of analysis, test, and simulations. Uncertainty pertains to random variations in design input variables at all levels and the

corresponding random variations in the design attribute (outputs). These variations are about mean values and are determined via historical data bases, tests, and expert opinions. Margin pertains to the difference between some measure of capability and some measure of demand. Understanding uncertainties and application of adequate margins throughout the various stages of the project provide the necessary confidence in the design of systems with high power densities.

The following are lessons related to this principle:

11. Robustness
12. Understanding Sensitivities and Uncertainties is Mandatory
13. Program Margins Must Be Adequate

Lesson 11: Robustness

- ***Strategies that enable robustness***
  - **Design for simplicity, number of parts, joints, interfaces etc.**
  - **Design structures for simplicity of load paths**
  - **Get the joints right**
  - **Don't overlay complexity with complexity in solving problems or issues. Overlay complexity with simplicity.**

The goal of design is to achieve the best balanced design in consideration of all requirements, constraints, etc. At the same time, the design needs to be robust. Robustness can be defined as follows:

1. A robust design is one where the response of the system is inherently insensitive to perturbations.
2. A robust design is one where the response of the system can be sensitive to perturbations, but can be adequately managed.

Robustness can be achieved by applying simple strategies; the following are some examples of those strategies. For instance, design for simplicity, minimum number of parts, simple joints and interfaces, etc. The original fuel turbopump housing on the Space Shuttle Main Engine (SSME) had about 469 welds and 315 were uninspectable and sections of the housing were sheet metal. The bearing material was 440C steel. When the alternate turbopump was designed the housing consisted of investment castings that eliminated welds and sheet metal. The bearing material is silicon nitride and the rotating assembly has about half the number of parts as the original design. Another design goal would be to simplify load paths. This would reduce stress concentrations and reinforcing substructures; thus, less weight. In addition, design joints so that the loads are spread out instead of focused to a point that has to be reinforced. Finally, don't overlay complexity with complexity in solving problems; overlay complexity with simplicity. To resolve rotordynamic instabilities in the SSME turbomachinery complicated design fixes were considered to stiffen the rotating assembly. However, a damping seal was implemented to stabilize the system. Application of the damping seal was simple in comparison to other approaches considered.

Examples:

- Six Elements of Robustness
- Saturn V Five Engines on the 1st and 2nd stages
- Saturn V Structural Capability
- Inertial Upper Stage (IUS) Robustness

Six Elements of Robustness

1. Margins/Tolerant Design

Sometimes the general notion associated with robustness is “add more margin.” If that can be done without compromising the design in terms of safety, performance, cost, and schedule, then it’s appropriate. However, in some situations adding more margin will not be appropriate and other means will be necessary to achieve balanced design goals.

2. Redundancy

Redundancy can be illustrated in terms of the number of strings of avionics added to the system. For instance, assuming no common-cause failures, if one string has a reliability of .9, two strings will be .99, and three strings will be .999. If one string has a reliability of .99, two strings will be .9999, and three strings will be .999999. Thus, this simple example shows what is involved in achieving various levels of system reliability with redundancy.

3. Simplicity

Simplicity is one of the most important aspects of a wisely designed system. For instance, it is simple to design, analyze, test, and operate. Achieving balance through sensitivity analysis can be simple as well as assessing uncertainty and eventually determining risk.

4. Desensitization to Parameter Uncertainties

Uncertainties usually pertain to random variations in a quantity about a mean value. The attributes (outputs) of the design are affected by design variables (inputs) and other parameters. Since there can be random variations in the inputs and parameters; there can be random variations in the output variables. For small variations, the output variations are about equal to the sum of sensitivity factors multiplied by random variations of the inputs (could also include parameters with random variation). This is the basis for the root-sum-square (RSS) methodology. Since there is a product relationship (sensitivity times random variation), by reducing the sensitivity factor the variation in the output can be reduced. This is an approach toward determining, controlling, and managing variations in the design attributes (output).

5. Control of Parameter Variations

In some instances control of parameter variations is difficult. For instance, a way of dealing with random variations in the atmospheric winds has been to measure day of launch winds and fly the vehicle for suitable conditions. In structural design, controlling tolerances is an approach that enables the structural designer to control stress and deflection. In avionics, the variation in electrical components can be controlled by hand picking parts that fall within specified tolerance limits. In all these examples, it can be seen that controlling parameter variations can have a significant impact on cost.

6. Operational Procedures

One of the goals of design is to minimize maintenance and operational procedures. In a generic sense, it would desirable to reduce the number of purges, electrical checkouts, change out of components and parts, number of fluids (Initially, Shuttle had eleven major fluids), etc. In the early days of Space Shuttle flights, the turbomachinery was removed after every flight to replace turbine blades and bearings at the cost of three million dollars per pump. The life time of the present high pressure fuel turbopump is 3354 seconds; this includes one acceptance test and five flights. At the present time there will be no rebuild of turbopumps since there are enough flight assets to fly out the remainder of the manifest.

The above six elements and others are important factors that lead to robust balanced designs with minimal risk. They increase reliability and safety and reduce cost; they should be practiced through all stages of the design process and in operations. [Ryan, R., AIAA Paper 93-0974, 1993]

Saturn V Five Engines on the 1st and 2nd Stages

In the original conceptual design of Saturn/Apollo, there were four F-1 engines on the S-IC stage and four J-2 engines on the S-II stage. There were concerns regarding the weight estimates of the Saturn/Apollo system. A decision was made to add another F-1 engine to the S-IC stage to provide margin. Then a radiation shield was inadvertently omitted in the design of the spacecraft and had to be added. To account for the added shield, the S-II stage diameter was increased and a fifth J-2 engine was added. The addition of the fifth F-1 and J-2 engines provided margin that allowed for unexpected weight growth and future missions of the Lunar Rover and Skylab.

The loss of the fifth engine on the S-II stage during the Apollo 13 flight did not impact the mission. The other four engines burned longer to achieve the correct insertion velocity.

Adding these engines is an example of prudent design practice where margin enabled the moon landing, saved Apollo 13, and enabled Lunar Rover and Skylab.

Saturn V Structural Capability

The Saturn V composite design line loads are shown in Figure 11-1. The vertical axis is vehicle station in inches and the horizontal axis is the total structural load. It can be seen that the lower portion was designed by ground winds. (The term “designed by” means that the specified environment causes the maximum load event.) The interstages and upper part of the vehicle were designed by maximum product of dynamic pressure and angle of attack ($q\alpha$) and rest of the vehicle was designed by 1st stage cutoff. In addition, the safety factor is shown.

The design strategy used to develop these loads includes rigid and elastic body effects. This strategy was developed in the early design stages and resulted in a loads combination equation (LCE). This was an attempt to determine loads that would be equal to or less than the .99865 probability level. The Saturn V rigid-body loads strategy included: 1. 95% scalar wind speed (worst month), 2. RSS'd 99% wind gust and shear, 3. three-σ variations on all response parameters, and 4. no wind biasing. The elastic body effects included three-σ bending dynamics – turbulence. Additional margin was achieved during operations by flying with monthly mean biasing.

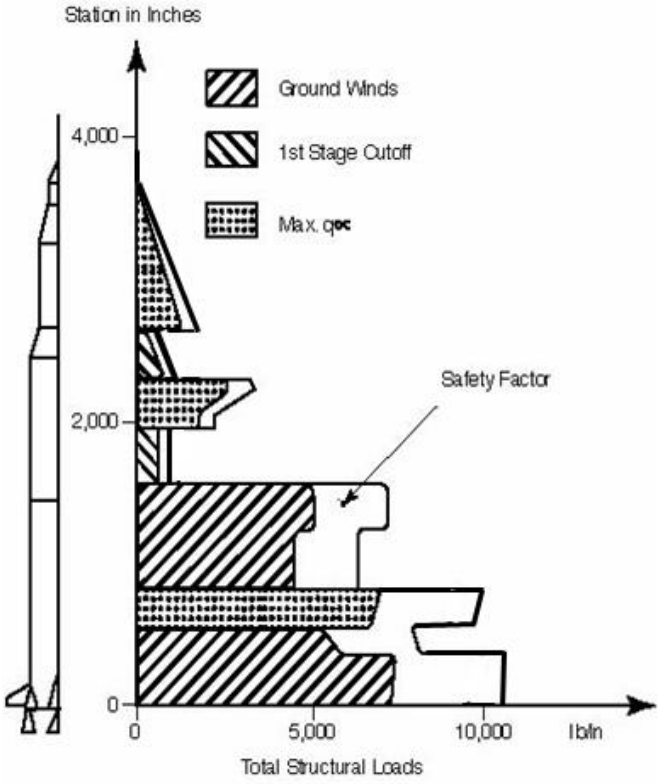


Figure 11-1. Saturn-V Composite Design Line Load

Strategies as shown above provided margin without compromising payload capability. In fact, it enabled the Saturn to be used for the Lunar Rover and Skylab.

Inertial Upper Stage (IUS) Robustness

The IUS is a highly redundant stage that can be commanded from the ground. It inserts payloads (~5000 lbs) into higher orbits (geo-sync) than primary boosters such as Shuttle or Titans. It operated from 1982 until 2004 that included 24 missions; 15 NASA and 9 DOD. In addition, it was functionally redundant. Shown on figure 11-2 is a description along with some of its characteristics, see reference [Dunn, 1984].

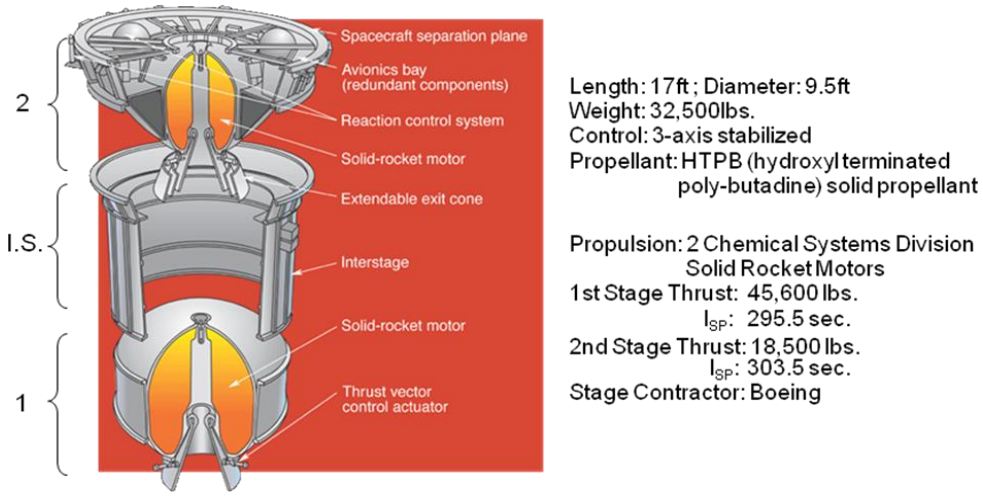


Figure 11–2. Inertial Upper Stage and Characteristics

The first stage boosts the second stage and payload into geo-transfer orbit and the second stage provides the energy to put the payload into a circularized geo-sync orbit.

There were three incidents out of twenty four missions. Because of its ability to be commanded from the ground and being functionally redundant only one mission was lost. The three missions where there were incidents were: IUS-2, IUS-1, and IUS-21. Our experience was with IUS-1 and IUS-21, and only those will be discussed.

IUS-1 was flown on Space Shuttle STS-6 in 1983 and the payload was the Tracking and Data Relay Satellite (TDRS-1). During the IUS-1 second stage flight, a critical seal in the nozzle failed. The nozzle canted and locked up in the canted position and the control system lost its ability to position the nozzle and control the system. The IUS/TDRS tumbled for about half of the circularization burn and ended in a 13,579 by 21,980 statue mile orbit. While tumbling the IUS and TDRS were separated by ground command. Over a two month period the TDRS was boosted to the desired 22,300 mile orbit; it required thirty nine maneuvers and consumed 64% of the hydrazine fuel.

Shown on Figure 11-3 is a cross section of the second stage nozzle. Hot gas leaked through the Grafoil seal. The titanium housing of the Techroll seal got hot and the seal's casing lost its material properties and burst under pressure. The seal collapsed and the nozzle shifted down and canted. To fix this condition for succeeding flights, the tack bonding of the Grafoil seal was eliminated. In addition, the seal's density was increased along with removing the chamfer from its surfaces. [Chase, et. al., 1984]

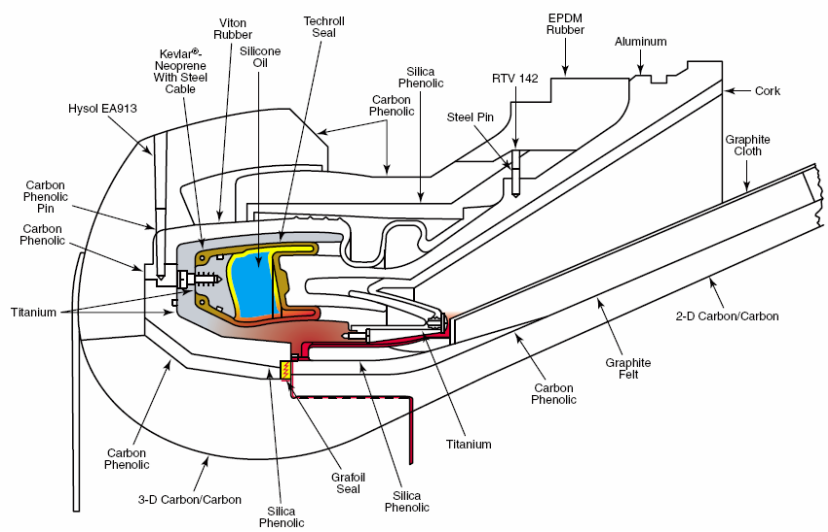


Figure 11-3. Cross Section of IUS Second Stage Nozzle

The next example pertains to IUS-21. It was flown on Titan IVB-27 in 1999 and the payload was Defense Support Program -19 (DPS-19). About six and a half hours after liftoff and when IUS was in the trans-geo flight the IUS initiated separation of the stages. The two stages did not fully separate and when the second stage fired the system tumbled into an unusable highly inclined elliptical Earth orbit. [Brinkley, et. al., 2008]

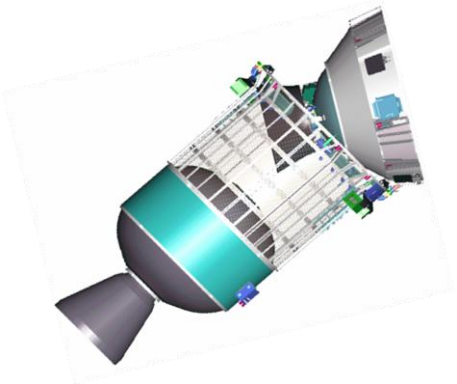


Figure 11-4. Sketch of IUS First and Second Stage

Shown in Figure 11-4 is a sketch of the two stages in the unseparated state before the second stage was fired. The failure was a result of an electrical connector plug/jack and harness not disconnecting, preventing the two stages from separating.

Investigation revealed that technicians wrapped thermal insulating tape too close to the connector preventing stage separation; see the left figure in Figure 11-5. Technicians applied the thermal wrap according to the 1978 detailed operations procedures (DOP). The

DOP omitted unique requirements relating to the separation function, instead stated the tape should be applied within 0.5 inches of the mounting bracket flange.



Figure 11-5. Electrical Harness as Built and Corrected

There was a change in the DOP that stated: apply the thermal wrap no closer than 0.5 inches and no further than 1.0 inches from the mounting bracket flange, see the right figure in Figure 11-5.

- **A key message from Lesson 11:**

  Design for Robustness
  - ***Make system insensitive to perturbations and/or make the response manageable***
  - ***Stress simplicity in the design***

Lesson 12: Understanding Sensitivities and Uncertainties Is Mandatory

- **Determining system sensitivities leads to successful products.**
  - **Provides insights into design choices to achieve balance; (enables decision making)**
- **High performance systems have high sensitivities and uncertainties; this complicates the design process (no small changes)**
- **Incorporate appropriate philosophy and procedures for handling sensitivities and uncertainties throughout the process.**
  - **System sensitivities should be determined in conceptual design and evaluated throughout the design cycle**
  - **High sensitivities require more attention to design details; managing them leads to best design choices and reducing them reduces effects of uncertainties**

- **Uncertainties need to be determined for all inputs/outputs associated with system design**
- **Design must reduce uncertainties and provide appropriate margins**
- **In early phases of design, ensure that adequate margins are provided to cover the sensitivities and uncertainties of a specific vehicle, considering the immaturity of system definition**

Throughout the design of complex systems with high power densities numerous decisions are required to achieve the best balanced design. Sensitivity factor analyses provide insights in providing the best choices; thus enabling the best designs. For example, in the design of a liquid rocket vehicle system, the payload can be increased by increasing the engine specific impulse. Suppose a payload gain of 400 pounds could be achieved for a one second increase in engine specific impulse. Then for a 20 second increase in specific impulse, the payload would increase 8000 pounds. Thus the designer can decide how much to increase the specific impulse to achieve the payload requirement. In that decision process, the impact on engine design would have to be assessed along with other consequential interactive effects. In this example, the sensitivity factor would have been obtained through system performance analysis. In other situations, sensitivity factors can be also obtained through test or simulation

High performance systems have high sensitivities and uncertainties which complicates the design. If a comparison is made between the design efficiency (power/pound) of a rocket stage and an airplane, the rocket stage is about two orders of magnitude higher in design efficiency. If compared to an automobile, the rocket stage is about three orders of magnitude higher. In consideration of uncertainty, one of the complicating factors in designing a launch vehicle is the uncertainty in the atmospheric winds. To deal with this uncertainty, the winds on the day of launch are measured to verify that conditions are satisfactory to fly.

Sensitivities and uncertainties have to be determined and assessed through all stages of the design process. This requires attention to design detail to assess the best design decisions and potential for reducing uncertainty. In fact, uncertainty can in some cases be reduced by reducing sensitivities. Uncertainties can be determined from historical data bases, tests, and expert opinion. A major concern in design is determining the uncertainties in the output variables in terms of uncertainties in the input variables. Some of the methods used to assess uncertainty are root-sum-square (RSS) and Monte Carlo simulations.

In the early phases of design it is important to ensure adequate margins are provided to assure headroom for unknown effects of sensitivities and uncertainties. As the design activity proceeds every effort must be made to understand sensitivities to achieve the best balanced design and to reduce uncertainty to reduce risk and provide design confidence.

The following is an overview of uncertainty in rocket engine and structural design. In rocket engine design, high uncertainty results in high development cost. Figure 12-1 illustrates the effect of uncertainty on high cost. [Havskjold, 2004]. The figure on the left is the number of rework cycles (corrective actions) as a function of technical uncertainty factor for

various subsystems. As the uncertainty increases the number of rework cycles increases. The uncertainty is a result of high static and dynamic flow induced loads, thermal transients and gradients, high pump speeds, welds, etc. In the figure on the right is the cost versus the number of years in the development. It can be seen that 73% of the development cost is a result of corrective actions (test-fail-fix). In the development of the SSME there were 38 significant incidents that cost over $30 million per incident.

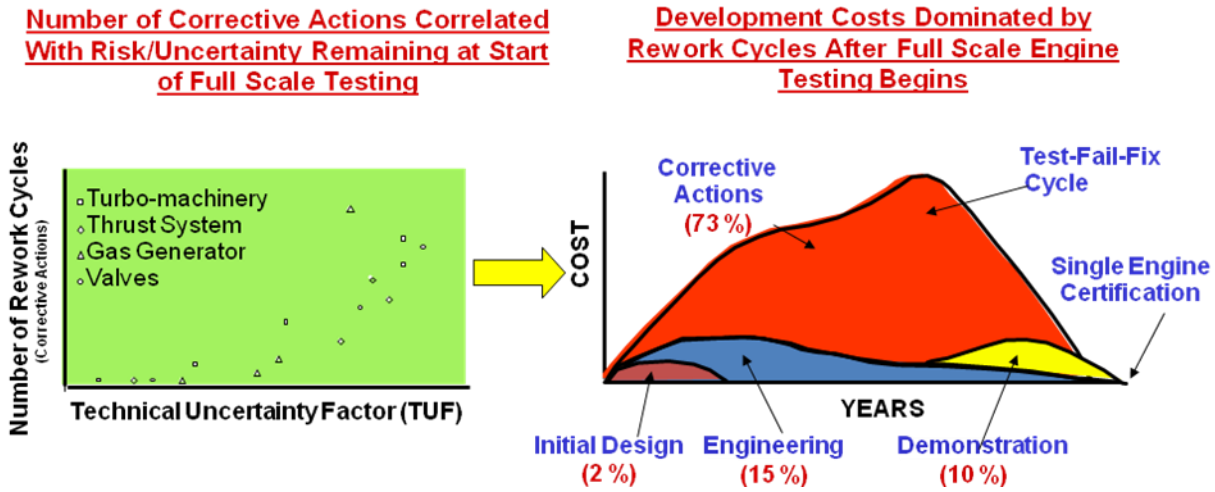


Figure 12-1. Technical Uncertainty Leads to High Cost

Having the experience shown in Figure 12-1, what can be learned to improve the effects of uncertainty? Shown in Figure 12-2 is an indication of how reducing uncertainty and improving processes can reduce development cost.

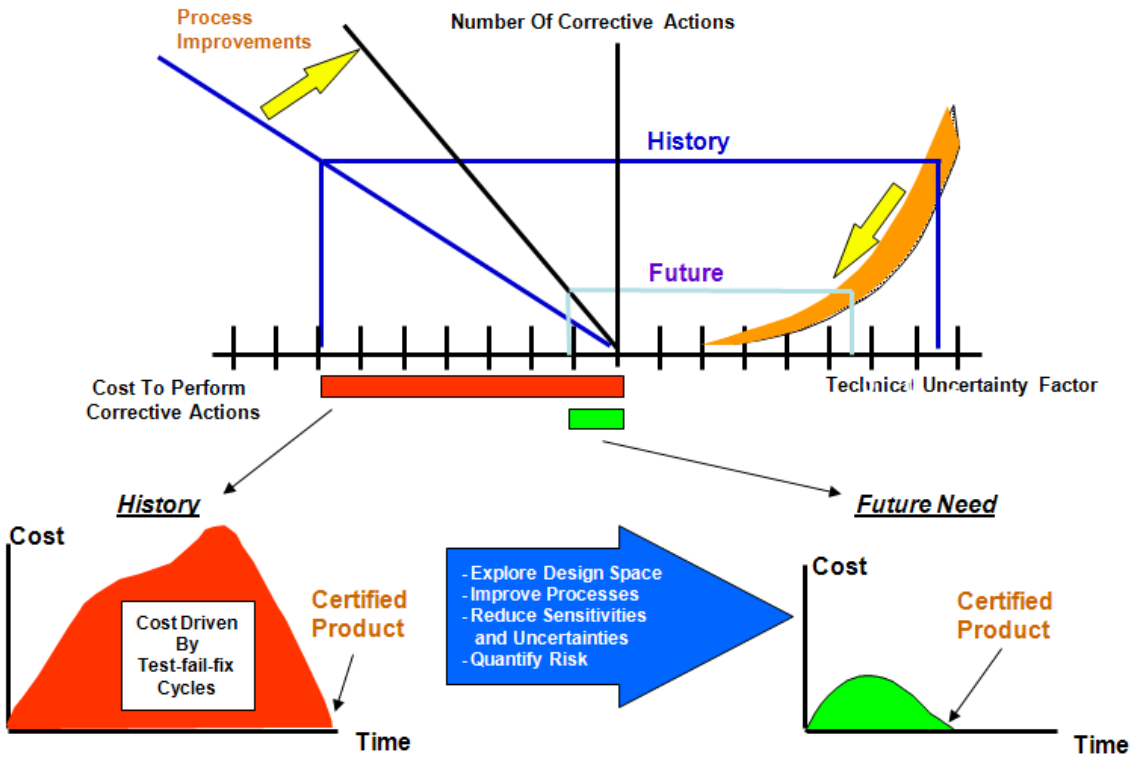


Figure 12-2. Combined Effect of Low Uncertainty and Improved Process to Reduce Cost

Figure 12-2 indicates that as the uncertainty is reduced the number of corrective actions can be reduced and by process improvements the cost of corrective actions can be improved. The net effect will be reduced cost to achieve a certified engine. Uncertainty can be reduced by lowering the static and dynamic flow induced loads, e.g. decrease chamber pressure and open up flow areas. In addition, uncertainty can be reduced by reducing pump speeds, improved definition of environments, etc. Process improvements can be achieved by minimizing welds, application of friction stir welding, bonding by high isostatic pressing, reduced part count, etc. Overall by building on our experience base as shown in Figure 12-2 and by implementing new design technologies, significant cost reductions can be expected in the future.

Uncertainty in structural design is illustrated in Figure 12-3. In the middle of the figure

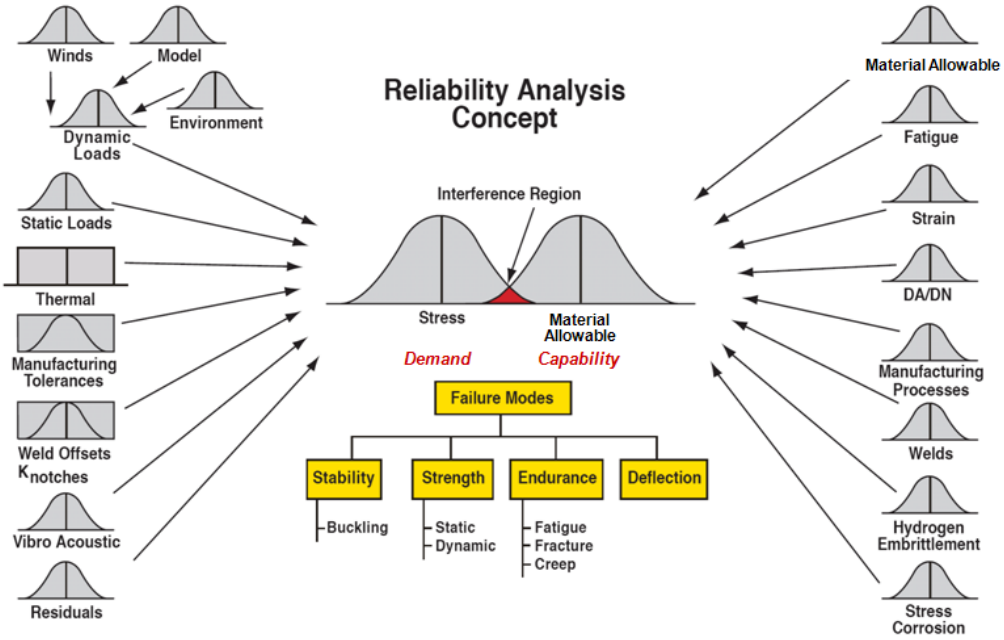


Figure 12-3. Uncertainty in Structural Design

are the probability density functions (PDF) of the working stress and the material allowable. In the region where there is overlap, failures will occur. In this example, the design has considered all the failure modes and the failure mode of concern is the strength. The variability in the material allowable can come from the random variations as characterized by the right-hand PDF's and for the stress the variability can come from the random variations associated with the PDF's in the left hand column. Knowing the associated PDF's, the reliability of the design can be determined. In the example shown, the design would be unacceptable because of the size of the interference region. Various changes can be made. The mean stress can be reduced by reducing the load or changing geometry. The uncertainty could be reduced by restricting the uncertainty in the load, changing tolerances, improving welding, etc. The material properties can be improved by changing the material to one that has a higher allowable or one with less uncertainty or both.

Sensitivity and uncertainty play important roles in the design of complex designs where there are high power densities. Sensitivities provide insights regarding developing the best balanced design and also aid in reducing uncertainties. Knowing the uncertainty provides a means for assessing risk and provides confidence in the design. Understanding past experiences (lessons learned) and applying new design tools provide visions toward design improvements to reduce cost in the future.

Examples:

- Saturn V Hold Down Post
- Space Shuttle Liftoff Loads
- Alternate Turbo Pump Vibration
- SAFE Solar Array Day-Night Frequency Shift

- Space Shuttle Parameter Uncertainties Matrix
- SRM Thrust Bucket and SSME Throttling (Lofting vs. Throttling)
- SRM Gimbaling Nozzle

Saturn V Hold Down Post (Liftoff Loads)

Safety requirements dictate that all liquid engines of the initial flight stage be at full power and healthy before releasing the vehicle from the launch pad. To meet this requirement the vehicle is attached to the launch pad with large mechanisms with sufficient strength to counteract the thrust force pad environments with margin. As a result the total thrust (7.5 million pounds) of the Saturn V first stage is stored in the structure as strain energy (potential energy). When the engines are all declared healthy the vehicle is released from the pad to fly into space. This release of energy creates a very large structural dynamic response of the vehicle and increases the loads significantly in the vehicle first stage with some increases in the loads in the other vehicle stages. These load increases would result in performance loss due to the structural weight increase required to handle the loads. As a result a soft release was employed as illustrated on Figure 12-4. It consisted of a tapered bolt that was severed using a pyrotechnic device. The tapered bolt was then pulled through the smaller diameter skirt attachment hole, slowly releasing the energy and decreasing the loads by approximately 30%. Summarizing:

- Engines are started and are at full thrust in order to assure engine health, before releasing the vehicle from the launch facility.
- Engine thrust energy is stored in the thrust frame and other vehicle structures.
- The stored energy, that is suddenly released, creates a large dynamic response.
- Saturn V used a soft release mechanism in order to reduce the dynamic response (loads).
- The release was an extruding bolt through an orifice as shown on the next figure.
- Loads in the rear of the vehicle were reduced more than 30%.

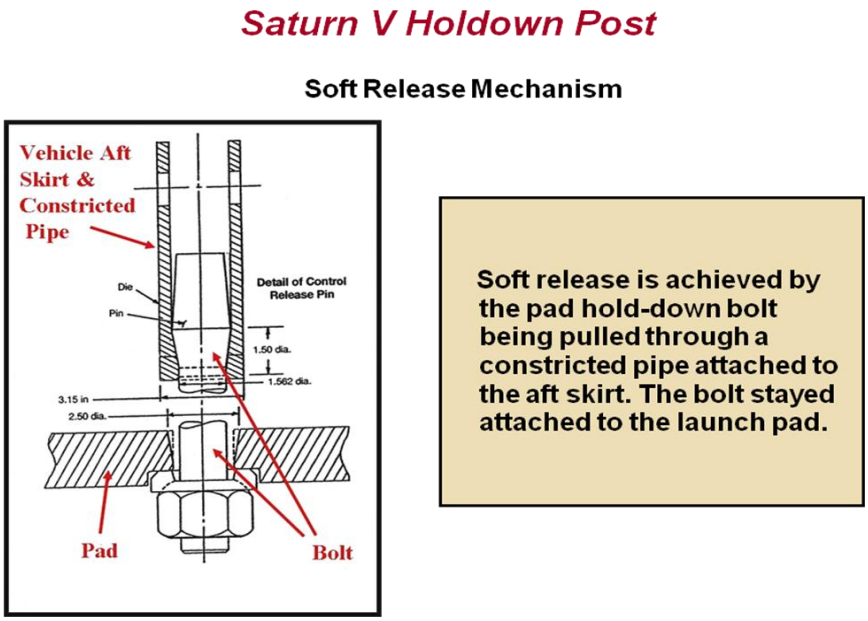


Figure 12-4. Saturn V Hold Down Post Soft Release Mechanism

Space Shuttle Liftoff Loads

Space Shuttle had the same requirement as Saturn V with a much more complex dynamic system and with a very sensitive performance issue. Therefore it was mandatory that structural mass be as minimum as possible. The Shuttle is a five body system connected with interfaces called struts and/or attachment mechanisms. The vehicle is unsymmetrical in the pitch plane with the orbiter attached on the side of the External Tank and Solid Rocket Motors. The vehicle is held to the Mobile Launch Pad (MLP) with four pyrotechnic bolts on each solid. See the following figure. The vehicle is first filled with the cryogenic liquid propellants which shrinks the External Tank longitudinal and in diameter. For example the aft SRB to ET attachment strut is at 7 degrees to perpendicular before filling the tank and becomes perpendicular due to the cryogenic shrinkage when the tanks are filled. In addition its diameter shrinks approximately 2 inches. This stores energy into the structure. At the start of the on pad liftoff cycle the SSME's are ignited and carried to 90% thrust to ensure engine health. The engines are canted for c.g. tracking and are offset from the vehicle center line several feet. This stores additional energy in the structure in two ways. The orbiter is lifted up bending the vehicle over the attached points introducing a large bending moment in the system. This can be illustrated visually by watching the launch of Shuttle observing the tank tip moving laterally approximately 36 inches. This sets up a dynamic motion of the vehicle on the pad about the mean moment introduced by the SSME thrust. Since the engines are offset, they also push the Orbiter and ET between the two motors that are holding the vehicle to the pad. [Ryan, 1996]

At SRB bolt release all this stored energy is released creating a large complex dynamic response. The interaction of the four vehicle bodies plus the payload body requires approximatly 300 bending modes to simulate the response and calculated all the system

loads. At release two additional forces add to these dynamic responses, thus loads. These are the expansion of the Solid Rocket Motor due to the 960 psi of internal pressure created by the burning propellant. This pressure goes from zero to the 960 psi in 500 milliseconds after motor ignition. The ignition of the motors and the large thrust created moves through the launch pad thrust tunnel creating a overpressure wave that travels up the vehicle. Since the Shuttle is a 1½ stage vehicle it is very performance critical, thus these high dynamic loads had to mitigated to reduce structural weight.

As stated above the SSME thrust at engine start and buildup creates a dynamic motion laterally as shown on Figure 12-5. The vehicle motion of moving back to a minimum position has a minimum energy point at which time if the vehicle is released from the pad will have the lowest load. Shown as stored bending moment on Figure 12-6 is the time dependency of the bending moment. As a result it was decided to burn the SSME's 2½ seconds beyond the point where they are declared healthy, greatly reducing the loads. This delay of liftoff from the time of verified SSME's to the minimum energy point reduces vehicle performance but at a much lower level that would be the impact of the increased loads. Figure 12-7 is a plot of the predicted liftoff response versus a flight response.

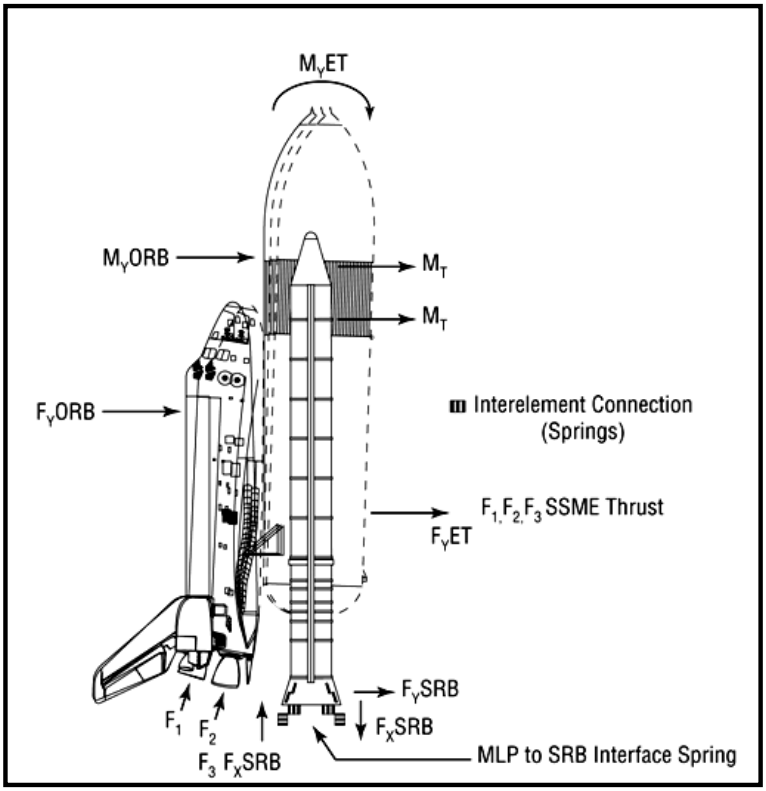
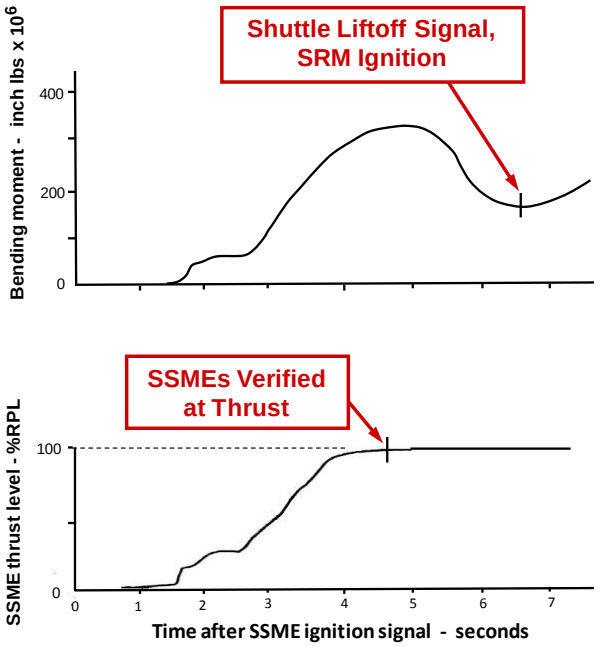


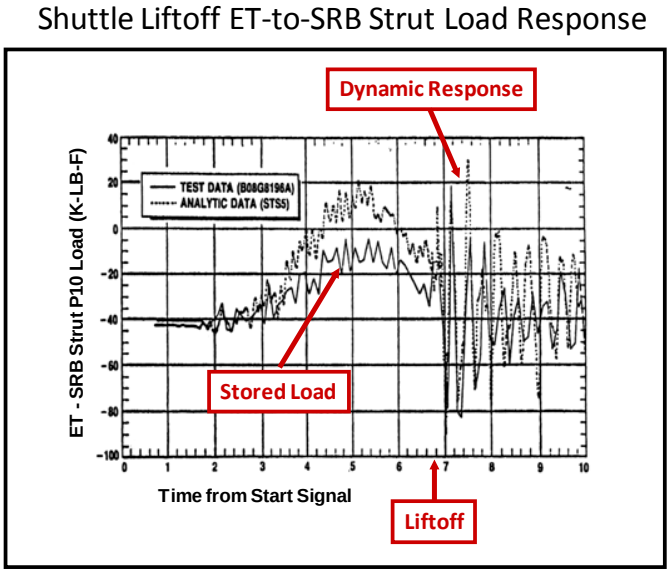
Figure 12-5. Shuttle Liftoff Dynamics



- The bottom figure shows the SSME thrust history.
- The top figure shows the bending moment stored in the vehicle as a function of time after SSME's ignition.
- SRM ignition and liftoff is deferred about 2 seconds until the bending moment is minimum.

Figure 12-6. Shuttle Liftoff Timing

In Figure 12-7 one can see the stored load and the minimum energy release point followed by the large dynamic response discussed above. The plot is for the ET to SRB strut load response. The difference in prediction versus flight is explained by the fact that the prediction was for 3-sigma conditions while the flight was near nominal conditions.



- The stored energy is shown from 0 to 7 seconds.
- The dynamic response is shown from 7 to 10 seconds.
- The magnitude and complexity of the response varies with vehicle location.

Figure 12-7. Shuttle Liftoff Loads

These two examples show how the uncertainty and sensitivities of a system were understood, resulting in a better performing system.

In summary:

- Space Shuttle, due to its asymmetrical configuration, stores energy as the SSME's thrust lifts the Orbiter and pushes the Orbiter and External Tank between the SRB's.
- The energy is stored by deflecting the External Tank (36" at the tip) and twisting the SRB's pad attach hardware.
- The liftoff response is very dynamic and sensitive. Loads can change 30% with small changes in the configuration or its operating parameters.
- The liftoff signal is delayed approximately 2 seconds in order to have the system at a minimum stored engine condition.
- The liftoff delay cost approximately 1,000 lbs of payload, which was less than the payload impact of designing to the unmitigated load.
- The loads sensitivity at liftoff requires loads analysis and verification for each launch/payload. The consequence is *operational complexity.*

Alternate LOX Turbopump Vibration Problem

The SSME did a block upgrade on the high pressure turbopumps to eliminate most of the fracture and fatigue problems associated with the original turbopumps. These new pumps were called ATD pumps (Alternate Turbopump Development pumps). During development test of the ATD LOX turbopump, the pump experienced large synchronous vibrations which would shut the test down. The following plot and pump schematic (Figure 12-8) shows response that would nearly instantaneously increase to a high level shutting down the test. The solution turned out to be the bearing dead band after much effort had been expended on trying to decrease the hydrodynamic forcing function. The pump response was so sensitive that changing the dead band 2 mils (two thousandths of an inch—less than the thickness of a sheet of paper) would stop the vibration, while reversing it would reinstate the problem. This placed a strict manufacturing tolerance on assembling the pump. Through understanding this sensitivity, the pump has not had any vibration problem over many Shuttle flights. [Problem solution team working notes and Ryan et al, 1994]

ATD Synchronous Vibration Fix Summary

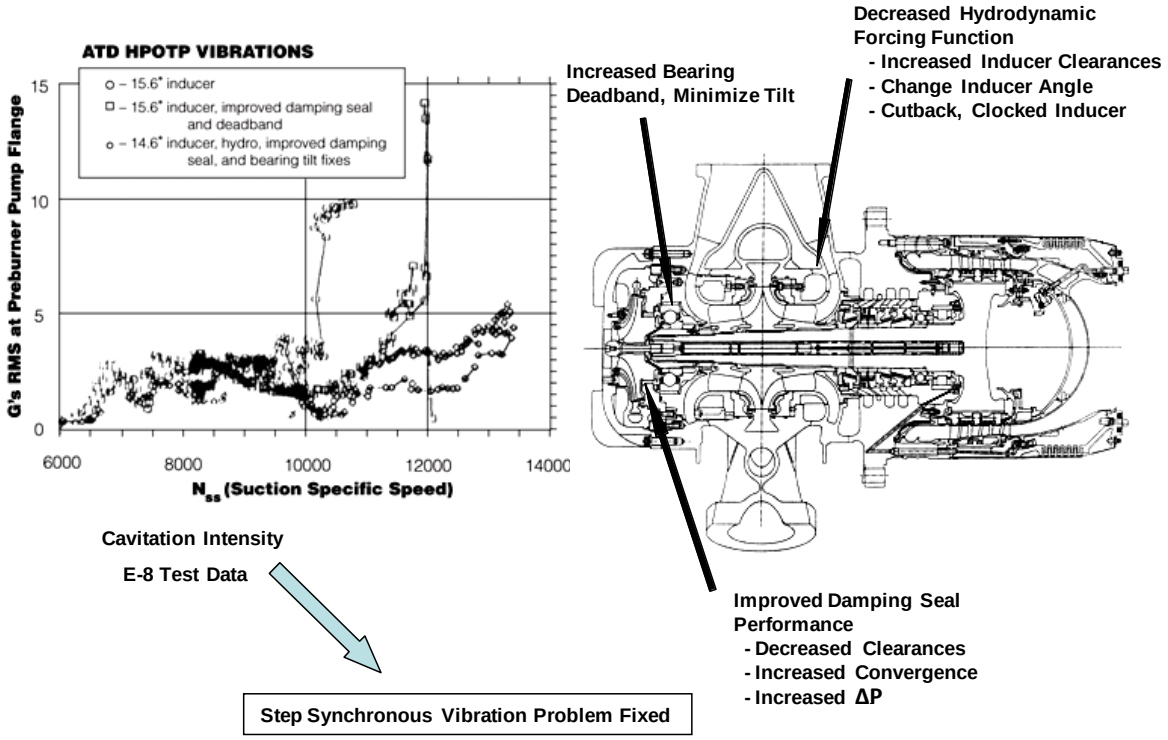


Figure 12-8. Alternate LOX Turbopump Vibration Fix Summary

Solar Array Flight Experiment (SAFE) Day-Night Frequency Shift

The solar array flight experiment had two objectives: (1) Develop a method for dynamic testing of large space structures in space, (2) Evaluate the effectiveness of a new design for solar power. See Figure 12-9, showing the solar array extended out of the Shuttle cargo bay. During the experiment a shift occurred in the natural frequency of the array when going from night to day during the orbit; this was not predicted. The reason for the shift was the thermal induced contraction and expansion of the array changing its moment of inertia. This can be seen in Figure 12-10 as a cupping of the array during the night portion of the orbit. Although thermal effects on structure are well known it was not expected to have much effect on this large a structure. Again the lessons keep repeating themselves; understand and quantify sensitivities. The experiment was very successful showing that dynamic testing of large structures in space was feasible. [Schock, et al, 1986]

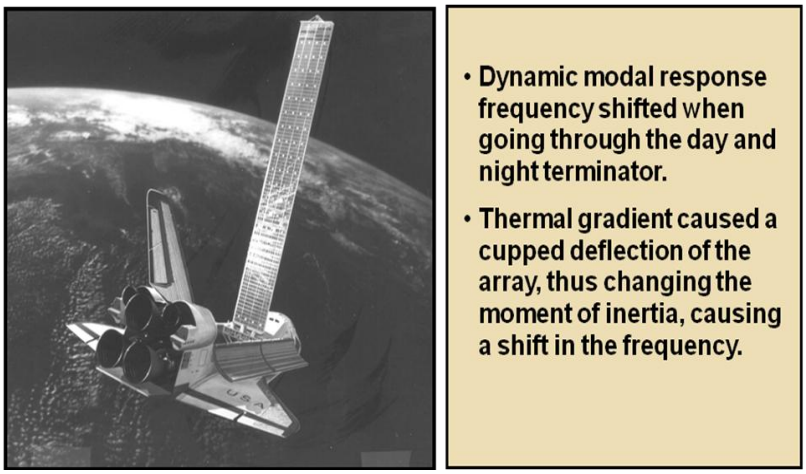


Figure 12-9. Artist's Conception of the SAFE Solar Array Experiment On Orbit

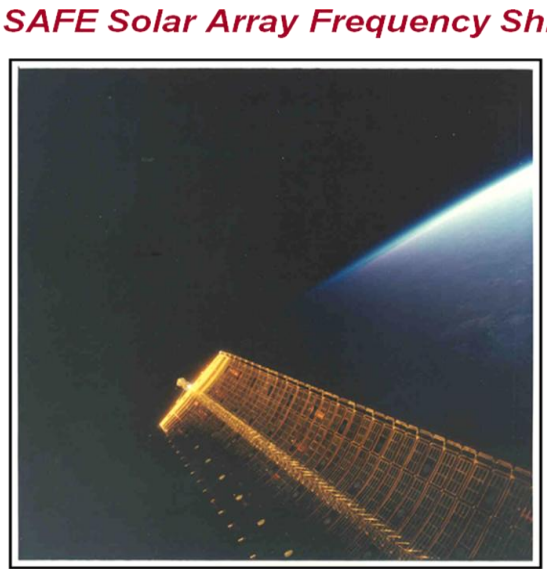


Figure 12-10. Picture of Deployed SAFE Solar Array Made from Space Shuttle

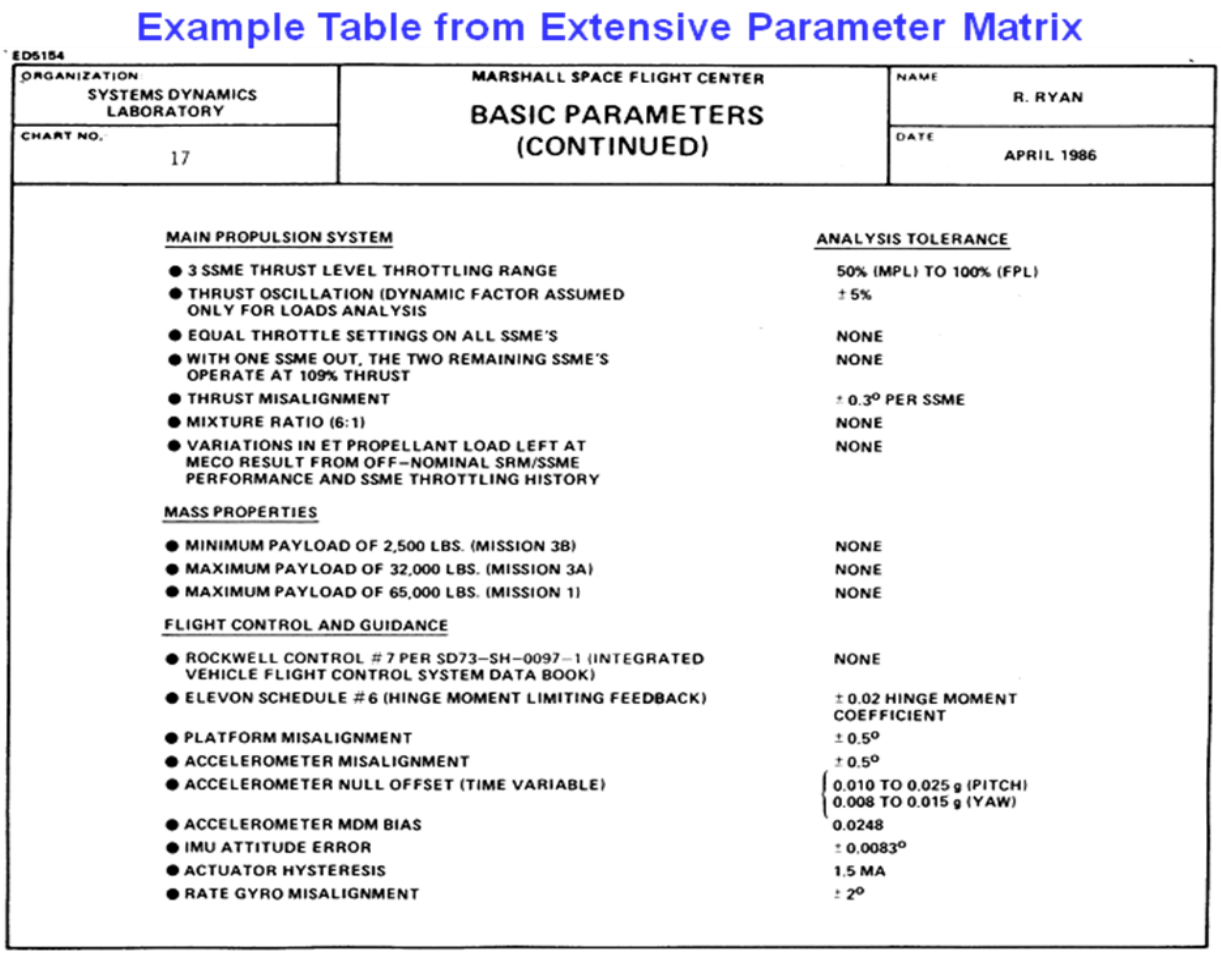
Space Shuttle Parameter Uncertainties Matrix

In the early days of Shuttle design it became very clear that the sensitivities of the Shuttle system to parameter uncertainties required a concerted effort to define all the parameter uncertainties that affected the vehicle induced environments, etc. This was a concerted effort coordinated by the Ascent Flight Integration Working Group (AFSIG). It took approximately two months to complete the initial version. The uncertainty levels were burned down as the program progressed and more data was collected from test and flights. The lesson is clear;

each project must develop and put under control all parameter uncertainties and continue to burn them down throughout the lifecycle. The guidelines for development of this data follows:

- In order to achieve a balanced design for Space Shuttle, the vehicle driving parameters required determining their mean values and their 3 sigma variations.
- These variations had to be established for each mission event and each major design function.

Figure 12-11 shows a partial listing of the parameter variations, illustrating the format and the magnitude of the task. This compilation was a large document that was placed under configuration control.



Example Table from Extensive Parameter Matrix

ED5154

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
SYSTEMS DYNAMICS LABORATORY	BASIC PARAMETERS (CONTINUED)	R. RYAN
CHART NO. 17		DATE APRIL 1986

MAIN PROPULSION SYSTEM	ANALYSIS TOLERANCE
● 3 SSME THRUST LEVEL THROTTLING RANGE	50% (MPL) TO 100% (FPL)
● THRUST OSCILLATION (DYNAMIC FACTOR ASSUMED ONLY FOR LOADS ANALYSIS	± 5%
● EQUAL THROTTLE SETTINGS ON ALL SSME'S	NONE
● WITH ONE SSME OUT, THE TWO REMAINING SSME'S OPERATE AT 109% THRUST	NONE
● THRUST MISALIGNMENT	± 0.3° PER SSME
● MIXTURE RATIO (6:1)	NONE
● VARIATIONS IN ET PROPELLANT LOAD LEFT AT MECO RESULT FROM OFF-NOMINAL SRM/SSME PERFORMANCE AND SSME THROTTLING HISTORY	NONE
MASS PROPERTIES	
● MINIMUM PAYLOAD OF 2,500 LBS. (MISSION 3B)	NONE
● MAXIMUM PAYLOAD OF 32,000 LBS. (MISSION 3A)	NONE
● MAXIMUM PAYLOAD OF 65,000 LBS. (MISSION 1)	NONE
FLIGHT CONTROL AND GUIDANCE	
● ROCKWELL CONTROL # 7 PER SD73-SH-0097-1 (INTEGRATED VEHICLE FLIGHT CONTROL SYSTEM DATA BOOK)	NONE
● ELEVON SCHEDULE #6 (HINGE MOMENT LIMITING FEEDBACK)	± 0.02 HINGE MOMENT COEFFICIENT
● PLATFORM MISALIGNMENT	± 0.5°
● ACCELEROMETER MISALIGNMENT	± 0.5°
● ACCELEROMETER NULL OFFSET (TIME VARIABLE)	0.010 TO 0.025 g (PITCH) 0.008 TO 0.015 g (YAW)
● ACCELEROMETER MDM BIAS	0.0248
● IMU ATTITUDE ERROR	± 0.0083°
● ACTUATOR HYSTERESIS	1.5 MA
● RATE GYRO MISALIGNMENT	± 2°

Figure 12-11. Partial Listing of Shuttle Parameter Variation Matrix

SRM Thrust Bucket and SSME Throttling (Lofting vs. Throttling)

Constraints on space system designs are necessary; however, they always cost the system in terms of flexibility, performance, and programmatics. The Space Shuttle dynamic

pressure constraint at max q is a good example. The constraint was necessary for the elimination of buffeting of the Orbiter tail section and to keep induced environments such as loads within bounds. The vehicle performance is very sensitive to the constraints of controlling dynamic pressure and staying within the longitudinal acceleration limit of 3.15 g's. The following listing shows the sensitivities and general characteristics. In general reducing q by 1 psf by throttling is a loss of 25 pounds of payload while lofting cost 250 pounds of payload for a 1 psf reduction. In order to implement these constraints the SSME has to throttle to the minimum possible which is determined by the dynamic loads in the nozzle as thrust is lowered. This is a result of the requirement that the nozzle shape be optimized for operation from ground to vacuum and is a compromise of the nozzle instability versus maximum performance in vacuum. The SRM grain had to be shaped such that there was also a SRM thrust reduction during Max q. Finally an adaptive guidance scheme for SSME throttling was instituted to obtain increased vehicle performance as compared with a predetermined SSME throttling profile. [Ryan, 1996] Just remember *"Constraints Cost."*

Dynamic Pressure Constraint
(Lofting vs Throttling)

- SSME throttles to maintain the longitudinal acceleration at 3.15 g's and to keep the dynamic pressure (q) within the 650 psf nominal limit.
- During atmospheric flight SSME cannot throttle below 65% full thrust due to the nozzle side loads.
- The 65% limit means that lofting must be used in conjunction with throttling to maintain q within 650 psf.
- The penalty for lofting is approximately 250 lbs payload loss for each 1 psf q reduction, while the penalty for throttling is 25 lbs payload loss for each 1 psf q reduction.
- Dynamic pressure limits can be traded for structural weight.

SRM Gimbaling Nozzle

In the early phases of Shuttle design, it was hoped that gimbaling the three main engines on the Orbiter would provide sufficient controllability during ascent flight. Therefore, the initial design had fixed nozzles on the Solid Rocket Motors (SRM's). As more information was obtained on SRM characteristics and other parameter variations, it became apparent the vehicle would not be controllable by the main engines alone due to uncertainties in SRM thrust direction and other perturbations. Thrust vectoring capability had to be added to the SRM's, as indicated in Figure 12-12. [Ryan, 1996]

- **Because of uncertainties in SRM thrust direction and other parameters, Space Shuttle was not controllable without thrust vectoring on the Solid Rocket Motors.**
- **Vectoring the thrust on solids is a major design problem.**
- **A flex bearing and seal was required. This bearing/seal is made of eleven rubber/steel laminations.**
- **Moving the nozzle (thrust vectoring) requires large actuator forces due to the stiffness of the flex bearing/seal.**

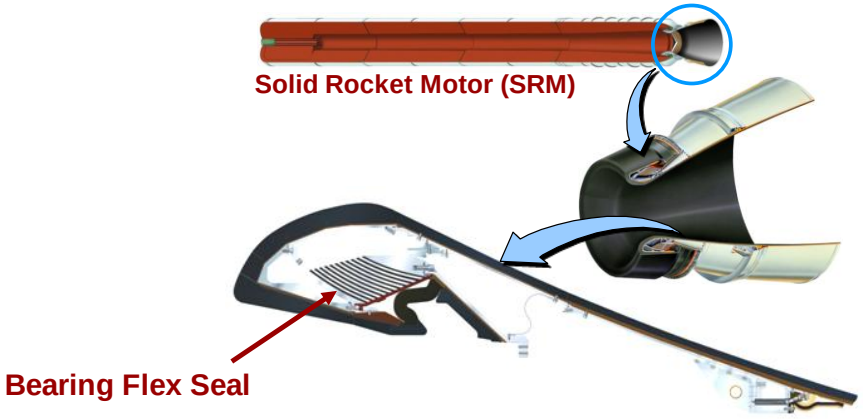


Figure 12-12. Solid Rocket Motor Gimbaling Nozzle

This was a major impact to the SRM design and the total Shuttle vehicle. Vectoring a solid rocket motor nozzle greatly increases its complexity. The approach taken was to use a flex bearing and seal made of eleven rubber/steel laminations. Moving the nozzle to vector the thrust requires large actuator forces to overcome the high stiffness of the flex bearing and seal, plus other loads such as aerodynamic forces. Actuator deflections, rates, and accelerations must be adequate for controllability and control stability. In turn, large actuator forces require high output hydraulic power supplies in the aft skirts, along with the attendant complexities of handling hazardous fuels. So an inherent uncertainty in the system led to major operational and cost impacts.

Here again we are dealing with uncertainties and sensitivities that must be understood, quantified and ameliorated or the design will not work. Not only must these be understood and managed, but also the derived requirements flowing from uncertainties and sensitivities often are design drivers that must be accurately determined.

- **A key message from Lesson 12 is:**

  Quantifying sensitivities, uncertainties, and margins enables balancing risk.

  To ignore system sensitivities and uncertainties is a recipe for failure.
  Quantify
  Understand
  Manage

In the next lesson we will apply the understanding of sensitivities and uncertainties as a measure for the requirements of a system to have margins in the design.

Lesson 13: Program Margins Must Be Adequate

- **Margins must be adequate to cover anticipated growth during design, TRL immaturity, and sensitivities. Otherwise, many design problems, overruns, and reduced performance will occur.**

We have just discussed the importance of understanding of sensitivities and uncertainties. This understanding is one of the main drivers for intelligently adding margins of the system in addition to providing means of covering uncertainties and unknowns that are always present in a system. The following lesson, Margins must be adequate, will deal with Space Shuttle lack of margins and techniques to recover the induced performance losses and the SSME pump bearing corrosion issue.

Examples:

- Space Shuttle Performance Margins
- SSME LOX Pump Bearing Race Failure

Space Shuttle Performance Margins

During the Space Shuttle design process and first test flights the lack of margins and the solution to encountered problems resulted in an approximate 45,000 pound payload performance deficit for the Air Force mission. Many of these issues were seen during the design cycle that resulted in numerous weight reduction strategies and planned block changes to the Shuttle elements such as SRM, ET, SSME and Orbiter. The solutions also resulted in many operational procedures and constraints. An example is structural loads that require a Day of Launch I-Load update based on wind measurements made 4 hours prior to launch. The following listing shows these modifications that were baselined to recover the payload losses and solve other problems.

Increase Performance of Propulsion System
- SSME @ 104% thrust design operating point and later upgrade to ATD Pump
- Large Throat, and Two-duct Manifold

Weight Reduction Program
- Light Weight Tank and later upgrade to Super Light Weight Tank
- Orbiter weight reduction
- High performance SRM
- Reduced wind criteria
- Flight derived dispersions

Operational Problems

- Additional maintenance, refurbishment, and inspection
- Additional day of launch analysis / constraints
- Additional day of launch operations

Details will be shown in Lesson 15

Many of these solutions created other problems; for example, the SSME thrust increase created increases in dynamic environments in the engine which resulted in many fracture and fatigue issues that had to be resolved with engine component block upgrades. Part of the original solution also resulted in giving up some of the launch availability to reduce loads. Not only did the program accomplish upgrades, but a major effort was made to take conservatism out of criteria, environments and design parameters.

SSME LOX Pump Bearing Race Failure

After Mission STS-27, post-flight inspection of the SSME LOX Pump found that the inner race of the turbine-end bearing had cracked through. Fractography showed that the crack had occurred before engine start, indicating that the engine had run its full duration with a cracked bearing race in the presence of liquid oxygen. This very hazardous situation was not revealed until the post-flight hardware inspection. Location of the turbine-end bearing is highlighted in the circled area of the turbopump cross-section on Figure 13-1.

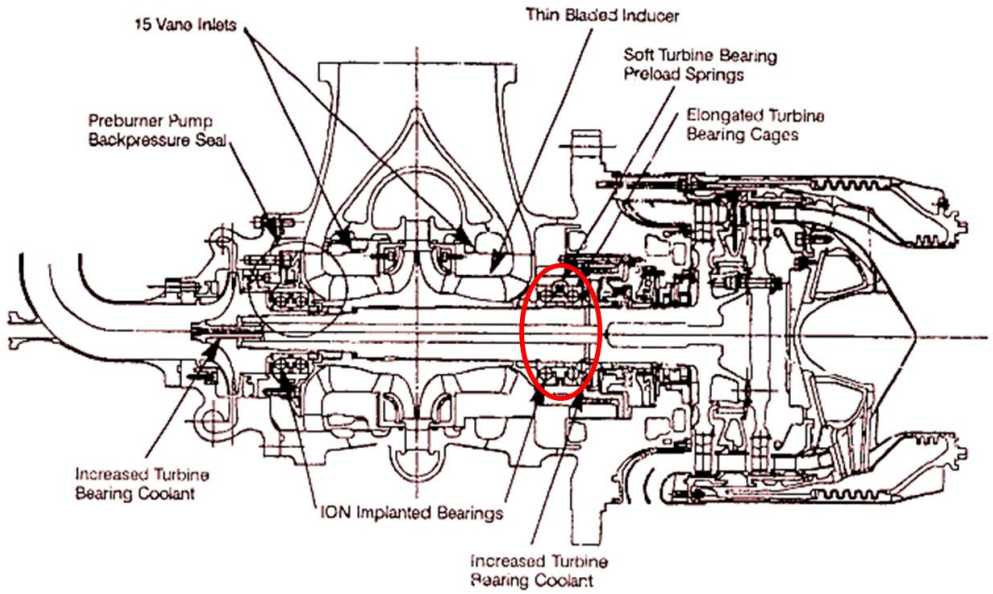


Figure 13-1. SSME LOX Pump Cross-Section Highlighting Bearing Location

The cause of the fracture was determined to be stress corrosion in a high stress condition. During assembly, the shaft is cooled with liquid nitrogen to achieve an interference fit of the bearing onto the shaft. The resulting residual hoop stress in the presence of water that condensed during assembly led to the fracture. Also, there was potential contamination from the Freon cleaning solution.

The hoop stress caused by the interference fit was 30 ksi or greater, which was excessive for the inner race material. To gain adequate margin, the design was adjusted to limit the hoop stress to 24ksi, and the contamination and condensation issues in the assembly clean room were addressed. This solved the stress corrosion cracking problem. Also, in some later applications for the Advanced Turbopumps, the race material was changed to a stronger material, which gained additional margin.

- **A key message from Lesson 13 is:**

  Allocate adequate technical and programmatic margins or you will pay for it later.

Principle VI: Project Success is Determined by Life Cycle Considerations

This principle recognizes the importance of life cycle issues—its effect on design choices available, the large role that concept selection plays, recognition of how requirements have far-reaching, sometimes unintended consequences, and the need to achieve the best design for the entire life cycle.

Four lessons will be discussed:

14. **The Design Space is Constrained Based on Where You Are in the Life Cycle**
15. **Concept Selection and Design Process**
16. **Requirements Drive the Design**
17. **Design for the –ilities and Cost**

Lesson 14: The Design Space is Constrained Based on Where You Are in the Life Cycle

- **Three Life-Cycle Categories**
  - **Conceptual/Initial Design**
    - **Open design space for choices and trades**

- **Detail Design**
  - **Design space constrained by concept choice**
- **Verification/Operations**
  - **Design space constrained by the as-built system**
  - **Must make system work. Solution options limited**

As we proceed through the system's life cycle, the range of choices available to affect the design and its operation become more constrained. Consider three timeframes within the life cycle: (1) at Conceptual/Initial Design, (2) at Detail Design, and (3) at Verification/Operations. At Conceptual/Initial Design, the design space is open, allowing essentially free choice of design variables to meet the mission requirements. By the time of Detail Design, the concept has been selected and preliminary design decisions have been made. This severely limits the freedom of the designer to choose variables. The majority of the system performance and cost attributes are determined by the concept that has been selected, as will be addressed in Lesson 15. Once the system has been manufactured, at the time frame of Verification or Operations, the design space is constrained by the as-built system. Unless there is to be a major redesign cycle, the system must then be made to work by minor adjustments or by operational constraints. Solution options are very limited at this point. It is clear that early choices have a major constraining effect on the range of downstream choices that can be made.

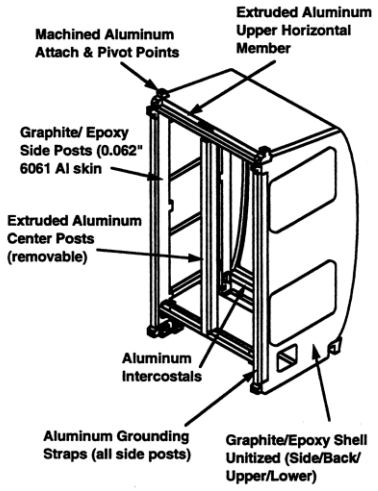
Examples:

- International Space Station Rack Design
- Replacement of SSME Baseline Turbopumps with Alternate Design Turbopumps

International Space Station Rack Design

In designing the International Space Station (ISS) science racks (Figure 14-1), four issues were paramount. (1) The racks needed to be lightweight. (2) Flexibility in mounting and operating various experiments was desired. (3) Because some of the experiments would need a low-gravity environment, the presence of crew motion and other disturbances meant that a vibration-isolation system should be incorporated into the racks. (4) The racks had to be sufficiently stiff to meet minimum frequency requirements as a Shuttle payload, to avoid dynamics and loads problems during launch. [Bookout, 1996]

- **Four issues were paramount in the design of the ISS Science Racks**
  - **Weight reduction**
  - **Experiment operations and mounting flexibility in rack**
  - **Vibration isolation at zero g**
  - **Meeting Shuttle frequency requirements**



Constraints create unwanted compromises of a design.

Figure 14-1. ISS Science Rack Design

Initial consideration of the design requirements and constraints led to a choice of composite material as a means of saving weight and achieving acceptable stiffness; however, when all the constraints, requirements, and accommodations were met, the weight saving of composites as compared to aluminum was not realized. It would have been simpler and less expensive to have gone with metal construction from the start.

Also, design of the active vibration isolation system was difficult because of geometric constraints in addition to the other constraints and requirements listed above. It is clear that constraints create unwanted compromises of a design.

Another aspect of ISS rack design related to the need to use the racks for many different functions. A number of them are illustrated in Figure 14-2. Granting the flexibility of a single design to accomplish all these functions created design and verification problems. However, in general, the advantage of commonality outweighed the design issues.

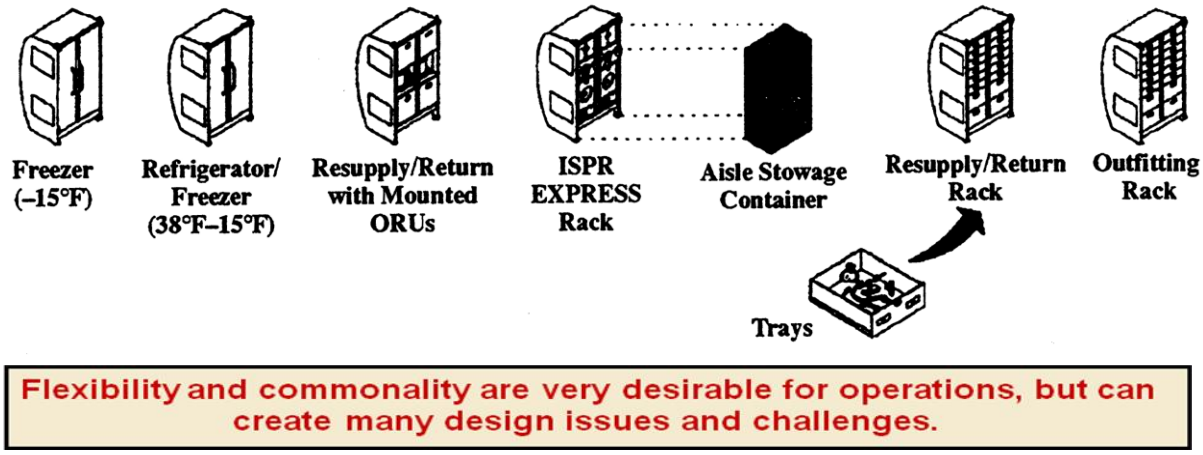


Figure 14-2. ISS Rack Functions and Configurations

The Space Shuttle Orbiter configuration is another example of this issue. The Shuttle was developed to a multi-agency set of requirements from both NASA and the Department of Defense. Military requirements dictated larger payloads and greater reentry cross-range than did NASA's requirements. DoD required a 1500 nautical mile cross-range to enable landing at the launch site after a once-around delivery orbit. NASA's cross-range requirement was less, being dictated by abort considerations. There were two competing Orbiter configurations: a delta-wing design needed to produce sufficient hypersonic lift/drag ratio to achieve the DoD cross-range requirement, and a simpler straight-wing design that could satisfy the NASA requirement. Because the vehicle design had to envelope both requirements, a delta wing was chosen.

Obviously, there is no way of determining how a matured straight wing design would have performed, although predictions at the time indicated it would have a simpler thermal protection system and a less-demanding landing system. Because of subsequent developments, the DoD never made use of the Orbiter's cross-range capability, but the Shuttle program has continued to pay the operational costs associated with the delta wing configuration and its thermal protection system.

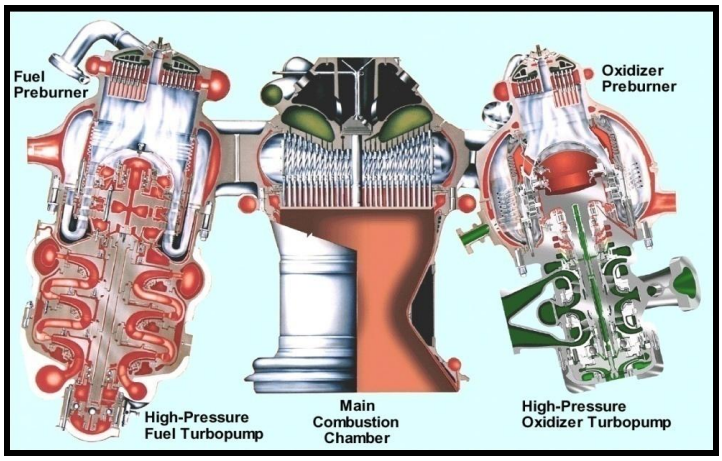
Flexibility and commonality are desirable goals, but they usually constrain the design space and can create design issues and challenges. Early in the project, make sure that commonality requirements are indeed firm, and that their downstream implications are understood.

Replacement of SSME Baseline Turbopumps with Alternate Design Turbopumps

The replacement of the original Rocketdyne turbopumps by the Pratt and Whitney alternate turbopumps (Figure 14-3) drew on lessons learned from the original pumps to improve reliability and maintainability. The weight allowance for the alternate pumps was increased over that for the original pumps. The increased weight allowance accommodated

significant improvements in turbopump design and reliability; however, the alternate pump designs had to interface with the existing engine system, including the powerhead and ducts. Geometric, pressure, and thermal interfaces had to be matched while meeting weight requirements. Because of these constraints, the alternate pumps couldn't make full use of the lessons learned and produce a fully optimized design.

- The P&W Alternate High Pressure Turbopumps were designed using lessons learned from the Rocketdyne pumps.
- Full advantage of the lessons could not be utilized since the pumps must be compatible with the existing engine powerheads, ducts, etc.
- These constraints were:
  - Geometric
  - Pressure
  - Thermal
  - Weight



Constraints required to use a new component in an existing system in general lead to a non-optimal design and higher costs.

Figure 14-3. Alternate High Pressure Turbopumps

In general, interfacing constraints required to use a new component in an existing system lead to a non-optimal design and higher costs.

So, the lesson is to recognize life cycle effects on the design space. As we progress through the design process, fidelity increases and uncertainty decreases, but the design choices decrease. Minimize constraints to increase design opportunities.

- **A key message from Lesson 14 is:**

Recognize Life Cycle Effects on the Design Space
- Fidelity increases
- Uncertainty reduces
but
- Design choices decrease
Minimize Constraints to Increase Design Opportunities.

Lesson 15: Concept Selection and Design Process

- 80 % of the project problems are locked in with concept selection

Lesson 14 indicated how the freedom to make design choices decreases as the design matures. This lesson shows that the constraining effect is powerful; that choices made early in the design process determine the great majority of the system's final attributes—how it operates, the problems it experiences, and what it costs.

- **The right concept selection is critical. The best detailed design will not correct a flawed concept.**
- **Put sufficient effort into front-end engineering (Quality Lever).**
  - **Ensure that options are fully explored, converging with successive refinement (greater detail) of concepts and requirements.**
    - **Pick a concept only after appropriate convergence of the various concepts or options; i.e. don't "Eureka" the answer.**
  - **Attain sufficient fidelity before selecting concept**
    - **Don't depend on sizing programs alone.**
    - **In early phases, discipline specialists must assess validity of sizing program results.**
  - **Employ technologies of adequate readiness levels**
    - **Avoid concepts having too many low Technology Readiness Levels.**

- **Don't roll the dice**

Choice Choice Choice

Selecting the right concept is critical. The best detailed design will not correct a flawed concept. (Conversely, a good concept can be ruined by poor detailed design.) This means that we must put sufficient effort into front-end engineering. Three aspects of what must be done in concept development and selection are highlighted: (1) Fully explore options, (2) Penetrate competing concepts with sufficient fidelity before selecting concept, and (3) Employ technologies of adequate readiness levels.

Fully explore options. Design activity involves conceiving a wide range of competing architectures, concepts, and design alternatives that are candidates to meet system requirements, then sifting and screening out unsuitable or less desirable alternatives to arrive at the best architecture, concept, and design. Additional candidate architectures, concepts, and design alternatives may come to light as the process progresses. These are added to the previous candidates and the screening and successive refinement continues. It is important to ensure that the options are fully explored. We must resist the natural tendency to jump to a solution that appears attractive initially. We should not "Eureka" the concept; instead, use a disciplined approach of applying consistent logic to all alternatives, ensuring that each gets a fair assessment. Pick a concept only after appropriate convergence of the possible concepts.

This philosophy applies in other activities as well. Failure investigations are especially prone to the "Eureka" trap. All possibilities should be explored, and alternatives should be discarded only after clear, consistent logic dictates.

Penetrate competing concepts with sufficient fidelity before selecting concept. Fidelity of definition increases throughout the design process. Before downselecting, it is critical to attain sufficient fidelity in the competing concepts to allow valid comparisons; else the wrong choice may be made. Experience has shown that at the concept selection level, we shouldn't depend on the fidelity of sizing programs alone, but should involve discipline specialists to assess the validity of the sizing program results. An integrated engineering assessment similar to the Vehicle Integrated Performance Analysis (VIPA) approach can be valuable in this regard.

Employ technologies of adequate readiness levels. Concepts that require too many technologies at a low readiness levels should be avoided. There are various rules of thumb concerning this, the most common being to have no more than two technologies at readiness levels below TRL 6. Any immature technology should have a sound development plan, with off-ramps to alternative approaches should the technology not pan out.

These recommendations are directed toward converging to the right concept in a comprehensive, logical manner. Don't roll the dice, but make deliberate, correct choices.

While this lesson deals specifically with concept selection, the principles apply also to other phases of the design cycle where alternatives are being assessed, such as trade studies, problem solutions, and block change assessments.

Examples:

- Quality Lever
- Saturn V Concept Selection History
- Space Shuttle Concept Selection History

Examples to be cited are the Quality Lever and a comparison of the concept selections for Saturn and Shuttle. The consequences of the Shuttle's concept selection on its performance evolution are illustrated.

Quality Lever

The Quality Lever (Figure 15-1) is a classic representation of the leverage and importance that early decisions have on a project. Investment during concept selection and early design is the most influential on product quality. Later in the life cycle the leverage decreases, and after the product is manufactured, the choices are limited to operational procedures required to make it work. Although this principle is generally known, one can make the observation that the reward systems of most organizations give greater recognition to problem solving in the downstream life cycle phases than to the avoidance of problems through good upfront work.

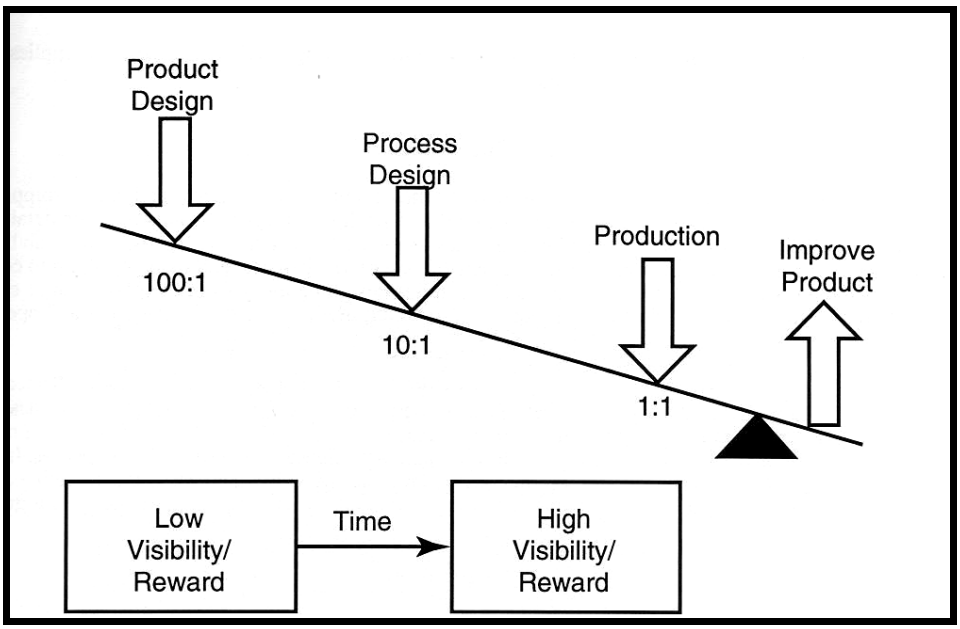


Figure 15-1. Quality Lever

Saturn V Concept Selection History

The Saturn V concept selection and design was an evolutionary process, built on experience from prior systems including Redstone, Jupiter, Saturn I, Saturn IB, and unmanned Saturn V flights (Figure 15-2). This process is described in detail in *Stages to Saturn*. [NASA SP-4206, 1980]

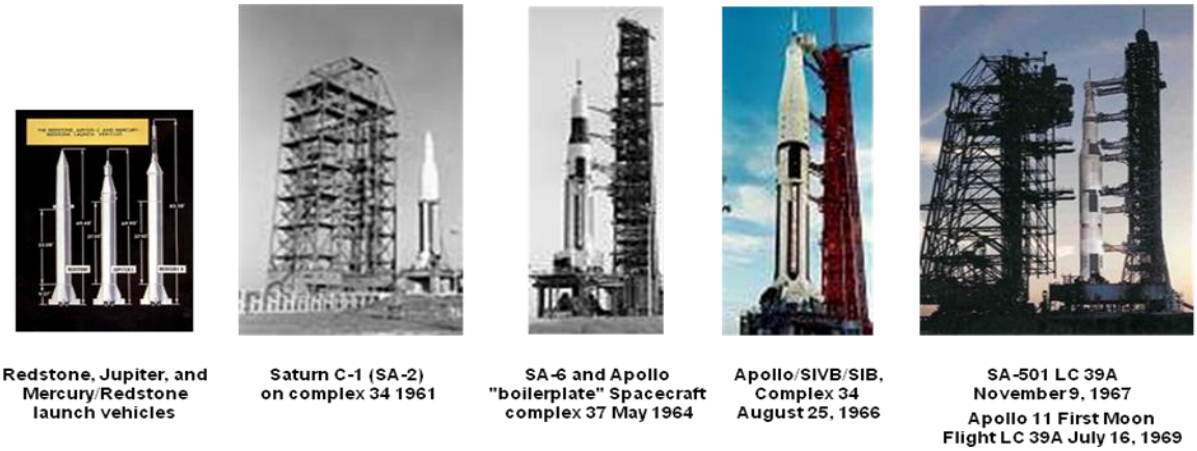


Figure 15-2. Building Blocks for the First U.S. Satellite, First Manned Space Flight, and Saturn/Apollo

Although building a system the size of Saturn V was stepping into uncharted territory, most of its technology and systems represented quantitative steps from prior systems versus qualitative leaps. In addition to this building block approach, the vehicle itself was conceived and designed for simplicity and a minimum number of interfaces, which reduced the number of downstream unknowns and problems. Also, there were three unmanned test flights of Saturn V before a crew was put on the vehicle. This careful process led to successful Apollo launches, culminating in the mission successes represented on Figures 15-3 and 15-4.

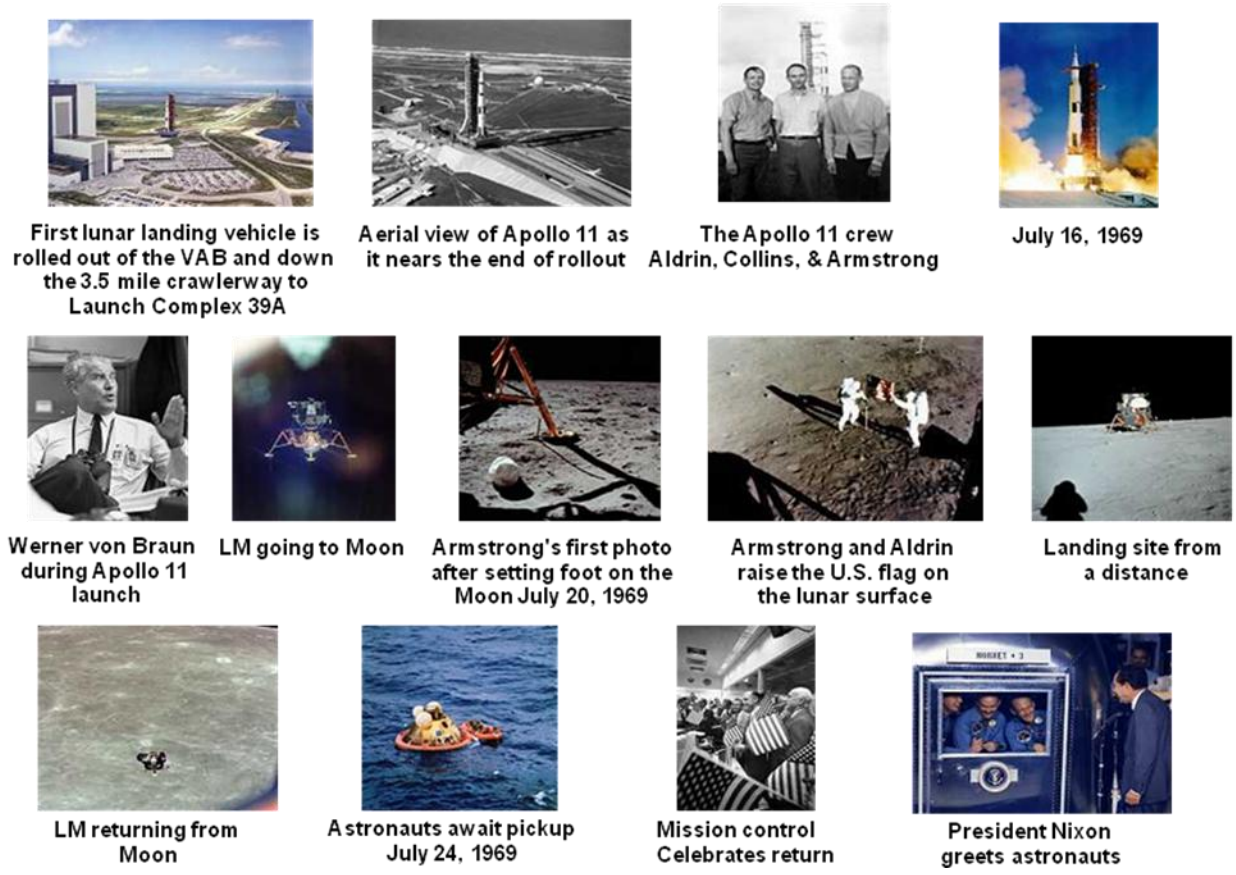


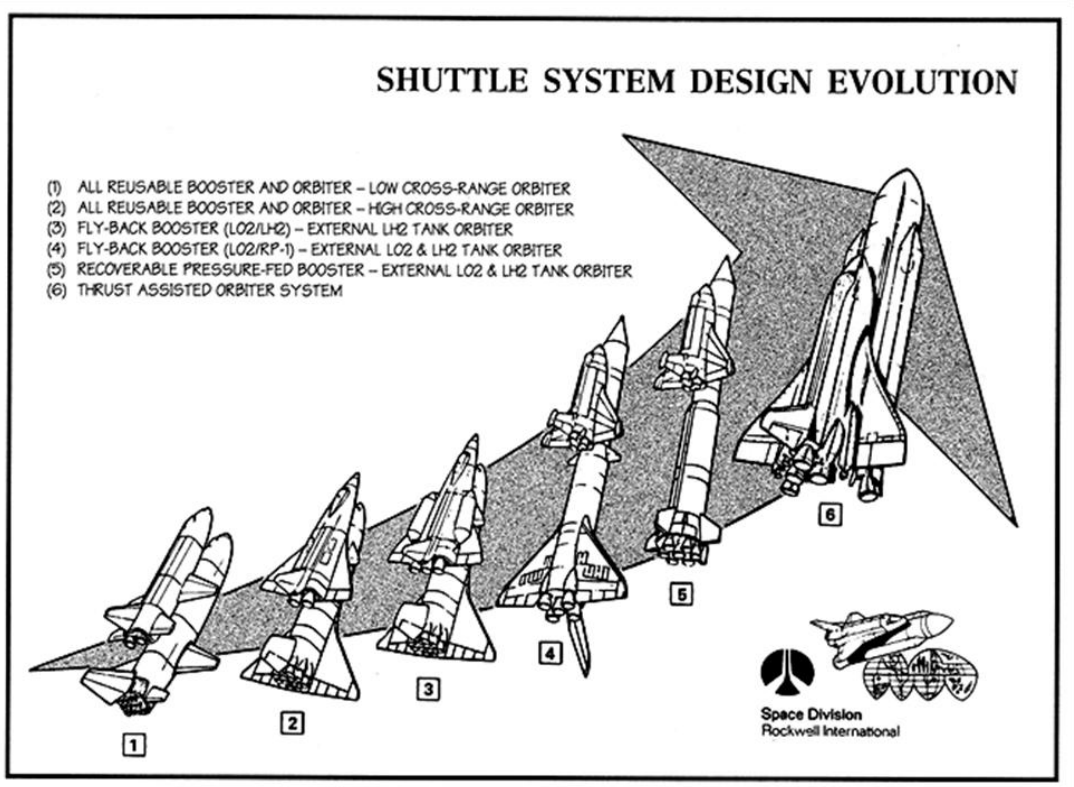
Figure 15-3. Saturn Apollo to the Moon



Figure 15-4. Apollo 11 Lunar Base

Space Shuttle Concept Selection History

The Space Shuttle concept development followed a path quite different from that of Saturn V. Dennis Jenkins' book [Jenkins, 1997] provides an excellent description of the process, both technical and political. The initial idea was to have a fully-reusable system, which would have provided the lowest operational cost for the traffic model envisioned at the time. Many studies involving much effort were focused on two-stage concepts where both the booster and the orbiter were fully reusable. The problem with this approach was the development cost, which was estimated at $13.5 billion. The budget and political situation at that time did not allow this level of funding, but instead limited funding available for development to $5.5 billion. This constraint provided little leeway for concept choices. After exploring what could be developed within the funding constraint, NASA converged on the solid-boosted, stage-and-a-half , partially reusable configuration of the current Shuttle (Figure 15-5).



At the end of the Phase B Extension, North American included this chart in their final report showing the conceptual evolution of the space shuttle from Phase A through Phase C. (North American Rockwell)

Ref: *SPACE SHUTTLE – The History of the National Space Transportation System*, Dennis R. Jenkins, 1992-2001

Figure 15-5. Space Shuttle Concept Evolution

This configuration had few applicable precedents, and the interfaces were complex instead of simple. Also, the extreme efficiencies demanded by the stage-and-a-half approach resulted in a highly sensitive system. New technologies were required in thermal protection, propulsion, and other areas. Consequently, the development program had many difficulties and operation of the Shuttle remains complex and expensive. The concept that was chosen determined the subsequent complexities and costs.

A look at the evolution of Shuttle payload performance illustrates the sensitivity of the configuration. Lesson 13 addressed the performance loss of the Shuttle due to various design problems and issues. Also discussed were the solution approaches including block upgrades. The following table shows the source of those performance losses and some of the solutions applied. [Author's working papers]

Space Shuttle Performance Evolution

Representative Changes

	EVOLUTION ITEM	IMPACT
1.	**Orbiter design against real requirements led to not meeting weight target.**	**-27,000 lbs**
2.	**Environments (loads) increase due to employing quartering high q winds. Several impacts resulted:**	**-5,000 lbs**
	- Baselining monthly mean wind biasing for design	
	- Three-axis and elevon load relief	
	- Increased analysis and testing	
	- Aerothermal/thermal protection system impacts (SRB and ET)	
	- Performance loss from path deviations	
3.	**SRM fixed nozzle was redesigned to a flex gimbaled nozzle for adequate control.**	
4.	**Lift-off loads increases:**	
	- Staggered SSME start and abort shutdown	
	- Ground winds constraints	
	- Weight increases / redesigned Shuttle elements (individual payload impacts not documented)	**-1,200 lbs**
	- Pre-tensioned SRB/ET struts until LWT tank	
5.	**Missed aerodynamic predictions / STS-1 lofting**	**-5,000 lbs**
	- Trajectory constraints on q, SRB separation, alpha trim	
	- Performance loss	
	- TPS impacts on ET and SRB	
	- Reduced launch probability for winter months	**80%**
	- Orbiter wing mods (leading edge)	
	- Day of launch I-load updates	
	- Flight-derived dispersions	
6.	**Isp did not meet design goals**	
	- SSME	**-2 ½ sec**
	- SRM	**-1 sec**
7.	**STS-1 SRB ignition overpressure**	
	- Modified water injection system (water into thrust buckets)	
	- Water troughs over drift hole	
	- Payload loads increases (limited redesign / reverification)	
8.	**Orbiter tile debond and debris damage**	
	- Operations	
9.	**Other**	
	- Landing gear and brakes	
	- Engine upgrades	
	- SSME fatigue and fracture problems	
	- ET fracture control	
	- Isp loss for plugged LOX post	**-1 sec**
	- SRB recovery	

* Water impact damage
* Acoustics (reentry)
* Thermal (reentry)

Approximate Total Payload Loss **- 45,000 lb**

The following graph (Figure 15-6) shows the approximate original Shuttle performance and the approximation of the current performance. This performance is plotted for the Air Force mission mentioned earlier. Listed beside the last two bars are performance enhancement solutions that were applied to partially recover the initial losses.

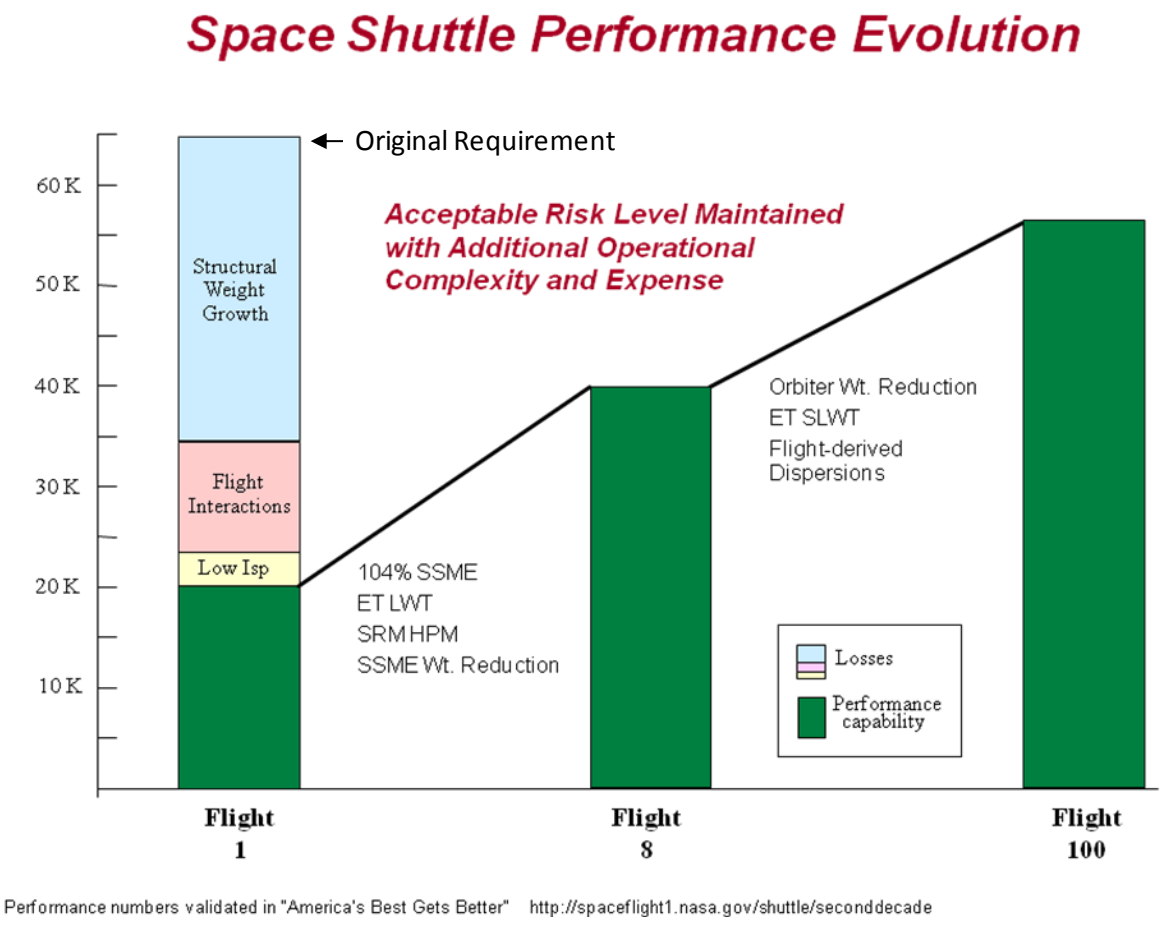


Figure 15-6. Shuttle Performance Evolution

In summary the Shuttle concept was driven by external requirements and constraints which resulted in complex technical problems, high cost, and operational complexity which entailed a very high sustaining engineering effort. The lesson is clear; we must constantly

drive back on performance requirements and make every effort to obtain as robust a system as possible yet still meet the performance and programmatic requirements.

Was the wrong concept decision made? Addressing this issue in a discussion group, John Yardley acknowledged the Shuttle's operational challenges and costs, but said that the Congressional mandate on constraining development cost had been clear. "Had we not made the choices we did, there would not have been a Shuttle program." Given the political reality, the right choice was made.

The Saturn V and Shuttle examples illustrate the power of concept selection on the life cycle attributes of a system. We need to get it right, up front. Choose the best concept for the total life cycle, after exploring all alternatives. Does this mean that the choice will be free of political or policy considerations? No—it never has been and never will be. And those considerations will seldom be aligned with technical preferences. It is the engineers' responsibility to push back on unrealistic or short-sighted requirements. After the issues have been clearly delineated and vetted, it is the task of engineering to achieve the best system within the remaining constraints.

Achieving the best system entails putting sufficient upfront effort in the project and penetrating competing concepts with sufficient fidelity to reveal main issues and design attributes. This will lead to selecting the right concept, thus providing a major determinant of subsequent project success.

- **A key message from Lesson 15 is:**

Challenge Requirements and Constraints
Penetrate Competing Concepts with Sufficient Fidelity

Select the Right Concept

Lesson 16: Requirements Drive the Design

- ***Requirements drive the design. The higher the performance requirements, the greater the sensitivity of the response. Constraints imposed greatly alter the design.***
  - **External/political considerations and constraints strongly drive design**
  - **Technical constraints also drive design, so apply them carefully and judiciously**
  - **Analyze and challenge requirements, constraints, and criteria at all levels to obtain the greatest possible engineering design flexibility**
  - **Do not accept unrealistic schedules and budgets**
  - **Poorly defined and vacillating top-level requirements cost the program dearly in terms of wasted design effort and compromised design**

- **Over-specified criteria suppress the creativity of the design engineer**
- **Criteria must be tailored for the specific project**

"For any given set of TRL's and basic performance requirements there is a natural shape/size. If you push in one area it will push out in another, creating technical problems and cost and schedule over-runs." – Garry Lyles

Requirements are the mantle that determines the design, according Pugh in his book *Total Design*. A principle that we have learned the hard way is that "The higher the performance requirements the greater the sensitivity of the design to all parameters which influence the design and the response of the design". External/political considerations as well as constraints drive the design, many times in undesirable and or unpredictable ways and should be scrubbed to the greatest degree possible. This includes pushing back on unacceptable cost and schedules. Another area that greatly influences requirements is that technical people tend to be very conservative in the development of the design criteria. These criteria should be tailored for each project and be at the minimum required for adequate or acceptable risks.

Examples:

Sensitivity Versus Performance
Quotes from Pye and Others
SSME Experience of Major Failures
    Fatigue and Fracture Problems
    LOX Post Failures
    4,000 Hz LOX Splitter Vane Problem
    Additional SSME Problems
Super Lightweight External Tank

Sensitivity Versus Performance

A principle we learned many years ago in working the numerous SSME problems and failures says: The higher the performance requirements the greater the sensitivity of the system to any parameter uncertainties. Figure 3-3 was a generic plot of the principle. It is repeated here as Figure 16-1. There are two curves shown: one for current technology and one for advanced technology. The shape of the curve does not change with improved technology but shifts down and to the right indicating that one way to reduce sensitivity is to improve the system technologies. The curve also indicates that the higher the performance requirements the greater the effort and depth of analysis and test that will be required to design and operate at that point.

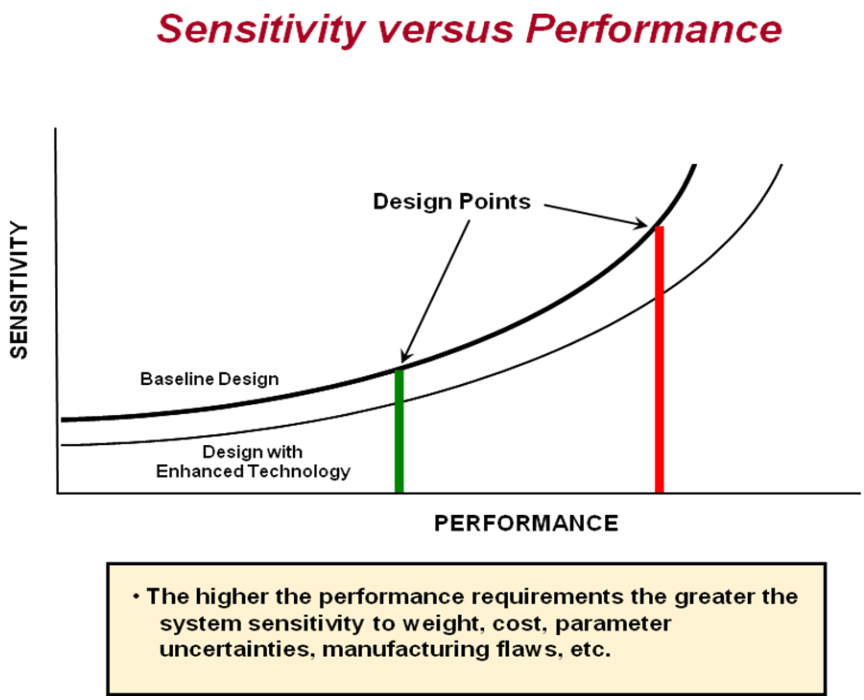


Figure 16-1. Sensitivity versus Performance

Quotes From David Pye & Others

We have collected several quotes that deal with the principle of sensitivity versus performance requirements that are given below without comment.

- "When you put energy into a system you can never choose what kind of changes shall take place and what kind of results remain. All you can do, and that only within limits, is to regulate the amounts of the various changes. This you do by design" - David Pye

- "The requirements for design conflict and cannot be reconciled. All designs for devices are some degree failures…The designer or his client has to choose to what degree and where there shall be failures." - David Pye

- "All structures will be broken or destroyed in the end. Just as all people will die in the end. It is the purpose of medicine and engineering to postpone these occurrences for a decent interval. The question is: What is to be regarded as a decent interval?" - J.E. Gordon

- "Mother Nature does not read our paper. If we don't follow her way, she lets us fail." - German Proverb

- "Paper is patient. Sense or nonsense, it accepts what we write." - German Proverb

- "Cooperate with Mother Nature to the maximum extent possible; minimum energy solutions are almost always the most reliable." - John Junkins

- "To understand what engineering is and what engineers do is to understand how failures can happen and how they can contribute more than successes to advance technology." - Henry Petroski

- "All design is essentially creative work and the state of mind of the creator is everything; which is to say that the state of mind of the designer is likewise everything where design is concerned" **-** Unknown source

SSME Experience OF Major Failures

The performance, weight, and geometric requirements for the SSME Block II are shown below in Figure 16-2. These requirements were derived from Space Shuttle flight requirements that were significantly influenced by the Air Force for payload size and weight and by NASA for a reusable spacecraft. These types of requirements have resulted in an engine with a very high power density of about (879 HP/#). The SSME's have achieved a 100% flight success and a demonstrated reliability of .9995. There have been six configurations leading to the current Block II configuration. The high chamber pressure (~3000 psi), chamber temperature (~6000° F), and high turbopump speeds (fuel pump ~36,600 rpm) were the root causes of many problems because they were out of the design experience band. For example, a number of problems were related to metal fracture and fatigue failures and that resulted in rework cycles.

Maximum Thrust: (109% Power Level)	At Sea Level: In Vacuum:	418,000 lb 512,300 lb
Throttle Range:	67% – 109%	
Pressures:	Hydrogen Pump Discharge: Oxygen Pump Discharge: Chamber Pressure:	6,276 psia 7,268 psia 2,994 psia
Specific Impulse: (In Vacuum)	452.3 sec	
Power: High Pressure Pumps	Hydrogen: Oxygen:	71,140 hp 23,260 hp
Area Ratio:	69:1	
Weight:	7,774 lb	
Mixture Ratio: (O/F)	6.03:1	
Dimensions:	168 in. long 96 in. wide	
Propellants:	Fuel: Oxidizer:	Liquid Hydrogen Liquid Oxygen

Figure 16-2. Block II Space Shuttle Main Engine Requirements (109% Power Level)

The development cost of the SSME was about $2.5 Billion (1996 dollars) and required 163 rework cycles to achieve a certified man rated engine, see references [Havskjold, G., Parts 1, 2, and,3, 2009]. As shown in figure 12-1 about 73% of the development cost was related to correct actions (rework cycles).

The following picture is a typical SSME in the test stand during a hot fire test.



Figure 16-3. Space Shuttle Main Engine Firing

The SSME is a staged combustion engine that has two low pressure pumps that attach to the Orbiter, two high pressure pumps attached to the engine. The LOX pump pairs and the fuel pump pairs are connected with ducts which have sections with bellows so that the engine can be gimbaled. The other elements are shown on Figure 16- 4, such as, the nozzle, combustion chamber, preburners, controllers etc. There were many problems and failures of these elements during development testing. [Cikanek, 1987] The engine that is flying today has had six block upgrades to solve these various issues, some that have already been discussed in previous sections.

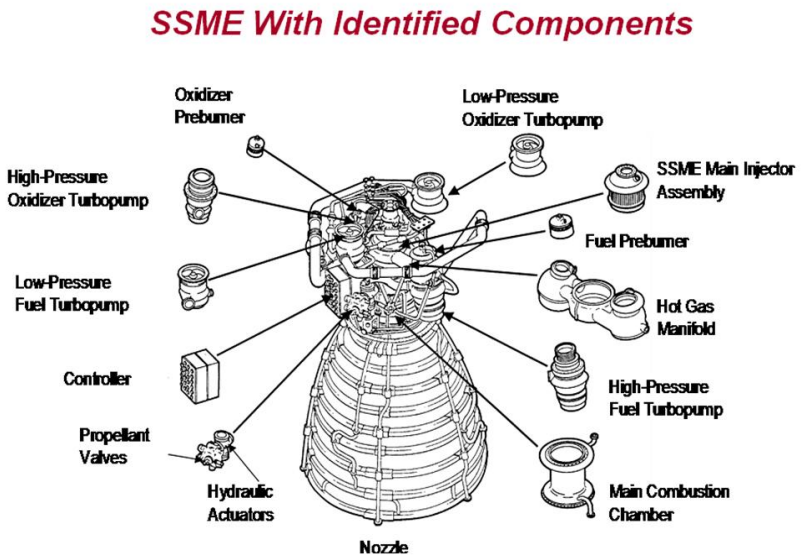


Figure 16-4. SSME Components

The total SSME component corrective actions during full scale development is summarized in Figure 16-5, see references [Havskjold, G., Parts 1, 2, and, 3, 2009]. As can be seen there were 163 rework cycles, but the cost of about half of these rework cycles was very little.

Engine	Number of Failure Modes Internal to Engine	Turbomach-inery	Combustion Devices	Engine System	Valves	Intercon-nects	Other
SSME	163	51 HPOTP 42 HPFTP	8 Nozzle 6 Main inj 3 Fuel prebr 0 MCC	17			37 heat exch, low press pump, sensors, controller

Figure 16-5. Total Failures During SSME Development

However, shown in Figure 16-6 are 38 significant failures that occurred during development testing. There were eighteen $50 million engines totally consumed. Figure 16-6 provides an indication of the variety of different hardware elements that failed. The cost of each of these failures was $30 Million or greater. Since the SSME was an advanced technology engine there was a lack of understanding of environments, hardware characteristics, advanced computational tools, and overall design experience.

Failure Number	Date	Test Number	Failure	Engine S/N	Rocketdyne Report
1	March 24, 1977	901110	HPOP Pri Lox Seal	0003	RSS-8595-11
2	August 27, 1977	901133	Fuel PB Burnthrough	0004	none
3	September 8, 1977	901136	HPOP Bearing	0004	RSS-8595-13
4	November 11, 1977	902095	HPFP Turbine Blade	0002	none
5	December 1, 1977	901147	HPFP Turbine Blade	0103	none
6	March 31, 1978	901173	Main Injector Lox Post Failure	0002	none
7	June 5, 1978	901183	Main Injector Lox Post Failure	0005	none
8	June 10, 1978	902112	Eng Fuel Supp Blockage	0101	RSS-8595-14
9	July 18, 1978	902120	HPOP Cap. Probe	0101	RSS-8595-15
10	October 3, 1978	902132	MOV Improperly Installed	0006	none
11	December 6, 1978	901222	HX Failure	0007	RSS-8595-17
12	December 27, 1978	901225	MOV Freting	2001	RSS-8595-18
13	May 14, 1979	750041	Nozzle Steerhorn Failure	0201	RSS-8595-19
14	July 2, 1979	SF06-1	MFV Housing	2002	RSS-8595-20
15	November 4, 1979	SF06-3	Nozzle Steerhorn Failure	2002	RSS-8595-21
16	July 12, 1980	SF10-1	FPB Burnthrough	0006	none
17	July 23, 1980	902198	Main Injector Lox Post Failure	2004	none
18	July 30, 1980	902284	MCC Lee Jet	0010	RSS-8595-22
19	January 28, 1981	901307	FPB Injector Lox Post	0009	RSS-8595-24
20	July 15, 1981	901331	Main Injector Lox Post Failure	2108	none

21	September 2, 1981	750148	Main Injector Lox Post Failure	0110	None
22	September 21, 1981	902249	HPFTP Blade Failure- FPB Deactivated Lox Posts	0204	RSS-8595-23
23	October 15, 1981	901340	Fuel Pump Turnaround Duct	0107	none
24	February 12, 1982	750160	FPB Fuel Supply Blockage - Ice	0110F	RSS-8595-27
25	April 7, 1982	901364	Kaiser Hat Nut	2013	RSS-8595-28
26	May 15, 1982	750168	OPOV Leak	0107	RSS-8595-29
27	August 27, 1982	750175	HPOP Disch. Duct (U/S FM)	2208	RSS-8595-30
28	February 14, 1984	901436	Coolant Liner Failure	0108	RSS-8595-37
29	February 4, 1985	901468	FPB Instr Boss Crack	0207	none
30	March 27, 1985	750259	MCC Outlet Neck Blow	2308	RSS-8595-39
31	July 1, 1987	902428	OPB Injector Braze	2106	none
32	June 6, 1989	902471	LPF Flex Joint	2206	RSS-8595-43
33	June 23, 1989	904044	HPOP Pump End Bearing	0212	RSS-8595-44
34	November 6, 1991	901674	CCV Failure	2032	
35	June 18,1992	902562	OPOV Leak	2107	
36	January 25,1996	901853	HPFTP Blade Failure	0523	
37	August 27, 1997	901933	Nozzle Tube Rupture	0524	
38	June 6, 2000	902772	FPB Fuel Manifold Tape Contamination	0523	

Figure 16-6. Significant SSME Failures

In a comparison of the SSME to the F-1 and J-2 engines, it can be seen that all three are advanced technology engines and their technical uncertainty factors are high and similar. As a consequence their development costs and their rework cycles are similar. To reduce development costs in the future, it is clear that the technical uncertainty factor has to be reduced. Finally, it is noted that the SSME is the only reusable rocket engine certified for human flight.

SSME Fatigue and Fracture Failures

In the baseline design of the SSME there were *no fracture mechanics design requirements and the material properties were based upon predicted minimum values*. A fracture mechanics plan was established in 1973 after the basic design was completed and drawings released. In May 1980 a structural audit was completed [Mulloy, et.al., 1980] before the first flight. The main findings relating to structural practices were: the structural design data base of the SSME is mature and analytical practices are state-of-the- art; material properties are *predicted minimums*. The main findings relating to component assessments were: eleven components did not meet verification criteria and of these three had failure probabilities of an order of magnitude less than others. Nozzle failures are a dominant factor in reducing structural criteria and that is a result of process control and contamination not structural design deficiencies. The major findings related to structural reliability were: a comparison of the SSME to The J-2 indicated the emanation rate of UCR's was similar and failure rate trends of both engines were similar with reliability expected to improve substantially with increased firing time. As of March 30, 1980 the probability of a structural failure of an STS-1 engine during a mission resulting in loss of life or mission was 0.05.

In the activity associated with the 1973 fracture mechanics plan, 150 welds were identified as “fracture critical”. They were implemented based on NDE improvements as opposed to redesign [Rocketdyne Presentation, 1989]. Prior to 51L, welds were selectively assessed. After 51L, the Critical Items List (CIL) assessment for welds was expanded to identify all critical welds. The idea was to prepare rationale for retention for all welds prior to flight, identify and implement corrective action as required, and establish a weld data base for rapid screening of future weld issues. At that time, the material data base contained 1150 pages of design properties. Forty-three percent of these were *predicted minimums* with some unverifiable sources, extrapolations, and empirical relationships. The material data base was upgraded to include 26 SSME materials tested in 8500 tests with 1400 in high pressure hydrogen. In addition, the fracture mechanics data base was expanded including weld defect testing.

During the weld assessment [Rocketdyne Presentation, 1989], the FMEA/CIL weld statistics included 3,165 welds. Initially, there were about 2000 welds operating at yield conditions and this condition resulted in failures during hot fire testing. The system was sensitive to manufacturing tolerances resulting in eccentricities and misalignments in weld offsets. As can be seen in the illustration in Figure 16-7 below, there were weld mismatches in duct joints. Wax molds were required for each weld to determine the exact geometry for structural lifetime assessments.

A total weld count was undertaken on the SSME Block I configuration and there were 23,055 welds; 10,698 welds were made by Prattt & Whitney Rocketdyne and 12,357 made by suppliers where 12,000 of these were resistant spot welds on metallic TPS. [Zimmerman, 2010] A weld comparison of the SSME Phase II configuration (1988) to the presently flying Block II configuration shows that over 1000 welds have been eliminated from the engine in the combustion devices and the turbopump components. [Benefield, 2010]

Although there were no fracture mechanics requirements and material properties were predicted minimum values in the baseline design, material properties have since been established through laboratory and hot fire testing. The weld joints margin and reliability have been increased by improvements in weld processing, verification and inspection, analytical assessment, design, hot fire measurement, and materials testing.

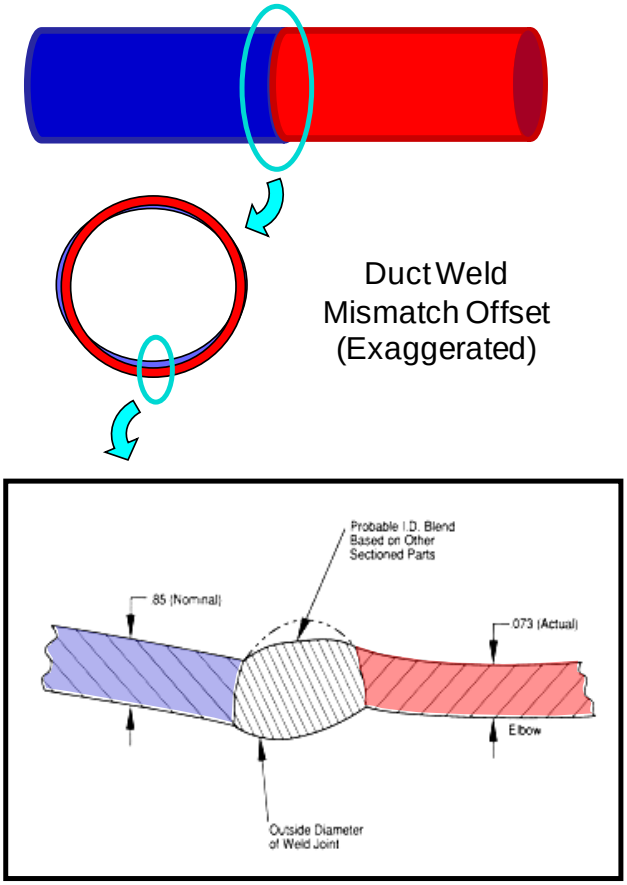


Figure 16-7. Weld Offset Mismatch

SSME Fatigue and Fracture LOX Post Failures

During the development of the SSME there were five engine failures caused by high cycle fatigue (HCF) of LOX posts in the main injector assembly. During inspection of all other injectors, there were an additional two found with cracked LOX posts. Shown in Figure 16-8 below are the power head, main injector, and turbo-pump assemblies.

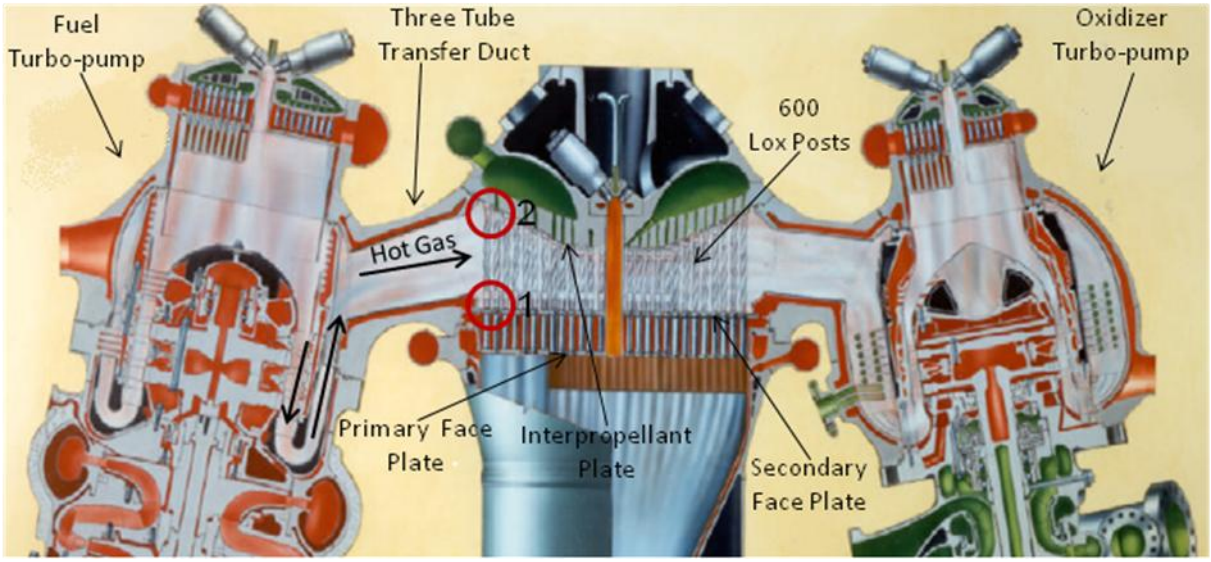


Figure 16-8. Power Head, Main Injector, and Turbo-pump Assemblies

There are 600 LOX posts in the injector that transport LOX to the primary face plate of the injector. The HCF failures were caused by static stress (thermal and pressure) and dynamic stress i.e., vortex shedding about the posts. About 70% of the hot gas comes from the fuel side while 30% comes from the oxidizer side [Pelaccio, et. al, 1984]. The hot gas from the fuel turbine swirls as it goes through an 180° turn and then abruptly enters the three tube transfer duct, see Figure 16-8. This highly energetic, non-uniform, separated, and turbulent flow then impinges on the LOX posts. The failures resulted from the 70% hot gas flow from the fuel side and were in the regions indicated by the circles 1 and 2.

Shown in Figure 16-9 are failed LOX posts from the first incident (Engine E0002). On the left side of the figure, the deformation due to loading can be seen and on the right side, the post burn out can be seen as viewed looking at the primary face plate.

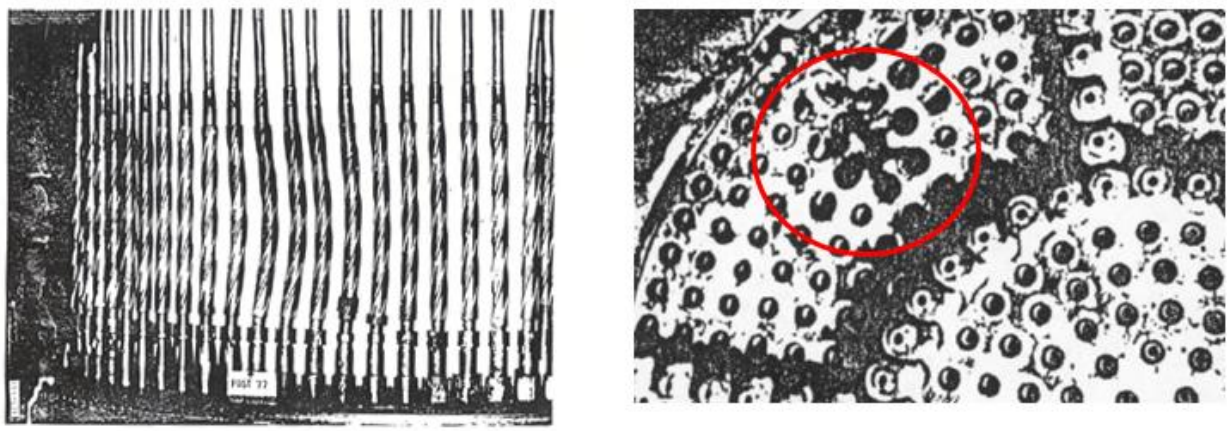


Figure 16-9. Lox Posts Failures (Engine E0002)

Initially cracking occurred in the threads of the LOX posts tips as shown in Figure 16-10. Once there was a through crack, high pressure LOX flowed into the fuel region of the post causing a fire in the LOX post. When the post burned through, it allowed LOX flow into the fuel rich region between the secondary and primary face plates of the injector causing burning of other LOX posts between the face plates. The region of the failure is shown in Figure 16-8 by circle 1.

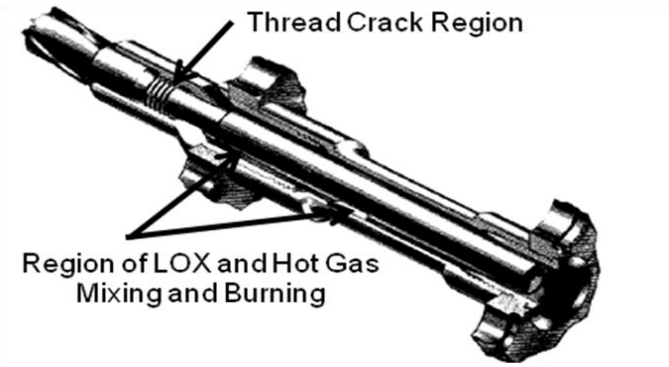


Figure 16-10. LOX Post Failure Mechanism

LOX post failures as described above were on: Engine E0002, 3/31/78; Engine E0005, 6/5/78; and Engine E2004, 7/23/80. [Hopson, August 1980] After Engine E0005 failure, flow shields were added, but with a different injector. After testing cracked shields were found but no burn-throughs. The next engine with flow shields was Engine E2004. The purpose of the flow shields was to divert the flow and carry some of the load. However, posts still cracked and burned but around the side of the injector where there were no shields, see Figure 16-11.

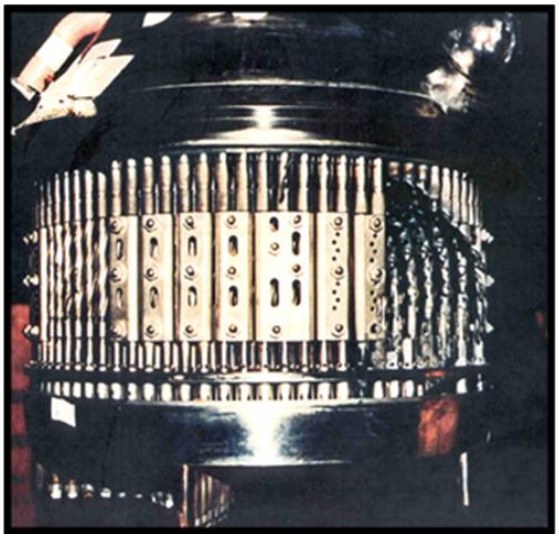


Figure 16-11. Engine E2004 Injector Failure

Locations of LOX failures on engines E0002, E0005, and E2004 are shown in Figure 16-12.

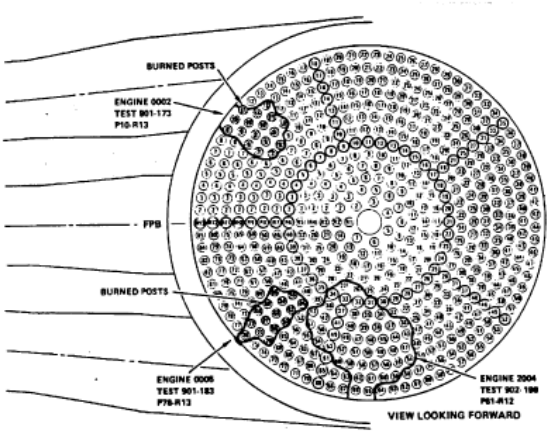


Figure 16-12. LOX Post Failure Pattern

In order to continue engine development testing, additional modifications were made to the injector. The LOX posts were made of 316L Cres steel and for engine E2108 the material of the tips of the posts was changed to Haynes 188. In addition, flow shields were put on all injector posts around the outside circumference of the injector. In the test of engine E2108 (7/15/81) [Hopson, July, 1981] and engine E0110 (9/2/81) [Hopson, September, 1981], LOX posts again failed due to HCF. However, these cracks occurred at the top of the posts in the inertial weld region in the vicinity of the interpropellant plate, see Figure 16-8, circle 2. LOX flowed through the cracks into the region between the interpropellant plate and the secondary face plate causing a fire. It is thought that the E2108 failure resulted from a more severe (unanticipated) flow environment in going from RPL to FPL and from modifications to the fuel turbopump to achieve FPL. The LOX posts were then redesigned for the more severe environment. In the case of the subsequent engine E0110 failure, inspection of some of the undamaged posts revealed manufacturing defects in the inertia weld even though there had been pretest inspections. Inspection procedures were improved to mitigate future failures. Eventually, all LOX post material was changed to Haynes 188. The changes made to the injector assembly resulted in a reduction of the engine I_{SP} of about 1.5 seconds (600 pound payload reduction).

In order to increase margin and performance while improving safety and reliability, efforts were taken to redesign the hot gas flow path on the fuel side of the hot gas manifold. The three tube transfer duct was changed to a two tube transfer duct with an increase in area of 30%; increased the turnaround duct exit area by 68.5%; and increased the fishbowl cross-sectional area 75.3%. These increased cross-sectional areas have the effect of reducing the dynamic pressure ($\frac{1}{2}\rho V^2$) and thus the static and dynamic flow loads. Then inlet and outlet regions of the tubes were rounded. The transfer ducts were flared into the fuel preburner housing and main injector housing. In addition, contoured turning vanes were used to make the flow into the transfer ducts from the fuel turbine more uniform and decrease the fuel turbine exit pressure gradient. The effect of these changes was to make the flow more

uniform [Pelaccio, et. al., 1984]. In the two tube transfer duct design 72 welds were eliminated and there were 52 fewer detailed parts. This lead to a 40% cost reduction in comparison to the three tube system [Jue, 1997].

Shown in Figure 16-13, are blended pressure contours of the three tube and two tube transfer duct configurations obtained from CFD computations [Ames Research Center, 2000]. It can be seen that the flow of the two duct system is more uniform than the three duct system, thus reducing loads and flow losses.

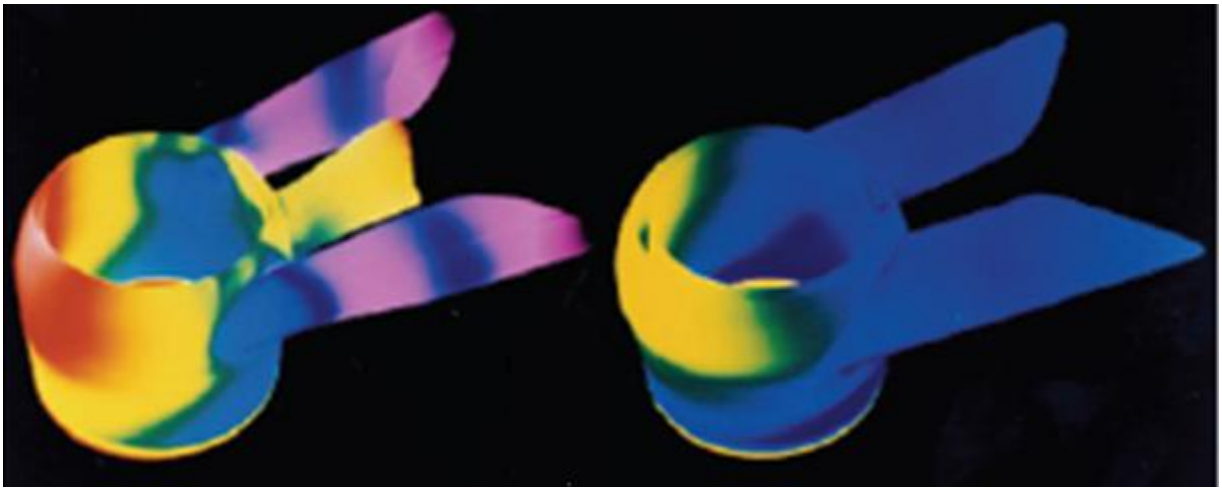


Figure 16-13. Fuel Side of the Hot Gas Manifold

Shown in Figure 16-14 is a comparison of the circumferential total pressure distribution of the three tube and two tube transfer ducts. It can be seen that the two tube system is significantly more uniform than the three tube system.

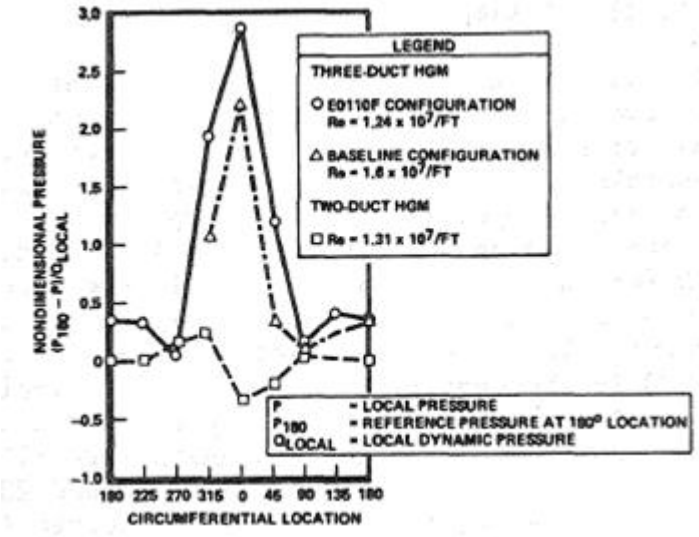


Figure 16-14. Total Pressure Variation Downstream of the Turnaround Duct 180°-Turn

In the initial development of the SSME the severity of the flow environments in the hot gas manifold were not anticipated. There were no adequate requirements regarding flow static and dynamic environments or effects of flow uniformity in the design of the gas path or injector. The consequences were failures of five engine injectors. In addition, there were two distinct types of failures. Extensive measurements were made in hot fire tests as well as scale model tests to finally understand the flow environment and design out failure mechanisms. Subsequently, this configuration became the baseline and was certified for flight.

This configuration was designated Block I and was first flown on the STS-70 flight in July 1995. The SSME has been further upgraded and the changes describe herein are in those upgraded engines.

4000 Hz LOX Splitter Vane Problem

During development testing of the SSME, the power levels of the engines were increased incrementally over time to assess the overall performance and condition of the hardware as the power level increased. When the power level was increased to109% accelerometers on the gimbal bearing of engine E2025 recorded high vibration levels that were close to 100 g's RMS at a frequency of 4000Hz, [Jones, et, al., 1994]. The source of the vibration was traced to LOX inlet/tee location on the SSME Powerhead, see Figure 16-15.

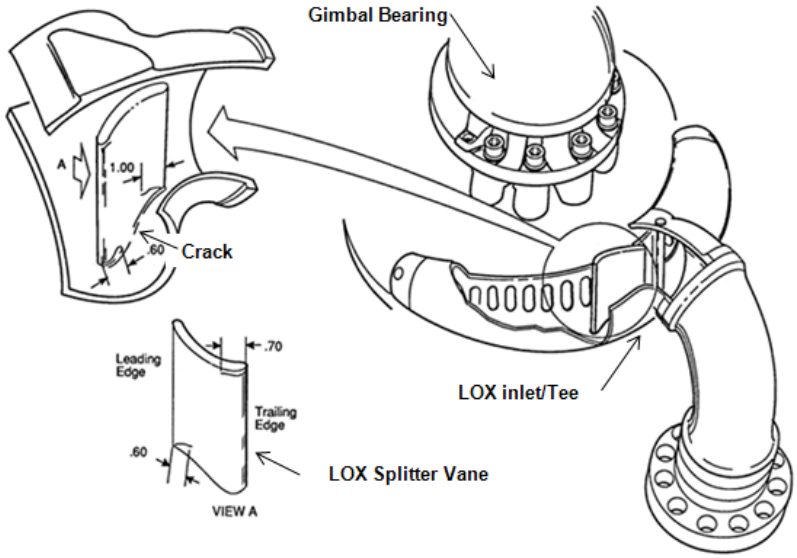


Figure 16-15. Gimbal Bearing, LOX Inlet/Tee, and Splitter Vane

The E2025 engine hardware was examined and there was no evidence of damage. A review of data from 22 engines and 14 power heads revealed that only engines tested at power levels above 100% (and not all of them) had the 4000Hz vibration. Inspection of the hardware revealed that it was within manufacturing tolerances. However, there was cracking on one vane near the outer shell of the tee on engine E2116 and on engine E0005B both vanes were cracked.

Simultaneously, structural and CFD modeling, water flow and LN_2 tests, and careful examination of the hot fire vibration data revealed vortex shedding from the LOX inlet Tee's splitter vanes' blunt trailing edge at a frequency of 4000Hz. [O'Connor, et. al., 1988] It was determined that this frequency tuned with the vane's first torsional mode frequency resulting in high vibration levels. While tuning is the most significant factor, the high amplitudes were the result of the flow's high dynamic pressure ($\frac{1}{2}\rho V^2$) of about 275 psi.

To eliminate the high vibration levels two distinct changes were made to the hardware. One change was to asymmetrically bevel the trailing edge of the vane to suppress the vortex shedding. The second change was to scallop the leading edge of the vane to shift the torsional mode frequency higher and out of the operational range, see Figure 16-16. It also reduced the turbulence induced background noise.

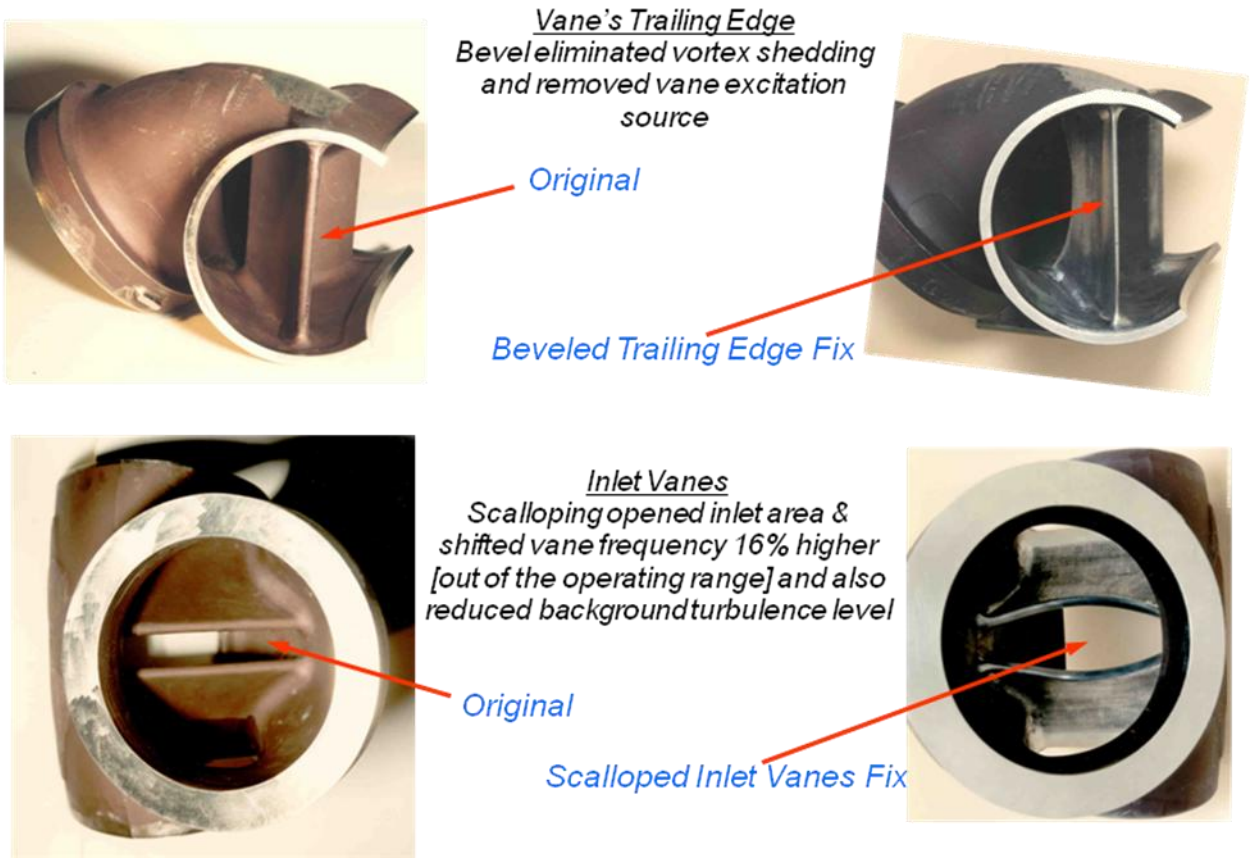


Figure 16-16. 4000Hz Splitter Vane Fixes

These changes were developed after extensive analysis and testing and were verified by water flow testing. The bevel at the vane's trailing edge completely eliminated the vortex shedding source. The inlet vane change was made in order to provide an added margin of safety. These fixes were eventually certified on hot fire testing and all engines were appropriately modified. It was first flown on STS-26 in September 1988. Both 4000 Hz changes described above were first implemented on E0212. Engine E0212 (which was originally named E2025) provides a direct comparison, with and without the 4000 Hz modification, and is shown in Figure 16-17. This is the gimbal bearing accelerometer measurement and it dramatically demonstrates the effectiveness of the fix.

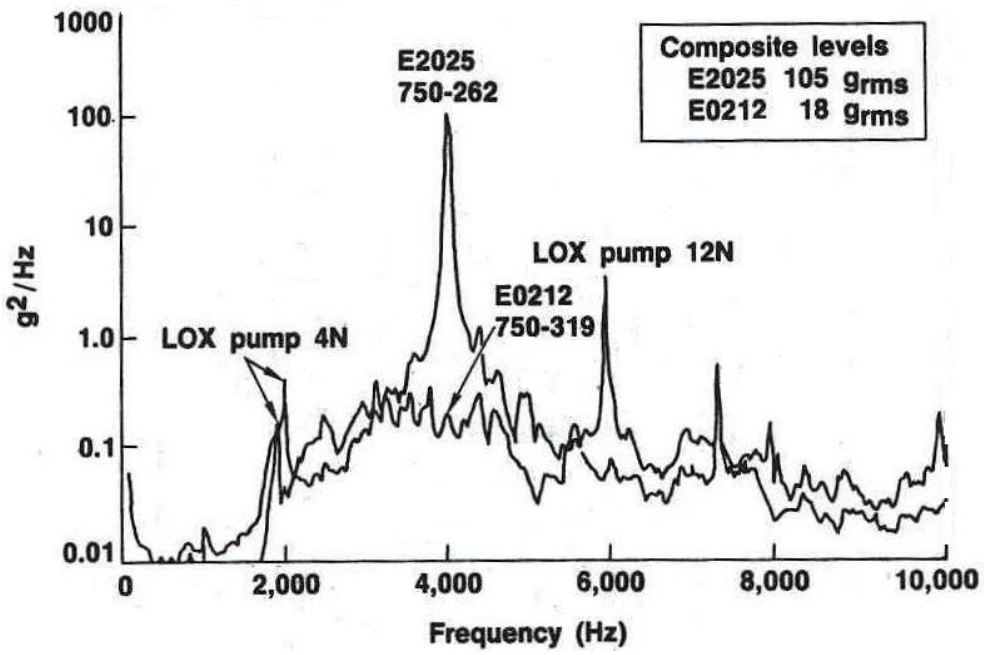


Figure 16-17. 4000 Hz Eliminated

The 4000Hz LOX splitter vane is a situation where the hardware was manufactured and inspected and met design specifications. However, this falls into a category of an unknown/unknown, since requirements were not anticipated to adequately design the splitter vane system. As the power level of the engine increased the vortex shedding frequency tuned with the vane first torsional mode frequency along with the condition of a high dynamic pressure resulting in vane cracking. This failure was caught in the act before it consumed any engines.

Additional SSME Design and Operational Problems

One SSME Subsystem is shown on Figure 16-18 as an example of the historical data available.

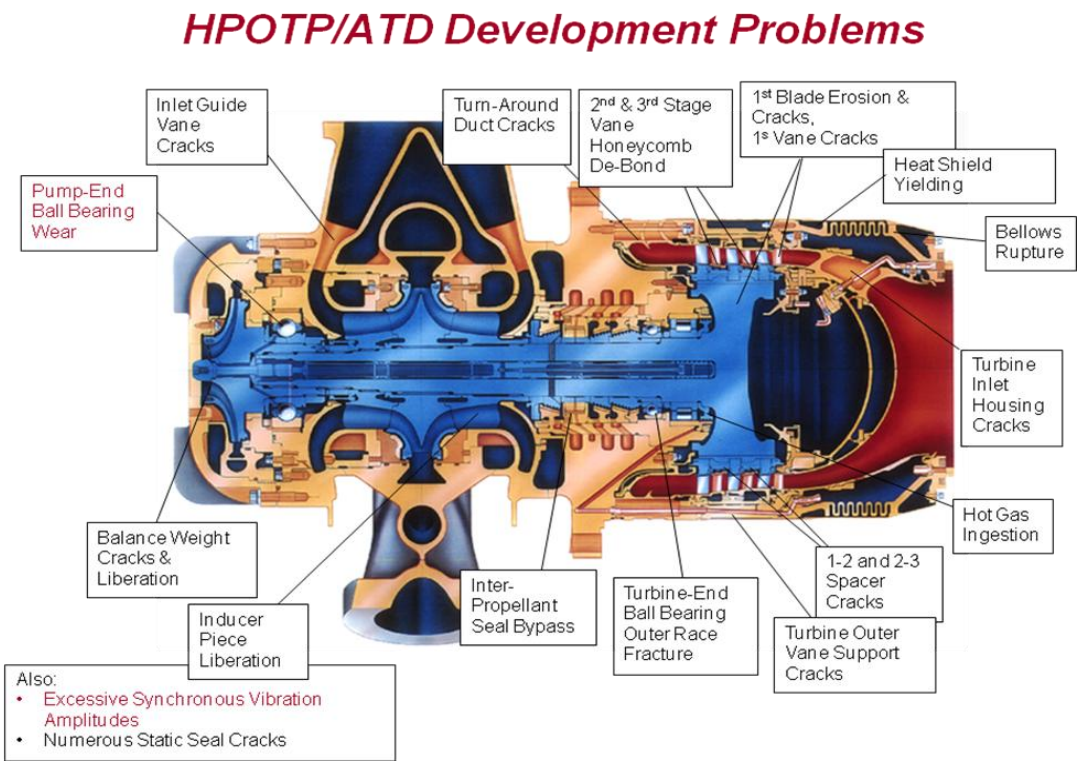


Figure 16-18. Development Problems of the SSME Alternate High Pressure LOX Turbopump

Super Lightweight External Tank

The requirements for the Space Shuttle to launch and service the International Space Station (ISS) resulted in the need to increase the Shuttle ascent performance. The Shuttle had been flying several years and was basically a fixed configuration. Therefore the major approach open for performance increase was a weight reduction program of the major components of the Shuttle. The External Tank was a prime target for mass reduction, since a one pound tank weight reduction produced a one pound performance increase. Figure 16-19 illustrates that by changing the material of the tank to aluminum lithium and changing its construction to orthogrid while maintaining its external configuration and tank volume saved 7,500 pounds of weight and resulted in a payload increase of 7,500 pounds. To accomplish this dramatic change, a reverification of the structure and the fracture mechanics program was required. [Presentation by Neil Otte, Ryan's working papers] Also the manufacturing process and the weld repair process had to be changed and verified. Protoflight testing of the hydrogen tank in conjunction with proof test was an additional complication that required each tank built to have the protoflight test to insure the tank had adequate buckling margins. The lesson is clear-- changing requirements during operations of a program adds additional risks and cost.

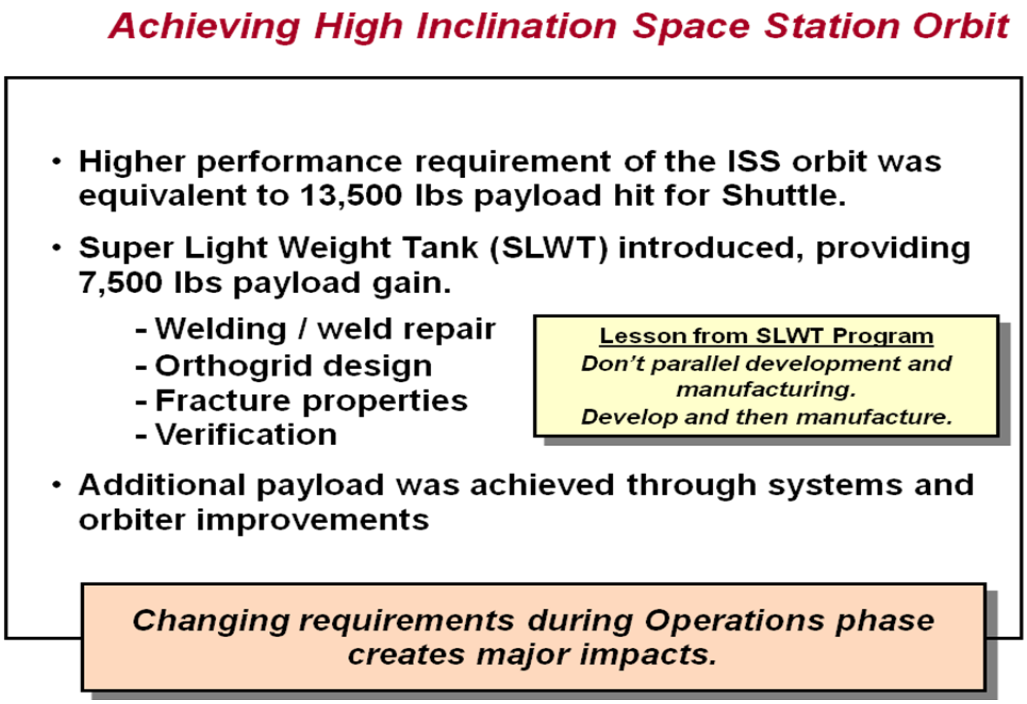


Figure 16-19. Impact of ISS Orbit Requirements on External Tank

- **A key message from Lesson 16 is:**

High Performance Requirements Cause

High Power Density
High Sensitivity
Unwanted Interactions

which result in

Lower Margins
Higher Risk
Higher Cost
Operational Complexity

Push Back on Requirements and Strive to Achieve Robustness.

Lesson 17: Designing for The –ilities and Cost

- **The –ilities and Cost Must Be On the Design Table If We Are To Be Successful**
- **Challenge Requirements and Constraints**
- **Penetrate Competing Concepts with Sufficient Fidelity**
- **Select the Right Concept**

The success of a launch system is measured not only by its physical performance parameters such as how much payload it can lift to orbit, but by its reliability, its operability, how much it costs, and numerous other attributes. A successful system must be designed from the start for these "-ilities" and costs as well as for physical performance. In order to do this, the designer must be provided functional relationships that connect the design variables available to him/her with how they affect vehicle's future operation—its -ilities and costs. We call this "putting the –ilities and cost on the design table" (or more currently, "on the CAD system"). The –ilities and costs can then be part of the system optimization along with physical performance.

Examples

- Space Shuttle Day of Launch I-Load Update (DOLILU)
- Designing Considering the Total Life Cycle
    - How We Previously Designed for the –ilities and Cost
    - How We Should Design for the –ilities and Cost

We will first look at the Shuttle Day of Launch I-Load Update process as an example of operational complexity not foreseen in the initial design, then compare how we have designed for the –ilities and cost in the past with how we should design for them in the future.

Shuttle Day of Launch I-Load Update

Wind biasing as a means of reducing structural load was discussed in Lesson 6 on the Balancing Act. There we noted that the Shuttle was intended to be designed with enough structural strength to allow launch using a trajectory biased for the monthly mean wind. Because of the aerodynamic anomaly described in Lesson 4, the Shuttle in fact wasn't strong enough to be launched with monthly mean biasing, but required biasing for the winds measured on the day of launch. A Day of Launch I-Load Update (DOLILU) process was required, which entailed significant operational complexity and expense. Wind biasing involves calculating the guidance parameters based on the bias wind, and loading them into the flight computer. With monthly mean biasing, this process can be accomplished and verified well ahead of launch day, but with day-of-launch wind biasing, all this must be done in a short time span based on winds measured a few hours prior to launch. [Norbraten, 1992]

Figure 17-1 shows some example elements of the DOLILU process for Shuttle. At several times prior to launch, balloons are used to measure winds and atmospheric parameters. The wind measured at L minus 3:45 hours is smoothed and used to bias the first-stage guidance commands so that if the vehicle in flight should experience that same wind, there would be no wind-induced loads. In actuality, the wind will change between the time the balloon measures it and the vehicle flies through it, but biasing to the balloon-measured wind will minimize the wind-induced load. The biased first-stage guidance commands that have been generated must be verified, approved, and then loaded into the flight computer prior to launch. The trajectory command set is called an I-load.

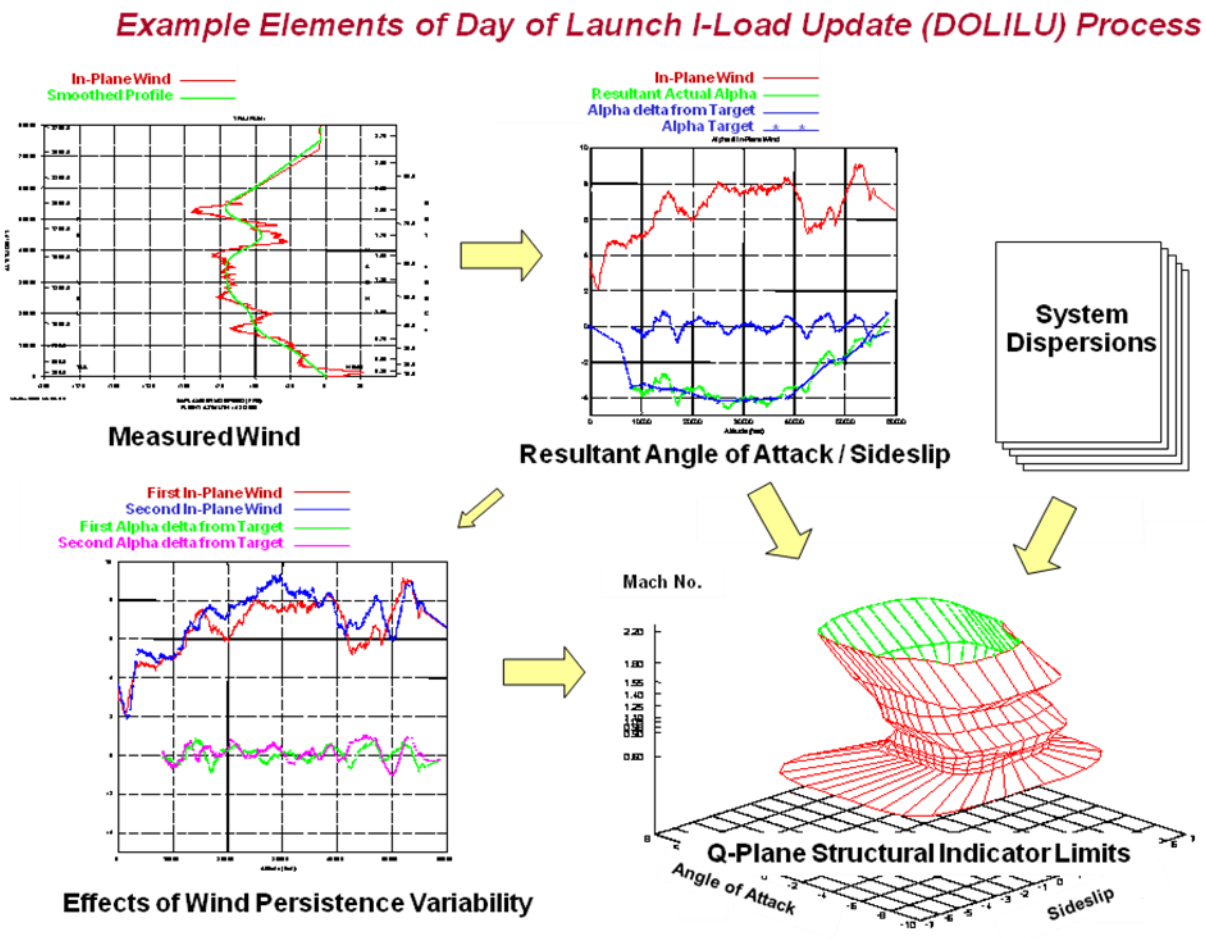


Figure 17-1. Elements of Day of Launch I-Load Update (DOLILU) Process

The biased trajectory profile must be assessed to ensure that when the vehicle flies that profile, the loads will not exceed the structural capability. This requires taking into account the many vehicle parameter variations and the variability of the wind between the time of balloon measurement and launch. These variations are combined statistically as "knock-down" factors on the structural capability to produce load indicator boundaries called Q-planes as a function of altitude. The simulated response of the vehicle using the I-load must lie within these boundaries; otherwise, the launch is no-go. An additional Q-plane check is made using the wind measured by a subsequent balloon closer to launch (L minus 2:00 hours). There is sufficient time before launch to make this verification check, but not to create an updated I-load set.

Figure 17-2 shows some of the process, with the balloon releases indicated by stars along the timeline leading up to launch (L-0). Wind data from the L-3:45 balloon is combined with other information to create the I-load for the onboard flight computers. For redundancy, two organizations independently generate I-load input in parallel, which must compare identically before this flight-critical item is loaded onto the flight computers. The load is them read back to the ground systems for confirmation.

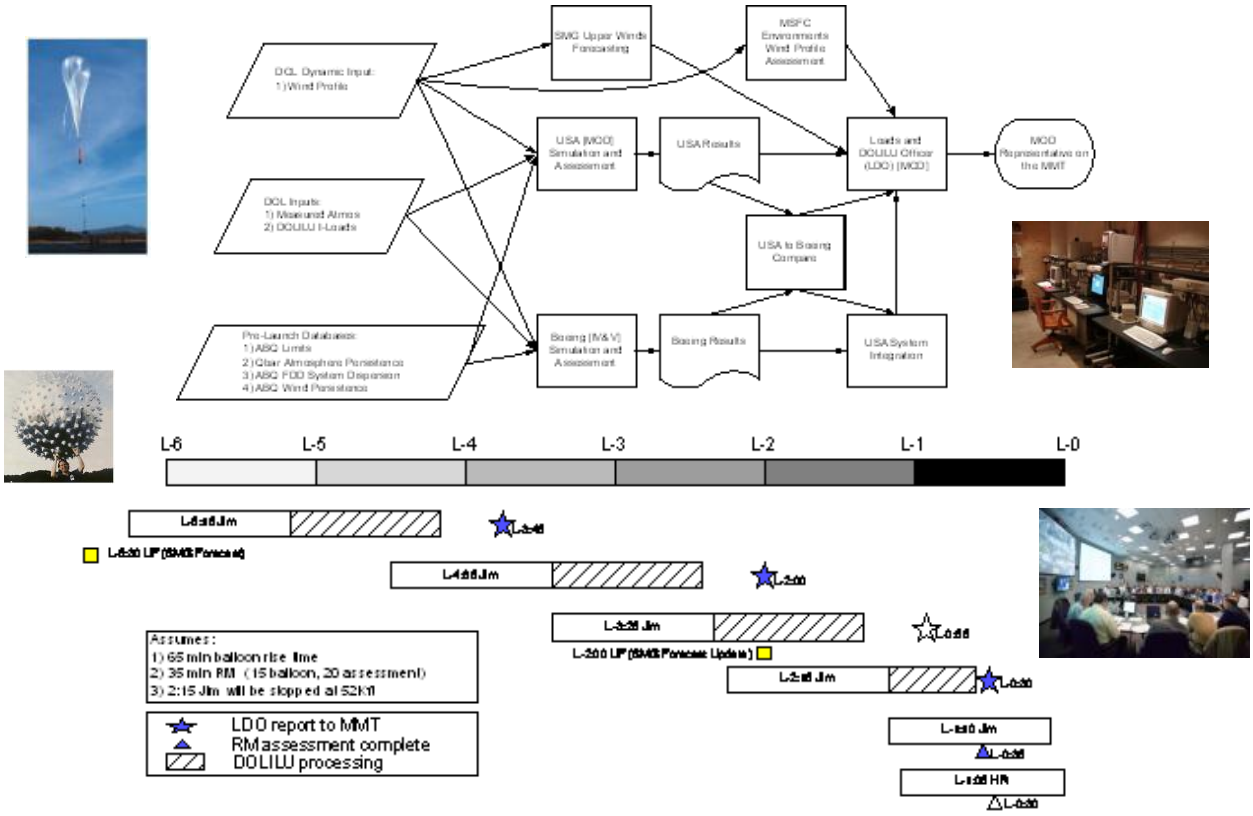


Figure 17-2. Shuttle Day of Launch I-Load Update Data Flow and Timeline

"Some graphics on Figures 17-1 and 17-2 are from a presentation on DOLILU Operations by Brian Harrington, USA, April 20, 2005."

Although the process has been streamlined from earlier DOLILU approaches, it is clear that the Day of Launch I-Load process requires significant operational effort and complexity. Because the Shuttle is not structurally robust, the program has to pay the operational cost of this process to safely achieve a reasonable launch probability. This is an example of operational complexity not in the original plan.

Design Considering the Total Life Cycle

In the past we typically focused our design activities on the physical performance of the vehicle, then assessed the design for operability, reliability, and cost. What is needed is to design for the total life cycle, which means designing not only for performance, but also (and concurrently) designing for the –ilities and cost.

Figure 17-3 shows a listing of typical metrics of design—those attributes that measure how the system performs, operates, and costs. We can collect them into three categories: (1) *Performance*, which describes how the physical system behaves, (2) *The –ilities*, which includes attributes such as safety, reliability, manufacturability, operability, etc., and (3) *Costs*, which includes various measures of cost. Because our systems are highly interconnected, changing one of these attributes typically will affect the others, within the same category as well as in the other categories.

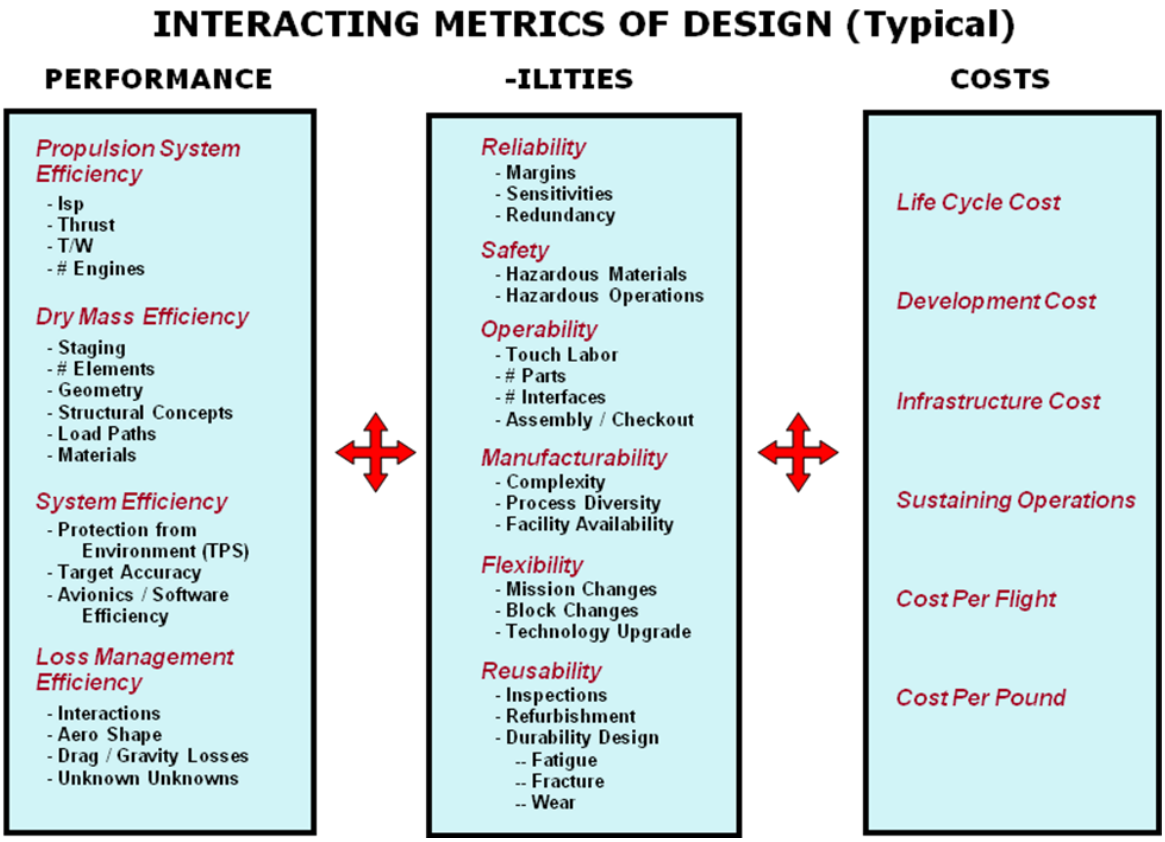


Figure 17-3. Interacting Metrics of Design

In order to obtain a balanced design that meets –ilities and cost goals as well as performance, we must take a systems design/optimization approach across all aspects of the life cycle (Figure 17-4).

- **In order to meet operability, cost, and other goals in addition to performance, we must take a systems design/optimization approach across all aspects of the life cycle.**
- **The goal: While achieving necessary safety, obtain the best balance among performance, the -ilities, and cost.**

- In order to meet operability, cost, and other goals in addition to performance, we must take a systems design/optimization approach across all aspects of the life cycle.
- The goal: While achieving necessary safety, obtain the best balance among performance, the -ilities, and cost.

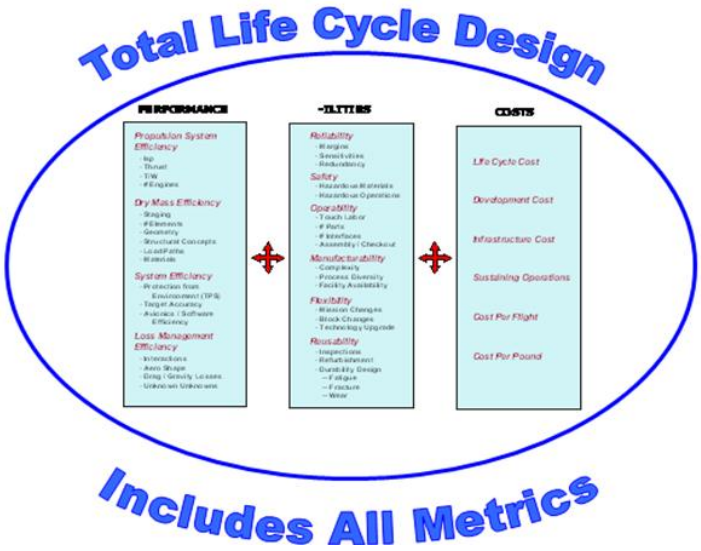


Figure 17-4. Design Considering Total Life Cycle

How We Previously Designed for the –ilities and Cost

The previous design approach is illustrated in Figure 17-5, showing the initial concept being designed iteratively for performance, then subsequent assessments and adjustments being made for –ilities and cost. The –ilities and costs are harder to predict than are measures of physical performance. This process is iterative and sequential, and produces a less than ideal design.

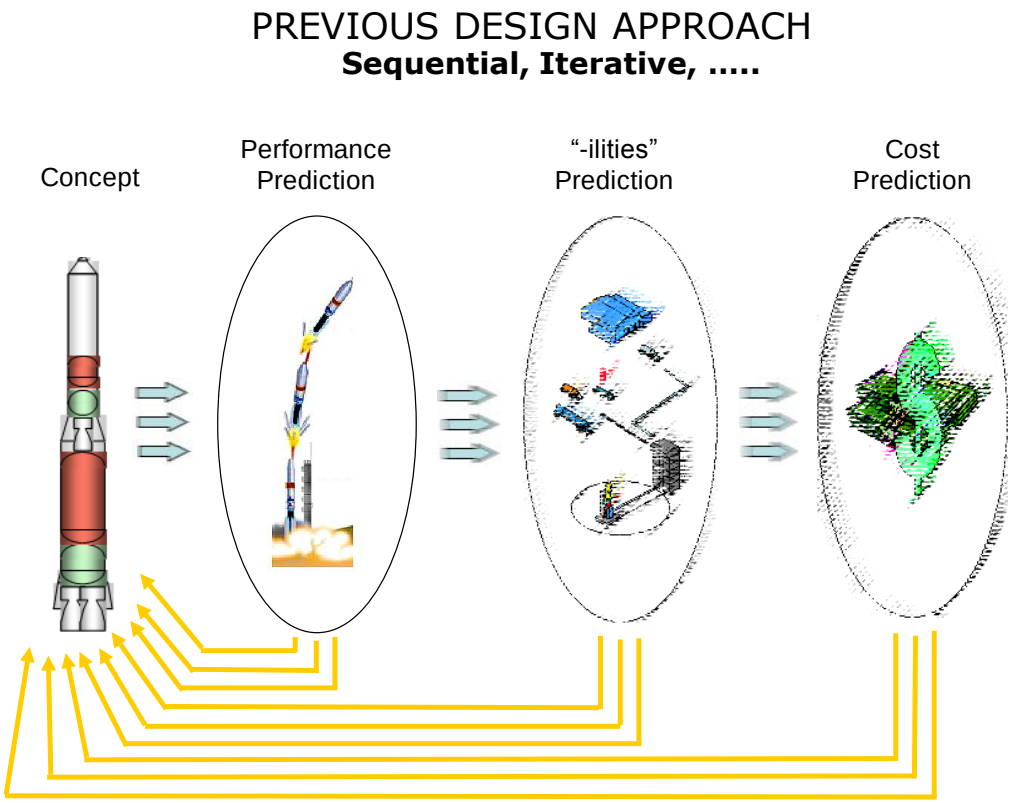


Figure 17-5. Previous Design Approach

How We Should Design for the –ilities and Cost

What is needed is a comprehensive process that addresses downstream –ilities and costs concurrently with performance. As discussed earlier, we describe this as "putting –ilities and costs on the design table". In order to do this, we need to have functional relationships that provide the designer with measures of costs, operability, reliability, manufacturability, etc., as a function of the design parameters that the designer can choose (Figure 17-6). Another design process improvement represented on the figure is integrated system analysis that where possible unifies analysis of subsystems, design functions, and discipline functions that are currently compartmentalized.

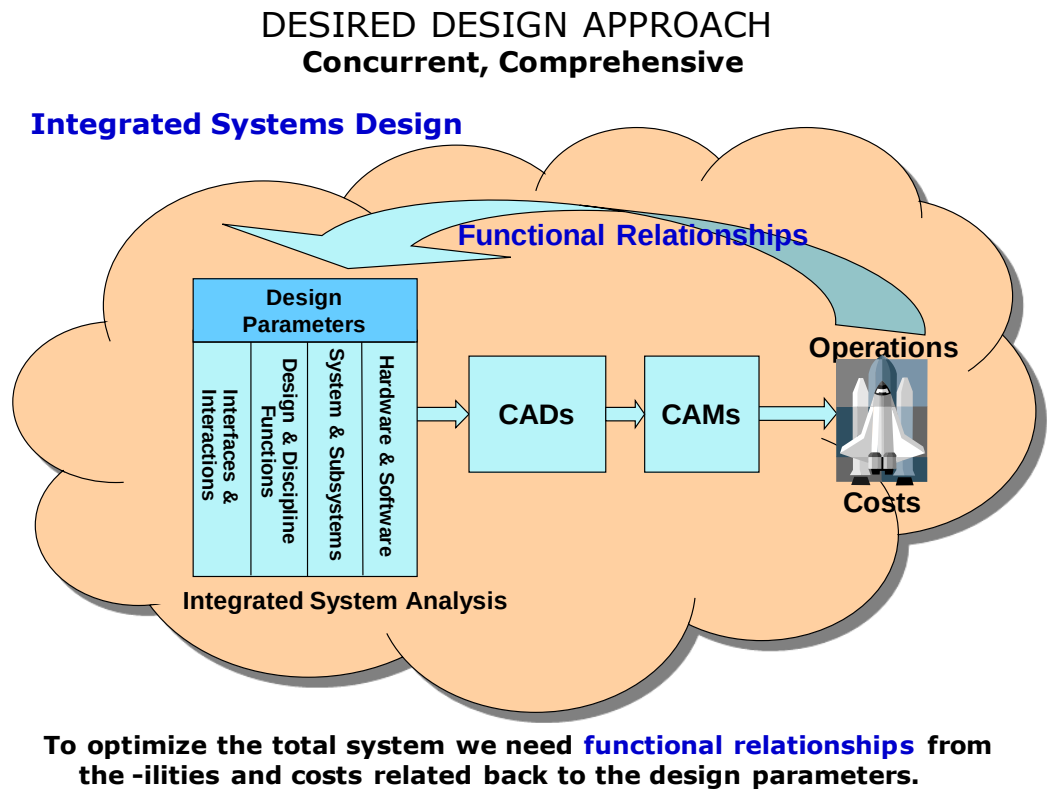


Figure 17-6. Desired Design Approach

Obtaining functional relationships between the –ilities/costs and design parameters would enable an ideal concept assessment process illustrated notionally in Figure 17-7. Here the different concepts or designs are mapped into an attribute space (represented simplistically on the figure as three-dimensional) that includes all metrics. Comparisons and directions for improvement would be direct, enabling unified design for the total life cycle.

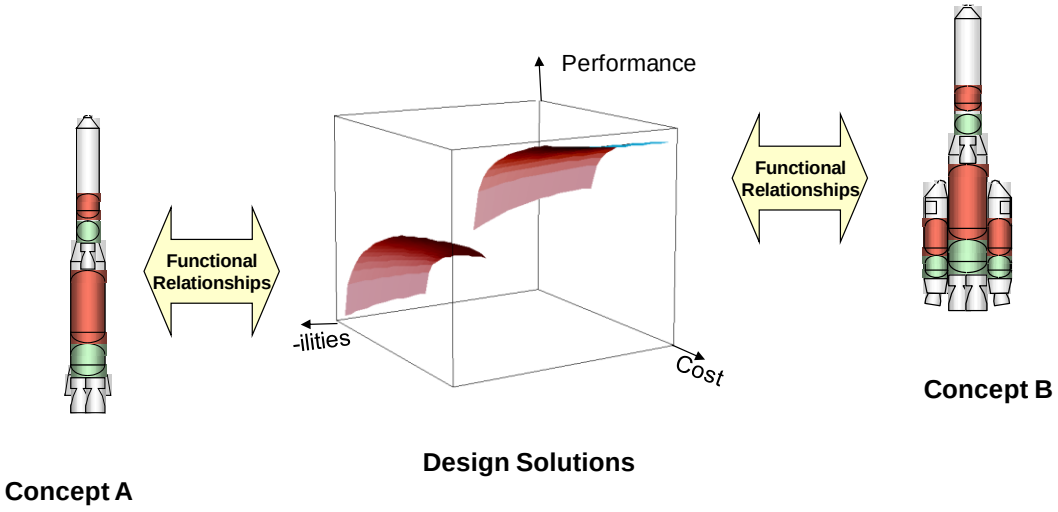


Figure 17-7. Functional Relationships Enable Design Solutions for Multiple Concepts

Obtaining the functional relationships needed for the above process is a challenge—only a few are currently available. Based on historical or other data, people in all technical areas should work to identify functional relationships that connect the –ilities and cost to design variables, thus working toward making the –ilities and cost concurrent "design-to" attributes along with performance.

- **A key message from Lesson 17 is:**

  Work toward making the –ilities and cost concurrent "design-to" attributes along with performance.

Principle VII: Testing and Verification Have an Essential Role in Development

Testing and verification are central activities in the development process. Their importance is reflected in the large proportion of project cost that is dedicated to testing and verification activities. This principle will be addressed in the following lessons:

18. Hardware and Its Data Have the Answers
19. Can Test Now or You Will Test Later
20. Independent Analysis, Test, and Design Keys To Success
21. All Analyses and Tests Are Limited
22. Scaling Is a Major Issue

Lesson 18: Hardware and the Data Have the Answers

- **Read The Hardware and Its Data –They Have The Answers**
  - **Don't rationalize what is seen**
  - **Look for the hidden message**

The real system is the hardware and software—it is not analysis models or even our mental models of the system. We must look to the actual hardware and software for answers to the actual system behavior.

In developing an engineer's capabilities, there is no substitute for experience with the actual hardware. Hardware experience can be acquired as the hardware is being manufactured and assembled, and during testing—development tests, qualification tests, certification tests, hardware-in-the-loop simulations, etc.—as well as flight experience. Persons working the design/development process should take every opportunity to gain hardware experience, to understand the reality of the actual system.

Hardware inspection observations and data acquired during test and flight are keys to understanding. There is usually more information there than first meets the eye. Plow the data deeply to extract the message. If the data doesn't correspond to your expectations, the initial reaction often is to assume it is bad data. Resist that reaction—the data is usually valid, and it contains a message about the real system. Look for the hidden message and don't rationalize away what is seen.

Examples:

- 51-L Challenger Failure
- Hubble Space Telescope Mirror Aberration
- X-33 Liquid Hydrogen Fuel Tank Failure

51-L Challenger Failure

The failure of the Shuttle on Mission 51-L in 1986 provides an example of the need to intently focus on what the hardware and data is telling us, and not discount anomalies that may be precursors to failures. The 51-L failure and its causes have been extensively documented, and will not be repeated here except to highlight some perspectives relating to the lesson at hand. [Rogers, 1986]

The original design of the SRM field joint had some inherent flaws that were not initially apparent. When the SRM was ignited, the pressure increase caused rapidly-opening deflections at the joint sealing surfaces (Figure 18-1). The sealing surfaces at both the primary and secondary O-ring seals exhibited this characteristic, and although the secondary deflection was smaller than the primary, the two seals did not provide independent redundancy. Putty was applied as a thermal barrier between the facing surfaces of the mated segment insulation. As the segments were joined during assembly and the seals were leak checked, trapped air often caused blow-holes in the putty that created pathways to the joint for the combustion gas. Depending on the extent of the pathways, the response of the specific joint and O-rings, and other variables, the hot combustion gas could impinge on the O-rings and cause heat-affected areas and erosion.

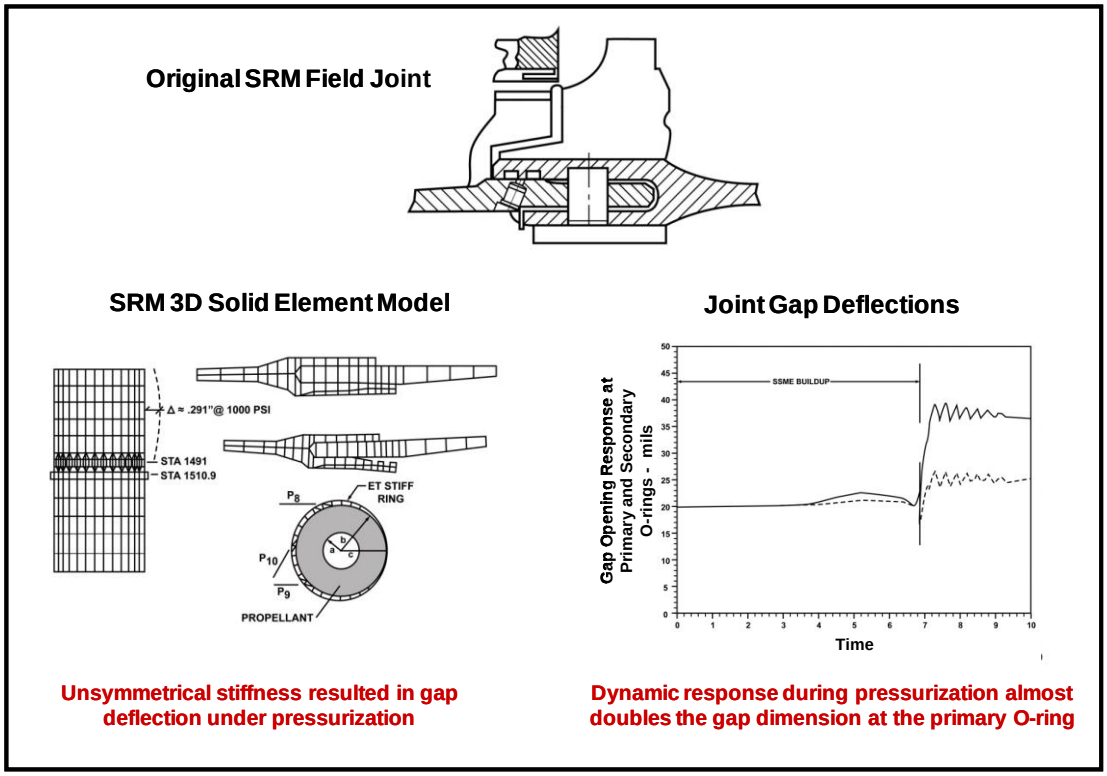


Figure 18-1. STS 51-L SRM Field Joint and Gap Deflections

There had been several occurrences of SRM joint O-ring distress in flights previous to Mission 51-L, where hot gas from SRM combustion had penetrated through breaches in the putty between the segments and impinged on the O-rings. These anomalies were assessed, but as they recurred on subsequent flights, they tended to be rationalized as being within the experience base. This is an example of "normalizing the deviances" and not taking action on impending problems. As a member of the investigating commission, J. R. Thompson commented, "It was winking at us."

Figure 18-2 is taken from the final report of the commission on the Challenger accident. It was developed by commission staff members to summarize the correlation of O-ring damage experience with temperature. The top display in the figure plots the number of O-ring distress incidents versus temperature. By themselves, these data did not indicate a clear correlation of distress with temperature. But when data from flights with no distress is added, as in the bottom display, a different picture emerges, and the temperature correlation is more evident. The lesson is to consider all information when making decisions.

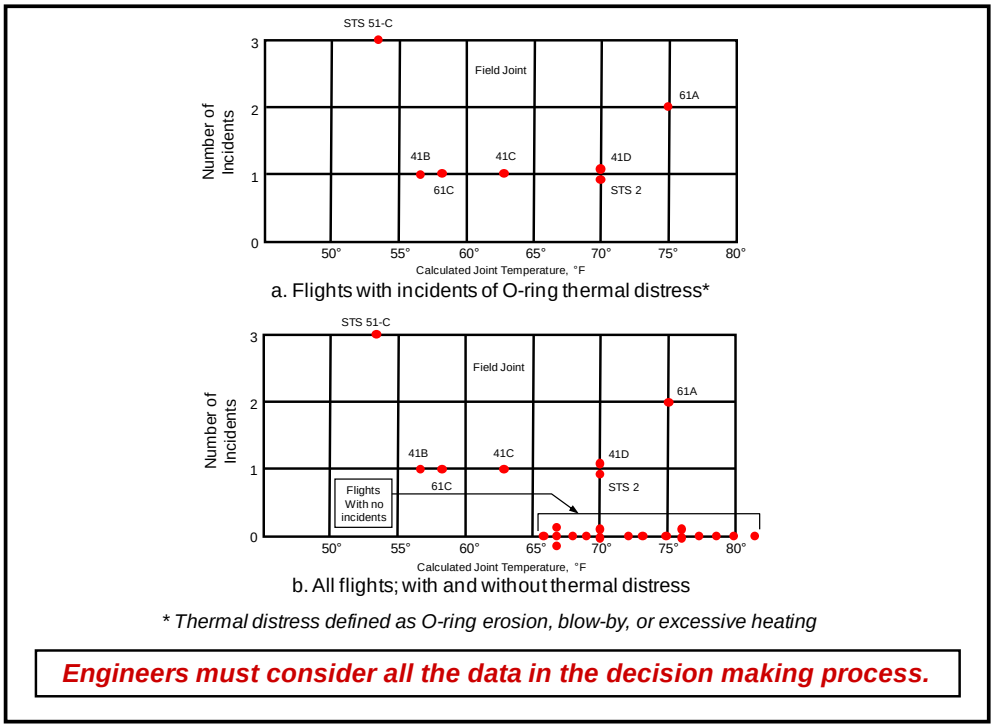


Figure 18-2. SRM Field Joint Flight Data – Thermal Distress Incidents vs. Temperature

Most major failures have more than a single cause, and this was the situation for 51-L. The gap at the clevis-tang joint opened when the SRM ignited and pressurized the case, exceeding the ability of the primary and secondary O-rings to resiliently respond at cold temperatures and maintain the joint seal. In addition, there were factors that contributed to the failure of that specific SRM joint. Although it is not considered good design practice to rely on pressure to actuate O-ring seals, pressure going around and under the O-rings had most likely aided the material resiliency to seal most SRM joints. The O-ring groove tolerances on the SRMs allowed the possibility that both sides of the O-ring could be in contact with the groove, which would have hindered pressure actuation. Furthermore, the relative diameters of the tang and clevis were a factor. When the SRM cases are reused and proof tested, their diameters undergo a slight permanent change. There had been several reuses of the tang-side case on the joint that failed on 51-L, making it likely that the tang surface and clevis surface were in contact, pressing the O-ring into the groove and reducing the likelihood of pressure actuation assistance. (Figure 18-3). The question should have been “What is the real hardware doing?” instead of a reliance on idealized concepts or models.

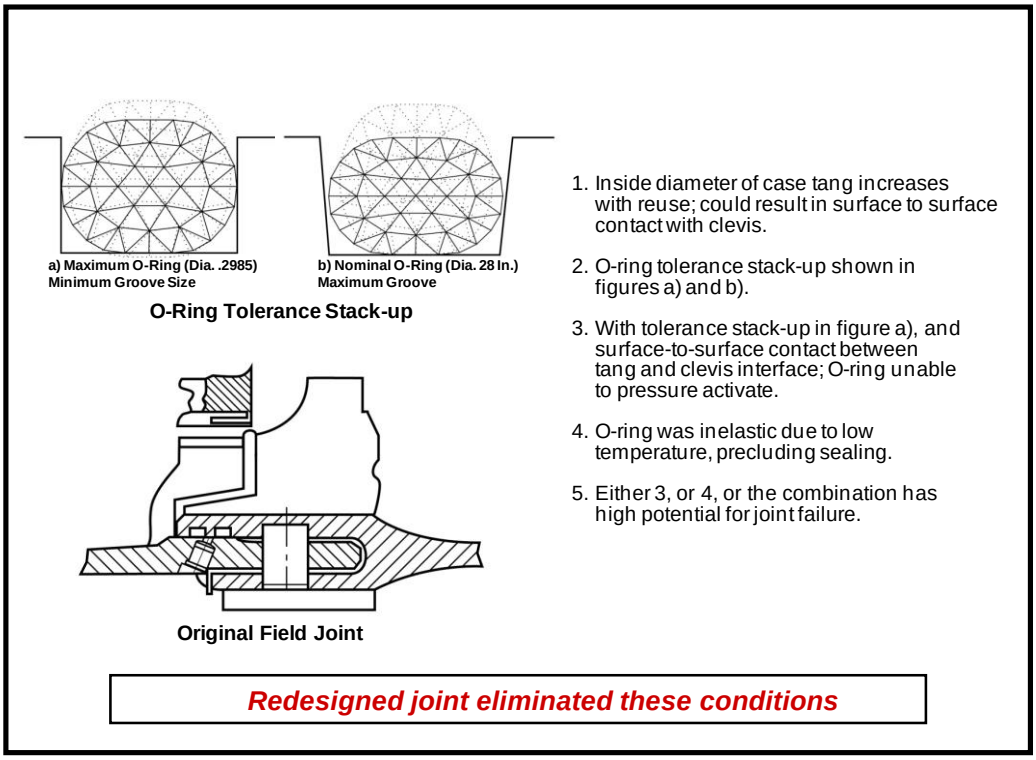


Figure 18-3. STS 51-L Field Joint – O-Ring / Groove Tolerance Effects

Redesign of the SRM joint following the accident corrected its various shortcomings, and produced a design that has multiple layers of protection against a joint breach. [Perry, 1989] These improvements include a tang/clevis capture feature that greatly reduces gap opening at pressurization, improved groove tolerances, better sealing checks, sealed insulation, joint heaters, and better assembly procedures. (Figure 18-4). The redesign has flown successfully ever since, with no indications of seal problems.

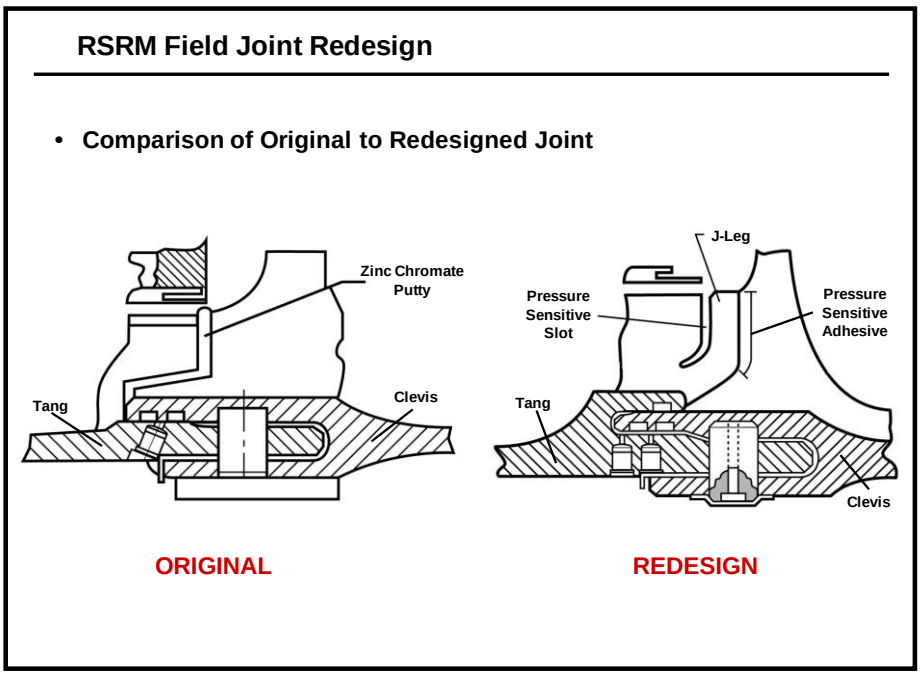


Figure 18-4. RSRM Field Joint Redesign

Hubble Space Telescope Mirror Aberration

The Hubble telescope, see Figure 18-5, was launched in April 1990 on Space Shuttle Discovery (STS-31). Its weight is 24,500 lbs. and the main mirror's diameter is 94.5 inches. The orbit is near circular and at an altitude of 347 miles. Its inclination is 28.5 degrees with a period of 96/97 minutes.



Figure 18-5. Hubble Space Telescope

After the launch it was learned that the main mirror was incorrectly ground. Efforts were taken to determine what could be done to fix the mirror system and how the mirror was incorrectly ground. A method was established to fix the telescope while in orbit, since the telescope was designed so that it could be serviced. So the first servicing mission took place in December 1993 and several instruments and other equipment were installed over 10 days, returning the telescope to full capability.

During the manufacturing of the mirror there were tests to determine the shape of the mirror's surface. Tests with the new "flawless and superior" reflective null corrector device showed the mirror's surface to be perfect. However, during the setup of the mirror and reflective null corrector device, a 1.3 mil spacing error was caused by the intentional placement of washers to make the reflective null corrector device match the laser reflection from a NBS precision metal calibration bar. So whenever the surface was measured it showed perfect when in fact it wasn't.

Other surface tests were made during manufacturing. One was with an inverse null corrector device and the other was a refractive null lens. Both of these indicated that something was amiss. However, the mirror manufacturer, Perkin-Elmer Corp., discounted these results in favor of the "flawless and superior" method; see reference [Allen, 1990].

From this experience it can be seen that, see reference [Chapman, et.al., 1997]

1. Questionable test results were not understood and they were discounted.
2. There was no requirement for an independent check.
3. Didn't compare to the Eastman Kodak mirror and select the best.
4. No system test required.
5. NASA didn't follow through with insight-oversight.

X-33 Liquid Hydrogen Fuel Tank Failure

Single Stage to Orbit vehicles require a very high mass fraction for performance efficiency in order to reach orbit. One method for achieving this structural efficiency is using the technology of composite cryogenic propellant tanks, which is a new technology for achieving the high mass fraction. The X-33 fuel tank was designed to develop and demonstrate this technology. The X-33 hydrogen tank failed during verification testing under cyrogenic conditions. The tank wall design was an inner skin of 13 composite plies with a layup pattern, a 1½ inch honeycomb core for insulation, and outer skin (face sheet) of 7 plies as shown on Figure 18-6.

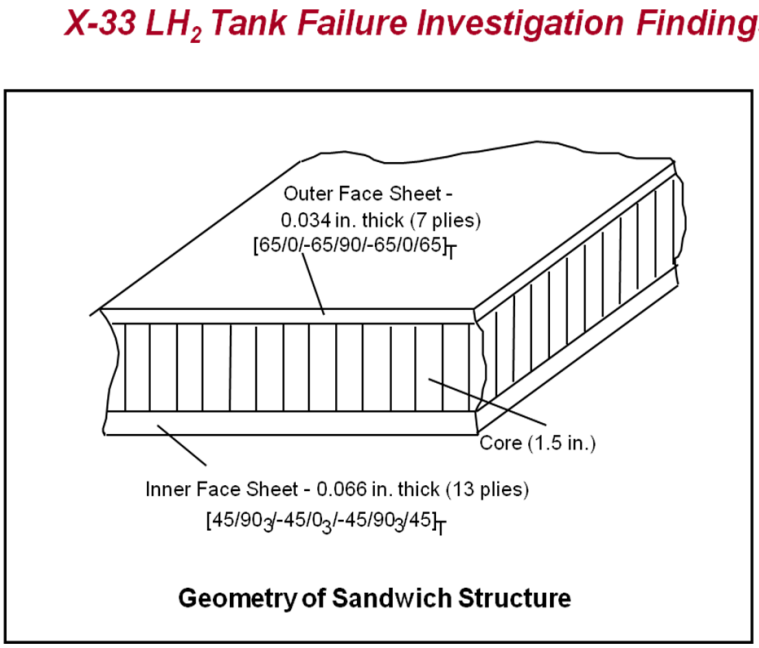


Figure 18-6. Geometry of Sandwich Structure of X-33 Fuel Tank

The design approach of the outer and inner sheet over the honeycomb had problems during manufacturing. The process was verified using a 2 foot square panel, and then the first full panel was made. When it was taken out of the autoclave and laid on the floor the outer panel delaminated. This was investigated by a special panel. It was realized that there was a lowering of the qualities of the adhesive used to fasten the sheets to the honeycomb in the full scale article due to the extended time between adhesive application and autoclave cure (the adhesive *out-time*). The process was reworked. Also, everyone knew and was worried about cryopumping during flight causing a failure. Therefore, the panel also recommended that the TRL level be reduced and that the cryogenic verification test of the flight tanks have special instrumentation to ensure no cryopumping and other potential problems.

The program proceeded to build the two flight hydrogen tanks and brought them to MSFC for the cryogenic and structural loads verification tests. The articles were all instrumented with the special instrumentation including thermal and strain gauges and pressure gauges in the honeycomb. The first test was conducted using liquid hydrogen with the flight tank pressurization system and appropriate flight-like loads. After the test the tank was drained and in the depressurization process the outer face sheet was blown off. The basic cause was not the expected cryopumping but was caused by the hydrogen gas penetrating the inner skin, due to micro cracking of the inner composite panel, filling the honeycomb core with liquid hydrogen. After the test, the tank was drained of liquid hydrogen, and the hydrogen trapped in the honeycomb warmed up and blew the outer skin off the tank (Figure 18-7).



Figure 18-7. Failed X-33 Fuel Tank

The cause of the gas penetration into the honeycomb was micro cracking of inner face sheet due to the thermal strain between the outer face sheet being at ambient and the inner face sheet being at -420 degrees plus the stress introduced by the tank internal pressure. Figure 18-8 shows plots of the pressure variation in the tank and in the honeycomb at various locations. Notice the heavy line is the tank internal pressure actual profile during the test. The lighter lines are pressures at various locations in the honeycomb. Notice that the honeycomb pressure does not track the internal tank pressure but starts rising when the micro cracking starts. As the tank was drained the honeycomb pressures starting coming down to the point that when the internal pressure was low enough the micro cracks sealed and the honeycomb pressures continued to rise, until the outer skin blew off. This phenomenon was duplicated on small panel testing at Southern Research Institute and by LaRC engineers using analytical fracture analysis of composites.

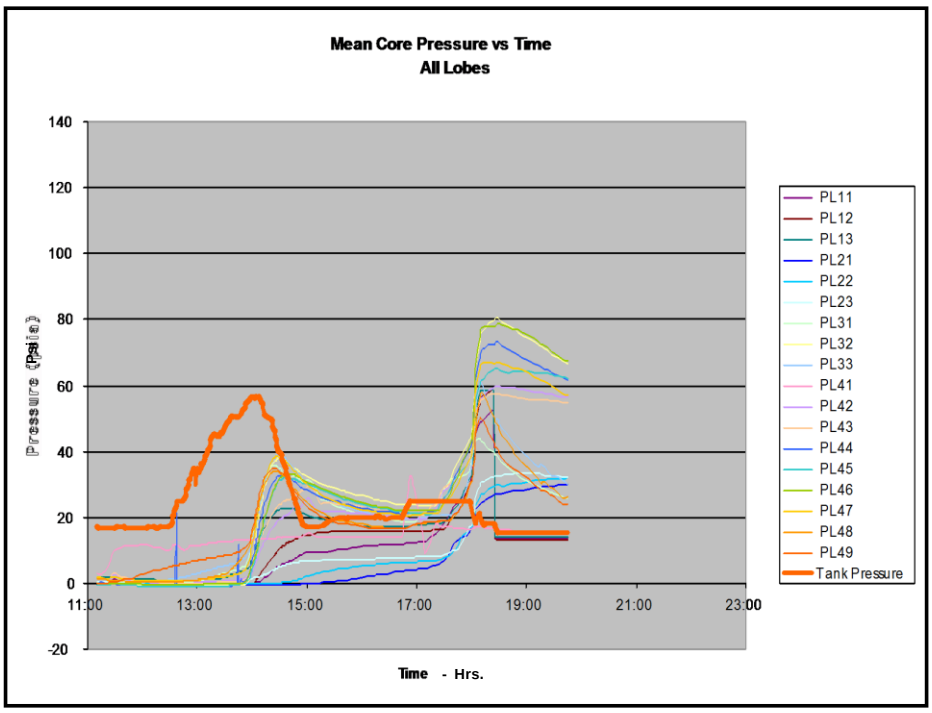


Figure 18-8. Pressures in Failed X-33 Fuel Tank

The X-33 LH_2 Tank Failure Investigation findings were:

- Scaling of manufacturing processes is a major verification issue.
- Adhesive out-time before autoclaving lost strength.
- Micro-cracking of composites was not well understood before committing tank to design and manufacturing.
- Design of attachments to take out the thrust load (thrust busters) is a major design and manufacturing challenge.
- Verification of new technologies generally requires full scale testing.

A key message from Lesson 18 is:

There is no substitute for experience with the actual hardware. Look closely at what it tells you.

Lesson 19: Test Now or You Will Test Later

Testing is an essential element of the design process.

"Test what you fly, fly what you test." - Jack Bunting, Lockheed Martin
Development and verification testing is at the heart of design.

- **Testing should be a building block approach, i.e., subscale and full scale, component and systems.**
- **Different types of testing are needed: Development, Qualification, Verification, Certification, Acceptance.**
- **Tests are no better than the assumptions used.**

Testing is mandatory for all high performance systems. As the title of the lesson says, "You can test now or you will test later". This makes the point that the initial time a product is operated will be first and foremost a test if adequate testing has not been accomplished already. In addition, no test can fully duplicate all the combined environments of operations, thus for most systems the first few uses are indeed development tests, since this is the first time all the combined environments have been experienced. This is especially true for launch vehicles that must traverse through a varied and complex set of natural and induced environments. The following discussion emphasizes some of the basic principles of testing and verification with the overarching principle "Testing is an essential element of the design process."

Jack Bunting of Lockheed Martin has said "Test what you fly and fly what you test." Others have said; "Development and verification testing is at the heart of design." Developmental testing provides understanding of the system before it is built so that those characteristics can be incorporated into the design, while verification testing determines if the as built design meets the system requirements. Testing is best accomplished using a building block approach so that the elements and the system as well as system interactions are understood. In today's world cost restrictions are eliminating many of the building block tests and/or the final system tests. This places more risks on the first flights and can result in design changes after hardware is built which within itself is as costly. This principle has been demonstrated in most space flight projects. Avionics components and mechanisms have at least six types of tests: development, qualification, verification, certification, assurance, and acceptance. Finally any test is based on a set of assumptions; therefore, no test is better than the assumptions used in the test hardware and the test conditions and environments.

Types of Tests

The following is a list of the types of tests generally used on space systems.

1. Development Tests
2. Qualification Tests
3. Certification Tests
4. Process Assurance Tests
5. Acceptance Tests
6. Systems Integration and Verification Tests
7. Flight Readiness Firing
8. Other Tests (Flight tests, etc.)

Development Tests are tests conducted throughout the design cycle of a project and are used to get basic information about the characteristics of the system, so that the design incorporates these characteristics and can handle the situations induced. Developmental

tests include wind tunnel testing, scale model dynamic testing, thermal testing, materials testing, component vibration testing, acoustical testing, etc. and are fundamental in understanding systems. Component vibration tests and thermal vacuum tests uncover design flaws that can be corrected before final design is completed.

Qualification Tests are generally of flight type or flight hardware that are tested to at least 3 sigma levels of the environments with the component carrying out certain flight type functions. Minor changes are easily made after these tests and if changes are required, the tests are generally repeated.

Certification Tests are usually for things like liquid propulsion system engines that can be ground tested under flight conditions using both flight hardware and flight operational procedures. For example certification of the Space Shuttle Main Engines requires that two identical engines be tested under flight profiles and operational procedures for 20,000 seconds. Some of the major problems experienced during certification testing will require hardware changes and a repeat of the certification testing or flying the engines under waivers and operational constraints.

Process Assurance Tests are generally for solid rocket motors and pyrotechnic devices. Hardware like this is either very costly or is destroyed in the tests so lifecycle testing is not appropriate. The test program usually consists of a few (say 5) motors or devices before flight. During the operational program, a motor or device is periodically pulled from the manufacturing line and tested to ensure that the build process is still meeting requirements.

Acceptance Tests are usually of avionics and mechanisms where each unit is tested when it comes off the production line. The tests are not of full flight duration and are at reduced environments. This testing is to eliminate manufacturing or infant mortality flaws. Flight liquid propulsion engines are tested in this manner using a short duration hot firing of the engine. At various times in space programs the engines attached to flight stages are ground hot fired for short durations to understand the interaction of the engines with the main propulsion systems.

Systems Integration and Verification Tests are of many types to checkout the integrated system, validate analytical models and induced environments. The following is a partial list of integrated tests for launch vehicles.

- Hardware integration and checkout
- Integrated ground vibration (dynamic) tests to validate dynamic models
- Main propulsion tests to understand the integration of engines with the main propulsion system elements and software.
- Integrated avionics tests using hardware/software components.
- Large scale wind tunnel verification testing for aero and thermal environments.

We can also do ***Flight Readness Firings*** on the launch pad, of short duration burn time, of launch systems with liquid propulsion systems. This is done to check out the MPS of any major changes made from prior configurations. One final test program is the ***Flight Test*** programs of launch vehicles, where the first two or three flights are test flights that are heavily

instrumented in order to determine combined environments and interactions that are that are not possible to accomplish in the above discussed tests. Flight testing has uncovered many major problems that were not found during the above tests. The following is a discussion of some major tests of previous space systems.

Examples:

- Saturn V Dynamic Tests
- Space Shuttle Dynamic Tests
- Summary of Dynamic Test Impacts
- Space Station Static and Dynamic Tests

Saturn V Dynamic Tests

Saturn V was dynamically tested as both scale models and full scale flight-like hardware. The full scale dynamic test was of the total system and of each stage of launch vehicle flight in free-free boundary conditions. A hydraulic bearing was developed to create a free-free boundary in the lateral planes. Liquid hydrogen was simulated using ping-pong balls. Water was used to simulate liquid oxygen. The on-pad modes were verified with the famous “Tennis Shoe Test” where engineers went to the top of the assembly facility and excited the first bending mode by pushing with their feet. Tennis shoes were worn so as not to damage the Command / Service Module.

Several issues were uncovered in the free-free full scale dynamic test that included excessive rotational deflections of the rate gyro attachment plate (as described in Lesson 5). This required moving the rate gyro to smaller deflection area in the Instrument Unit (IU). Overall there was good correlation of all test lateral modes with analytical predictions. A table shown at the end of this section contains all the major findings in the dynamic tests conducted at MSFC. [Grimes et. al., 1979]

Space Shuttle Dynamic Tests

Figure 19-1 shows the Space Shuttle Orbiter being moved into the dynamic test stand for mating with the External Tank and the Solid Rocket Boosters. Also shown are the various dynamic tests conducted for Shuttle and the basic characteristics of the complex Shuttle configuration consisting of four bodies connected with forward and aft interface joints. This resulted in approximately 200 bending modes below 20 Hz. [Jewell et. al., 1980]

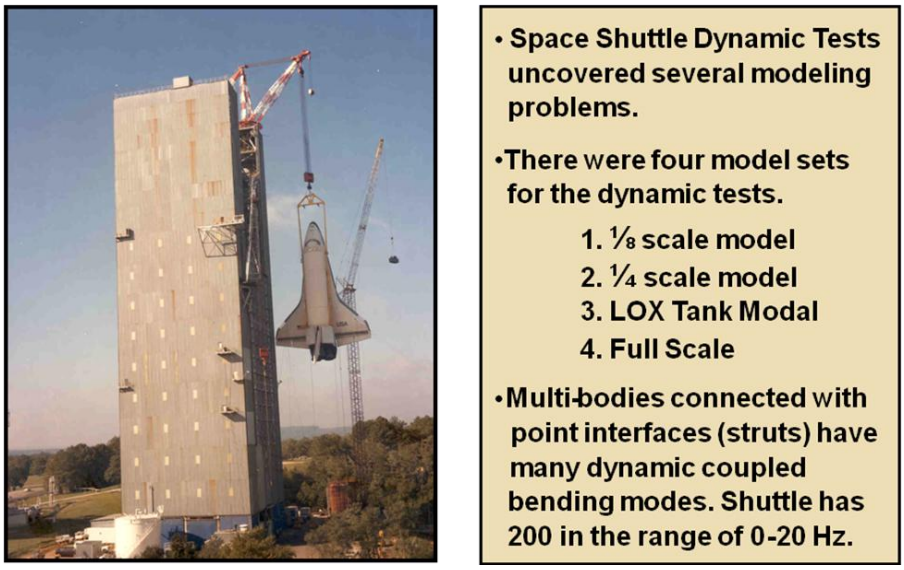


Figure 19-1. Shuttle Orbiter Being Installed Into Dynamic Test Stand

Initially it was deemed that a full scale dynamic test was not needed and in addition not doing the test would save the program at least $20M. The method used to justify the test was based on risks and their consequences on the various disciplines that used the dynamic vehicle characteristics for response and stability design. Typically these disciplines are:

1. Control response and stability
2. Dynamic response and loads
3. Aeroelasticity
4. Pogo

Figure 19-2 illustrates how various dynamic tests increase confidence and reduce the flight risk for the pogo discipline. Similar charts were developed for the other above listed disciplines. Combination of the four resulting risk reductions and the impact on the program complexity and risk if the test was not completed, resulted in the dynamic test being justified and accomplished.

Shuttle Dynamic Tests

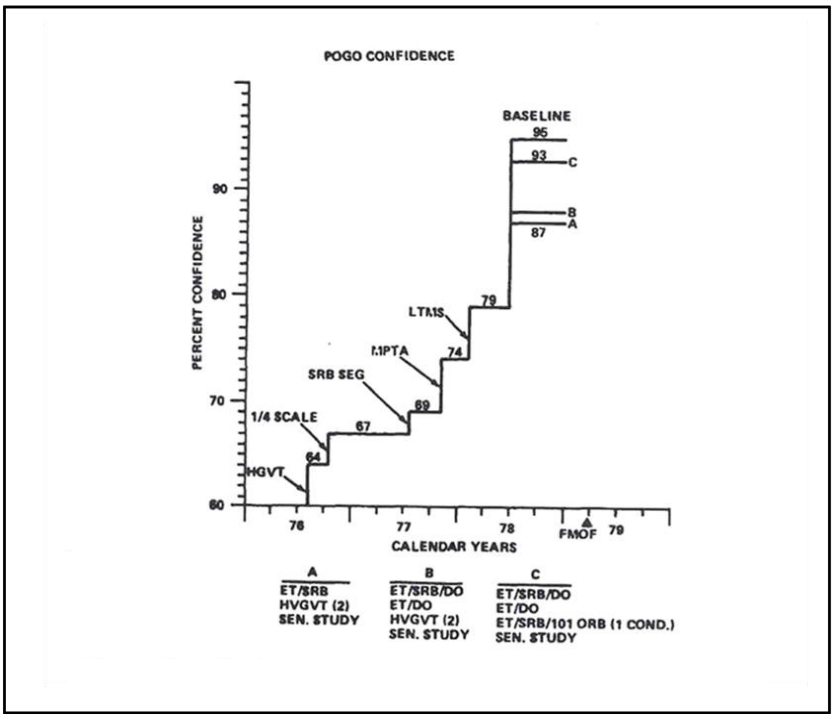


Figure 19-2. Pogo Confidence Factor Increase with Tests

One important test for validation of the pogo analytical model used for stability analysis and pogo solution design was full scale hydroelastic test of the LOX tank. This validated model was then combined with the overall vehicle model validated by the MVGVT. This was a very interesting test of the full scale LOX tank filled using water to simulate various flight conditions. The test configuration is shown on Figure 19-3. The first test condition was a full tank, and when the hydroelastic mode was excited there was basically no damping in the mode. This was the case for tests at lower fill levels until the tank was about two-thirds full, at which time the damping became the expected value.

Shuttle Dynamic Tests: LOX Tank Modal

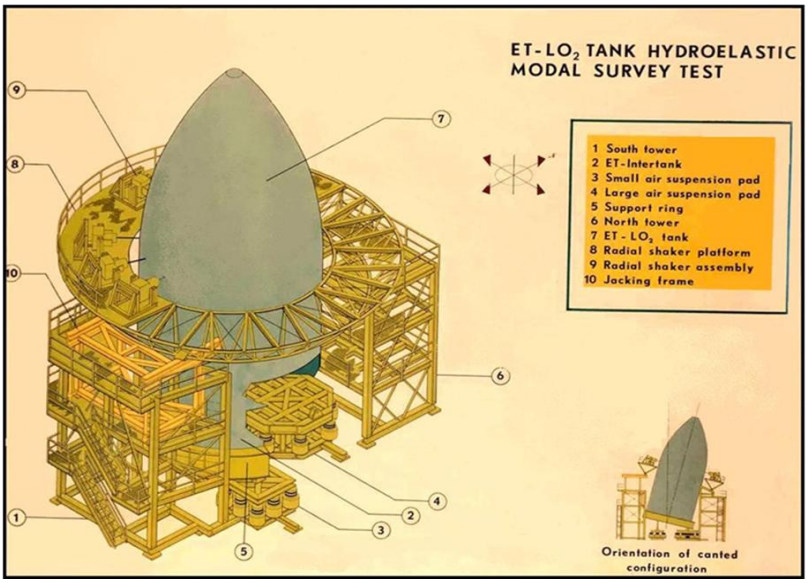


Figure 19-3. Shuttle LOX Tank Hydroelastic Test Configuration

The plot of damping versus fill level on Figure 19-4 illustrates the results just discussed. Once the model of the test condition was validated, then LOX instead of water was used in the analytical model. The use of LOX instead of water decoupled the structure from the fluid mode and no flight fix was required. The results illustrate the sensitivity of dynamic coupling and the need to conduct building block testing approaches. [McComas, 1980]

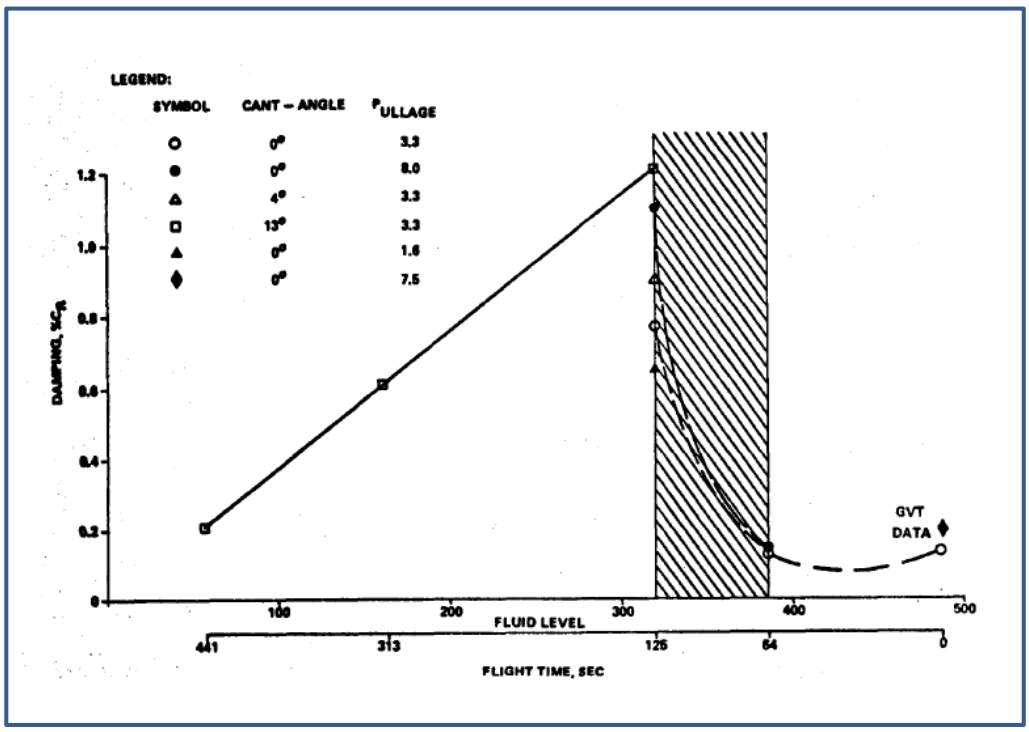


Figure 19-4. Shuttle LOX Tank Propellant Damping

Summary of Dynamic Test Impacts

The following tables (Figure 19-5) summarize dynamic testing experience and its impacts on the projects. [Jewell et. al., 1980] [Emero, 1979] Shown in the first column is the test program, with the second column being the problem discovered. The hardware impacted is the third column and the consequence if not discovered is the last column. The first item is the local deflection of the Saturn V IU mentioned earlier and the potential impact of a bending mode control coupling instability if it had not been discovered.

Dynamic Testing Impacts (a)

TEST PROGRAM	PROBLEMS DISCOVERED	HARDWARE IMPACTED	CONSEQUENCES IF NOT DISCOVERED
SATURN V DTV	LOCAL ROTATION OF THE FLIGHT GYRO SUPPORT PLATE. VEHICLE DYNAMIC SHEARS AND MOMENTS DEFORMED SUPPORT PLATE. THE MATH MODEL UNDER PREDICTED THIS DEFORMATION BY 135 PERCENT.	THE GYROS WERE RELOCATED TO THE BOTTOM OF THE SUPPORT PLACE WHERE THE LOCAL ROTATION WAS MUCH LESS. THIS REQUIRED WIRE HARNESSES OF NEW LENGTH. THE FLIGHT CONTROL FILTER NETWORK WAS REDESIGNED	FLIGHT CONTROL INSTABILITY RESULTING IN LOSS OF VEHICLE.
MARL	DESIGN DEFICIENCY IN THE IU STABLE PLATFORM. COUPLING BETWEEN THE STABLE PLATFORM AND THE RING MODES OF THE IU PRO-VIDED A MECHANISM FOR ACOUS-TICALLY DRIVING THE PLATFORM ACCELEROMETER AGAINST THE STOPS.	SHORT CHANNEL STIFFENERS WERE ADDED TO AS 501 ON THE PAD. DAMPING MATERIAL AND A SOFTWARE "REASONABLENESS" TEST WERE ADDED LATER IN THE PROGRAM.	LARGE GUIDANCE ERRORS THAT COULD CAUSE LOSS OF LUNAR MISSION.
SATURN V DTV	DESIGN DEFICIENCY IN THE CSM INTERFACE. THE SINGLE TORSIONAL SWAY BRACE PRODUCED UNPRE-DICTED HIGH COUPLING BETWEEN COMMAND MODULE TORSIONAL MOTION AND S-1C ENGINE DEFLECTION.	ADDITIONAL TORSIONAL SWAY BRACES WERE INSTALLED ON AS 501 ON THE PAD. SUBSEQUENTLY, THE F 1 ENGINES WERE REORIFICED TO REDUCE LOADS AT ENGINE CUTOFF. AN ENGINE PRECANT PROGRAM WAS IMPLEMENTED TO MAINTAIN STRUC-TURAL INTEGRITY IN CASE OF ENGINE OUT.	STRUCTURAL FAILURE OF THE CSM INTERFACE WITH LOSS OF VEHICLE AND POSSIBLE CREW LOSS.
SATURN V DTV	DESIGN DEFICIENCY IN THE SPS TANK SUPPORTS. UNEXPECTEDLY HIGH LOCAL RESONANT COUPLING WAS DETECTED BETWEEN SPS TANK AND BULKHEAD SUPPORT.	THE UPPER SUPPORT BRACKET FOR THE SPS TANKS WAS REDESIGNED TO ELIMINATE A STRONG TANK CANTI-LEVER MODE.	HARDWARE FAILURE RESULTING IN LOSS OF MISSION AND POSSIBLE CREW LOSS.
SATURN V DTV	HIGH LOX AND FUEL DYNAMIC TANK BOTTOM PRESSURES. THESE PRES-SURES WERE UNDER PREDICTED BY A FACTOR OF 2. THE SIGNIFICANCE OF THESE PRESSURES WAS NOT UNDERSTOOD UNTIL AFTER POGO OCCURRED ON AS 502.	THE HIGHER TANK PRESSURES CON-TRIBUTED TO THE S 1C POGO.	POTENTIAL LOSS OF VEHICLE AND CREW DUE TO POGO.

Dynamic Testing Impacts (b)

TEST PROGRAM	PROBLEMS DISCOVERED	HARDWARE IMPACTED	CONSEQUENCES IF NOT DISCOVERED
SATURN V DTV	HIGH 18 HZ S–1C CROSSBEAM MODE GAINS. DTV DATA SHOWED THAT AN ACCUMULATOR SHOULD NOT BE USED ON THE INBOARD ENGINE.	ELIMINATION OF A PLANNED INBOARD ENGINE ACCUMULATOR.	POTENTIAL LOSS OF VEHICLE AND CREW DUE TO POGO BETWEEN AN 18 HZ ACCUMULATOR MODE AND THE 18 HZ CROSSBEAM MODE.
SATURN V SHORT STACK	STRONG PITCH/LONGITUDINAL COUPLING CAUSED BY THE LUNAR MODULE INCREASED THE S–1C POGO GAIN FACTOR BY 30 PERCENT. THIS EFFECT COUPLED WITH THE TANK PRESSURE UNDERPREDICTION WAS THE REASON AS–502 POGO WAS NOT PREDICTED.	DEVELOPMENT AND INSTALLATION OF THE OUTBOARD LOX ACCUMULATORS.	POGO INSTABILITY WITH POTENTIAL LOSS OF VEHICLE AND CREW.
SATURN V MINI A/C	THE MECHANISM TRIGGERING S–II POGO WAS DEFINED. COUPLING BETWEEN THE FIRST FOUR LOX TANK HYDROELASTIC MODES WHEN THEY COALESCED WITH THE 16 HZ CENTER ENGINE CROSSBEAM MODE PRODUCED THE POGO INSTABILITIES.	AN ACCUMULATOR WAS DEVELOPED FOR THE CENTER ENGINE. A BACK–UP CUTOFF SYSTEM WAS ALSO DEVELOPED. THE ACCURATE MATH MODEL DEVELOPED DURING THIS TEST SUPPORTED EXTENSIVE THRUST STRUCTURE DESIGN MODS ON SUBSEQUENT VEHICLES WITHOUT FURTHER TESTING.	POGO INSTABILITY WITH POTENTIAL LOSS OF VEHICLE AND CREW.
SKYLAB ATM TEST	STRONG CROSS COUPLING BETWEEN LONGITUDINAL AND LATERAL MOTIONS INDICATED A POSSIBLE STRUCTURAL FAILURE AT S–1C CUTOFF.	A 1–2–2 ENGINE CUTOFF HARDWARE AND SOFTWARE MOD WAS DEVELOPED TO REDUCE THE LONGITUDINAL INPUT TO THE ATM. HARDWARE REDESIGNS WERE LAID OUT IN EASE THEY WERE PROVEN NECESSARY BY FURTHER STUDY.	HARDWARE FAILURE WITH POTENTIAL LOSS OF MISSION.
SKYLAB MODAL SURVEY	THE STRONG CROSS COUPLING IN THE ATM PROVED TO BE ATTENUATED RATHER THAN AMPLIFIED BY THE WAY ATM CROSS COUPLING REACTED THRU VEHICLE INTERFACE.	TEST OF THE TOTAL SKYLAB LAUNCH CONFIGURATION PROVED THE 1–2–2 FIX WAS ADEQUATE AND THAT NO HARDWARE CHANGES WERE REQUIRED.	THIS TEST SAVED A POSSIBLE REDESIGN OF THE ATM BY VERIFYING STRUCTURAL INTEGRITY UNDER THE 1–2–2 CUTOFF.

Dynamic Testing Impacts (c)

TEST PROGRAM	PROBLEMS DISCOVERED	HARDWARE IMPACTED	CONSEQUENCES IF NOT DISCOVERED
SHUTTLE MVGVT	SRB MOUNTED RATE GYROS EXHIBITED ABNORMALLY HIGH TRANSFER FUNCTIONS. THE RATE GYROS MOUNTED ON THE FORWARD SRB RING FRAMES RESONATED AT LOCAL FREQUENCIES AND HIGH GAINS, WHICH WERE CRITICAL TO FLIGHT CONTROLS.	STRUCTURAL REDESIGN WAS REQUIRED TO STIFFEN SRB RING FRAME, WHICH REVISED THE LOCAL RESONANT FREQUENCIES AND REDUCED THE GAIN.	FLIGHT CONTROL INABILITY AND POSSIBLE LOSS OF VEHICLE.
SHUTTLE MVGVT	AXIAL SSME FREQUENCIES AND MODE SHAPES DID NOT CORRELATE WITH PRETEST ANALYSIS. A HALF SHELL DYNAMIC MATH MODEL USING SYMMETRY WAS USED IN THE PRETEST ANALYSIS.	A NEW THREE DIMENSIONAL ASYMMETRIC MATH MODEL OF THE SSME ENGINES AND THRUST STRUCTURE WAS REQUIRED. NO HARDWARE CHANGES WERE NECESSARY.	POGO STABILITY ANALYSES WOULD HAVE BEEN SUSPECT.
SHUTTLE MVGVT	TEST RATE GYRO VALUES SHOWED GREATER RESPONSE VARIATIONS THAN ANALYSIS. RESPONSE VARIATIONS BETWEEN RGA'S WERE MUCH LARGER THAN THOSE USED IN THE ANALYTICAL STUDIES IN DETERMINING THE REDUNDANCY MANAGEMENT (RM) TRIP LEVELS.	RM SOFTWARE TRIP LEVELS AND CYCLE COUNTER LEVELS WERE INCREASED. THE FAULT ISOLATION ROUTINE WAS MODIFIED TO INHIBIT KICKING OUT RGA'S AND ACC'S AFTER FIRST SENSOR FAILURE. (FOR STS-1 FLIGHT ONLY; OTHER FLIGHTS WILL BE EVALUATED.)	FLIGHT CONTROL INSTABILITY AND POSSIBLE LOSS OF VEHICLE.
SHUTTLE QUARTER SCALE	INTERNAL SRB PRESSURE EFFECTS ON STIFFNESS OVER PREDICTED.	LOAD IMPACTS WITH MINOR REDESIGN OF INTERFACE BACKUP STRUCTURE.	POTENTIAL FAILURE OF INTERFACE AND LOSS OF VEHICLE.

Figure 19-5. Dynamic Testing Impacts

Space Station Static and Dynamic Tests

It is a requirement that all payloads flown on the Space Shuttle must be dynamically tested to ensure human flight safety. Accomplishing this test for the Space Station modules required that there be a solid fixture to provide a very rigid attachment for the Orbiter payload bay attach hardware. This heavy steel fixture was anchored in 20 ft of concrete so that it would not move and therefore establish accurate boundary conditions for the payload. The test setup is shown on Figure 19-6. This fixture was applied to resolve any issues related to the indeterminacy of the payload attachment to the Shuttle Orbiter. It provided correct simulation of the boundary conditions between the payload and the Orbiter attachment. The tests provided data to verify dynamic models that were used in design to ensure crew safety. [Author's working files]

Space Station Static/Dynamic Test

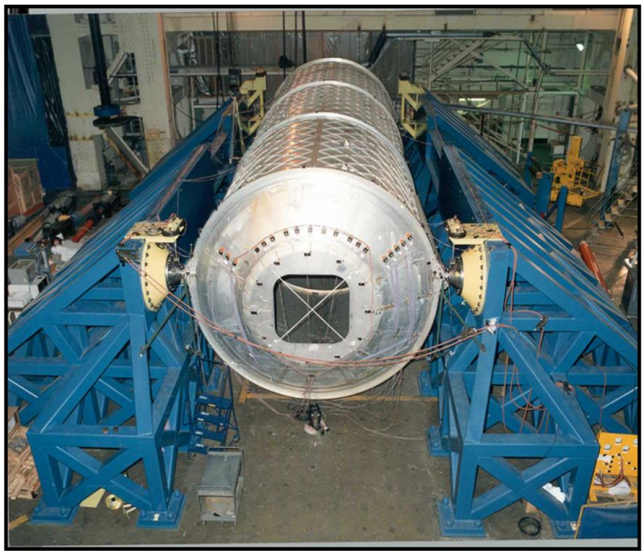


Figure 19-6. Space Station Module Test Setup

- **A key message from Lesson 19 is:**

  Test what you fly.

  Fly what you test.

Lesson 20: Independent Analysis, Test, and Design Keys to Success

- **Complex systems require independent analysis, test, and design; this provides in-depth insight.**
  - **Space Systems are so complex, no one analysis or test can provide all of the answer.**
  - **The creativity of the human mind is the source of our solutions. Initially we need to hypothesize and assess various solutions.**
  - **We must be open to other insights. (Senge's advocacy/inquiry).**

During design and development, some problems that are encountered are out of our experience band. This happens in situations where there are high power densities and when the system limits are expanded. In rocket propulsion systems, effects of high chamber pressures and temperatures along with reduced size (reduced weight) are examples where

problems can be expected. As a result, independent analyses, tests, and designs are needed to provide insights to avoid catastrophic events. In most cases the physics are so complex no one analysis or test can provide all the solutions. To achieve an understanding of complex situations, it takes multiple analyses, tests, and especially the creativity of the human mind. In this process, engineers must be open to the insights and questions of all participants. It takes a combination of human minds to put together these highly interactive complex puzzle solutions.

Examples:

- SSME Whirl Solution
- SSME LOX Pump Spalled Bearings
- SSME Main Oxidizer Valve Buzz Solution

SSME Whirl Solution

Both the fuel and LOX turbopumps experienced rotordynamic whirl instabilities during the development of the SSME. When a system is rotordynamically unstable, the shaft can precess in either a forward or backward direction. An example of whirl instability is shown in Figure 20-1.

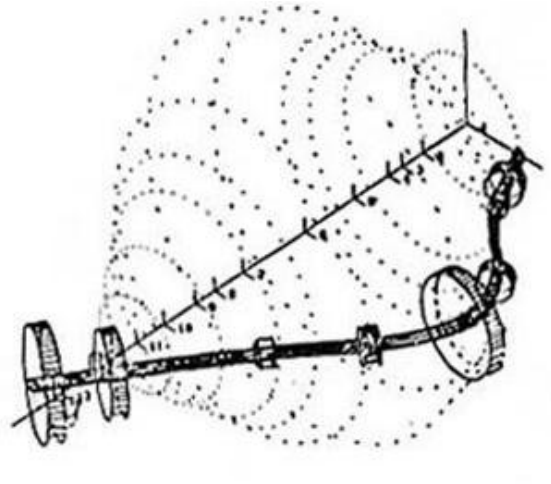


Figure 20-1. Turbopump Whirl

In this figure the shaft is rotating at some required speed, i.e., synchronous frequency, about its center line. Simultaneously precessional motion occurs, represented in this figure by the bent distorted shape. The rotational speed (frequency) of the bent distorted shape is the precessional speed and it is usually at a subsynchronous frequency. For a linear system, this frequency is one of the system natural frequencies. The ratio of the subsynchronous to the synchronous frequencies depends upon the cause of the instability. Rotordynamic instabilities have been caused by effects of internal rotor friction, annular journal bearings, turbine blade Alford forces, impeller-diffuser interactions, pulsating torque, axial-radial coupling, etc.

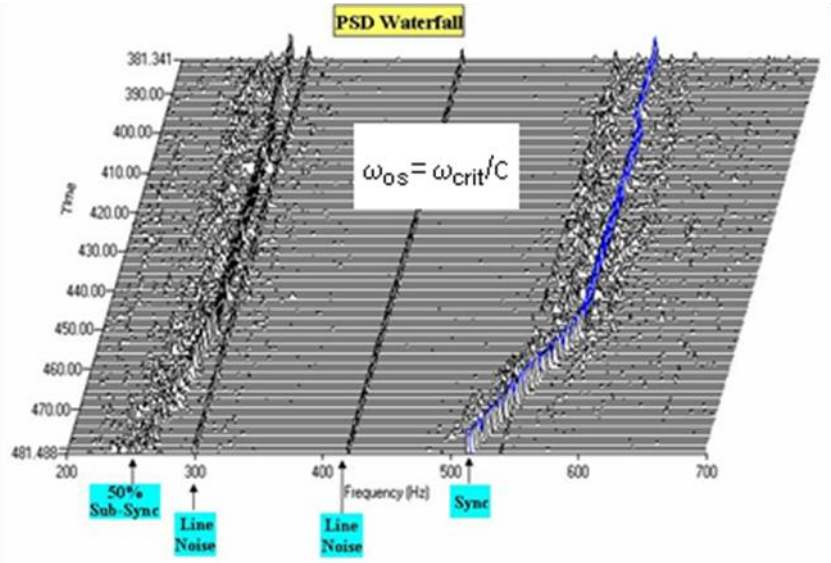


Figure 20-2. Acceleration Power Spectral Density (PSD) Isoplot

Shown in Figure 20-2 is an isoplot of the output of an accelerometer on a turbopump where there is rotordynamic instability. In this three dimensional plot the power spectral density (PSD) amplitude is the vertical axis and the axes in the plane represent time and frequency. If there were no instability, the acceleration response would be only the synchronous frequency as shown on the right side of the figure and in addition there would not be a significant amount of noise. However, when there is rotordynamic instability, in addition to the synchronous frequency there will be a subsynchronous frequency as shown on the left of the figure. As seen in Figure 20-2, the ratio of the subsynchronous frequency to the synchronous frequency is about 1/2. This is typical where instabilities are induced by effects associated with journal bearings, see reference [von Pragenau, 1982]. In journal bearings the flow between the rotor and stator is Couette flow and the Couette flow factor C=1/2 since the velocity profile is linear.

In the development of the SSME, the first incident of rotordynamic instability was in 1976. The instability was in the high pressure fuel turbopump. In this case the interstage seal was changed from a labyrinth seal to a step smooth seal along with stiffening the shaft and bearing carriers. The critical frequency went from about 9,500 rpm to 18,000 rpm. Thus the onset speed would be about 36,000 rpm.

The SSME LOX pump first experienced rotordynamic instability in 1982. A damping seal bearing was implemented on the pump end. LOX is supplied by the preburner pump impeller and discharges through the pump end bearings. As a consequence of the damping seal bearing, the instabilities were suppressed. In the region of the damping seal bearing, the stator was roughened and Couette flow no longer had a linear velocity profile. The Couette flow factor was reduced moving the onset speed out of the region of operation. Although George von Pragenau conceived the damping seal in the mid-1970's, it wasn't implemented until 1982. The damping seal bearing was a technical breakthrough that enabled

rotordynamic stability in both the LOX and fuel turbopumps. It moved the instability onset speed out of the operating range with significant margin.

In 1986 there was an attempt to operate the SSME at 109% power level. The speed of the fuel pump would be near or slightly exceed 36,000 rpm (potential onset speed). A production pump was built without a damping seal bearing with the thought that if there was instability a damping seal bearing could be added. In the initial test, the pump speed was 36,860 rpm and there was instability. The interstage step smooth seal was replaced with a damping seal bearing and instability was eliminated.

Whirl motion results in high static and dynamic loads that catastrophically impact the system through bearing wear and/or rubbing of the rotating assembly. This is unacceptable and will result in loss of hardware. Action must always be taken to eliminate whirl instabilities in rotating machinery.

SSME LOX Pump Spalled Bearings

Before the first flight of the Space Shuttle, there was spalling (pitting) of the pump end bearings in the SSME LOX pump. Shown in Figure 20-3 is the Rocketdyne LOX turbopump. The duplex bearings are shown on the pump end.

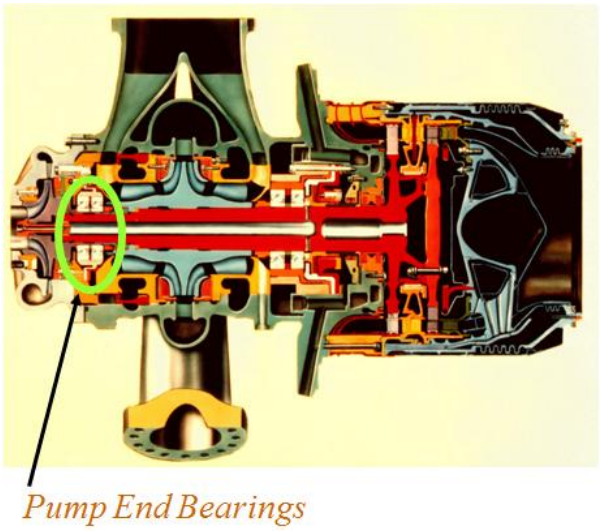


Figure 20-3. Rocketdyne LOX Turbopump

The cause of spalling was unknown. In fact, it was not known if it occurred at startup, steady state running, or shutdown. In addition, there were no engine failures because of spalling during development testing.

It was not known if spalling was a failure mode. It was decided to put spalled bearings in several turbopumps and test them for 800 seconds. All the turbopumps had redline protection and it was thought that if there was an incident the redline protection would shut

the engine down before serious damage could occur. It turned out that the pumps were tested without an incident.

As a consequence of these tests, spalling would not be a flight issue and the first flight was successful. However, the bearings were replaced after every flight. In addition, turbine blades were replaced after every flight. The cost of these replacement activities was $3 million per pump. The turbopumps that are being flown today have silicon nitride bearings and this is no longer a concern.

SSME Main Oxidizer Valve Buzz Solution

During development testing there were two major engine failures caused by acoustically induced vibrations in the vicinity of the main oxidizer valve (MOV). In addition, it was observed that about 20% of the engines had these vibrations without serious consequences. Initially it was determined that the high vibrations were coming from the MOV. This was perplexing since the MOV had no moving parts. Shown in Figure 20-4

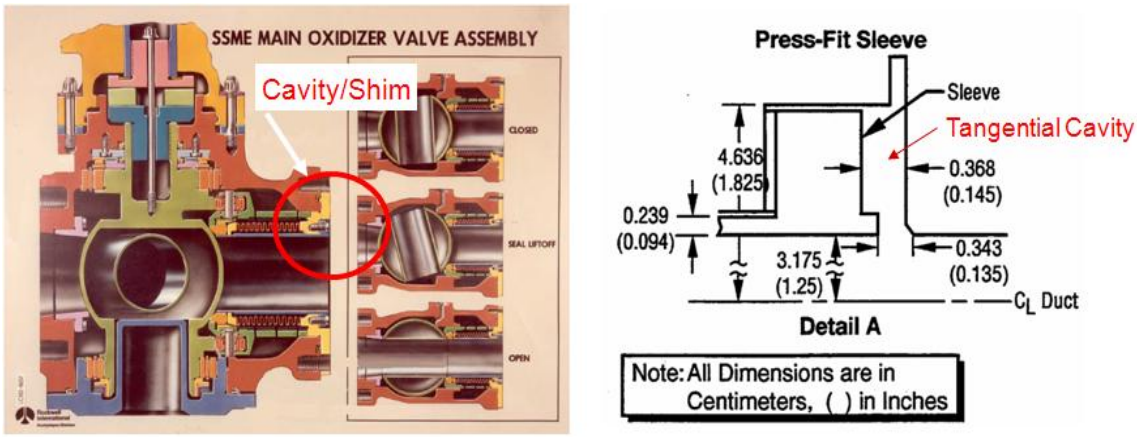


Figure 20-4. Main Oxidizer Valve

is a MOV pictorial cross-section on the left and on the right is a cross-sectional sketch of the cavity/shim region. In the valve there is a bellow spring and at the end of it is a Kel-F seal. The purpose of the spring and seal is to keep the MOV from leaking. Each MOV has to be individually adjusted to obtain the required sealing. In the figure on the right, it can be seen that the region in the vicinity of the tangential cavity a “gap” is formed that varies horizontally depending on the sealing adjustments. The LOX inlet flow to the MOV develops vortex shedding frequencies across the .343 inch gap thereby producing “edge tones” which are then tuned with the longitudinal acoustic duct mode and the tangential cavity acoustic mode. This tuning resulted in a “whistle” with an RMS pressure amplitude of about 165 psi and a fundamental frequency of about 7,300 Hz. These high pressure amplitudes vibrated the parts inside the valve until rubbing occurred causing a fire and significant hardware damage. A contributing factor to the high amplitude pressure oscillation was the 800 psi dynamic pressure in the LOX line (e.g. high power density).

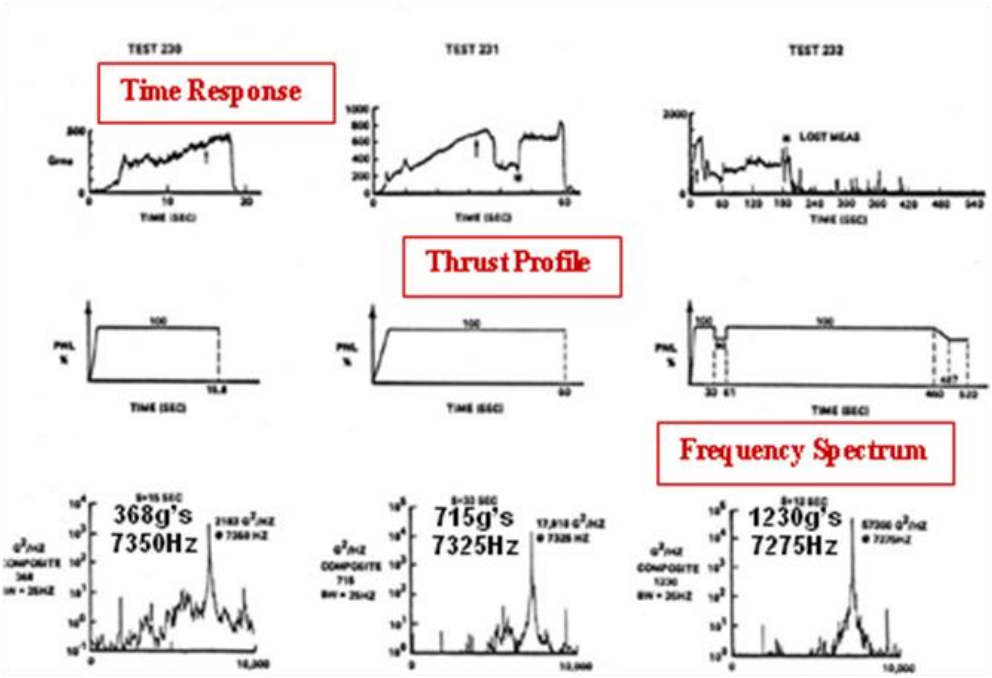


Figure 20-5. MOV Vibration Test-to-Test Response

Figure 20-5 shows data from a consecutive sequence of SSME tests. At the top are the MOV vibration responses, G_{rms} , as a function of time, in the middle are the thrust profiles as a function of time, and at the bottom are PSD's of the vibration for each test. Each of these tests were at the same power level, but as can be seen the vibration levels increased from test to test. At the bottom of Figure 20-5, it can be seen that the vibration levels went from 368 to 1230 g's.

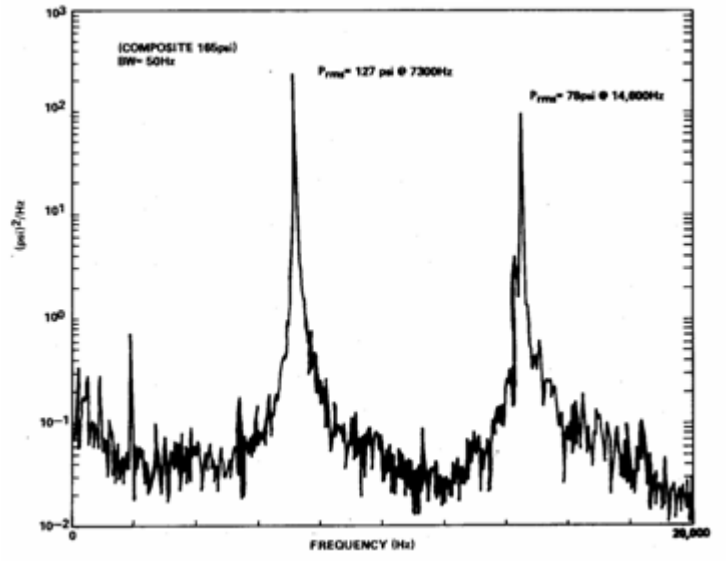


Figure 20-6. MOV Inlet Pressure Fluctuations

Shown on Figure 20-6 is a typical PSD of the pressure fluctuations at the inlet to the MOV. It can be seen that overall rms level is 165psi. At 7,300 Hz. the rms value is 127psi and at 14,600 Hz the rms value is 78 psi. These high fluctuating pressure levels are a consequence of frequency tuning of the vortex shedding, longitudinal acoustic duct mode, and tangential acoustic cavity mode. This tuning situation is compounded by the fact that the amplitude of the pressure fluctuations is proportional to the dynamic pressure and it is about 800 psi.

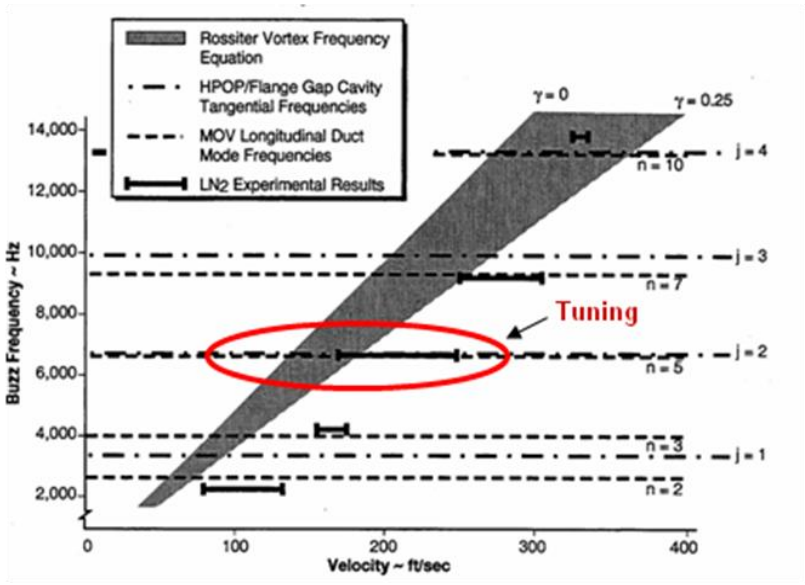


Figure 20-7. Acoustical Mechanism

Shown in Figure 20-7 is a Campbell diagram that illustrates and verifies the tuning mechanism. In the region where the tuning is indicated, it shows frequency results from LN_2 flow testing of the MOV, Rossiter's vortex shedding equation, longitudinal duct mode, and flange gap cavity tangential mode. All these frequencies coalesce resulting in tuning of high pressure fluctuations that caused the MOV high vibration levels, see reference [Schutzenhofer et. al., 1980].

The approach to eliminating these high acoustical pressure fluctuations was to put a shim in the flange gap cavity so as to "fill/close" the tangential cavity gap and prevent the vortex shedding/edge tones from being generated. Thus, the source was eliminated.

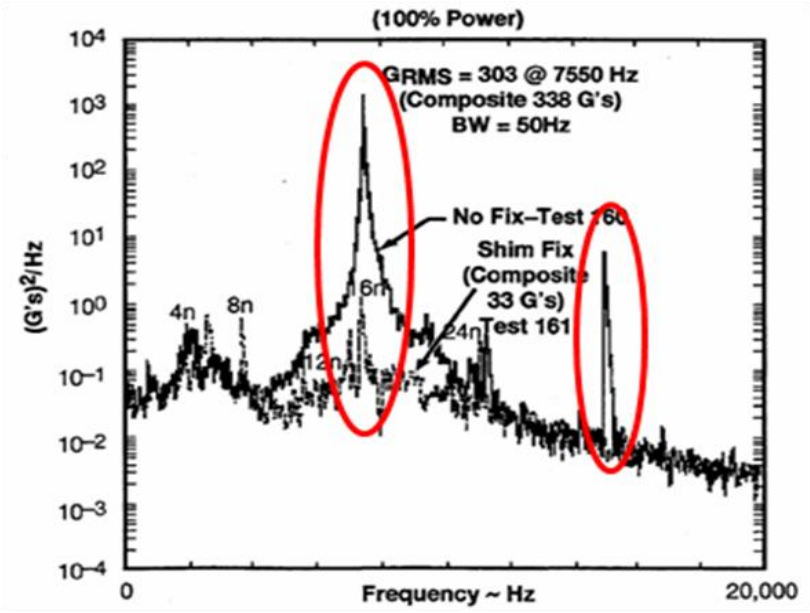


Figure 20-8. Effect of Fix

Shown in Figure 20-8 is a comparison of vibration responses of the MOV with and without the shim. It can be seen that the g-level went from 338 g's to 33 g's. Thus, the mechanism was verified along with the shim fix.

In rocket propulsion systems there are high power densities. This can be illustrated if a comparison is made between the dynamic pressures of a launch vehicle in flight and the dynamic pressure of flow (e.g. MOV) in a rocket engine. In the flight of a launch vehicle the maximum dynamic pressure is about 5 to 6 psi. This is important because all the point, distributed, and unsteady loads are proportional to the dynamic pressure. In the case of the MOV the dynamic pressure was 800 psi. Here too, all the steady and unsteady loads are proportional to the dynamic pressure. The consequence is: things that may usually be unimportant now become important. In this case, two SSME's were lost to an otherwise seemingly "benign whistle" that produced MOV vibration levels as high as 1230 g's; caused by tuning and high dynamic pressure. Eventually, the MOV problem was resolved by independent analyses and component tests.

- **A key message from Lesson 20 is:**

  Our history tells us that critical areas require independent parallel analyses, test, and design activities; along with the creativity and innovation of analysts and designers.

Lesson 21: All Analyses and Tests are Limited

- **All analyses and tests are limited. They are based on a set of assumptions. Don't extrapolate beyond the assumptions.**
  - **Analyses are limited: boundary and initial conditions, physical parameters, sub-models, numerical methods, etc.**
  - **Analyses should precede tests**
  - **Tests are limited: similarity parameters, boundary conditions, partial test models, lack of combined environments, instrumentation, data processing, etc.**
  - **Benchmarking analyses and tests is required to extrapolate to flight conditions**
  - **Determine sensitivities with respect to key variables**
  - **Analysis and test results should have associated uncertainties identified**

All analyses and tests are limited. They are based on assumptions and models. Don't extrapolate beyond a validated set of analyses and tests.

The level of analyses has significantly advanced due to the speed and capacity of high performance computers. However there are limitations due to numerical methods, sub-models, definition of initial and boundary conditions, physical parameters, etc. Similarly, there are limitations in testing, for instance: lack of ability of achieving similarity, boundary conditions, partial modeling, lack of combined environments, etc. Even though these limitations exit, the designer has to use a combination of analyses and tests to achieve the best balanced design.

Initially, both the analyses and tests may be immature due to lack of definition of the design space. Analyses should always precede testing as a guide to test definition. After the test, the physics and design space will become clearer. Then the analytical modeling can be updated. This will lead to clarification of the design space and provide direction for additional testing. In complex situations there may be a series of iterations to both determine the design space and converge the modeling and testing, i.e. anchoring the model.

In some cases there may not be exact similarity because of an inability to achieve testing in exact dynamically similar conditions; for instance, high Reynolds number flows, chemically reacting flows, etc. In these cases, methods have to be developed to account for lack of similarity. Sensitivity analyses with respect to key variables can provide insights into these effects and how to account for them in design. The ultimate determination in some of these cases is through flight testing, e.g. rocket engine plume effects.

In both analyses and tests, uncertainty has to be determined. This can be achieved by comparisons to historical data bases, test, and expert opinion.

Examples:

- External Tank GH_2 Diffuser
- SSME Dynamic Environments / CFD

External Tank GH_2 Diffuser:

During the first test of the Space Shuttle Main Propulsion System (MPS), the GH_2 diffuser failed due to high cycle fatigue. Shown in Figure 21-1 is the MPS. The GH_2 diffuser is shown as the cylindrical object inside and at the top of the hydrogen tank. It promotes controlled mixing of hot incoming autogenous gas minimizing: ullage temperature, pressurant residuals, and gas impingement on the liquid surface during the start transient. The design goal is for the ullage gas to be like a piston pushing the liquid hydrogen out of the tank.

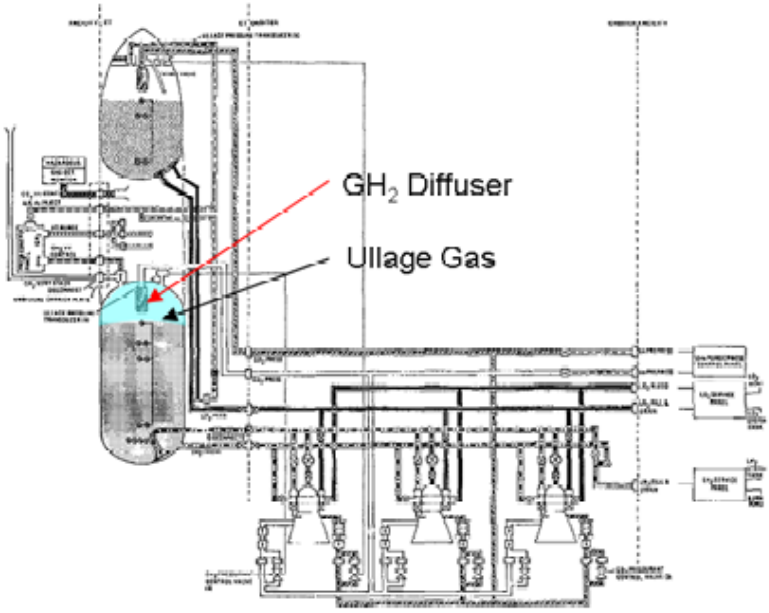


Figure 21-1. Space Shuttle MPS System

The design of the diffuser is based on the diffuser in the Saturn/Apollo S-IVB stage. The present configuration went through stress analysis and flow qualification testing. The results indicated that the diffuser had margin and was adequate for MPS testing.

However, the diffuser was sensitive to flow induced vibrations. After 26 hours of helium purging and 1.19 seconds of hot fire testing, the diffuser failed in the center of the cylinder with six pieces and portions of screen falling to the bottom of the LH_2 tank. Shown in Figure 21-2 is the failed diffuser.



Figure 21-2. GH_2 Diffuser

Initial analyses and testing indicated that the system was adequate. Subsequent to the MPS failure additional analyses and testing could not determine the failure cause. It was observed that a significant number of strain gages and accelerometers were on the test articles for the purpose of measuring response. This instrumentation dampened the response and all were removed except for three strain gages. In subsequent testing the response increased significantly and the diffuser failed in flow facility testing. Shown in Figure 21-3 (on the left) is the rms stress versus mass flow rate during helium flow tests. [Norquist, 1979] On the right side of the figure is the rms stress versus the number of cycles to failure. It can be seen that the rms stress is above the endurance limit of Aluminum 6061 and cyclic fatigue failure is imminent.

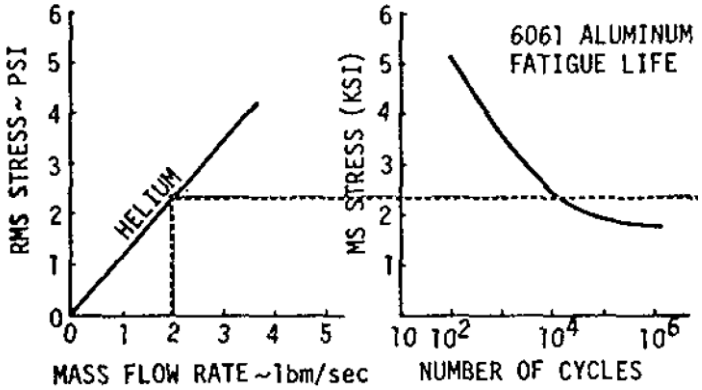


Figure 21-3. RMS Stress for Aluminum 6061 before Fix

The diffuser was redesigned and the .050 inch wall thickness of the aluminum was changed to a .085 inch wall thickness of 21-6-9 steel. In addition an inlet nozzle was used instead of a flat plate to reduce noise levels. The results of flow tests, shown in Figure 21-4, indicate that the redesigned diffuser's rms stress was below the endurance limit. In subsequent MPS testing the diffuser functioned adequately.

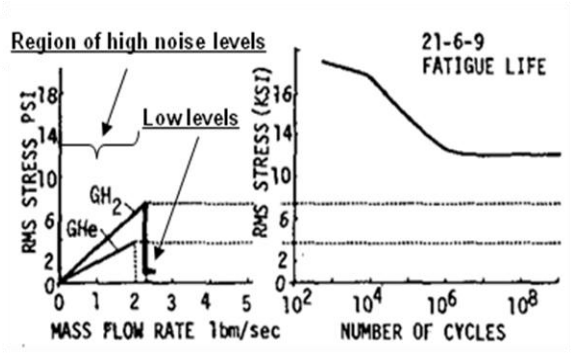


Figure 21-4. RMS Stress for Steel 21-6-9 after Fix

SSME Dynamic Environments / CFD

During development of the SSME there were numerous fatigue problems; many were the result of high static and dynamic environments driven by the high chamber pressure and exacerbated by tortuous flow paths with protuberances and cavities. Examples of failures include: LOX posts, main oxidizer valve, flow meter, splitters, high pressure fuel pump impeller, capacitor probe, etc.

Prediction capability in these extreme environments was limited to nonexistent. For example, flow analyses in the H-1, F-1, and J-2 engine programs were one and two dimensional and the chamber pressures were: P_c = (H-1, 652psi; F-1, 982psi; and J-2, 763psi). In addition, these engines were expendable. In comparison to the SSME, its chamber pressure is 3100psi and the engines are reusable. The static and dynamic flow induced loads can increase by at least the ratio of the chamber pressures (e.g. factor of three from F-1 to SSME).

At the beginning of the SSME program the flow analyses were mostly one and two dimensional. However, it became clear that knowledge of the environments needed to be improved. Although computational fluid mechanics (CFD) had been tried over the years, its lack of maturity did not support design activities. However, improved computer capacity and speed, advanced numerical methods, and turbulence modeling could potentially enable application of CFD to design. In 1987 CFD was introduced into the design process with the goal of making it a design tool. To achieve that goal the following requirements were implemented: (1) Integrate/improve the capabilities of propulsion contractors, academia, CFD specialists, and government flow analysts; (2) Improve CFD methods/codes as required for design; (3) Benchmark CFD methods/codes for engine application; and (4) Implement results into design process.

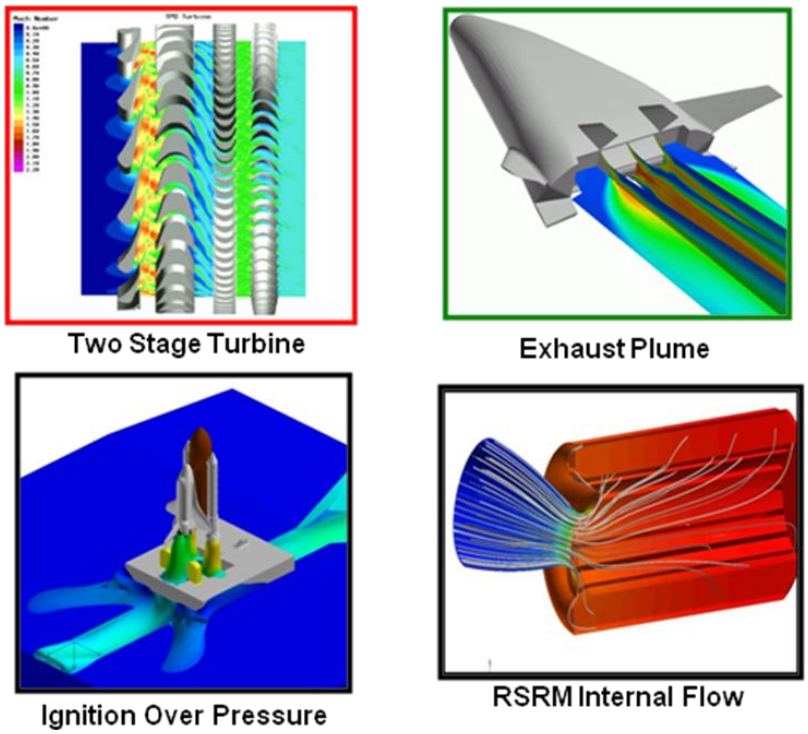


Figure 21-5. Examples of Computational Flow Dynamic Results

A consortium of CFD analysts and flow testing specialists was formed to focus activities on improving efficiencies of turbines, pumps, and combustion devices. Three respective teams were formed and about $5-6 million/year was allocated for CFD and $2-3 million/year for benchmark testing. Within a period of 4 years efficiencies in turbines and pumps were improved to the extent that the number of stages could be reduced. The cost savings for a program were $70 million for the turbine and pump stages each.

Shown in Figure 21-5 are typical examples of CFD results. These activities support steady and unsteady flow loads, heat fluxes and thermal environments, and trajectory and performance analyses. CFD has evolved into a significant design tool and has improved the fidelity and reduced the uncertainty of new design.

While analyses and tests are critically important tools in design and development of high performance systems, the designer has to be aware of associated assumptions and limitations; including effects of uncertainty. If not thoroughly understood, misleading or incorrect results lead to very costly development problems, operational costs, and hardware redesigns. Check sensitivities; they provide indicators where there may be problem areas.

- **A key message from Lesson 21 is:**

Be aware of the assumptions and limitations of your analysis/test model.
Don't eat the menu!

Lesson 22: Scaling Is a Major Issue

- **Scaling is a major consideration.**
  - **Manufacturing process development**
  - **Scale model testing**
  - **Data analysis**
- ***Scaling is so commonly used that it sometimes is applied without critical examination.***
- **To preclude misleading results, question and understand scaling effects and the bounds of their applicability.**

Scaling is a major consideration in design, testing, and manufacturing. Scaling is used for many purposes, including:

- Relating smaller test articles to full-scale hardware.
- Relating and extrapolating test environments to flight environments.
- Developing manufacturing processes using test articles that are smaller and less expensive than full-scale hardware.
- Relating and extrapolating data bases derived from configurations different from the predicted flight configuration.

Because scaling is used so commonly and frequently, it is easy to become complacent in its application. However, as is the case for so many aspects of the design process, scaling must be carefully and judiciously applied so as to understand its effects and not exceed the bounds of its applicability.

Examples:

- X-33 Fuel Tank
- Saturn I Scale Model Dynamic Test

X-33 Fuel Tank

The X-33 Fuel Tank failure of Lesson 18 gives an example of a scaled manufacturing process that produced misleading results. The adhesive strength of the small-scale test panels was found to be adequate in test, but the size of the full-scale panels required a longer out-time for adhesive application before going to the autoclave. This longer out-time resulted in approximately 50% loss of adhesive strength in the full-scale hardware.

Saturn I Scale Model Dynamic Test

The Saturn I scale model dynamic test provides another example of unexpected scaling effects. It was planned to use a one-tenth scale model of the Saturn I for precursor dynamic tests. The small scale was chosen for expected economy and ease of testing. It was found that to obtain valid results, the tolerances and fasteners of elements had to be

proportionately scaled down. This entailed extreme accuracy of the test hardware, which was a challenge to produce. Only by using these scaled manufacturing tolerances could representative structural mode shapes and frequencies be obtained. [Grimes, 1970]

- **A key message from Lesson 22 is:**

  Scaling is a major issue in design, testing, and manufacturing verification. To preclude misleading results, critically question and understand scaling effects, and apply validated scaling laws.

Principle VIII: Anticipating and Surfacing Problems Must be Encouraged

Many of the lessons cited in this report are derived from failures. What is needed is to find ways of precluding failures—to prevent them from happening. Three lessons on avoiding problems will be addressed:

23. Must Hear and Understand All Technical and Programmatic Opinions
24. There Are No Small Changes!
25. Expect the Unexpected

Lesson 23: Must Hear and Understand All Technical and Programmatic Opinions

- **Minority opinions are necessary and provide insight.**
  - **All our answers are incomplete, based on assumptions we select.**
  - **Different assumptions and perspectives are needed to get a more complete picture.**
  - **Our systems are very complex, highly interactive; therefore, we need all the insights we can get in order to ensure success.**
- **Apply Critical Thinking and avoid normalization of deviances.**
  - **Think about how the real system will perform, and what could go wrong.**
  - **Recognize and question model/test assumptions and deviations in data trends.**

As has been emphasized, space systems are exceedingly complex. Because of this complexity, our understanding of the systems is always limited and incomplete. Consequently, we must continually press to increase our understanding of the system and to

anticipate problems that may arise. Lesson 18 emphasized scrutinizing the hardware and its data in order to advance our understanding. Lesson 20 advocated independent analysis, test, and design as another component of understanding. This lesson addresses the importance of encouraging multiple viewpoints and opinions, for many perspectives are needed in the quest for the true composite picture of the system.

In many cases, minority opinions can be the most valuable, as they often come from people who have a creative or unconventional thought process that may provide a unique insight. While it is sometimes inconvenient or uncomfortable to deal with minority opinions, they should be encouraged. They are often the best examples of the critical thinking that is essential to product success.

Example:

Wernher von Braun – Saturn I Test

Consider the response of Wernher von Braun on a Saturn I dynamic test issue. The issue concerned data from the dynamic test for Saturn I which was used in control system design. One engineer, who was a creative individual, analyzed the data in an unconventional way, separating out the effects of the suspension system on the dynamic modes. Using these so-called corrected modes meant that the control system as designed would be unstable.

Two weeks were allocated to study the problem. Further study revealed that the new modes were not real, but were a result of an artifact in the numerical analysis. At the end of the two-week period, a presentation was made to Dr. von Braun, showing that the mode shapes were good as originally analyzed; therefore, the system was stable and safe to launch.

A laboratory director at the meeting complained that we had wasted two weeks “chasing rabbits”. Dr. von Braun’s response was, “What if he had been right? We always have time to get the right answer.”

Twenty-five years later, this creative engineer who had analyzed the Saturn I dynamic data invented the program-saving damping seal for turbomachinery. Did Dr. von Braun do the right thing in valuing and nurturing this kind of minority opinion and creativity?

- **A key message from Lesson 23 is:**

  We must listen to all technical and programmatic opinions.

  Listen
  Listen
  Listen!

Lesson 24: There are No Small Changes!

There are no small changes. All changes occur in a system and therefore affect the whole system.

The familiar saying “There are no small changes” means that all changes occur within a system and therefore affect the whole system, often in unexpected ways. This principle is sometimes called the Law of Unintended Consequences.

Engineering history is replete with cases where this often-painful lesson has been experienced. We will cite four such examples.

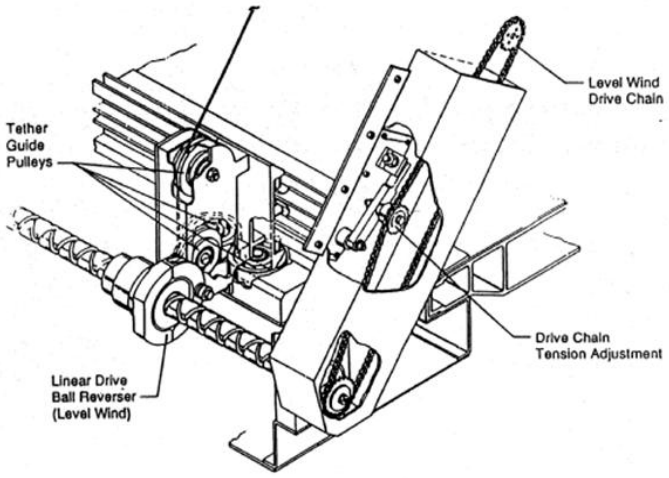
Examples:

- Tethered Satellite Level Wind Bolt
- Saturn SI-C Pogo
- Saturn S-II Pogo
- External Tank Insulation Blowing Agent

Tethered Satellite Level Wind Bolt

The Tethered Satellite was intended to be deployed from the Shuttle Orbiter payload bay on a 22 km tether, to explore numerous promising technologies that tethered systems might enable. The tether was deployed and retrieved from a spool in the payload bay through a level wind mechanism similar to those found on some fishing reels (Figure 24-1).





Level Wind Mechanism

Figure 24-1. Tethered Satellite and Level Wind Mechanism

As the first tether mission was approaching flight readiness, an analysis showed that a bolt on the level wind mechanism did not have sufficient strength for the predicted stress. A change order was prepared to change the bolt to one having stronger material. Since the hardware was already assembled, there was a concern that there might be some shifting of the parts when the bolt was removed, so in order to make sure the threads of the new bolt would engage, it was made longer as well as stronger.

Running a tether deployment test after the change would have caused a schedule impact, since the tether reel system was already in the payload assembly facility. So no system verification test was done after this “minor” change.

On orbit, the Tethered Satellite began its deployment without event, but when it reached 256 m, it stopped and would not progress farther. The longer bolt had jammed the level wind mechanism. While a few mission objectives were achieved by this short deployment, the main objectives were not. [Branscome, 1992]

The second Tethered Satellite mission attained 19.7 km of its planned 20.7 km deployment before the tether broke and the satellite was lost. Subsequent assessment attributed the failure to an arc from the conducting part of the tether to the deployer, severing the tether. The arc probably initiated through a pinhole in the tether insulation. This failure likely was not predictable, but could fall in the category of unknowns that the experiment uncovered. [Szalai, 1996]

While there have been some subsequent smaller tether experiments, failure of the two large Tethered Satellite System missions essentially resulted in this very promising technology being set aside, which is a significant loss. And it began with a change thought to be so small as to not require verification.

There should be system verification after any change. No change can be assumed to be “small”.

Saturn SI-C Pogo

Pogo is a vehicle longitudinal structural oscillation that is coupled with the Main Propulsion System and the liquid propulsion engines in a closed loop manner, which increases the oscillation and creates instability. It is named pogo after the classical children’s pogo stick. Figure 24-2 illustrates the analogy between the pogo stick on the left and a launch vehicle structural and MPS system combined to produce the closed loop instability.

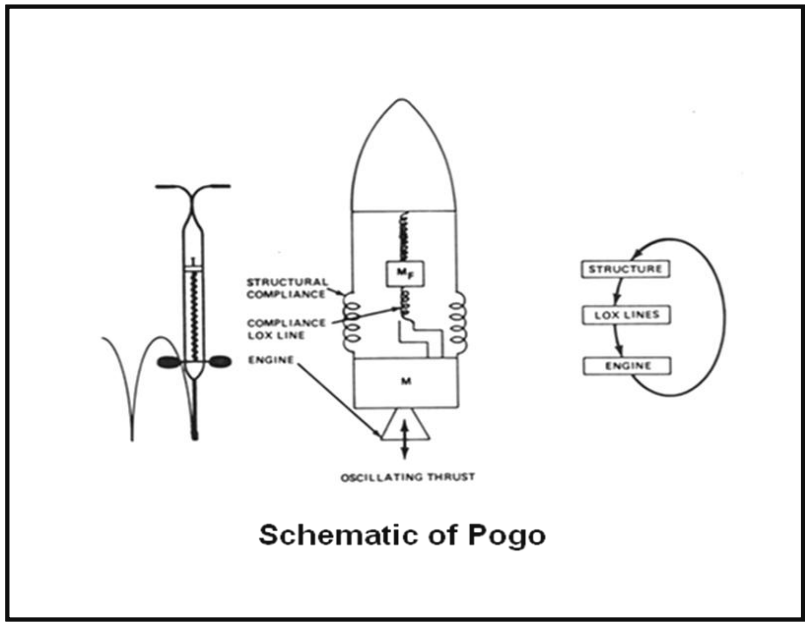


Figure 24-2. Pogo Oscillation Mechanism

Saturn V had two pogo instances. The first one occurred on the second Saturn flight AS-502 during first stage burn. The second occurred during second stage burn on the famed Apollo 13 mission. The first Saturn V vehicle AS 501 had no indication of pogo. Saturn AS-502 had a major incidence of pogo near the end of first stage (SI-C) burn. There were indications of pogo on the second stage (S-II) burn throughout the early program flights but were believed to be managed and under control; however, during the Apollo 13 flight, a near disaster occurred during the first 120 seconds of S-II stage burn. [Ryan, et al, 1969]; [Larsen, 2008]

The difference in the AS-501 and AS-502 vehicles was very minimal. The changes were small changes in the Apollo elements in order to better simulate their mass and dynamic characteristics. The changes were a shift in the mass of about 2,000 pounds in Service Module and Landing Module and 200 pounds added to the Launch Escape System (LEM) and 600 pounds added to the Command Module (CM). The mass change out of a liftoff mass of 6,000,000 pounds was a total of 900 pounds. This change on the front end of the vehicle increased the modal gain of the first longitudinal vibration mode about 30% and changed its frequency about 5%, causing it to couple with the LOX line mode. This caused the system to tune up and go unstable. Figure 24-3 shows the modal gain change, the frequency change and the coupling of the two modes near SI-C stage burnout.

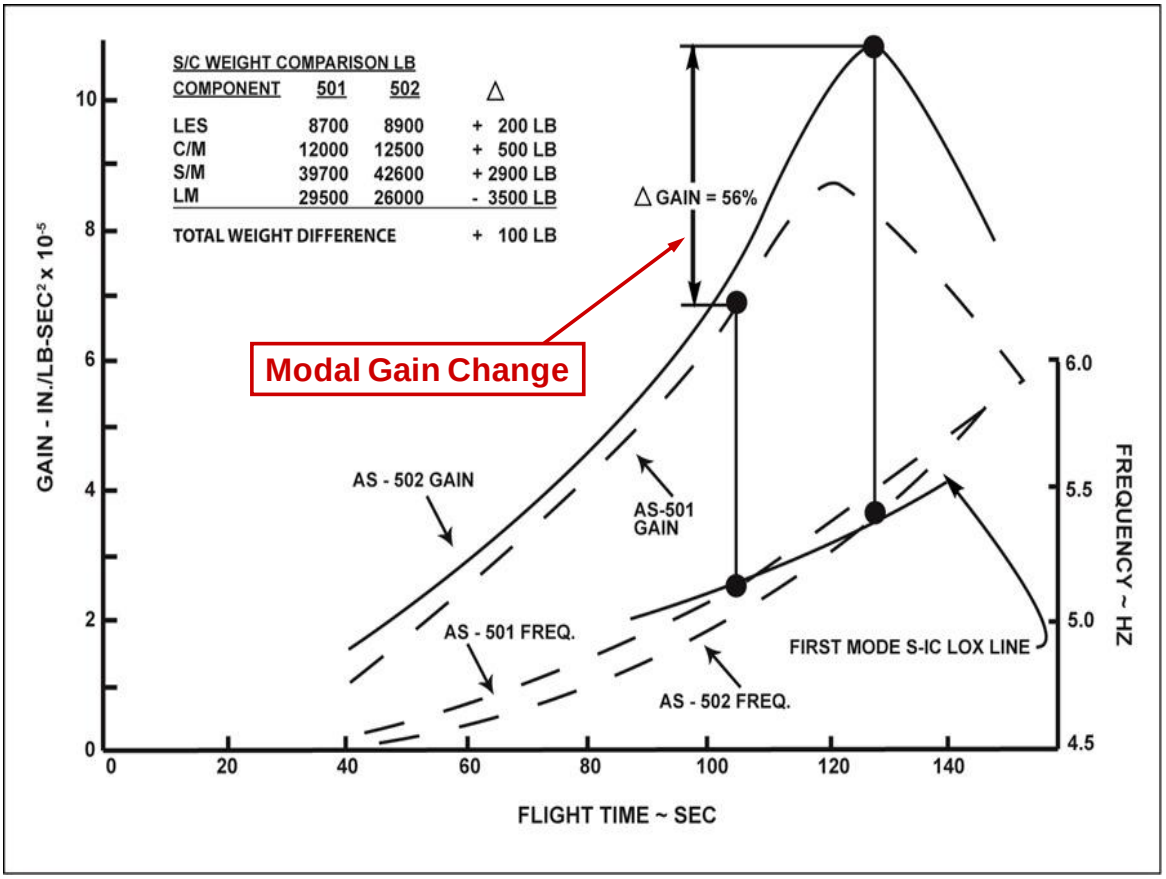


Figure 24-3. Comparison of SI-C Longitudinal Dynamic Characteristics

The fix was fairly simple and easily implemented, including a pogo accumulator around a prevalve (Figure 24-4). The accumulator detuned the LOX line from the first longitudinal line and the SI-C stage did not experience any pogo on the remaining flights. It truly is amazing that that such a small mass change on the front end of the vehicle that weighed 6 million pounds at liftoff could have such a large change on the dynamics of a vehicle the size of Saturn V. [Ryan, et. al., January 20-23, 1969]

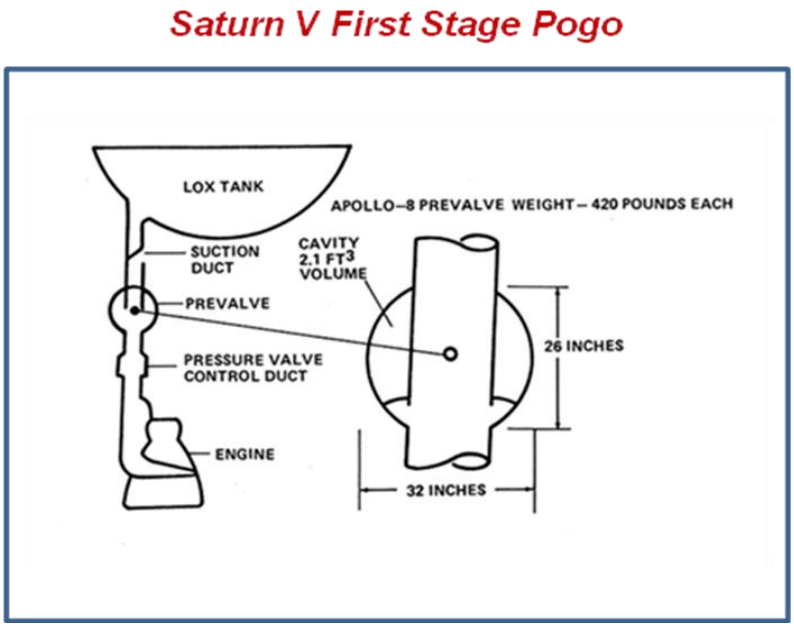


Figure 24-4. S-IC Pogo Accumulator

Saturn S-II Pogo

The S-II stage had shown on basically every flight some small coupled oscillations that were indicators of the pogo phenomenon. Most of these occurrences were a ballooning and decaying crossbeam acceleration at approximately a 12 Hz longitudinal mode, which was occurring during the whole burn of the S-II stage. They were of small amplitude except during the last 60 seconds of burn. There was a pogo working group that was composed of engineers from all the NASA centers, academia and industry who were working on the problem. It was decided that because the large amplitude was occurring the last 60 seconds of S-II burn, the center engine of the S-II stage would be shut down at that point and the other four engines burned longer so as not to have performance loss. Figure 24-5 is a composite of data from several S-II stage flights.

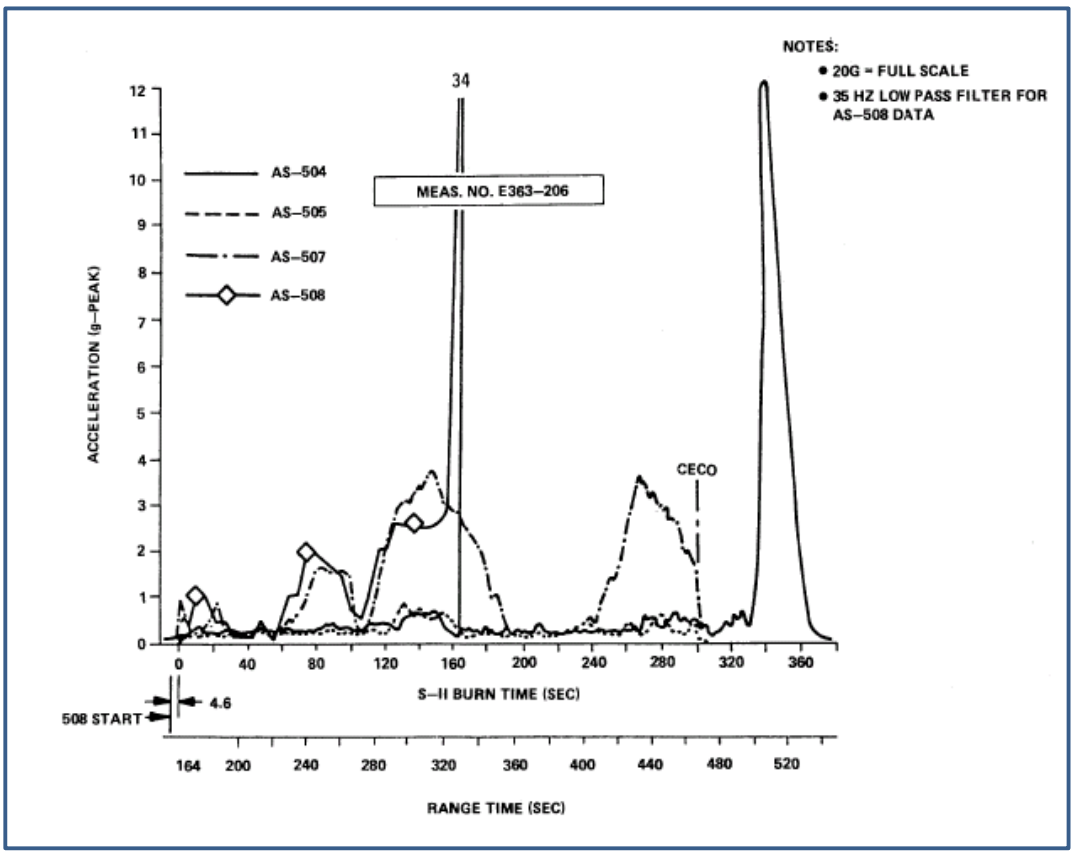


Figure 24-5. Pogo Occurrences on S-II Stage Burns

The center engine was the main contributor to the coupled oscillation as it had a strong coupling with the thrust frame participation in the longitudinal vehicle mode. In addition to the planned early shut down of the center engine, a “g” cutoff system was added to the gimbal area of the center engine as insurance to prevent vehicle failure. It was obvious that the engineering community did not fully understand the sensitivities and characteristics of this system, for on Apollo 13 around 120 seconds into S-II stage burn a large pogo oscillation occurred, shutting down the center engine due to excessive engine pump pressures. In reality the oscillation of the thrust frame/engine gimbal point reached 34 g’s and probably yielded the thrust frame. This oscillation is seen on Figure 24-5. The fix was putting a pogo accumulator at the end of the LOX line, detuning the system and solving the problem. [Ryan, et.al., December 1970]

External Tank Insulation Blowing Agent

The Shuttle External Tank (ET) is insulated on the outside skin by blowing insulation onto the tank as it rotates within a fixture. Blowing agents used in the past do not meet current EPA requirements, necessitating a change to an environmentally-friendly blowing agent. Any change like this, and in particular one that influences such a large area must be recertified. It is standard practice to verify these kinds of systems by testing at the corners of

the environments boxes. In this case the environmental variables were pressure, temperature and flow conditions. When the tests were completed no difference in the response of the insulation was noted and the system was flown. Cameras were installed to see what would happen in flight and the insulation on the intertank was caught in a massive pop-corning of the insulation as the high temperature and low pressure condition were experienced. The old insulation had not shown this effect. The problem was worked extensively by a special team and in that process someone said that maybe the test should be run at nominal conditions and not in the corners of the environment combinations. When this was done the insulation pop-corned as it did in flight. It was found that when testing at the corners of the combined environments box that the extreme environments were venting the trapped blowing agent gases and there was no pop-corning but that when you tested at nominal environments the only way the insulation could vent the trapped blowing gas was to blow off small pieces of insulation. The message is twofold in that (1) no change is small, and (2) certification must be performed at all environmental combination levels. The fix was to punch small holes in the insulation after it was blown on so that it would have vent capability. Since that fix has been implemented there is been very little pop-corning of interstage insulation. Figure 24-6 shows a flight photo where half of the area had the small holes punched and had no pop-corning, whereas the other half without the fix did show pop-corning.

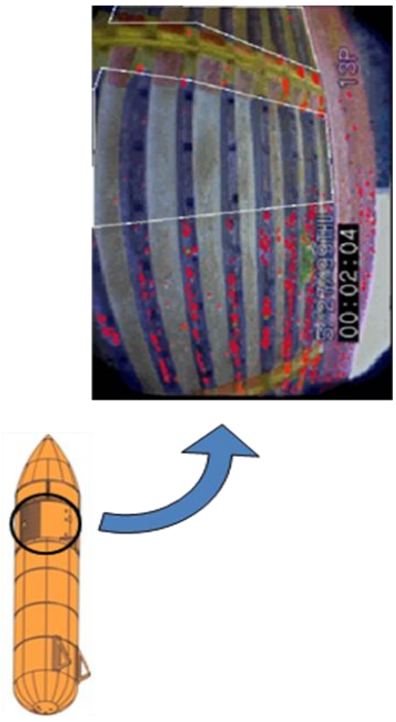


Figure 24-6. ET Intertank Insulation With and Without Pop-corning Fix

- **A key message from Lesson 24 is:**

  Don't make unnecessary changes.
  - Better can be the enemy of good

- Be very careful if a change is required
- Understand system interactions

Verify the system <u>with changes</u> before flying.

Lesson 25: Expect the Unexpected

- **Expect the unexpected -- Things are never exactly what they seem.**

Ambiguity is ever present in aerospace systems. Many things are basically unpredictable due to the immense complexity of the systems and many unexpected things happen. The unexpected events take many forms, from human, to nature, to the physics of the system we are dealing with. The nature of design and operations of space systems means that we must constantly be on the watch for signs and characteristics of these unexpected events.

Example:

Woodpeckers on the ET Ogive

Only one example is used to illustrate these occurrences - the presence of a woodpecker pecking holes in the LOX tank ogive insulation while the vehicle is sitting on the launch pad (Figure 25-1). The vehicle had to be moved back to the VAB to repair the holes, and means of keeping woodpeckers away were implemented. “Evil-eye” balloon scarecrows and owl decoys were placed near the launch pad.

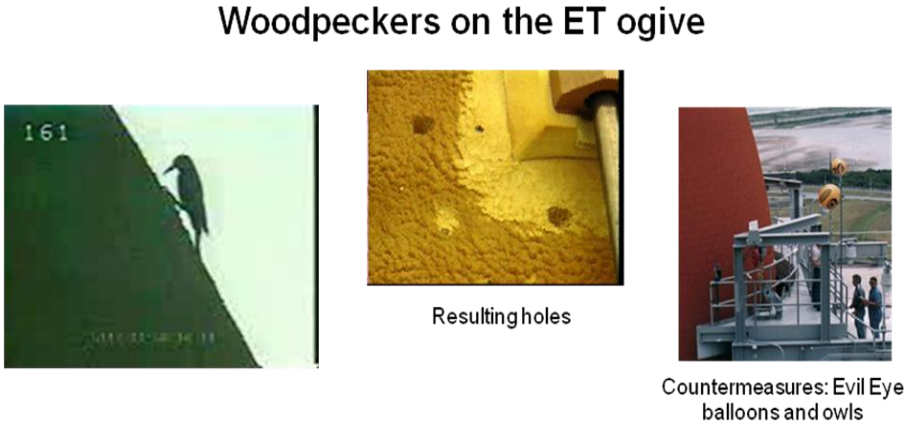


Figure 25-1. Woodpeckers on the ET Ogive

Expect the Unexpected!

- **A key message from Lesson 25 is:**

  Design and operations of space systems require that you constantly must deal with ambiguity and the unexpected. This requires a constant focus on looking for the ambiguities and the unexpected.

Principle IX: Leadership is the Foundation

We started this report with the principle of the primacy of people. We are returning to this basic area with the principle that "Leadership is Foundational". In any engineering organization two key tasks to success are management and leadership. Both are necessary and important; however, leadership creates the vision that sets the sails of the organization. Without leadership any organization will eventually fail since there is no clear path of where it is going. There are several aspects of leadership but only two will be discussed: *integrity*, and *focus beyond yourself*.

26. Integrity
27. Focus beyond yourself

Lesson 26: Integrity

- ***Sing your own "Music"***
- ***Integrity is matching what you do and how you do it with what's inside you.***
  "Your Calling"

There are many facets or dimensions to integrity that are important to leadership. One that is pivotal is the match of what you are inside with what you say and do. It is of major importance that you are doing what is you, what is your way? Until you are working your inner calling the outward and inner are disconnected. The song "I Did It My Way" conveys some of what is meant here. Until what you are inside is what you are outside, leadership will have problems of trust by the organization. There are many examples of the application of this principle. George McDonough used to say about engineer's writings, "As long as they are technically correct and get the message across, don't get hung up on the style."

Example:

Floyd Briscoe: "You must coach it your way. You can't coach my way."

When Robert Ryan was coaching basketball in his second year as coach he got as a principal a former successful coach. The principal told him, "Coach, I will come to your

practices and help 'you' train the team." After one week of trying to help in the gym, he called Robert into his office and said, "Coach, it won't work having me in the gym to help. You have a different style and the boys can't learn two styles. They need one leader and one system. I will stay in the office and we can have discussions where I can pass on to you what I know. I will try to adapt what I know to your system. You must coach it your way, not mine." Did his approach work? Yes, in Robert's second year of working with him the team won the Alabama Class "A" 8th District and State basketball tournaments. The next year the team won the Alabama Class "A" 8th District and 2nd place State basketball championships. The other aspects of integrity are very important as well. If leadership is to be successful then all the aspects of integrity must be engaged.

- **A key message from Lesson 26 is:**

  Without integrity, what you do and say is meaningless.

Lesson 27: Focus Beyond Yourself

- **You must focus beyond yourself, beyond the immediate. It's <u>Being</u> versus <u>Having</u>.**

The tendency of individuals in an organization is to focus on their own interests and work areas and ignore other considerations. Everything we do in organizations is a system and what each individual does affects the total system. Because of these interactions it is imperative that we focus beyond ourselves and not build silos around our work and our self. One principle Bob Ryan learned from a professor at Vanderbilt-Peabody University was stated in the following way. "Each has a choice between focusing their life on *having* or *being*. The *having* focus is social in nature emphasizing what one can get, whether it be recognition, money or position. *Being* is spiritual in nature and focuses on what one can become. It deals with what you are and how you contribute meaning to the organization, the individuals and society." This requires that we not only perform our tasks in an excellent manner, but also focus on the whole. As Stephen Covey says in his book, The Eighth Habit, "Find your own voice, help others find their voice."

Example:

Building Silos

Eighty percent of problems occur due to a breakdown in the system, not in the individual discipline. However, we sometimes get so wrapped up in our discipline work that we fail to see the whole picture. Even worse, we often build protective "silos" around our turf. We must focus on the whole system so that we can see the interactions.

- **A key message from Lesson 27 is:**

"Everything acts as a system; nothing acts independently. It is a whole where all the parts interact, many times in unexpected and unpredicted ways." -- Jim, Bob, Luke

"Systems engineering is one engineer" -- Max Faget

SUMMARY

This completes a study of *Lessons Learned in Engineering*. The lessons derived from the authors' experience have been distilled into principles that should be applicable across all technical areas. The principles and lessons are only important if applied. The key issue we face is the application of these principles and lessons to engineering organizations as well as their products.

A related question asked by the Directors of Engineering at MSFC was: "How do we achieve excellence in engineering?" The authors' approach to answering this broader question was a short course on Excellence in Engineering which is documented in a future NASA CR titled *Excellence in Engineering.*

We started this report with a set of nine generic principles based on 27 lessons derived from our experiences in space flight systems. These principles and corollaries are repeated below.

Lessons Learned Principles

I. System success depends on the creativity, judgment, and decision-making skills of the people
- People are our most important resource

II. Space systems are challenging, high performance systems
- High energy, high power density
- Therefore, high sensitivity

III. Everything acts as a system (whole)
- We design by compartmentalization and reintegration
- Understanding interfaces and interactions is crucial
- Requires pervasive communications

IV. The system is governed by the laws of physics
- Reality can't be ignored
- Look to the real performance of the hardware and software

-

V. **Robust design is based on our understanding of sensitivities, uncertainties, and margins**
   - Must consider sensitivities, uncertainties, margins, risks
   - Aim for robustness

VI. **Project success is determined by life cycle considerations**
   - Program constraints can result in a non-optimal design
   - Requirements can drive the design in unexpected ways
   - Early phases of project most influential on design
   - Design must consider full life cycle including manufacturing, verification, and operations

VII. **Testing and verification have an essential role in development**
   - We understand by testing
   - Must know limitations

VIII. **Anticipating and surfacing problems must be encouraged**
   - Critical thinking
   - Think out of the box
   - Listen

IX. **Leadership is the foundation**
   - Integrity
   - Outward focused
   - People centered

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14. ABSTRACT

This Contractor Report (CR) is a compilation of Lessons Learned in approximately 55 years of engineering experience by each James C. Blair, Robert S. Ryan, and Luke A. Schutzenhofer. The lessons are the basis of a course on Lessons Learned that has been taught at Marshall Space Flight Center. The lessons are drawn from NASA space projects and are characterized in terms of generic lessons learned from the project experience, which are further distilled into overarching principles that can be applied to future projects. Included are discussions of the overarching principles followed by a listing of the lessons associated with that principle. The lesson with sub-lessons are stated along with a listing of the project problems the lesson is drawn from, then each problem is illustrated and discussed, with conclusions drawn in terms of Lessons Learned. The purpose of this CR is to provide principles learned from past aerospace experience to help achieve greater success in future programs, and identify application of these principles to space systems design. The problems experienced provide insight into the engineering process and are examples of the subtleties one experiences performing engineering design, manufacturing, and operations.

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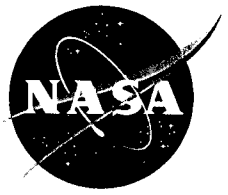

Logistics Lessons Learned in NASA Space Flight

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May 2006

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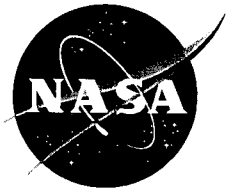

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Executive Summary

The Vision for Space Exploration sets out a number of goals, involving both strategic and tactical objectives. These include returning the Space Shuttle to flight, completing the International Space Station, and conducting human expeditions to the Moon by 2020. Each of these goals has profound logistics implications. In the consideration of these objectives, a need for a study on NASA logistics lessons learned was recognized. The study endeavors to identify both needs for space exploration and challenges in the development of past logistics architectures, as well as in the design of space systems. This study may also be appropriately applied as guidance in the development of an integrated logistics architecture for future human missions to the Moon and Mars.

This report first summarizes current logistics practices for the Space Shuttle Program (SSP) and the International Space Station (ISS) and examines the practices of manifesting, stowage, inventory tracking, waste disposal, and return logistics. The key findings of this examination are that while the current practices do have many positive aspects, there are also several shortcomings. These shortcomings include a high-level of excess complexity, redundancy of information/lack of a common database, and a large human-in-the-loop component.

Later sections of this report describe the methodology and results of our work to systematically gather logistics lessons learned from past and current human spaceflight programs as well as validating these lessons through a survey of the opinions of current space logisticians. To consider the perspectives on logistics lessons, we searched several sources within NASA, including organizations with direct and indirect connections with the system flow in mission planning. We utilized crew debriefs, the John Commonsense lessons repository for the JSC Mission Operations Directorate, and the Skylab Lessons Learned. Additionally, we searched the public version of the Lessons Learned Information System (LLIS) and verified that we received the same result using the internal version of LLIS for our logistics lesson searches.

In conducting the research, information from multiple databases was consolidated into a single spreadsheet of 300 lessons learned. Keywords were applied for the purpose of sorting and evaluation. Once the lessons had been compiled, an analysis of the resulting data was performed, first sorting it by keyword, then finding duplication and root cause, and finally sorting by root cause. The data was then distilled into the top 7 lessons learned across programs, centers, and activities.

The Top 7 Lessons Learned

1. Resulting problems from lack of stowage specification may include growing time demands for the crew, loss of accountability, loss of access to operational space, limits to housekeeping, weakened morale, and an increased requirement for resupply. Therefore, include **stowage requirements** (volume, mass, reconfigurability, etc.) in the design specification.

2. A **common logistics/inventory system**, shared by multiple organizations would decrease the problem of differing values for like items across systems.

3. **Packing lists and manifests** do not make good manual accounting systems. Parent-child relationships are fluid and need to be intuitively handled by a system updated by the movement of both parents and children.

4. **Commonality** is a prime consideration for all vehicles, systems, components, and software in order to minimize training requirements, optimize maintainability, reduce development and sparing costs, and increase operational flexibility.

5. **Design for maintenance** is a primary consideration in reducing the logistics footprint. An optimization is preferable, taking into account tools, time, packaging, stowage, and lifecycle cost.

6. **Plan for and apply standards** to system development. A simple example of this is standard and metric tools. In most cases, where there are multiple standards, there is an interface required, and the interface then requires support.

7. Include **return logistics** requirements in the design specification. Understand and model packaging requirements, pressurization, and reparability/disposability for the return or destructive reentry of items ahead of time.

A Space Logistics Community Survey was developed by integrating the top 7 lessons learned into a 10-part questionnaire. Most questions asked the respondent to rate his/her level of observance of each issue as well as his/her recommendation of each. The final survey analysis is based on a sample of 35 responses from members of NASA, academia, the DoD, and space-affiliated industry.

It was found that virtually all areas surveyed were highly recommended for implementation in current practices. Thus, the survey validated that the top 7 lessons learned are of considerable importance to all participants surveyed, whether from NASA, the aerospace industry, or other industries represented. The survey results also highlighted several weaknesses in current logistics practices. There was a notable need and gap in areas where the observed practice did not meet the recommendation levels. Specifically, the three areas requiring most attention are use of *commonality in systems, inventory management, and design for maintenance*. While some of these may be areas of current mitigation, as exemplified in a separate survey question, some may be areas where there is less ongoing development. In addition to the results of the survey, the method of analysis used revealed that a standard regimen of reviewing lessons learned, consolidating them, and looking for root causes would probably allow broader use of the lessons in new developments.

The conclusion of this report offers recommendations that we believe will help NASA to ensure that logistics is at the forefront of consideration for the Constellation Program and beyond, potentially leading to a substantial cost savings in operations.

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"Strategy and tactics provide the scheme for the conduct of military operations; logistics the means therefore."

Lieutenant Colonel George C. Thorpe, USMC

"More than any other, Antarctic science is dependant on logistics, on the ability to place and maintain a scientist and his equipment in the right place at the right time. Expeditions to Antarctica up to 1925 depended on techniques of transport, communication, survival, which remained largely unchanged for 100 years....after 1925 the development of mechanized transport, the airplane, radio and technology based on better understanding of human physiology, were to make access to the Antarctic, travel within it and survival in its hostile environment, much less difficult."

Beck, P.J., The International Politics of Antarctica, London, Croom Helm Inc., 1986, p.131

1 Study Objective

The Vision for Space Exploration [2] sets out a number of goals as strategic and tactical objectives. Many of these goals, such as the ones listed below, have profound logistics implications:

Space Shuttle

- Return the Space Shuttle to flight as soon as it is practical, based on the recommendations of the Columbia Accident Investigation Board [3]
- Focus use of the Space Shuttle on completing assembly of the International Space Station
- Retire the Space Shuttle as soon as assembly of the International Space Station is complete

International Space Station

- Complete assembly of the International Space Station, including the U.S. components that support U.S. space exploration goals and those provided by foreign partners
- Focus U.S. research and use of the International Space Station on supporting space exploration goals, with emphasis on understanding how the space environment affects astronaut health and capabilities
- Conduct International Space Station activities in a manner consistent with U.S. obligations contained in the agreements between the United States and other partners in the International Space Station [4]

The Moon

- Undertake lunar exploration activities to enable sustained human and robotic exploration of Mars and more distant destinations in the solar system
- Starting no later than 2008, initiate a series of robotic missions to the Moon to prepare for and support future human exploration activities
- Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than 2020
- Use lunar exploration activities to further science and develop and test new approaches, technologies, and systems, including use of lunar and other space resources, to support sustained human space exploration to Mars and other destinations

At the inception of the Exploration Systems Research and Technology study entitled *Interplanetary Supply Chain Management and Logistics Architectures [5]*, the investigators determined that there should be a set of studies on terrestrial analogs for space exploration. The decision to add a study on NASA logistics lessons learned was based on data needs for space exploration, challenges encountered in the development of a logistics architecture, as well as in the design of space systems, and a need for guidance in the development of a logistics architecture for future missions to the Moon and Mars (Figure 1).

The study, assigned to United Space Alliance LLC in Houston, TX, was to review as many sources of Logistics Lessons Learned as were available, and to attempt to draw some conclusions about the current state of NASA's logistics architecture and any challenges to developing an interplanetary supply chain.

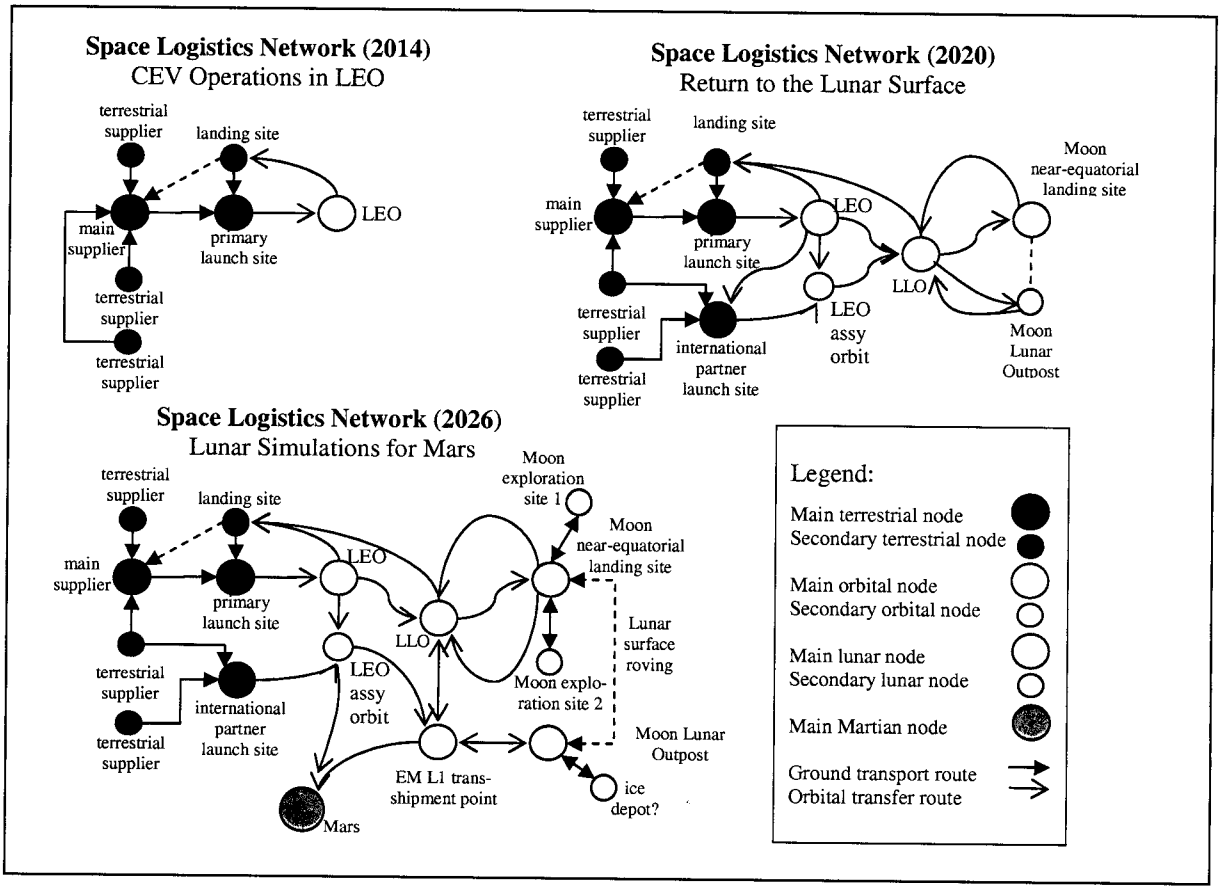

Figure 1: The growing complexity of the NASA logistics network architecture

We believe it important to document and learn from the past. As part of this task we investigated lessons learned from both ISS and Shuttle space logistics. Our team had and gained significant practical experience to distill these lessons learned, and to bring supporting data to the models and simulations in support of future exploration logistics.

A result of this study is significant insight into logistics lessons learned within NASA. This analysis provides both role-based and program-based perspectives over the programs and activities studied. In performing the study, we also developed a methodology for looking across programs for logistics lessons, which may be applied to future research.

2 Current Practices for Space Shuttle and ISS Logistics

To ground this study in current practices, we include a brief overview of logistics procedures for both the Space Shuttle Program (SSP) and International Space Station (ISS). Among the logistics practices examined are manifesting, stowage, inventory tracking, waste disposal, and return logistics. These topics are among those that served as the basis for extracting the lessons learned and lessons not learned from the programs examined.

2.1 ISS Cargo Lifecycle

Since the inception of the ISS in 1998, much of NASA efforts in human space flight have been centered on assembling and supplying the ISS. As such, we have focused our discussion of current practices on the complex task of getting cargo from Earth to the ISS and the management of this cargo on-orbit.

2.1.1 Manifesting for ISS

The process of sending an item to ISS or returning an item from ISS begins with the submission of a manifest request (MR). Any hardware owner or responsible group may submit an MR. MRs are reviewed at the weekly Manifest Working Group (MWG) meeting. Once reviewed by the MWG, the MR is forwarded to either the affected launch team or increment team for their review and approval/disapproval. If the MR is approved, the request will appear on the next manifest change request (CR) with all other approved MRs. The CR receives a community wide review and is evaluated based on cost, delivery schedule, certification, stowage space on launch/return vehicle, stowage space on ISS, power requirements, etc. Figure 2 below illustrates this process.

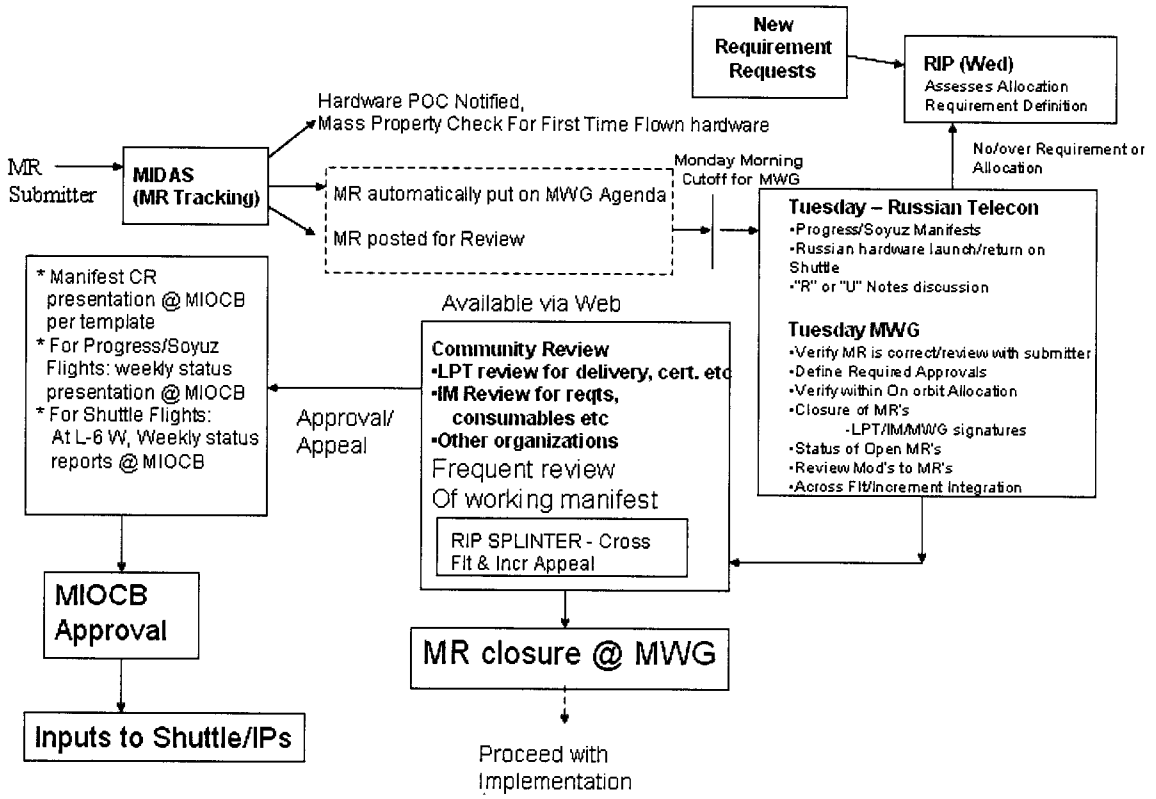

Figure 2: ISS Manifesting Flowchart

2.1.2 Cargo Review Cycle

A simplified overview of the ISS cargo review cycle is shown in Figure 3 below. ISS cargo manifesting is duplicative in many ways, since the vehicle that will transport it is unknown at the time the cargo is identified and subject to change based upon availability of the transportation system. Currently, the available launch vehicles include the Russian Progress, the U.S. Space Shuttle, and to some extent the Russian Soyuz. In the next few years, the Japanese Aerospace Exploration Agency (JAXA) HII Transfer Vehicle (HTV) and European Space Agency (ESA)'s Automated Transfer Vehicle (ATV) [6] will also be viable launch options.

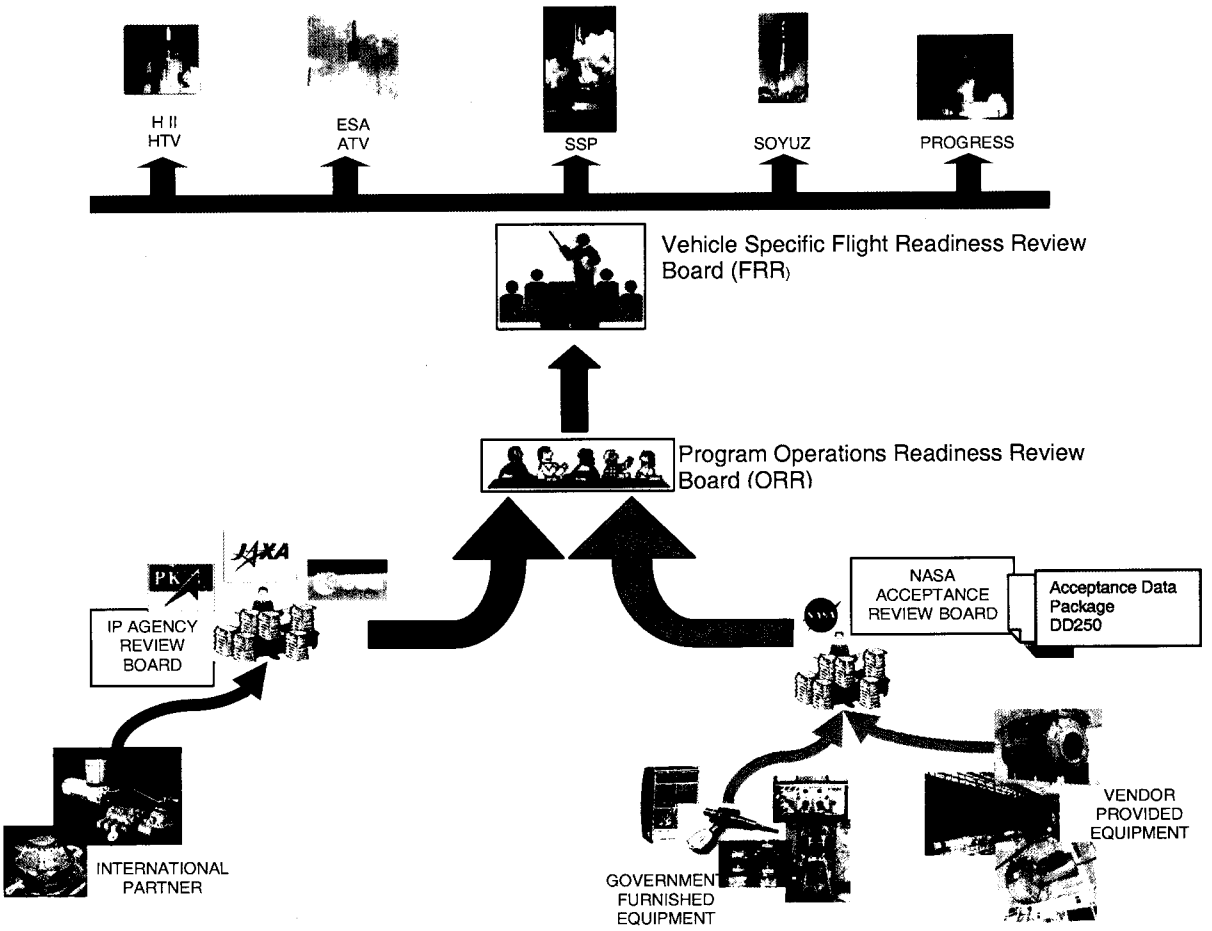

Figure 3: Simplified ISS Cargo Review Cycle

2.2 Space Shuttle Logistics

Once a cargo item passes through the review cycle depicted in Figures 2 and 3 above and is designated to launch on the Space Shuttle, the cargo is then categorized as a Shuttle payload. Shuttle payloads fall into three categories, primary, secondary, and middeck. A definition of each follows:

- **Primary:** A primary payload justifies a Shuttle mission, either alone or in combination with other payloads, and meets the criteria of the Shuttle use policy set forth in NMI 8610.12B, *Policy for Obtaining Office of Space Flight Provided/Arranged Space Transportation Service for NASA and NASA-Related Payloads*, as determined by the NASA Flight Assignment Board and approved by the NASA Administrator. A primary payload typically defines the critical path of the integration process, including KSC processing, flight design and mission operations preparation, and postflight processing and data reduction.

- **Secondary payload**: In general, a secondary payload does not define the critical path of the integration process, but has requirements that use significant SSP resources. However, a

combination of secondary payloads may represent justification for a Shuttle mission in the same sense as a primary payload. A secondary payload, or combination of secondary payloads, which defines the critical path of the integration process, including KSC processing, flight design and mission operations preparation, and postflight processing and data reduction will be treated as a primary payload for manifesting purposes.

- **Middeck:** A middeck payload is a payload which uses the accommodations in the Shuttle middeck (as defined in NSTS 21000-SIP-MDK and/or NSTS 21000-IDDMDK). In general, a middeck payload does not define the critical path of the integration process, but has requirements that use significant SSP resources. A picture of the Shuttle middeck lockers is shown in Figure 4.

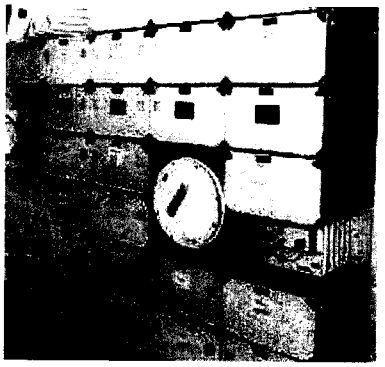

Figure 4: Shuttle Middeck Lockers

Once the proper payload designation is made for all cargo on that Shuttle mission, a Shuttle manifest change request (CR) can be developed for the vehicle. The Shuttle payload integration flow, shown in Figure 5, illustrates this process.

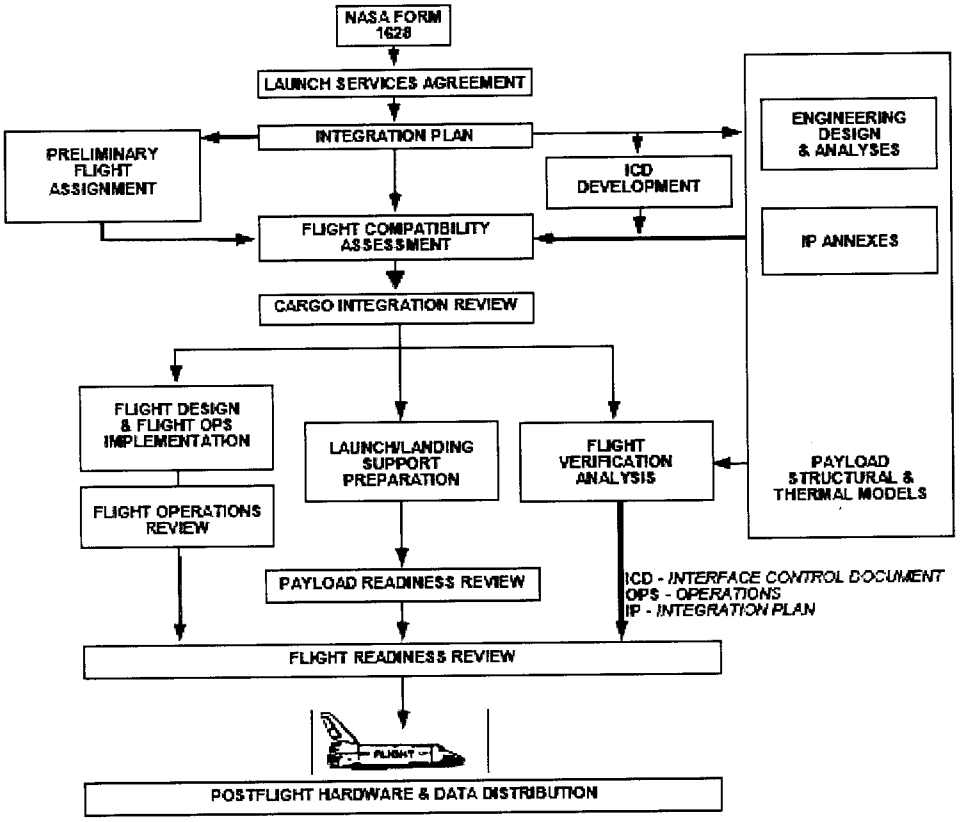

Figure 5: Shuttle Payload Integration Process

2.3 ISS Logistics

2.3.1 Stowage Planning for ISS Resupply

The Shuttle stowage group reviews the manifest CRs and determines the launch and return stowage configurations for the Multi-Purpose Logistics Module (MPLM), middeck crew compartment, and payload bay. Overview drawings are produced to show how bags and items are packed into the U.S. launch vehicles. Detailed drawings are also produced to show the internal configuration of compartments and bags. Ascent packing configurations are driven more by hardware delivery schedules and launch requirements (packing material) than by the on-orbit use and stowage of an item. When possible, ascent packing materials are returned on the launch vehicle so that the impact on ISS stowage space is minimized.

The nested complexity of cargo in the Space Shuttle, ISS, MPLM, etc. is one of the major challenges in current space inventory management practices. Figure 6 below illustrates this complexity. The components of Figure 6 are explained in the sections that follow.

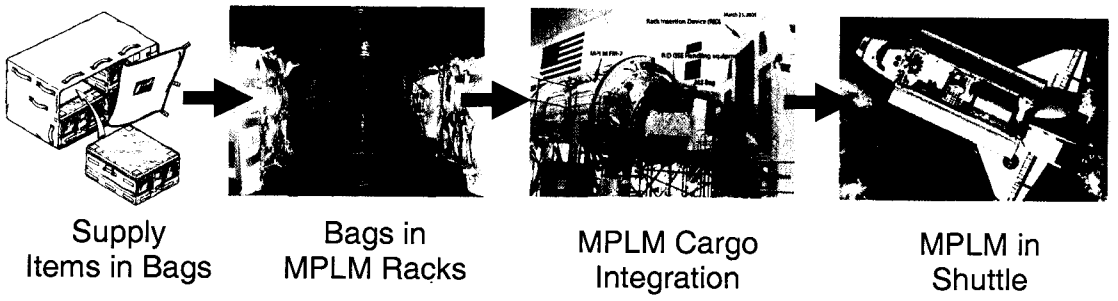

Figure 6: Nested Complexity of Shuttle Cargo in an MPLM

2.3.2 Carriers

The Shuttle middeck and MPLM provide accommodations for internal cargo. The payload bay provides stowage accommodations for external (unpressurized) cargo.

The Shuttle middeck includes lockers and floor/ceiling bags. Each middeck locker has dimensions of about 20"x18"x10". There are two types of floor/ceiling bags; one type holds 5 middeck locker equivalents (MLE) and the other holds 10 MLEs. The lockers and floor/ceiling bags can be packed with cargo transfer bags (CTBs), mesh bags, or loose hardware. When necessary, the hardware items are packed in foam cushions. Since the relatively small size of the middeck lockers restricts the size of the items that can be launched, the floor and ceiling bags provide the capability to launch and return oversized items.

The MPLM has 16 rack bays. Each rack bay can be configured to carry a Resupply Stowage Platform, a Resupply Stowage Rack, an Express Transport Rack, or be left empty.

2.3.3 Containers

2.3.3.1 Racks

A Resupply Stowage Platform (RSP) is a flat plate that can pivot at the bottom. Large M-bags are mounted on the front and back sides of the RSP. Cargo can be packed loosely into the M-bags or packed into CTBs before being stowed in the M-bags. RSPs are only flown in the MPLM and do not transfer to ISS. RSPs provide the capability to launch and return oversized items in the MPLM.

A Resupply Stowage Rack is a metal rack with locker compartments of various sizes. Hardware can either be packed loosely into the compartments or within CTBs that are then placed in the compartments. RSRs are flown in the MPLM and can be transferred and installed on ISS as needed. RSRs provide a limited capability to launch and return large items.

An Express Transport Rack (ETR) is a metal rack that is primarily used to transfer payload cargo to ISS. ETRs are flown in the MPLM and do not transfer to ISS. An ETR has accommodations for locker mounted payloads and International Sub-rack Interface Standard (ISIS) drawers that interface with the Express Racks on ISS.

On ISS, there are 4 types of racks; Express racks, Zero-G stowage racks, RSRs and system racks. An Express Rack is a metal rack installed on ISS and designed to accommodate payloads. Express racks usually consist of 8 locker compartments equivalent to a middeck locker and 3 drawers. The locker compartments can be used for powered payloads or passive stowage. The drawers are used for passive stowage.

Zero-G Stowage Racks (ZSRs) are fabric racks that are used on ISS to provide stowage accommodations. The internal compartments of the ZSRs are reconfigurable so that different size cargo can be stowed.

System racks are metal racks that have been outfitted with particular system hardware. When the entire rack space is not needed for the system components, lockers are built into the rack to provide additional stowage. Most of these lockers are the same size as RSR lockers.

2.3.3.2 Bags

Cargo transfer bags (CTBs) are the primary packing container for ISS. CTBs are available in four sizes to provide maximum flexibility when packing hardware. The single CTB was designed to fit inside a middeck locker. Half size CTBs (half the size of a middeck locker), double CTBs, and triple CTBs are also available. CTBs were primarily designed to modularly interface with the ZSRs, although the half and single CTBs are also compatible with the Express rack lockers and most locations in RSRs and system racks.

There are three sizes of M-bags; M-01 (6 CTBE), M-02 (4 CTBE), and M-03 (10 CTBE). Their capacity is defined in cargo transfer bag equivalents (CTBE). A single CTB is 1 CTBE, which corresponds to a volume of 1.86 cubic feet.

2.3.4 Transfer Operations

Transfer Operations describes the transfer of cargo between the Shuttle and ISS. The transfer team uses the approved manifest CRs and the ascent/descent stowage drawings to develop the transfer list that the crew uses. The transfer list is an Excel spreadsheet that is printed in hardcopy for the crew to use during the Shuttle flight. Changes to the transfer list are up-linked either as pen and ink changes that the crew handwrites into their transfer book or as an electronic file that the crew can print on-orbit. At the end of each mission day, the crew reports through a voice call-down the transfers that were completed that day. The transfer team updates an electronic copy of the transfer list and distributes the updates to others in the control center.

A similar process is followed for the unloading of a Progress cargo vehicle. This process is managed by the Russian ground control team with inputs from the U.S. team if U.S. hardware was launched on that Progress flight.

2.3.5 Inventory Management on ISS

The Inventory Management System (IMS) is the database that contains the official ISS inventory. The IMS database resides on ISS and at multiple locations on the ground. On ISS,

the IMS resides on the file server but can be accessed from any laptop. The crew may also use the hand-held Bar Code Readers (BCR) to record changes to inventory (Figure 7). The Inventory Stowage Officer (ISO) and the Russian Inventory Stowage Specialist (RISS) may also enter changes to the onboard inventory to help alleviate some of the crew time required to properly maintain the database. Each crew member is allocated on the order of 20 minutes per day for IMS updating. Changes to the database are exchanged electronically between the ISS, Mission Control Center-Houston (MCC-H), and Mission Control Center-Moscow (MCC-M) IMS modules on a daily basis.

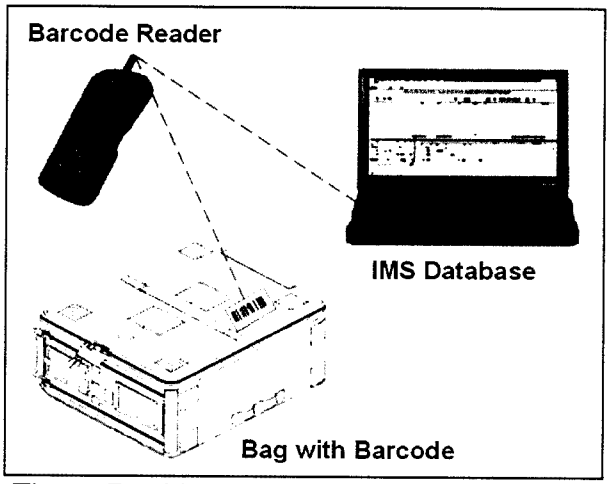

Figure 7: ISS Inventory Management System

Prior to each flight to ISS, whether it is a Shuttle, Progress, or Soyuz, a dataset containing all the necessary information on the resupply items is provided to the ISO team. The dataset is an Excel file that can be automatically loaded into the IMS. For Progress flights, the ISO team builds plans in IMS that updates IMS as the crew unloads the vehicle and stows the items. The crew can also use the BCR or call down their accomplishments at the end of each day. Due to the high activity level during Shuttle flights, the crews usually ask the ISO on console to update IMS with the transfers completed that day.

2.3.6 Stowage Planning for ISS

The Inventory Stowage Officer team performs stowage planning for U.S. items on ISS. The ISS stowage planner determines the final stowage locations for all U.S. items transferred to ISS from any launch vehicle. ISS stowage locations are provided to the transfer team for inclusion in the transfer list. For those items that cannot be transferred to their final stowage locations during the Shuttle flight, an unpack list is generated by the ISO team. After Shuttle undocks, the unpack list, an Excel spreadsheet, is up-linked to the crew. As the crew unpacks, they can choose to update IMS themselves, use the BCR, or call down the completions to MCC-H. If the crew chooses to call down their completions, the ISO on console will update IMS.

2.3.7 Trash

2.3.7.1 Trash Staging

Each day the crew generates common trash. Common trash is defined as food waste, used wipes, dirty clothes, and used hygiene items. This trash is collected into trash bags. Solid and liquid human waste is collected into special containers. All trash is staged in the aft portion of the Service Module for future packing into the departing Progress vehicle. Broken equipment is usually left in its current stowage location until Progress trash packing is initiated. The U.S. team schedules time prior to the actual Progress packing for the U.S. crewmember to gather the U.S. items for disposal and pack into the Russian provided trash bags. A photo of the completed trash gathering is taken so that the Russian team can determine the amount of volume that the U.S. items will require.

2.3.7.2 Trash List

Before any U.S. item that is not designated as common trash can be considered for disposal on Progress, a Waste Manifest Request (WMR) must be submitted. Approved WMRs are then collected into a change request and approved by the community. For the U.S. trash gathering activity, the trash ISO uses the approved waste CR to generate a crew message identifying which items should be collected for disposal. This message is an Excel spreadsheet and is up-linked via the Orbital Communication Adapter (OCA) to the ISS crew. To accompany the electronic crew message, an IMS plan is built so that the crew can update IMS, if they choose, as they execute the crew message. The crew may also use the BCR to track their trash gathering as they retrieve the U.S. items and pack them in the Russian-provided trash bags. Although the IMS plans and BCR are available, the primary method that the crews have used to report trash gathering has been a voice call-down to MCC-H. An ISO then updates IMS with the changes. It is ultimately the diligence of the crew that ensures that valuable items are not accidentally disposed of with the trash.

2.3.7.3 Trash Packing into Progress

Approximately one week prior to the planned undock of the Progress vehicle, the crew begins packing the trash items into the vehicle. The Russian team provides the crew an OCA message that directs them where to place each approved trash item. IMS is usually updated by the RISS after trash packing is complete.

2.3.8 Return

Items must be manifested for return using the same process that applies to launch items. Stowage plans are developed for the return vehicles. The ISO team uses the approved CRs and stowage drawings to develop a pre-pack list. The pre-pack list is an Excel spreadsheet that provides the crew with direction on which items to collect and how to pack them for return. CTBs, which are the primary method of collecting items for return, are labeled and staged for easy retrieval during transfer operations. To accompany the Excel spreadsheet, an IMS plan may

be built to help the crew with updating IMS as the pre-packing occurs. The crew may opt to report accomplishments at the end of each day and have the ISO on console update IMS.

2.4 Assessment of Current Logistics Practices

The current Shuttle/ISS logistics system has many advantages and disadvantages. The current system is seen as a large improvement over the logistics systems used in past space programs such as MIR and Skylab. The system works well and training for crew and ground personnel is minimal.

The shortcomings of the current system include a high-level of complexity, redundancy of information/lack of a common database, and a large human-in-the-loop component. The complexity of the system is so great that it is difficult to find a person in the Space Shuttle Program or ISS Program that understands the entire process. Figure 8 illustrates the interaction of just some of the numerous documents and databases that govern the Shuttle/ISS logistics flow.

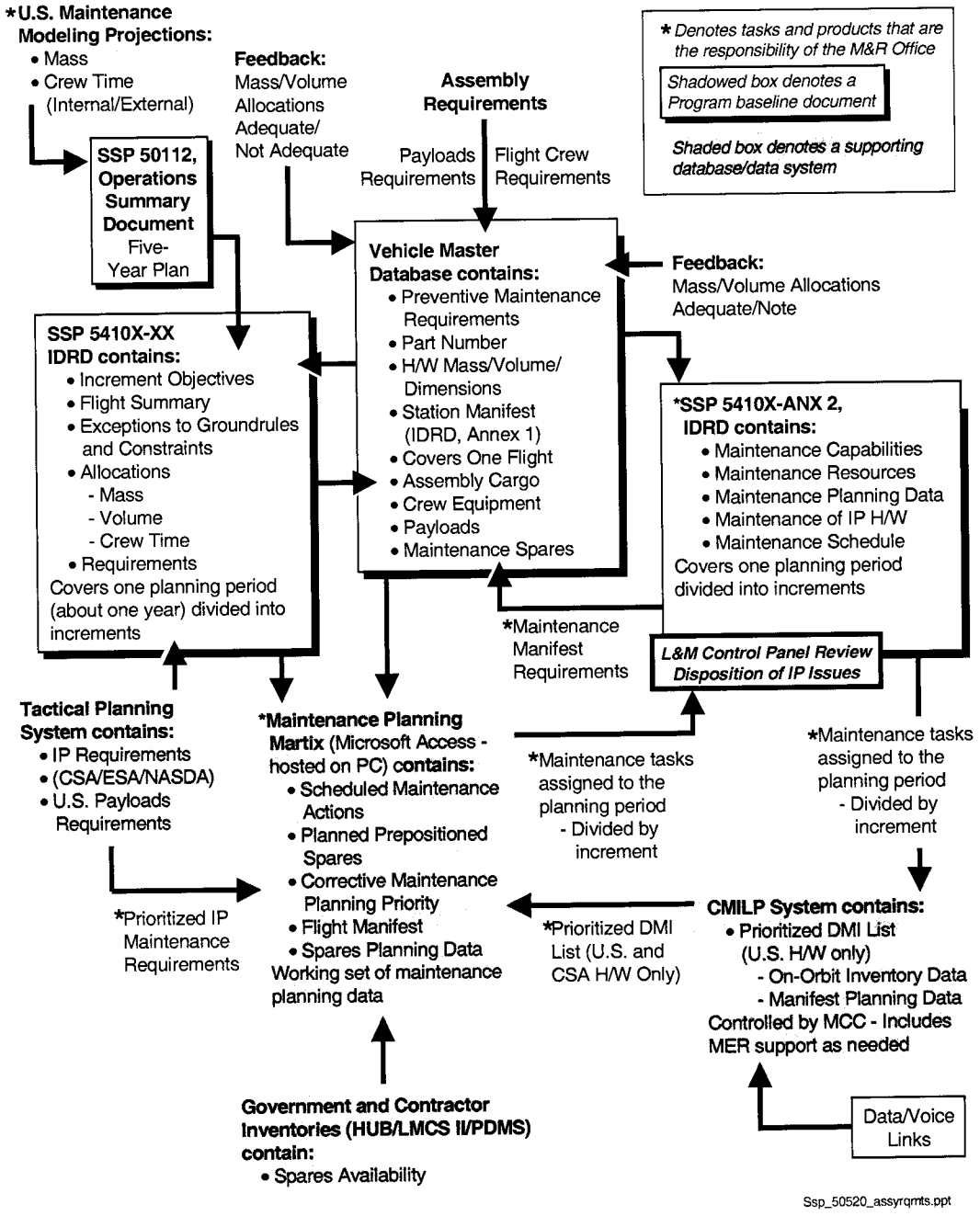

Figure 8: ISS support planning process

The lack of a common database to handle manifesting, inventory management on the ground, and on-orbit inventory management is another weakness of the current system. Presently there are separate databases/applications to do manifesting, ground tracking, manage the parts catalog, on-orbit inventory management, etc. Very few, if any, of these databases can interact with each other, causing a lot of extra work for personnel who need to transfer information between the systems. This extra human intervention also expands the chance that an error is made.

As was stated above in section 2.3.5, the current method of inventory management on the ISS is based on the Inventory Management System (IMS) and barcode readers. While this system is reliable (only 2-3% of items on ISS are tagged as "lost"), it is also very time consuming. Significantly more than the allotted 20 minutes per day are spent by the crew for managing the onboard logistics.

The ISS has also experienced a shortfall of stowage space. Some of this is the result of the reduced Shuttle flight rate and down mass capacity and some of it stems from an inadequate consideration of stowage and micro-logistics inside the ISS during station design and planning. Resultantly, spaces that were never intended for stowage, such as the joint airlock, the pressurized mating adapters (PMAs), and the Russian docking compartment, are being used as closets (Figure 9). This "overflow" of stowage affects the habitability of the ISS and adds additional time to on-board activities that require accessing any of locations being used as closets. It also affects crew morale.



Figure 9: The Overflow of ISS Stowage in the Joint Airlock
[http://spaceflight.nasa.gov/gallery/index.html]

Another example of the complexity involved in space logistics can be easy illustrated in the breadth of nomenclatures used to describe a "container type-device". Table 1 below shows a sampling of the nomenclature used by the Space Shuttle and ISS Programs to identify "containers". On one hand, this large number of terms does reflect the real complexity involved in space logistics, on the other hand the excess may be due to a lack of coordination across programs and could be interpreted as superfluous complexity.

Table 1: Nomenclature Survey

• Pocket • Container • Carrier • Module • Segment • Compartment • Element • Pallet • Assembly • In-space Facility • Node • Vehicle	• Item • Drawer • Kit • Locker • Unit • Rack • Lab • Platform • MPLM • Payload Bay • Fairing	• Component • Subsystem • System • SRU • LRU • ORU • CTB • M-01 • M-02 • M-03

It should also be noted that accommodation mass can consume much of the useful payload mass of a launch vehicle. The comparison in Table 2 below shows that for Shuttle the fraction (percentage) of useful payload mass is significantly lower than for a dedicated logistics vehicle such as Progress. The mass of the orbiter is a "payload" in terms of the Shuttle first stage (SRBs) and ET, however much of the useful payload mass for Shuttle is consumed by the accommodation mass described in Sections 2.3.2 and 2.3.3. This effect is slightly more pronounced when the Shuttle launches to an inclination of 51.6 because the dry mass of the orbiter acts as a lever, further reducing the relative percentage of useful upmass capability. Efforts will have to be made to explicitly account for and design accommodation mass into the system both for crewed flights of the CEV as well as robotic resupply or pre-positioning flights.

Table 2: Mass Comparison (Note: Shuttle numbers are given for the MPLM configuration.) [12][13][14]

Mass (kg)	**Shuttle (i=28.5)**	**Shuttle (i=51.6)**	**Soyuz-TM (i=51.6)**	**Progress-M (i=51.6)**
Total launch mass (TLM)	2,032,000	2,032,000	290,000	290,000
Vehicle dry mass	76,985	76,985	6,190	4,740
Total propellant mass	11,853	11,853	~880	1,750
Basic performance	17,690 (@ 407 km)	17,055 (@ 407 km)		
Accommodation mass	2,288 (general overhead) 4,491 (MPLM tare mass) 1,204 (flt-spec overhead) 3,044 (ISPRs, etc.)	2,288 (general overhead) 4,491 (MPLM tare mass) 1,204 (flt-spec overhead) 3,044 (ISPRs, etc.)	81 (seatliners)	(included)
Useful payload upmass	6,481*	6,028**	479	2,550
Useful payload downmass	6,481	6,028	439	1,700 (all destructive)
% payload upmass as a fraction of total launch mass (TLM)	0.32%	0.30%	0.17%	0.88%

* Limited by MPLM maximum payload of 9,071 kg less 3,044 kg accommodation plus mid-deck capacity of 454 kg

** Limited by Shuttle basic performance

3 Lessons Learned from Past and Current Human Spaceflight Programs

The bulk of the work performed in this study was focused on gathering lessons learned from NASA's past and current human spaceflight programs. The following sections describe the methodologies and results of this effort.

3.1 Ground Rules and Assumptions for Data Analysis

We began our research by making some ground rules and assumptions:

A. Multiple space programs have maintained some form of lessons learned data
B. Logistics lessons are not always straightforward
C. There are usually different views of logistics lessons
D. Limited lessons learned data is available
E. Lessons, either learned or repeated (and not learned), are valuable information

Each of the ground rules or assumptions involved some preparatory work in order to adequately take them into account.

A. Multiple space programs have maintained some form of lessons learned data.
To consider the perspectives on logistics lessons, we searched several sources within NASA, including organizations with direct and indirect connections with the system flow in mission planning. We utilized crew debriefs, removing all reference to individual crew members and missions. We made use of John Commonsense, the lessons repository for the Mission Operations Directorate since Apollo. We used the Goddard Space Flight Center Flights Programs and Projects Directorate (FPPD) database and searched the Skylab Lessons Learned databases at both Johnson Space Center and Marshall Space Flight Center. Finally, we used the public version of the Lessons Learned Information System (LLIS) and verified that we received the same result using the internal version of LLIS for our logistics lesson searches. See Appendix E for a complete listing of the resources used in our search.

B. Logistics lessons are not always straightforward.
To address the issue that there are many terms used to describe logistics, we developed a taxonomy, using both a selection from the body of knowledge from SOLE - The International Society of Logistics and from our experience as space flight operators. The proof of this ground rule is fairly easy to demonstrate. We ran a search on LLIS and found two hits using the word logistics, 16 with the word stowage, 28 with the word maintenance, etc. Logistics functions, as defined in Blanchard [7], provided the framework for our search.

• Logistics	• Inventory
• Packaging	• Accountability
• Handling	• Tracking
• Transport	• Stowage
• Maintenance	• Design
• Parts	• Trash
• Supplies	• Shipping
• Spares	• Warehouse
• Support	• IMS
• Manifest	• Pre-pack

Figure 10: Logistics Lessons Taxonomy

C. There are usually different views of logistics lessons.
We stated, as an assumption, that there were multiple perspectives—most notably those of the project/program manager, design engineer, logistics analyst/engineer, ground controller, crew member, and business manager. We decided to design role perspectives into a survey at the end of the research and note perspectives as we found lessons. This was not always possible with all resources shown in Appendix E.

D. Limited lessons learned data is available.
Our assumption was that there was little data available for a single on-orbit node or mission. We believed that we needed to find sources of lessons that covered at least the Phase I /Mir and the Skylab, in addition to the data available for the ISS, in order to get any significant amount of data.

E. Lessons, either learned or repeated, are valuable information.
We believed that we would find more affirmation of developments and capabilities than negative references, but we made this ground rule so that we could capture both. Lessons are not problems; they are something learned by performing a task either correctly or incorrectly. In most cases, what we found was that logistics lessons are noted as unmitigated and then repeat themselves, program after program.

3.2 Methodology for Data Analysis

Once the ground rules were established, our next task was to conduct the research of lessons learned, utilizing multiple databases (see Appendix E), and consolidating the data into a single spreadsheet. In some cases, we searched relational databases (e.g. LLIS) for the set of keywords listed in Figure 10 that we developed for this purpose. In other cases, we combined a review of the documents (e.g. JohnCommonsense, Apollo Mission Histories) and our knowledge of logistics to pull out the related lessons. We reviewed the crew comments, sanitizing them to take out restricted information such as the identity of individuals, the missions, etc. We also did some limited interviews with Shuttle and ISS flight controllers.

Our search returned approximately 300 lessons learned regarding space flight logistics. The 300 filtered and edited lessons learned are included in this report as Appendix A. Keywords were then applied to the gathered lessons for the purpose of sorting and evaluation. Once the lessons were compiled, an analysis of the resulting data was performed, first sorting it by keyword, then finding duplication and root cause, and finally sorting by root cause. The root cause analysis used a simple fishbone diagram [8] for cause and effect mapping to derive the root lessons.

Once this analysis was done, in order to gain perspective, the interim product was distilled to derive the root lessons from the data. The result revealed agreement between the independent views of the lessons, with seven top lessons prevailing. The top seven lessons learned are detailed in Section 3.3.

Finally, a survey was designed to validate the lessons learned research in current programs. The survey used the lessons themselves as a framework to measure exposure to the lessons, knowledge of the problem, expectations for future programs, and role-based perspectives on the lessons surveyed. The formation and results of that survey are discussed in Section 4.

3.3 The Top 7 Lessons Learned

The following seven lessons represent the review of nine separate data sources (Appendix E) for lessons learned across programs, centers, and activities. This list is an attempt to look across perspectives to derive a root lesson and address the root causes.

1. **Stowage** is the most mentioned lesson in all databases. Resulting problems from lack of stowage specification may include growing time demands for the crew, loss of accountability, loss of access to operational space, limits to housekeeping, weakened morale, and an increased requirement for re-supply. Potential mitigation is to include stowage requirements (volume, mass, etc.) in the design specification.
    1. Reconfigurable stowage volume is recommended.
    2. For high turnover, small items, pantry stowage is recommended (i.e. resupply the pantry, not the items in it).
    3. A system for naming and numbering stowage volumes should be established and maintained.
    4. Entryways, docking compartments, and other interconnections must take into account pass-through and cargo transfer operations.

2. A **common logistics/inventory system,** shared by multiple organizations would decrease the problem of differing values for like items across systems. Configuration management is enhanced with this type of system architecture, as well. Additionally, a single inventory system lends itself to a common naming system.

3. **Packing lists and manifests do not make good manual accounting systems**. Parent-child relationships are fluid and need to be intuitively handled by a system updated by the movement of both parents and children.

4. **Commonality** should be a prime consideration for all vehicles, systems, components, and software in order to minimize training requirements, optimize maintainability, reduce development and sparing costs, and increase operational flexibility. Failure to do this increases the logistics footprint.

5. **Design for maintenance** should be a primary consideration in reducing the logistics footprint. Smaller parts may be possible for repairs, consistent with the ability to test the sufficiency of the repair and the tools and training provided to the crew. An optimization is preferable, taking into account tools, time, packaging, stowage, and lifecycle cost.

6. **Plan for and apply standards** to system development. Multiple standards applied to the same area increase the logistics footprint. A simple example of this is standard and metric tools. In most cases, where there are multiple standards, there is an interface required, and the interface then requires support. A corollary to this is the use of commercial off the shelf (COTS) hardware. Unless it is delivered built to an existing standard, it automatically becomes a source of extra support requirements.

7. Include **return logistics** in the design specification. Need to understanding and model packaging requirements, pressurization, and reparability/disposability for the return or destructive reentry of items ahead of time. Trash growth and disposal should be modeled as part of the crew timeline.

4 Space Logistics Community Survey

We developed a Space Logistics Community Survey by integrating the top 7 lessons learned into a 10-part questionnaire (Appendix B). Most questions asked the respondent to rate his/her level of observance of each issue (e.g. the use of commonality in vehicles, system, or software) in current crewed spaceflight practice as well as his/her level of recommendation for each. The group of approximately 80 who were notified of the survey were selected as either participants of a Space Logistics Workshop [9] or as others affiliated with the areas of Space and Logistics. The participants were notified by email and told that their personal information would be kept confidential to ensure the fidelity of the data. The analysis is based on the 35 responses that were received. See Appendix C for a listing of survey respondents.

4.1 Survey Methodology

Data was collected using a web-based form. Each participant filled out the survey online and the responses were emailed directly to the survey administrator. The administrator collected the data as a series of numbers, 1-6, each referring to a measure on the scale used for that question (e.g. scale: 1. Unnecessary, 2. Somewhat Unnecessary, 3. Neutral, 4. Recommended, 5. Strongly Recommended, 6. N/A). After all the data had been received and collected, it was analyzed for observable patterns and statistical significance.

A copy of the survey used in this study is accessible at
http://spacelogistics.mit.edu/survey/startpage.htm.

We distributed requests to complete the survey by email to all the participants with the web link. A copy of the survey is included in this report as Appendix B.

4.2 Results and Statistical Significance

4.2.1 Statistical Tests

Both chi-squared and t-tests were performed on the data to test its statistical significance. The chi-squared test is a test for independence of the data. For each question, the test was performed to determine whether the data was independent from a random result. The responses were compared with the baseline value of a random response for all questions. A random response was represented as an even ranking of all possible answers by the participants. Table 3 below shows the response to the question of the relative importance of logistics practices and the percentage likelihood that the results could be due to chance.

Table 3: Relative Importance of Logistics Practices

Surveyed Element	Rank	X^2	Confidence
Design for maintenance considerations	1	0.5%	99.5%
Use of commonality in systems	2	27.9%	72.1%
Design of an integrated inventory system	3	8.4%	91.6%
Design for stowage considerations	4	21.0%	79.0%
Planned use of standards in system development	5	47.0%	53.0%
Design for return logistics	6	0.2%	99.8%

What this table shows is that *design for maintenance* was considered the most important consideration and *return logistics* the least among the six practices with strong confidence in the data, 99.5% and 99.8% likelihood respectively. Similar calculations were performed for all questions in the survey, showing a propensity for a chi-square value under 10% for those questions that asked about recommended future considerations and about 20% for those questions regarding previously and currently observed space logistics practices. In other words, for the questions in which the respondent was asked to rank how they recommended an issue for the future, the result was significant with 90% confidence. For questions asking about observance in current practice, responses were significant with an approximate confidence value of 80%. With a sample size of 35, these responses show a high measure of fidelity according to the chi-squared test.

A t-Statistic test was used to compare how responses varied among the role of the participant in his/her organization. T-statistics are used to compare two sample sets of data to determine whether the underlying populations have the same mean. In this context, it was used to determine whether two sets of data were statistically different from each other. The ranking of importance for the six main logistics considerations is shown in Table 4 below. A "1" indicates the most important aspect identified and "6" the least important. For the most part,

program/project managers had a slight variation in responses from the engineers, logisticians, and from the group as a whole.

Table 4: Ranking of Importance

	All	Engineers	Logisticians	Program/Project Managers
1	Maintenance	Maintenance	Maintenance	Maintenance/ Inventory/ Commonality
2	Commonality	Commonality	Commonality	
3	Inventory	Inventory	Inventory	
4	Stowage	Stowage	Stowage/ Planned Standards	Stowage
5	Planned Standards	Planned Standards		Return Logistics
6	Return Logistics	Return Logistics	Return Logistics	Planned Standards

We calculated a two-tailed non-paired t-statistic because for each pair of data sets there were two samples with unequal variances. This test was performed for each of the six possible pairs of data for engineers, logisticians, program/project managers, and the group as a whole (e.g. All v. Engineers, All v. Logisticians, Engineers v. Logisticians, etc.). The results illustrate the probability that the two sets of data being compared are statistically different from each other. The most significant differences were in how the program managers ranked compared to the rest of the group. There was an 87.9% significant difference between Program/Project Managers (PMs) and Logisticians in their ranking of return *logistics*. Similarly, comparing PMs to Engineers on their ranking of design for maintenance, there was an 88.1% difference. Somewhat surprisingly, there was a 92.4% difference in the way Engineers rank maintenance from the rest of the group. While each group ranks it as the top priority, Engineers do so overwhelmingly, leading to the large difference in the t-statistic. The rest of the data that was analyzed showed lower t-statistics in the data comparisons, making the differences in responses less significant. The full results of the statistical tests are shown in Table 5 below.

Table 5: T-test results showing the statistical difference between data

Statistical difference in ranking of	All v. Engineers	All v. Logisticians	All v. PMs	Eng. v. Log.	Eng. v. PMs	Log. v. PMs
Design for stowage considerations	0.508	0.480	0.384	0.726	0.073	0.552
Design of an integrated inventory system	0.229	0.350	0.057	0.087	0.101	0.171
Use of commonality in systems	0.579	0.156	0.334	0.385	0.599	0.390
Design for maintenance considerations	0.924	0.240	0.606	0.871	0.881	0.456
Planned use of standards in system development	0.407	0.202	0.318	0.478	0.559	0.082
Design for return logistics	0.757	0.971	0.513	0.900	0.103	0.879

While this data is certainly telling, it is somewhat less dependable than the statistics performed on the data set as a whole, since the groups become smaller when dividing them by role. Specifically, for the 28 participants that answered the previously discussed question, 7 identified themselves as engineers, 11 as logisticians, and 6 as PMs. It is important to note the difference in the way that the groups rank each factor, but the actual numeric comparisons should not be considered precise using the small data sets.

4.2.2 Data Charts

The rest of the results from the questionnaire are presented below. To compile the raw data into charts, a system of weights was imposed. All answers in the "Least Important" category were given a weight of one, with each succeeding category given an additional weight. For questions with six answer choices, the weights ranged from one to six with six being the "Most Important". For each question, the number of responses at each level in the answer scale were summed and then multiplied by their weight and summed all together to give a total score. Finally, all scores were normalized by diving the total score by the number of responses for that question, to give a normalized weight between zero and the maximum weight possible for that question. The charts compare the normalized scores of all possible answers for each question.

The overall relative importance of logistics considerations is depicted in Figure 11 below.

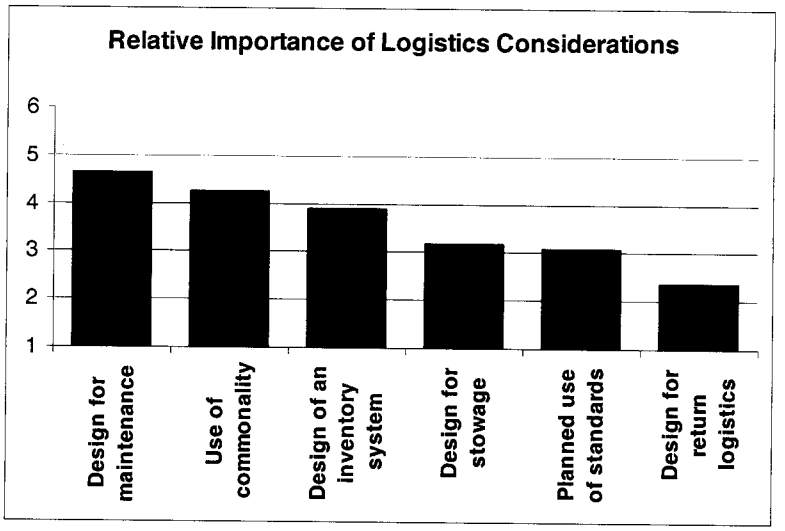

Figure 11: The relative importance of the top logistics lesson areas

However, when sorted by role, we see the slight divergence by program/project managers. While all roles agreed that maintenance planning was most important in the design, there were differing priorities beyond that. Interestingly, Engineers and Logisticians agree in all categories.

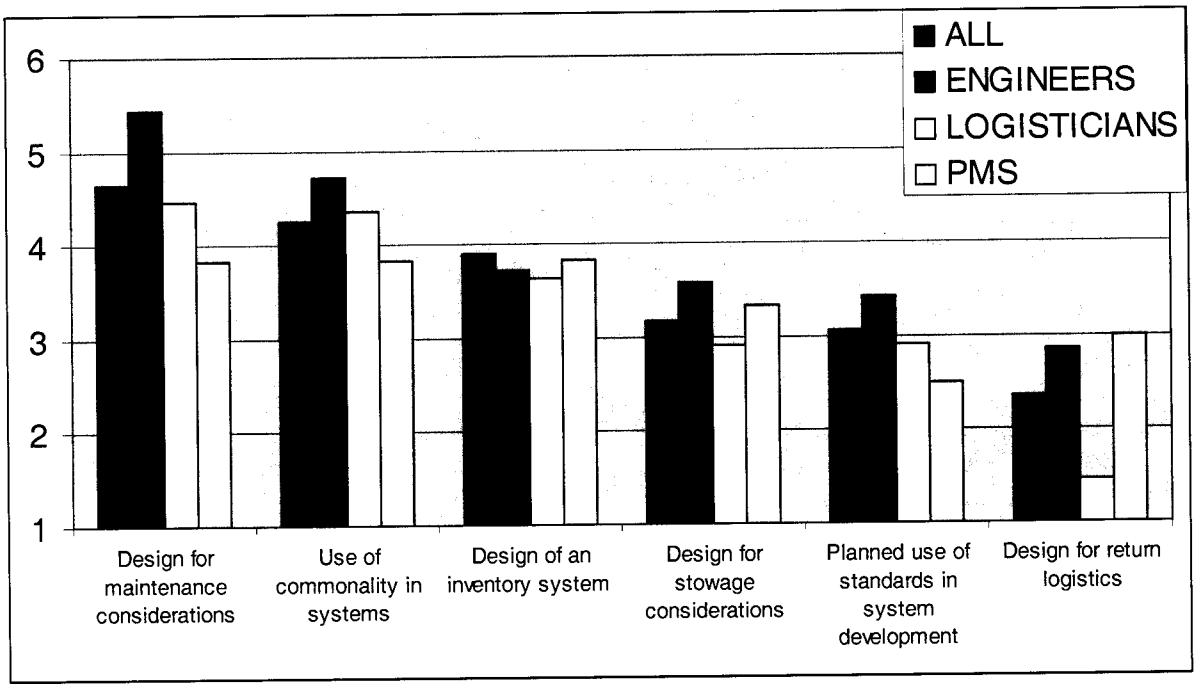

Figure 12: Relative importance of logistics considerations by role

Neither engineers nor logisticians correlated the importance of standards in the development of commonality, although that correlation was expected. Program/Project Managers rated all considerations differently from the group as a whole, giving maintenance, inventory, and stowage equal weight. They also did not correlate commonality and standards, showing a lack of connection between the two in the design and/or implementation process.

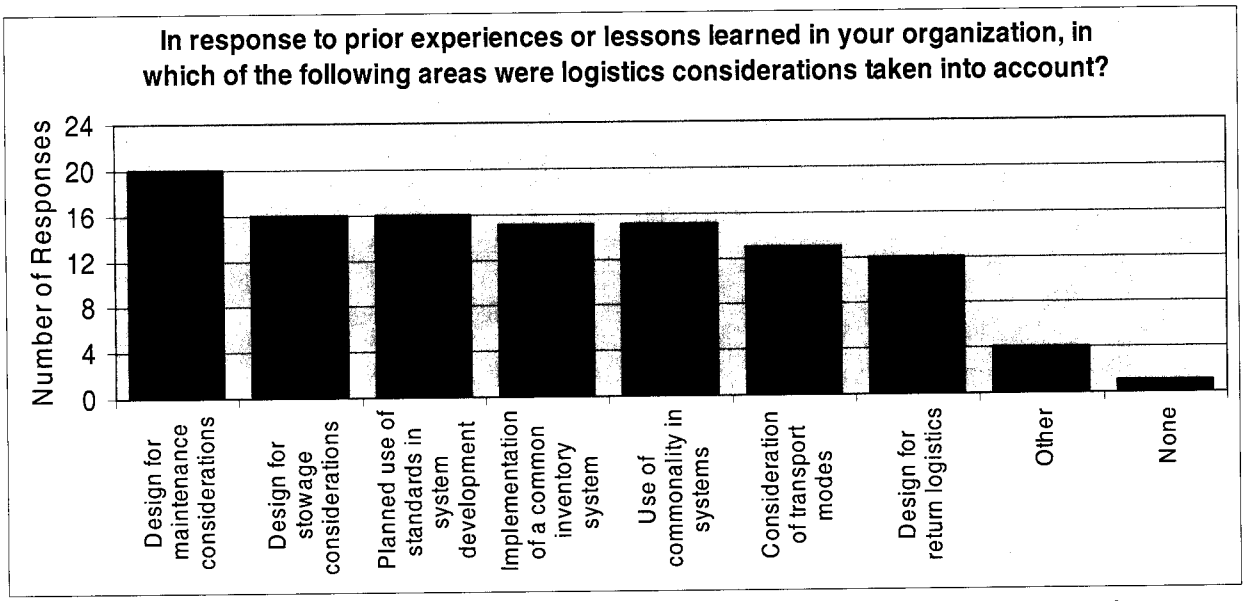

Figure 13: Ranking of previous efforts in addressing space logistics lessons learned

Figure 13 illustrates where emphasis on addressing these lessons has been placed in the past according to the respondents. In this question, it was asked where potential mitigation of problems had occurred in past experience. Maintenance again stands out as the overwhelming concern, with the others following relatively closely.

Figures 14-16 illustrate the gap between observed logistics practices in the past and recommended logistics practices in the future. Of the areas surveyed, including use of commonality, design for maintenance, design of an integrated inventory system, stowage considerations, and return logistics, three areas stand out as those requiring the most attention. Design for *commonality, inventory, and maintenance* all had noticeable gaps where observation levels did not meet recommendation levels. These are the areas that potentially need the most focused effort to close the gap. While Figure 13 shows that recent efforts have been directed towards improving design for maintenance in particular, *inventory* and *commonality* do not rank among the top previous efforts. These two issues in particular should be of high priority in future consideration of space logistics as they can also lead to large hidden costs.

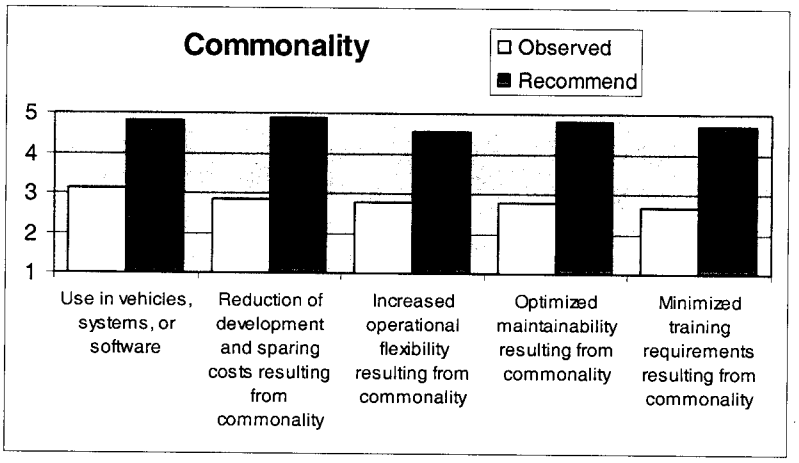

Figure 14: Observed and Recommended Commonality Measures

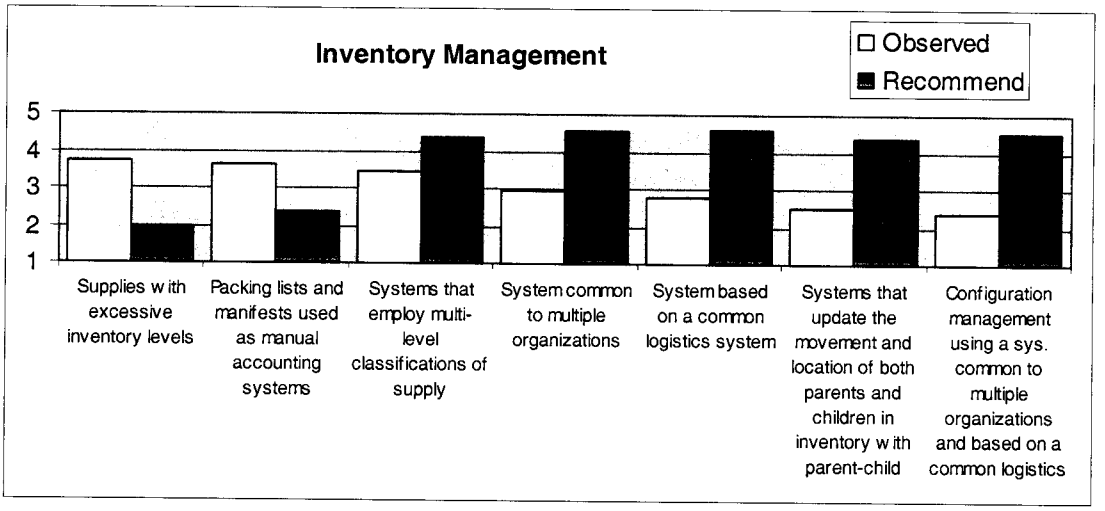

Figure 15: Observed and Recommended Inventory Management System Development

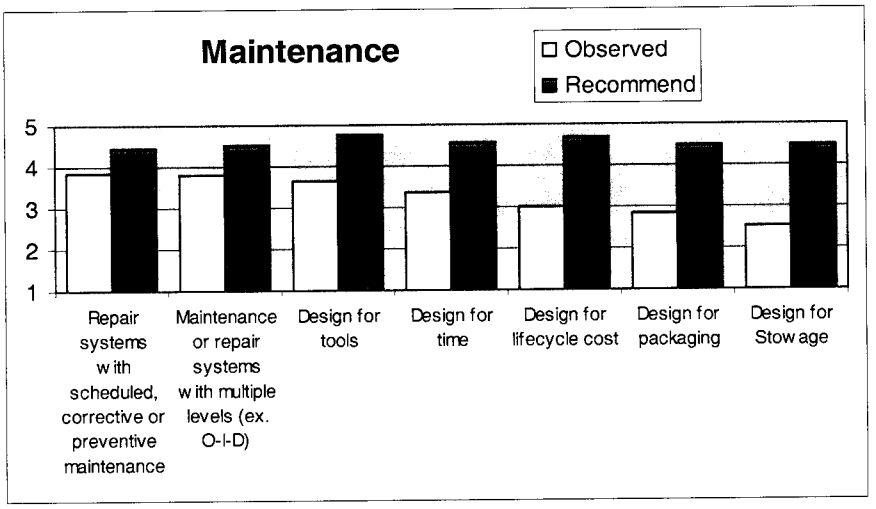

Figure 16: Observed and Recommended Emphasis on Maintenance Considerations

Additional charts compiled from the survey data concerning specific logistics lessons, including stowage difficulties and transport modes, are shown in Appendix D.

5 Conclusions

5.1 Analysis Method

It should be noted that our analysis method had some shortfalls. The first is that the LLIS is not a completely integrated Lessons Learned Information System. The other sources are a combination of documents and databases, but provide perspective that should be available in LLIS. A standard taxonomy might be helpful in general searches of the LLIS, which is instead divided into specialized areas. Logistics and disciplines such as systems engineering can only effectively apply lessons learned information if they are able to see multiple perspectives on the same problems. The method of analysis used here revealed that a standard regimen of reviewing lessons learned, consolidating them, and looking for root causes would probably allow broader use of the lessons in new developments and operational programs.

5.2 Current Space Flight Logistics

The current space logistics practices were reviewed for Shuttle and ISS and it was found that they represent a significant advance over the state of the art during Skylab and MIR. Nevertheless there is significant room for improvement. Interestingly, many of the current issues have their root in organizational issues, not purely technical issues. Areas of concern are:

- Fragmented databases between various logistics functions (manifesting, cargo integration, on-orbit operations) and organizations (NASA Centers, International partners). This dispersion of data leads to redundancies and errors and results in a large workforce to compensate for these shortcomings.

- Stowage issues on ISS are significant and are in part due to the lower flight rates experienced after the Columbia accident, and in part due to insufficient planning for micro-logistics during ISS development. Micro-logistics refers to the detailed flow of crew and supply items between modules and vehicles.

- Real-time awareness of system health and logistics inventory levels is challenging to obtain. While the bar-code based Inventory Management System (IMS) has proven to be effective, it is also time-consuming for the crew and ground controllers. New technologies such as Radio-Frequency Identification (RFID) could potentially alleviate this by transitioning to a more automated system, but technology maturation and system integration challenges remain.

- From an administrative and managerial perspective, the current ISS and Shuttle logistics processes are overly complex and bureaucratic and very few people are able to coherently describe the process in an end-to-end fashion. Whilst it is essential that on-orbit inventory be carefully planned, approved, and monitored, the processes to accomplish this could be significantly streamlined in future operations.

- Current logistics practices within NASA are structured along program/project lines, which can lead to inefficiencies when considering the costs and impacts of duplication of effort and inconsistencies in requirements as viewed from an Agency-wide perspective.

Also, it should be noted that the space logistics lessons learned presented in this report focus in particular on the space segment and that large capital investments and operational costs are tied up in the ground infrastructure and supplier network. Important lessons learned from the Shuttle and ISS programs exist in terms of dealing with technology obsolescence, strategic supplier relationships and long-term supplier viability as well as the establishment of policy directives and regulations that promote – rather than hinder – commonality, reuse and efficiencies across programs. We recommend a separate effort on capturing lessons learned from a ground infrastructure, logistics and supply chain management perspective.

5.3 Survey Observations

The perspectives of project managers, as opposed to engineers and logisticians, are appreciably different. In a system where decision-making is predominately top-down, this can lead to situations where priorities are not balanced with all perspectives. The survey pointed out specific areas where program managers view competing priorities differently from engineers and logisticians. This is perhaps a good direction for future research.

There is also a noticeable lack of correlation between commonality and standards for all groups surveyed. This seems to indicate that there is a misunderstanding of how to develop commonality. From the DoD (DoD Logistics Transformation Study [10]) to commercial logistics, there is a recognized requirement for both to exist for either to succeed. Again, this perceived difference between commonality and standards points to an area where further education and/or development can be established to enable proper use of either to be effectively implemented.

While stowage and inventory are ranked closely, there is a priority for inventory design over design for stowage. Visibility and easy accessibility of assets is the primary goal of both stowage and inventory management systems. Design for stowage benefits from the capability of tracking and locating stowed items. A common inventory management system allows for single source input of data, with a middleware connection to specialized data. We expected to see more of a correlation between these related functions in the future. Design for stowage and inventory management should be more closely linked to ensure effective use of both.

In the Figures 14-16 above, where there is a large gap between observed and recommended practices, there is evidence of either, mitigation, system design, or technology requirements in current and future systems. Virtually every area surveyed had highly recommended efforts where there was a low level of observation in current practice. Based on the *recommended* responses, the survey validated that the top 7 lessons learned are of considerable importance to all participants surveyed, whether from NASA, or the aerospace industry. While all had strong recommendations of logistics considerations, the ranking of observed practices was significantly lower. There was a notable need in areas where the observation did not meet recommendation levels, specifically in design for *commonality, inventory systems*, and *maintenance*.

While some of these may be areas of current mitigation, such as design for maintenance, as exemplified in a separate survey question, some may be areas where there is less ongoing development, as with the use of commonality and integrated inventory management. This study has proven beneficial in both pinpointing the areas of importance in logistics, but also in identifying the areas where further progress can be made.

5.4 Impact of Logistics on Flight Safety and Public Awareness

During the period that this report was assembled we have also monitored press releases and media reports regarding space logistics. Since the Columbia accident there has been significant interest in the relationship between traffic models and resupply capability, and on-board inventory. Additionally, there has been recognition both within and outside NASA that critical shortages and logistics related events – not just vehicle malfunctions – can have a profound impact on spaceflight safety and mission assurance.

Two events from the recent past - as reported by the media - illustrate this point:

Dec. 10, 2004, 12:24PM
Space station crew endures food shortage
NASA says a Russian capsule will bring supplies on Christmas Day
By MARK CARREAU
2004 Houston Chronicle

A food shortage on the international space station means its two crew members must eat less until a Russian supply capsule arrives Christmas Day, NASA officials said Thursday. Supplies are so low that if the usually reliable Progress spacecraft missed its delivery, American Leroy Chiao and Russian Salizhan Sharipov would be ordered back to Earth by mid-January, halfway through their six-month mission.

Mar 23, 2006 10:59: AM
ISS spacewalks on hold
ORLANDO SENTINEL

...
On a related note, mission managers said Wednesday that four canisters used to purge Russian spacesuits of carbon dioxide are missing. Station residents Bill McArthur and Valery Tokarev so far have been unable to find them. The issues are nothing new. Both have been known to NASA officials for some time and were mentioned in an internal ISS status report posted last week on SpaceRef.com. More details are available in stories from Reuters and The Associated Press.

It may be true that some of the reporting on space logistics events by the media may not always be grounded in fact or may be somewhat over-exaggerated. Nevertheless, it is becoming clear that effective logistics is essential in ensuring crew effectiveness and mission safety. This includes, but is not limited to the pre-emption of critical shortages, the incorporation of lessons learned on stowage, sparing requirements and consumables usage, and effective communications between the crew and ground controllers.

As Project Constellation lays the groundwork for a human return to the Moon, new vehicles and procedures will have to be developed – taking into account the lessons of the past – while addressing the challenges of the future.

6 Recommendations

As the Shuttle program comes to a close with anticipated retirement by 2010, we have come to realize that without the ability to collaborate, integrate and standardize the current decision making process relevant to logistics and the supply chain as a whole, NASA will find it increasingly difficult to work as an informed collaborator with suppliers and contractors in bringing new systems and sustainment processes to fruition. The cost of operating and sustaining the resulting systems will continue to grow, exceeding designated budgets. We have also come to learn that the path to optimizing operability and sustainability is by consideration of the entire supply chain.

As such, we recommend the following course of action to ensure that logistics is at the forefront of consideration for the Constellation Program and beyond, potentially leading to a substantial cost savings in operations:

1. Establish a list of **space logistics relevant requirements** that must be taken into account during development of the Constellation Program (CxPO) overall and CEV, CLV, CaLV, LSAM, EDS, and Lunar Outpost/Base design specifically, as well as adaptation of ground processing infrastructure.

2. **Empower a position responsible for logistics oversight** early in the process, the equivalent of a Chief Logistics Officer (CLO). This position should be in charge of creating and enforcing standards across program elements, identifying opportunities for lifecycle cost savings as well as ensuring that past lessons are taken into account when formulating future space flight logistics requirements.

3. **Space Logistics modeling and analysis investment**: Currently, among the technology areas recommended for funding by the ESAS report [11, Chapter 9], the areas on analysis and integration (11A, 11B) only have two logistics-related projects listed. Additional analysis, modeling and optimization investments for space logistics should be developed, validated and also applied to future considerations of operations and supportability including commonality, interoperability, maintainability, logistics, and in-situ fabrication (area 12A).

4. **Reduce the overlap in the logistics tracking system.** The lack of a common database to handle manifesting, inventory management on the ground, and on-orbit inventory management is a weakness of the current system. It is unrealistic to think that future programs will handle all these critical functions with one database but it is important to have fewer databases that can easily pass information amongst themselves.

5. **Automated inventory tracking and system updating.** There is a need to develop new technologies and integrated system solutions that allow for automated tracking of agents, supply items, and assets in the space logistics area, including automatic updating of inventory during cargo integration and on-orbit operations.

6. **Redesign and simplify packaging and stowage.** Current packaging and rack equipment on the Shuttle and ISS are modular and effective in protecting experiments and supply items from vibrations, shocks and other environmental hazards. However, accommodation mass and volume is significant and – in some cases – exceeds the mass of the useful payload itself. Accommodation mass and modular, reconfigurable stowage must be explicit considerations in the design of the CEV, LSAM, and other future flight hardware elements.

7. **Move the NASA knowledge capture into one system** (LLIS) and develop an ontology for assigning keywords. Additionally, there should be an effort to identify root causes and group lessons, which could easily be integrated into the relational database.

8. Institute **standard contract requirements, performance and evaluation criteria, and reporting requirements.** Having programs fully aligned in their logistics and supportability posture will appreciably reduce costs and improve responsiveness. Some areas where commonality can prove beneficial are:

- Certified Sources
- Contract requirements and management
- Cross-Project resources and materials

List of Abbreviations

ATV	Automated Transfer Vehicle
BCR	Barcode Reader
CEV	Crew Exploration Vehicle
CaLV	Cargo Launch Vehicle
CLV	Crew Launch Vehicle
CR	Change Request
CTB	Cargo Transfer Bag
CTBE	Cargo Transfer Bag Equivalent
DOD	Department of Defense
EDS	Earth Departure Stage
ESA	European Space Agency
ETR	Express Transport Rack
HTV	HII Transfer Vehicle
IMS	Inventory Management System
ISO	Inventory and Stowage Officer
ISPR	International Standards Payload Rack
ISS	International Space Station
JAXA	Japanese Aerospace Exploration Agency
JSC	Johnson Space Center
KSC	Kennedy Space Center
LLIS	Lessons Learned Information System
LSAM	Lunar Surface Access Module
MCC-H	Mission Control Center-Houston
MCC-M	Mission Control Center-Moscow
MLE	Middeck Locker Equivalent
MPLM	Multi-Purpose Logistics Module
MR	Manifest Request
MSFC	Marshall Space Flight Center
MWG	Manifest Working Group
OCA	Orbital Communication Adapter
PMA	Pressurized Mating Adapter
RISS	Russian Inventory Stowage Specialist
RSP	Resupply Stowage Platform
RSR	Resupply Stowage Rack
SSP	Space Shuttle Program
WMR	Waste Manifest Request
ZSR	Zero-G Stowage Rack

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Appendix A: Composite of 300 Lessons Learned

Event	Logistics applicability	Source	Number	Keyword(s)
Any comments on the usability of the BCR software?	Barcode system was inadequately sized to run application. A more generic discussion is the necessity to log users in and out on orbit. There are only six persons. A more reasonable implementation might be an open application that asks for the operator's name.	Crew Comments	44	Barcode
Have there been any issues with cable or hose labels coming off?	Barcode labels come off, in particular the wraparound vinyl flaps.	Crew Comments	74	Barcode
Please comment on any Bar Code Reader (BCR) performance issues with respect to the location/module the barcode reader was being used (problems with scanning, delay in response time, etc).	Transactions involving more than three items were better handled using the computer display instead of the BCR.	Crew Comments	81	Barcode
There was a kit of various sized bar code labels provided for you to use as you chose. Did you ever find them necessary or useful? If so, did you use one of the labels more frequently than the others?	Crew will use barcode label size that fits the item.	Crew Comments	53	Barcode
Any comments on the communication between the crew and the ground regarding IMS?	Reinforce testing and training of barcode reader before flight.	Crew Comments	38	Barcode, IMS
Did we give you enough time to prepack items before a Shuttle flight? We duplicated the prepack paper plan in IMS, why or why not was that useful/helpful? What could have made it more useful for you?	Pre-pack is the preparation and pre-positioning of on-orbit cargo prior to arrival of the transport vehicle. This requires movement of the item(s) from their stowage position, kitting and subsequent stowage in staging area.	Crew Comments	32	Barcode, Prepack, IMS, Transfer
Do you have any comments on the ISS inventory audits? How effective and useful were they? Any recommendations for improvement?	Transfer kitting needs to be accounted for in IMS system. Storage locations should have barcoded labeling	Crew Comments	75	Barcode, Storekeeping, Packing
How much did you use the barcodes? Which barcodes did you use – those on bags, those on items, both? What did you use the barcodes for?	Transfer and packing kits need barcode labels.	Crew Comments	52	Barcodes
Consumables low-level indications	Low-level indications for consumables should be such that there will be sufficient time for corrective action without having to depend upon an emergency system. The indications should be available to the ground.	John Commons ense	N/A	cargo, consumables

There were too many sources of information for basic engineering data. Data was being obtained from multiple Payload Element Developer (PED) personnel, post-Acceptance Test (AT) results and destow data, many of which were inconsistent and did not agree with approved CCB data. These discrepancies made it difficult to control manifest information and maintain reliability of the data.	There are many users and customers for logistics information, a central repository and single points of contact will keep the information flow in synch.	Phase 1/MIR	2-9.	certification
Contractor building rehab job superintendent not available during construction meetings	Meeting attendance and participation may be a contractual issue requiring statement of work direction	NASA PLL	749	Communication
Add a logistics move coordinator to team in modification and rehabilitation projects	Add a logistics move coordinator to team in modification and rehabilitation projects	NASA PLL	860	Communication
During the flight, problems were noted with the ops nomenclature in O2/N2 procedures matching up with equipment labels on the O2 panel in the Airlock (A/L1A2).	Reinforce necessity of procedures and equipment nomenclature match.	Crew Comments	13	Communications Maintainability
	All rotating components must be designed to preclude fragmentation damage should a failure occur. The design of all rotating components should consider contribution to ambient noise levels in the crew cabin.	John Commons ense	N/A	Component design
Non configuration managed drawing used to service high voltage equipment	Using documentation applicable to configuration	NASA PLL	443	Configuration management, maintenance procedure
Bearing failure broke centrifuge due to excessive loading	Conduct testing and operations readiness reviews	NASA PLL	494	Configuration management, operations logs and situational awareness
Description of efforts to eliminate leaking reaction control system (RCS) valves	Changes to processing and design of a deployed component will have a logistics impact	NASA PLL	1000	Continued Product Improvement
Use of robotic removal of Solid Rocket Booster Thermal Systems	Continuous improvement can yield productivity efficiencies in post recovery refurbishment	NASA PLL	832	Continuous Process Improvement, Design for maintainability
Fasteners used in ground support equipment for the MPLM come loose and are tracked into module	Operations analysis should include realistic assessment of components subject to high traffic.	NASA PLL	1205	Continuous product improvement

How do you assess the process of cargo stowage for cargo that is: delivered, returned, and disposed?	Each crew will consume consumables at a different rate	Crew Comments	76	Crew Provisioning
No single database to control all pertinent payload manifest information. Multiple databases were controlled by multiple organizations, which did not communicate efficiently with each other. Data on the same hardware was inconsistent, throwing the reliability of all databases into question.	There are many users and customers for logistics information, a central repository and single points of contact will keep the information flow in synch.	Phase 1/MIR	2-18.	data; manifest
Late parts development caused unqualified parts to be installed until qualified parts were available	Unique design of space hardware imposes unusual logistics requirements, late deliveries and extensive work at launch site	NASA PLL	479	Delivery
EEE parts selection criteria	Reinforces necessity for creation, application, and enforcement of standards.	NASA PLL	725	Design
Use of concurrent design	Reinforces necessity for creation, application, and enforcement of standards.	NASA PLL	681	Design for logistics
Factors associated with spacecraft maintenance concept	Effective development of a maintenance concept can enhance the effectiveness of maintenance support planning and aid both logistics planning and design of a maintainable system. The maintenance concept can also provide assessments of cost savings for maintenance activities and resources allowable at each maintenance level	NASA PLL	724	Design for maintainability
Extra Vehicular Activity (EVA) event design considerations	Establish standards for tool, material and task design factors when performing EVA operations	NASA PLL	834	Design for maintainability
Use of proposed venting scheme reduces number of components in system	Reduction in material and maintenance costs	NASA PLL	854	Design for Maintainability
Benefits of Implementing Maintainability on NASA Programs	Implementation of maintainability principles can reduce risk by increasing operational availability and reducing lifecycle costs.	NASA PLL	835	Design for maintainability, Product lifecycle
Mean Time To Repair (MTTR) predictions	NASA has established guidance for MTTR prediction analysis	NASA PLL	840	Design for Maintainability, Systems Engineering
Availability Prediction and Analysis	NASA has established guidance for availability Prediction and Analysis	NASA PLL	841	Design for Maintainability, Systems Engineering

Design considerations when using composites	Reinforces necessity for creation, application, and enforcement of standards.	NASA PLL	682	Design for maintenance
Use of high reliability parts in design enhance reliability	Sparing and qualification of parts designated and qualified as high reliability	NASA PLL	709	Design for maintenance
Crew-use hardware such as fasteners, electrical and plumbing connectors, switches, circuit breakers, and screws, etc., should be standardized as much as possible to facilitate crew operations, reduce crew errors, and reduce crew training requirements. Each common usage also reduces total sparing levels. This approach will simplify design, documentation, sparing, and actual in-orbit usage.	Standardize and minimize variety of devices	JSC Skylab Lessons	1-15	design for maintenance, commonality
Designing preventative maintenance strategies using reliability centered maintenance (RCM) analysis	Process improvement revisiting preventative maintenance strategies based on performance data	NASA PLL	891	Design for maintenance, reliability and process improvement
Spacelab interfaces not standardized	Operators not involved during design phase caused mismatch of equipment to Spacelab	NASA PLL	326	Design for operations
Space fastener selection and design criteria	Reinforces necessity for creation, application, and enforcement of standards.	NASA PLL	675	Design for operations and maintenance
Microelectronic circuit design considerations	Reinforces necessity for creation, application, and enforcement of standards.	NASA PLL	678	Design for operations and maintenance
Microcircuit design experience documented in checklists	Reinforces necessity for creation, application, and enforcement of standards.	NASA PLL	680	Design for operations and maintenance
Spacecraft deployed appendage test guidelines	Ground based testing requirements must be coordinated with logistics to ensure GSE is available	NASA PLL	716	Design for preflight processing
Spectral fatigue reliability	Reinforces necessity for creation, application, and enforcement of standards.	NASA PLL	696	Design for reliability
Fracture Mechanics Reliability	Reinforces necessity for creation, application, and enforcement of standards.	NASA PLL	700	Design for reliability
Use of Government-Industry Exchange Program (GIDEP) and Failure Experience Data Exchange (FEDI) programs	These and similar data interchange programs contain significant problems are identified on parts, components, processes, equipment, materials, specifications, or safety hazards.	NASA PLL	805	Design for Reliability

Analyzing system reliability using block diagram models	Using block diagramming methods for model construction and predictive analysis	NASA PLL	825	Design for reliability
Quantitative Reliability Requirements Used as Performance-Based Requirements for Space Systems	Quantitative Reliability Requirements Used as Performance-Based Requirements for Space Systems	NASA PLL	827	Design for reliability
Maintainability Program Management Considerations	Establishing maintenance and logistics concepts early in the conceptual phase of the program	NASA PLL	831	Design for Reliability
Preflight testing exhausted power supply spares	For various reasons development activities may continue post delivery at the launch facility, planning and design must take this into account.	NASA PLL	601	development, sparing and pre-launch operations
Are there any other cargo areas that additional pantry groupings would be beneficial?	Stuff piles up when ground is reluctant to disposition equipment no longer required. Early on the crew found the plenum voids in the FGB a good place to store stuff. The Russian module manufacturer objected strenuously	Crew Comments	103	Disposal, Excess
Do you have any suggestions for aiding in the identification and selection of cargo items that are currently on-orbit which can be returned/trashed due to lack of use or any other reason?	Crew wants to advise on suitability of material for disposal. Proposed current and future end use for every item in inventory should be known for ground to provide timely approval on disposal.	Crew Comments	100	Excess, Storekeeping, Stowage
Do you have any suggestions for aiding in the identification of cargo items that are currently on-orbit which can be returned due to lack of use or any other reason?	Program needs to assess what equipment is to remain on orbit taking up space. Crewmember referenced an on board spare that can only be changed when orbiter is present and broken equipment still on-orbit.	Crew Comments	89	Excess, Storekeeping, Stowage
From a Habitability/Operations perspective, how would you describe the overall on-orbit stowage situation?	Ground needs to keep on top of disposing of no longer required equipment	Crew Comments	98	Excess, Stowage

Trash should be separated into biologically active and inactive material. Daily disposal of active material is necessary, whereas less frequent disposal of inactive material is satisfactory. Stowage of collected trash "external" to the habitable volume of the spacecraft is highly desirable. Food containers make up the bulk of the trash and should be designed to consume minimum volume when expended. A compactor seems like a desirable feature. Backups and contingency plans are necessary.	Separate trash into biologically active and inactive material	JSC Skylab Lessons	1-6	excess; trash
Project cancelled after it became apparent that proposal was inadequately prepared, reviewed and implemented	Logistics analysis required to determine adequacy of proposed implementation	NASA PLL	1366	Feasibility evaluation and assessment
Pre-flight Problem/Reporting Procedures	Considerable development work/testing may occur at the launch facility, documented anomalies are a significant factor in qualification and flight certification.	NASA PLL	733	Flight qualification, Flight readiness review, operational readiness review
Did you typically eat three meals a day?	Crew Eats three meals a day	Crew Comments	68	Food, Crew Provisioning, Timeline
Did you feel that there was enough variety in your eight-day menu cycle or does the cycle need to be lengthened?	Large variability in crew food preference	Crew Comments	66	Food, Provisioning
Non-flight hardware is critical to support program milestones and needs to be documented and transported with the same level of support as flight hardware.	Generally speaking the focus is on flight hardware, but it is just as important for non flight equipment to be where it's needed when it's needed.	Phase 1/MIR	5/37	GSE; transport
A comprehensive database was not developed early enough to track all NASA/Mir hardware. When the database was implemented, much of the hardware had lost traceability and could not be adequately tracked in the database. Also, the database had two disadvantages: - Links were never established to Payload Integration Planning System (PIPS), which could have served as the master database for the program. - Microsoft Access required more in-depth computer programming knowledge than traditional spreadsheets in order to make modifications.	Failure to have integrated stowage and manifesting tools before the advent of operations leads to inefficiencies and lost time.	Phase 1/MIR	5/9	IMS
Any comments on the communication between the crew and the ground regarding IMS?	Crews quickly weary of daily calls to locate on orbit items.	Crew Comments	38	IMS

Any comments on the communication between the crew and the ground regarding IMS?	Crew believes there should be tighter integration between performance of procedure, e.g. installation of component, and follow-up IMS update	Crew Comments	38	IMS
Do you have any suggestions for enhancements/improvements to the IMS software?	System should be able to locate available empty stowage	Crew Comments	39	IMS
Do you have any suggestions for enhancements/improvements to the IMS software?	Suggested IMS improvements: Hourglass indicator to show processing is occurring Full screen as default Introductory logo displays take up time Server needs to be more responsive	Crew Comments	39	IMS
How do you assess the search for and inventory of items, and working with the IMS?	The crew primary search function used numbers instead of names for items.	Crew Comments	77	IMS
How much daily overhead is there to keep the IMS database updated to reflect the daily changes? Do we need to add this to your daily timeline?	At least one hour of work daily required maintaining IMS; this time was not timelined.	Crew Comments	29	IMS
IMS can display the data in a "tree" or graphically. Which do you prefer? Are they both beneficial? What changes and or improvements would you make?	IMS can display the data in a "tree" or graphically, Crewmember noted that tree was preferred.	Crew Comments	46	IMS
IMS performance (loading time, response time during searches, etc.) has been an issue in the past. Different crewmembers have given varying responses on the "lack of performance". Could you please offer your opinions?	IMS server and LAN are not adequately sized to handle traffic	Crew Comments	83	IMS
The program office is now supplying dimensions (length, width, height, mass) in IMS for many of the new items flying up. Would dimensional data in IMS have been any use for your work?	Dimensional information in IMS assists in search for item	Crew Comments	88	IMS
Was the search capability easy, adequate, or cumbersome to use?	Synonym capability would be desirable in locating items along with English names for Russian items.	Crew Comments	43	IMS
Was the time that Russia scheduled for you to transfer/stow items and update IMS post Progress docking sufficient?	Adequate time to properly update the IMS must be accounted for in the crew timeline.	Crew Comments	31	IMS
What are some troubleshooting issues that should be addressed by training?	Add indicator that software is working or when application needs to be restarted	Crew Comments	48	IMS

What were the least used features of the software?	Graphical features of software were not used	Crew Comments	41	IMS
What were the most used features of the software?	Search and move capabilities of software were used most often	Crew Comments	40	IMS
Which IMS capabilities did the crew feel needed better emphasis from a training perspective?	Ensure crews receive adequate IMS training on ground	Crew Comments	47	IMS
In about 5% of your BCR scans, the BCR misinterpreted a barcode. Can you comment on the condition of the barcodes (i.e. dirty, scratched) that you scanned that gave erroneous information?	Barcode reader had difficulty reading curved surfaces.	Crew Comments	82	IMS, Barcode
Do you have any comments on the ISS inventory audits? How effective and useful were they? Any recommendations for improvement?	During inventory audit activities the crew prefers that ground perform data entry	Crew Comments	75	IMS, Storekeeping
A practical and streamlined equipment stowage inventory management and accounting system is needed during the mission operations phase of the program. The system should output crew data in the exact format to be used by the crew and should be compatible with the real time uplink to the orbiting spacecraft for presentation on board. The system should also track other onboard data references affected by a given stowage change.	It's easy to lose sight of the crew interface as the various logistical information management systems are devised	JSC Skylab Lessons	8-7	IMS, stowage, inventory, storekeeping
Do you have any comments on the ISS inventory audits? How effective and useful were they? Any recommendations for improvement?	Inventory audits are useful	Crew Comments	75	IMS, stowage, inventory, storekeeping, audit
General Crew Comment	Crew works directly with an Inventory and Stowage Officer (ISO) console position who is solely responsible for providing help.	Crew Comments	21	IMS, Transfer, Stowage
Observation: Tracking hardware manifests is a labor intensive job that requires dedicated personnel. Background: Numerous documents are developed by various organizations for different purposes and formatted differently although they all contain a large percentage of common information. Examples include the MMO Manifest, the WG-6 004 document, the Phase One Requirements Document and the Phase One 0005 document. At present a great deal of manpower is expended trying to ensure the various documents are in agreement. Recommendation: Develop a hardware tracking database which has common use for all organizations and which is accessible by all parties. Dedicated	Despite prevalence of computers, databases and associated reports, many organizations and programs are document driven. Any logistics apps must be integrated and allow for collaborative activities	Phase 1/MIR	2-2.	IMS; manifest; inventory

support (including knowledgeable engineers as well as software experts) is required to maintain this database and ensure its accuracy.				
Every item that is on ISS must be expected to be returned from ISS on Shuttle or any other manned return vehicle.	Single mission execution processes must be adapted when planning a multi-mission campaign. This LL is not applicable to a destination operations environment.	Phase 1/MIR	3/1	IMS; manifest; inventory
On-board inventory tracking and return prep readiness checking needs help.	Failure to have integrated stowage and manifesting tools before the advent of operations leads to inefficiencies and lost time.	Phase 1/MIR	5/1	IMS; prepack; stowage
A user-friendly, graphics-based configuration tool was never developed to allow the ground team to perform real-time assessments or emergency replanning of hardware/stowage relocations on Mir.	An integrated stowage and analysis tool is desirable.	Phase 1/MIR	3/16	IMS; Stowage
There was no convenient portable method for recording inventory. Long duration crewmembers were of the opinion that the ground did not need to know in detail where every piece of hardware was located and therefore, did not want to do inventories. They felt that as long as the crewmember onboard was aware of the location of hardware, that should be all that was required (even after the Spektr collision). They also felt that the onboard crewmember is the best source for identifying where hardware should be stowed and the one to provide the resupply bag stowage plan. Most crewmembers do not think the bar code reader is the solution.	There are pros and cons to the various inventory management strategies practiced in the space program. Factors such as ease-of-use and practicality must be considered when designing a system.	Phase 1/MIR	5/29	IMS; stowage
A Spektr inventory was performed during NASA 2 and files were left for the NASA 3 crewmember. In addition, the NASA 3 crewmember would send down updated files when he relocated hardware.	To keep accurate stowage locations of on board inventory, daily call downs may be necessary.	Phase 1/MIR	5/30	IMS; stowage, inventory
Personnel moves require facility setup and infrastructure installation	Institutional logistics is generally responsible for ensuring facilities meet user's needs	NASA PLL	746	Infrastructure
Lack of availability of standard office equipment hampered Columbia accident board investigation	Institutional logistics rapid response to infrastructure needs aids investigation	NASA PLL	1453	Institutional logistics
Lack of availability of office space hampered Columbia accident board investigation	Institutional logistics rapid response to infrastructure needs aids investigation	NASA PLL	1455	Institutional logistics

Lack of availability of IT hampered Columbia accident board investigation	Institutional logistics rapid response to infrastructure needs aids investigation	NASA PLL	1456	Institutional logistics
Lack of witness interview processes and equipment hampered Columbia accident board investigation	Institutional logistics rapid response to infrastructure needs aids investigation	NASA PLL	1458	Institutional logistics
Lack of accident scene documentation equipment hampered Columbia accident board investigation	Institutional logistics rapid response to infrastructure needs aids investigation	NASA PLL	1461	Institutional logistics
Application of development collaborative information management and modeling tool inconsistent through accident investigation	Institutional logistics rapid response to infrastructure needs aids investigation	NASA PLL	1475	Institutional logistics
Individual hardware suppliers should not independently establish hardware quantities required for program activities. The program organization must establish a consistent approach in determining quantities of equipment required to support a program. A combination events chart and requirements checklist was a useful tool for quantity determination.	The development and deployment of space equipment involves many versions (flight, training; test article, etc) of the equipment for a myriad of users.	JSC Skylab Lessons	1-21	inventory, classification
Resupply of the station is an international and complex endeavor covering clothes, food, tools, and the like. The international aspect of logistics coupling differing cultures, ops concepts, products, etc. further adds to the overhead in this area.	Stowing of consumables next to each other aids during inventory audits. Coordination among international partners is essential.	Crew Comments	86	Inventory, stowage
There was a lack of inventory management system onboard Mir. Each long duration crewmember preferred to use their own method of stowing items. The Russians have no established system and therefore moved items at will. The Russians would not provide detailed technical information, which would allow the U.S. side to develop accurate ground based computer or physical simulators of the Mir Station.	Affirmation of need for inventory management	Phase 1/MIR	5/36	inventory; IMS; stowage
An attempt was made to track GSE by kits composed of several pieces of equipment required to perform a particular function. The approach proved to be ineffective since in many instances the kits were delivered on a piece by piece basis. As a result, control and management visibility of the GSE were difficult until adoption of the more realistic approach of tracking individual pieces of equipment rather than groups.	Assemble kits only when all pieces are available. The CM overhead on partial kits is tedious and time consuming.	MSFC Skylab Lessons learned	2.5.4a	kitting, GSE, PHS&T
What label issues cost you time and why?	Stress importance of proper and consistent labeling	Crew Comments	3	Label

There was no clearly defined process to provide manifest inputs into the Phase 1 Requirements Document. As a result, some working groups or their supporting PED organizations established their own independent paths for manifesting payloads aboard Mir without coordinating with other working groups (ex: Extra-Vehicular Activities, Space Medicine Program, International Space Station Risk Mitigation).	If permitted, organizations supplying material to be transported will strike separate deals with vehicle providers.	Phase 1/MIR	2-19.	manifest
There were philosophical differences in manifesting between the Russian and U.S. sides. Russians had no established system by which they tracked launch manifests, resulting in an inability by the U.S. side to verify information in time to meet mission milestones. U.S. manifests are baselined at L-12 months, but Russian manifest information is not provided until after transfer on Mir.	Manifesting processes tend to be vehicle and agency centric. A common process that ensures transportation access needs to be agreed to by responsible individuals in both organizations	Phase 1/MIR	2-20.	manifest
Observation: Shuttle manifest changes are constant leading up to a flight. These changes occur due to science changes, operations, and problems that occur during long duration increments.	The greater the granularity of insight into manifested material, the more changes will occur as the flight matures. An open change process ensures that all parties are coordinated.	Phase 1/MIR	2-24.	manifest
A "below the line" manifest was maintained prior to freeze dates to identify additional payloads which might be added to the official manifest in the event a manifested payload had to be removed because of hardware failure or inability to meet schedules.	Not all material manifested for a flight is ready when needed. To mitigate this, NASA maintains a priority system and backup manifest to maximize transportation resources	Phase 1/MIR	2-7.	manifest; contingency
The same program level manifesting system should be used for every vehicle going to ISS. On the esoteric side. Ideally, the same manifesting system should be used for every vehicle going to ISS. Similar to an airline reservation system, if an item comes up with a requirement to be on the ISS by x-date, then a computer program could review the item's development milestones and mass properties against the various launch vehicle flow requirements to find a potential launch vehicle.	Common manifesting system desirability. If not provided with a software application, owning organizations will develop their own apps.	Phase 1/MIR	2-1.	manifest; IMS;

Too many nomenclature schemes were used to identify the same piece of hardware on different manifests. Drawing names, label names, crew names and Principal Investigator (PI) names were all used based on the needs/preferences of the user.	Despite previous experience in the identification and tracking of transported material, the operations community feels more comfortable with naming items than using part numbers and revisions	Phase 1/MIR	2-12.	manifest
PED/PI organizations were requested to provide the same manifest data to multiple manifesting organizations, creating the potential for inconsistencies between the data provided and taxing limited PED resources.	No enforced central repository for information causes the owning organization to supply the same information multiple times to different requesting organizations.	Phase 1/MIR	2/13	manifest
The manifesting of all Mir transfer hardware was controlled by the MOIWG and Phase I - the program drove the manifest, not the carrier. This eliminated an additional approval path through the Shuttle program and enabled Phase I management to establish priorities and effectively implement its science program.	If permitted, the transport vehicles will attempt to own the manifest process. Clear lines of control must be established and adhered to.	Phase 1/MIR	2-14.	manifest
Items sent to Russia for launch on Progress or Soyuz were prioritized by Phase I and/or MOIWG. This prioritization was particularly important because launch opportunities for U.S. payloads aboard these vehicles were uncertain due to mass and volume constraints. The prioritized list allowed the Russians to understand which items were critical for the mission and to plan accordingly.	It is a fact of life that manifested cargo will not be ready when needed or the vehicle will not have the published payload capability. To optimize the manifest process cargo will be prioritized and placed on standby.	Phase 1/MIR	2-15.	manifest
Multiple paths for manifesting payloads resulted in numerous disconnects in the manifest. Radiation Monitoring Equipment (RME), Extra-Vehicular Activity (EVA) and Med Ops payloads had alternate approval paths which did not supply the necessary manifest information to the MOIWG	A central controlling board must be established and publicized to prevent unrealistic expectations of material transport	Phase 1/MIR	2-16.	manifest
The lack of a controlled process for manifesting payloads aboard Progress or Soyuz led to difficulties in finalizing the launch manifests for these vehicles. Data was provided to the U.S. side only after the vehicle docked to the Mir and items were successfully transferred. In addition, a great deal of effort had to be expended to transport items to Russia with no guarantee that the items would ultimately get loaded onto the vehicle.	Manifesting processes tend to be vehicle and agency centric. A common process that ensures transportation access needs to be agreed to by responsible individuals in both organizations	Phase 1/MIR	2-17.	manifest

were the repair of the teleprinter and replacement of the printed circuit boards in the video tape recorder. The flight backup and test units on limited-production programs should be considered as spares sources within reasonable refurbishment effort, launch delay, and reprocurement time considerations.				
Did you have any problems with maintenance procedures?	Reinforces need for procedure and training standards.	Crew Comments	96	Maintenance, Standards
Tools initially selected for Skylab were primarily those required for specific tasks. A few contingency tools were included such as a pry bar, a hammer, and the Swiss Army knife, which proved to be valuable assets. Wrenches were provided only for specific applications. The crew activities and evaluation indicate a tool kit should contain all the tools normally found in a tool collection for comprehensive home usage, as well as the special tools required for special aerospace hardware. Good quality off-the-shelf hand tools are adequate and no special features are required for use in space. An improved tool caddy for carrying tools from place to place should be developed for easy location of the needed tool after arriving at the work station. Transparent material would be desirable. The caddy should also hold small parts in an accessible manner as the work is done, since containing and locating these items was a problem in zero gravity.	Include GP tools in toll kit. Facilitate transport of tools and securing of tools and parts in a zero g environment.		2.6.2 Selection of tools	maintenance, tools
Brakeline not connected on DC-X caused subsequent accident during recovery	Prototype design process did not place emphasis on development operations maintenance	NASA PLL	638	Maintenance; operation; documentation
Non-critical late changes to the manifest were accepted by the CCB without assessing the impacts to resources and schedules. These changes were primarily items requested by PEDs/PIs to cover potential contingency situations in flight (e.g., spare parts, back-up cables, additional logbooks, and disks).	There are many customers for the manifesting process, it is important to keep the controlling board(s) and the supporting logistics functions coordinated.	Phase 1/MIR	2-10.	manifest
Some payloads were not tracked by serial number, leading to uncertainty in which item was to be manifested for the mission and ultimately loaded onto the vehicle.	Not all material providers follow strict configuration management procedures; use of serial number tracked items permits an extra degree of granularity.	Phase 1/MIR	2/11	manifest

investigation of in-orbit anomalies during the Skylab missions.				
Initial design concepts should include in-flight maintenance provisions, with the necessary design features to facilitate failure detection, isolation, corrective action, and verification of repair. Provisions should be made for tools, spares, maintenance equipment, and space for maintenance work. Accessibility to equipment attaching hardware, electrical connections, and plumbing is imperative, even in areas where maintenance is not planned. All contingencies cannot be anticipated, but corrective maintenance action can be taken if the general design is consistent with this approach. In much of the unplanned Skylab repair work, it was necessary to remove cover plates held in place by an inordinate number of fasteners, which were not always of the design best suited for operational removal. Allen head screws and hexagon head bolts were much preferred over other types by the crew. A substantial effort had to be spent in identifying, to and by the crew, components, cables, and tubing to be repaired or replaced. A simple system of identification decals should be used to facilitate identification.	Initial design concepts should include in-flight maintenance provisions, with the necessary design features to facilitate failure detection, isolation, corrective action, and verification of repair. Provisions should be made for tools, spares, maintenance		2.6.1 Criteria for Design	maintenance, design for maintainability
Result of steam line accident mishap investigation board	No individual was responsible coordinating work	NASA PLL	1084	Maintenance, project management
Spares selection should include repair parts for critical items whose design permits in-flight bench repair, as well as replaceable assemblies. Skylab has proven that the crew, when provided the proper tools, procedures and parts, is capable of performing bench repair of failed assemblies beyond prior expectations. Although there were initially no repair parts aboard, these were provided on subsequent revisits and used successfully. A good example is the tear-down of tape recorders by the crew of SL-3 and the subsequent furnishing of repair parts and repair by the SL-4 crew. This reduced the volume requirements for resupply by providing a few repair parts instead of an entire new assembly. This philosophy could reduce the number of primary spares required on board initially, if the capability to repair the failed items is provided. Other examples of detail repair on Skylab	Crew can repair equipment to the lowest practical limit, regardless of SMR codes, provided that they have tools and parts.		2.6.3 Selection of spares	maintenance, spares

indicator lights from the front of the panels. 12. Design external protective covers for experiments and other equipment for manual operation by EVA as well as by automatic opening. An EVA manual override may be necessary if automatic opening fails. 13. Single force fasteners should be used to close out all access panels in lieu of slotted or Phillips head screws.				
Routine maintenance of experiment hardware residing in Moscow was well planned and coordinated by PED/PI personnel. For example, routine GASMAP maintenance in Russia was planned and supported by PED personnel during the course of the program.	Operations and maintenance planning must include remote servicing activities if required	Phase 1/MIR	5/6	maintenance
What is your general impression of the serviceability and supportability of the station?	Identify equipment requiring service to designers so that convenient access can be instituted in design	Crew Comments	97	Maintenance
What's your general impression of the serviceability and supportability of the station?	Access panels need to be designed for convenient removal in operation environment. Specifically panels that require large amount of fasteners to endure launch loads may only require 2 to 3 fasteners in zero-g	Crew Comments	106	Maintenance
Protection of electrical connectors for GSE	Installation of appropriate electrical connector caps when not mated.	NASA PLL	850	Maintenance procedures
Provide a depot repair, maintenance, and modification capability for delivered experiment hardware. Schedule and manpower expenditures were minimized because of the quick turnaround capability afforded by the depot concept of operation and the physical location of the depot in relation to the receiving and shipping docks. The ability to repair items in the depot or to go directly to the proper specialty manufacturing area within the company greatly enhanced the time it took to achieve needed repairs. The members of the small team of people used to run the depot were all "graduates" of the qualification-acceptance test phases (engineering, test, and quality). This fact made the decision process more accurate and timely. Subsequent repairs and tests were accomplished more efficiently because of the experience of the personnel involved. The depot provided a suitable location for the mission support testing to assist in the	Depot staffed by experienced developers and located in proximity to operations provides timely repair activity and troubleshooting support	JSC Skylab Lessons	1-18	maintenance, depot

Do you have any suggestions on improving station hardware, station maintenance tasks?	Need to involve logistics standards early in design. Reduce number of and types of tools required.	Crew Comments	105	Maintainability
Excessive failure analysis time causes slow turnaround	Delays in accomplishing failure analysis causes excessively slow turnaround times for many repairable components	NASA PLL	221	Maintainability, Failure Analysis
For the location codes, would using an alternate color or increasing the label size make the label easier to locate/read?	Use of color codes for label criteria is acceptable	Crew Comments	57	Maintainability, labels
Logistics depot development	Establish a logistics depot	NASA PLL	220	Maintainability, SMR
Fiber-Reinforced Polymer Composite Material Selection	Reinforces necessity for creation, application, and enforcement of standards.	NASA PLL	689	Maintenance
Two individuals were left in manhole unattended	Lax attitude contributed to failure to follow procedures	NASA PLL	1085	Maintenance
In-orbit repair and maintenance can be performed satisfactorily in zero g. In-flight maintenance guidelines should include the following: 1. Consider extravehicular activity (EVA) as a normal means of repair. 2. Provide proper procedures, tools, and equipment for crew usage. 3. Design equipment to facilitate potential in-flight maintenance. 4. Consider EVA inspection and repair during the design requirements phase of a program. 5. Provide for the effective containment of nuts, bolts, washers, tools, hardware components, etc., by means of tool and/or retainer boxes, bungee cords, etc. 6. Provide for a worksite, repair bench, or equivalent equipped with adequate restraints for tools and equipment. 7. Provide spares for those hardware items most likely to require servicing and/or replacement. 8. Promote the use of standard-size screws, bolts, etc., in the spacecraft design. 9. Provide a high-fidelity maintenance training simulator. 10. Provide the capability to reservice fluid and gas systems from the interior of the spacecraft. Fluid/gaseous connectors (B-nuts, weld or solder joints) should be located and configured such that they can be inspected by the crew for leaks. ll. Design panels to allow replacement of	Design considerations for operations and maintenance	JSC Skylab Lessons	1-2	maintenance

Apollo-era ground infrastructure for the Space Shuttle Program requires revitalization	Multi Program use facilities such as centers must perform continual logistics analyses to maintain capabilities.	NASA PLL	1233	Lifecycle planning
Strategic Resources Review (SRR) facility closure decisions	To make most cost effective decisions logistics analysis are performed.	NASA PLL	1234	Lifecycle planning
Insufficient amount of Simplified Aid for EVA Rescue (SAFER) units available for unplanned contingencies	Required logistics analysis to determine probability of sufficiency	NASA PLL	1113	Logistics Analysis
The current EMU is adequate for the near-term needs of the ISS and the Space Shuttle, but its obsolescent technology, high cost, and other limitations make it unsuitable for future exploration and development of deep space	Required logistics analysis to determine predicted lifecycle costs	NASA PLL	1126	Logistics Analysis
Parts Obsolescence May be Caused by Several Issues Including Vendors Going Out of Business, Discontinuance of a Part, and Environmental Law Changes	Contingency planning includes maintaining a priority list of top issues	NASA PLL	1013	Logistics program
Addresses Aviation Safety Assurance Panel (ASAP) concern regarding availability of Shuttle LRU spares	Required LRU forecasting and 'what if' scenarios	NASA PLL	1051	Logistics program
Transition and development of the LOGISTICS tasks for the orbiter and its ground operations under the SFOC are proceeding efficiently and according to plan	NASA and USA should continue the task of management integration of the formerly separate LOGISTICS contracts and retain and expand the roles of the experienced LOGISTICS specialists therein.	NASA PLL	1052	Logistics program
long-term projections are still suggesting increasing cannibalization rates, increasing component repair turnaround times, and loss of repair capability for the Space Shuttle LOGISTICS program	NASA and USA should reexamine and take action to reverse the more worrying trends highlighted by the statistical trend data	NASA PLL	1053	Logistics program
Process for reviewing MIR/Phase 1 lessons learned for applicability to ISS Program	Late stowage requirements for flights to MIR caused design of late load capability into the ISS Multi-Purpose Logistics Module (MPLM)	NASA PLL	1056	Logistics program
Components from a operational orbiter were removed to repair a non operational orbiter	Inadequate sparing causes cannibalization of orbiters to support launch	NASA PLL	197	LSA, Sparing
IUS design has no connectors, cables must be spliced	Maintainability assessment must include analysis of repairs that may occur during testing	NASA PLL	313	M&O

Colored labels were used on the CTBs to track bags returning and those going to Mir: pink for ascent and blue for descent.	Use of color coded labels to categorize cargo can be useful	Phase 1/MIR	3/14	label; packaging
Do you have any comments about the labeling of emergency equipment or emergency lockers?	Crew wants 'time of usable air' on O2 bottles in addition to amount remaining	Crew Comments	73	Labeling
Were there any identification labels that kept you from identifying hardware?	Stress importance that material labeling and procedure material identification match.	Crew Comments	70	Labeling, Maintenance
If the components of an assembly all had IMS barcodes label, was it difficult to determine which of the IMS barcode labels was the parent in IMS?	When components in an assembly had barcode labels it was sometime difficult to determine the parent.	Crew Comments	56	Labels, IMS
How much did you utilize the decals (i.e. O3, P1) located on the standoffs in the MPLM and US Lab? Would it be adequate (on future modules) to only label the rack bay (1,2,3) and have decals on the endcones indicating forward/aft and overhead/port/deck/s	Use a standard rack labeling scheme, use the Lab as an example.	Crew Comments	18	Labels, Stowage
Project budget bled by reliance on facility with small customer base and shifting NASA priorities	Stresses importance of supplier risk analysis	NASA PLL	1342	Lifecycle Analysis
Project underestimated complexity when using COTS navigation product in shuttle	Reinforces logistics role in overall systems engineering process	NASA PLL	1370	Lifecycle analysis
There is no systematic plan to counter obsolescence and assure the availability of adequate facilities, GSE, and specialized test-and-checkout equipment throughout the expected lifetime of the Space Shuttle.	Logistics should be responsible for providing a systematic plan to counter obsolescence and assure the availability of adequate facilities, GSE, and specialized test-and-checkout equipment throughout the expected lifetime of the Space Shuttle.	NASA PLL	1138	Lifecycle planning
Potential International Space Station (ISS) Supportability Problems With Existing Extravehicular Activity (EVA) Assets	Required logistics analysis to determine predicted lifecycle costs	NASA PLL	1144	Lifecycle planning
The funding of the EVA R&T program is not adequate to provide the maximum safety benefit in terms of new equipment and procedures that lower the risk of extravehicular activities	Required logistics analysis to determine predicted lifecycle costs	NASA PLL	1147	Lifecycle planning
The current and proposed budgets are not sufficient to improve or even maintain the safety risk level of operating the Space Shuttle and ISS	Logistics analysis required to draw conclusion	NASA PLL	1231	Lifecycle Planning
Elements of the Shuttle systems upgrades portfolio may be delayed or deferred necessitating a need to ensure adequate long-term **LOGISTICS** planning for mature systems	To make most cost effective decisions logistics analysis are performed.	NASA PLL	1232	Lifecycle planning

The manifest was maintained in Russian and English on the same page, and used only metric values. Therefore, the manifest provided to the Russians via hardcopy was the same as that used by the U.S., which eliminated error associated with maintaining multiple versions.	When dealing with international partners, careful consideration must be given in establishing language and measurement standards. Although dual language and measurement capabilities were a concession, the impact on future transactions with other international partners were not considered.	Phase 1/MIR	2-6.	manifest; IMS
Observation: A great deal of time and effort is expended in manifesting items such as ziplock bags, tape, pens, dry wipes and paper. Recommendation: a. Set aside an area onboard station for stowage of common-use supplies. b. At a specified time prior to the next shuttle launch, have a crew person inventory the supplies on hand. C. On the ground, have a catalog of core pre-approved supplies that FEPC maintains to replenish those supplies. d. Remove these items from the standard manifesting process. Under the present system, it takes almost as much manpower to manifest a ziplock bag as it does to manifest a payload. Background: Any time the long duration crew needed these types of items, they had to be processed through the CR route. Drawings had to be changed, safety certifications generated and CCB approval obtained in the same manner that major hardware is processed.	Establishing and maintaining a qualified parts list will expedite the manifesting of materials on space transportation	Phase 1/MIR	2-3.	manifest; IMS; certification; loadmaster
Working Group 6 found it difficult to determine third-party (international) hardware ownership to obtain usage agreements. (ex. French camera)	Lines of ownership can become confusing as material passes through multiple providers.	Phase 1/MIR	2-32.	manifest; ownership
The trade-off between planning too many experiments and too few is very important. Processing reserve experiments would be very beneficial in the event that planned payloads drop out late in the process. However, even the planning process is expensive and PIs want to fly their experiments if they do the initial preparation.	Lower priority cargo may not be flown imposing significant operations and preparatory costs on supplying organizations.	Phase 1/MIR	2-35.	manifest; research

Component Terminology Simplicity and Consistency	Nomenclature selected for vehicle components should be simple, concise, and refer to common everyday terminology where possible (I.e. instead of calling a light a General Luminaire Assembly (GLA), call it a light). When complex terminology s used, it must be recognized that additional system familiarization and training for the crew and operational personnel are required. In addition, identical components should use the same terminology throughout the entire vehicle. Differences between engineering and operations nomenclature should be minimized.	John Commons ense	N/A	Nomenclature design
During recent Multi-Purpose Logistics Module (MPLM, S/N FM1) operations, some loose debris was generated by the Personnel Access Floor (PAF, S/N 002). The source of the debris was found to be from the personnel access floor rivets (Part Numbers MS21140 &	Design of GSE should include usage analysis to ensure product holds up under anticipated traffic	JSC Lessons Learned	369	outfitting, preparation for launch, PHS&T
Robust Systems Consumables	The overall system should be designed with sufficient consumable margins to accommodate foreseen contingencies. Lack of robust consumable margins requires very detailed design optimization that reduces mission flexibility and responsiveness to changing r	John Commons ense	N/A	overall system design
	Wherever possible, all circuit design and packaging of similar hardware or function will be standardized at the lowest possible level for supportability, maintainability, and interchangeability.	John Commons ense	N/A	Packaging design
Certification requirements should take into account the extremes of the ground storage and transportation and space environment. Hardware sometimes sat in cold warehouses.	Packaging specifications should identify the transport environment to the destination node. This must include all internodal transport to intended and potential vehicles.	Phase 1/MIR	3/5	packaging; transport

The process for packaging and processing CTB shipments to KSC was performed well due to well defined schedules and adequate lead times. The hardware was shipped directly to Spacehab and required good coordination between Stowage and Logistics.	Kitting can be delivered packaged for flight, providing that standards are followed.	Phase 1/MIR	3/12	packaging; transport
The Collapsible Transfer Bag (CTB) concept allowed greater flexibility for the ground and the crewmember for packing and transferring items.	The Collapsible Transfer Bag (CTB) concept allowed greater flexibility for the ground and the crewmember for packing and transferring items.	Phase 1/MIR	3/13	packaging; transport
Hardware packaging requirements were not compatible with actual transportation conditions in Russia. Thermal and shock loads encountered during transportation by rail or truck often exceeded the design capability of the shipping containers. In addition, the U.S. had no control over the mode of transportation within Russia.	Packaging specifications should identify the transport environment to the destination node. This must include all internodal transport to intended and potential vehicles.	Phase 1/MIR	5/10	packaging; transport
Crew Transfer Bag (CTB) packaging schemes were determined primarily by one specialist, resulting in a potential single point failure.	Logistics processing staffing must ensure capabilities are available when required.	Phase 1/MIR	3/2	packing; transfer; packaging
It has been noted through review of IMS data, that you have begun using the pantry concept for some items (bungies, tape, etc.). Any suggestions on how the stowage group can aid in the development/implementation of a broader pantry plan to include more l	Utility of pantry provisioning needs to be assessed and optimized for each application	Crew Comments	16	Pantry
Pantry-type food storage as opposed to meal-sequence food storage: Particularly for long-term flight, it is recommended that a pantry-style food storage system be implemented. In this type system, all identical foods are stored in the same location	Reinforcement of pantry stocking concept	JSC Skylab Lessons	1-5	pantry; provisioning; stowage
Delimitation of nozzles as a result of storage environment factors	Problem discovered during receiving inspection	NASA PLL	466	PHS&T
Circuit boards deteriorated during storage	Equipment doesn't always launch when scheduled, spares for launched systems may be used for other projects	NASA PLL	607	PHS&T
Monitoring spacecraft exposure to magnetic fields during storage and transportation	Space systems may be susceptible to damage from magnetic fields during storage or transportation and may require monitoring	NASA PLL	706	PHS&T

Maintenance & Test Criteria for Circuit Breakers to be performed prior to or during installation.	Pre-installation testing may be required for circuit breakers due to previous instances of process variables, inspection techniques, and even fraud	NASA PLL	848	PHS&T
During transportation of the X-33 fuel tank, the transport truck struck an underpass	Lead truck passed under overpass in center, transport truck did not follow exact track	NASA PLL	1068	PHS&T
Spacecraft damaged due to mismatch of spacecraft and GSE	Stresses importance of analysis and readiness reviews	NASA PLL	1089	PHS&T
Flight equipment not properly packed for shipment	Conflicting contractor and center PHS&T requirements result in confusion regarding correct configuration	NASA PLL	1211	PHS&T
Recipient of tool shipment refused delivery because tool was improperly packaged	Reinforces fracturization of logistics among organizations to the point where no entity is responsible for successful completion of task.	NASA PLL	1272	PHS&T
GSE interferes with installed payload in MPLM	Importance of design reviews and adherence to Interface Control Documentation	NASA PLL	1323	PHS&T
Closed cell material used for stowage restraints should have an allowable tolerance to account for changes in volume at different pressures.	Packing of materials transported through space must include a thorough analysis of encountered environments and effect on dunnage	JSC Skylab Lessons	2-7	PHS&T
Interface verification matrices should be established to ensure adequate fit checks of critical Government furnished equipment (GFE) hardware interfaces. A specific organization should be charged with the responsibility for generating and completing these matrices.	Regardless of analysis, reviews, certifications and qualifications, fitchecks to verify equipment mates will be requested. For equipment delivered packed for flight this may necessitate unpacking and mating unless it can be shown that the equipment was mated to other flight certified equipment.	JSC Skylab Lessons	14-1	PHS&T
Printed wiring boards solder connections have shelf life issues	Logistics support analysis must include shelf life analysis	NASA PLL	402	PHS&T, shelf life
Many of the orbital workshop equipment restraints appeared to be oversized. Simpler concepts would have probably saved cost, weight, complexity, and crew time. Operational equipment restraints should be standardized and should be simple and easy to use. Bungee-type restraints attached to stowage lockers, walls, doors, etc., would be adequate for many of the in-orbit equipment	Launch restraints are not used when equipment is on orbit	JSC Skylab Lessons	2-36	PHS&T, stowage

stowage and handling activities. Specific book restraints are needed at work sites to retain checklists and to keep them open to a given page. If a press-fit restraint is used for loose hardware, care must be taken not to insert the hardware too deeply or too tightly into the retention device. A specific means for keeping clothing spread out to dry while the crew sleeps would be desirable.				
Contaminated part sent to shipping	Tracking system must include special handling instructions	NASA PLL	99	PHS&T, Special Handling
Electrostatic precaution measures during ground processing	Reinforces necessity for creation, application, and enforcement of standards.	NASA PLL	685	PHS&T; marking
NASA budget reductions affect transitioned logistics functions	Budgetary squeezes increase cannibalization and component turnaround times	NASA PLL	1012	Planning, logistics program
General Crew Comment	Communications regarding the pre pack were beneficial in resolving questions	Crew Comments	65	Pre pack, communication
Discuss the role the ISS Loadmaster performed.	Transfer arrangement call for manned vehicle crewmember to be responsible for transferring cargo between vehicle and ISS. This person is designated as loadmaster	Crew Comments	85	Pre pack, Loadmaster, Transfer
The original plan was to discard the pre-pack list once the transfer lists arrived with the shuttle crew. Did this happen, or did you continue to use the pre-pack list?	Early crew used pre pack lists which did not always agree with final transfer lists	Crew Comments	59	Pre pack, transfer
Pre-flight processing and testing results in excessive mates and demates of flight connectors	Significant wear and tear occur to flight equipment prior to launch	NASA PLL	316	Pre-flight processing
Electrostatic Discharge (ESD) control in flight hardware	Reinforces necessity for creation, application, and enforcement of standards.	NASA PLL	732	Pre-flight processing
Integration and Test Practices to Eliminate Stresses on Electrical and Mechanical Components	Reinforces necessity for creation, application, and enforcement of standards.	NASA PLL	729	Pre-flight processing
Do you have any suggestions for us to make the pre-pack list and all the changes we send you easier to use? Would sending the same file back and forth and allowing the crew to insert comments and the ground to add new items be useful?	Commonality in packing and transfer lists	Crew Comments	9	Prepack, manifest
Did you ever reference the Station Flight X Transfer List prior to Station Flight X+1 arrival?	Reinforce need for coordination and commonality in stowage and transfer record identification.	Crew Comments	58	Prepack, Transfer

Fuel cells not properly isolated from shuttle electrical busses	Procedures did not address circumstances	NASA PLL	1184	Procedures
Quick Release Pin from gantry platform kickplate was found on shuttle	The less stuff you have that requires the use of QRPs the less QRPs you'll have available to get lost	NASA PLL	923	Procedures, Design for maintainability
Orbiter project is currently working to reduce the number of outstanding drawing changes	Reinforces necessity for performing obsolescence reviews and maintaining an active supplier surveillance program.	NASA PLL	1243	Procurement
Project difficulties due to inadequate budgeting, planning and engineering	Budgeted procurement time underestimate time to get vendors under contract	NASA PLL	1397	Procurement
Separate Center and contractor procurements of the same or similar items should be avoided, because this approach can result in several specification number or part number callouts for the same item. Common requirements for the same item by more than one Center or contractor should be coordinated, and the commonality aspects should be managed to the advantage of the program.	Separate Center and contractor procurements of the same or similar items should be avoided, because this approach can result in several specification number or part number callouts for the same item	JSC Skylab Lessons	5-3	Procurement, standards
NASA aircraft used for both Space Shuttle operations and astronaut training are increasingly out of date and, in several respects, may be approaching the unsafe	Logistics assessments required for cost benefit analysis for extension/replacement	NASA PLL	1102	Procurement/Planning
Design practices followed to make the Solid Rocket Boosters (SRB) reusable	Refurbishment and process improvements and their effect on lifecycle costs	NASA PLL	836	Product Lifecycle
Plans to fly Shuttle until 2012 necessitate phased upgrades to maintain schedules	Lifecycle improvements impact logistics support requirements	NASA PLL	999	Product lifecycle
Lessons learned from Chandra X-Ray Observatory Program	A good listing of programmatic lessons learned, see actual lessons learned section	NASA PLL	987	Program
Substantial Benefits to projects from use of Blanket Purchase Agreement (BPA) during procurement	Use of Blanket Purchase Agreement (BPA) during procurement allows flexibility during Indefinite Delivery/ Indefinite Quantity (IDIQ) contracts	NASA PLL	1218	Purchasing
AT by Accompanying Documentation (AD) was negotiated with the Russians to aid the processing of reflown payloads.	Vehicle specific flight qualification certifications must be established between vehicles, organizations, and agencies.	Phase 1/MIR	3/7	qualification; manifest; certification

There was a need for consistent definition of certification requirements for payloads. - Although certification requirements were defined in the 002 document, these requirements were always open to interpretation depending on the Russian specialist involved in the Acceptance Testing. - Russian and Shuttle certification requirements are different, thereby causing confusion PEDs. Russian requirements are general, whereas U.S. requirements tend to be specific. - Most problems were in fluid containment and verification and offgassing limits.	Vehicle specific flight qualification certifications must be established between vehicles, organizations, and agencies.	Phase 1/MIR	3/11	qualification; manifest; certification
Broken chairs are repaired under warranty	Maintain warranty records in event equipment does not perform as specified	NASA PLL	931	Record Keeping
As EEE components are processed and packaged original lot information is lost	Aerospace components have the added requirement for pedigree determination, lost information can cause non or loss of flight certification	NASA PLL	982	Record Keeping
Crane use even though out of operational configuration and past due servicing	Reinforces necessity for record keeping and maintenance planning	NASA PLL	565	record keeping; maintenance; operations
Checklist development of factors that affect long-term storage of devices	Reinforces necessity for creation, application, and enforcement of standards.	NASA PLL	684	Reliability; PHS&T
Poor weather visibility prevented technicians from adequately monitoring N2 tank filling	Operations procedures should be analyzed for all credible hazards	NASA PLL	871	Safety
Guidelines for close call reporting at GSFC are not clear	None other than as a participating organization	NASA PLL	1086	Safety
Vehicle launched despite abort directive	None other than as a participating organization	NASA PLL	1090	Safety
A 55-gallon drum of paint wastes subsequently ruptured after being over packed into an 85-gallon salvage drum due to leakage from the original drum	Reinforces handling procedures for transported and stored goods	NASA PLL	1181	Safety
Operators suffered extremity damage while performing work	None, other than as a participating organization	NASA PLL	1361	Safety
Uncoordinated work resulted in water deluge system activation	None other than as a participating organization	NASA PLL	1183	Safety, operations
Improper configuration of vehicle led to damaged fuel cell	Configuration not properly documented in repair procedures	NASA PLL	1182	Safety; procedures
Oil pumps were overfilled	Maintenance & Operations (M&O)	NASA PLL	216	Servicing

Ni-Cd battery handling and storage factors	Ni-Cd batteries can be damaged and irreversibly degraded through improper use and handling prior to launch	NASA PLL	644	Shelf life; issue processing; limited life
Super Ni-Cd battery handling and storage factors	Ni-Cd batteries can be damaged and irreversibly degraded through improper use and handling prior to launch	NASA PLL	694	Shelf life; issue processing; limited life
The shipping/logistics team developed a schedule and process for the return of U.S. hardware from Russia. To implement the plan, personnel were sent to Moscow to perform detailed inventories, review dual-language hardware lists with the Russians, determine which items would be transferred to RSA or Phase II, negotiate three-way protocols, and package the hardware for shipment. The efforts have resulted in the successful return of approximately $1.5 million of hardware, despite the numerous obstacles presented by RSA and Russian Customs officials.	The necessity of developing a end-to-end material lifecycle process is affirmed	Phase 1/MIR	5/15	shipping
The Russian organization structure required multiple levels of approval for hardware shipments. Personnel supposedly authorized to prepare documentation or approve shipments were unwilling to initiate a process without higher approval.	The necessity of developing a end-to-end material lifecycle process with empowered control gates is affirmed	Phase 1/MIR	5/18	shipping; manifest
Personnel hand carrying hardware into Russia were met with varying application of customs regulations based on the whim of customs officials. These items, as well as parcels sent through various express delivery companies, were more likely to be detained	The necessity of developing a end-to-end material lifecycle process with empowered control gates is affirmed	Phase 1/MIR	5/23	shipping; manifest
The standard shipping form (JSC 290) was created on a Macintosh software platform which was not available in PC format. This limited access to the form once PCs became the JSC standard desktop system.	Common software standards for forms and applications must be implemented prior to advent of operations	Phase 1/MIR	5/11	shipping; transport
The shipping template from JSC to Moscow (2 weeks) was not compatible with late changes to training, which required payload training hardware to be at GCTC.	Shipping of materials across international boundaries requires extensive lifecycle planning	Phase 1/MIR	5/44	shipping; transport
Having hardware facilitator/coordinators both in Moscow and the U.S. helps shipping, and tracking the hardware.	Use of expediters in foreign locations is justified when the amount of material shipped is extensive.	Phase 1/MIR	5/45	Shipping; transport

Many hardware shipping requests were not submitted in compliance with the shipping process. Inadequate lead times and incorrect shipping information provided by the requester resulted in rework of shipping forms and delays in the schedule. Some organizations opted to bypass the MOIWG entirely and ship/carry hardware on their own, resulting in unnecessary delays and additional costs.	If there is no coordinated approved process ahead of time, organizations supplying material to be transported will strike separate deals with transport agencies and organizations.	Phase 1/MIR	5/14	shipping; transportation
Organizational interrelationships on the Russian side were not properly defined, resulting in individual PEDs/PIs working directly with their Russian counterparts and/or special channels to deliver and process hardware.	If there is no coordinated approved process ahead of time, organizations supplying material to be transported will strike separate deals with transport agencies and organizations.	Phase 1/MIR	5/19	shipping; transportation
Sparing, Resupply, & Logistics strategy	Preposition spares to ensure mission success	John Commons ense	N/A	Spares provisioning
Sparing, Resupply, & Logistics strategy	Provide cannibalization options (component swapping due to failure or for system augmentation).	John Commons ense	N/A	Spares, swapping, provisioning
Russian spares philosophy is different from US. Russians do not use "new' spares, they reuse old, or previously failed parts (cannibalize).	Inadequate on-orbit sparing may lead to cannibalization	Phase 1/MIR	5-2	spares; maintenance
Critical or multi-use hardware items needed onboard backups. Careful analysis is required for long-duration spaceflight impacts, e.g. impacts on electronics due to Single Event Upsets (SEUs). This list of critical or multi-use items requiring spares is typically outside the standard set used for Shuttle missions.	Initial lifecycle planning for some station components and payloads was based on a Shuttle model and did not take into account longer duration in a space environment	Phase 1/MIR	5/43	spares; maintenance; analysis;
Obsolete parts	Involves balancing the alternatives of purchasing and storage of excess parts, establishing manufacturing facilities and skills or potentially facing critical shortages	NASA PLL	222	Sparing and provisioning
As for the cargo stowage areas inside the compartments: do they hinder your work?	As the station is being built, there are open areas awaiting outfitting. Because not designated as a reconfigurable stowage location they are not involved in the stowage locations.	Crew Comments	78	Staging

At L-4 weeks, we uplinked a "Transfer Big Picture" message that included an overview of the items planned for return.	Crew liked the idea of early prepack coordination so that volume may be seat a side for stowage of large items	Crew Comments	84	Staging, Flight Arrival Preparation
As the construction of the Station progresses and more and more cargo is being delivered, is unloading cargo (MPLM, Middeck, Progresses) in staging areas, to be put away at a later time, still a viable plan?	Unused system areas, in this case the airlock, will be pressed into use for permanent and temporary stowage resources.	Crew Comments	17	Staging, stowage; Transfer
The LDM crewmembers often used the Progress and the CTBs as a staging area and worked from the bags directly instead of stowing items onboard Mir.	Transfer operations require a staging area to efficiently stow materials and cargo	Phase 1/MIR	3/15	staging; stowage; transfer
A staging area for Shuttle resupply was not defined. Therefore, each crewmember had to clear space to receive all packed bags. As bags were transferred to the Shuttle, resupply bags could be brought to Mir from the Shuttle.	Transfer operations require a staging area to efficiently stow materials and cargo	Phase 1/MIR	3/19	staging; stowage; transfer
We would like to continue doing the reverse audit (you only tell us what you need) for office supplies, and start including hygiene, six weeks prior to crew rotation when Shuttle flights resume, by sending the resupply form. Do you have any suggestions?	For many consumables, the crew may perform the inventory and provide the ground with the demand.	Crew Comments	95	Storekeeping
Do you have any suggestions on how the ground can better track consumable status while limiting the impact to the crew to provide the data? Our plan is to revise usage rates and resupply at the beginning of each increment.	Improve intra-ground communications. Use all available ground logistics resources before requesting additional data from crew.	Crew Comments	26	Storekeeping, Communication
Pre-packing of hardware on orbit is accomplished as tasks are completed and is typically not presorted. As a result, many categories of equipment may be packed in the same return bag; i.e. early destow science with R+3 and R+5 hour requirements, nominal destow items, crew personal items, GFE, etc. Destow operations are a complex and manpower intensive operation and need to be well organized to preclude loss of science and potential misrouting of hardware. As a result of early destow operations the "STS-81 U.S. Hardware Destow Ground Operations Process" (JSC-27665) was developed to formalize the Mir/Shuttle destow ground operations. However, this document does not control the organizations at KSC that deliver the hardware. Upon landing, hardware still may be returned from the runway by four different organizations,	The on-orbit crew packs the return manifest; a handful of individuals will accomplish the work performed by a hundred on the ground. It is important to plan and practice returned cargo dispositioning with all interested organizations and agencies.	Phase 1/MIR	6/4	stowage, pre-pack; manifest; staging

the shuttle flight crew equipment (FCE) personnel, the KSC payloads organization, Spacehab Inc. personnel, and in some cases, by VITT team members. These organizations deliver hardware to, respectively, the FCE lab at SSPF, the O&C high bay, the SPPF facility and the crew quarters. This makes inventory control a monumental activity. Each group operates using their own paper for defining requirements, e.g. the Launch Site Disposition Plan (Shuttle), the Phase 1 Destow Plan (Phase 1), Turnover TAP's (KSC Payloads) and customer ICA's (Spacehab), which are not necessarily recognized by other parties. Use the documentation plan as a model for future ground destow operations. A list of specific recommendations are included as highlights: 1. Establish a destow and inventory team, representing the operations organization (Shuttle) and the user organizations (Phase 1, (cut and paste error - see 6-5) ISS, Spacehab). 2. Hardware would be delivered to a central location for dispositioning and inventory control. 3. The requirements would be documented in one universally recognized destow document. 4. Alternatively, require the crew to pack all early destow and nominal destow items in separate bags (requires more space and crew coordination on-orbit). 5. Exception to the above rule is that cold stowage or other fragile items should be delivered to an off-line laboratory for processing by qualified personnel and inventoried on a non-interference basis. 6. Conduct a pre-landing meeting with the destow team members to ensure that all team members understand their duties and responsibilities. 7. Conduct a pre-landing meeting with the PED representatives to ensure that they are informed of potential turnover times and understand shipping requirements. 8. Ensure adequate PED support at Edwards in the event of a contingency landing. 9. Sort the Master Destow List several ways (by PED, bag, and part number) to meet the needs of the various destow operations. 10. Prepare preprinted labels containing hardware name and part number to facilitate the photography process for the descent				

hardware.				
Designers of onboard stowage facilities for future spacecraft should consider the following: i. Individual food stowage items should be located conveniently near the crewman's place in the wardroom. Spacecraft control panel numbers and stowage location	Stowage design considerations	JSC Skylab Lessons	2-6	stowage
Volume/space management for payloads within Mir was flexible enough to maximize module usage. Velcro, tethers, brackets or other devices could attach payloads wherever usable volume was available and crew safety would not be compromised. Constraining manifests by limiting payload accommodations would have resulted in fewer experiments.	Use of velcro and tethers within habitable space can create stowage volume.	Phase 1/MIR	¾	stowage
There were no established U.S./Russian Interface Control Documents (ICDs) or agreements citing stowage locations, allocations, or available nonstructural interfaces within Mir. It was believed that we had verbal agreements establishing the use of locations in the Spektr and Priroda modules that held U.S. hardware when the modules were launched. Over time, some of these locations were filled with non-U.S. items.	Coordination between organizations and agencies must be developed to the implementation level.	Phase 1/MIR	3/18	stowage
Stowage locations were not incorporated into the procedures. Stowage changes remained very dynamic throughout the program. Crew members usually stowed items in a manner to suit their needs and operational requirements.	It is necessary for procedures to reference accurate stowage locations.	Phase 1/MIR	3/20	stowage
Stowage Locations - Mir does not have dedicated stowage locations which greatly affects operations. This results in wasted time trying to locate items.	Configurable stowage locations must be included during vehicle development	Phase 1/MIR	3/21	stowage
Russians have a different philosophy on stowage planning and pre-launch stowage timing. Stowage needs extensive planning - especially for waste and used items. Removal of these items needs planning. Be prepared for late changes. Russians don't do as much pre-flight contingency situation planning as we do.	Configurable stowage locations must be included during vehicle development	Phase 1/MIR	3/22	stowage

Any suggestions for improving communications and/or content of communications between on-orbit stowage planners and crew?	Some expedition crews wanted a more active role in stowing items. The "item location lookup" orientation of the IMS did not accommodate this. A key lesson learned is that the best stowage schema for transportation is not necessarily the best for user	Crew Comments	14	Stowage
Does the non-standard stowage have some negative impact to your operational efficiency or is there just no impact at all to the current non-standard stowage that you're dealing with?	Stowage in general purpose workspace reduces availability of the space for other purposes	Crew Comments	8	Stowage
General Crew Comment	International partner participation in stowage activities is not guaranteed. In example cited 75% - 80% of equipment and tools in IP segment were found with prolonged search and consultation with other control centers.	Crew Comments	93	Stowage
To what extent would you say your work and every day activities were impeded by stowage on walls and in corridors? Do we need to add additional time to unstow cargo for any activities?	Item retrieval times are influenced by the amount of time it takes to clear path to access stowage area.	Crew Comments	107	Stowage
Were the crew provisions packed in an efficient manner?	Crew may restow items to meet crew peculiar needs.	Crew Comments	11	Stowage
Were the crew provisions packed in an efficient manner?	Crew recommends packing like items together.	Crew Comments	24	Stowage
What label issues cost you time and why?	All stowage locations should have the same location-labeling scheme.	Crew Comments	2	Stowage
During Shuttle flights an equipment list was built, replacement for daily stowage notes. Was the change in format confusing?	Do not change format of lists without training and informing crew.	Crew Comments	37	Stowage, Communication
Please indicate the top two habitability and human factors issues you experienced with ISS	Constant stowage flux affects housekeeping and quality of life.	Crew Comments	1	Stowage, Communication
How did the pantry style stowage work?	Pantry style stowage worked well	Crew Comments	67	Stowage, Crew Provisioning, Pantry
What suggestions do you have to minimize overall stowage inefficiency? How can the ground help to facilitate stowage consolidation and minimize large numbers of partial CTBs?	Daily consumption of food generates trash that must be disposed of.	Crew Comments	101	Stowage, excess, food

How did cargo and stowage management impact your mission?	Early IMS was inaccurate and difficult to use. Crew found it easier to have a daily listing rather than access IMS.	Crew Comments	4	Stowage, IMS
General Crew Comment	Reinforces necessity for periodic audits to synch the inventory to the IMS	Crew Comments	91	Stowage, IMS
Was an overabundance of stowage an impact to your time on-orbit?	Stowage discipline is the key to efficient use of time.	Crew Comments	6	Stowage, IMS
Pre flight we worked with the transfer folks to integrate our assembly procedures more into Work prep and the Transfer List and hope to streamline the process in the future. Do you have any comments on Work Prep, the Equipment List, IMS and the Transfer	Use of equipment lists are helpful and saves crew time	Crew Comments	12	Stowage, maintenance
	Crew will rearrange supplies as expedient during a mission. What seems to be a logical stowage scheme for the ground or a crew may be meaningless to another.	Crew Comments	103	Stowage, Pantry
Stowage Commentary	What seems to be a logical stowage scheme for the ground or a crew may be meaningless to another.	Crew Comments	27	Stowage, Pantry
Stowage Commentary	The initial estimates of time need to stow items are always too low.	Crew Comments	28	Stowage, Pre-Pack
Do you have any recommendations for items that should not be included in IMS?	Crew is mainly interested in IMS use for non-system inventory purposes. If an ORU is installed they are not interested in its location; it is part of the ISS assembly.	Crew Comments	33	Stowage, Storekeeping
Do you have any recommendations for items that should or should not be tracked in IMS?	There is a sort of Laffer Curve at work regarding storekeeping tasks in the crew workload. A realistic assessment must be made as to the smallest level of detail required to be tracked to effect a responsive logistics system as opposed to the lowest level	Crew Comments	108	Stowage, Storekeeping, Provisioning, Barcode
We are considering adding an "empty/full" field in IMS and on the BCR in a future version. We know that for items such as CTBs, CWCs, food containers, etc., that you were asked this a lot. Would this have been useful for you to use?	Add provision for crew to pack items into kit and then move entire kit.	Crew Comments	87	Stowage, Stowage, transfer, packing

General Crew Comment	Use of transfer packing item numbers on return bags is sufficient information, provided that the contents are tracked somewhere else.	Crew Comments	61	Stowage, transfer
General Crew Comment	The practice of tracking arrived supplies by when they arrived can be accomplished through use of color coded labels.	Crew Comments	64	Stowage, transfer
General Crew Comment	Transfer between shuttle and ISS is performed using Cargo Transfer Bags (CTB) as a result CTBs become the standard by which cargo is judged	Crew Comments	19	Stowage, transfer
How accurate was the ground's understanding of the on-board operational constraints associated with the management of stowage/cargo? (E.g., time to load/unload, staging volume).	Stowage and transfer is an evolutionary process, the early increments did not feel that the ground had a sound concept of the principles involved	Crew Comments	5	Stowage, transfer
Consumables' tracking was not established. An attempt to track consumables and hardware life was made during Increment 7, but because this required a methodical approach from the inception of the program, the effort was inadequate.	Affirms requirement for reasonable consumables tracking	Phase 1/MIR	5/28	stowage; consumable
Need multiple locations for critical and multi-use hardware items to reduce mission risk due to potential loss of these items if a particular module becomes uninhabitable (e.g., the Spektr incident).	A dynamic stowage system is flexible to accommodate loss of stowage volume	Phase 1/MIR	3/6	stowage; IMS
Kit contents were not tracked early in the program, creating problems with knowing where to find an individual item (such as scissors) and difficulty knowing how many items were still on board as the increments progressed. Individual contents were often returned not the whole kit. Starting with Increment 5, kit contents were tracked to provide insight into current stores of kit items.	Affirms importance of creating parent/child relationships when kitting	Phase 1/MIR	5/27	stowage; IMS
There was limited tracking of hardware items below kit level on the manifest. This led to difficulties in tracking piece parts on orbit and determining which items required resupply and which kits required refurbishment. As a result, unnecessary resupply items were approved and flown.	There is a complex relationship between manifests, inventory, and stowage that, if not understood completely, can drive data to excruciating minutiae that imposes a tremendous paperwork burden.	Phase 1/MIR	5/41	stowage; IMS; manifest

Hardware nomenclature should be standardized throughout a program. On Skylab, many names existed for a single item, and this nonstandardization resulted in confusion, ambiguity, and lost time during communications among various user groups.	Nomenclature issues will consume an inordinate amount of time. Establishment of standard to use name and part number in all labels, descriptions, procedures, etc. will mitigate this issue	JSC Skylab Lessons	12-1	stowage; label
The Dimensional Installation Drawings (DIDs) and Dimensional Sketches (DSs) did not go through the JSC release system because the drawing requirements agreed to in the US/R-002 document were not consistent with JSC requirements. In addition, the Russians reviewed the drawings in an open-ended iterative cycle, and there was no efficient way to release the drawings through the JSC system after each iteration without compromising mission milestones.	Configuration management between differing organizations and agencies must be coordinated using lifecycle objectives	Phase 1/MIR	3/8	stowage; packaging; transfer
Reflown items needed DID verification against the known module or station configuration since the configuration changed over time. However, since the Russian ground team did not have detailed knowledge of station configuration at any point in time, ground assessments using DIDs and DSs were often inconclusive	Configuration management between differing organizations and agencies must be coordinated using lifecycle objectives	Phase 1/MIR	3/9	stowage; packaging; transfer
The use of a Shuttle crewmember to assist in transfer, unpacking and locating hardware was extremely helpful to the LDM crewmember and to the ground in establishing the configuration for the next increment.	Use of transport vehicle personnel to transfer equipment optimizes resource loading and training	Phase 1/MIR	5/32	stowage; transfer
Every item flown to ISS should have an electronic picture available to the flight control team. Every item flown to ISS should have an electronic picture available to the flight control team. These images should not be on the main LANS or fileservers supporting the vehicle and flight controllers, but should be on a system that a flight controller could get to. The issue here is that LAN bandwidth can be impacted if too many positions begin reviewing too many images across the LAN at the same time. Each image should be accompanied by the relevant safety data, mass property data, flights manifested on, current location, etc.	Use photographs for every item of material manifested aids locating items on orbit. There is, however, a penalty associated with photographing, cataloging, and cross referencing each object. This LL is important when working with material delivered in a foreign language.	Phase 1/MIR	5/46	stowage; transfer; inventory

Design Commonality	Commonality should exist at the Line Replaceable Unit (LRU) subassembly level across all vehicles. By using common subassemblies across the vehicle, maintenance costs can be much lower as the need to assemble a wide array of spare parts lessens. This also reduces up-mass and on-board spares volume requirements. Commonality also reduces the number of hand tools that must be maintained onboard. The smallest number of different tools should be maintained on the space vehicle - for work both IVA EVA.	John Commonsense	N/A	Subassembly design
Interchangeability of Consumables	Consideration should be given to designing vehicle subsystems to that consumable items in common with other subsystems on the overall vehicle can be interchanged (I.e., S-IVB-stage pressurization and pneumatic He). The ability to transfer the fluids between the systems should be implemented.	John Commonsense	N/A	subsystems design
Component Removal and replacement	Systems should be designed so as to permit the easy removal and replacement of components. While in-flight replacement of malfunctioned units will not normally be a consideration for short mission space vehicle, it must be considered in the case of vehicle employed in missions of long duration. Replacement units should be located internally to expedite the replacement process. The following concepts should be considered in system/component design: a. Ease of maintenance (access, safing/hazard isolation, tool interface); b. Restrict pre-maintenance hazard isolation to item being maintained; c. Repair rather than replace; d. Replace at the lowest hardware level possible; e. Assume intermediate-level	John Commonsense	N/A	System/component design

	(LRU) subassembly) maintenance will be performed.			
The only trash disposal method identified on Mir was the use of the Progress vehicles. Incomplete information was supplied on items disposed of in the Progress.	Trash disposal manifests must be created to maintain an accurate on board inventory picture.	Phase 1/MIR	5/25	transport; manifest; trash; excess; stowage
As for the cargo stowage areas inside the compartments: do they hinder your work?	As materials are moved to/from from the transport vehicle, an ad hoc staging area is developed for temporary storage.	Crew Comments	78	Transfer
Do you have any suggestions for us to make the pre-pack list and all the changes we send you easier to use? Would sending the same file back and forth and allowing the crew to insert comments and the ground to add new items be useful?	Highlight changes in packing lists	Crew Comments	9	Transfer, manifest
To what detail would you prefer on-orbit stowage planners to be involved in transfer plan locations?	Communications are necessary to coordinate pre pack and identifying staging areas	Crew Comments	15	Transfer, prepack, staging, communications
To what detail would you prefer to see cargo transfer plans identify on-orbit stowage locations: A) Leave entirely up to the crew; B) provide specific locations for all cargo items being transferred; or C) provide locations only for items with specific	Communications are necessary to coordinate pre pack and identifying staging areas	Crew Comments	90	Transfer, prepack, staging, communications
The lack of real-time U.S. support at the Russian launch site prevented verification of the as-loaded list for Russian launches.	Other agency manifest processes may not ensure as-built documentation.	Phase 1/MIR	3/3	transfer; manifest
Logistics function is transitioning smoothly to Space Flight Operations Contract (SFOC).	Processes and procedures used in transition plan are effective	NASA PLL	1011	Transition
For some missions, it may be necessary for the Orbiter to land at the Dryden Research Center. These flights will be carrying science payloads, which require special handling and laboratory processing. Hardware off loaded at DFRC will have to be inventoried and turned over to a number of different experimenters. Facilities at DFRC are inadequate to perform these functions. The Mission management/WG6/Phase 1 office destow team has one office trailer available to receive, inventory, weigh, photograph and turnover the off-loaded hardware. On occasion, we have been asked to share this trailer with shuttle-sponsored payloads. No FAX capability exists and there is no water or restroom facility. Some lab capability is available at the PRF Facility, located several	Have a transport plan in place for the backup landing sites as well as the primary.	Phase 1/MIR	6/1	transport

miles away. The PRF is an ARC-owned facility and is not normally staffed unless ARC has payloads on board, except by special request. It is our understanding that this facility may be closed in the near future.				
The STS-76 mission landed at DFRC. Processing activities were a challenge, taking twice as long as KSC operations and 76 carried only a single Hab module. Had a fully loaded double Hab Shuttle-Mir Flight landed at DFRC, the available facilities would have been overwhelmed. Use of DFRC for ISS missions should be expected. Recommendation: Some minimal facility with adequate processing and laboratory space needs to be identified or constructed at DFRC for ISS use. The potential loss of long duration science would far exceed the cost of an adequate facility.	Have a transport plan in place for the backup landing sites as well as the primary.	Phase 1/MIR		transport
MOIWG had a dedicated shipping/logistics group with trained personnel and adequate resources to assume the responsibility of processing all hardware shipments within the NASA/Mir program.	Although each NASA site has a shipping/receiving unit, it is necessary to have a program specific function accountable for program assets	Phase 1/MIR	5-3	transport; handling; shipping
Shipping/logistics personnel coordinated well with program personnel and utilized all available resources to ensure success in shipping/hand carrying items to and from JSC. Communication with JSC Transportation, the NASA Travel Office, and PEDs/Payload Investigators (PIs) was well coordinated to identify potential couriers both to and from Russia.	Although each NASA site has a shipping/receiving unit, it is necessary to have a program specific function accountable for program assets	Phase 1/MIR	5/4	transport; handling; shipping
Shipping/logistics personnel took the initiative to stay abreast of all pertinent domestic and international import/export regulations. Contractor personnel recognized the need for such training independently and identified seminars and classes that would be beneficial (i.e., Export Control seminars conducted by the Bureau of Export Administration). JSC/JB7 identified similar needs at the same time.	Transportation functions must kept abreast of organizational and international export, import and shipping regulations.	Phase 1/MIR	5/5	transport; handling; shipping
The MOIWG shipping process for inbound and outbound shipments was developed early, and in compliance with JSC JB7 Transportation Shipping plans.	Although each NASA site has a shipping/receiving unit, it is necessary to have a program specific function accountable for program assets	Phase 1/MIR	5/12	transport; handling; shipping

An Integration Liaison was established in Moscow to assist with shipments and coordinate with U.S. Embassy personnel, Russian Customs and Russian Phase I personnel. The liaison was highly effective in establishing strong working relationships which contributed to the success in processing expedited shipments.	Although each NASA site has a shipping/receiving unit, it is necessary to have a program specific function accountable for program assets. This would include liaisons with foreign entities if traffic warrants it.	Phase 1/MIR	5/13	transport; handling; shipping
Shipping processes were developed based on State Department export regulations. While understanding of these regulations by shipping personnel matured over the course of the program, information on process, time, and cost was often ignored by hardware developers and those who developed the schedules. As a result, the MOIWG did not enforce strict compliance with the shipping process, and "smuggling" activity never met with disciplinary action due to the desire to meet schedules. Other related issues include the following: - Shipping considerations and constraints were not addressed in decision-making forums. The Configuration Control Board (CCB) Change Request review process did not include review by shipping/logistics personnel to verify that program schedules could be met. - The responsibility for hardware shipment was not fiscally tied to the MOIWG. All shipping costs were covered by JSC Transportation and were transparent to the MOIWG; as a result, the MOIWG had no appreciation for the labor and difficulties involved in expediting shipments, nor was there any financial oversight to manage the shipping function and impose accountability.	Transportation functions must kept abreast of organizational and international export, import and shipping regulations.	Phase 1/MIR	5/24	transport; handling; shipping
Hardware received from other NASA centers or private institutions did not have appropriate documentation which would qualify it for flight status (i.e., JSC form DD1149, COFR). As a result, these items could not be received formally into the JSC bond system until the correct documents were provided.	Different organizations, centers, and agencies have different standards. A program centric standard that applies to all material must be developed and in place prior to the advent of operations.	Phase 1/MIR	5/21	transport; handling; shipping; qualification; certification

All returning data products need to be identified in time to be incorporated in the destow documentation. As a result of the data from different experiments being recorded on common data recording devices, a general policy was established requiring all data products be archived at JSC prior to dissemination to the various experimenters. Some data products are unique to a specific experiment and cannot be duplicated.	Return cargo is subject to the same processes as launch cargo.	Phase 1/MIR	6/2	transport; manifest
The Destow Plan should be available electronically so that personnel needing it can receive it by email - or even via download from a web page. Destow Process. O&C vs. FCE. Hardware difficult to track down.	Ensure that return cargo manifests and dispositioning instructions are disseminated.	Phase 1/MIR	6/3	transport; manifest
Trash Management	Provide for immediate disposal of trash, rather than the stockpile method.	John Commonsense	N/A	Trash Management
The Russians kept all hardware left behind on the Mir and it did not seem that they threw anything away. This created cluttered conditions in the aisles onboard Mir.	It is important to understand need for all material on orbit and maintain a disciplined approach to stowage.	Phase 1/MIR	3/17	trash; stowage; disposal
Trash Disposal	Backup disposal provisions should be provided for all trash, garbage, food residue, feces, urine, etc., which could provide hazardous environmental conditions if the operational disposal system failed.	John Commonsense	N/A	Vehicle cargo, stowage design
Soft Stowage	Soft racks should be used for stowage (e.g. ZSR). Stowage locations should be easily accessible (one-handed accessibility), and locations should have dividers that are reconfigurable.	John Commonsense	N/A	Vehicle cargo, stowage design
Soft Bags 1	Soft bags should be designed to best fit soft stowage racks and hard stowage racks (I.e. payload or system racks) on the orbital station as well as stowage locations on the transport vehicle.	John Commonsense	N/A	Vehicle cargo, stowage design
Soft Bags 2	Soft bags should be available in various sizes (e.g. 0.5, 1.0, 2.0, and 3.0 CTB's, M-01 and M-02 bags)	John Commonsense	N/A	Vehicle cargo, stowage design

Stowage Locations	Design of all stowage locations should maximize available volume (I.e. locations depth should be as close to module shell as possible).	John Commons ense	N/A	Vehicle cargo, stowage design
Panel Front Stowage	Module panels should be designed so stowage may be located on the panel fronts throughout the vehicle for extended periods of time.	John Commons ense	N/A	vehicle design
Design and Component Compatibility	Commonality should be a prime consideration for all vehicle, system, component, and software in order to minimize training requirements, to optimize maintainability, reduce development and sparing costs, and increase operational flexibility. Special attention should be made to prevent failure propagation and allowances should be made for incorporation of system optimization. This extends to units of measure from design specification through system operation.	John Commons ense	N/A	vehicle design
Design the Vehicle for Maintainability	Assume that maintenance will need to be performed on any system. Manual interfaces should be easily accessible. Components should be designed so that maintenance tasks are simple. Panels should be designed so that any components behind the panel can be easily and quickly accessed.	John Commons ense	N/A	Vehicle design
Sparing, Resupply, & Logistics strategy	As much as possible, eliminate manual intervention to perform routine reconfiguration tasks. Provide additional level of FDIR software that performs 'BIT' functions for integrated systems and vehicles.	John Commons ense	N/A	vehicle design, reconfiguration
Transfer	Crew, passenger, and cargo transfer should normally be an intravehicular (IV) transfer operation. Design of the crew cabin must provide for efficient transfer and stowage of cargo	John Commons ense	N/A	Vehicle design, transfer operations, crew cabin design

On-orbit COTS	Usage of COTS products for on-orbit vehicles should be carefully weighed against the costs and risks of certifying and operating such products in a space environment.	John Commonsense	N/A	Vehicle hardware, components
During testing a 'banana plug' test connector contacted a ground strap, the subsequent arc tripped the circuit breaker	Existing stock of plugs in inventory were modified and impose requirements on new procurements	NASA PLL	985	Warehouse
The control of non-JSC tagged flight hardware through JSC bond pre and post flight was not well defined or understood. Numerous times flight hardware was delayed shipping to KSC/SPPF due to no records of certification even though the hardware was reflown hardware. Also, problems returning flight hardware once the Principal Investigator (PI) had completed data download was difficult requiring a new form 1149. ISS should have a process setup and separate bond room for ISS hardware that is shipped and controlled at JSC.	A program wide logistics plan and process must include center-centric processes	Phase 1/MIR	5/39	warehouse; transport
Hardware shipped from other centers to JSC was difficult to get into JSC Bond. Also, JSC quality rules changed for the paperwork requirements.	A program wide logistics plan and process must include center-centric processes	Phase 1/MIR	5/42	warehouse; transport
Flight articles need to have a designated bonded storage facility unique to program requirements to maintain configuration and quality control.	Strict access and configuration control is a must for equipment in storage and transit	Phase 1/MIR	5/38	warehouse; transport
Agreements with the Russians were made early to provide storage space at NITS, GCTC, and TsUP which would adequately accommodate the volume of hardware needed throughout the program. The storage space was not 'bonded' in a manner consistent with NASA centers. The rooms were secured only by a key which was kept by the building custodian. No safe, controlled storage facility for U.S. hardware was provided in Moscow, with the exception of Gagarin Cosmonaut Training Center (GCTC). Conditions at NITS were often detrimental to the hardware, and the volume of activity occurring at NITS with non-U.S. personnel made security a problem.	Warehousing and environmental requirements must be established prior to transportation	Phase 1/MIR	5/7	warehouse; transportation; packaging
Electronic Daily Products	Use of a integrated daily electronic product enhances accessibility	John Commonsense	N/A	

Sparing, Resupply, & Logistics strategy	The sparing, resupply, and logistics strategy should include development of quantitative dormant reliability parameters (probability that given component will operate as designed after a specified period of being inactive).	John Commons ense	N/A	
Sparing, Resupply, & Logistics strategy	Consider on-orbit fabrication of structural and mechanical replacement parts	John Commons ense	N/A	
Inventory Management	Long duration vehicles require capability to manage stowage and inventory including system configuration and compatibility (for swapping), and maps units to interior parts (for cannibalization). The capability should not require significant effort.	John Commons ense	N/A	
Tool Design	The smallest number of different tools should be maintained on the space vehicle - for work both IVA and EVA.	John Commons ense	N/A	
Tool Design #2	All tools should be certified for both IVA and EVA use so duplicate tool sets are not required.	John Commons ense	N/A	
Fastener Design	Establish common sizes of fasteners for components.	John Commons ense	N/A	
Tool Design #3	Develop no-tools-required replaceable components and access panels (especially for routine preventive maintenance).	John Commons ense	N/A	
Tool Design #4	Do not combine English and SI units (require the use of SI "metrics" sizes). Additionally, a tool set should minimize number of tools requiring calibration.	John Commons ense	N/A	
Battery optimization	Common usage batteries (for hand-held type devices) should be of a common type/design to maximize interchangeability. While not optimizing a battery to a particular application may reduce capability, providing a common set of batteries would reduce the amount of logistics and spares required while	John Commons ense	N/A	

	increasing operational flexibility.			
	Handhold attach points should e provided for handling large vehicle components. Also connections should be provided to permit breaking down large items to transportable size.	John Commons ense	N/A	

Appendix B: Survey Questions

1. To what degree have you observed the following in your work? To what degree would you recommend or agree with the use of the following?

Please select an option from each of the categories.

		Observed	**Recommend**
a.	Design specification for stowage	- Never - Rarely - Somewhat - Frequently - Often - N/A	- Unnecessary - Somewhat Unnecessary - Neutral - Recommended - Strongly Recommended - N/A
b.	The use of reconfigurable stowage		
c.	The use of pantry stowage (i.e. re-supply the pantry, not the individual items) for high turnover, small items		
d.	A naming and numbering system for stowage volumes		
e.	The consideration of cargo transfer operations when designing or configuring entryways or docking compartments		
f.	The use of an automatic inventory tracking system		

2. To what degree have you observed the following problems, resulting from or relating to stowage difficulties?

		- Never - Rarely - Somewhat - Frequently - Often - N/A
a.	Increased time demand for crew	
b.	Increased requirement for re-supply	
c.	Loss of access to operational space	
d.	Limits to housekeeping	

3. To what degree have you observed the following in your work? To what degree would you recommend or agree with the use of the following?

Please select an option from each of the categories.

		Observed	**Recommend**
a.	An inventory system common to multiple organizations	- Never - Rarely - Somewhat - Frequently - Often - N/A	- Unnecessary - Somewhat Unnecessary - Neutral - Recommended - Strongly Recommended - N/A
b.	An inventory system based on a common logistics system		
c.	Configuration management using an inventory system that is common to multiple organizations and is based on a common logistics system		

d. Packing lists and manifests used as manual accounting systems
e. Systems that update the movement and location of both parents and children in inventory with parent-child relationships
f. Inventory system that employs multi-level classifications of supply
g. Supplies with excessive inventory levels

4. To what degree have you observed the following in your work? To what degree would you recommend or agree with the use of the following?

Please select an option from each of the categories.

	Observed						**Recommend**					
	- Never	- Rarely	- Somewhat	- Frequently	- Often	- N/A	- Unnecessary	- Somewhat	Unnecessary	- Neutral	- Recommended	- Strongly Recommended	- N/A
a. The use of commonality in vehicles, systems, or software													
b. Minimized training requirements resulting from commonality													
c. Optimized maintainability resulting from commonality													
d. Reduction of development and sparing costs resulting from commonality													
e. Increase operational flexibility resulting from commonality													

5. To what degree have you observed the following in your work? To what degree would you recommend or agree with the use of the following?

Please select an option from each of the categories.

	Observed						**Recommend**					
	- Never	- Rarely	- Somewhat	- Frequently	- Often	- N/A	- Unnecessary	- Somewhat	Unnecessary	- Neutral	- Recommended	- Strongly Recommended	- N/A
a. When designing for maintenance, the following are taken into consideration:													
i. tools													
ii. time													
iii. packaging													
iv. stowage													
v. lifecycle cost													
b. Maintenance or repair system with multiple levels (ex. Operational-Intermediate-Depot)													

c. Repair systems with scheduled corrective or preventative maintenance

6. To what degree have you observed the following in your work? To what degree would you recommend or agree with the use of the following?

Please select an option from each of the categories.

	Observed	**Recommend**
a. The design of return logistics with respect to:	- Never - Rarely - Somewhat - Frequently - Often - N/A	- Unnecessary - Somewhat Unnecessary - Neutral - Recommended - Strongly Recommended - N/A
i. packaging requirements		
ii. pressurization		
iii. repairability/stowability		
iv. hazardous materials		
b. Retention and storage of all waste		
c. Off board discharge of waster		
d. Classification of waste as retained or discharged		

7. When designing or choosing transport modes for supplies, which of the following are taken into consideration, and rate their importance.

	- None/Not considered - Little Importance - Somewhat Important - Very Important - Essential
a. Cost of various modes	
b. Time	
c. Quantity that can be carried	
d. Materials/resources available	

8. Rate the level of importance of each of the following.

	- None/Not considered - Little Importance - Somewhat Important - Very Important - Essential
a. Design for stowage considerations	
b. Design of an inventory system	
c. Use of commonality in systems	
d. Design for maintenance considerations	
e. Planned use of standards in system development	
f. Design for return logistics	

8A. Rate the same characteristics according to their relative importance using a scale from 1-6, 1 being the most important and 6 being the least important.

__ Design for stowage considerations
__ Design of an inventory system
__ Use of commonality in systems

___ Design for maintenance considerations
___ Planned use of standards in system development
___ Design for return logistics

9. Are there more important logistics considerations that are problematic? If so, please explain briefly.

10. In response to prior experiences or lessons learned in your organization, in which of the following areas were logistics considerations taken into account?

___ Design for stowage considerations
___ Implementation of a common inventory system
___ Use of commonality in systems
___ Design for maintenance considerations
___ Planned use of standards in system development
___ Design for return logistics
___ Consideration of transport modes
___ Other: _____
___ None

Appendix C: Survey Participants

Name	Organization	Position
Andre Goforth	NASA	Engineering
Benjamin S. Blanchard	Virginia Tech	Engineering
Bryan Austin	Boeing	Flight Operations
Charles Murphy	United Space Alliance	Logistics
Dave Garten	Honeywell Defense & Space	Engineering
Dennis Martinez	Boeing	Logistics
Donald Blick	Raytheon	Other
Elizabeth Pierotti	Honeywell-D&S Glendale	Logistics
Frank Camm	RAND	Other
James Visentine	Boeing ISS Logistics Support	Engineering
Jim Weisheit	BAE Systems	Program Management
Joe Parrish	Payload Systems Inc.	Program Executive
John Bull	Lockheed Martine Space Systems Company	Engineering
John Lauger	Boeing	Logistics
Kevin Wolf	Boeing	Logistics
Linda Patterson	Mission Ops-ISS Mechanics and Maintenance	Flight Operations
Martin J. Steele	Systems Engineering and Integration	Engineering
Michael Galluzzi	MK-SIO SSP	Program Management
Michael Ross	SMC/ISGL	Logistics
Olivier de Weck	MIT	Engineering
Richard Hicks	Orbital Sciences Corp.	Project Management
Robert Shishko	JPL	Engineering
Susan Voss	NASA JSC OC	Program Management
Sarah James	SOLE	Logistics
Sarah Shull	MIT/JSC	Logistics
Sean M. Van Andel	Boeing ISS Product Support	Engineering
Anthony Butina	NASA	Logistics
Terrence B. Johnson	Missile Defense Agency System Engineering Team	Logistics
Todd Hellner	NASA-ISS Program Office	Program Management
Tovey Bachman	LMI Government Consulting	Logistics
Ursula Stockdale	United Space Alliance	Flight Operations
Walter Tomczykowski	ARINC	Program Management
William A. Evans	Flight Operations	Logistics
William Robbins	NASA	Logistics
Anonymous	---	---

Appendix D: Additional Survey Results

Responses to additional survey questions are included below. Figure 17 shows that the transportation question regarding importance of various design considerations was inconclusive, since it showed little variation in the importance of considerations. Similarly, regarding possible problems arising from stowage difficulties, increased time demand for crew ranks number one, though there is little difference between the four options (Figure 18).

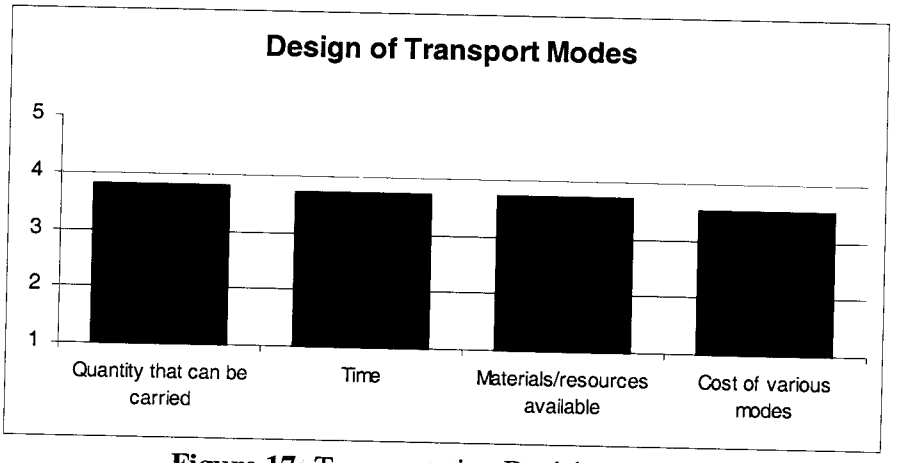


Figure 17: Transportation Decision Criteria

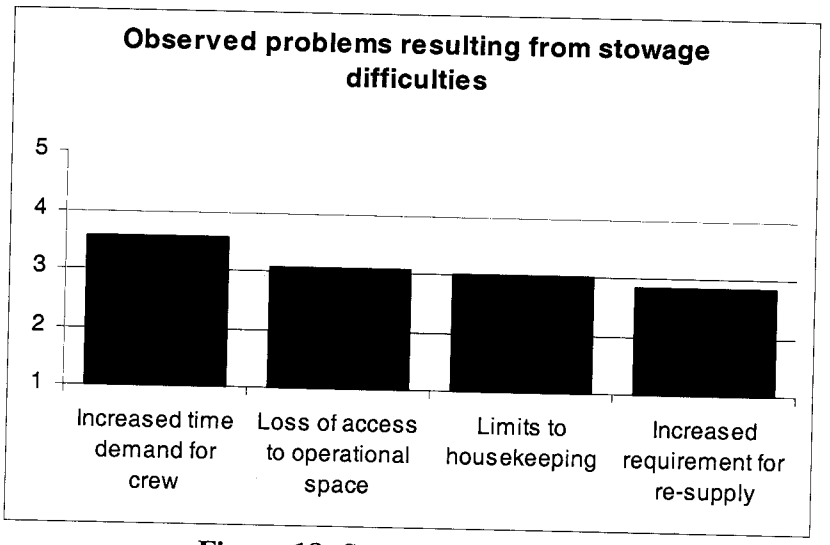


Figure 18: Stowage Observations

For the rest of the survey questions, participants ranked both their level of observation and recommendation of the various considerations. Where there is a large difference between *observed* and *recommend*, there may be opportunities for technology development or standardization to address the individual areas. This divergence also points to a need identified by the respondent where there may or may not be current mitigation to resolve the problem.

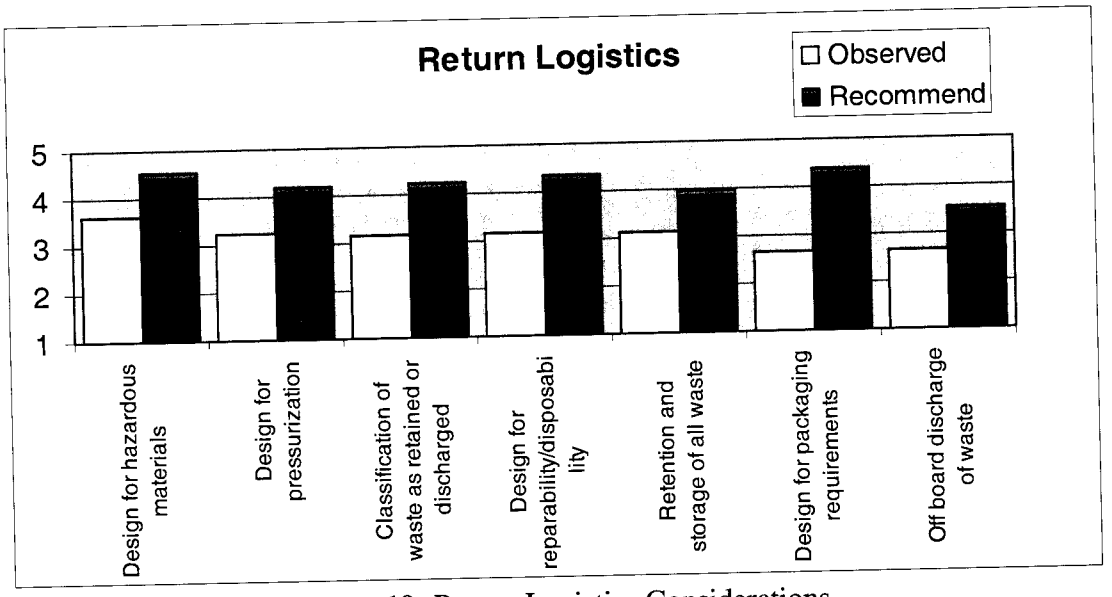


Figure 19: Return Logistics Considerations

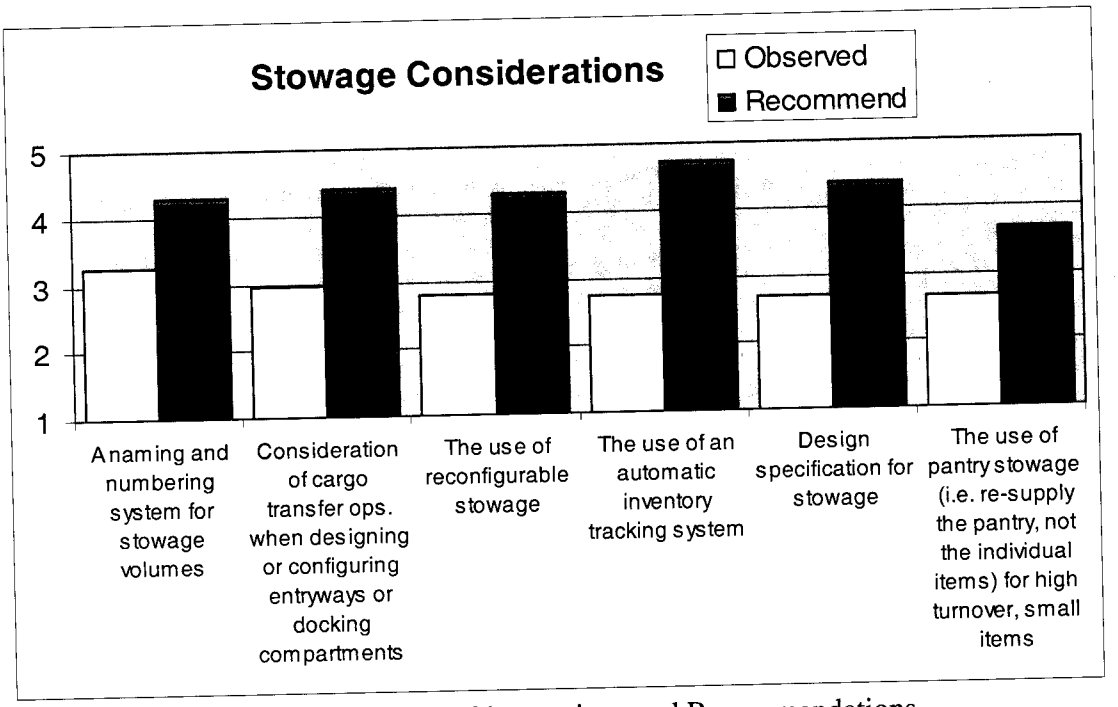


Figure 20: Stowage Observations and Recommendations

While Figures 19 and 20 do show evident differences between *observe* and *recommend*, these differences were found to be less significant that in other logistics areas, specifically commonality, inventory management, and maintenance. However, return logistics and stowage considerations are still prime candidates for future consideration when designing for logistics. Additionally, these charts present the opportunity to narrow the focus from *stowage* (Figure 20)

to specific aspects of stowage of high importance, including *design specification for stowage* and the *use of an automatic inventory tracking system.* The survey results showing gaps between observed and recommended practices can be constructively used to identify specific issues in logistics where further measures can be taken.

Appendix E: Resources for Lessons Learned

Resource	Location	Search term(s)	Methodology	Date Complete	Product Developed
NASA Public Lessons Learned Database	http://llis.nasa.gov/llis/plls/index.html Publis Access http://www.nasa.gov/offices/oce/llis/home/new	Logistics	Using search terms 132 records were recovered. Relevant information cut and pasted into product file. Review interpreted information and produced summary	13 Jul 05	NASA PLL.xls
NASA Internal Lessons Learned Database	http://llis.nasa.gov/llis/llis/llis.html (Restricted Access)	Logistics	Spot checking of recovered records using search indicates same results as Public Lessons Learned database.	06 Jul 05	None
Crew Comments	http://mod.jsc.nasa.gov/dt/HTML/ECWGWeb/postflight/uspostflight.html (Restricted Access)	Logistics; packing; provisioning; IMS; Maintenance; stowage	IMT, MIOCB lessons learned and Crew Provisioning, Extra Vehicular Activity, Flight Crew Equipment/Food/Trash/Crew Provisioning/Habitation, Inventory Stowage Officer/Inventory Management System, Logistics and Maintenance, Prepack, and Stowage debriefs for 11 increments were reviewed and 108 comments extracted. Comments were sanitized and results interpreted as they apply to project.	14-Jul-05	Crew Lesson Learned.doc
JSC Lessons Learned	http://iss-www.jsc.nasa.gov/ss/issapt/lldb (Restricted Access)	Logistics	Using search term logistics, one record recovered. Same as PLL1205.	07 Jul 05	JSC #1
MSFC Skylab Lessons Learned	http://klabs.org/history/ntrs_docs/manned/space_stations/nasa_tm_x-64860_msfc_skylab_lessons.pdf (Public Access)	N/A	PDF file reviewed for logistics applicability. Relevant paragraphs cut and pasted into product file and keywords added. NASA Technical Memorandum X-64860	20 Jul 05	Skylab lessons learned.xls
JSC Skylab Lessons Learned	http://klabs.org/history/ntrs_docs/manned/space_stations/jsc-09096_jsc_skylab_lessons.pdf	N/A	PDF file reviewed for logistics applicability. Reviewed document and relevant paragraphs cut and pasted into product file and keywords added. NASA Technical Memorandum X-72920	20 Jul 05	JSC-Skylab.xls
FPPD Lessons Learned	http://eo1.gsfc.nasa.gov/miscPages/fppd-ll-database.html (Public Access)	N/A	Non searchable database containing 31 records, with last entry being 2001. Review of record titles does not identify any logistics applicable entries	20 Jul 05	None
EVA Lessons Learned	http://evaweb.jsc.nasa.gov/ccb/LessonsLearned (Restricted Access)	logistics	Search terms generated no hits. Reviewed each record for applicability and placed results in product	26 Jul 05	EVA Lessons Learned.xls

Resource	Location	Search term(s)	Methodology	Date Complete	Product Developed
Human Space Systems Operational Design Criteria Manual	http://mod.jsc.nasa.gov/Da8/exploration_vision/JOHN%20COMMONSENSE_JSC%2007268A%		Commonly referred to as 'John Commonsense' document (JSC 07268A). Review document for space logistics applicable passages	28-Jul-05	JohnCommonsense2.xls
Phase 1 Lesson Learned	http://iss-www.jsc.nasa.gov/ss/issapt/lldb/lldb_data/phase1lessons.doc	logistics	Each record reviewed for applicability and relevant items copied into product file and project applicability added	2-Aug-05	P1/MIR LL Extract.xls



Lunar Reconnaissance Orbiter: Lessons Learned

Presented by:
Rachel Rivera
Charles Lorentson
Marcello Rodriguez

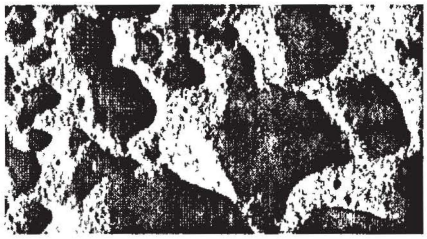
Contamination and Coatings Team

- Charles Lorentson/Lead CCE/GSFC
- Rachel Rivera/CCE/GSFC
- Joe Hammerbacher/I&T Lead/SGT
- Glenn Rosecrans/Analyst/SGT
- Leon Bailey/CC Technician/Analex
- Patsy Dickens/CCE/SGT
- Alfred Wong/CCE/SGT
- Karrie Houston/CCE/GSFC
- Scott Freese/CCE/SGT
- Craig Jones/CCE/SGT
- Wanda Peters/Coatings Lead/GSFC
- Marcello Rodriguez /CCE / Coatings/Purge
- Grace Miller/Coatings/SGT
- John Petro/Coatings/SGT

TO The Moon…



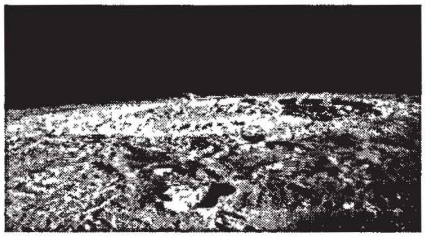
*Earth Rise, December 1968



LROC NAC Lunar North Pole July 2009

http //lroc.sese asu edu/news/?archives/71-Scanning-towards-the-north-pole html

NASA Mission:
"…to extend life to there,
To find life beyond"



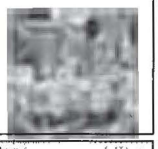
*Copernicus from Lunar Orbiter 2, November 1966, 45 km altitude

*Pictures from D Everett Systems presentation 11/08

LRO Instruments

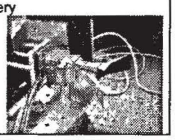
LOLA: Lunar Orbiter Laser Altimeter
- Topography
- Slopes
- Roughness

Full Orbit
Autonomous



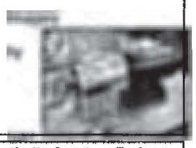
LROC/WAC: Wide-Angle Camera
- Global Imagery
- Lighting
- Resources

Day Side
Autonomous



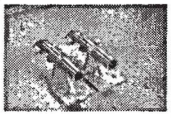
LROC/NACs: Narrow-Angle Cameras
- Targeted
- Hazards
- Topograp

Day Side
Timeline Dr



LR: Laser Ranging
- Topography
- Gravity

GSFC LOS
Autonomous



DLRE: Diviner Lunar Radiometer Exp.
- Temperature
- Lighting
- Hazards
- Resources

Full Orbit
Autonomous



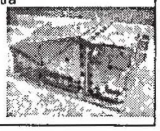
Mini-RF: Synthetic Aperture Radar
- Tech Demonstration
- Resources
- Topography

Polar Regions
Timeline Driven



CRaTER: Cosmic Ray Telescope…
- Radiation Spectra
- Tissue Effects

Full Orbit
Autonomous



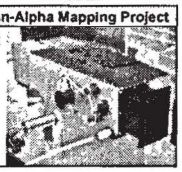
LEND: Lunar Explr. Neutron Detector
- Neutron Albedo
- Hydrogen Maps

Full Orbit
Autonomous



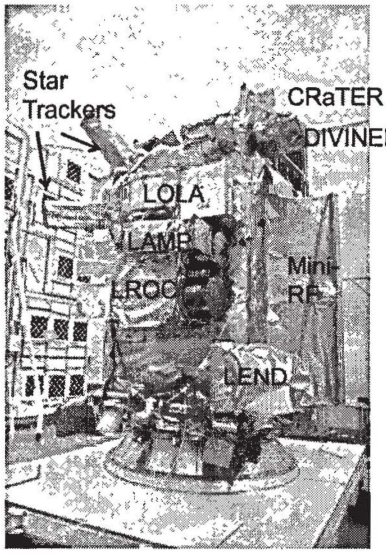
LAMP: Lyman-Alpha Mapping Project
- Water-Frost
- PSR Maps

Night Side
Autonomous



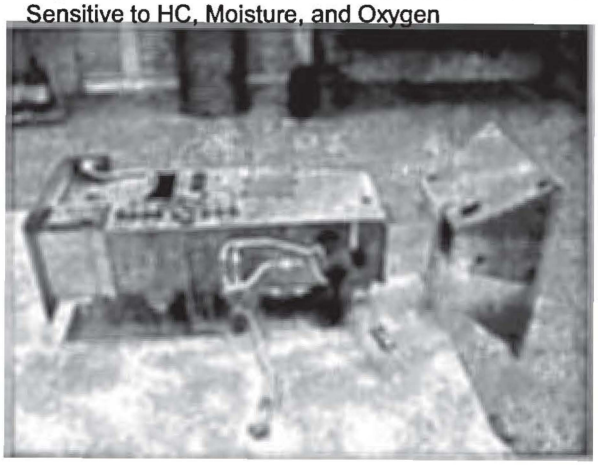
LRO Orbiter





LAMP Requirements

Lyman-Alpha Instrument with most contamination critical requirements: Internal Surface Cleanliness 400 A/20
Sensitive to HC, Moisture, and Oxygen

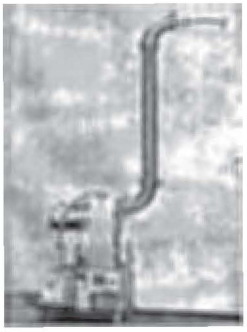


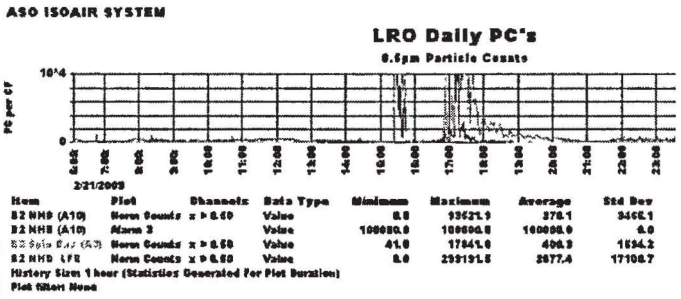
•LAMP internal molecular requirements were exceeded upon delivery to GSFC. NVR swab yielded Level C.
•LAMP chose to not re-clean their instrument and take the risk because internal witness plates performed at expected levels.
LL: Ensure risks are discussed and agreed upon with other teams prior to Integration

LAMP Vacuum Pump

Vacuum Ion Pump: "cleanroom approved" leaked small particles within cleanroom. PC picked up 300k 0.5um particles. Exceeding 10k room levels. Analysis indicated aerosolized oil (fluid loss).
Action taken was to run vacuum line and exhaust outside of cleanroom.

LL: Molecular contamination can show up as particulate. Plan ahead to remove pumps and exhaust from cleanrooms.





LAMP MGSE

Star Tracker Requirements

LRO External Cleanliness Level Requirements for Sub-systems upon delivery to I&T was 450 A/2.

- Star Trackers failed NVR Levels twice at Level C, B.
- Star Trackers were wrapped in pink polyester
- NVR FTIR data showed polyesters consistent with pink poly
- Star Trackers failed NVR levels for both LRO and SDO projects.
- Final cleaning and inspections eradicated NVR level failures.

LL: Even though pink poly has been on a "do not use" list, vendors are still using it.

Silicones, Silicones, Silicones

Nusil Controlled Volatility (CV) 2946: Silicone Bonding Agent
Contact Transfer was the main issue. NVR foils in curing tests showed no silicones
Application **Mitigation Techniques** on Flight H/W:

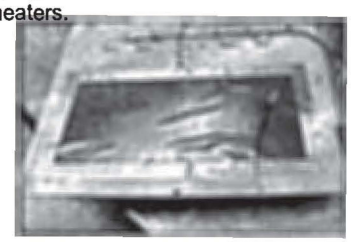
- Disposable Garments
- Glove Change-out
- Restricted Activity
- Separate trash cans used/bags removed from cleanroom
- CC person present

Testing post cure showed no contact transfer

Tayco Heaters:
Acrylic adhesive but Pressure Sensitive Adhesive (PSA) slip agents contained silicones
Cleaning would not remove silicones. Too late to change heaters.
Application **Mitigation Techniques:**

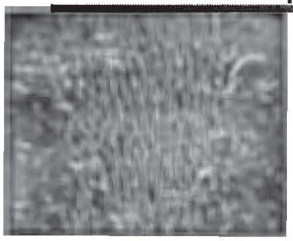
- Clean front side with Hexane
- Use tweezers
- Change-out gloves

Kapton Tape:
Analex screens tape for silicones
Check labels for Analex testing
Green Flashbreaker Tape: Acrylic Adhesive
TML 1.02 CVCM 0.25
Difficult to remove and not flight approved



Tayco produced Kapton Heaters

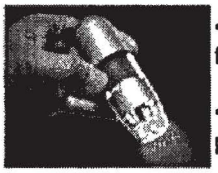
Solar Array Gimbal Radiator Micro-Cracking



Ag/FEP micro-cracks (~10x mag.)



IFM

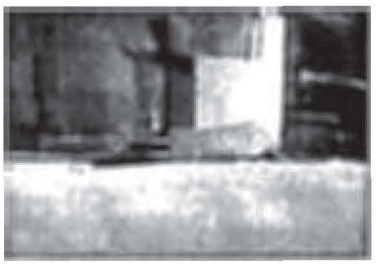


Dino-Lite

- Thermal coating Silver Teflon (Ag/FEP) micro-cracks affect thermal alpha properties as adhesive bleeds through the cracks; UV light photo-polymerizes and blackens the adhesive.
- Micro-cracks found on substrate are typical for bended applications.
- Infinity Microscope (IFM) analyses found little micro-cracks.
- Affect of UV radiation on thermal properties was ascertained on a sample.

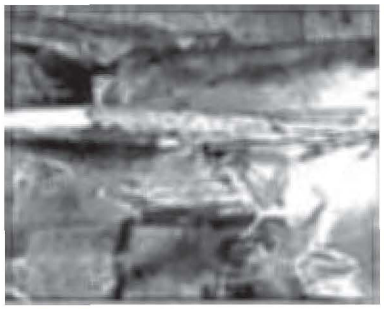
LL: Beneficial uses of IFM and Dino-Lite in the field to check for microscopic damage.

LOLA Radiator NS43C



LOLA's NS43C coated Radiator had damaged coating on outer edges
Thermal ascertained a touch-up was aesthetically needed and not performance driven.

- The touch-up job performed at ASO on the Orbiter caused continuous flaking noted on the surrounding MLI.
- Initial cleaning of the coating did not eliminate the flaking. Continued cleaning kept pulling coating. Cleaned to original coating levels.
- LL: No last minute aesthetic touch ups; Potential contamination risk from particle generation/flaking.

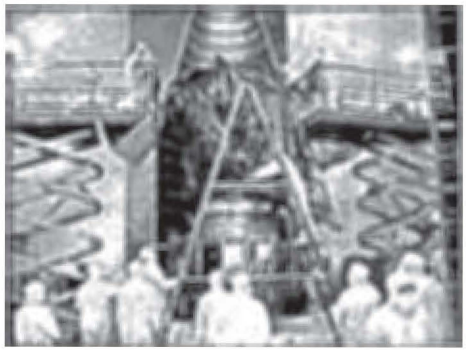


LRO Bagging Lessons

- Contamination concerns required bagging the spacecraft for I&T testing
- Access to the lift points became a significant concern
  - Lift points were well within bagged volume
  - Necessitated cutting large holes in bag for lifting operations
    - Sometimes jeopardizing the mechanical integrity of the bag
  - LL: Consider bagging needs when designing lift points on contamination sensitive payloads
- Bagging during installation into the GSFC SES thermal vacuum chamber was required
  - SDO experience showed significant buildup of particles on their bag
  - Use of a thermal vacuum fixture surrounding the observatory made bag removal a challenge. Less than 1 ft clearance in some areas
  - Bag design provided by Joe Hammerbacher was removed with no issues
    - Bag incorporated modular pieces that could be removed separately
    - Bag removal incorporated the use of parachute cords to gain access

LRO Bagging Lessons - ASO

- Bag removal prior to encapsulation was performed in the middle of the night to limit the exposure of the observatory to contaminants
  - Removal of the bag was again challenging due to the stack of two payloads
  - Access was very limited due to risk of contact with either payload or the stand on which the fairing would be placed
- Scheme was designed again using parachute cord to lift the bag vertically off the spacecraft
- There were many meetings to address concerns about removing the bag with the limitations
- Bag removal occurred with minimal difficulties in less than 1 hour



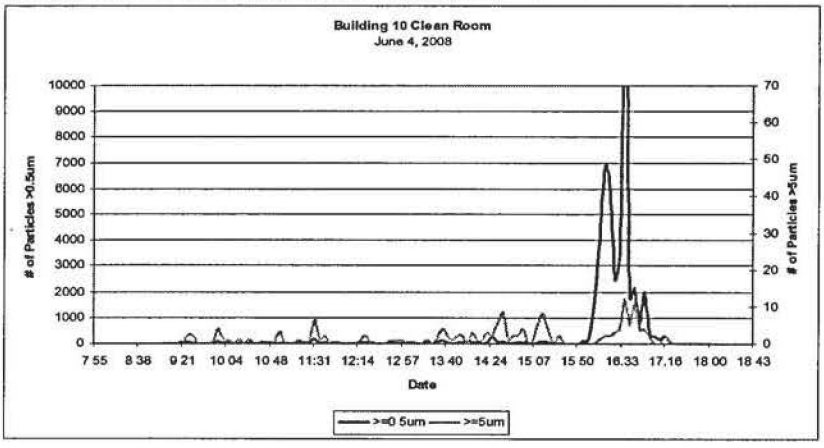
White House Cleanroom

- With space limited at GSFC, LRO was to be housed in brand new 100k facility known as the "white house"
  - LRO cleanroom requirement was class 10K cleanroom
- A class10k Laminar Flow Enclosure (LFE) was designed to house LRO in order to meet cleanliness requirements within available facilities
  - *LFE is a laminar flow tent with no roof, HEPA/ULPA – carbon filtration(supply and return), with sufficient air flow to meet class 10k cleanliness levels*
  - A similar LFE was successfully used by STEREO at ASO
  - The LFE provided significantly cleaner air cleanliness than the facility itself
  - The STEREO LFE was again used when LRO was transported to ASO
- The time frame for LFE design, fabrication and installation was less than three months
- LL: The small room used as a garment change room for the "white house" became an issue during LRO processing
  - Small size limited personnel entry rates, cause delays on entry
  - Small size created contamination risks due to lack of space for necessary garmenting and waste removal

LFE Lesson Learned

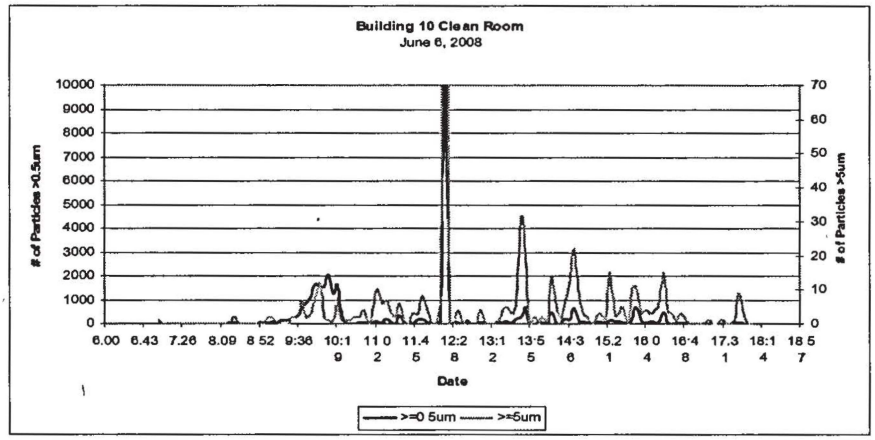
- LL: The use of the LFE provided a safe contamination environment for the LRO I&T program where no other facility was available and at significantly less time and cost than a new facility
- LL: The motors used in this LFE to drive the fans were very loud however, and exceeded OSHA decibel exposure limits.
  - The fan speeds were reduced to meet OSHA sound limits with minimal air flow impact. Laminar flow was maintained
  - Despite the reduction, crane operations required the fans to be shut off due to the noise impact on lift safety
- LL: The tent modular design allowed flexibility in tent entry, however, entrance into the tent for large items such as LRO still required removing the return wall
  - Removal of the wall required power to be cut off to the return wall
  - Power supply design required shutting down the supply wall as well if the return wall power was disabled
- LL: The independent power for the LFE enabled the tent to continue to operate even if the White House facility failed
  - The LFE does not have an independent HVAC system, so humidity and temperature control is lost with failure of the room HVAC system
  - LRO temperature and humidity limits were occasionally exceeded in LFE

LFE Particle Data During Power Off



- Fans shut down from 16:02-17:22. Return wall was opened and ARONSON table brought into the room. 0.5µ counts rose to 13,703 (10K limit is 10,000 0.5µ particles.) *(Used from Joe Hammerbacher - SGT)*

LFE Particle Data During Power Off

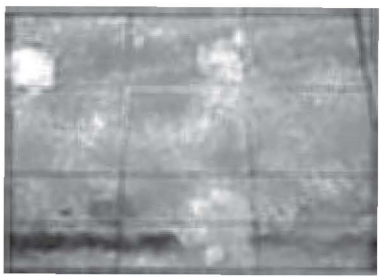


•Fans were shut down around 11:50-12:20. The LRO spacecraft was rotated on the ARONSON table. 0.5µ particle counts rose to 10,659 *(Used from Joe Hammerbacher - SGT)*

OSR Contamination

•A blue cloth material provided by the vendor was required to protect the OSRs from scratches
•This cloth turned out to be a significant contamination source
•Particulate: Cut edges created significant particles and fibers
  •Folding and "hemming" the edges reduced particulate contamination but did not eliminate these fibers
•Molecular: Testing of the cloth revealed methyl silicone contamination in an IPA rinse (release agent used on the threads of the cloth?)

•After final cleaning of the OSRs at ASO, spotting and smearing on the OSRs was noted
  •Gentle swab cleaning of each individual OSR was necessary to remove visible contamination
•LL: Less contaminating alternative methods/materials should be used to protect OSRs
  •Material standoffs, hard covers, other materials should be considered



Fairing Clean Tents

- The LRO observatory was transported to the launch pad already encapsulated per normal Atlas procedures
- At the launch complex, the payload area of the Vertical Integration Facility (VIF) is not a cleanroom
- Access into the fairing was required by ULA and the LCROSS project from both the mission unique doors as well as the boatail doors.
  - Full garmenting was required for this access
  - Exposure of cleanroom garments to the "unclean" area was not acceptable
- Two mission unique door tents and four boatail door tents were designed and fabricated
  - The mission unique tents included a separate garmenting area, the bowtail tents did not
  - The requirements for all tents was class 100K, however the goal for the mission unique tents was a 10K environment
  - All tents were operated well below the class 10K goal as measured by particle counter data monitored during activity within the tents

Fairing Clean Tents

- LL: The operation of these tents exceeded expectations and enabled the protection of the contamination sensitivities required by LRO
  - Future use of this design is recommended where contamination sensitivity is required
  - These tents exceeded all expectations on cleanliness operations
  - Provision for clean room garment use for these tents should be clearly worked out prior to operations



Boatail Door Clean Tent

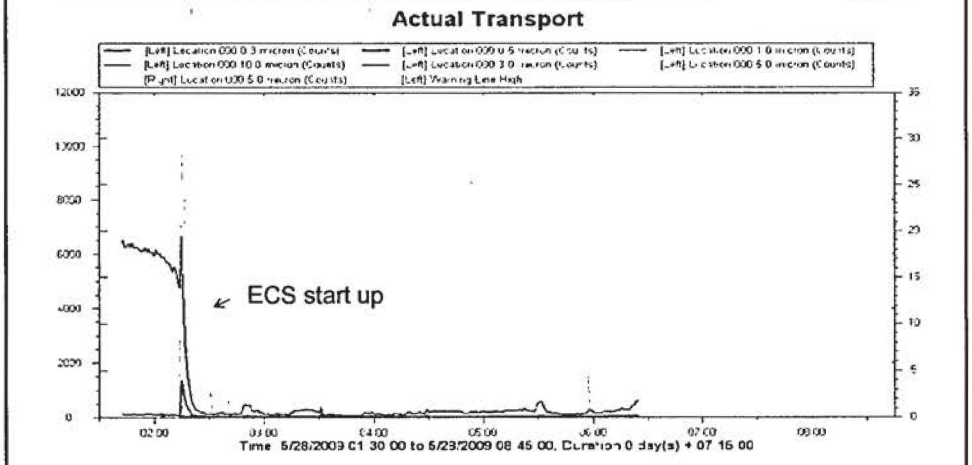
LRO Fairing Transport from ASO to VIF

- Particle counts were taken within the actual fairing and not just at the air supply
  - •Believe this is the first data of this type for this fairing
- •Wireless capability provided real time monitoring and saving of the data
  - •RF activity was approved for use by ULA , KSC and GSFC safety
- • Battery change out was required on a 4 hour basis
  - • Safety also approved use of battery system on transporter
  - •Transport stop points provided battery change points (5 minutes to change)
- • Counts show clean air after ECS system settled

Particle Counter Lighthouse's SOLAIR 3100+ used to monitor fairing air during transport



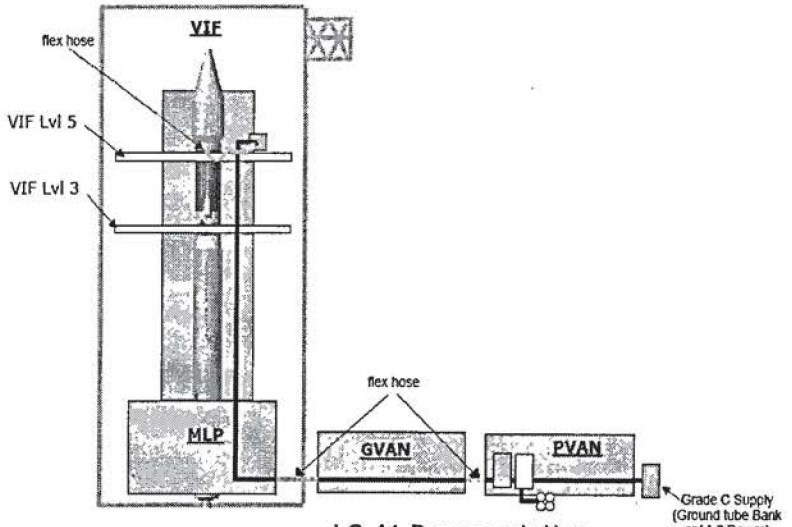
LRO Fairing Transport from ASO to VIF



- •Counts show fairing interior met cleanliness requirements after ECS system settled
- •New RF capability provided this information/analysis prior to fairing hoist into VIF
- •Fairing environment meets cleanliness, caution should be used on ECS startup

Other Lessons

- ULA reluctant to accept IEST particle counting for Level 450 Cleanliness Requirements
  - Cleanliness in the fairing verified by 450 PAC equivalent
  - Cleanliness easily met LRO requirements
- Instrument teams familiarity with cleanliness requirements and procedures was sometimes more limited than indicated
  - More assistance was required than originally anticipated
- Creation of a Purge Engineer position within the contamination group for this project was a dramatic benefit
  - Timely access to someone familiar with, and able to make changes to the LRO purge system
  - Greater understanding of the needs both of the purge system and the spacecraft
  - Greater flexibility in purge system tweaking and alteration to meet changing needs, particularly at the launch site



LC-41 Representation
Note: Drawing NTS

Launch Site Purge Problems

- Gas sampling from the tube bank passed, but sampling downstream at the PLF (Payload Fairing) failed
  - H_2O levels were not meeting instrument specification
- Purge suitcase located in the PVAN (van allocated for S/C GSE)
  - Upstream of 300+ft of Stainless Steel tubing
  - SS flex hoses braided over PTFE teflon lines used at several locations along the 300+ft
    - 50-75ft worth of flex hose
    - Permeability of PTFE was seen as the likely cause for high moisture content
- LRO/CC considered the installation of an additional Aeronex purifier on the Atlas MLP (Moveable Launch Platform) Mast the best way forward
  - To be installed in-line downstream of the ULA particle 5µm filter ~300ft downstream of the PVAN
  - The closest location you can get to the PLF interface

Aeronex Purifier

- Entregris Aeronex purifier CE-100KF-I-4R used to purify GN_2 gas to 99.999999% purity
  - Removes O_2, H_2, CO, CO_2, and H_2O to sub ppb (part-per-billion)
- Selected for its oxygen removal capability
  - Oxidation sensitivity to mirror coatings inside the LAMP instrument
  - Part of the 'Inert' gas series which uses a nickel oxide catalyst which reacts to remove the oxygen and other contaminates
- Previously used on New Horizons for the ALICE instrument
  - ALICE is heritage Lyman-Alpha UV instrument for LAMP

Purifier Installation Obstacles

- Short turn around time on flight configuration request
  - Large amounts of paper work and trails for such a change
- "Spontaneously combustible" label identified on the purifier raised concerns and resistance
  - Passive purifier not identified on the MSPSP
  - Several ERBs (Engineering Review Boards) were conducted to justify its implementation and address any potential safety concerns
  - Study by manufacturer showed any hazards to be limited to flowing incorrect gas through the purifier
    - In the extreme scenario where air was flowed through an 'inert' purifier at a maximum rated flow rate showed an very high heat up of the cartridge but no combustion occurred *(Exposure of Nickel Based Inert Gas Purifiers to Air, Don Alvarez, Jr., Joshua Cook, Jeffrey J. Spiegelman, AERONEX, INC.)*
  - Time constraints and reluctance led to a compromise to use a non-reactive version which would purify the high moisture content found in the lines

Lessons Learned

- Conduct sampling as soon as possible
  - Need tube bank ordered and in place
  - Keep parties involved aware of any potential contingencies
- Work early with LVC (Launch vehicle Contractor) to strive to get the purge system set-up as downstream as possible
  - Atlas V Vertical Integration Facility (VIF) level 5 is a very active area post PLF mate
- Don't rely on heritage and contractually delivered items when it comes to safety
  - Identify all components *(including passive GSE components)* to safety along with their MSDS
    - Ensure its documented on the MSPSP for any potential launch site issues
  - Consider safety hazards based on the location of possible use

MC-1 ENGINE VALVES, LESSONS LEARNED

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Abstract

Many lessons were learned during the development of the valves for the MC-1 engine. The purpose of this report is to focus on a variety of issues related to the engine valves and convey the lessons learned. This paper will not delve into detailed technical analysis of the components. None of the lessons learned are new or surprising, but simply reinforce the importance of addressing the details of the design early, at the component level. The Marshall Space Flight Center (MSFC), Huntsville, Alabama developed the MC-1 engine, a LOX / RP-1, 60,000 pound thrust engine. This engine was developed under the Low Cost Boost Technology office at MSFC and proved to be a very successful project for the MSFC Propulsion team and the various subcontractors working the development of the engine and its components.

Design Philosophy and Background

Historically, rocket engine valves have been a significant percentage of the cost of an engine. One objective of the MC-1 engine was to reduce engine cost by an order of magnitude. The solution proposed to the valve designer was to use commercial-off-the-shelf (COTS) valves. Unfortunately, because of the extreme environments and stringent requirements typical of rocket engines, COTS valves do not exist. The purge control valves could approach the concept of COTS, but these valves are by no means "off-the-shelf". Many aerospace valve suppliers were solicited to participate in the MC-1 development, including suppliers with commercial aircraft valve experience and little or no experience with rocket valve technology. There were no COTS valves identified that could meet the MC-1 requirements. There was also pressure to use "facility" valves to reduce cost. It was concluded that the flight requirements would drive the "facility" valves toward "flight" type valves in terms of design and as a result, cost and schedule. Another solution proposed to the valve designer was to combine functions required of the valves. Again, because of cost and schedule, combination of valve functions was limited in order to maintain a conventional valve design, and therefore minimize valve development.

Procurement specifications were generated for the Main Oxidizer Valve (MOV), Main Fuel Valve (MFV), Gas Generator Oxidizer Valve (GGOV), Gas Generator Fuel Valve (GGFV), Oxidizer Bleed Valve (OBV), Fuel Bleed Valve (FBV), Ignition Fuel Valve (IFV), Main Fuel Purge Valve (MFPV), Oxidizer Purge Valve (OPV), and Gas Generator LOX Purge Valve (GLPV) prior to the development of an engine specification. The specifications were written to allow the suppliers to use their existing designs, specifications, and standards to the maximum extent. The MOV, MFV, GGOV, GGFV, OBV, and FBV were competed as a mid-range, firm fixed price procurement.

The MFPV, OPV, GLPV, and IFV requirements were met by existing valve designs that had been used extensively on test stands and flight vehicles. A sole source justification was accepted to procure the MFPV, OPV, GLPV, and IFV.

The check valves were existing designs and were ordered as catalog valves. These check valves are used extensively in aerospace applications and some certification data was already available.

Because of the short schedule and tight budget, it was agreed that some of the valve development testing, normally performed, would be eliminated. It was understood that some problems would occur as a result of this decision and that those problems would be worked during engine development.

Before the discussion of the valve problems, it should be specifically stated that the performance and support provided by the valve suppliers during the MC-1 program was excellent. The many long and late hours contributed to the development of these valves, by many individuals, are greatly appreciated and will not be forgotten.

Valve Description

MOV and MFV

The MOV and MFV were proposed as identical valves to take full advantage of hardware commonality. The valves are normally closed, pneumatically actuated, 2.6-inch full port ball valves. The actuator is spring-loaded in the closed position and controlled with a three-way, two-position pilot valve that is mounted on the actuator body. The pilot valve was supplied to the vendor by a sub vendor.

The design of the valve was a derivative of the RL10 Oxidizer Inlet Valve (OIV). The MC-1 operating pressures were significantly higher than the OIV pressures. Some changes were made to accommodate the higher pressures. The ball seal is a Teflon jacket, spring and pressure-energized seal and is an upstream seal. The valve has a primary and secondary shaft seal with a vent port in between. The shaft seal is a formed Kapton seal. Static seals are Teflon jacket, spring and pressure-energized seals.

The actuator is a spring-loaded piston that rotates the ball shaft through a linkage assembly. The piston seal is also a Teflon spring and pressure-energized seal. The pilot valve controls Helium pressure to the piston. Orifices are installed on the inlet and vent port of the pilot valve to control the pressurization rate and therefore the opening and closing times. A paddle that is attached to the actuator shaft activates separate open and closed position indication switches. The position indicators are hermetic switches.

The pilot valve is a three-way, two-position, direct acting solenoid valve. The seats are Vespel. A pushrod attached to the solenoid armature allows a ball to seat on either the inlet or vent seat. The pilot valve was a cartridge valve that is installed into the supplier's manifold. The pilot valve has been used extensively in applications where the temperature was –65F to 150F. The predicted temperatures on the cryogenic valves were as low as –80F. The fuel valve pilot valves used elastomer o-rings. The elastomer seals were replaced with Teflon spring and pressure-energized seals for the oxidizer valves.

GGOV, GGFV, and OBV

The GGOV, GGFV, and OBV were proposed as identical valves to take full advantage of hardware commonality. The valves are normally closed, pneumatically actuated, poppet valves. The main seal is a Teflon jacket, spring and pressure-energized seal. An inlet bellows assembly and outlet bellows assembly serves as the shaft seals. At the closed position the bellows are at their free length. A compression spring, which is part of the outlet bellows assembly, provides seating force. The effective area of the bellows is slightly larger than the effective area of the seat, such that inlet pressure increases the seat load. Paddles on the end of the poppet assembly activate position switches. The position switches are identical to those used on the MOV and MFV.

The inlet bellows also acts as the actuation mechanism. Actuation pressure to the inlet bellows is controlled with a three-way, two-position pilot valve that is mounted on the valve body. The pilot valves are identical to those used on the MOV and MFV.

FBV

The FBV is a normally closed, two-way, two-position direct-acting solenoid valve. The valve was an existing design with position indication added. The valve has been used extensively on flight vehicles and facility systems. The seats are Vespel. The stem seals and other soft goods are Viton. There are primary and secondary stem seals on the solenoid end of the poppet with a weep hole in the valve body.

IFV

The IFV is a normally closed, two-way, two-position direct-acting solenoid valve. Valve development testing revealed that the original valve could not meet the flow capacity requirement and was modified to accommodate a solenoid with greater pull-in force. The body and poppet were also redesigned. The IFV also has position indication. The position switch is identical to the FBV position switch. The seats are Vespel. The stem seals and other soft goods are Buna-N. There are primary and secondary stem seals on the solenoid end of the poppet with a weep hole in the valve body.

MFPV

The MFPV is a normally closed, internally piloted three-way, two-position valve. The pilot valve is a three-way, two-position direct-acting solenoid valve. The seats are Vespel and Kel-F. The stem seals and other soft goods are EPR and Buna-N. The vent of the pilot valve is ported through the valve body to a hole with a screen installed.

OPV

The OPV is a normally open, three-way, two-position direct-acting solenoid valve. The seats are vespel. The stem seals and other soft goods are Butyl and Fluorosilicone. There are primary and secondary stem seals on the solenoid end of the poppet with a weep hole in the valve body.

GLPV

The GLPV is a normally closed, three-way, two-position direct-acting solenoid valve. The seats are Vespel. The stem seals and other soft goods are EPR and Buna- N. There are primary and secondary stem seals on the solenoid end of the poppet with a weep hole in the valve body.

Check Valves

The check valves are all catalog items. The check valve design incorporates a floating o-ring. The spring is completely removed from the flow path; however the floating o-ring may be in the flow path. Because the floating o-ring may be in the flow path, there was concern that fluid force could roll an elastomer o-ring off of the poppet. This concern was the primary reason that Teflon o-rings were used in the fuel system as well as in the oxidizer system.

When the engine is installed in vertical configuration, a check valve was installed as a pump inlet high point bleed valve. This valve was originally made for an application with operating pressure of 225 psig. However, the supplier provided a letter stating that the valve could operate at the MC-1 operating pressure levels, as the components were designed for 3000 psi. In addition, the valves were proof pressure tested to MC-1 requirements to verify structural integrity.

Design Evolution

During development of the valves, a number of problems were encountered. Some problems occurred early in the development, some late in the engine test program. The following sections will address the significant problems and resulting changes, by issue and in somewhat chronological order.

Nonlinear Slew Rate of MOV and MFV

During valve development testing, the MOV and MFV actuation, or position vs. time plots, showed some non-linearity. Engine system performance analysis indicated that the observed non-linearity would result in unacceptable pump cavitation and pressure oscillations during start and shutdown.

The non-linearity was caused primarily by stiction between the ball and ball seal. On open command, the pilot valve opens, sending gas to the actuator. Pressure in the actuator increases until the actuator force overcomes the breakaway friction. Then two events occur. The friction force between the ball shaft and seals decreases instantly because of the difference between breakaway and running friction. And as the ball shaft rotates open, the ball seal "falls" into the port, leaving only part of the seal circumference supported by the ball. As a result, the ball seal deforms, decreasing the seal load on the ball and therefore decreasing the friction between the ball seal and ball. Because of the sudden decrease in friction, and because the actuation medium is a compressible gas, the valve would "snap" partially open instantly, hold that position, then ramp open in a fairly linear response.

Several solutions were considered. Because of schedule pressure, the solution that required the least change impact was implemented. The decision was made to install a commercially available, rotary viscous damper with thermal compensation. The supplier of the damper provided test data showing effective thermal compensation to –20F. Component bench testing performed on valves with the damper installed showed good linear response and no problem associated with nonlinear response was reported during engine testing.

Following the addition of the damper, some verification was repeated. A baseline actuation test was performed. Then the endurance and vibration tests were performed, followed by actuation testing. The testing was successfully completed with no shift in response time or any damage to hardware.

Vent Line Isolation

Originally the actuator vent lines were routed to a common drain line so that one line each, for fuel and LOX, would carry all fluids outside of the aft compartment. The LOX valve drain line was provided a continuous purge to prevent moisture from collecting and freezing in the components. Early in the engine development, during engine checkouts prior to the first hot-fire, the MFV was inadvertently opened. The inadvertent valve actuation was caused by leakage from the MFPV into the drain line. The drain line was undersized and the backpressure that was created opened the MFV actuator. As a result, the decision was made to isolate the fuel valve vent ports to prevent this inadvertent pressurization. In addition, the position switch cavities of the GGOV, GGFV, and OBV were also routed to their respective actuator vent lines. It was discovered that the actuator venting was sometimes activating the position switches. The switches were hermetic switches and therefore could be activated with external pressure. The plan, prior to cancellation of the program, was to isolate all of the vent lines to prevent these failures.

OBV Slow Closing Due to Pusher Binding

Post test data review of test H1-1, showed that the OBV had a slow closing time. The closing time was milliseconds slower than expected. The consequences of the slow closing time were minimal. Because the effects were minimal, testing continued while resolution was being worked. Subsequent tests showed closing times increasing to several, then hundreds of seconds. Review of the data revealed that the pilot

valve was the cause of the slow response. It was suspected that there was binding between the pusher, which is made from stainless steel, and the inlet seat, which is made from vespel, at the low temperatures due to the difference between the coefficients of thermal expansion (CTE). The supplier's pilot valve design is used in many other applications, some of which are low pressure. For low-pressure applications, the pusher, loaded with a spring, provides the seat force for the ball against the vent seat while in the open position. For high pressure applications, such as the MC-1, it was determined that the actuation supply pressure provides adequate seat force and the pusher is not required. The resolution therefore was to remove the pusher and its spring from the valve.

MFV Ball Seal Failure

At engine shutdown during engine test H1-6, observers reported a fire at the nozzle exit post shutdown. Post-test leak checks revealed a blowing leak through the MFV. Borescope inspection of the valve while still installed on the engine revealed that the seal and its energizer spring had been expelled from its groove. The valve was removed and shipped to the supplier for failure investigation.

Valve disassembly and inspection at the supplier's facility revealed that the valve was nearly closed and the seal was pinched between the edge of the through hole of the ball and the seal groove. Witness marks on the valve body provided evidence that the energizer spring was expelled, at least, previous to the valve closing cycle. A fault tree was developed. The most probable cause identified was that of hydrodynamic force expelling the seal and energizer from its location while in a transient position. A water flow test set-up was built by the supplier within a week. The existing configuration was water flow tested, and the failure was successfully duplicated. The test was performed by pressurizing a water tank with GN2 upstream of the closed MFV. The MFV was then opened and closed while maintaining tank pressure. Valve position, upstream pressure, and downstream pressure were recorded. The first test was performed with a delta pressure of 100 psid. The pressure was increased until at approximately 350 psid, the seal failed. Interestingly, the engine Helium spin start pressure had been increased just prior to test H1-6 to provide faster gas generator prime time. With this change the MFV delta pressure, during engine start, changed from approximately 150 psid to approximately 320 psid.

The supplier redesigned the valve to withstand greater pressure differential. The valve supplier added a retainer ring, which was fastened to the inlet flange with lockwired screws. This ring interfaced with a groove cut into the existing seal design, positively capturing the seal. The redesign was water flow tested up to a pressure differential of 600 psid.

As mentioned previously, the valve on which this design was based was the RL10 Oxidizer Inlet Valve. The RL10 valve is a cryogenic valve, and operates at lower pressures and pressure differential than for the MC-1 application. That coupled with the fact that Teflon is approximately ten times stiffer at cryogenic temperature than at 70°F made the use of this seal design in the MC-1 application unacceptable.

MFV Inlet Flange Leakage

During engine pretest leak checks, it was discovered that there was Class II external leakage at the MFV inlet flange to valve body joint. Disassembly and inspection of the valve at the supplier's facility revealed that the shim between the valve inlet flange and the valve body was deformed into the seal gland allowing leakage.

Adjustment of the ball seal preload is made by shimming between the valve inlet flange and the valve body. The shim is sandwiched between the valve inlet flange and the valve body. A Teflon jacket, spring-energized seal on each side of the shim, makes the seal between the inlet flange and valve body. The shim ID is inboard of these seal glands, sandwiched, in metal-to-metal contact with the valve inlet flange on one side, and the valve body on the other side, which forms a "poor seal" inboard of each gland. This "poor seal" results in a transient pressure differential across the shims as the glands pressurize at different rates as the engine pressure increases. This pressure differential, acting on the surface area of the seal gland, tends to deflect the shim into the gland that has the lowest pressure. This pressure differential resulted in yielding of the shim and subsequent leakage.

The shims were made from a soft material, Aluminum 1100-T0 which has a yield strength of 5 ksi. In addition, the shim thickness was decreased to accommodate the ball seal modification, to capture the seal, discussed previously. Analysis performed showed that a shim of thickness 0.010 inch would yield at approximately 250 psid. This problem was duplicated on the bench at the supplier's facility by pressurizing and depressurizing the valve body at approximately the same rate as during engine testing.

The following two changes were made to the design of the MFV to eliminate this problem. The two Teflon, spring-energized, face seals were replaced with

Fluorosilicone o-rings. The Fluorosilicone o-ring acts as packing that increased the stiffness of the shim seal system. The second change made to the MFV was to select a stiffer shim material. Aluminum 6061-T6 (yield strength of 40ksi) was selected for the new shim material.

GGFV Seat Failure

At engine shutdown during engine test H3-1A, observers reported a fire at the nozzle exit post shutdown. Posttest leak checks revealed GGFV internal leakage. Valve disassembly and inspection at the supplier's facility revealed that the seat seal was displaced from its gland. The energizer spring was expelled into the cup of the outlet poppet.

A fault tree was developed. The most probable cause was expulsion of the seal from its gland by the engine transient pressure differential, similar to the MFV ball seal failure. Water flow tests, similar to those performed for the MFV ball seal failure, were performed using the same facility. Again, the failure was duplicated.

A new seal configuration was developed. A solid Teflon seat was designed. The solid seat design was tested and found to perform well at ambient temperatures at MC-1 operational pressures.

The cause of the seal failure was also attributed to the greater ductility of Teflon at ambient temperatures. The energized seal employed on the GGFV was originally designed for use at cryogenic temperatures.

Because of the uncertainty of the operational environments for the GGOV on succeeding MC-1 tests, the GGOV temperature was uncertain. This caused concern that a failure similar to the GGFV could occur on a GGOV. Therefore, the solid seal design was incorporated into the GGOV. Because the OBV is adequately chilled prior to engine start, this same concern did not exist and did not require the added strength of the solid seal.

Slow Pilot Valve Response Due to Grease

Engine pretest checkouts, before its first cold box test, were performed and all valve responses were within the nominal ranges. The pretest checkouts were performed at ambient temperature of approximately 70°F. The cold box was then activated to obtain ambient air conditions of approximately –25° F around the engine. The temperature was held for several hours prior to hot-fire. At engine start the MOV and OBV responses were slow. The limit switch data did not show OBV valve movement until nearly 60 seconds and MOV movement for 2 seconds.

Evaluation of the test data revealed that the pilot valves were the most likely causes of the problems. A series of response time tests at varying temperatures were performed on the pilot valves at the supplier's facility. The slow response times were duplicated. Disassembly and inspection revealed that the pilot valve had lubricant on some of the sliding parts. Interviews with the sub vendor's assembly personnel revealed that lubricant was used as an assembly aid. Therefore the cause of the problem was identified as the uncontrolled application of an uncontrolled lubricant to the assembly. This lubricant then froze or stiffened, resulting in slow response of the pilot valve. Parts were cleaned and drawings changed to preclude the use of any grease.

During this investigation it was also discovered that the pilot valve was leaking in excess of the specification requirement at temperatures below approximately –120F. The main valve supplier requirement for pilot valve temperature operating range was 140F to –100F. This was a derived requirement from the MSFC specification which stated a –65F ambient environment and a 6 minute LOX chill through the OBV. During engine testing, LOX chill times were as long as 2 hours, allowing the pilot valve temperatures to reach approximately –180F. The leakage was attributed to the static seals within the pilot valve and the static seals between the solenoid cartridge and the main valve supplier's manifold. The "girth" seal between the cartridge and the manifold is the primary suspect as this seal must be stretched over the cartridge OD to fit into its gland. This could not be verified by test because each seal cannot be isolated. It was suspected that this seal is damaged during the stretching procedure. As a result, a redesign effort was initiated to accommodate the new pilot valve temperature requirements. These new temperature requirements also drove changes to the verification and acceptance test procedures.

A number of redesigns were considered and tested. The approach was to maintain the pilot valve basic design and, included configuration changes, elimination of the cartridge-manifold interface, and seal material changes. Test results were not promising. Leakage rates were either high or sensitive to assembly/disassembly. The decision was made to simply off-mount the pilot valves from the GGOV and OBV, which were the only valves that approached pilot temperatures of –150F. Of course modifications would be required for the engine assembly, but there would be minimal impact to the pilot valve design. The modification to off-mount the pilots was not approved prior to program cancellation.

Slow IFV Response Due to Grease

Engine tests H4-2, H4-3, and H4-4b were conducted with an enclosure around the engine that was chilled with LN2 to obtain ambient conditions of approximately –25 Deg F around the engine. The temperature was held for several hours prior to ignition. During engine start, the IFV current trace showed an open response time ranging from approximately 425 to 565 msec on the three tests. Previous engine hot-fires utilizing these valves had response times ranging from 175 to 280 msec.

Three IFV's were chilled and tested at the supplier's facility for response time. All response times were slow. The cause for the slow response was the use of Krytox 240AC grease, which was freezing at the lower temperatures. Corrective action included changing from Krytox 240AC to Braycote 601.

In addition, engine test data revealed that the hypergol flow rate could be reduced. This meant that the flow coefficient for the IFV could be reduced. Therefore, the coil/armature gap was reduced to provide increased pull-in force.

MFV Leakage at Low Pressure Due to Application of Backpressure

During engine pretest leak checks, it was discovered that the MFV was leaking internally such that the fuel system could not be pressurized. The valve was removed and returned to the supplier for investigation. The as-received leak checks at the supplier's facility showed no leakage. The valve was then returned to the engine for installation to verify the leakage measured. The valve again had a blowing leak. The valve was again returned to the supplier. This time the leak check was performed at a low pressure, 5 psid, and the leakage was repeated.

Disassembly and inspection revealed that the ball seal had zero preload. A fault tree was developed. It was suspected that reverse pressure resulted in yielding of the ball seal energizer spring. The main ball seal has an internal spring, which upon valve assembly is compressed to give a preload of the seal on the ball. When reverse pressure is applied to the valve, the Teflon jacket can squeeze the internal spring. When pressure is high enough, the spring will take a permanent set. All preload by the seal on the ball is then lost. The valve will leak at low pressures but seal at high pressures. Tests were performed where 50 psig and 250 psig back pressure was applied to the seal. The 50 psig back-pressure resulted in little loss of preload. The 250 psig back-pressure resulted in a significant loss of preload.

Review of engine operations revealed that during engine leak checks the MFV is back pressurized to 35 psid. Relief valve settings, to prevent throat plug failure, are below 50 psig. The cause of the back pressure was never identified.

OBV Seat Fracture

Post-test R2-1A engine leak checks revealed a blowing internal seat leakage of the OBV. Data review revealed that that the OBV was leaking at engine start. The Gas Generator was starved for LOX because of the blowing leak through the OBV.

The valve was sent to the supplier's facility for failure investigation. After disassembly, examination of the seal showed a crack through the Teflon jacket with the spring intact and in place. The valve seat showed no apparent damage. Additionally during valve disassembly, marks and included particles were discovered on the inlet plunger. The included particles were determined to be composed primarily of aluminum. Investigation into the origin of the inclusions and marks on the inlet plunger were progressing at the time of program cancellation.

Examination of the seal continued at MSFC where an Environmental Scanning Electron Microscope (ESEM) could be employed and material properties could be determined. ESEM showed no material inconsistency at the crack. The seal was examined with an optical microscope, which showed porosity in the Teflon at the break.

The specification on supplier's source control drawing controlled the Teflon as raw material. Under this spec, three samples out of a lot of Teflon are tested for porosity. A corrective action for this problem was being worked at program cancellation. The proposed corrective action included a density or specific gravity test, of the machined Teflon part.

Bellows Free Length Set and Spring Rate

As part of an OBV seat leakage investigation, the valve was disassembled and the bellows length and spring rate were measured. The spring rate of both bellows, were higher than specified by the valve supplier's drawings. Both bellows had taken a permanent set in the valve open direction. This particular OBV was a high cycle valve. This condition was discovered on other poppet valves.

Several meetings, attended by the bellows supplier, valve supplier, and MSFC, were held to gain an understanding of the nature of the bellows as manufactured and over time with use. The bellows supplier reported the permanent set was not an unexpected occurrence. Rather, it should be considered in the design of a bellows. At the time of program cancellation, work on this issue was continuing.

Summary of Lessons Learned

Engine valves provided a considerable share of the problems encountered during the engine test phase of the program. As a result, there were a number of lessons learned during the valve development that may be of some value. The following sections will attempt to cover these lessons learned.

Contract Type

Because the valves were procured under the premise that existing designs would be used, and that design and development would be fairly straightforward, a fixed price contract was used. The use of a fixed price contract proved to be a significant mistake. In something as complex as an engine development program, there exists too many unknowns to use a fixed price contract. As the engine is developed, valve requirements are likely to change. If requirements change, a contract modification will be required. It then becomes very difficult to assess the impact of the new requirement. For this reason alone, a fixed price contract is not acceptable. Also, when writing the procurement specification, it is unlikely that the verification and acceptance test requirements will be known because the design details are unknown. Changes to the acceptance and verification test requirements also require a contract modification. Failure analysis, determination of corrective actions, and associated testing proved to be very difficult under a fixed price contract. For example, one of the contract modifications had 22 items or tasks identified to resolve a problem. The final resolution of the problem was significantly different from what was originally planned. In the end, some of the original 22 tasks were performed, some were not performed either because they were not required with the new approach or they simply had not completed the task. Needless to say the next contract modification was even more complex.

If *any* development is required, a fixed price contract is not the best means for procuring a valve. In development of an engine, because requirements typically are not fully defined, or may change, valves should not be procured under a fixed price contract.

The Fifteen Percent Rule-of-Thumb

As discussed previously, the propellant valves were procured under the premise that existing designs would be used to minimize development and testing requirements, and therefore cost and schedule. The original design point of the existing valve must be known. Some use a rule-of-thumb that if the design point of the new application is more than 15% greater or less than the original design point, then significant redesign or development is required. For example, one of the problem areas on the MC-1 valves was the ball seal design. The MOV and MFV were derivatives of the RL10 Oxidizer Inlet Valve (OIV). Because seat design is a large portion of a valve's development cost, it was believed that by using the OIV seat design, a large savings would be recognized. The MFV and MOV operating pressures were greater (by more than 15%), and the pressure differentials were greater (by more than 15%) than the OIV design points. Even more obvious and embarrassing was the fact that the MFV seal was at ambient temperature, while the OIV design point was cryogenic temperature. In sealing applications, it is typical to assume that cryogenic temperature is the worst case. However, what was neglected was the fact that Teflon stiffness at cryogenic temperature is ten times that at 70°F, and the potential for seal structural failure is more probable at the higher temperature. If the 15% rule had been considered for all requirements, a potential problem would have been more likely identified. Despite these large differences, the OIV development testing of the seat design was heavily relied upon. Engine testing revealed the errors in this approach.

When considering buying an existing design, one must know the nominal design points for that design, then compare the new application's requirements to those original design points. If the 15% rule is violated, assess how it impacts the function of critical elements of the component. If the 15% rule is violated, this should alert one to address those areas early in the project.

Development Testing

Because of the short schedule and tight budget, it was agreed that some of the valve development testing, normally performed, would be eliminated. It was understood that some problems would occur as a result of this decision and that those problems would be worked during engine development. This approach, again, proved to be a flawed. The most obvious example of this was the problem associated with seal failures. During development of the specifications,

flow testing was not specified to reduce cost and delivery schedule. As mentioned above, during the failure investigation, the first task performed was a flow test. It was quickly recognized that the seal design was not acceptable. The time required to set-up and perform the test was approximately one week. One week would have been insignificant during the valve development but discovery of the problem during the engine testing phase resulted in significant costs.

Test at the component level early in the development. The cost of finding design shortcomings during the engine development phase will most likely exceed that of performing the test early at the component level.

Acceptance Testing

Another problem revealed during engine testing was that the acceptance testing was not screening all hardware problems. For example, there were a number of problems with inappropriate grease applied to valves. Review of the acceptance test procedure revealed that in some cases, the valve response was not being measured at the low temperature requirement. In addition, appropriate measurements must be taken to verify that the worst case environment is indeed simulated. Acceptance testing is performed to screen hardware for quality escapes.

Acceptance testing should be performed at worst case conditions. Not testing at the worst case conditions will allow some quality escapes to pass through the system only to be discovered, at a high cost, at the engine level.

Spares

Again, in an effort to minimize cost, neither spare valves nor spare piece parts were procured. This obviously proved to be a problem especially during the engine test phase. The problems experienced during the engine test phase and the lack of spare hardware made logistics of providing valves for engines difficult. Engines were continuously cannibalized to provide valves to the engine currently being tested. Frequently the engine testing was delayed while valves were being transported and modified.

The lack of spare valves or development valves also hindered engine development and failure investigations. Some testing at the component level could have been performed at MSFC, but hardware was not procured to support that effort.

Another thing to consider is that during the engine development phase, the specified life of components will likely be exceeded. During engine testing, the cycle life on valves exceeded the specified cycle life. One way to deal with this is to procure enough valves so that when the cycle life is exceeded, they are simply replaced. Another more feasible approach may be to identify, early in the project, life limited parts and replace those parts at appropriate intervals.

Spares should be specified and procured at the beginning of the program to minimize the logistical problems during the engine development phase.

Engine Flight vs. Development Requirements

Some of the engine flight requirements may be different from the development requirements. Obviously some of the environments, thermal and vibration for example, will be different, but consider also any operational requirements. The specifications for the valves included the flight requirements for the duration of engine conditioning, which was specified as six minutes. Therefore, the supplier's analysis predicted the pilot valve minimum temperature to be -100°F, based on a six minute engine conditioning period. However, during engine development testing the duration of the engine conditioning typically lasted for hours. As a result, the pilot valves reached -180°F. In this case, failure to consider longer durations for engine conditioning resulted in pilot valve leakage problems. Had the requirement for longer durations of engine conditioning been specified, the supplier would have proposed a different design, most likely to off-mount the pilot valves.

Both the engine development operational requirements as well as flight operational requirements must be considered.

Range Safety

Range safety requirements were not addressed until late in the program. At that time, the decision was made to add new requirements for some of the engine valves. Some of the engine valves were to become part of the flight termination system (FTS). The FTS requirements had serious impacts on the valve designs. The flight ranges specify requirements such as structural safety factors, margin on thermal environments, margin on vibration test requirements, acceleration requirements, acceptance vibration, and acceptance thermal cycling to name a few.

Range safety requirements should be addressed early and incorporated into the procurement specifications.

Reverse Pressure

The MC-1 valve specifications did not address application of reverse pressure on the valve. In this case, application of reverse pressure on the engine did not result in damage. During routine engine leak checks, 35 psig is applied downstream of the valve. It was later discovered that the ball seal might be damaged with application of 50 psig reverse pressure.

Consider the potential for reverse pressure on the valve from either engine checkout operations, engine operation, or component testing. The capability or limitation of the design due to reverse pressure should be identified early in the project.

Weep Holes and Vents

Initially, the actuator vent lines were routed to a common drain line so that one line each for fuel and LOX would carry all fluids outside of the aft compartment. In addition, a purge barrier was maintained in the LOX drain to prevent moisture from entering the specific areas on the engine including valves. This was done to prevent moisture from freezing within the pilot valves. Initially, the MC-1 drain line was so undersized that leakage into the drain system resulted in inadvertent valve actuation. The decision was made to isolate the actuator vent ports. However, some design solution was required to prevent contamination from entering through these vent lines.

Some of the valves procured had weep holes and vents in the valve body open to the atmosphere. Although this did not result in any problems, the potential existed. The component will be exposed to rain on the test stand and in transit, in different orientations. With any open holes, the potential for getting rain water in the valve and later freezing exists.

Design of the vent and drain system should not be overlooked. Detailed system analysis must be performed to assure that leaking or venting components that are routed to a common drain line do not negatively interact with other components. Assure that vents and drains are specified to be designed to prevent contamination from entering the system.

Instrumentation Interface Requirements

Review of engine test data sometimes showed anomalous position switch data. Discussions with the switch vendors revealed that, although the switches are hermetic, some oxidation of the contacts does occur and that some minimum current is required to clean the contacts.

The valve specification should provide the instrumentation interface requirements.

Leakage Measurement

On one occasion, the valve passed the acceptance test and was delivered to the test stand. During engine leak checks, the data revealed that the valve just installed, had a blowing leak. It was discovered, during the acceptance testing the pressure was applied rapidly and therefore seated the pressure-energized seal. During the engine level leak checks, because of the large volumes, the pressure increases at a slower rate. The valve did not have adequate pressure to energize the seal.

Acceptance tests should be performed to simulate the same conditions as the engine level checkouts, as well as the engine operating conditions. For example, if pressure energized seals are employed, part of the acceptance test at the supplier's facility should be a leak check at a very low pressure as well as the engine checkout pressure. This will capture valve discrepancies prior to installation and allow a direct comparison between the acceptance test data and the engine level checkout data.

Acknowledgments

Special thanks to Mr. Richard Sheller, Sr. Engineer, Sverdrup Technology, Huntsville, Alabama and Mr. Kevin Ward, MSFC, TD62, for their review and inputs.

NASA Materials Related Lessons Learned

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Background

Lessons Learned have been the basis for our accomplishments throughout the ages. They have been passed down from father to son, mother to daughter, teacher to pupil, and older to younger worker. Lessons Learned have also been the basis for the nation's accomplishments for more than 200 years. Both government and industry have long recognized the need to systematically document and utilize the knowledge gained from past experiences in order to avoid the repetition of failures and mishaps.

Through the knowledge captured and recorded in Lessons Learned from more than 80 years of flight in the Earth's atmosphere, NASA's materials researchers are constantly working to develop stronger, lighter, and more durable materials that can withstand the challenges of space. The Agency's talented materials engineers and scientists continue to build on that rich tradition by using the knowledge and wisdom gained from past experiences to create futuristic materials and technologies that will be used in the next generation of advanced spacecraft and satellites that may one day enable mankind to land men on another planet or explore our nearest star. These same materials may also have application here on Earth to make commercial aircraft more economical to build and fly.

With the explosion in technical accomplishments over the last decade, the ability to capture knowledge and have the capability to rapidly communicate this knowledge at lightning speed throughout an organization like NASA has become critical. Use of Lessons Learned is a principal component of an organizational culture committed to continuous improvement.

What are Lessons Learned?

Lessons Learned are the result of experiences with people, nature, and the products of our labors. The experiences may be positive, as in successful tests or missions, or negative, as in a mishap or failure. A Lesson Learned must be significant in that it has a real or assumed impact on operations, valid in that it is technically correct, and applicable in that it addresses a specific design process or decision that mitigates or eliminates the potential for failures, or reinforces a positive result.

The documentation of materials related Lessons Learned is important in order to convey information on usage experiences, test results, safety, and performance. Thus, they are an important and critical resource that can be used by materials engineers, scientists, and technicians to support the design of flight and ground support hardware, facilities, and procedures.

Lessons Learned should communicate only lessons, and should not be used as a replacement for other management information functions like self-assessment, failure investigation and corrective actions systems.

How are Technical Standards and Lessons Learned Related?

As life becomes more complex, more guidance is needed. Technical Standards are the documents that infuse this guidance throughout the social structure. The scope of Technical Standards includes standards, specifications, guidelines, recommended practices, and handbooks. Technical standards are: (1) Systematic collections of proven guidance/methods/requirements (frequently gleaned from Lessons Learned) integrated into recommended practices, (2) Generally based on inputs from many activities combining the expertise of national or even international experts, and (3) The basic tools commonly used as the foundation for the normal design/development process. Technical Standards educate users, simplify information, and conserve experiences. They are the essential tools in the interaction of people with their environment. They enable us to intelligently pass on knowledge and associated Lessons Learned for others to build upon. Technical Standards are a very logical way to communicate Lessons Learned.

The Problem.

The Agency's materials engineers and specialists are constantly trying to improve the formulas of materials and with the "explosion" in technical accomplishments during the last few decades, the ability to rapidly communicate Lessons Learned, and the knowledge gained from them has become critical. This is especially true for activities associated with NASA's advanced Programs and Projects such as the Space Launch Initiative (SLI). The Agency's quest for affordable and routine access to space will require new generations of materials and material technologies, which will in turn enable the development of new reusable launch vehicles and associated spacecraft systems. Expecting the Agency's materials engineers to search through the ever-increasing number and contents of materials lessons learned databases have proven to be less than productive.

A Solution.

The "marriage" of Lessons Learned with current Technical Standards offers the opportunity for significant improvement in our goal to achieve advanced products and the use of current products. The NASA Technical Standards Program through the development and use of its Preferred Technical Standards database available to the Agency's users via the NASA Technical Standards Website (http://standards.nasa.gov) offers the foundation to accomplish this goal. Figure 1 shows the homepage of the NASA Technical Standards Program's Website.



Figure 1. NASA Technical Standards Program Website

The Approach.

All NASA Programs/Projects are based on the application of Technical Standards, whether produced by NASA, other government organizations including DOD, or by non-Government standards developing organizations such as SAE, ASTM, ASME, and so on. These and other Technical Standards have gone through an extensive Agencywide review process pending their adoption/endorsement as NASA Preferred Technical Standards. Given this select database of Preferred Technical Standards, along with the existence of screened materials related lessons learned databases, a productive "marriage" is now readily possible. Figure 2 shows an example of the Document Summary Page with "linked" Lessons Learned.



Figure 2. Document Summary Page with Linked Lessons Learned.

On the surface this "marriage" or linkage appears to be an easily achieved action. However, such is not the case. While the task is readily achievable, it requires the talents of dedicated and experienced engineers who must

also possess the gifts of persistence and meticulous attention to detail. The material involved must be read and interpreted and then correlated. The lessons learned databases that contain specific materials related lessons learned must be related to the NASA's Preferred Technical Standards database which currently has over 1500 entries. The result will be an invaluable database whereby any NASA Preferred Technical Standard related to materials and required for an Agency Program or Project design, development, or operations process will also have identified with it any relevant materials related lesson(s) learned.

Value.

NASA conscientiously investigates, documents, and tracks all of its successes and failures. Yet, all of this effort is meaningless if the Agency fails to incorporate these experiences into our ongoing and future Programs/Projects and their operations. They need a viable mechanism to identify and incorporate Lessons Learned into their design, development, and operations efforts, thus reducing mission risk. The cost of achieving the "marriage" of Lessons Learned and Technical Standards will be modest compared to the significant results that will be achieved. Only one Mission saved, or whose performance is enhanced, will repay the cost of developing this Integrated Technical Standards System many fold.

Gill, Paul S., William W. Vaughan, and Danny Garcia, "Lessons Learned and Technical Standards: A Logical Marriage". ASTM Standardization News, Vol. 29, No.11. November 2001.

END

NASA Procurement Lessons Learned

Glenn Butts
NASA
Kennedy Space Center

The source of knowledge is experience.

Experience is of two kinds-our own, & that of others.

Knowledge gained from our own experience is most expensive.

Mystery & ignorance are always coexistent.

Learn the truth & the mystery will disappear.

National Aeronautics & Space Administration

NASA's Constellation program – based largely on existing technologies – was based on a vision of returning astronauts back to the Moon by 2020.

However, ***the program was over budget, behind schedule***, & lacking in innovation due to a failure to invest in critical new technologies.

The President's Budget ***cancels Constellation*** & replaces it with a bold new approach that invests in the building blocks of a more capable approach to space.

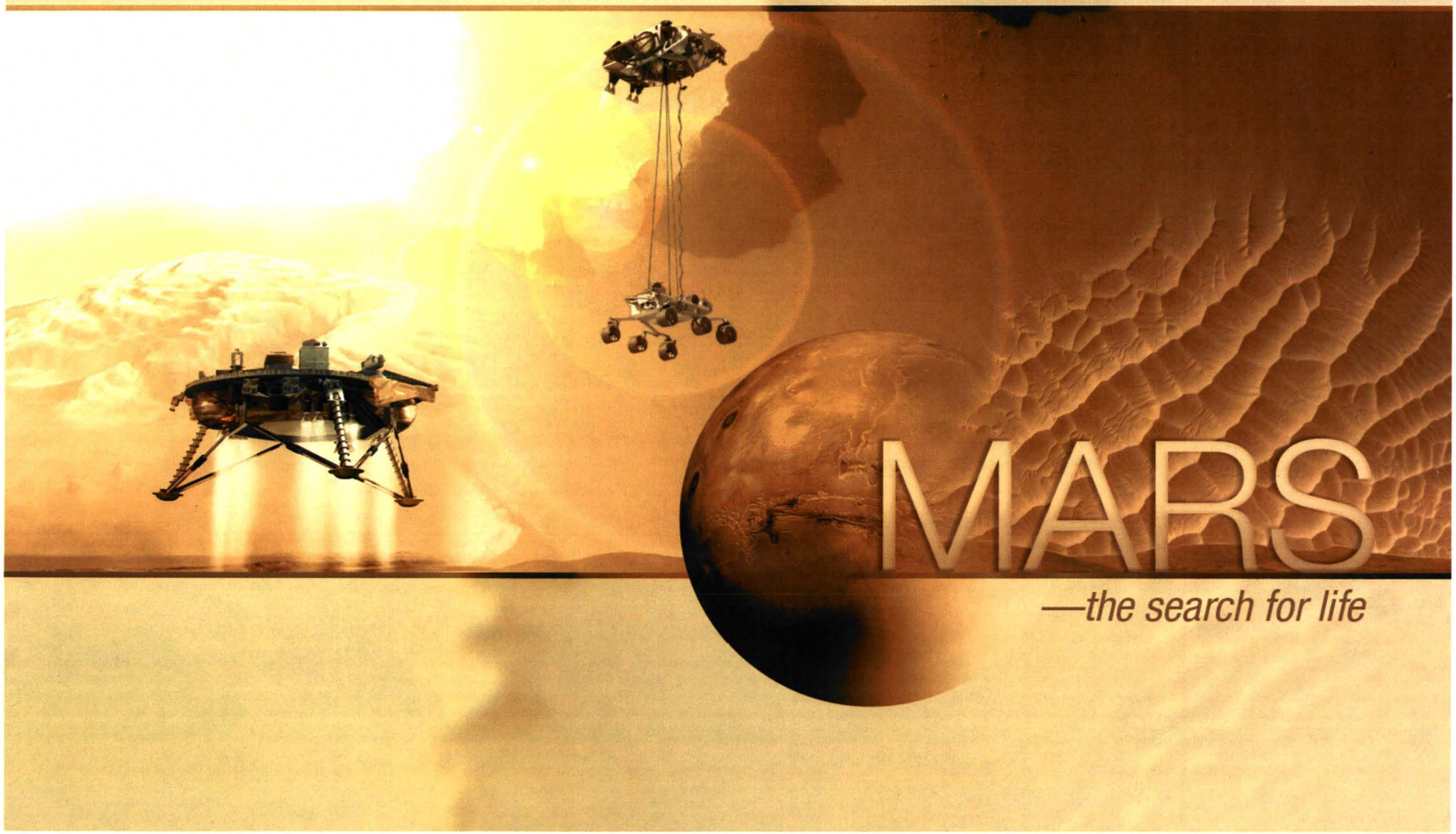
In the last 20 years NASA has spent at least $21B on canceled Space Transportation Programs

~7% of its Budget

Overruns can have real consequences

National Aeronautics and Space Administration

Mars Science Lab (MSL) Status



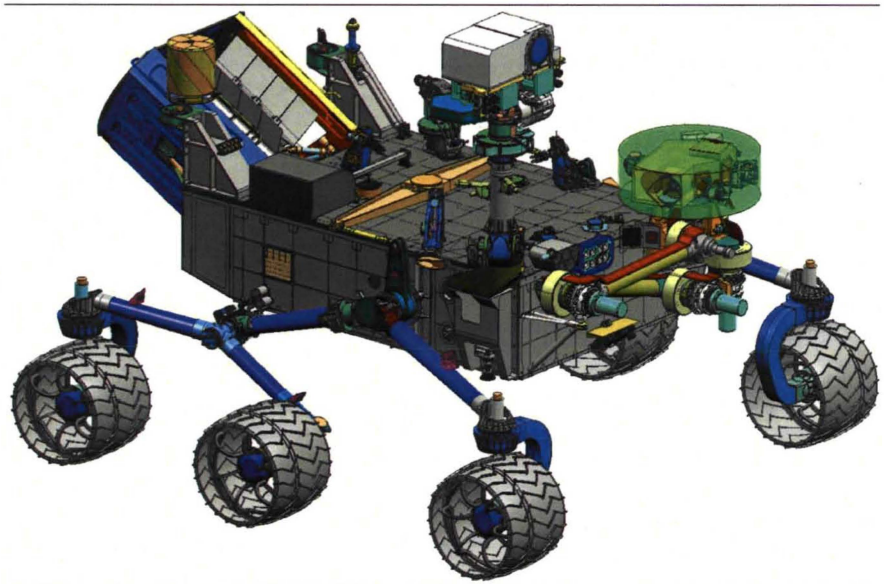
MSL Project Overview

Science

Focus on Past & Present Habitability of Mars
Highly Capable Analytical Laboratory
Next Generation Remote Sensing & Contact Investigations
Suite of Environmental Monitoring Instruments



Planned Launch: Oct-Dec 2011



Technical Capabilities

One Mars Year surface operational lifetime (669 sols/687 days)
Discovery Responsive over wide range of latitudes and altitudes
Precision Landing via Guided Entry
Skycrane Propulsive Landing
Long Distance Traverse Capability (20 km)
Flexible & Robust Sample Acquisition & Processing

MSL Growth Timeline

Pre Phase A — $650M

Legend: KDP — $1,381M 2005 — Life Cycle Cost — Date of Review

Phase A	$1,381M	2005
SRR	$1,546M	12/2005
PDR	$1,645M	8/2006
CDR	$1,645M	6/2007

KDP accelerated up from Baseline

Rebaselines

Descope Review	$1,671M	8/2007
Re-Baseline	$1,886M	6/2008
Re-baseline	$2,031M	10/2008
Re-baseline	$2,271M	12/2008

- One instrument Deleted & two instruments have descopes
- ~$27M in descopes in addition to cost increase

10/2007 AA reinstates Instrument Descopes

~$200M increase

- ~$140M increase

- ~$240M increase
- LRD delayed from 2009 to 2011

Rebaseline Review 06/2009

Cost: $2,394M

2011 Cost $2,470M

Current Launch date late 2011

Original plan to launch in 2009

MSL Finding #4

- Lack of quantitative evidence for findings provided at KDP & Rebaseline Reviews

Findings - Schedule

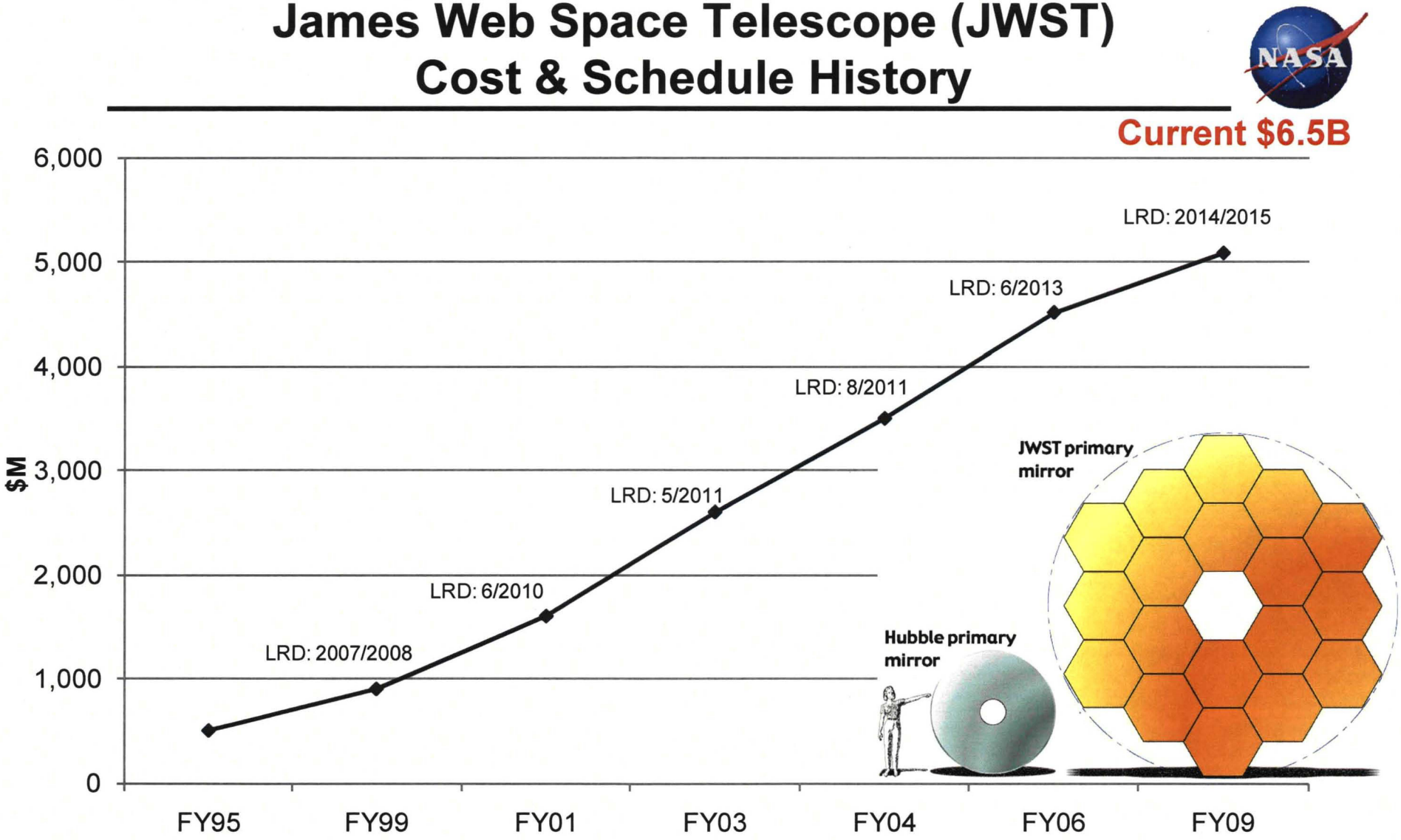
Mars Science Laboratory

- Schedule has healthy margins
  - 3 month early delivery to launch site part of the plan
  - Plan includes completion of all flight S/W builds before launch
  - 2 launch windows offer potential additional schedule relief (each has different implications for coverage during EDL)
    - Type II Oct 15-Nov 18, Type I Nov 25-Dec 18
  - Integrated cost/schedule risk analysis shows LRD at early opening of window has a 97% or better probability, assuming adequate and timely budget is made available

Same statement shown at both 6/2008 and 6/2009 Review

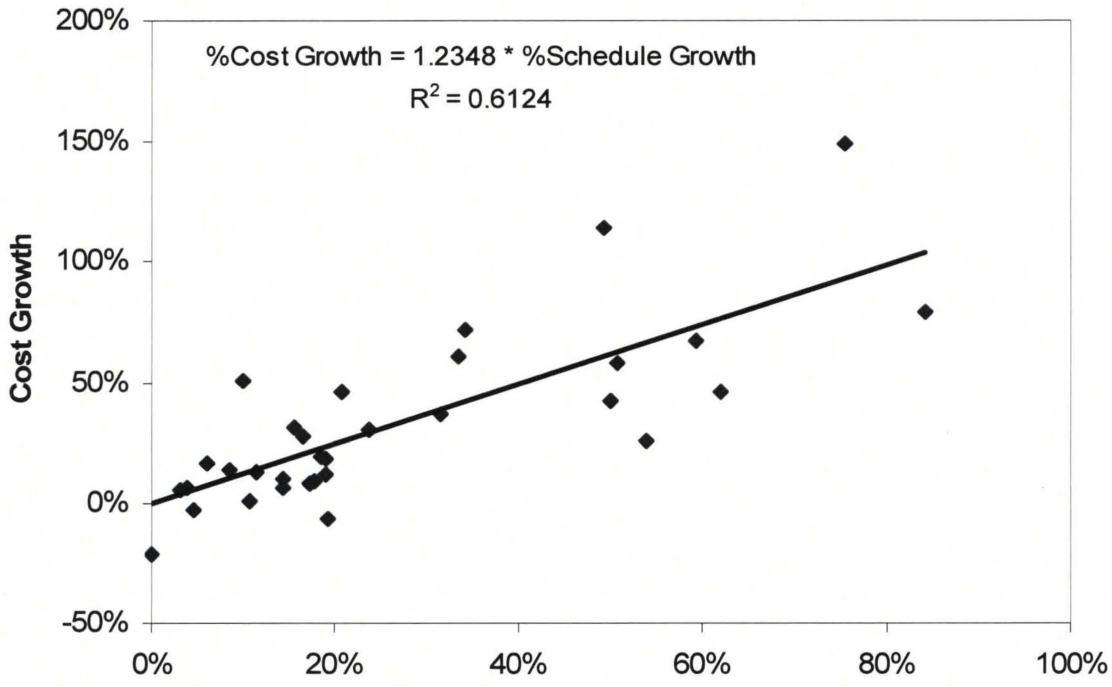
- Avionics system (including hardware and software), actuators, rover power system, SAM instrument represent a significant threat still
- Project evaluating options for ATLO flow. SRB believes that options beyond the baseline "option 2" add technical and programmatic risk

James Web Space Telescope (JWST)
Cost & Schedule History



Current launch date rumored to be between 2018-2024

History on 40 Spacecraft Projects
Interrelationship of Cost and Schedule*



Interrelationship of Cost and Schedule Growth for Non-Restricted Launch Window Projects

Spacecraft Rule of Thumb: For every % Schedule Growth leads to equal or greater % of Cost Growth

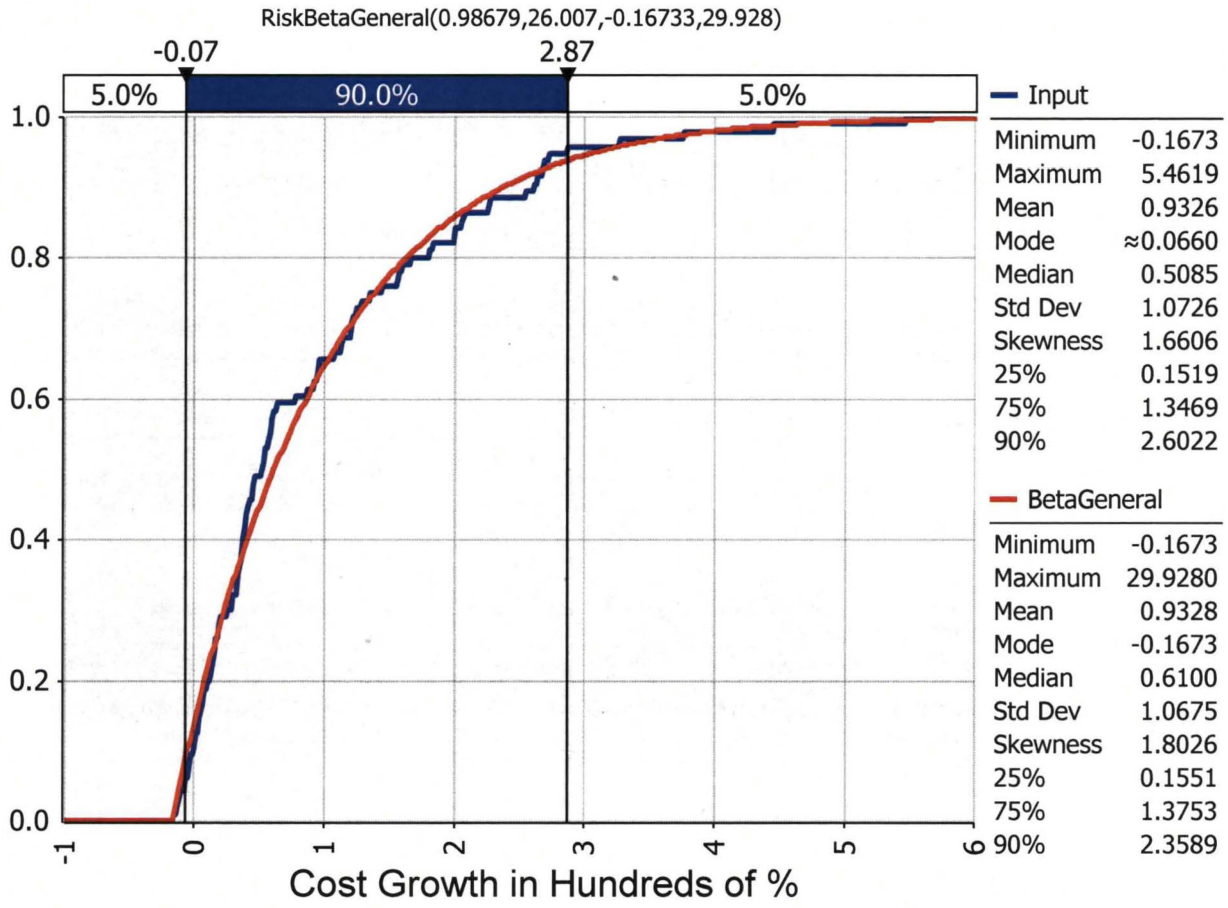
- Recent results from study of 40 NASA missions show correlation between cost & schedule growth
- The corresponding relationship states that for every 10 percent of schedule growth, there should be a corresponding 12 percent increase in cost growth.
- Although the variations can be significant, a general rule of thumb could be followed that states that for every percent of schedule growth, there will more than likely be an equal or greater percent of cost growth.

* Using Historical NASA Cost and Schedule Growth to Set Future Program and Project Reserve Guidelines
Presented at the IEEE Aerospace Conference, March 3-10, 2007, Big Sky, Montana

History of 96 Spacecraft Projects

1st Available Cost Estimate to Last Available Cost Estimate

Data includes projects at various phases of development.



Only 12.5% chance of completing project on or under budget.

Average cost growth: 93% & Median: 51%

If overruns are consistent they can be predicted

Probably understated due to re-baselining & cancellation events.

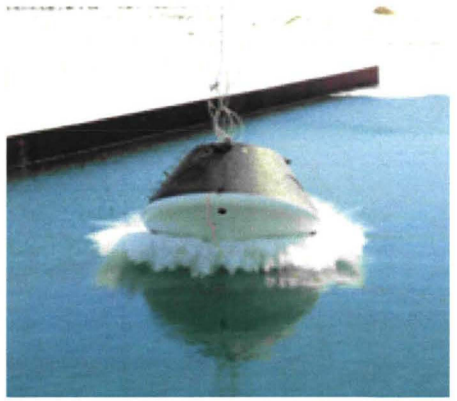
The project team protests....

"But these are spacecraft projects facilities are easier."

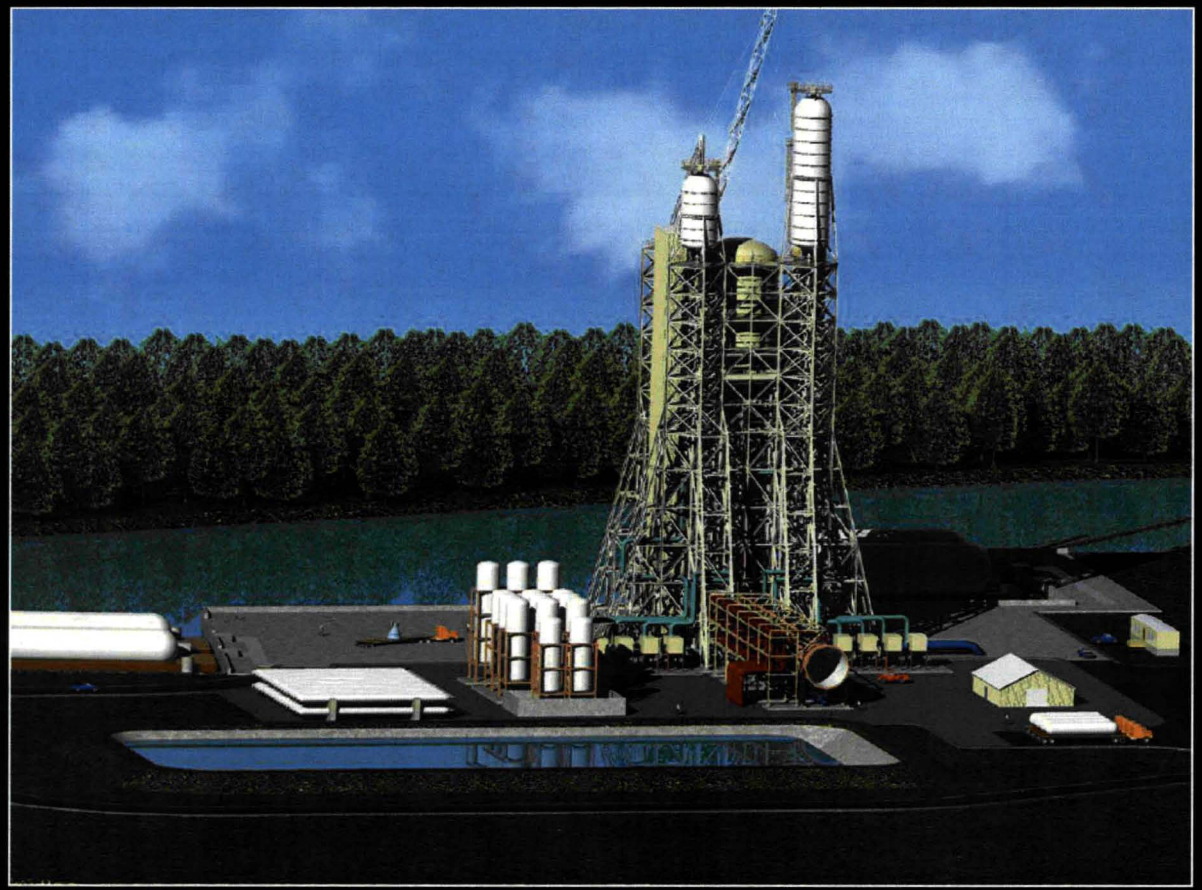
Recent Facility Cost and Schedule Growth

- ***A-3 Test Stand***
  - $157 M initial estimate
  - $320 M current project estimate
    - 2.04 times original
  - $366 M ICE estimate
  - *Latest available duration 7 years 1.75 times longer than original estimate*
- ***SET***
  - $ 63 M original estimate
  - $152 M latest available estimate
    - 2.41 times original estimate
  - *Latest available duration 7 years 1.75 times longer than original estimate*
- ***O&C IOZ***
  - $ 18 M original estimate
  - $55.2 M latest available estimate
  - $55.3 M ICE estimate
    - 3.07 time original estimate
  - *Construction Duration 18 months original - actual 27.3 months (1.52 times)*
- ***Hydro Impact Basin***
  - Conceptual Design Construction Cost Estimate: $1.89M
  - Final Design Construction Cost Estimate: $2.60M
  - Construction duration
    - 90 days estimate
    - 210 days reality
    - 2.33 times longer than original

Data suggests the larger the project the higher the cost growth



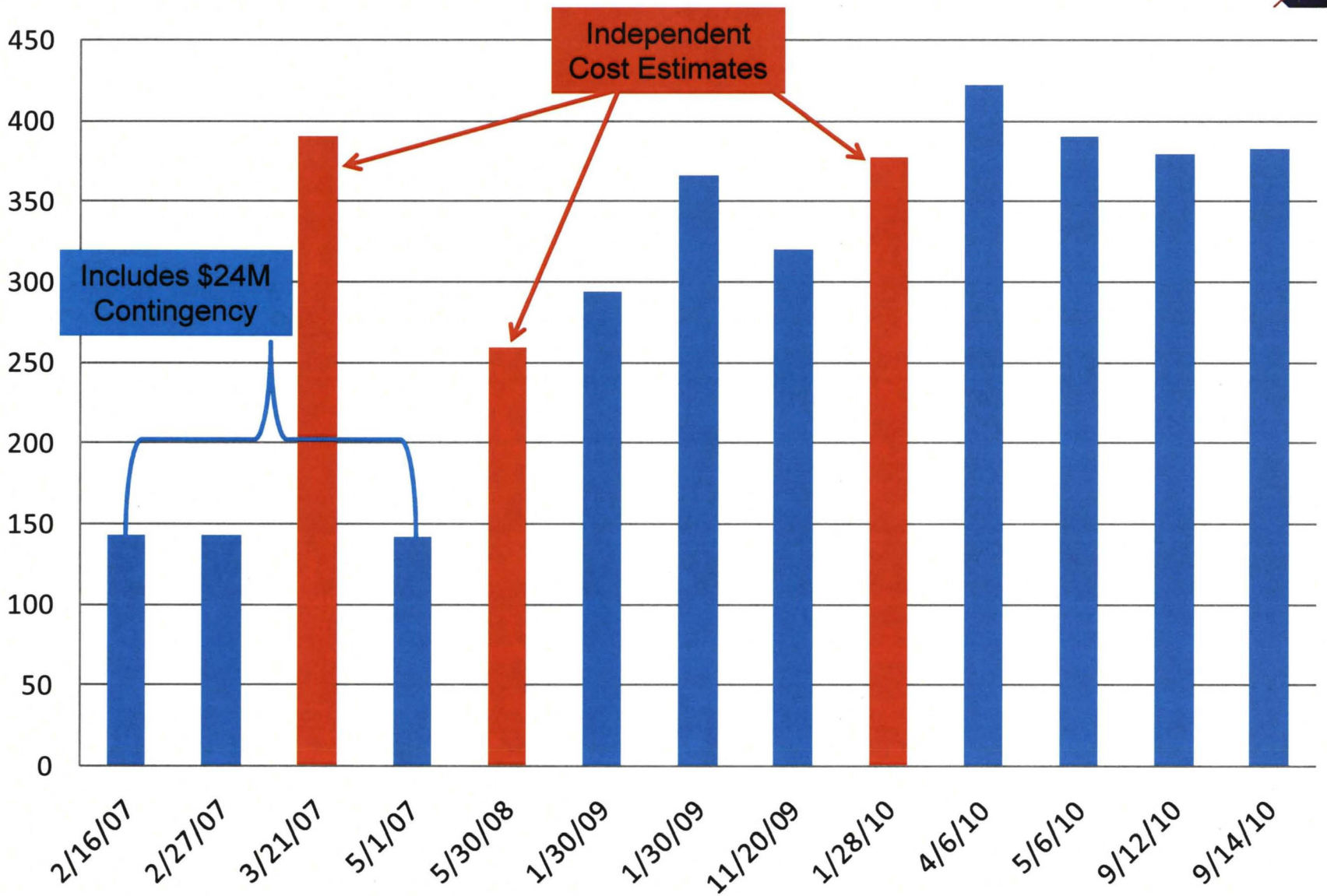
A-3 Test Stand



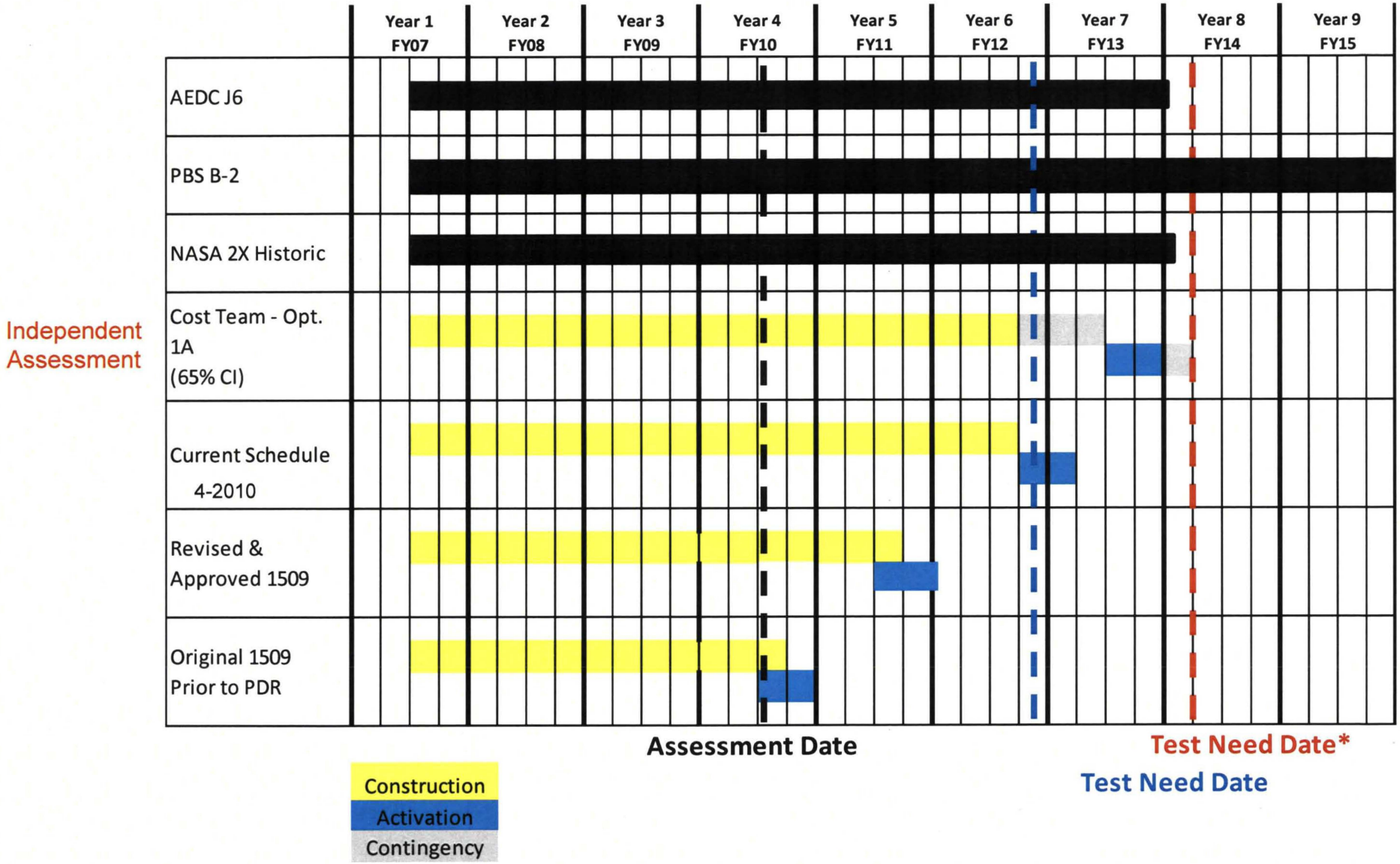
- 300 feet tall
- Open steel frame structure
- Up to 1 million pounds of thrust
- Simulates altitudes up to 100,000 feet by generating steam to create a vacuum

The new A-3 Test Stand will allow engineers to test operating parameters of the J-2X engine for the Ares launch vehicles by simulating conditions at different altitudes.

A3 Cost History

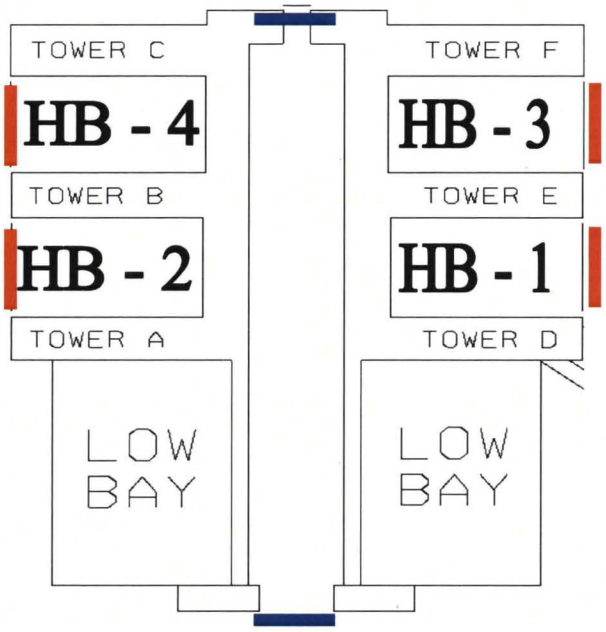


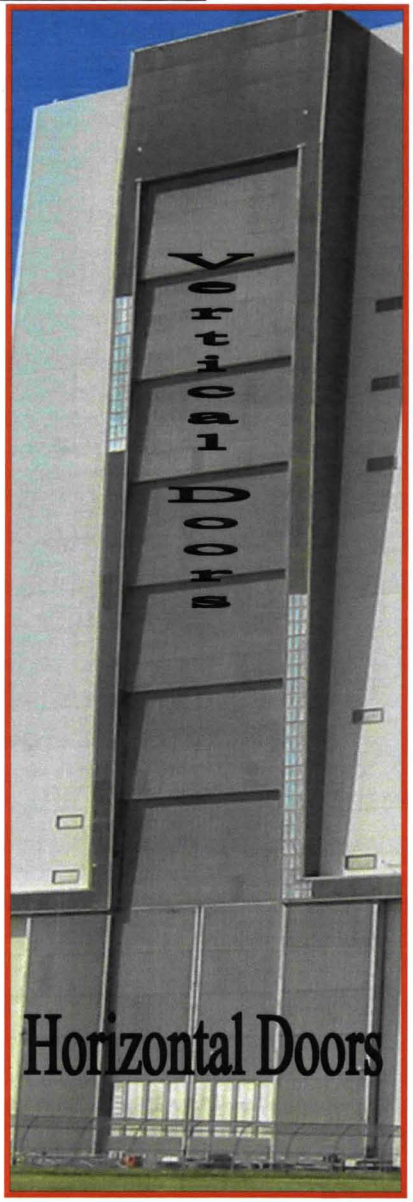
A3 - Schedule


Year 1 FY07
Year 2 FY08
Year 3 FY09
Year 4 FY10
Year 5 FY11
Year 6 FY12
Year 7 FY13
Year 8 FY14
Year 9 FY15
AEDC J6
PBS B-2
NASA 2X Historic
Cost Team - Opt. 1A (65% CI)
Current Schedule 4-2010
Revised & Approved 1509
Original 1509 Prior to PDR
Independent Assessment
Assessment Date
Test Need Date*
Test Need Date
Construction
Activation
Contingency

VAB Door Refurbishment
A Tale of Two Projects







- ½ building done cost plus
- ½ building done fixed price
- *Which one cost more?*



Transfer Aisle Doors

Other Recent Facility Projects
Cost and Schedule Growth

- **Cost Plus VAB Door Renovation**
  - $ 9.5 M original estimate
  - $56.5 M final cost
    - 5.95 times original estimate
- **Fixed Price VAB Door Renovation**
  - $27.0 M original estimate
  - $27.6 M final cost
    - 1.02 times original estimate
- **Cost Plus Processing Facility**
  - $135 M original estimate
    - $135M @ 60% design complete
    - $163M @ 90% design complete ± 5%
    - $180M @100% design complete
  - $370 M current estimate
    - 2.74 times original estimate
  - *Scheduled duration 8.6 years 1.75 times longer than original estimate*

Essentially the same scope done by the same contractor

Ok there *may* be some risk....

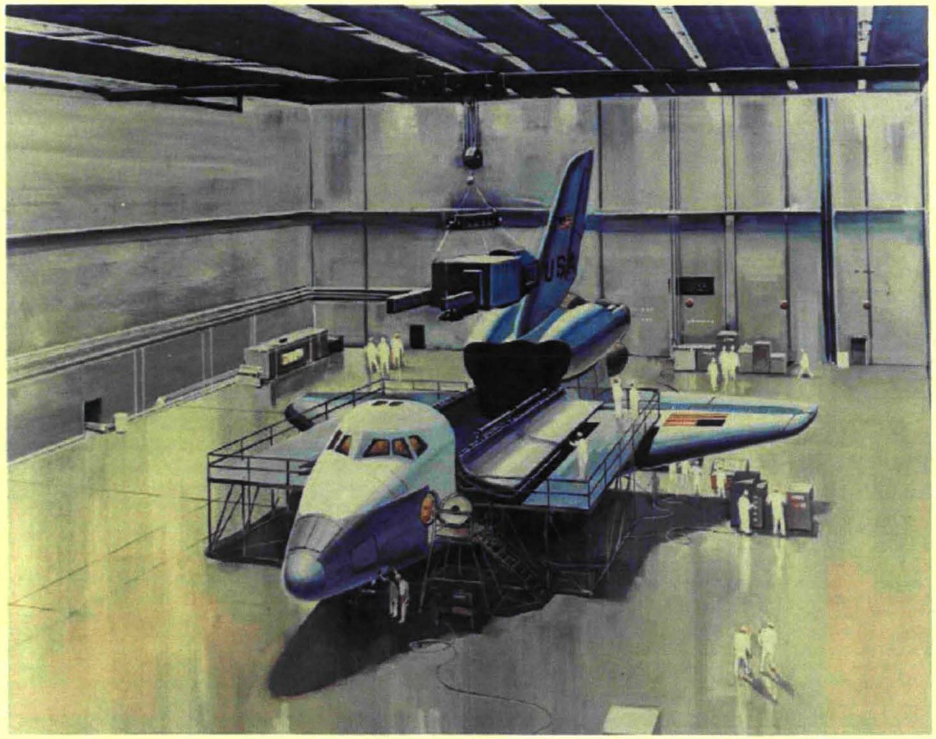
What are the causes?

My Personal Assessment
Root Cause Analysis

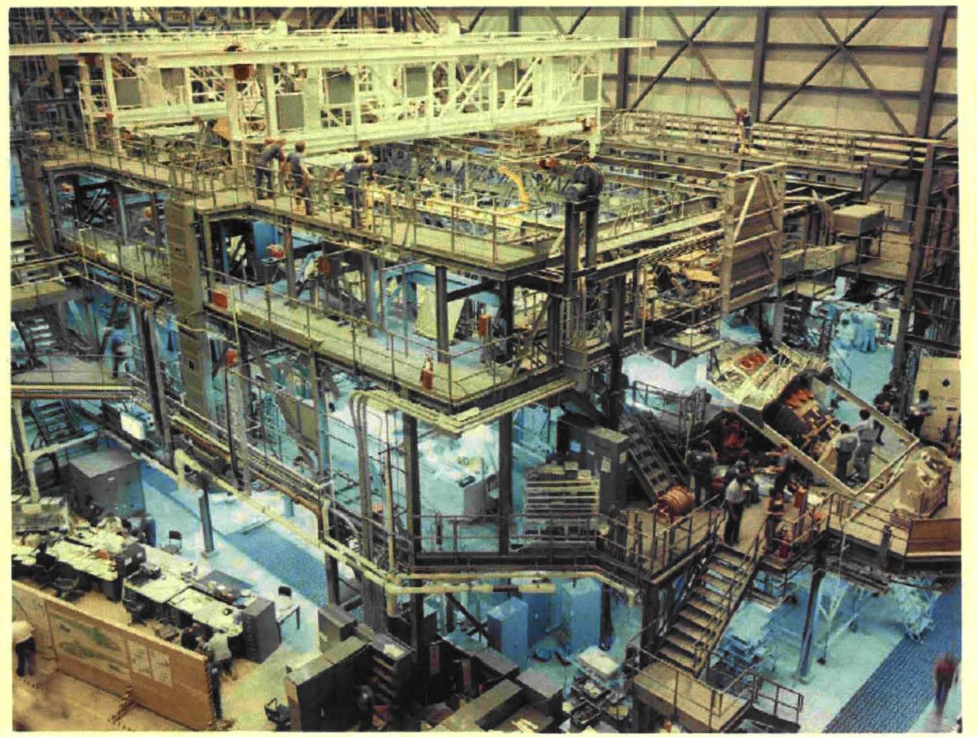


1. **Deliberate lowball estimates & optimistic assumptions**
   - ***Often with management "encouragement" to get project approved***
   - Once approved, and billions are spent, it's difficult to cancel project
   - Projects repeatedly understate required reserves
     - Despite history of overruns
     - What is there often transferred to other overrunning projects
     - When problems arise, money is "borrowed" from next task
     - Cash eventually runs out and, if more is not available, work gets delayed
     - Problems compound and project costs balloon
2. **Naïve**
   - Project optimistic about risks & ability to defeat technical challenges
     - Costs & schedules are based on best-case scenario and ignores risk impacts
   - Project always assume they will quickly overcome challenges
     - Problems that delay one task have ripple effect on next task, and the next one
       - Delays have associated cost impacts, such as keeping workers while awaiting resolution of big problems.
3. **Engineers want to build perfect systems**
   - Big difference in costs, and "good enough" is all that is required
     - Gets complex, and management cant or wont argue details
4. **Ignore/influence independent assessments**

Example of Assumption Problems



Shuttle Operations Concept 1974
What was estimated



OPF Today
What was built

Bad Assumptions = Bad Estimates

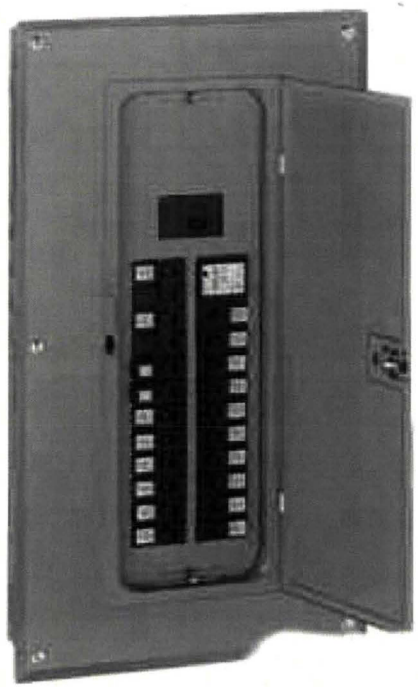
But we are Smarter Now!

& Better Looking!

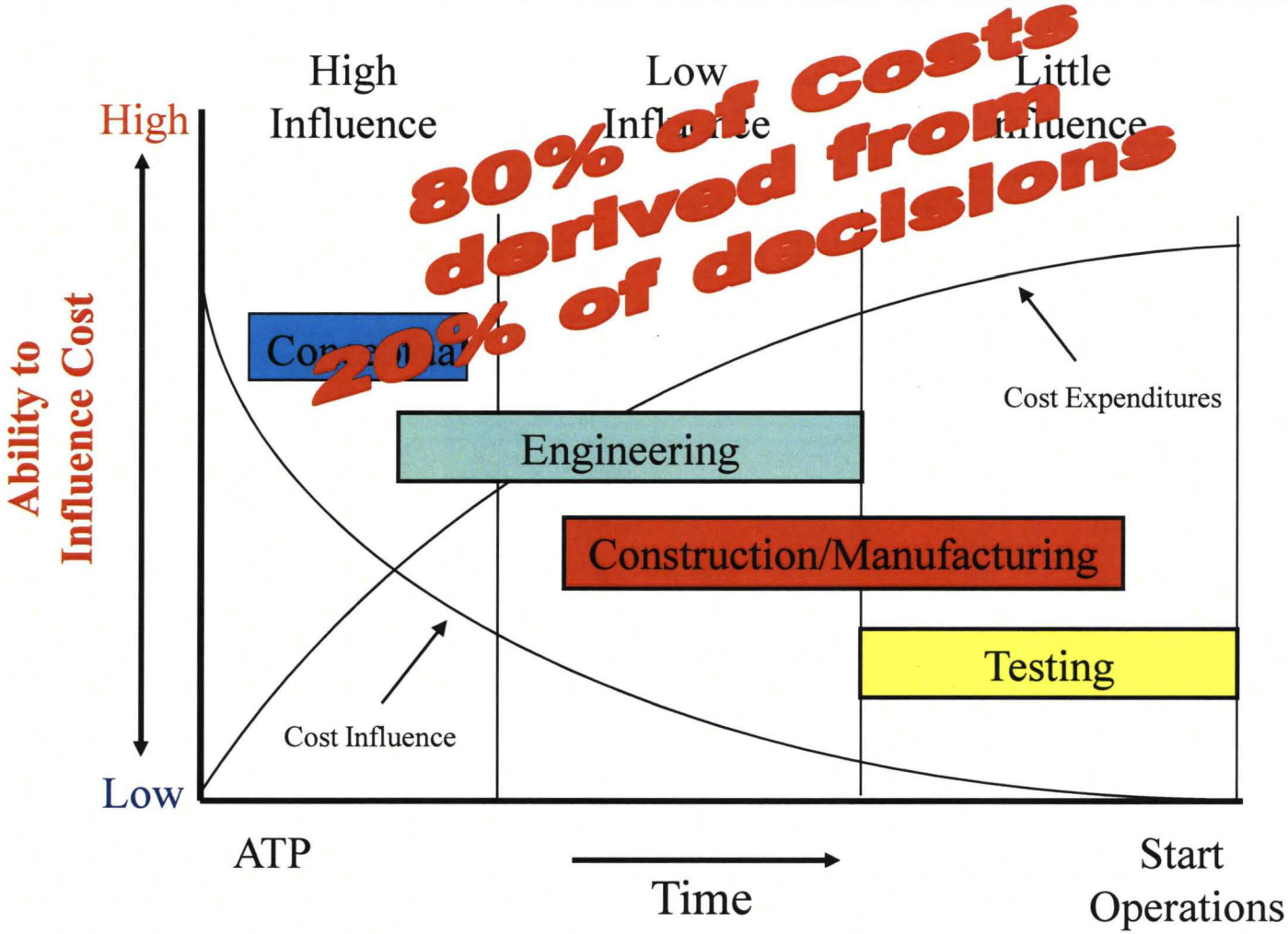
What is Good Enough?

- **Common for engineers to "gold plate" specifications**
  - They want a perfect system – This is safe
- **Example we built a 2,400 SF (223 SM) storage facility**
  - Engineers specified $18,000 electric panel when a $480 panel is more than adequate
  - **This is not a critical facility – Its for boat storage**





Early Design Choices
Affect Ability to Influence Costs



Rule of Thumb - The earlier a decision/change is made the lower the impact will be to schedule and budget and money


Avoid Change Orders!
Based on review of 5,000 change orders
Changes typically 25%–50% more costly than if incorporated early
Change Order
YAMAHA
Original Contract

Top Reasons Reality Exceeds Initial Projections

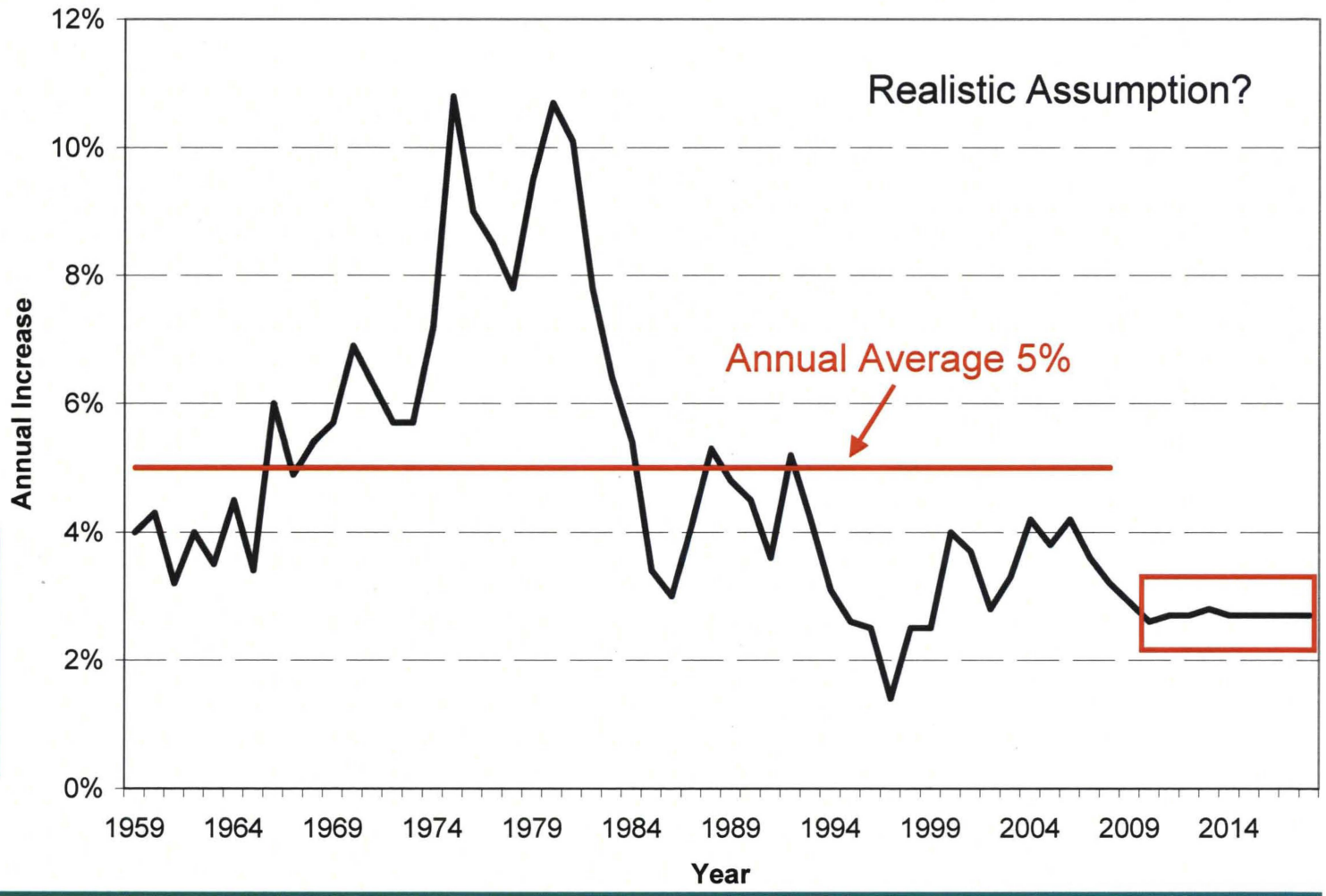


- **Planning Stage**
  - Budget is $100M so estimate has to be $100M or less
    - **Often driver of other issues**
    - Belief problems will be easily overcome
  - **Optimistic Assumptions**
    - Money will show up on time
    - We can use previous design from another project "as is"
    - Escalation will be low
  - Lack of accountability
    - Historically no real repercussions for overrun, but rewards for starting
    - Desire for perfection
  - We have to "hurry up" and award contracts to meet schedule
    - Initial schedule often politically set
  - Lack of adequate upfront planning
    - True requirements not clearly defined
    - Risks not identified
  - Insufficient contingency
- **Implementation Stage**
  - Deny existence of any problems as long as possible
  - Initial emphasis often placed on schedule
    - Drives shortcuts
  - Scope changes
    - "Desirements" creep in
  - Change orders required
    - Initial assumptions were optimistic & incorrect
    - Project not adequately planned due to schedule pressure
    - Zero cost change orders
  - Funding doesn't show up on time, or is cut
    - Big problem on international projects
  - Unintended consequences
    - the ripple effect
  - Lack of cost and schedule controls

Ignore/Influence Independent estimates

Escalation Assumptions Should be Realistic
NASA New Start Escalation Index

Rand - 1981 escalation accounts for 11.2% of project cost growth



88% probability assumed escalation will be exceeded

*"The current efforts to help revive the economy are **likely to produce inflation** that could be worse than what the country suffered in the late 1970s."*

Warren Buffett, March 2009

The Cost Of Change
Nothing is Free

- Every document, change, report, study, review, test, analysis, conference, telephone call, etc., has a cost in manpower & material. **All too frequently managers will delude themselves into thinking an action has "no cost" or "no impact"** when the true assessment would be that the action can be undertaken with a relatively small effort. Also, decisions to change an item are frequently made without a thought-out assessment of all aspects of the task & with only an assessment of the visible work involved.
- For example, when workshop was in the final stages of preparation, **a number of decals (containing operating instructions) were judged to be less clear than was possible.** When the final bill was known, **each decal change cost tens of thousands of dollars, all accountable**.** The visible task, removal of the old decal, the preparation & installation of the new, was only a few dollars, as you would suspect. However, good aerospace procedures were used & work orders had to be prepared & processed, the work had to be reviewed & inspected, the drawings had to be changed, the change had to be processed, drawing lists had to be modified, test procedures modified & reviewed, crew checklists had to be changed, & to all this, overhead costs had to be added.
- **Changing options, may reduce cost, but a price must be paid for everything.**
  - SKYLAB LESSONS LEARNED AS APPLICABLE TO A LARGE SPACE STATION, A dissertation submitted to the faculty of The School of Engineering & Architecture Of the Catholic University of America For the Degree Doctor of Engineering by William C. Schneider, Washington, D.C., 1976.

**Sticker changes cost in excess of 100K each in FY11 $

Don't Assume All Contractors Are Honest

Northrop Settles False Claims Case

Northrop Grumman Corp. has **agreed to pay $12.5 million to federal government to settle allegations that it submitted false claims** to government agencies in connection with electronic parts it supplied for navigation systems for military airplanes, helicopters and submarines.

Northrop's accused **of failing to test commercial-grade electronic components to ensure they would function at extreme temperatures required for military & space uses**.

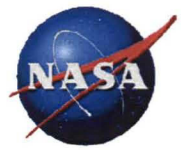
- **Number of DOD actions for contracting fraud FY01-FY10**
  - SAIC 139,331
  - Lockheed Martin 119,499
  - Northrop Grumman 99,454
  - Raytheon 76,515
  - General Dynamics 68,339
  - Boeing 51,856 Actions
  - Honeywell 55,078

"Rogue Contractors"

Pentagon Paid $998,798 to Ship Two 19-Cent Washers

- 2007 - Small South Carolina parts supplier collected ~$20.5 million over six years for fraudulent shipping costs, including
  - $998,798 to ship two 19-cent washers to Fort Bliss (Army base in Texas)
  - $455,009 to ship three machine screws costing $1.31 ea. to Habbaniyah, Iraq
  - **$293,451 to ship 89-cent split washer to Patrick Air Force Base, Florida**
- Exploited flaw in automated DOD purchasing system:
  - Shipping bills to combat areas or U.S. bases labeled "priority" usually paid automatically
- C&D & 2 of its officials barred in December from receiving federal contracts
  - Charlene Corley, 46, was fined $750,000.
  - Faces maximum prison sentence of 20 years on each count
- Fraudulent billing started in 2000
  - Started small & got more aggressive over time when invoices not questioned
  - **Purchase price** of items rarely reached $100 & totaled ~$68,000 over six years
  - **Total shipping charges** paid were $20.5 million
- Scheme Detected
  - In September after purchasing agent noticed $969,000 bill for shipping two 19-cent washers

Confirmation Bias



- **Philosopher Francis Bacon in 1620**
  - *"the human understanding, once it has adopted an opinion, collects any instances that confirm it, &* ***though the contrary instances may be more numerous & more weighty, it either does not notice them or else rejects them, in order that this opinion will remain unshaken****"*
- **People have an unjustified bias in favor of *their opinion***
  - Much tougher when critiquing validity of information that undercuts one of their currently held theories than they are in supporting information that apparently endorses one of their own tenets.
  - Employing this double standard, tend to dismiss information that doesn't fit with what they already believe.

Stating the Obvious



- **Estimates only as good as inputs provided**
  - In 2008 MIT surveyed 80 systems engineers
    - They were asked a series of questions that included
      - How many countries have McDonalds?
      - What is range of a Minuteman Missile in miles?
      - How long in minutes & seconds is song Stop in the Name of Love?
      - How many rulers has England had in the last 1,000 years?
      - How tall is Sears Tower in meters?
    - Asked large enough range to provide 90% certainty answer correct
      - Example - I am 90% sure that there are between 50 & 150 countries with McDonalds
    - 83% of Systems Engineers got 50% or less answers correct.
      - Worse in 221 times experts said they were 100% sure, only correct only 73% of the time
  - 1999 study of 27,000 expert predictions - did not vindicate their "expertness" as anticipated.
    - Error rates many times what experts predicted.
    - No advantage for experts holding advanced degrees.
- **Why is this important?**
  - If a system engineer tells you they are 90% certain about something - They will be WRONG much of the time!!
  - Base as many inputs as possible on objective data – not opinions

"In god we trust; all others must bring data" **Edward Deming**

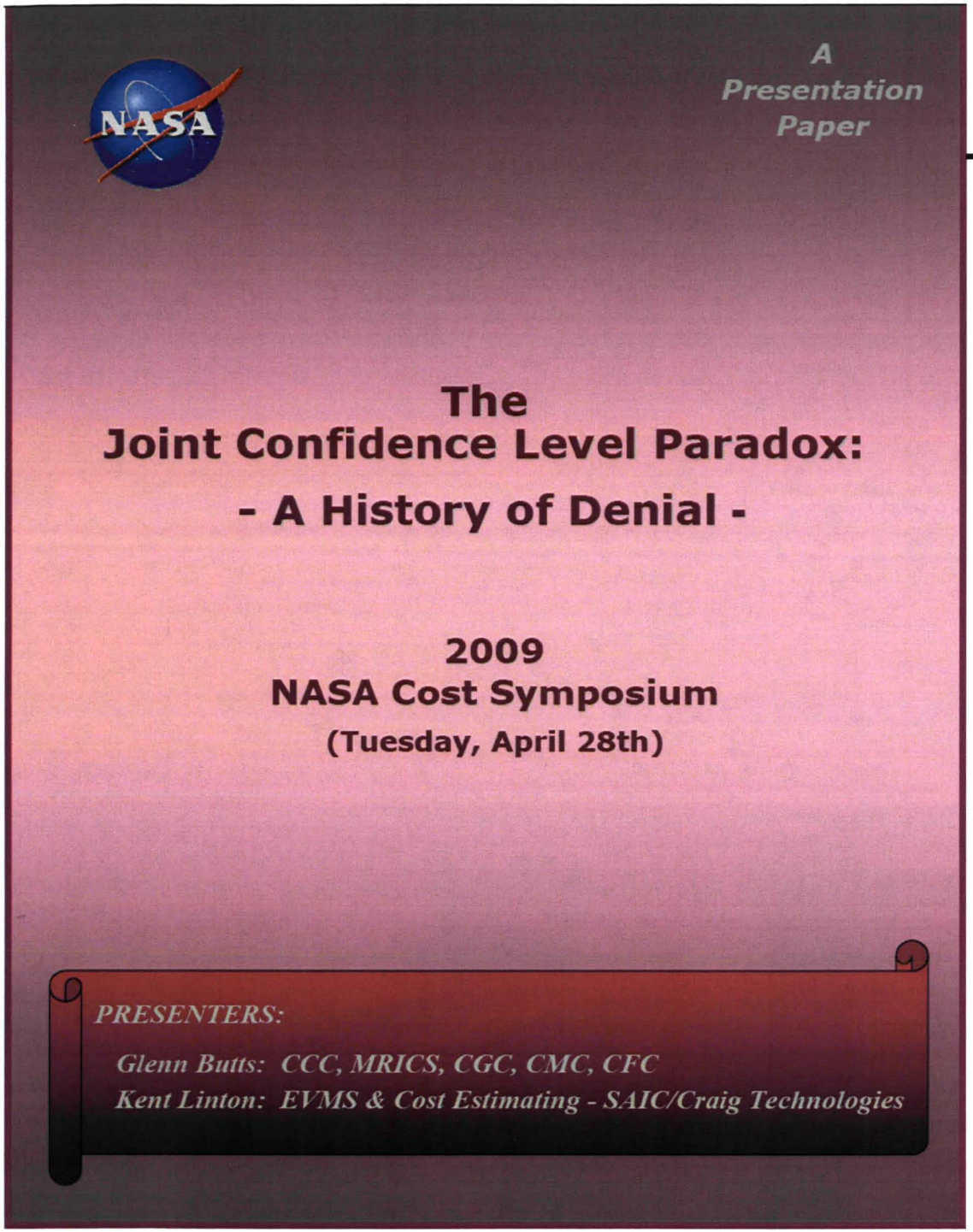
Conclusions

- **Presentation probably not what you expected**
  - Before you can get help you have to admit there is a problem
- **My crystal ball says there is a high probability that SKA will overrun current cost and schedule budgets**
- **I strongly suggest that project**
  - Build in options that can be easily cut, or done later, when problems arise
  - Do one or more independent assessments that are ***truly independent***
  - Have strong project management team with business background





Backup



- If you are interested in this topic, I wrote a 100 page paper on the subject
- Email me for copy
  - Glenn.C.Butts@nasa.gov

We Claim to Seek Accurate Estimates



- **Yet, we;**
  - Persist in submitting optimistic initial estimates
  - Omit probable scope from our estimates that often become "real."
  - Exclude credible risks from our analysis
    - SM&A actively mitigates risks with a likelihood of occurrence of only one in several thousand, & are supported by management.
- **Management mantra**
  - "if status quo is assumed, we will get the status quo"
    - Meaning status quo is too expensive
    - There are valid reasons for why things cost what they cost
    - Excuse for under-estimating projects
- **Possible conclusions:**
  - **Accurate estimates are impossible, especially at early stages**
    - The variables are too complex, unquantifiable, & incalculable - NOT
  - **We really don't want accurate estimates;**
    - Primary concern is keeping program viable & funded as long as possible
    - **Early estimates are deliberately misrepresented & meant to gain approval**

How Do We Underestimate?

- Let Me Count The Ways -

1. **OMIT PROBABLE SCOPE from estimate**
2. **OMIT POSSIBLE RISKS from analysis**
   - Internal & External
3. **UNREALISTIC, OPTIMISTIC assumptions**

} **Rand Study – Reason for 74% of Cost Growth**

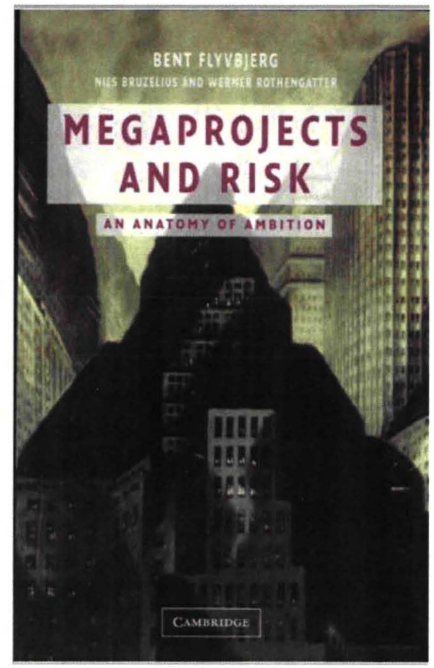
4. **Use historically LOW ESCALATION projections**
   - Rand Study – Reason for 11.2% of Cost Growth
5. **Issue cost estimates in BASE YEAR dollars**
   - Estimates should be in then year dollars (escalated to year in which it is spent)
6. **Many estimates NOT PREPARED BY A BONA FIDE ESTIMATOR**
   - Everyone's a estimator
   - Being certified no guarantee of having necessary experience
7. **REWARD failure, PUNISH honesty**
   - In my opinion many managers don't want good estimates
8. **NOT ENOUGH TIME to prepare CREDIBLE estimates**
   - Time often spent doing "what if" exercises, or splitting dollars into arbitrary buckets
   - Spend more time in reviews & defending estimates than preparing them

"I reject a system that rewards failure & protects a person from its consequences"

- Barack Obama -

Early Estimates are Often *Deliberate* Misrepresentation
Polite way of Saying Lying.....

- **Conclusions from the largest study of its kind:**
  - Examined 258 large ***transportation projects***
  - Underestimation has not decreased during past 70 yrs.
  - It was found with overwhelming statistical significance that cost underestimation cannot be explained by error.
    - "Is best explained by strategic misrepresentation, namely lying, with a view to getting projects started."
  - Cost overruns of 50% to 100% in real terms are common.
    - Overruns above 100% are not uncommon.
  - Accuracy is gained at each successive stage of progress.
  - Promoters routinely ignore, hide, or otherwise leave out important project costs & risks in order to make total costs appear low.

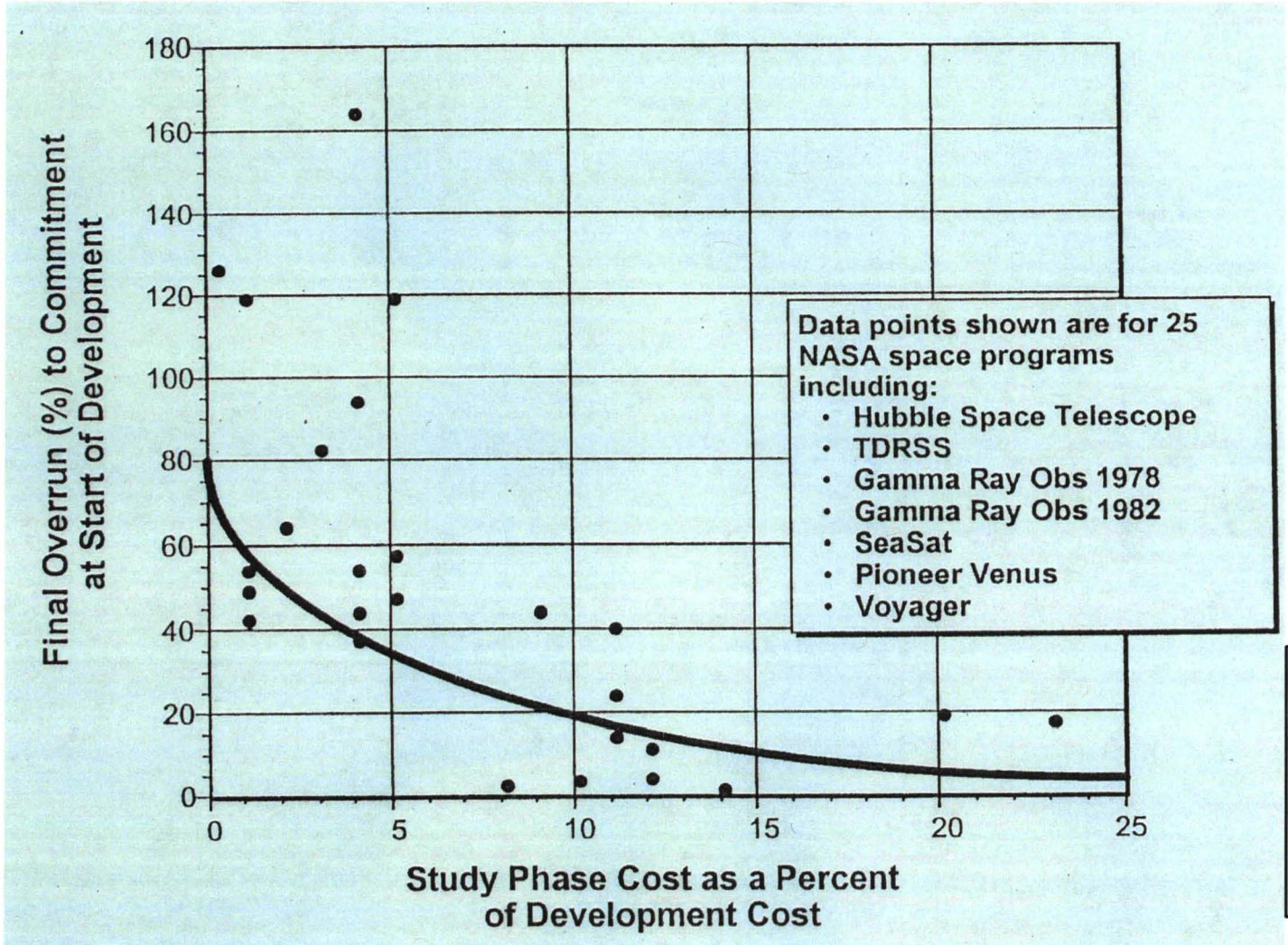


- Cost underestimation occurred in almost 9 out of 10 projects.
  - The likelihood of actual costs being larger than estimated is 86%
  - The likelihood of actual costs being lower than estimated is 14%

This study looked at comparatively simple projects.
Statistics for more complex projects would likely be worse!

Planning Stage

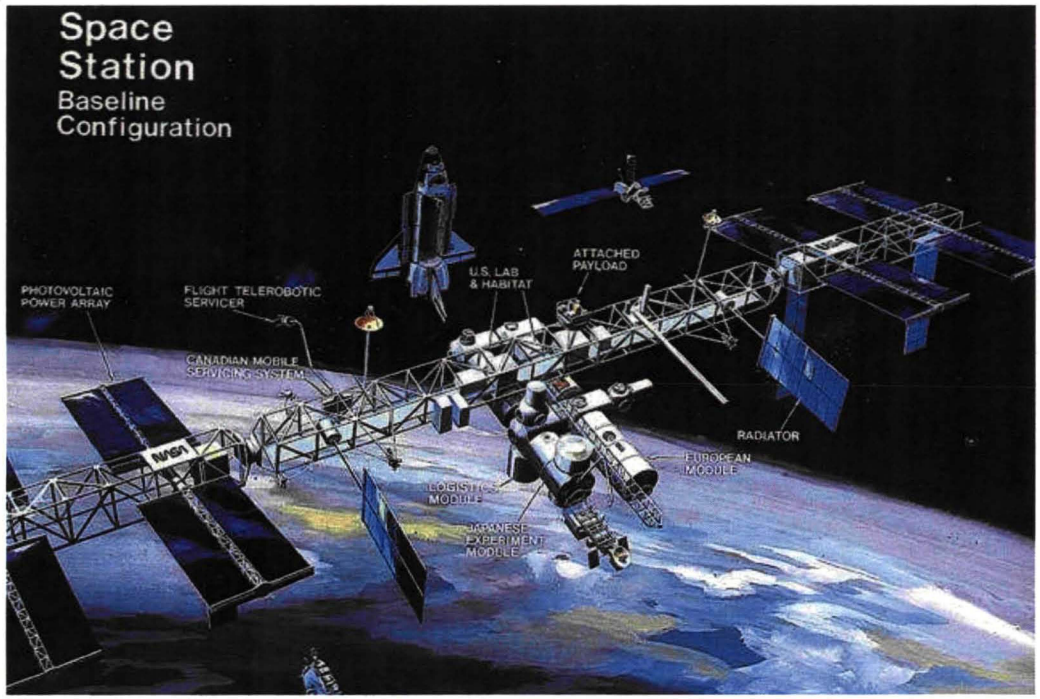
We don't adequately study project before we commit.
Don't want to "waste" money on studies.



Spending More Money During Early Phase = Substantially Less Cost Growth

International Space Station

- 1984 President Reagan directed NASA to build a space station within a decade and to invite other countries to join the endeavor.
- 1991 the US House of Representatives held the first of 22 separate votes on whether to proceed with the program.
  - As a result of overruns it came within 1 vote of cancellation in 1993.
- "For years the agencies cost overruns and schedule delays supplied ammunition for annual congressional attempts to kill the International Space Station" – Florida Today



Multiple International Partners Adds Complexity

- **The more partners the more risk is added to the project.**
  - If one partner has difficulties it often has ripple affects
  - ESA's way of doing business is even less efficient than NASA's because they have the added complexity of making sure on any given project all 18 member nations puts in funding for a given project that matches their percentage "ownership" in ESA.
  - This can often make their contracting more difficult because they just can't let Company X in Country A do something that they are most efficient at and instead have to let the work be done by Company Y in Country B to keep the percentages correct.



International Partners

- **The ISS**
  - "The U.S. developmental effort cannot be isolated from these occurrences and their associated impacts: the Program has experienced cost growth and schedule slippage associated with this broad level of international involvement." Source http://history.nasa.gov/32999.pdf
  - Another ISS resource about international partner risks – see Appendix C, International Participation. From http://oig.nasa.gov/congressional/testimony040401.doc
- **The ITER project**
  - "The expert panels identified a number of factors arising from significant changes in circumstances and the parameters of the work necessary and contributing to the increases of cost estimates between 2001 and 2008. The most important factors relate to: increased complexity of project integration in managing interfaces across seven ITER Parties (in 2001 only 3 Parties were foreseen to execute the project)" Source http://fire.pppl.gov/iter_europa_cost_050610.pdf
- **GAO report. From http://www.gao.gov/new.items/d09306sp.pdf**
  - "These partnerships go a long way to foster international cooperation in space, but they also put NASA projects in a vulnerable position when partners do not meet their obligations or run into technical obstacles they cannot easily overcome."
  - "Project officials also commented that Aquarius had changes to its baseline due to slips by its development partner, the CONAE, [Argentina] and that they believe the NASA contribution to this mission is on schedule for completion in March 2009. They added that the benefit of the international partnership, plus the groundbreaking information about the Earth's climate, out weigh the additional costs, which NASA has chosen to absorb within its budget.

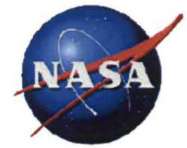
Report to the Committee on Science, House of Representatives
May 2004

GAO-04-642 Report @ http//www.gao.gov/cgi-bin/getrpt?GAO-04-642



- **"Lack of Disciplined Cost-Estimating Processes Hinders Effective Program Management"**
  - NASA lacks clear understanding of programs cost & schedules.
    - Estimates for more than half of programs reviewed have increased—as much as 94 percent.
    - Cost Estimates increased 80% of time
    - Variability in cost estimates indicates ***programs lacked sufficient knowledge needed to establish priorities, quantify risks, & make informed investment decisions, & thus predict costs.***
- **"NASA's basic cost-estimating processes—an important tool for managing programs—lack discipline needed to ensure that estimates are reasonable."**
  - None of programs reviewed in detail met all cost-estimating criteria.
- **"NASA has limited ability to collect program cost & schedule data needed to meet basic cost-estimating criteria."**
  - **NASA does not have a system to capture reliable financial & performance data—key to using effectively the cost-estimating tools that NASA officials state that programs employ.**
- ***NASA identified other barriers, including limited cost-estimating staff.***

GAO Cost Estimating Criteria



1) Objectives of estimate shall be stated in writing.
2) Life cycle to which estimate applies is clearly defined.
3) Tasks appropriately sized.
4) Estimated cost & schedule are consistent with demonstrated accomplishments of other projects.
5) Written summary of parameter values & their rationales accompany estimate.
6) Assumptions shall be identified & explained.
7) Structured process such as a template or format shall be used to ensure that key factors are not overlooked.
8) Uncertainties in parameter values are identified & quantified.
9) If schedule is imposed, estimate for normal schedule shall be compared to additional cost required to meet imposed schedule.
10) If more than one estimating approach is used, variances are analyzed & explained.
11) Independent assessment concur with the values & methodology.
12) Estimates kept current.
13) Estimates integrated with project planning & tracking.
14) EVM is used to manage program.

Basically – Good Processes & Documentation

Underestimates are Nothing New - *Quotes from 1964*

All but One from Apollo Executives Meeting

- *"I can think of a lot of programs in the Boeing Company where,* ***if the estimate had been realistic, you wouldn't have had the program, & that is the truth."***

  W. M. Allen - President, Boeing

- ***"You have basically built into the entire system a series of events which very much leads to under-estimating what the program is going to cost."***

  J. S. Parker - Vice President, GE

- ***"As advocates of new programs, government agencies have often encouraged contractors to estimate costs optimistically.***
  - *Recognizing that headquarters might be shocked out of supporting a program where true costs were revealed at the outset.*
  - *They have sought to disclose cost increases gradually, after programs have gained momentum & cancellation has become difficult."*

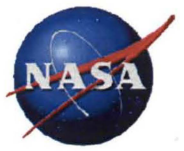
  Dr. Frederic Scherer - Harvard

- ***"We can give you estimates all the way to the end of the Saturn-IVB, but do you really want to know it?"***

  Donald W Douglas - President Douglas Aircraft

Underestimates documented back to 1869 – probably prior.

Common Causes of Cost Problems



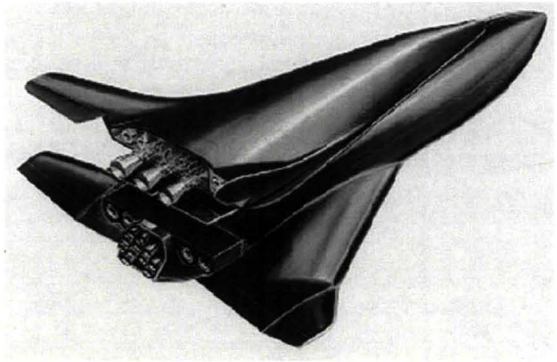
- Optimistic assumptions
- Poor estimating techniques/standards/processes
- Inadequate work breakdown structure
- Technology readiness
- Managerial edicts to reduce estimates by eliminating "fat"
- Inadequate planning that results in increased scope
- Requirements creep
- Unforeseen technical problems
- Schedule delays
- Inadequate workforce skill mix
- Contractor buy in
- Lack of historical data

Common Causes of Cost Overruns

- Failure to understand customer requirements
- Unrealistic assessment of current capabilities
- Underestimating time requirements
- Omissions (inadvertent or deliberate)
- Misinterpretation of information
- Inappropriate estimating techniques
- Failure to identify & concentrate on major cost elements
- Failure to recognize & plan for risks
  - Ignore external risks
- Pressure to compromise early
- Ceiling Costs
- Must win mentality (Success Oriented)
- Poorly written contractual requirements
- Proposal team different from Project team



Forgotten SPACE SHUTTLE Facts



- **Initially approved by 1 Vote**
  - Congress WAS concerned about estimates
- **FY 1972 Estimate**
  - DDT&E $5.5 Billion + 20% Contingency = $6.6 Billion
    - Contingency Reportedly Removed by Congress
  - Facilities $0.3 Billion
  - 1st Manned Flight projected by **June 1976** **(4 yrs.)**
- **Reality - 1982**
  - Total Cost $17.789 Billion
    - DDT&E $13.138 Billion
    - Production $ 3.900 Billion
    - **Facilities $ 0.703 Billion**
  - 1st Manned flight occurred in **April 1981** **(9 yrs.)**

"The chance of a Shuttle launch on November 20 1980 is probably 10 to 20%"
Dr. Frosch NASA - Administrator
Congressional Testimony 1980

- ***Increase WAS Foreseen . . .***
  - ***"Considering all of the technological & operational unknowns involved*** *in the shuttle development & the fact that no vehicles of similar function have ever been designed before or have ever operated over the range of flight regimes required for the shuttle, prudent extrapolation of prior experience would indicate that estimated development costs may be 30 to 50 percent on the low side. Thus, the estimates of $6.5 billion in RDT&E for the Mk I/Mk II shuttle program may range between $8.5 to $10 billion, reflecting increased program costs of $2.5 to $3.5 billion. Similar uncertainties must be considered to apply to other non-recurring costs such as production & facilities (amounting to about $4 billion). Thus a possible cost uncertainty of about $5 billion for total program costs might be envisioned giving* ***a high estimate of total non-recurring cost of about $15 billion."*** ***- October 1971 Report -***

Were to Start? – Elements That Influence Costs



- **What – is project scope?**
  - What are boundaries of work
  - Who will do required work outside boundaries?
- **Who – will do**
  - **Design?**
    - Self
    - On call A&E
    - New A&E
    - On board Support contractors
      - Self perform work
      - Sub out
  - **Work? – FFP or Cost Plus**
    - On board support contractors
      - Self perform work
      - Sub out
    - General Contractor
    - General Contractor & Sub Contractor's
- **How – will project be bid?**
  - Full & open
  - Source board
  - IDIQ
  - Sole source
    - 8a - Disadvantaged
    - Support contractor
    - Other
  - Best value
  - Design build
  - Cost plus
- **Where – will project be done**
  - On center
  - Off center
    - Costs may change with location change
- **When – will the project be done**
  - Required for escalation calculations
  - Anticipated market conditions
    - Negative or positive

Point

Details Matter!

Backup
Misc Projects Lessons Learned

CLCS Summary - Lessons Learned
$400 M Software Project

Huge Overruns Project Canceled

1. Independent Project Oversight
   - Vigorous independent review process critical to ensure early warning to senior management.
     - Senior management must follow-up on independent reviews & control performance
2. Control Project Requirements
   - Control requirements early & ensure understanding of them between stakeholders
   - Must be placed under configuration control – with no changes unless through analysis is done
     - Any changes must be carefully balanced by cost, development & operational risks
3. Risk Management Mitigation
   - Clear identification of each significant risk, their probability of occurrence, impact of risks on project, & clear plan for risk mitigation are critical to project success
   - Cultural impediment to implementation are significant and must be overcome
   - Implement periodic validation of risk assessment by group external to the project
4. System Integration & Performance Management
   - Implement an effective Systems Engineering group to be responsible & accountable for systems design, integration, performance analysis & verification
   - Lack of early planning manifests itself in cost overruns, failed acceptance testing, slipped schedules, and disruption of planned integration of interfacing systems.
5. Milestones
   - Project milestones must explicitly defines what capabilities are included in each
6. Communications
   - Project managers must focus on meeting approved requirements while controlling cost & schedule.
   - Communication, requirement definition & integration should be prime management metric.
7. Estimating
   - Sound cost & schedule estimating early, including a bottoms-up cost estimate, coupled with use of accurate performance management system is essential to meeting project goals.
8. Contract Vehicle
   - Contracts should be structured such that performance on important work has an overall effect on performance award.
   - Caution should be utilized such that the conflict of interests are created

NASA continues to relearn lessons already learned from the past.

A3 Lessons Learned



- **Phased Funding**
  - Not delivered when promised
    - Drove segmenting of bid packages
  - Budget cut
    - Have de-scope options planned ½ SKA?
- **Requirements**
  - Geographically separated teams maintain separate requirements documents
    - Drove Change Orders & Schedule slips
      - LOX barges pumps changed, new requirement for VFDs. Great impact to electrical power systems (requiring larger diameter wiring, conduit, etc). However, decision NOT coordinated with A-3 project.
  - All not available until design 30% complete – Impact cost and schedule
  - Concept, schedule & budget locked before all requirements known
    - Initial concept did **NOT** include plans for buildings to house electronic equipment required for facility control & capturing test data.
    - Planned availability dates for **necessary** buildings not incorporated into overall project schedule making it extremely difficult to plan for installation, verification, and activation tasks
  - Not reviewed by ALL the necessary stakeholders
  - All "rated" equally – some critical, some are not – all could not be met
    - Vendors unaware of importance did not meet some requirements with proposals
  - Project data maintained on three different database systems
    - Everyone does not have access to all systems, so data duplicated & not always updated

A3 Lessons Learned

- **Design changes**
  - Result of review comments and resulting in scope growth/cost growth
  - Design schedule difficult to maintain with changing scope
  - Cryogenic tanks resized due to high bids – driven by transportation costs
    - Drove changes to other systems
    - Original size tanks could have been shipped by barges, not investigated
  - Design errors / conflicting data
    - Driven in part by schedule, in part by late stage design changes
- **Rush to maintain schedule/budget**
  - Required contract awards before design complete – caused cost of some contracts to double
  - Defer factory work to field, where skills not always available to perform
  - Company who will install items did not order them
    - When they arrived late, installation contractor got change order
    - Another company responsible for transportation
  - Preliminary System Hazard Analysis was not performed in concept phase
    - Drove later changes to mitigate hazards
  - Short timeline on requests for budget / schedule actions
    - Does not provide sufficient time to properly evaluate requirements & formulate plan
      - Example - request to provide estimate for Low Speed Video System in one day
      - Subsequent costs were higher, and additional funding difficult to obtain

A3 Lessons Learned

- **Bureaucracy**
  - Nine months to order equipment, delivery only took 6-8 weeks after order finally placed
    - This occurred on small orders $150K & less
    - Small contracts should be treated differently than big ones
  - Excessive regular meetings that project consume time which could be applied to productive work
    - Three to six meetings a week in various forums, does not allow sufficient time to perform project actions
  - Failure to utilizing remote meeting capability effectively
    - It good to have face-to-face meetings yet as a project progresses, travel times for meetings can impact delivery schedules
    - Use of internet format meetings allows sharing of technical documents with minimal interruptions to productive work
  - Regulations on contract value limits drove splitting of bid packages into small packages
    - Increased confusion
    - Increase coordination work on project team
- **Risks**
  - Optimistic initial estimates by people with vested interest in gaining project approval
  - Failure to accept independent cost assessment
    - Exerted pressure to force retraction and agreement with projects number
  - Hurricane Katarina
    - Due to rebuilding efforts costs were substantially higher than estimated
- **Other**
  - Coordination of multiple contracts on scope & availability sometimes a problem
    - If project was one large fixed price contract you know who has scope
      - Items in design don't get lost in the shuffle

Lessons Learned



- **Project Formulation**
  - Watch out for unrealistic cost and schedule estimates resulting from:
    - Inaccurate/incomplete understanding of requirements for spaceflight end items
    - "low balling" in order to get an ATP
    - an overrating of the technology maturity
- **Procurement**
  - Never agree to a cost plus fixed fee contract for a research, design and development effort
    - The contractor bears no risk -- it's all on the government
    - The government has no leverage with the contractor -- no incentives (positive or negative) for addressing problems

Lessons Learned

- **Project management**
  - Contractor Project Manager should have a proven track record (deliveries, communications, risk management)
  - Don't skimp on oversight functions -- match each major contract skill/function with an accountable government counterpart
  - You must have reliable, accurate, and timely cost reporting
  - Pay close attention to environments:
  - Perform functional testing in relevant environment to the extent possible
  - For situations you can't thoroughly test for, do "what if" study to find possible effects and solutions
  - Don't ignore quirky test data -- it may be telling you something important
  - Develop back up plans for all reasonably possible contingencies
  - Conduct comprehensive failure or anomaly investigations
  - Take whatever action is necessary to control the contractor -- be prepared to descope or terminate
  - Take risks for good reasons and with management's buy-in
  - Trust dedicated, "can do" team members to come up with creative solutions to issues

Operational Lessons Learned from NASA Analog Missions

Larissa S. Arnold

December 1, 2010

ABSTRACT

National Aeronautics and Space Administration's (NASA) efforts in human space flight are currently focused on the Space Shuttle and International Space Station (ISS) programs, with efforts beginning on the future exploration opportunities.

Both the Space Shuttle and ISS programs are important to the development of a capability for human exploration beyond Low Earth Orbit (LEO). The ISS provides extensive research capabilities to determine how the human body reacts to long duration stays in space. Also, the ISS and Shuttle can serve as a limited testbed for equipment or entire systems that may be used on missions to the Moon, Mars, or to a near-Earth asteroid.

It has been nearly 35 years since the Apollo astronauts visited the Moon. Future space explorers will have to re-learn how to work and live on planetary surfaces, and how to do that for extended periods of time. Exploration crews will perform a wide assortment of scientific tasks, including material sampling and emplacement of automated instruments. Surface mission operations include the activities of the crew living and working, mission support from the Earth, and the operation of robotic and other remotely commanded equipment on the surface and in planetary orbit. Other surface activities will include the following: exploring areas surrounding a habitat; using rovers to collect rock and soil samples; setting up experiments on the surface to monitor the radiation environment and any seismic or thermal activity; and conducting scientific analyses and experiments inside a habitat laboratory. Of course, the astronauts will also have to spend some of their surface time "doing chores" and maintaining their habitat and other systems.

In preparation for future planetary exploration, NASA must design the answers to many operational questions. What will the astronauts do on the surface? How will they accomplish this? What tools will they require for their tasks? How will robots and astronauts work together? What vehicle and system capabilities are required to support the activities? How will the crew and the Earth-based mission control team interact? During the initial phases of manned planetary exploration, one challenge in particular is virtually the same as during the Apollo program: How can scientific return be maximized during a relatively short surface mission?

Today, NASA is investigating solutions to these challenges by conducting analog missions. These Earth-based missions possess characteristics that are analogous to missions on the Moon or Mars. These missions are excellent for testing operational concepts, and the design, configuration, and functionality of spacesuits, robots, rovers, and habitats. Analog mission crews test specific techniques and procedures for surface field geology, biological sample collection, and planetary protection. The process of actually working an analog mission reveals a myriad of small details, which either contribute to or impede efficient operations, many of which would never have been thought about otherwise. It also helps to define the suite of tools, containers, and other small equipment that surface explorers will use.

This paper focuses on how analog missions have addressed selected operational considerations for future planetary missions.

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John F. Kennedy Space Center
SPACEPORT ENGINEERING AND TECHNOLOGY

Orbiter Lessons Learned

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ASRC Aerospace Corporation

Kennedy Space Center

National Aeronautics and
Space Administration

ASRC Aerospace Corporation

Why Projects Succeed

- A close, interactive relationship is developed early in the project between the technology provider and the end user
- The problem and prospective solutions are clearly identified and well defined. This normally required multiple iterations.
- The solution demonstrates that:
  - It works satisfactorily in the relevant environment
  - It presents no danger or interference to existing systems.
- The provider remains involved with the user through installation, acceptance testing, and acclimatization of the new technology.

Steps in Transitioning a Low TRL Design to a Certifiable Product

- Establish a team composed of the product developer, the end user, and the GSE responsible organization.
  - Access experts as required (safety, reliability, etc.)
- Jointly develop a detailed set of requirements.
  - Performance, physical, environmental, safety, reliability, maintainability requirements
- Establish qualification process to certify product.
- Define documentation requirements for qualification process.
- Establish a quality control process to monitor the design, fabrication, testing, and integration of the product into the vehicle or ground system.

Requirements Considerations

- Performance
  - Levied by end-user. Identify specific parameters and tolerances.
- Physical
  - Size, weight, volume, mechanical and electrical interfaces.
- Environmental
  - Determined by mission to be performed: vibration, shock, corrosion, radiation, thermal management, etc.
- Safety and Reliability
  - Established by end-user. Assess materials compatibility early. Intrinsically safe designs for hazardous envoronments.

Flight Certification Processes

What is Flight Certification?

Flight certification is the process by which a system (hardware and/or software) is certified to be safe, functional, and meet all Space Shuttle requirements.

What do I need to do to certify my system?

There are several different ways to certify your system for flight in space. The process used depends on how your system is classified and where it will be installed.

Examples of these processes are:

- Standard Payload Process
- Government Furnished Equipment (GFE) Process
- Orbiter Hardware Process

What is the difference between the processes?

At a top level the processes are very similar. All of the processes are designed to ensure that the system is safe, is able to perform its function reliably, and will survive in the space environment.

At the detail level different processes will require interfacing with different organizations and complying with different (although similar) documentation and requirements.

The differences between the processes are largely due to programmatic differences and differences in the environmental requirements for the locations where the hardware is installed.

Typical Flight Certification Process

- Request Flight Assignment [1]
- Develop Requirements:
  - Developer supplied functional and operational requirements
  - NASA supplied workmanship, safety and environmental requirements [2]
  - Existing Interface Control Document (ICD) for existing systems being interfaced with
- Develop Preliminary Design -> PDR
- Prepare a Payload Integration Plan (PIP) (Payload Process Only)
  - Defines the Shuttle Program and customer responsibilities
  - Defines the technical baseline for implementation
  - Establishes guidelines and constraints for integration and planning
- Develop Interface Control Document (ICD)
  - Developer creates an Interface Definition Document (IDD)
  - Program creates an ICD based on the IDD (Payload Process Only)
- Phase-0 Flight and Ground Safety Reviews
  - Optionally conducted to allow the customer the opportunity to ask questions about the safety process and issues as early as possible in the design process. (Payload Process Only)
- Develop Models
  - Thermal, Structural
- Perform Preliminary Technical Analysis

Typical Flight Certification Process

- Conduct Phase-I Flight and Ground Safety Reviews [4]
  - First required safety meeting.
  - Purpose: To identify all potential hazards and hazard causes inherent in the preliminary design, to evaluate the means of eliminating, reducing, or controlling the risk, and to establish the preliminary method for safety verification.
  - A Payload Safety Data Package and Ground Safety Data Package are developed
  - Data packages are submitted to the appropriate Safety Review Panels for approval
- Develop Detailed Design -> CDR
- Conduct Phase-II Flight and Ground Safety Reviews
  - The purpose of the phase II safety review is to obtain PRSP/GSRP approval of the updated Safety Data Packages that reflects the Critical Design Review (CDR) level design and operations scenario of the payload.
- Fabricate Qualification Unit
- Initiate Acceptance Data Package (ADP) for qualification units
- Perform Acceptance Testing on Qualification Unit
- Perform Qualification Testing on Qualification Unit
- Prepare Certification Data Package

Typical Flight Certification Process

- Perform Phase-III Flight and Ground Safety Reviews
  - The final Safety Data Packages are prepared and submitted to the appropriate Safety Review panels for approval. The focus of this review is to assess safety verification testing and analysis results.
- Fabricate Flight Unit(s)
- Perform Acceptance Testing on flight units
- Conduct System Acceptance review (SAR)
- Install in Orbiter
- Certification Of Flight Readiness (COFR) Process
- Perform preflight tests (Includes any tests required to mitigate hazards)
- Launch

Flight Certification Lessons Learned

- Materials selection is critical. Certain materials can cause hazards in the space environment that are not apparent in the ground environment. Be sure to address this early.

- Involve the NASA safety community early (conceptual design if possible). Certification problems are often found late in design that could have been easily and less expensively avoided if they were known early.

- Involve ground and flight operations personnel early. These are the people who will be installing and operating your experiments. They understand the vehicle and support systems that will be required to support your experiment. They have seen many pitfalls and can help you avoid them.

- Be aware of the "clash of cultures." Scientist like to build the most scientifically perfect system possible regardless of the time it takes. Flow managers like to ensure that all experiments are integrated in the timeframe necessary to ensure the overall mission launches on time. (i.e. flow milestones do not move easily)

Flight Certification Lessons Learned

- Many references are available to help you understand the process:
  - Payload Web: http://shuttlepayloads.jsc.nasa.gov/flow/overview/overview.htm
  - NSTS 1700.7 "Safety Policy and Requirements for Payloads Using the STS"
  - JSC 28484 "Program Requirements Document for JSC Non-Critical GFE"
  - JSC 17038 "Flight Equipment Non-Critical Hardware Program Requirements Document"
  - SSP 50345 "ISS Non-Integrated Criticality 3 Generic Requirements Document"
  - JSC 26626 "EVA Generic Design Requirements Document"

Personal Air Vehicles Lessons Learned

Mark D. Moore
NASA Langley Research Center
Systems Analysis Branch



No ITAR Restrictions - Public

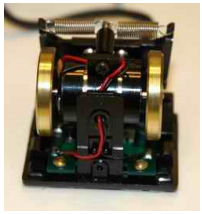
What's Changed in 10 Years

Cockpit Avionics
- Navigation
- Communications


Garmin G300


Cessna SkyCatcher

Digital Sensors and Systems
- Vehicle Intelligence
- Control

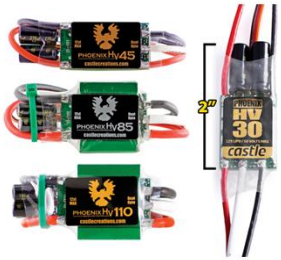




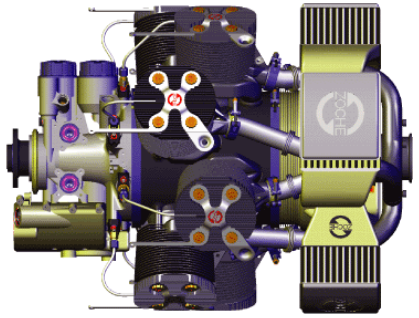
Prior generation mechanical gyro vs.
Current piezo crystal miniaturized gyro
(smaller, lighter, less power, reliable, cheap)

Electric Motors/Controllers
- Scale-Free Power
- Distributed Power Solutions





Heavy Fuel Engines
- Small Turbines
- Lightweight IC Engines

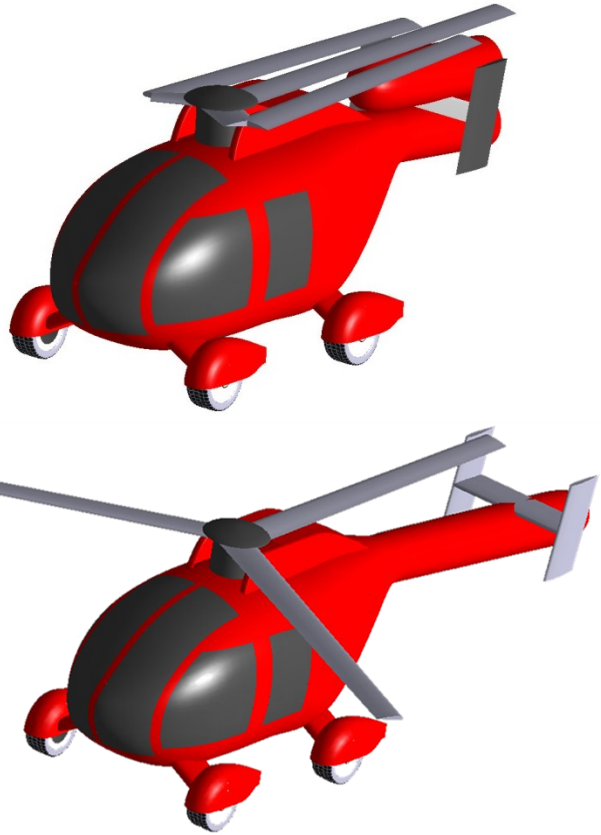


Highly Coupled Aero-Propulsive-Control Analysis

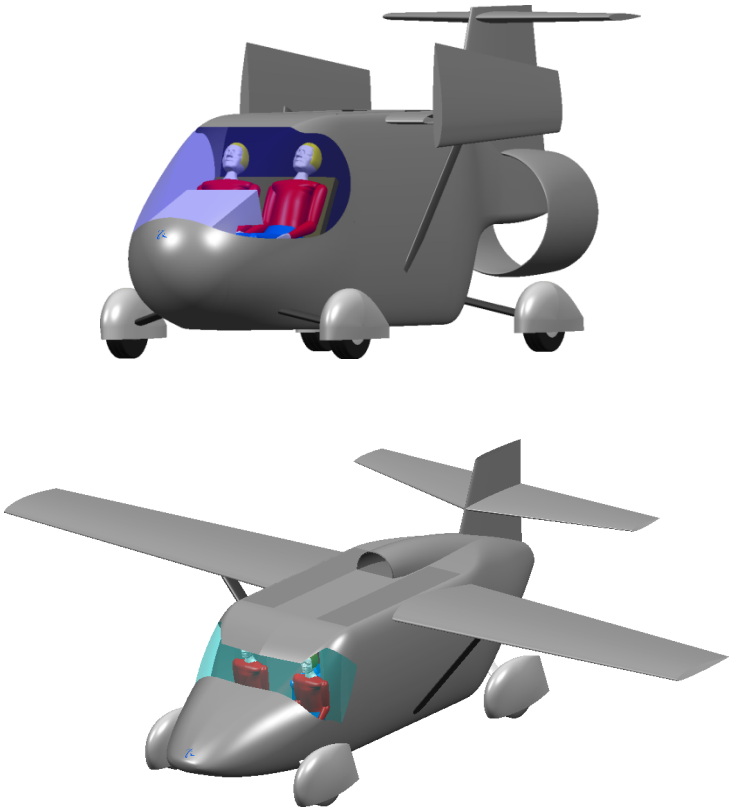
Noise Can't Be Wished Away

Dual Air-Road VTOL Concept Study, 2002

MD500 NOTAR-based Concept



Pulsed Ejector Thrust Augmentor (PETA) Concept



Information from "Dual Air-Road Transportation System (DARTS)" Public SAE Presentation, Nov 7 2002

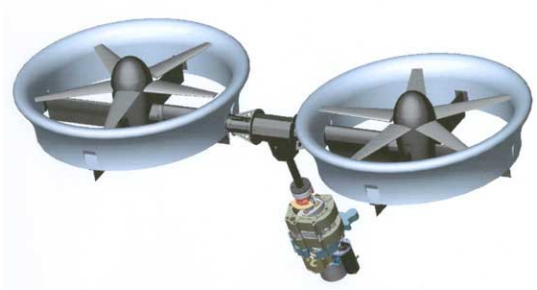
Not All Ducts are Created Equal

DARPA SoloTrek VTOL Demonstrator, 2004

Disc loading ~ 35 lb/ft2
Thrust / HP ~ 7.6 lbf/hp



NASA Tailfan
Low Noise
Duct, 2006



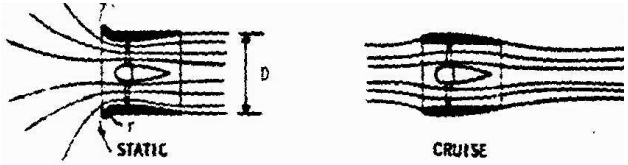




Disc Loading Rules

Tilt-Nacelle VTOL Concept Study, 2004

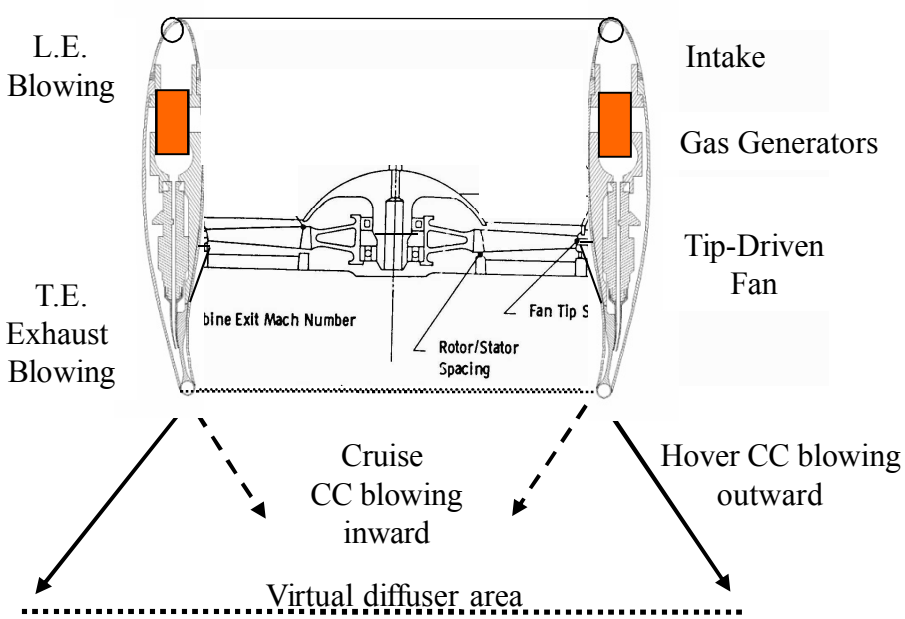
Problem: Ducted VTOL concepts suffer from the nacelle requiring two different shapes for best static and cruise performance.



Cruise and Hover Nacelle Shape Mismatch

Use of circulation control on inlet lip and diffuser could provide

- Cruise shaped nacelle to act as a bell mouth at static
- Increase duct lip suction at static (sizing) condition
- Increase effective exit area and mass flow in hover
- Decrease downwash velocity on ground plane
- Prevent flow separation in V/STOL transition
- Lower cruise spillage drag with turn down





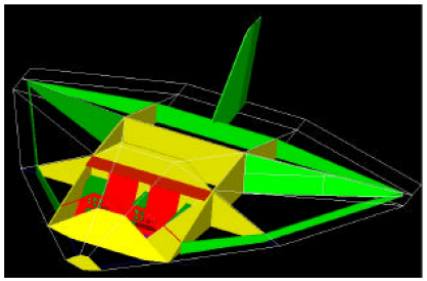


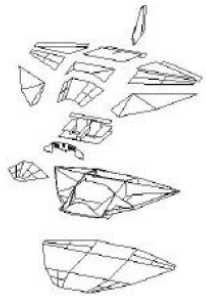
Quantity Has a Quality of It's Own

Design for Affordability, Tailfan Study, 2005

- Lean design to reduce touch labor
- Designed for automated manufacturing (higher production volumes than typical aircraft production)
- Use of COTS products
- Extensive use of symmetry for reduced parts count
- Simplified concepts for minimum gage structures
  - Foam core composite
  - Honeycomb composite
  - Spanwise and chordwise beading to achieve skin-stiffened structures

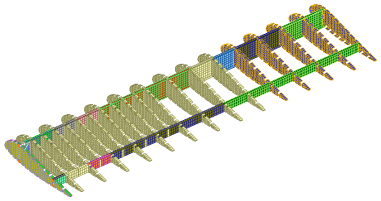


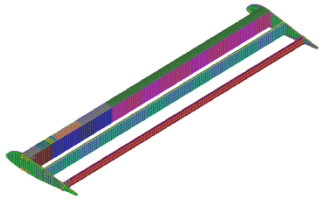


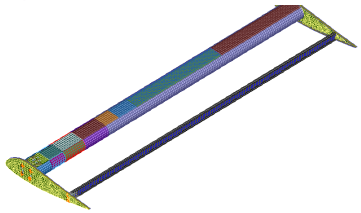


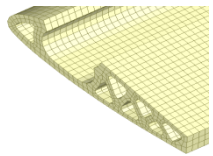
NASA STTR Facetmobile Conceptual Study









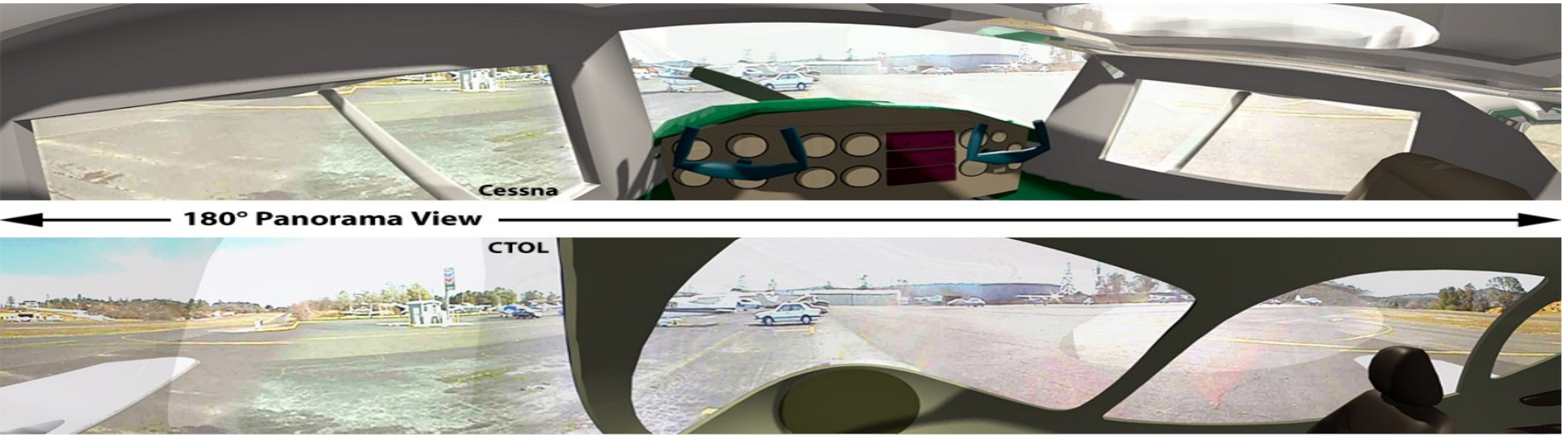


Don't Forget the Ilities

Many other factors

- Visibility critical for safe VTOL operations
- TO/Landing footprint
- Ground personnel safety
- Cabin environment NVH
- CG variability
- Mission flexibility
- Vehicle robustness and damage tolerance
- Altitude, temperature sensitivities





Electric Propulsion is a VTOL Enabler

- *Problem*: Small VTOL aircraft platforms are plagued with mechanical powertrain problems due to small turbine and reciprocating engines integration issues; resulting in complex, inefficient, noisy, and poor performance vehicles which are not capable of satisfying the current and future mission needs.
  - Poor efficiency and reliability of small engines, must be designed to accommodate engine-out through cross-shafting to multiple propulsors, highly sensitive to altitude and temperature, power only available at a single rpm, …
  - High VTOL power requirement is for less than 2 minute duration, with throttle down to 20-30% power for endurance missions.
  - High / Hot capability degrades air breathing engines by up to 30%
  - VTOL missions are typically in close proximity to people, so noise is a key concern.
- *Solution*: Electric propulsion offers a scale-free technology integration path, with new degrees of aircraft integration freedom.
  - Scale-Free: Electric motors have the same efficiencies (>90%) and power to weight (2 hp/lbm) across large changes in size (from 1 hp to 300 hp).
  - New Integration DOF: Able to design highly redundant propulsion systems that eliminate need to cross-shaft, able to design entire system for low noise.

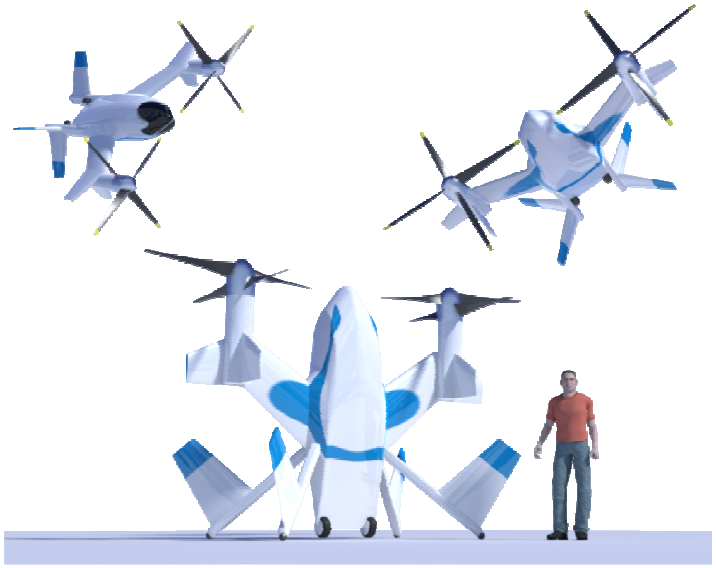
Electric Propulsion is a VTOL Enabler

Puffin VTOL Tailsitter Study, 2009

- Gross weight ~600 lb
- Useful load of 280 lb
- Hover power 60 hp
- Control power margin up to 120 hp (2 min)
- Cruise power 20 hp
- Cruise speed 150 mph
- Cruise L/D 14.5
- Cruise Range 50 nm with SOA batteries
- High altitude dash of 300 mph @ 30k ft

Electric Propulsion Attributes

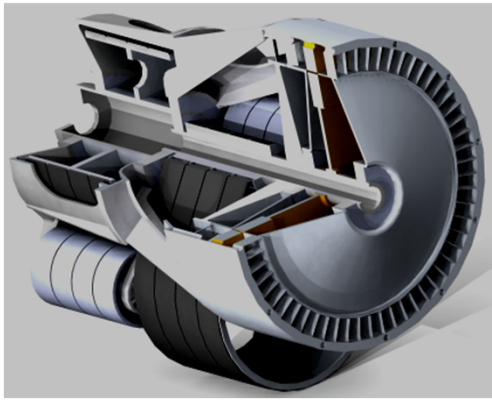
Extremely Quiet
Scale-free Integration
Safety through Redundancy
Low Cooling Drag
High Reliability
No thrust lapse with altitude
No warm up ground idle delay
Variable RPM Capability
Permits Low Tip-Speed Cruise

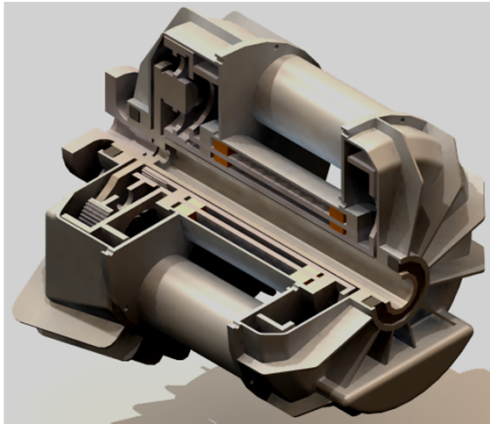


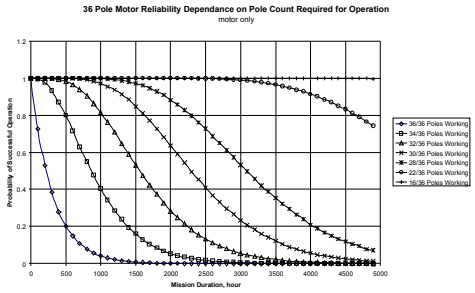


Electric Propulsion is a VTOL Enabler

- Designed 5 Redundant Electric Motor Systems
  - Integral motor and gearbox to achieve 30 hp at 500 rpm
  - Ring motors without gear reduction were shown to be infeasible at this power level (too heavy/power, too large of diameter for the required rpm).
  - 36 Pole Motor with Belt Drive weighs 28.6 lbs, 92% efficiency, can fail up to 4 poles and/or half of belts and still produce full power. Failure of 5th pole permits rated power for 2 minutes prior to thermal runaway.
  - Quad Motor with Planetary weighs 58.0 lbs, 92% efficiency, can fail 1 motor and/or a single gear planet and still produce full power. Failure of another motor permits rated power for 2 minutes prior to thermal runaway.
- Analysis to Satisfy FAA Multi-Engine Reliability
  - Fault tree analysis utilizing Navy reliability tool set, including individual component by component build-up to capture parts count, complexity, and failure rates of specific components.
  - Reliability during 1st 500 hour period of 99.8% (with no inspections or replacement during that period), with probability of success (no subsequent critical failure during 2 minute period emergency period) of 99.99997.

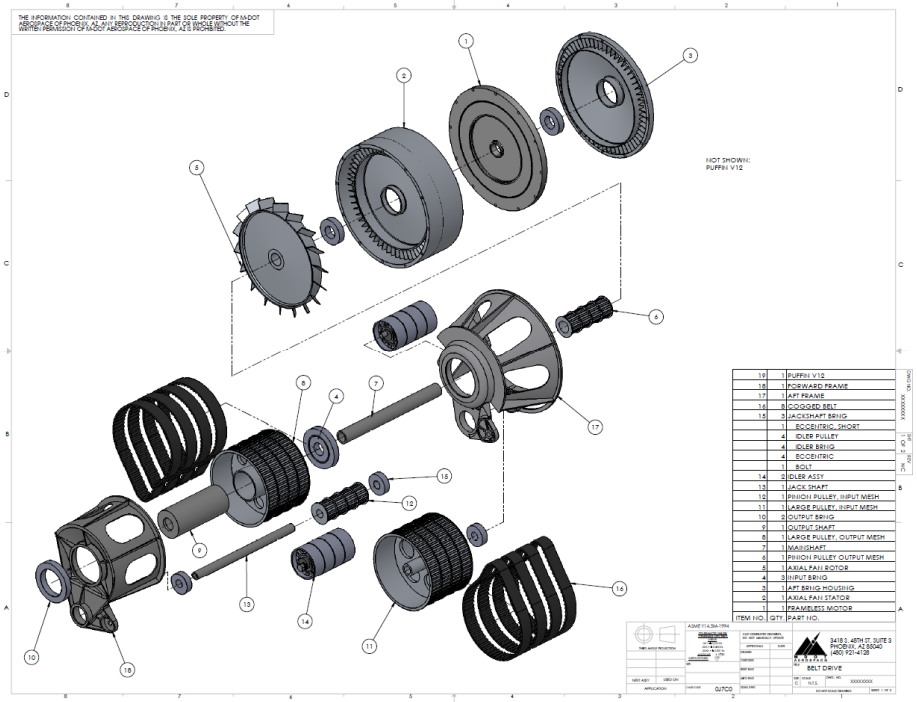


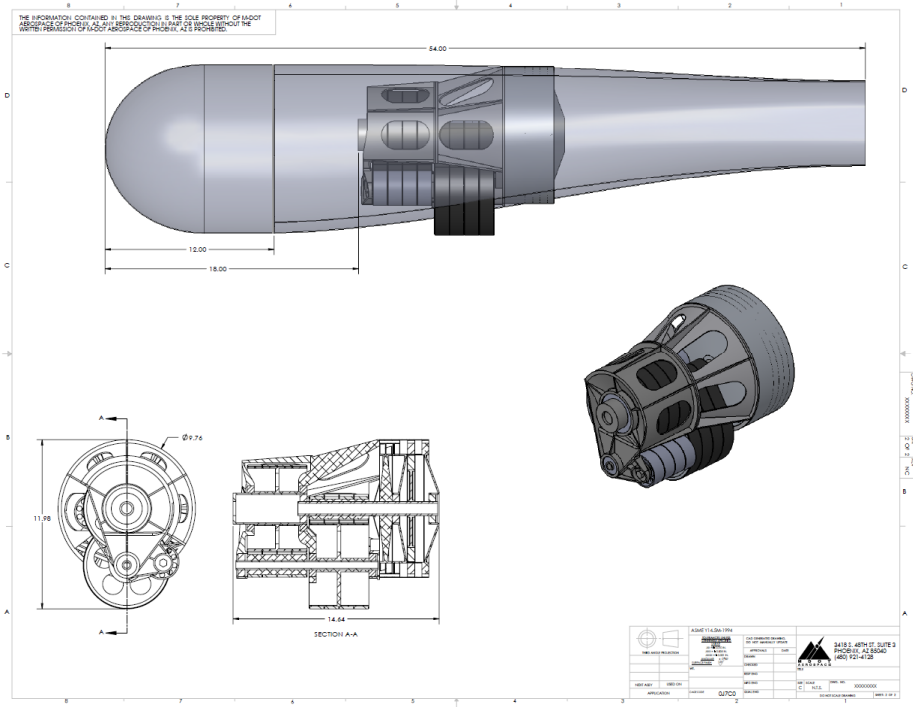




Electric Propulsion is a VTOL Enabler

36 Pole Motor with 8 Belt Reduction Redundant System





All VTOLs Can Fly, But Can They Transition

Dos Samara VTOL UAV Concept Study, 2009

Proof of a VTOL is successful transition through a robust corridor; sub-scale demonstrations can be very useful to validate the many transition control assumptions required during conceptual design.



All VTOLs Can Fly, But Can They Transition

Samarai Roadable VTOL Concept Study, 2010

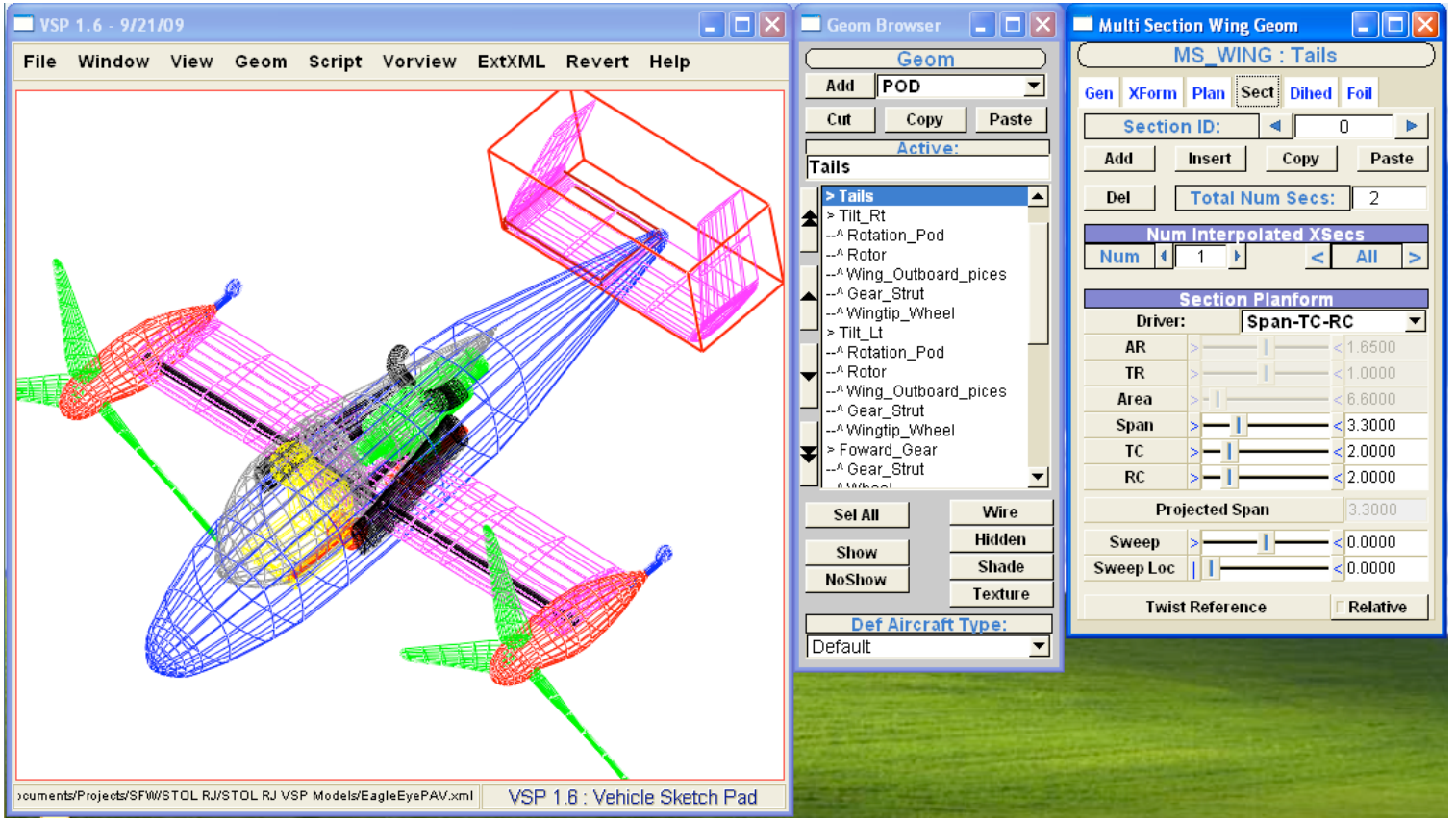
Attempts to achieve redundancy through the entire propulsion system (even blade failure), while maintaining lower disc loading without the need for cyclic (and maybe even collective) rotor control.



Tight Packaging Requires Creativity

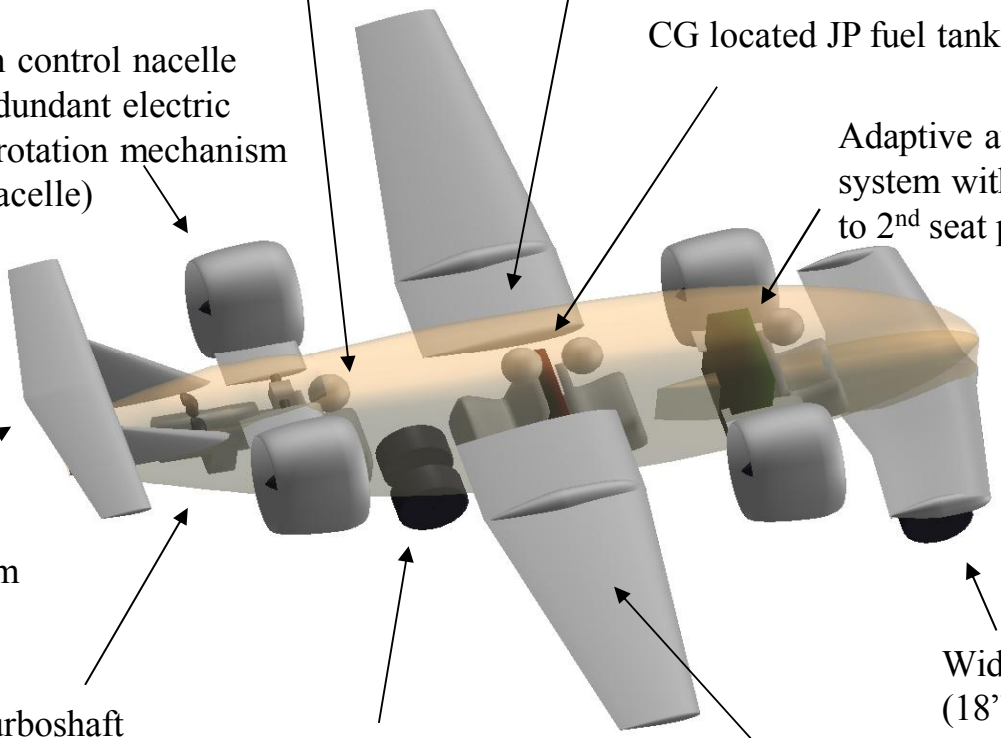
Vehicle Sketch Pad (VSP) Facilitates Rapid, Creative Design

Rapid and intuitive conceptual geometry front-end to design that using parametric input (Aspect Ratio, Sweep, Twist, etc– not like CAD). Available from NASA to U.S. citizens, including source, models, manuals, etc at no cost through a Software Users Agreement.



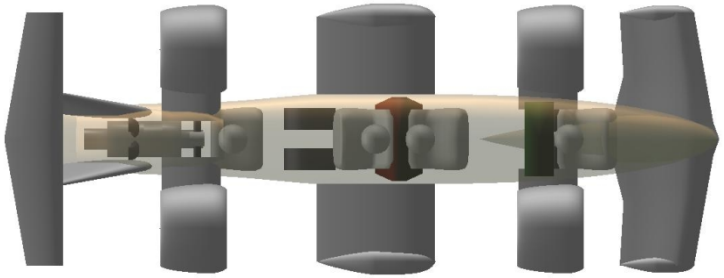
Tight Packaging Requires Creativity

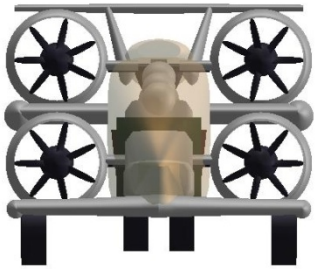
VSP Example

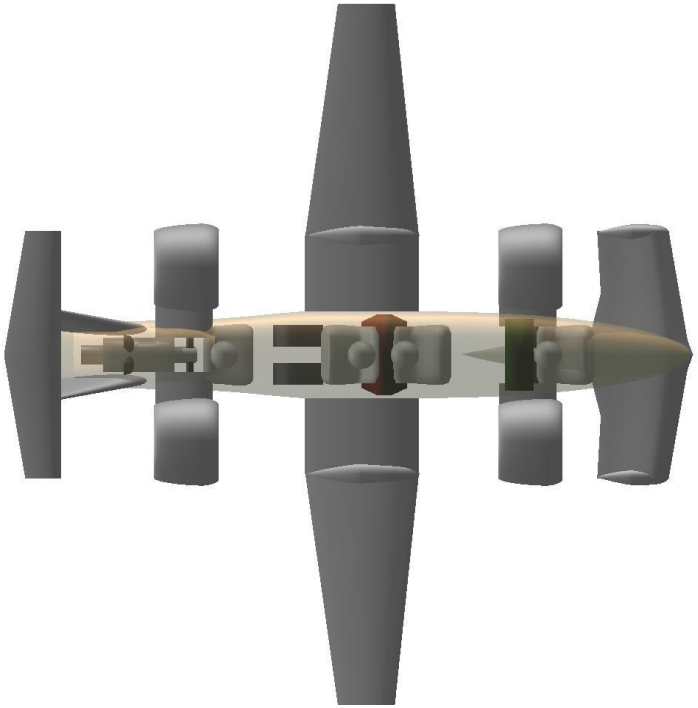


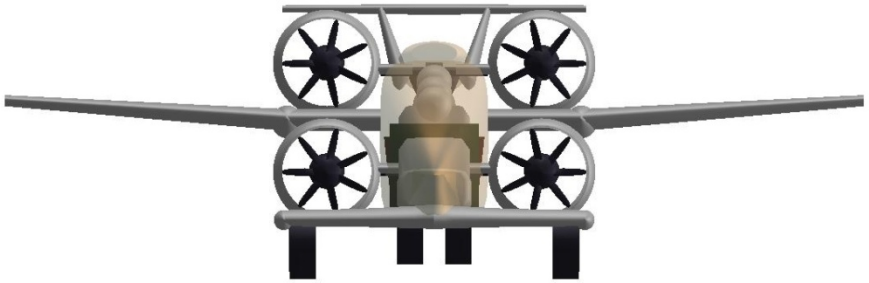
Tight Packaging Requires Creativity

VSP Example









Ramp Traffic Console (RTC) Lessons Learned

NASA ATD-2 Industry Workshop

Yoon Jung (NASA ATD-2)
Cynthia Freedman (NASA ATD-2)
Lindsay Stevens (NASA ATD-2)
Debi Bakowski (NASA/SJSU ATD-2)

Agenda

- Field Evaluations
- Feature Set for Situational Awareness
- Customization
- Surface Metering
- Design Principles
- Challenges
- Wish List

Agenda

- **Field Evaluation**
- **Feature Set for Situational Awareness**
- **Customization**
- **Surface Metering**
- **Design Principles**
- **Challenges**
- **Wish List**

Operational Field Evaluation is Essential

- 10 *Engineering* Shadow Evaluations over 15 months were not as impactful as 3 *Operational* Shadow Evaluations over 3 months.

- Operational Shadow Evaluation period was not long enough to address the sheer amount of feedback we received.

- Why? Because when the users had the chance to see/use the tool in the field and feel the imminence of using the tool, realization of needed functionality to perform their jobs and ideas about features that they would like to have began to flow. It's important for the users to see/use the tool in the operational environment in order to obtain the most feedback and understand field/user needs.

Agenda

- Field Evaluations
- Feature Set for Situational Awareness
- Customization
- Surface Metering
- Design Principles
- Challenges
- Wish List

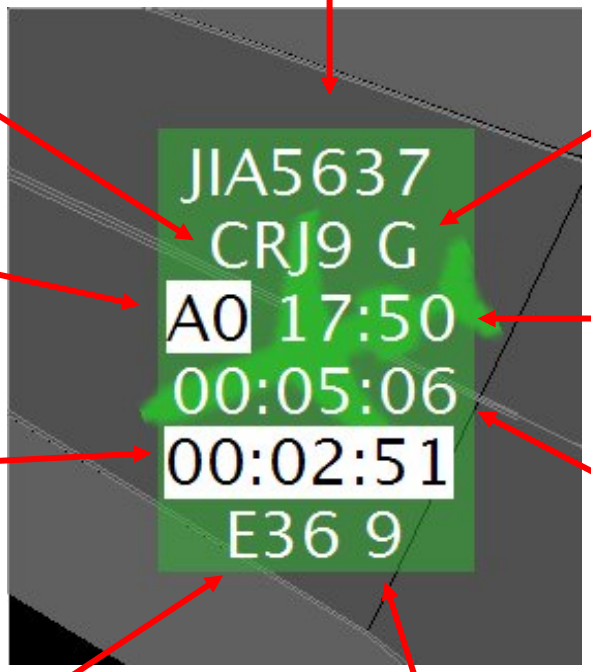
Situational Awareness

- Necessary features to provide situational awareness
  - Flight Data
  - Flight State
  - Aircraft Type
  - Flights to Expedite
  - Flights with TMIs
  - Target Management
  - Target Location / Orientation
  - Intent
  - Gate Status
  - Airport Status
  - Notifications
  - Count Lists
  - Search

RTC Overview



Arrival Data Tag Example



Callsign
(e.g. JIA5313)

Aircraft Type
(e.g. CRJ9)

Current Ownership
(e.g. “G” for Ground)

A0/A5/A14 alert
(e.g. A0)

Scheduled In-Block time
(SIBT)
(e.g. 17:50)

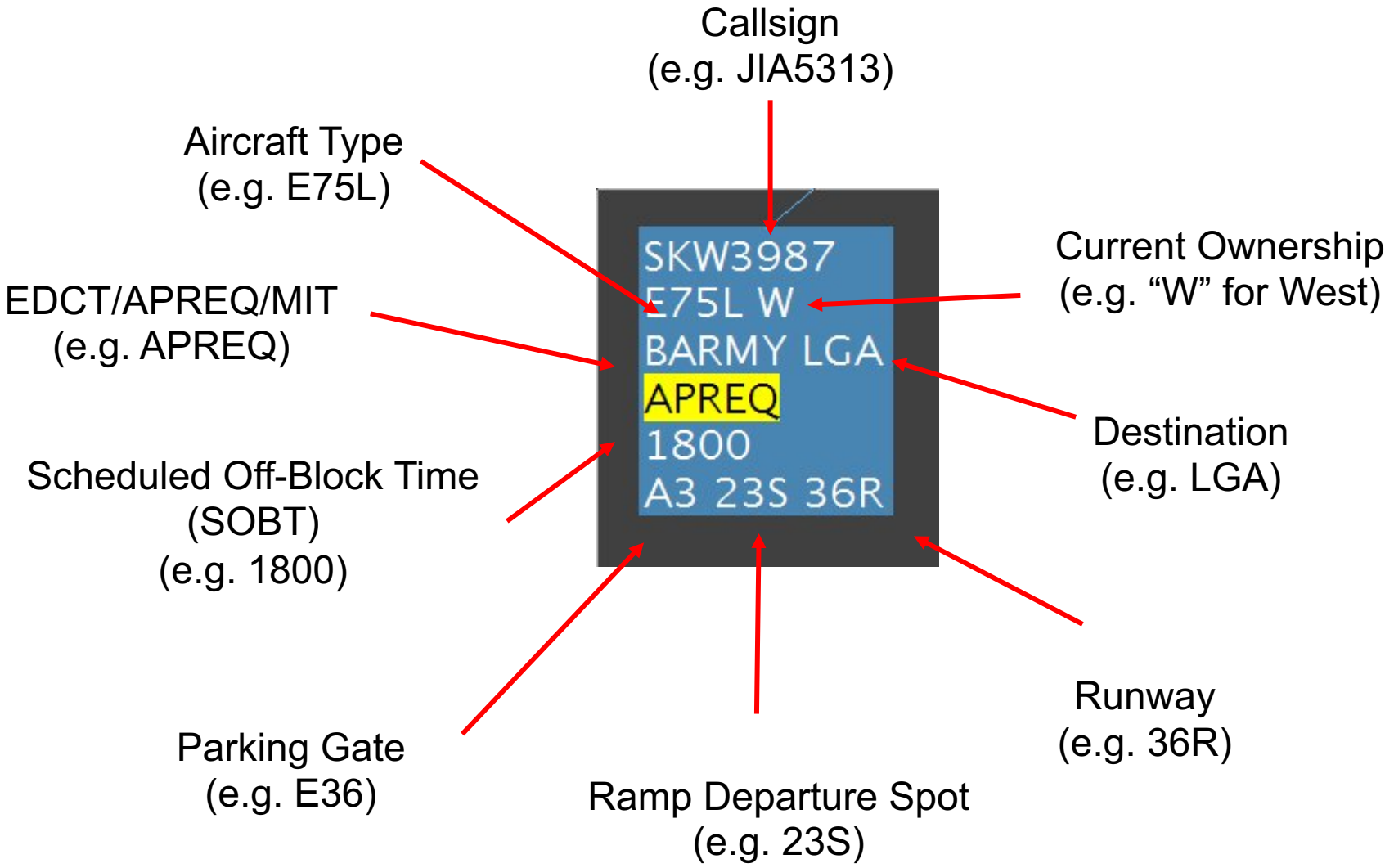
A0/A5/A14 alert timer
(e.g. 2 min 51 sec)

Time since Wheels
Down (ALDT)
(e.g. 5 min 6 sec)

Parking Gate
(e.g. E36)

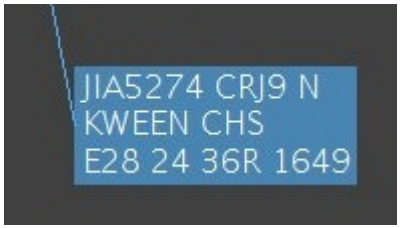
Ramp Arrival Spot
(e.g. 9)

Departure Data Tag Example



Indicate Flight State: Departures

At gate
not pushed back



At gate
spooling up /
pushing back



Pushed back,
proceeding to spot
– no tracks



Taxiing –
tracked



Indicate Flight State: Arrivals

Taxiing – tracked



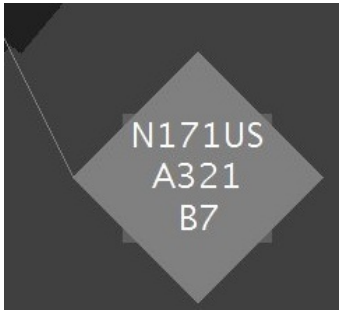
Taxiing – lost tracks



At gate, subsequent departure will be using the aircraft



Aircraft (no flight associated with the piece of metal)



Distinguish Large Aircraft



B757 aircraft



Heavy aircraft

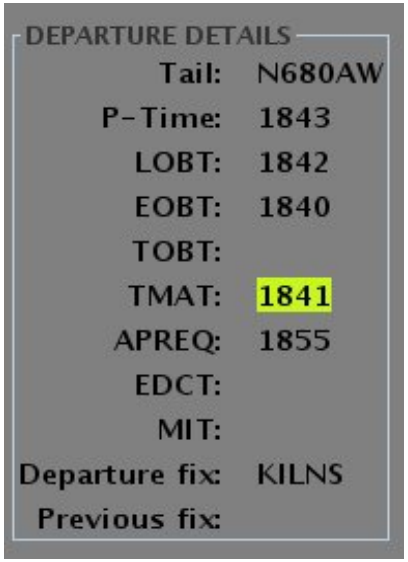
Flight Data

- Ramp Controllers still wanted a place to see all available flight data

Arrival Example



Departure Example

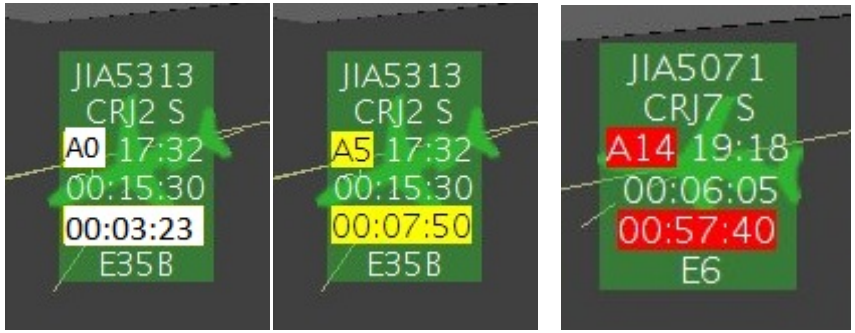


Flag Flights to Expedite (1)

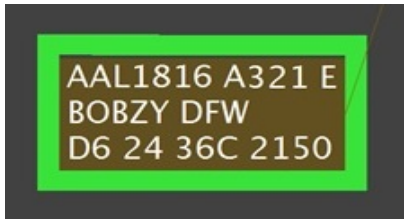
Emergency



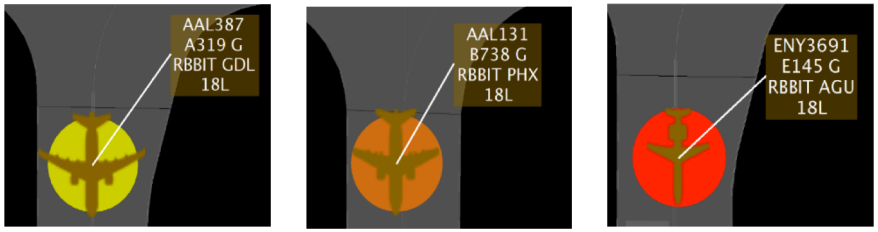
A0, A5, A14



Priority



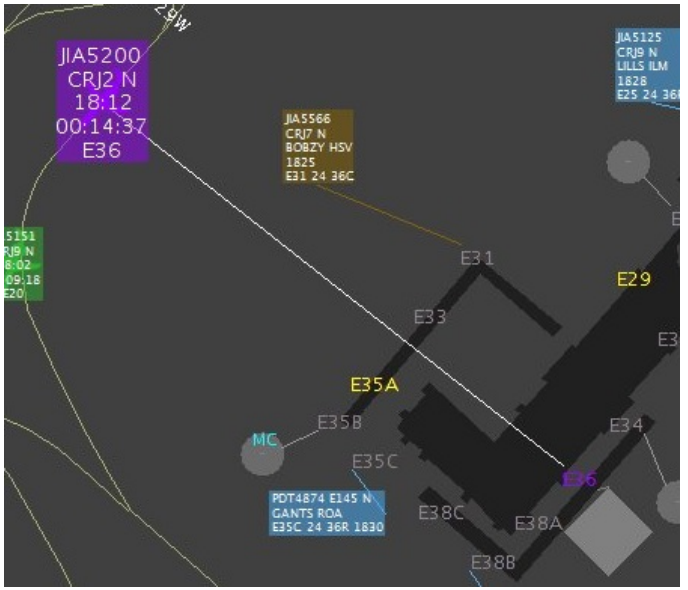
Long on Board



60 – 89	90 – 119	120+

Flag Flights to Expedite (2)

- Gate Conflicts flag the gate and the arriving flight
- Controller needs to expedite the departure or manage the arrival
- Clicking on the gate label draws a tether from the gate to each flight assigned to that gate, helping the user find the flight if it is not in the current field of view.



- Gate conflict also indicated if gate is blocked by a heavy at a neighboring gate
- Gate conflict begins to display when an arrival is N (user-configurable) minutes prior to landing

Indicate Flight TMIs

- APREQ but no release time – still at gate
- APREQ but no release time – pushed back
- APREQ with release time
- EDCT
- APREQ and EDCT
- Changed APREQ or EDCT
- Ground Stop
- Miles-in-Trail
- Departure fix change
- Departure fix closure



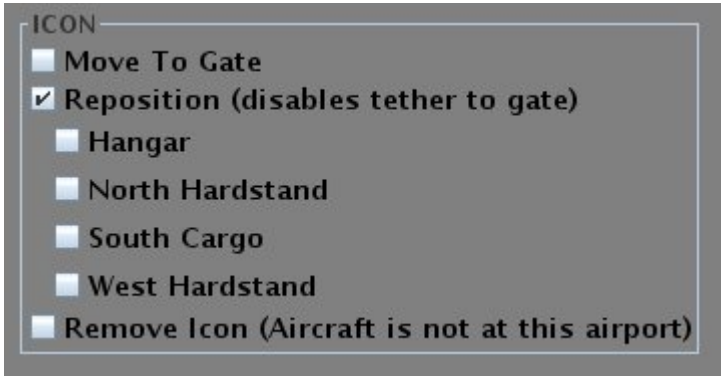
Examples of TMI indicators

Flight / Aircraft Management

- Create missing targets
  - Flight must be from system list
  - Aircraft can be created from scratch



- Strip/icon management
  - Reposition flight/aircraft to another location
  - Move flight/aircraft to gate
  - Remove target



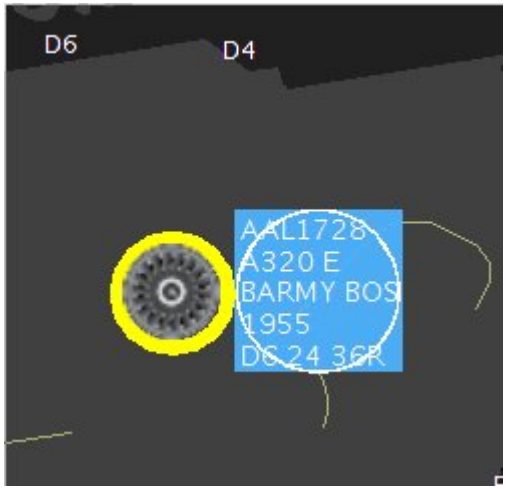
- DON'T show General Aviation/Cargo flights in their ramp
  - A distraction/clutter to controllers

Position and Orient to Expected Location

By default, strip for pushed flight displayed away from the gate



Controller can drag and rotate strip to expected position and orientation when it completes spool / pushback procedure



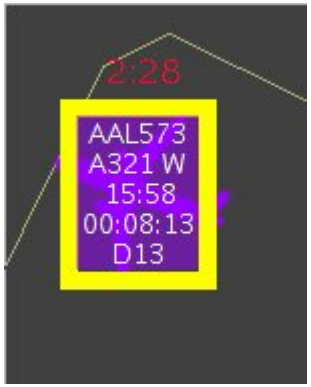


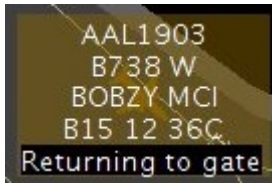
Hollow icons can also be rotated and dragged to their expected position and heading

Intent / Reminders

- Red “hold” border and yellow “hardstand” border communicates intent to other controllers
- Timers inform a controller how long a flight has been held
- Scratch pad used to communicate intent or convey important information to other controllers

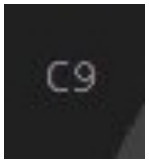






Gate Status

- Owned (white) 

- Unowned (gray) 

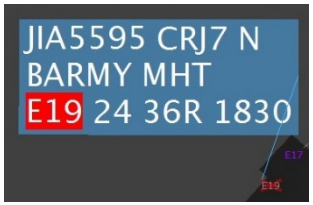
- Incoming Arrival (yellow) 

- Gate Conflict (purple) 

- Special Handling (red outline) 

- Closed (red X) 

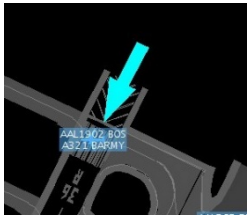
Gate Closure also reflected in flight datatag

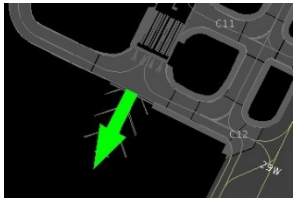


Airport Status

- Airport Configuration / Runway Utilization
- Runway Closure
- Taxiway Closure
- Ramp Status (Open, Pending Closure, Closure)
- Metering Status





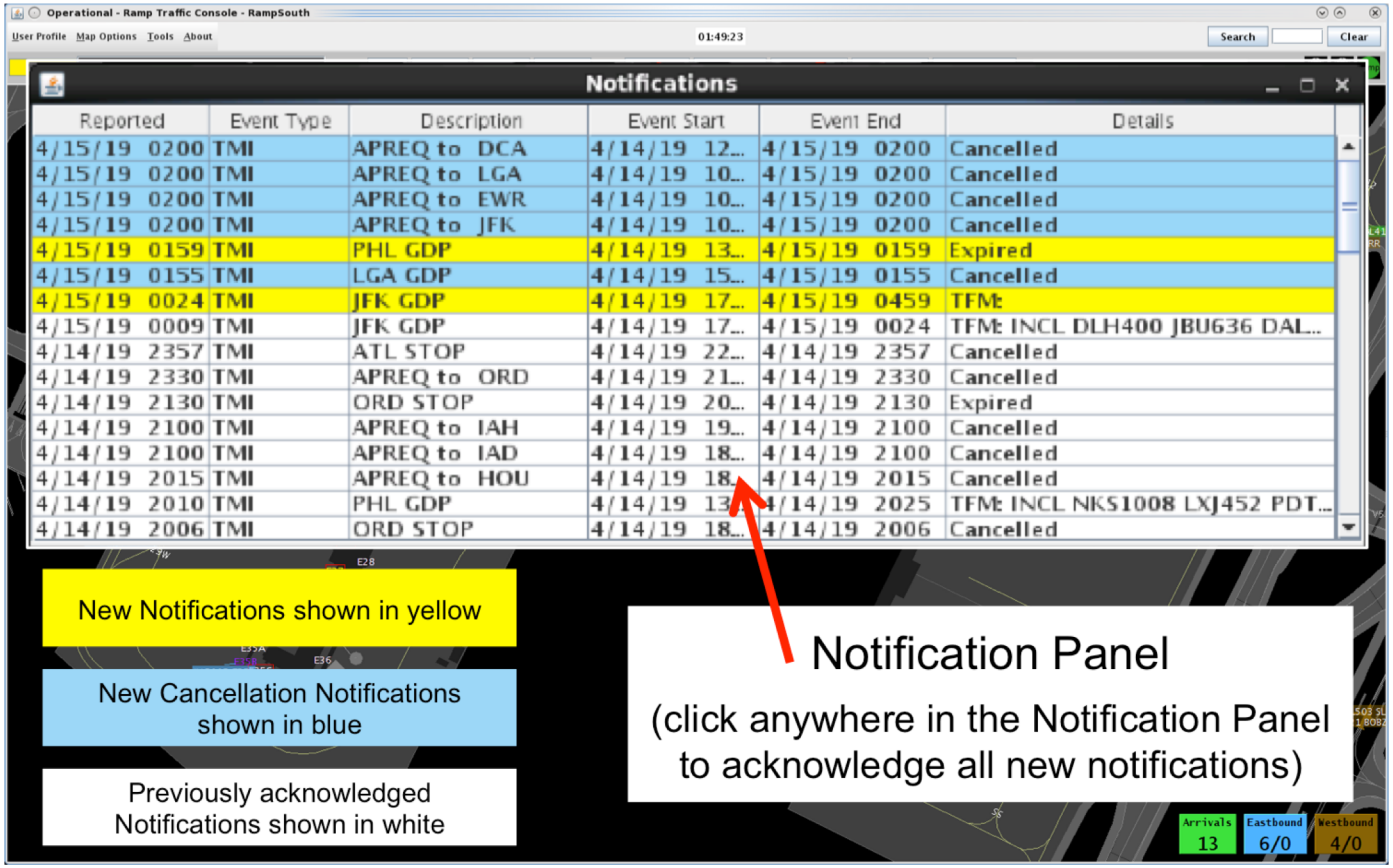






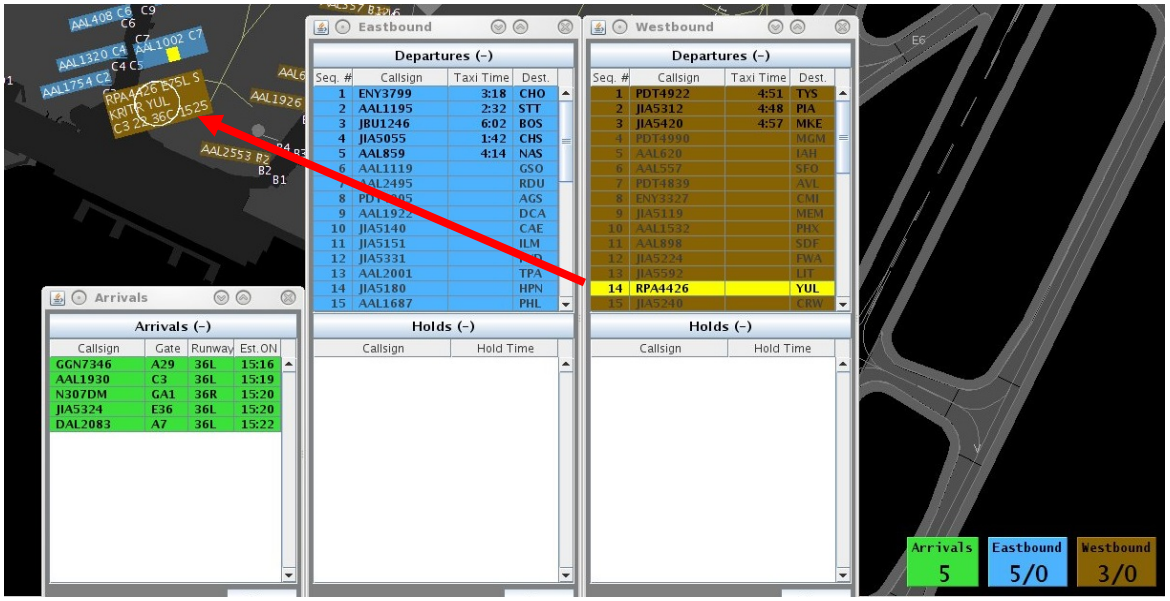
Notifications

- Airport or airspace events that affect multiple flights
  - Airport configuration, runway closures, departure fix closures, miles-in-trail restrictions, ground stops, APREQ schedules, metering status



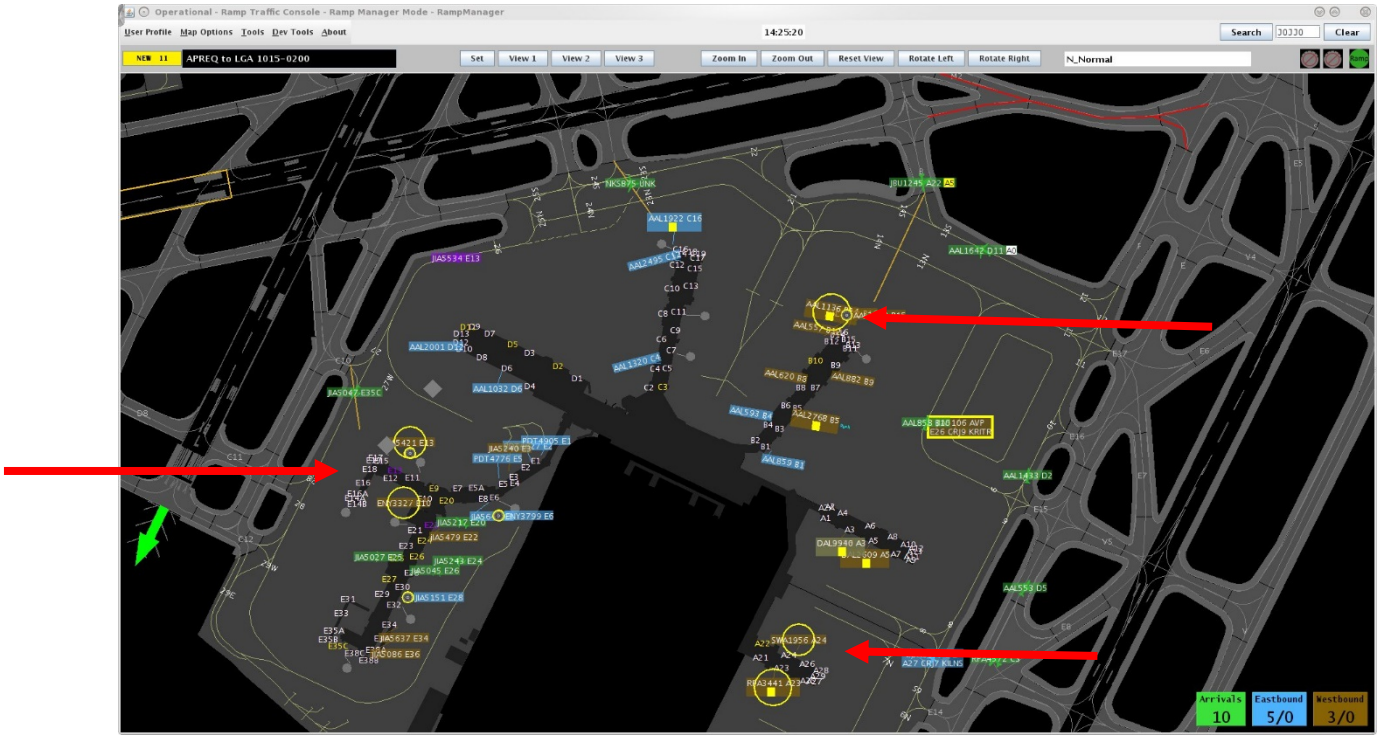
Count Lists

- Flights in each departure category (configurable) and Near Arrivals
- Clicking the count box details the list of flights in that category with pertinent information
  - Bold flights have pushed back
  - Gray flights are scheduled to push back
  - Selected flights also highlight on the map



Search

- Search by callsign, airline, airport, departure fix, arrival fix, or “GA”
- While typing, a “ping” is drawn around each matching flight



Agenda

- Field Evaluations
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Airport Customization

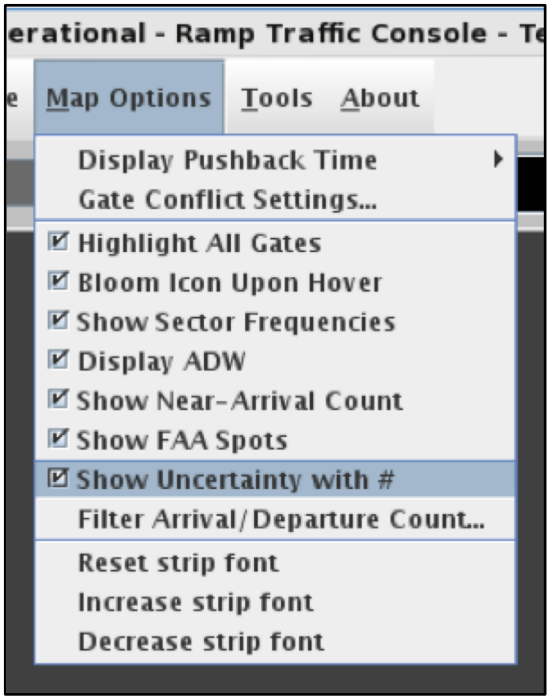
- Departure categories (e.g. Eastbound, Westbound)
- Colors (e.g. departure categories, arrivals, advisories, ...)
- Time thresholds
  - How soon before pushback to display flight strips
  - How soon before scheduled time to display advisory
  - Flight list population (Priority list, target creation list)
  - Target automatic removal
  - Etc…
- Flight strip orientation at each gate
- Pushback Direction options for each gate, if shown at all
- Count lists (look ahead window, sector filters)
- Data tag elements and location in the tag
- Metering mode – if any, advisories – TOBT vs TMAT
- Runway change due to Operational Necessity

Airport Surface Customization

- Sectors
- Sector frequencies, if displayed on map
- Hardstands
- Drop / Hold points
- Spots
  - Internal to the ramp vs the FAA transition point
  - Some displayed the same name at multiple locations (e.g. ramp spot “27” displayed from north approach and south approach)
- Ramp bypass (e.g. “Mike-Charlie” at CLT)
- Flag “Special Handling” gates (e.g. “AirStart required”)
- Reposition locations

Display Customization

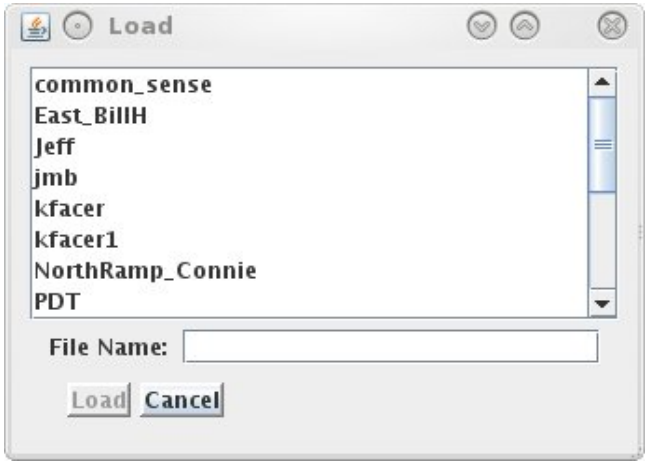
- Add options for configurability of the map and flights to provide users flexibility





- Allow users to save their preferences





Agenda

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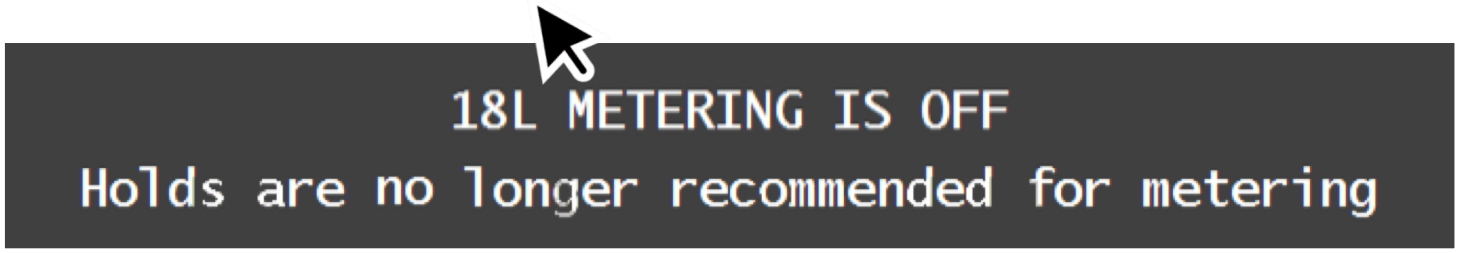
Active Metering

- Scheduling algorithm needs to have tolerances for when to activate and de-activate metering – advisories flickering on and off when at the “cusp” of metering was very distracting to controllers
- Controllers want surface metering to be per-runway, not airport-wide
- Controllers want to be notified when surface metering is de-activated for each runway



Flight Ready

- Pilot ready time entries are **critical** for surface metering.
  - No way to get those times except user inputs
- Selecting “Hold” or “Pushback Flight” sends a notification to the scheduler that the flight is ready



Expected Hold Times

- Ramp Controllers want to know expected times for metering holds
- “Uncertain” flights (e.g. with no EOBT) have higher uncertainty and may have fluctuating gate advisories
  - Controllers can optionally display “#” instead of a time





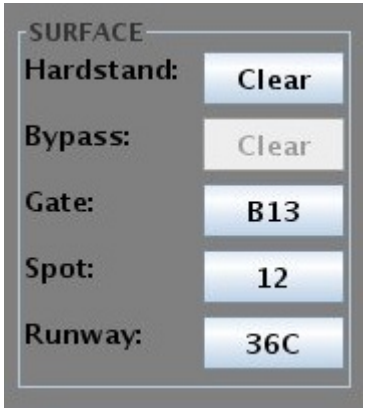
Advisories

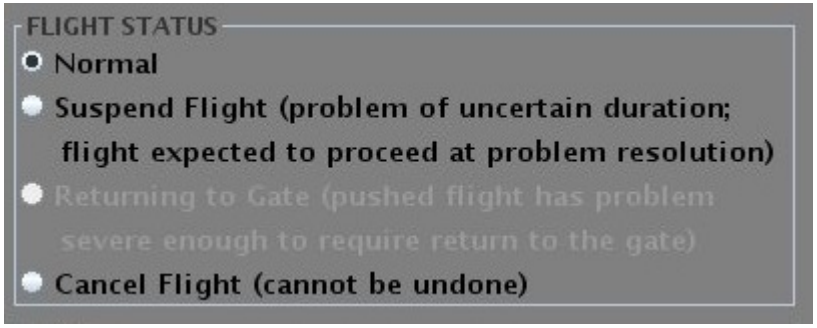
- Advisories for non-TMI flights are only displayed when surface metering is enabled
- Advisories for TMI flights are always displayed, even when surface metering is disabled
- Ramp Manager/Controller can exempt a non-TMI flight from metering or set a priority status



Improving Accuracy

- The user can provide additional intent information if needed; e.g., additional hold time
  - Notification is sent to the scheduler, which updates its schedule accordingly
  - Additional hold time will be reflected in new advisory
- Updating surface usage and flight status improves scheduler predictions and scheduler accuracy





Agenda

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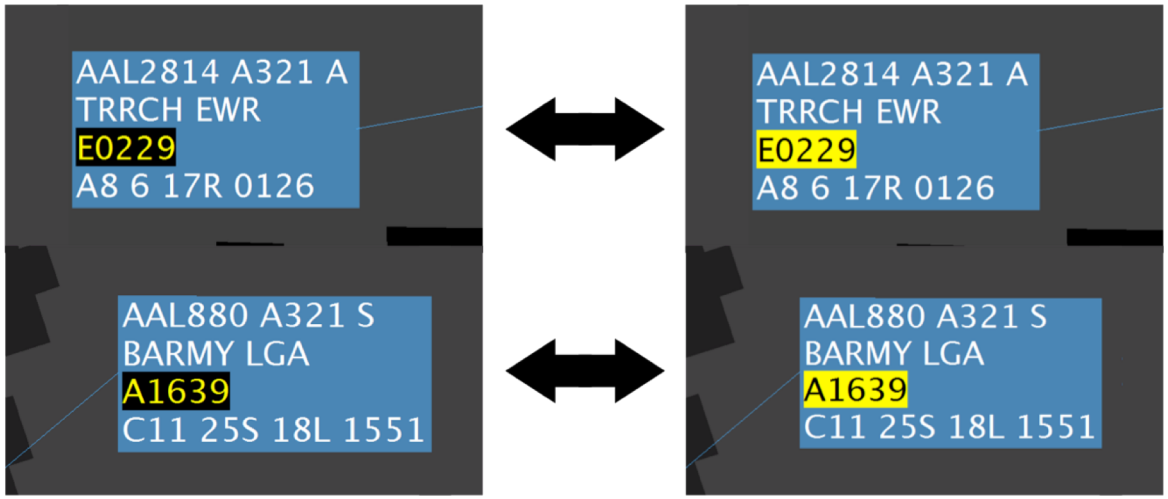
Human Factor Principles

- Judicious use of color
  - Red for stops/closures, yellow for TMI alerts
  - Avoid too many colors, shading nuances
- Consistency (e.g. use of borders or data tag fields)
- Affordances (a visual cue that offers an indication of how an object functions; e.g. the count boxes look like buttons and have a responding action to a mouse click)
- Salience (the quality of being noticeable; e.g. an APREQ turns red on the strip if the flight leaves the gate without a time)
- Keeping pertinent information in focus (e.g. hover to view full strip – no need to look at auxiliary display)
- Alerts that need to be acknowledged use peripheral vision (e.g. blinking alerts in flights strips)

Flight Notification Principles

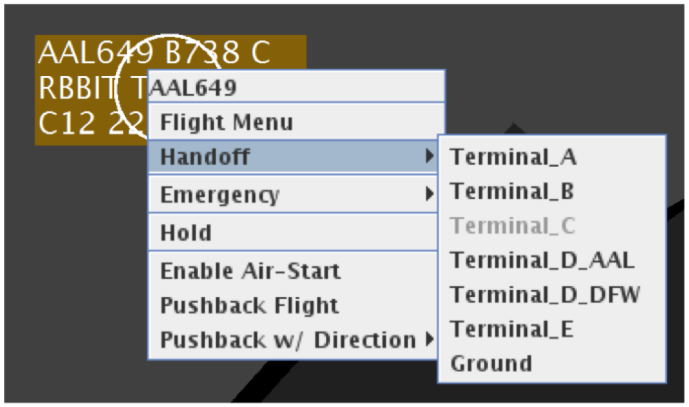
- Proximity principle: Flight strips get notification instead of central list to keep information in the field of view
- Flashing/alternating alerts flights are detectable with peripheral vision to attract Controller attention
- Clicking acknowledges the notification (turns off flashing)
- Only the flight owner / sector Controller receives and acknowledges the blinking alert instead of everyone

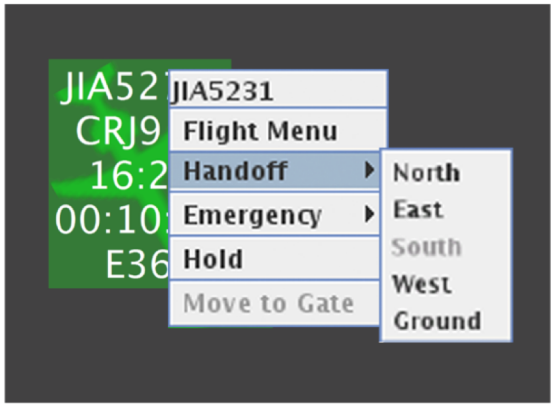


Alternating black and yellow highlighting to create blinking alert

Less is More when Mouse-Clicking (1)

- Ramp environment is fast-paced and users don't have time to make complicated entries
- Reduce physical workload: Fewer mouse clicks
  - Automate handoffs between sectors
  - Detect pushbacks from surveillance when able
  - Detect pushback location from surveillance rather than making Controllers manually move flight icons to expected pushback locations

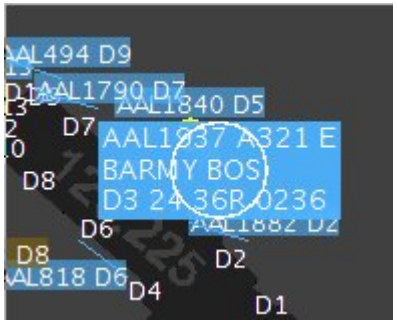




E.g., Handoffs are too complicated/time consuming to do for each flight

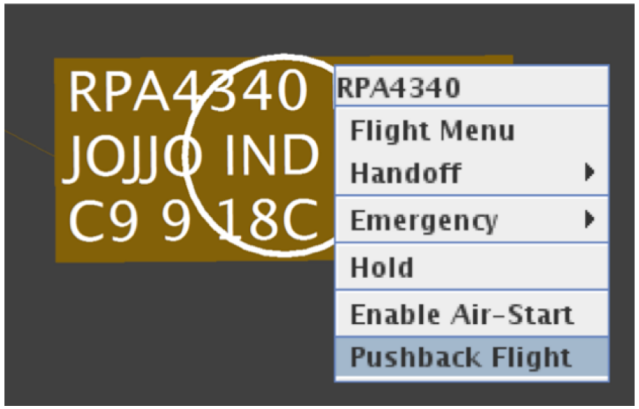
Less is More when Mouse-Clicking (2)

- “Bloom” on mouse hover allows controllers to keep map zoomed out for greater situational awareness but able to see flight details without clicking

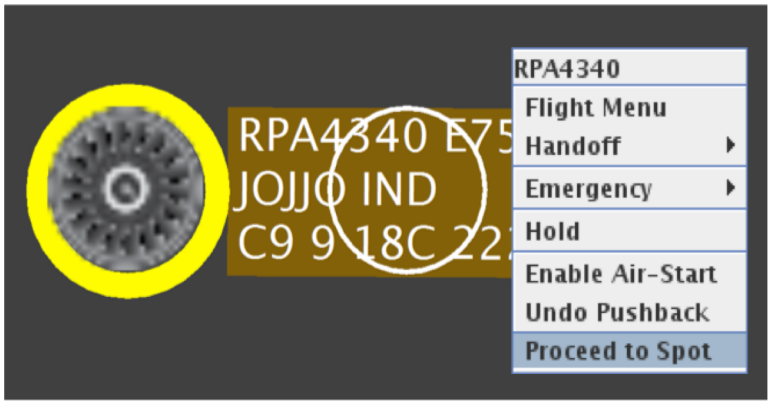


Logical Menus: Right-Click Menu

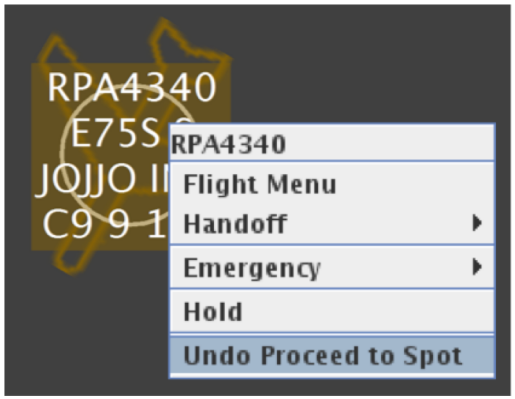
Options displayed are relevant for flight's current state.



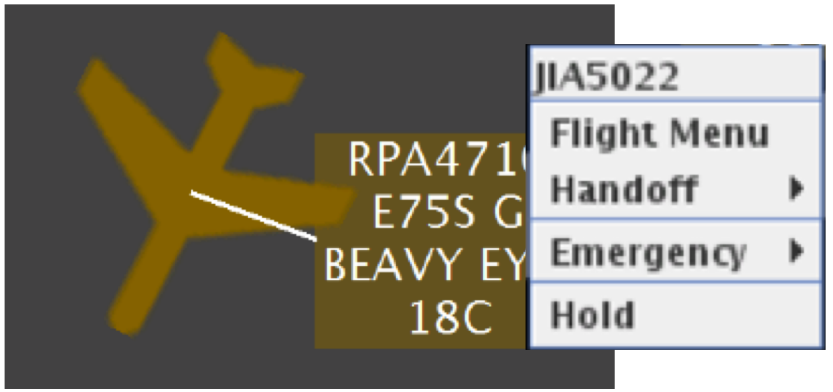
Flight Strip Parked at Gate, prior to Pushback



Pushback/Spool-Up State w/ Attached Engine Icon



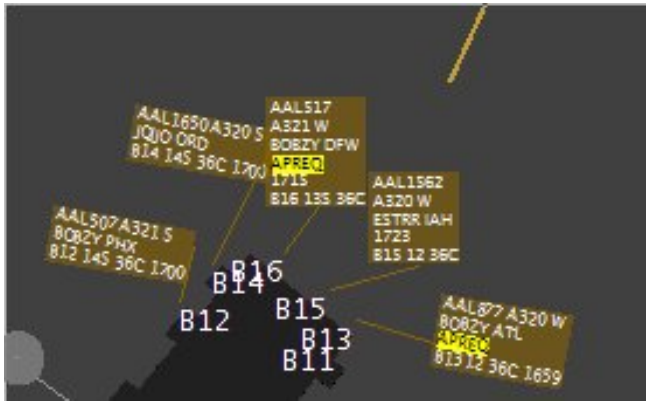
No Surveillance: Hollow Icon



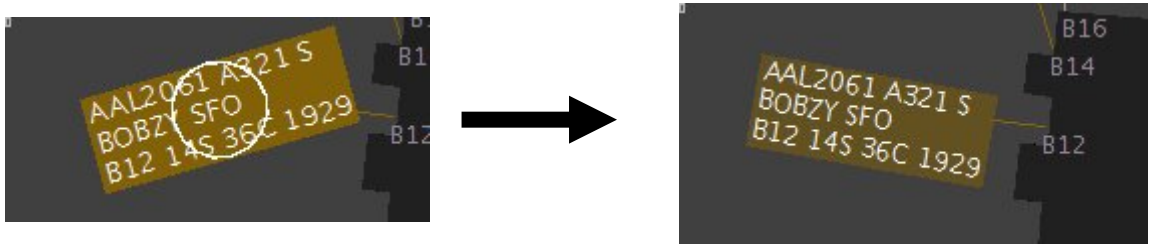
Surveillance Data: Solid Icon

Readability

- Many iterations with users to define font style and size
- Horizontal vs vertical orientation of strips at the gate set for each gate to reduce overlap



- Strips can be rotated, allowing controller to adjust overlap (circle shows region to grab)



Readability

- Ability to drag a flight strip away from the gate to avoid overlap



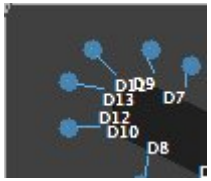
- Ability to drag a flight data tag away from the icon to avoid overlap; dragging tag back over icon re-attaches it



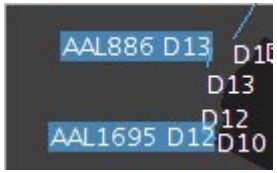
Zoom

- Five zoom levels show different levels of detail

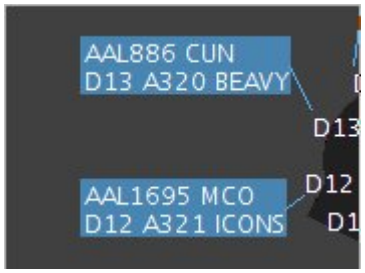
Colored disk with no text when zoomed out to full airport view



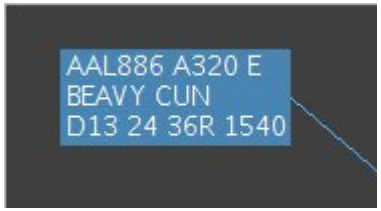
First zoom level - Single line of text with callsign and gate



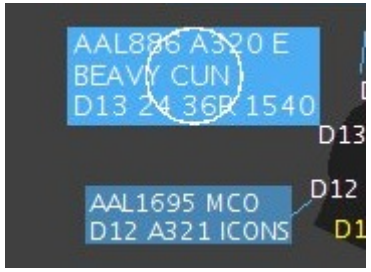
Second zoom level - Two lines of text line with callsign, destination gate, actype, fix



Third zoom level - Full text of callsign, actype, owner, fix, destination gate, spot, runway, gate time



Bloom zoom - Full text independent of zoom level when flight is selected

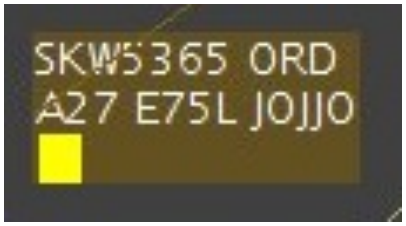


Notifications Needed at Far Zoom

- Ramp Controllers need to be aware of pertinent information but don't need to see the data all the time and so don't want the clutter of unneeded data
- Colored block notify the controller the flight has important information; controller can zoom in or bloom the strip if he wants/needs to see the data
- Yellow and red blocks correspond to their respective TMI fields, and white indicates a scratch pad entry
- Multiple blocks display if appropriate









Abandoned: Touch Screens

- On-going maintenance to keep them calibrated
- Arm-length distance to screen too close for large screens
- Fatigue is a serious problem with large screens
- Finger not as precise as a mouse, especially for zoomed-out displays or gentlemen with larger fingers
- Accidental touches hard to undo
- Reduced amount of functionality available
  - Finger: long and short press, swipe, pinch
  - Mouse: single and double click, drag, right mouse menu, mouse wheel
- “Cheetos factor” (dirty fingers make screens filthy/gross)

Agenda

- Field Evaluations
- Feature Set for Situational Awareness
- Customization
- Surface Metering
- Design Principles
- Challenges
- Wish List

Challenges (1)

- Flight matching
  - TFM, FBFM, SFDPS, STARS, ASDEX, FlightStats, Airlines, …
- Data Feeds vs. Out-the-Window
  - Knowing when in-gate arrival is parked at the gate vs towed elsewhere
  - Knowing when to display departure at the gate vs waiting for it to be towed from alternate location
- Gate conflicts
  - Uncertainty in knowing when aircraft is at the gate
  - Uncertainty in pushback times
- Noise in surface surveillance around gates

Challenges (2)

- Inaccurate/erroneous incoming data
- Differences in company policy for “OUT” event
- Only have gate assignments from participating airlines
- Controllers had different preferences on when they wanted to see large hold advisories in advance of flight pushback. E.g. if a flight had a 44 minute advisory, some controllers wanted to see that “44 min” to give them awareness of the flight’s status, while others found the “44 min” to be a distraction and didn’t want to see information until closer to when they would expect to interact with the flight



Agenda

- Field Evaluations
- Feature Set for Situational Awareness
- Customization
- Surface Metering
- Design Principles
- Challenges
- Wish List

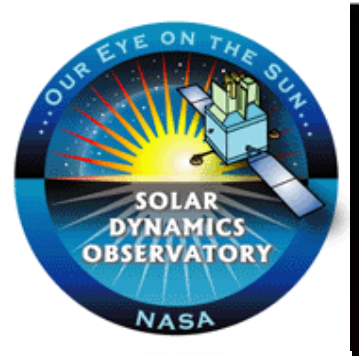
Wish List (1)

- Tugs
  - Display
  - Impacts metering
- Deicing
  - Display pads
  - Assign flights to deicing stations
  - Cannot meter during deicing
- Diverted flights
- Finer control on gate status: blocked vs out-of-service
- Ramp Manager notified if Ramp Controller has not acknowledged an alert
- User-customizable flight data tags (what fields display on what lines)

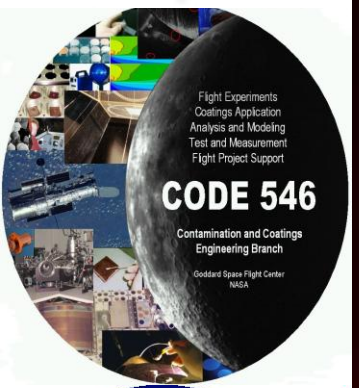
Wish List (2)

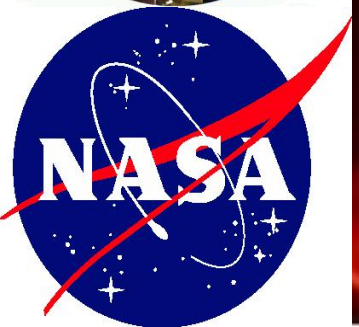
- Add customization to count lists
  - Time ranges
  - Colors based on time range
- Set strip pushback locations to match out-the-window
- Add option to not display unowned strips
- Draw on spot the list of flights assigned to that spot
- Provide aircraft types available for assignment to a gate
- History of scratchpad entries
- Customize gates that provide the “Air Start” menu option
- Allow spots to be closed
- Option to show time values in local time instead of UTC (per airport)

Questions?







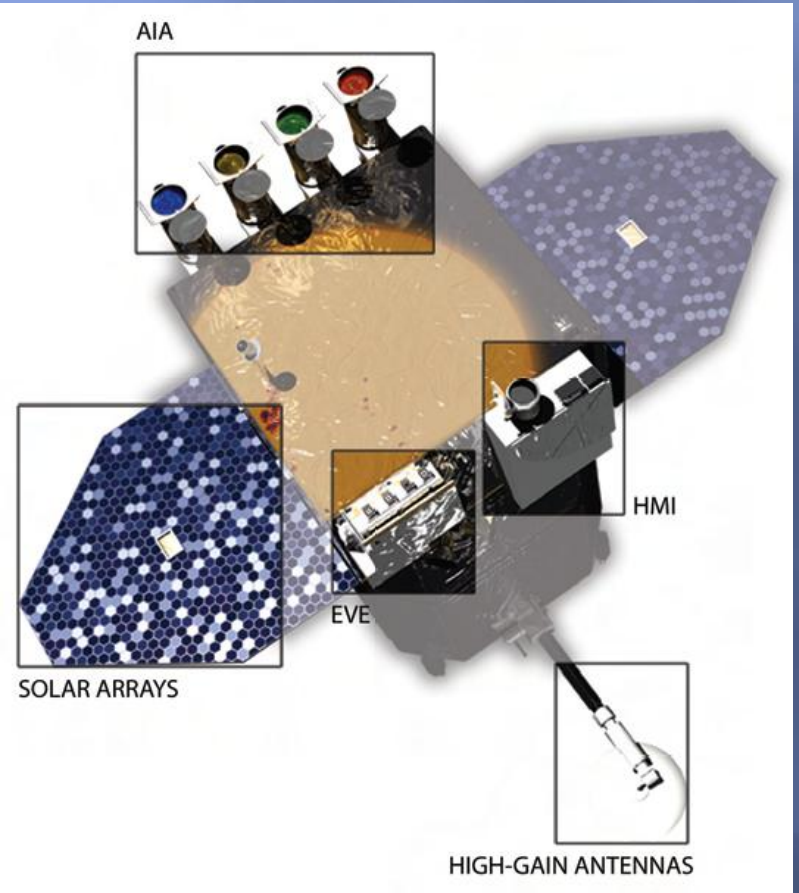


Solar Dynamics Observatory Lessons Learned

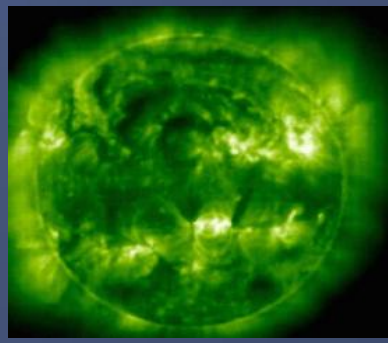
SPIE Conference San Diego, CA
August 4, 2010
Rachel Rivera/NASA GSFC
Mark Secunda/SGT
Drew Uhl/SGT

SDO Overview

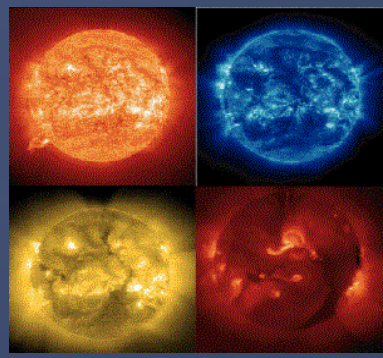
Mission is to study how solar activity is created and how space weather results from that activity.



- Atmospheric Imaging Assembly (AIA): High Resolution Images of 10 wavelengths every 10 seconds



- Extreme Ultraviolet Variability Experiment (EVE): Measure Sun's brightness in EUV.



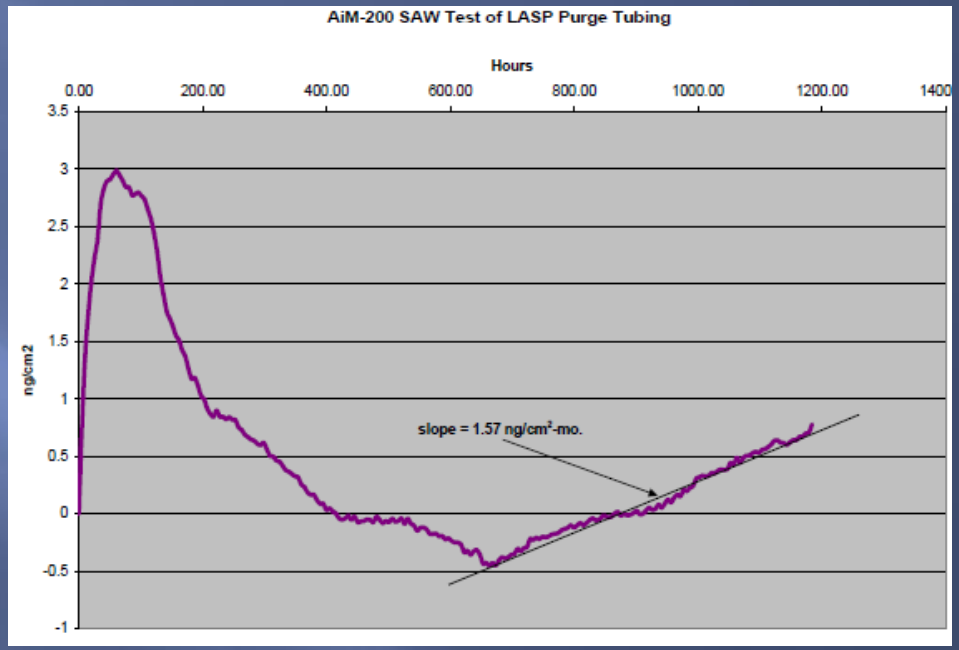
- Helioseismic and Magnetic Imager (HMI): Measures Doppler shift to study waves of the Sun.



- Launched February 11, 2010

Purge Tubing Monitoring

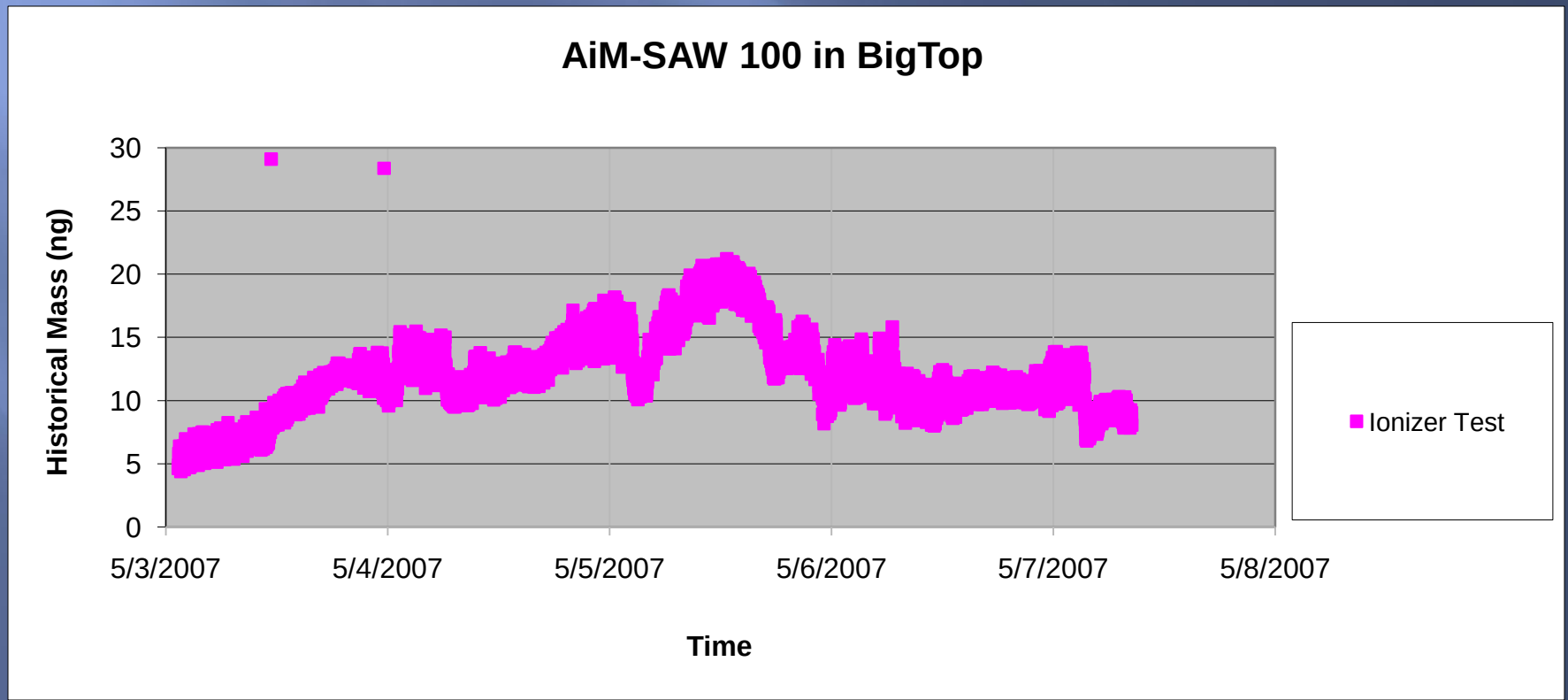
- EVE requirements stated as 3 ng/cm2-month.
- Used AiM-200 FT Surface Acoustic Wave (SAW) device to measure deposition.
- Old tubing (used for >1 year), was 1.75 ng/cm2-month



Material	Bake Out	NVR deposition
Chemfluor 367	No	129 ng/cm2-mo
PFA	No	52.4 ng/cm2-mo
PFA	baked @ 125C, 96 hrs	35.3 ng/cm2-mo
Chemfluor 367	baked @ 125C, 96 hrs	22.2 ng/cm2-mo

Ionizer Testing Prior to Use

- SDO ElectroStatic Discharge (ESD) requirement was Class 0 (sensitivity to < 250 Volts)
- Needed ionizers for many sensitive operations.
- Tested ionizer prior to cleanroom use.
- Ran ionizer for 4 days, measured NVR using an AiM-100 SAW
- Results show increase in NVR from room baseline after ionizer introduction
- Mandated 120 hours of run time for all new units prior to cleanroom use.



Bagging Material Study (Hypergols)

- SDO is sensitive to particle and molecular contamination.
- SDO must be bagged during all times outside a Class 10,000 environment.
- Many conflicting requirements.
  - Materials that are good for fueling are not good for EMI testing.
  - Materials with low contact transfer have poor ESD properties.
  - SDO was a Bi-Prop mission with Hypergolic Compatibility issues with Llumalloy

Type of Test	Standard	Screening Criterion
Electrostatic Discharge (ESD)	As per ASTM D257 or ANSI/EOS/ESD-S11.11-1993	Surface Resistivity: Between 10^5 and 10^{12} ohms/square (dissipative materials)
Non-Volatile Residue (NVR)	As per IEST-STD-CC1246D	Level A 1 mg/ 0.1 m^2
Particulate Cleanliness Levels	As per IEST-STD-CC1246D	Level 100
Outgassing: Total Mass Loss (TML)	ASTM E595	For low outgassing materials: TML<1.0 %
Outgassing: Collected Volatile Condensable Material (CVCM)	ASTM E595	For low outgassing materials: CVCM<0.1%
Hypergolic Compatibility	As per KSC report number MTB-175-88	Section 8: No significant reactivity observed as reported in KSC Form 3-539N.
Flammability	NASA-STD-6001	The material must meet the criteria of Test 1 (Upward Flame Propagation)
Static Decay	per MMA-1985-79	Triboelectric Method residual voltage after 5 seconds is not > 350 Volts

SDO Bagging Material Screening Criterion

1 mil (35% HSC)	**2 mil (35% HSC)**
Flammability: Passed	Flammability: Failed
Hypergolic: Side 1 : pass N_2O_4 Side 2: fail N_2O_4 Side 1 : fail N_2H_4 Side 2: pass N_2H_4 Side 1 : pass MMH Side 2: pass MMH	Hypergolic: Side 1 : pass N_2O_4 Side 2: pass N_2O_4 Side 1 : pass N_2H_4 Side 2: fail N_2H_4 Side 1 : pass MMH Side 2: pass MMH
Static Decay: passed	Static Decay: passed

Llumalloy Hypergolic Testing at KSC

Manufacturer/ Product Material Results/ Requirements	3M 1970 Static Shield	Caltex CP Stat 100	RCAS 4150	LF&P 8900C	KNF Film Orco-Ultra AN 109		Llumalloy (current material in circulation)	
ESD	Inner 9.65E+09 Outer 6.87E+09	Side A 1.83E+10 Side B 4.35E+10	Outer 1.1 X 10^9 Inner 3.2 X 10^9	Side A 4.08E+11 Side B 2.55E+11	Side A	Side B	Side A	Side B
					1.01E+13	7.93E+12	4.17E+14	3.14E+11
					2.02E+13	9.08E+12	5.99E+14	8.36E+11
					1.22E+13	8.04E+12	1.70E+15	1.07E+11
					1.88E+13	5.36E+12	5.36E+14	8.52E+11
					9.22E+12	7.16E+12	9.34E+15	3.62E+11
Particulate Cleanliness		Level 100	Suitable for Cleanrooms	Level 100				
Contact Transfer NVR	0.08 ug/cm^2	0.02 ug/cm^2	0.15 ug/cm^2	0.24 ug/cm^2	0.11 ug/cm^2		0.73 micrograms/cm2 10-day 0.17ug/cm^2 24 hour	
Extractable NVR	0.9 ug/cm^2	0.55 ug/cm^2	0.86 ug/cm^2	1.9 ug/cm^2	0.22 ug/cm2		0.03 micrograms/cm2 (to be re-tested)	
Outgassing	CVCM = 0.06% TML = 0.24%	CVCM = 0.02% TML = 0.19%	CVCM= 0.1% TML= 0.35%	CVCM= 0.19% TML = 0.39%	% CVCM = 0.33% %TML= 2.11%		CVCM= 0.00% TML=0.39%	
Flammability	Fail	Fail	Fail	Pass per KTI 5212C	Pass		Pass (1 mil)	
Static Decay	Pass	Pass	Pass	Pass per KTI 5212C	Pass		Pass (1 mil)	
Hypergolic Compatibility	Pass	Pass	Pass	Pass per KTI 5212C	Pass		Fail	

Bagging Material Study (EMI/EMC)

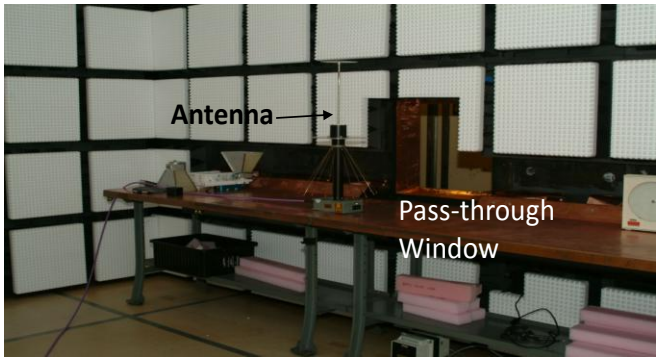
- EMI/EMC Testing can be a contamination risk to hardware due to particulate shedding from the room's foam
- The design of the room is optimized to meet cleanliness standards of Class 10k – Class 100 k
- Metallized bagging materials, such as Llumalloy, create Faraday Cages around the hardware and do not allow electromagnetic energy to pass through without attenuation
- An acceptable bagging material was needed for SDO that satisfied material selection criteria and was electromagnetically compatible

Bagging EMI/EMC Test Configuration

Llumalloy and two suitable bagging materials were tested for EMI/EMC in the smaller EMC lab of GSFC's Bldg.7

Bagging material was placed in a pass through between a transmitter and receiver in 2 separate rooms





- <3 dB signal attenuation response to frequency range 10 kHz to 30GHz
- 2 Acceptable Materials:

1- ATMI's Newform PE: *varied ESD properties lot-to-lot

2- Dupont's Melinex 1311

Dupont's Mellinex 1311: Static Dissipative, Cleanliness Level 0, NVR Contact Transfer Level A/10 and Rinse <Level A, Outgassing TML 0.26% and CVCM 0.00%
*Special Handling Procedures to maintain ESD properties

Atlas V Operations Cleanliness Monitoring

- New rocket, new environment.
- SDO slated to be first Atlas V NASA/Goddard mission.
  - Due to management priorities, LRO ended up being first, but much coordination between programs resulted in cost savings and good collaboration to explore environment.
- Needed to know processing environment
  - Encapsulation
  - Transport to Vertical Integration Facility (VIF)
  - Hoist to top of rocket at the VIF
  - VIF operations
- Developed strategy early on in program
  - Real-time measurements of particles with Particle Counter
  - Measure particles with fallout plates when possible
  - Real-time measurements of NVR with SAW
  - Measure NVR with witness plates.
- Difficult requirements to work around.
  - Issues with SAW not able to be worked out with Range Safety in time for use.
  - Real-time data for transport not available for SDO because of issues with RF energy limitations
- Still managed to get a good picture of environment.



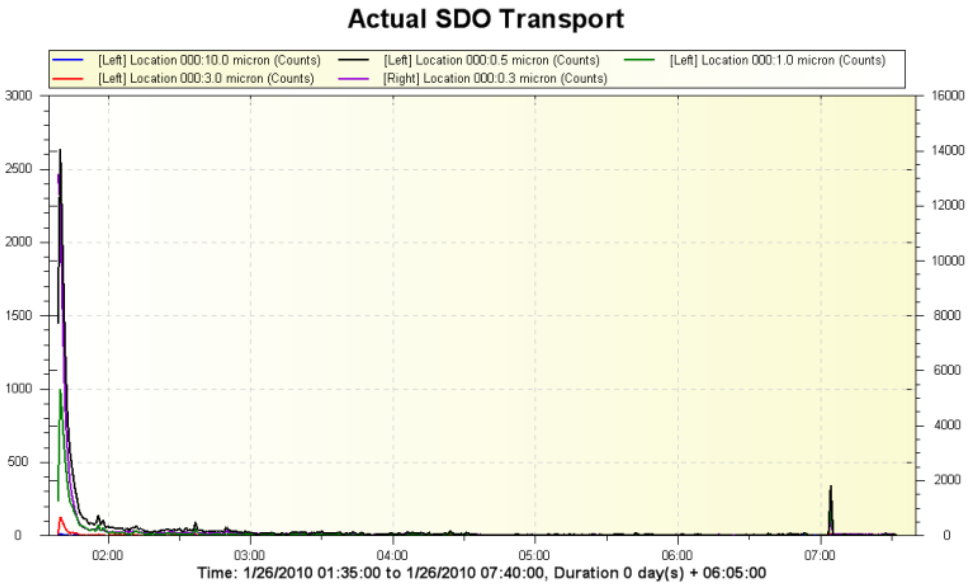
Launch Processing Activities





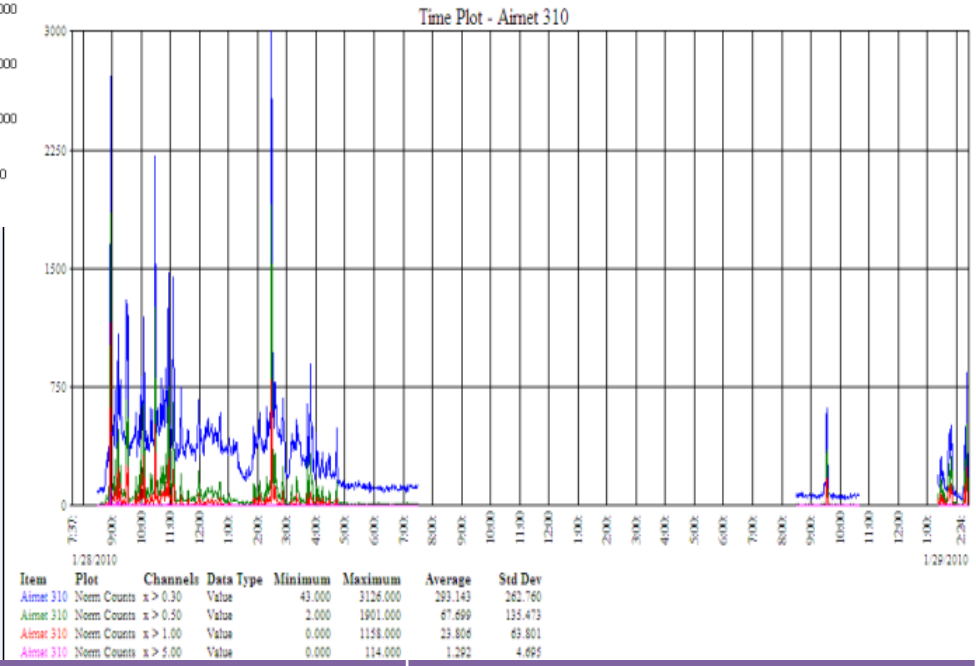


Atlas V 4 Meter Fairing Particle Counts



SDO transport from ASO to VIF

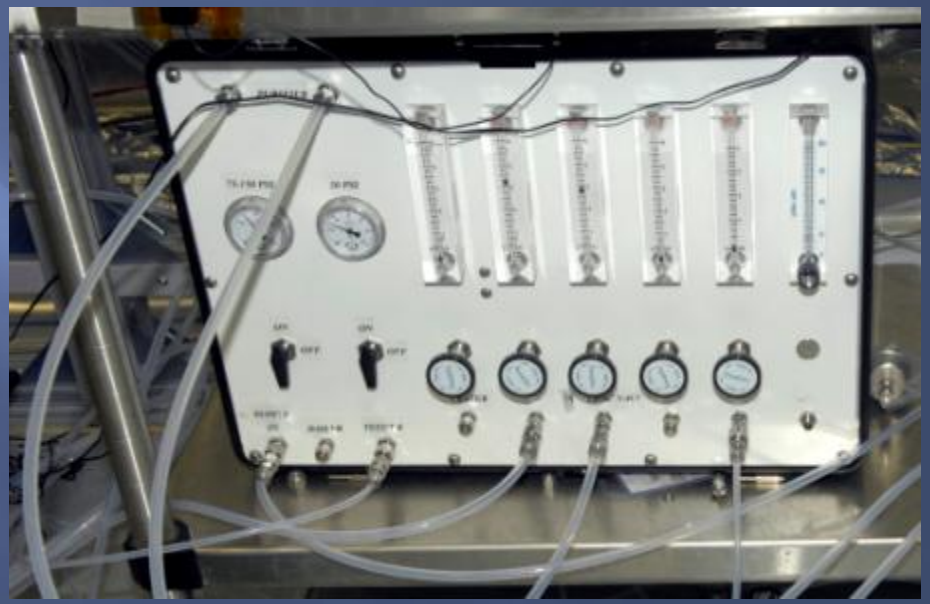
While at VIF



Exposure	Particles (2” silicone wafer)	NVR (12 in^2 plate)
Transport from Astrotech to the launch complex (7 days, 22 mi, 200 foot lift)	0.0048, 0.0044 PAC (~LVL 200)	0 mg/ft2 (blank same as or higher than test)
Launch complex operations to final fairing close-out (10 days)	0.025, 0.009 PAC (~LVL 200-300)	0 mg/ft2 (blank same as or higher than test)

Purge Systems

- Grade C Gaseous Nitrogen used to keep instruments clean and dry
- Purge Suitcase provided:
  - Different rates at different times
  - Filtration
  - Pressure Relief and Regulation
- Used 2 Purge Suitcases for leapfrogging
- Multiple dials used for early I&T led to confusion in later I&T
- Lack of clearly stated requirements also led to confusion
- 3 purge failures
  - Regulator failure at GSFC (SDO off line)
  - Shear failure of SSTL tubing during transport to FL
  - Purge not activated for rollout from VIF to pad
- Require tech to be on convoy
- Limit number of road trips



Purge Suitcase

Laminar Flow Enclosure (LFE)

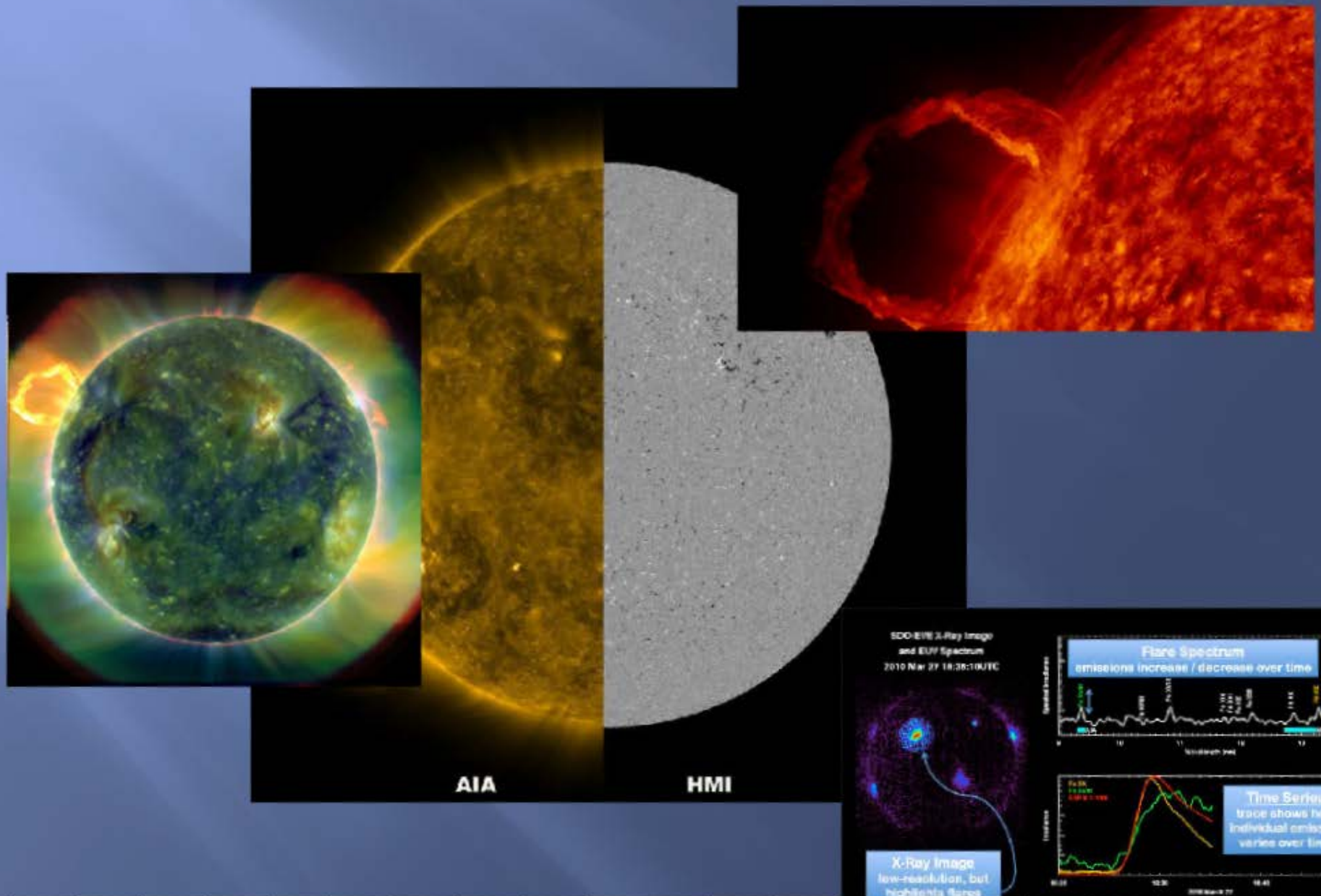
- SDO processed offsite of KSC at Astrotech.
- Using LFEs to make clean rooms into Class 10k cleanrooms were successful for STEREO and LRO; for SDO it did clean the room more so than without it, but not without issues
- In one incident, flow fields showed dramatic non-unidirectional flow
- Fans are loud
  - Safety issue especially during lifts – ended up turning off the LFE for lifts.
- Fans produced a major amount of heat
  - Led to trade-offs between cleanliness and thermal red limits of Observatory
  - Challenged the room's cooling ability
- 1 second power glitch will shut them down, need manual restart
- Tweaked fans and HVAC outlets to optimize flow and temperature
- Difference in room size/configuration may make major difference in acceptability
- Get a real cleanroom if possible
- Check flow field



One Liners

- Pens with SDO logo ended parade of unacceptable pens in the cleanroom, and made good swag
- Supposedly clean calrods weren't. Check 'em.

It Works!


AIA
HMI
SDO/EVE X-Ray Image
and EUV Spectrum
Flare Spectrum
emissions increase / decrease over time
Time Series
trace shows how
individual emission
varies over time
X-Ray Image

QUESTIONS?



SRMS History, Evolution and Lessons Learned

Glenn Jorgensen[1] and Elizabeth Bains.[2]
National Aeronautics and Space Administration

Early in the development of the Space Shuttle, it became clear that NASA needed a method of deploying and retrieving payloads from the payload bay. The Shuttle Remote Manipulator System (SRMS) was developed to fill this need. The 50 foot long robotic arm is an anthropomorphic design consisting of three electromechanical joints, six degrees of freedom, and two boom segments. Its composite boom construction provided a light weight solution needed for space operations. Additionally, a method of capturing payloads with the arm was required and a unique End Effector was developed using an electromechanical snare mechanism. The SRMS is operated using a Displays and Controls Panel and hand controllers located within the aft crew compartment of the shuttle. Although the SRMS was originally conceived to deploy and retrieve payloads, its generic capabilities allowed it to perform many other functions not originally conceived of. Over the years it has been used for deploying and retrieving constrained and free flying payloads, maneuvering and supporting EVA astronauts, satellite repair, International Space Station construction, and as a viewing aid for on-orbit International Space Station operations. After the Columbia accident, a robotically compatible Orbiter Boom Sensor System (OBSS) was developed and used in conjunction with the SRMS to scan the Thermal Protection System (TPS) of the shuttle. These scans ensure there is not a breach of the TPS prior to shuttle re-entry. Ground operations and pre mission simulation, analysis and planning played a major role in the success of the SRMS program. A Systems Engineering Simulator (SES) was developed to provide a utility complimentary to open loop engineering simulations. This system provided a closed-loop real-time pilot-driven simulation giving visual feedback, display and control panel interaction, and integration with other vehicle systems, such as GN&C. It has been useful for many more applications than traditional training. Evolution of the simulations, guided by the Math Model Working Group, showed the utility of input from multiple modeling groups with a structured forum for discussion.There were many unique development challenges in the areas of hardware, software, certification, modeling and simulation. Over the years, upgrades and enhancements were implemented to increase the capability, performance and safety of the SRMS. The history and evolution of the SRMS program provided many lessons learned that can be used for future space robotic systems.

[1] Shuttle Division Chief Engineer for the, Automation, Robotics and Simulation Divison, NASA-JSC, 2101 NASA Parkway, Houston,77058.
[2] Integrated Analysis Manager, Automation, Robotics and Simulation Divison, NASA-JSC, 2101 NASA Parkway, Houston,77058 and AIAA Associate Fellow.

I. System Description and Evolution of the Shuttle Remote Manipulator System

THE fundamental requirement of the Shuttle Remote Manipulator System (SRMS) was to deploy and retrieve payloads to and from space. To accomplish this mission, the system that was developed consisted of an anthropomorphic manipulator arm located in the shuttle cargo bay (shown in Figure 1), cabin equipment to provide an interface to the main shuttle computer, and a human interface to allow an astronaut to control arm operations remotely.



Figure 1. SRMS in the pre-cradle position looking aft in the shuttle payload bay

A. Hardware Overview

The manipulator arm consists of three joints, two arm booms, an end effector, a Thermal Protection System, and a closed-circuit television system. Figure 2 breaks down the primary SRMS components. The arm joints included a shoulder joint with two degrees of freedom (yaw and pitch), an elbow joint with one degree of freedom (pitch), and a wrist joint with three degrees of freedom (pitch, yaw, and roll). Each joint degree of freedom consists of a motor module driving a gear box to effect joint movement and appropriate local processing to interpret drive commands originating from the cabin electronics.

The cabin electronics includes a displays and controls subsystem that provides the human-machine interface to allow a crew member to command the arm and view displays of appropriate information, including arm position and velocity, end effector status, temperature, and caution and warning information. Additionally, in the displays and controls subsystem, two hand controllers allow man-in the-loop control of the end point of the arm. The main arm processor is the manipulator controller interface unit (MCIU) that is also part of the cabin electronics. It handles all data transfer between the arm, displays and controls panel, and the main shuttle computer. The main shuttle computer processes commands from the operator via the displays and controls panel; receives arm data to determine real-time position, orientation, and velocity; and then generates rate and current limit commands that are sent to the arm-based electronics. The arm is thermally protected with specially designed blankets to reduce the susceptibility

of the hardware to the thermal extremes experienced during spaceflight and has an active thermostatically controlled and redundant heater system.

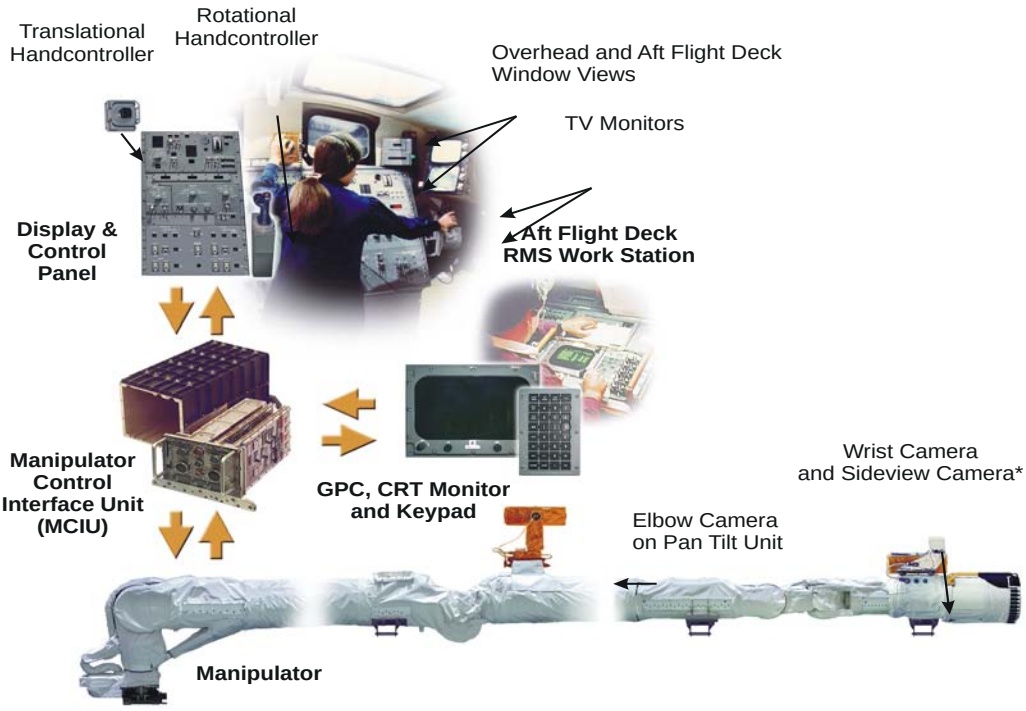


Figure 2. Primary SRMS Components **(Source – Reference 1)**

The closed-circuit television system consists of three cameras. A color camera on a pan/tilt unit near the elbow joint was used as a situational awareness camera for the SRMS operator. A second camera in a fixed location on the wrist joint was primarily used to view a grapple fixture target when the arm was capturing a payload. A third camera called the SRMS Side-view Camera was added after the Columbia accident. This was fixed on the inboard side of the wrist joint and was used as a situational awareness camera when the SRMS was performing Shuttle Thermal Protection System inspections with the Orbiter Boom Sensor System (discussed later).

Self-checks exist throughout all the Shuttle Robotic Arm electronics to assess arm performance and apply appropriate commands to stop the arm, should a failure occur. Caution and warning displays provide the operator with insight into the cause of the failure and remaining capability to facilitate the development of a workaround plan.

B. SRMS Operating Modes

The operating modes of the SRMS included Automatic modes, Manual Augmented modes, Single drive, Direct drive and a Back-up drive. Auto, Manual Augmented, and Single drive mode were supported with the main Shuttle computer and included servo joint rate control. Maximum joint rates were determined pre-flight and varied based on the payloads being handled. Direct and Back-up drive modes were hardwired, reduced capability modes that applied a fixed voltage to the joint drive amplifier.

Automatic modes included pre-programmed and operator commanded auto sequences. The pre-programmed sequences were developed prior to flight and loaded into the main shuttle computer. The operator commanded auto sequence mode required the operator to input a final SRMS position and orientation before arm motion was initiated. Auto sequences were used primarily for shuttle and payload surveys and lengthy repositioning maneuvers.

Manual Augmented modes allowed the SRMS operator to manipulate the SRMS position and orientation real time using the Translational and Rotational hand controllers. The Point of Resolution and co-ordinate axes could be varied depending on the operation being performed. This mode was used for grappling, berthing and un-berthing payloads, track and capture of free flying payloads, and coarse positioning of the SRMS.

Single joint drive allowed the operator to control each joint individually. This mode was used primarily to cradle and un-cradle the arm, and for fine positioning of the SRMS.

Direct and Back-up drive modes were used for contingency arm motion should computer supported modes be lost. They allowed only single joint control.

C. The SRMS End Effector

The interfacing end of the Shuttle Robotic Arm is equipped with an electromechanical End Effector. Figure 3 shows a picture of the End Effector on the end of the SRMS wrist joint. The wrist camera/light assembly is also shown. The End Effector is the equivalent to a human hand and is used to grapple a payload fitted with a specially designed interface known as a grapple fixture. A picture of a grapple fixture is shown in Figure 4.

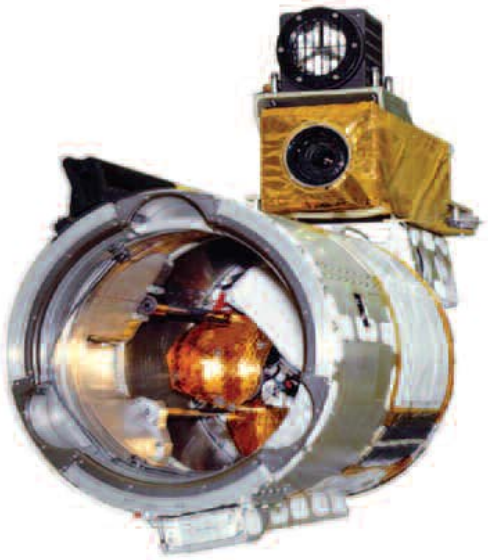


Figure 3: SRMS End Effector and Wrist Camera /Light
(Source – Reference 1)

The grapple fixture includes a grapple pin, a target, and three alignment cams that mate to cam lobes on the End Effector. The End Effector uses a three cable snare mechanism that closes around the grapple pin (see Figure 5). Once grappled to the pin, the snare mechanism is drawn inward into the main body of the End Effector to "rigidize" the payload to the SRMS. The cams ensure there is no End Effector/Grapple fixture motion once the payload is captured.

The standard grapple fixture is called a Flight Releasable Grapple Fixture, since it is equipped with a mechanism that can be activated by an EVA crewman to release the grapple pin should the End Effector fail while grappled to a payload.

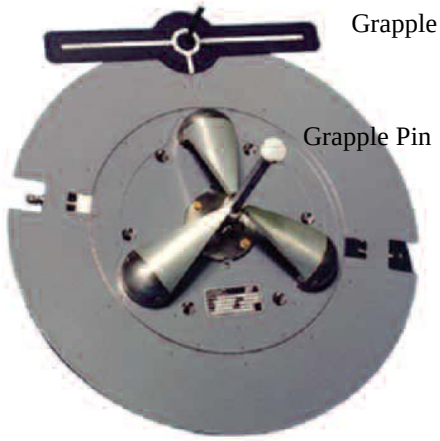


Figure 4: Grapple Fixture (Source – Reference 1)

The End Effector is also equipped with an electrical connector called a Special Purpose End Effector (SPEE) connector. This connector is fed with sixteen power and data lines from a cable harness routed along the length of the SRMS. This connector can mate to a specially designed grapple fixture called an Electrical Flight Grapple Fixture (EFGF). When captured, a payload equipped with an EFGF can be sent power and data signals through the SRMS cable harness. A switch panel within the Shuttle was configured to provide these signals.

To track and capture a payload required the use of the grapple fixture target in conjunction with SRMS wrist camera. The camera is oriented to allow a straight on view of the target. The camera video was displayed to the crew in the aft

flight deck, and helped the crew properly position the end effector relative to the grapple fixture prior to capturing a payload. An overlay on the CRT display was used to aid the crewman in determining when the End Effector was over the grapple pin and ready for capture. The SRMS was maneuvered to position the camera view of the grapple fixture target within the boundaries of the overlay. When satisfied with the relative position of the End Effector to the grapple fixture target, the crew used a switch on the Rotational Hand Controller to capture and secure the payload. The End Effector could be operated in either automatic or manual modes. In automatic mode the rigidize command would be initiated automatically after the snares were closed around the grapple pin. This was the standard mode of operation. Manual mode required the crewman to input the snare close and rigidize commands separately.

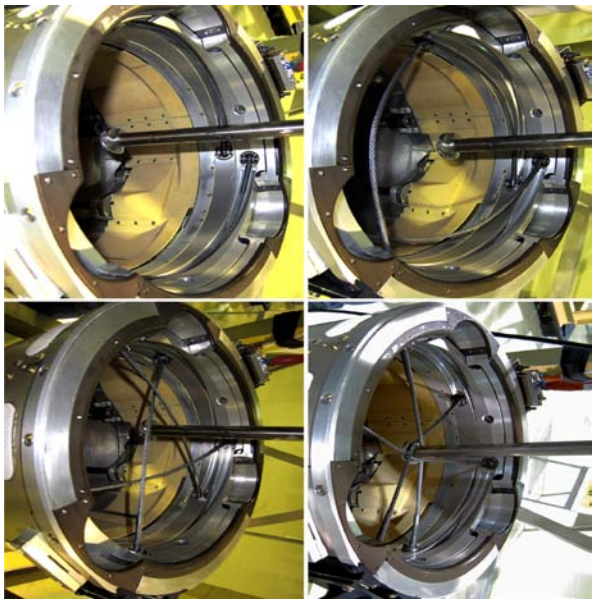


Figure 5: End Effector Snaring a Grapple Pin (Source – Reference 1)

II. SRMS History of Operations

The SRMS first flew on STS-2, and by the end of the Shuttle program it had flown a total of ninety-one missions. While originally envisioned only for satellite deployment and retrieval, the utility of a robotic arm for other tasks quickly became clear. Over the life of the program the SRMS evolved into an indispensible tool not only for satellite deployment and retrieval, but was used extensively for satellite rescue and repair, as an EVA platform, International Space Station construction, shuttle and payload bay surveys, as well as a host of contingency operations.

There were only three on orbit failures in the history of the SRMS program and only one of these failures prevented completion of the mission. This was STS-41B when the wrist yaw motor commutator failed causing loss of all primary modes of operation. The payload scheduled to be deployed (the SPAS satellite) had to remain in the payload bay. The second failure was on STS-51I when the power to the elbow joint electronics was shorted to ground. The crew managed to complete payload operations using back-up drive for the elbow joint and single joint drive for the other joints. The third failure was due to an incorrectly installed SPEE connector that prevented power and data transfer to the payload (EURECA satellite). The satellite was berthed and the data transfer took place via a payload bay connector.

Other less significant failures were experienced, and these were all worked by the ground team and the crew to allow completion of the mission with no loss of functionality in the SRMS. The reliability of the SRMS in its thirty year history is testament to the excellent design, manufacturing and testing teams, and to the ground support personnel working with the rest of the shuttle team. The SRMS has proven its worth and has provided a blue print for future robotic arms in space.

A. Satellite Deployment, Retrieval, and Servicing

The list of satellites that were deployed and retrieved by the SRMS is long and impressive. The heavy lift capability of the Shuttle combined with the capabilty of the SRMS allowed unique satellite missions to be designed that were not previously possible. The retrieving capability of the SRMS made on-orbit repair and maintenance of satellites a reality for the first time.

Figure 6 is a picture of the SRMS deploying the Gamma Ray Observatory (GRO) on STS-37. Other payloads of note deployed by the SRMS include the Earth Radiation Budget Satellite (ERBS) on STS-41G, and the Upper Atmosphere Research Satellite (UARS) on STS-48.

The majority of payloads deployed were also retrieved by the SRMS. The first successful capture of a free flying payload was on STS-7 when the SPAS-1 satellite, originally deployed earlier in the mission, was captured and berthed in the payload bay by the SRMS. Other deployments and captures include SPARTAN on STS-51G, the Plasma Diagnostics Package (PDP) on STS-51F, and the SPAS-2 payload on STS-39. The Long Duration Exposure Facility (LDEF) was deployed on STS-41C and retrieved on STS-32 (see Figure 7). The European Retrievable Carrier satellite (EURECA) was deployed on STS-46 and retrieved on STS-57.

The SRMS also played the primary role in rescuing malfunctioning satellites. For example, during STS-41C, it was used to grapple and berth the spinning Solar Maximum Mission satellite (Solar Max). It had been deployed in 1980 and had been fitted with a grapple fixture to allow capture with the SRMS. The track and capture capability of the SRMS was put to the test due to the high spin rate of Solar Max. The SRMS was used on STS-51A during the retrieval of two malfunctioning comsats, Palapa B2 and Westar VI, which were subsequently refurbished on Earth and re-flown. One of the more notable SRMS accomplishments was the deployment of the Hubble Space Telescope (HST) on STS-31 in April, 1990. This was followed by four successful HST servicing missions (STS-61 in 1993, STS-103 in 1999, STS-109 in 2002, and STS-125 in 2009) during which the SRMS was used to retrieve, repair and redeploy the space telescope. The final servicing mission, STS-125, is expected to extend the life of the HST to 2014.

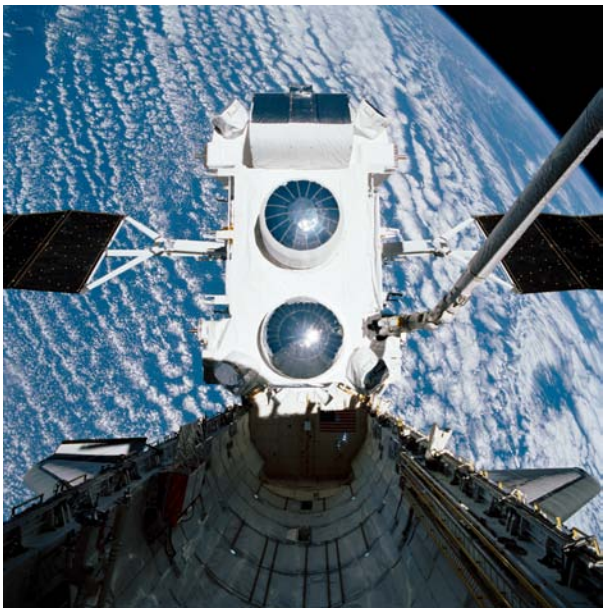


Figure 6. STS-37 - Deploying the Gamma Ray Observatory



Figure 7: Maneuvering the Long Duration Test Facility on STS-32

B. Extra Vehicular Activity (EVA) Platform

A mobile work platform for EVA astronauts became one of the most important uses for the SRMS. The arm was used extensively in this capacity, both for pre-planned operations and for contingency EVA's planned real-time that were needed for inspection or repair. The EVA crewmember could be mounted on a portable foot restraint attached directly to the SRMS, or he could be mounted to the Manipulator Foot Restraint (MFR) that was grappled by the End Effector, or the crewman could simply grab the EVA handhold attached to the End Effector. The arm operator inside the shuttle could easily position the EVA crewmember anywhere within the reach capability of the arm. The stable platform provided by the SRMS allowed the crewman to perform tasks much easier than if he were free floating. Radio communication between the EVA crewman and the arm operator enabled quick repositioning as

required. Tool stanchions and holders were developed to aid in the repair and maintenance activites. There are many examples during the life of the Shuttle program where the SRMS was used to support EVA, but none provide more concrete evidence of the value of a robotic arm as an EVA platform than the HST repair missions.

The Hubble Space Telescope, deployed on STS-31 (1990), gave the world a perspective of outer space never before seen. The first servicing mission repaired a problem with the telescope's main lens assembly. The subsequent missions replaced and enhanced onboard instrumentation. This improved the accuracy and extended the life of HST. Figure 8 shows an EVA crewman on the end of the SRMS preparing for a Hubble repair task. More than any other payload, the Hubble servicing missions displayed to the world the unique capabilities of the SRMS.



Figure 8: Hubble Space Telescope EVA Repair Work on STS-61

C. The Era of Space Station Construction

The SRMS was the primary mechanism used for early International Space Station (ISS) construction. During the later stages when the ISS was so large that the SRMS could not reach many berthing locations, the SRMS was used in conjunction with the Space Station Remote Manipulator System (SSRMS) to complete the construction. In fact, the SRMS served as the proof of concept for the SSRMS, and many of the design features, capabilities and operations of the SRMS were used in the design and development of the SSRMS. Figure 9 shows the ISS P5 Truss segment being handed off on STS-105. ISS elements that were handled by the SRMS included Nodes 1,2 and 3, the US Laboratory Module the Space Station Airlock, nine truss segments, many of which contained solar panels for power to the station; and the Space Station Remote Manipulator System (SSRMS). These activities required some modifications to the SRMS itself, as well as the addition of systems to enhance alignment and

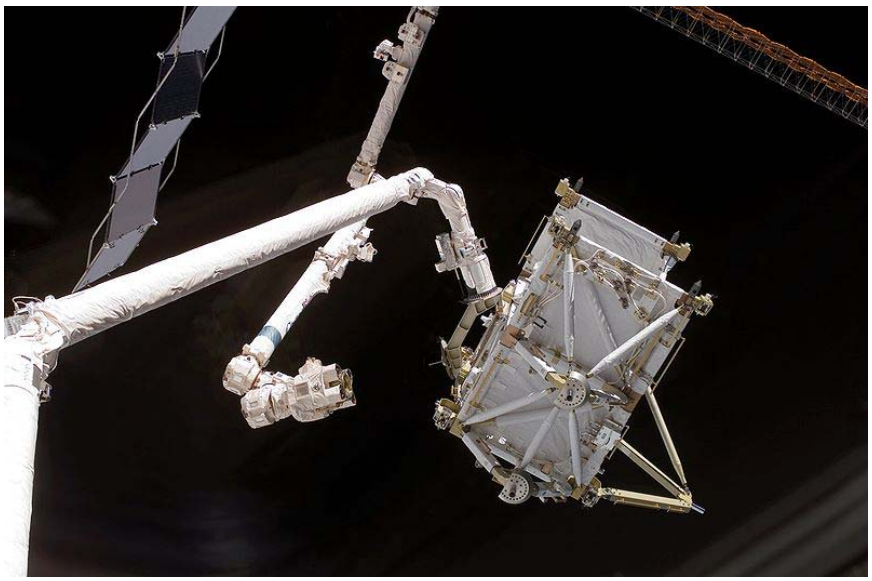


Figure 9: Handing off the ISS P5 Truss Segment from SRMS to SSRMS

berthing operations. During the preliminary planning, studies evaluated the adequacy of the SRMS to handle the anticipated payload operations envisioned for the space station construction. These studies determined that arm controllability would not be satisfactory for the massive payloads the arm would need to manipulate. Redesigning the Servo Power Amplifiers (part of the Arm Based Electronics) in each joint provided the necessary controllability. Also, the addition of increased self-checks assured better control of hardware failures that could cause hazardous on-orbit conditions. During the process of assembling the space station, enhanced berthing cue systems were necessary to mate complicated interfaces that would need to transmit loads and maintain a pressurized interior. The complexity and close tolerance of mating parts led to the development of several berthing cue systems, such as the space vision system and the centerline berthing cue system, to enhance the crew's ability to determine relative position between mating modules.

D. Return to Flight After the Columbia Accident – The Orbiter Boom Sensor System

During the launch of the Space Shuttle Columbia on STS-107 (2003), a piece of debris hit the shuttle, causing a rupture in the Thermal Protection System that is necessary for re-entry into Earth's atmosphere, thereby leading to the Columbia accident. The ramifications of this breach in the shuttle's Thermal Protection System changed the role of the SRMS substantially for all post-Columbia accident missions. Development of the robotically compatible 50-ft Orbiter Boom Sensor System (OBSS), carried on the starboard mai=nipulator positioning mechanisms, provided a shuttle inspection and repair capability that addressed the Thermal Protection System inspection requirement for post-Columbia Return to Flight missions. Figure 10 shows the OBSS grappled by the SRMS. Modification of the robotic arm wiring provided power and data capabilities to support the inspection cameras and lasers at the tip of the inspection boom. Two shuttle repair capabilities were provided in support of the Return to Flight effort. The first scenario required the SRMS, grappled to the space station, to position the shuttle and the space station in a configuration that would enable a crew member on the Space Station Robotic Arm to perform a repair. This was referred to as the Orbiter Repair Maneuver (ORM). The second repair scenario involved the Shuttle Robotic Arm holding the boom with the astronaut at the tip.



Figure 10: The SRMS Grappled to the Orbiter Boom Sensor System

All of the post-Columbia-accident missions employed the SRMS and Orbiter Boom Sensor System combination to survey the shuttle for damage. The SRMS and OBSS were used to inspect all critical Thermal Protection System surfaces. After the imagery data were processed, focused inspections occasionally followed to obtain additional images of areas deemed questionable from the inspection. A detailed test objective on STS-121 (2006) demonstrated the feasibility of having a crew member on the end of the OBSS grappled by the SRMS and performing actions similar to those necessary for Thermal Protection System repair. Test results showed that the integrated system could be used as a repair platform and that the system was controllable with the correct control parameters, good crew training, and proper extravehicular activity procedures development.

In support of shuttle repair capability using the Orbiter Repair Maneuver described earlier, the simulation model of the SRMS was updated to evaluate the handling of the space station as a "payload". This heavy payload model update proved useful when it was decided to repair the Hubble Space Telescope on STS-125. This is because after

the Columbia accident, a method of crew rescue was mandatory for all shuttle flights. A “Launch on Need” shuttle was manifested for crew rescue should the shuttle on orbit sustain damage that would prevent re-entry. Given that the space station would not be available for crew rescue for the final Hubble servicing mission, the SRMS would be used to grapple the failed Shuttle. For the crew from the disabled shuttle to get to the rescue shuttle, the Shuttle Robotic Arm would act as a path for crewmen to transfer between the two vehicles. The updated SRMS simulation for heavy payloads proved its worth when developing and validating this rescue scenario. Fortunately, neither of these repair/rescue capabilities—Orbiter repair maneuver or Hubble rescue— ever had to be used.

III. Unique Challenges in the Development of the SRMS

A. Mechanical Design

As with all space systems, a tradeoff between mass and strength/stiffness had to be considered in the mechanical design of the SRMS. With stiffness a primary consideration along with low mass, the material chosen for the booms of the SRMS was a carbon composite material. In addition to stiffness, the high strength to weight ratio of carbon composite makes it ideal for space applications.

Additionally stiffness was the driver in the design of the joints. The elbow joint, having only one degree of freedom, could not relieve forces and moments acting in off-axis directions, so strength was also a primary driver in its design. The joint construction was primarily fabricated aluminum housings, with some steel and titanium for higher load bearing components. The gears were made from Carpenter Custom 455 steel, an exceptionally high strength material (reference 1).

The joint actuation design was electro-mechanical using brushless DC motors and high ratio gear boxes. Identical motors were used in every joint to minimize qualification requirements. Hydraulic joints were considered however the potential for contamination from hydraulic fluid leakage eliminated this option. The choice to use relatively small motors driving the joint through a gear box, instead of larger motors in a direct drive configuration, was driven by the need to reduce weight. The gear ratios were adjusted based on the motor torque characteristics, and the requirement for high forward and backdrive efficiency, low backlash, and high drive train stiffness (reference 1).

Each gearbox was designed with two stages. The first stage was a high speed design and the gear reduction ratio varied from joint to joint to meet the specific joint torque requirement. The second stage was identical in all joints and was a planetary design that maximized the number of load paths and provided high stiffness and low backlash.

Backdrivability was a key driver in the design of the joints. High external loads can result in forces and moments applied to the arm that exceed its structural capability. Joints that can be backdriven will reduce the potential for this excessive loading. The back drivability requirement drove the need for high gearbox efficiencies.

The efficiency and back drivability requirements led to problems in the manufacture of the gearboxes. Tight tolerances in manufacture are necessary to achieve the degree of backlash and friction required to meet the control system requirements. Gears had to be chosen based on a "select-on-manufacture" program resulting in a low yield rate and higher costs.

To ensure the joints did not apply excessive loads when the joints were in forward drive mode, motor current limiting was implemented in the servo power amplifiers that provided the electrical power to the motors. The forward and backdrive current limits were matched to the gearbox effieciencies. Thus dynamic conditions were similar in all four quadrants of the drive system.

The joint motor was chosen to minimize weight and eliminate maintenance. The brushless design avoided the wear and tear of commutator brushes. The motor chosen was a frameless design, so it was assembled in a housing that included the motor and commutator, plus a brake and a tachometer. The entire unit was called the motor module and was common to all six joints. To ensure servo stability when the motor was driving in a no load condition, a flywheel was added.

Dynamic braking using the motor to decelerate the joint was also incorporated into the joint design. This eliminated the requirement to apply mechanical brakes each time a drive command was removed and prevented excessive wear on the brakes. This was required to meet the life requirements (originally 10 years but extended as the program evolved).

The SRMS electronics had extensive Built-In Test Equipment (BITE) that detected potentially catastrophic failures and automatically applied brakes to prevent joint runaway and inadvertent contact between the arm and external shuttle/payload structure. To reduce the potential to exceed the structural load limits of the arm under these malfunction conditions, the joints had to be backdrivable with the brakes applied. Thus the brakes had to be

designed not only to provide a minimum holding torque, but also a maximum torque. It was found that the holding torque of the original brake material (an asbestos derivative) degraded with prolonged exposure to a vacuum due to moisture loss. To solve this problem, the motor modules were refitted with ceramic brakes. Future space robotic systems that are exposed to long term vacuum conditions should consider the use of ceramic brake material.

B. Software-Singularity Management

The flight software (FSW) uses the Jacobian transformation matrix to relate joint rates to rates of the selected control point. When the SRMS is commanded to translate and/or rotate a defined point (tip of the SRMS or a selected point within the payload), the commanded joint rates are obtained using the inverse of the Jacobian. No solution for the commanded joint rates is available when the determinant of the Jacobian matrix is zero. There are three conditions that cause this for the SRMS; these three conditions are shown in Figure 11.
These singularities cause loss of one or more controlled degrees of freedom of the arm. With the wrist yaw joint above the shoulder joints, ± Y translation commands cannot be accomplished (shoulder singularity). With the arm straight out, commands in the +X direction in the EE mode are not possible (elbow singularity). With the wrist yaw joint 90 degrees from the arm pitch plane, some roll commands are not possible (wrist singularity).
These singularities are managed within the RMS software algorithms. The arm is driven through the shoulder and wrist singularities by the software in the automatic and manual modes. During software handling, the arm may deviate slightly from its commanded trajectory. The most dramatic deviation occurs if the operator commands a Y translation through the shoulder singularity. When the wrist yaw joint is 3 feet from being directly over the shoulder joint, the arm is re-oriented to drive in a circle around the singularity and then continues the Y translation.

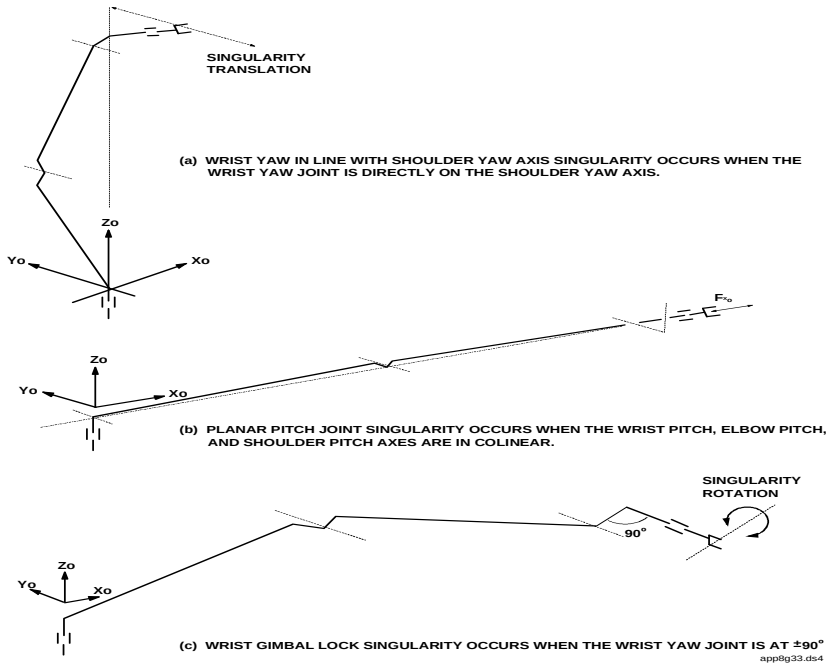


Figure 11: RMS singularity configurations. **(Source – Reference 4)**

The operator is advised via a caution light on the D&C panel when a singularity is approached or encountered. The elbow singularity occurs when the SRMS elbow is reaching its maximum reach; motion is permitted until the elbow approaches its limits of motion. This is handled as is any joint reaching its limit. The approach to the limit is first announced by a caution light on the D&C panel, and then the arm motion is stopped if the operator continues to move further toward the limit.

C. Software - Consistency Check

The SRMS, like most computer controlled systems, uses Built In Test Equipment (BITE) throughout the system to detect errors. In addition, there is also error detection in the FSW, including the consistency check used for runaway detection. Runaways were a particular concern for the SRMS because of the potential for damage to the orbiter if a payload were driven into the orbiter by a joint that had unlimited current applied to the motor. This never occurred during the history of the SRMS, but the potential damage required extra protection to limit the time that a runaway could exist. The consistency check provides an envelope around the commanded motor rate for each joint, as shown in Figure 12.

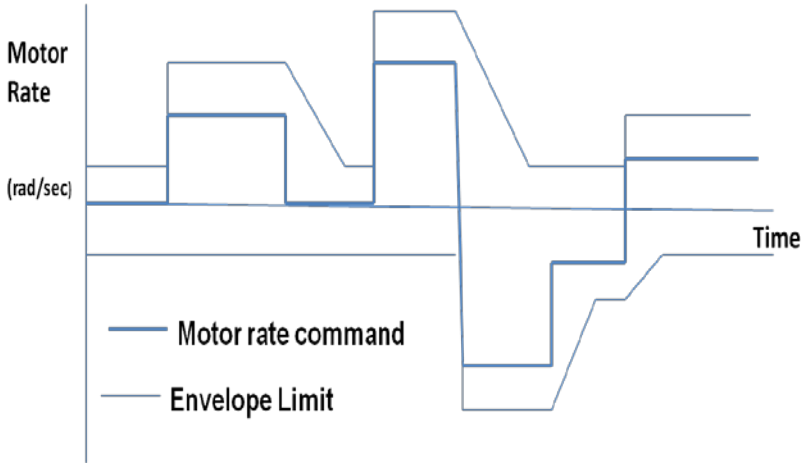


Figure 12: Envelope consistency check for motor rate.

Three components of the envelope define an offset from zero commanded motor rate, a second offset from a commanded rate, and a decay applied when a command is removed or changed. The actual motor rate is monitored and must remain within this envelope, although dynamic excursions outside the envelope are not annunciated unless the motor rate is outside the envelope for more than 4 consecutive computation cycles. Definition of the values for the envelope constants required considerable analysis at the start of the program to stop joint runaways within an acceptable distance of two feet, while ensuring false alarms were not generated. False alarms could be generated by dynamic excursions in motor rate during command changes.

D. Test and Verification

D.1 Air Bearing Test Rig

Since the SRMS could not support its own weight in a 1G environment, a unique test method had to be developed to verify the SRMS system as a whole. Individual joint drive tests could be performed with the arm supported in a mechanical “strong-back” ; however testing a complete arm assembly with multi-joint point of resolution control was not possible in this configuration.

An air-bearing flat floor test rig was designed to allow multi-joint operation of the SRMS (see Figure 13). The air-bearing rig allowed forced air to be piped through special air pads mouned on the feet. This counteracted the effects of gravity and reduced the friction between the floor and the test rig loaded with the mechanical arm, allowing the arm to be driven across the floor with minimum loading.

The arm could be mounted on the rig in pitch coupled mode or yaw coupled mode. In pitch coupled mode the three pitch joints could be driven, and in yaw coupled mode the two yaw joints could be driven. The wrist roll joint could be driven in either mode. Even though only one plane of motion could be tested at a time, it did provide engineers a method of verifying arm controls, tip accuracy, tip force, and multi-joint straight line controllability. This was the most comprehensive full up system test performed before the system was checked out on-orbit. Electrical Ground Support Equipment (EGSE) was used to provide power, GPC communication, and data monitoring.

In addition to multi-joint drive, the air bearing test rig provided a means to monitor arm response in a constrained motion envirionment. With the End Effector mounted to the arm, it could be used to grapple a “payload” weighted down to emulate constrained motion (see Figure 13). This configuration was also used to verify the force capability, joint current limit response, and arm response to End Effector/grapple fixture misalignments.

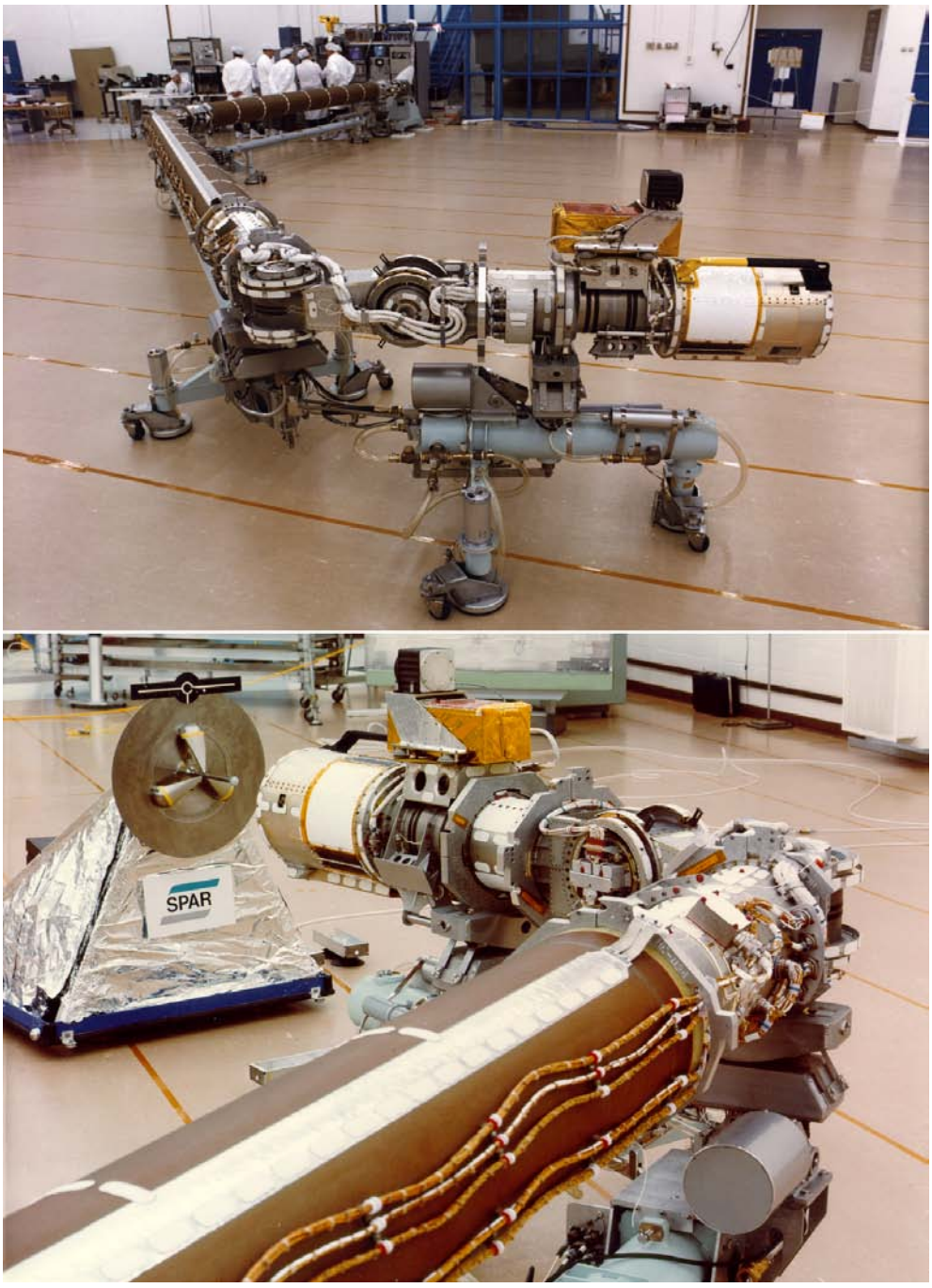


Figure 13: The SRMS on the Air Bearing Flat-Floor Test Rig (Source- Reference 1)

D.2 Simulations

Simulation of the SRMS was both a solution to the inability to fully test the SRMS on the ground and also presented unique challenges on its own, particularly for real-time simulation in the computers of the 70's and early 80's. When the SRMS was developed, modeling the 6-joint robotic arm was new. The coupled elements ranged from the orbiter (about 6216 slugs) to the light wrist links (the wrist roll joint when no payload was grappled is 3.09 slugs).

The bending modes of the long booms were also included, with very small effective mass. At JSC the equations were expressed in matrix form and generated a very ill-conditioned matrix. For non-real-time simulations these equations were solved in 64-bit precision. However real-time computers of the day that were fast enough for the SRMS equations generally had only 32 bit precision (and required assembly language programming). This became a significant implementation challenge at JSC.

A major JSC simulation capability throughout the Shuttle Program was the Systems Engineering Simulator (SES), a real-time, operator in the loop simulator that used functional FSW and a functional cockpit. As computers became more powerful throughout the 80's and 90's, the SRMS model was upgraded until it had the full capabilities of the best non-real-time model in 2004.

The models developed for the SES in the 80's and early '90s were also used in the Shuttle Avionics Integration Laboratory (SAIL) which had IBM General Purpose Computers with HAL flight software and a Flight cockpit with the hardware-in-the-loop MCIU for the SRMS. The remainder of the SRMS was a computer model. SAIL, which carried a Shuttle designation (OV-095), was used for verification of the FSW. Connecting the simulated SRMS model to the flight hardware was an additional challenge, involving special purpose hardware boxes as well as careful timing of the SRMS model.

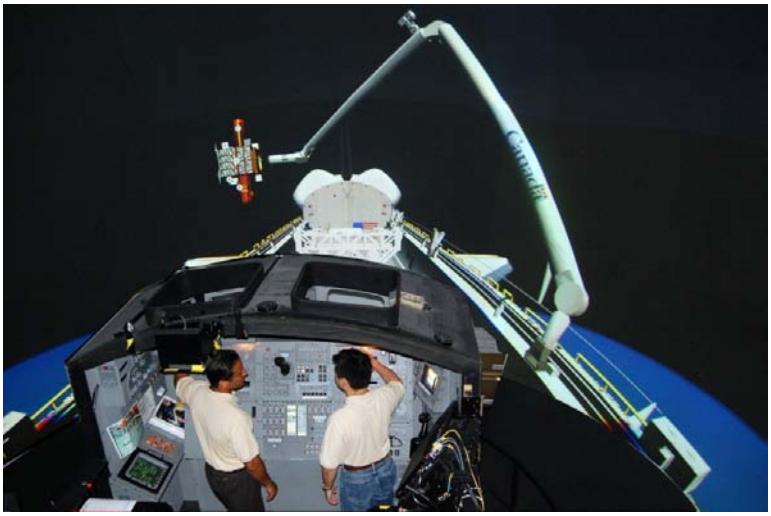


Figure 14. Astronauts Joseph Acaba (at the DAP station) and Akihiko Hoshide (at the SRMS station) in the SES Dome Aft Cockpit with the OTW scene projected on the Dome surface (Source-Reference 2)

The SES combines the SRMS simulation with 6 DOF dynamic motions of two vehicles. These vehicles are subjected to the effects of orbital dynamics, aerodynamics, the Orbiter Digital Auto Pilot (DAP) thruster firings, the payload control system, and the RCS plume impingement. In the late 90's, in response to the requirements of SRMS berthing studies for ISS assembly, various contact mechanism math models were also incorporated into the SES. The SES also provides the operator with out the window and camera views generated by electronic scene generators. Although scene generators are common today, the first electronic scene generator was developed for SES SRMS simulations. The capability was upgraded throughout the Shuttle program and today includes a dome simulator that provides a continuous view from overhead to the Orbiter payload bay. An overview of the SES aft cockpit mockup in the dome display system is shown in Figure 14. Modeling of the DAP as well as the SRMS in the SES allows coordinated operations of the SRMS operator and the DAP pilot. Throughout the Shuttle program the SES was used for engineering evaluations of changes to FSW or procedures that required operator inputs. In addition it was available for procedures development and crew training, and was used many times during flights to evaluate proposed solutions to on-orbit problems. Use of SES included evaluation of procedures for Detailed Test Objectives (DTOs) for the first five flights of the SRMS, track and capture of the first payload released and retrieved by the SRMS (SPAS-01 on STS-7), capture of rotating payloads, and assessing un-commanded motion. Other uses were berthing of payloads to various latching mechanisms on the shuttle and space station, assessment of proposed Orbiter repair techniques, and interaction between various modes of the Orbiter DAP and the SRMS holding the OBSS. It was also used for testing the Position Orientation Hold Submode (POHS) software implemented to control the un-commanded motion.

D.3 Early Missions

The first five flights of the SRMS included Detailed Test Objectives (DTOs) that started with the simple SRMS capabilities and gradually demonstrated more complex capabilities. The testing conducted on these five flights included:

STS-2: Unloaded arm tests, including single joint commanding, translational and rotational commanding of the tip of the SRMS, unloaded maneuvers for simulation validation, and auto mode checkout.

STS-3: Additional unloaded arm tests including test of the backup mode, soft stop tests, and PRCS/SRMS interaction. First grapple of a berthed payload, maneuvers around the payload bay, and re-berth. PRCS/SRMS interaction with the payload on the SRMS. A capture of a second payload was not attempted because the wrist camera failed and payload bay cameras did not provide adequate views for re-berthing.

STS-4: Grapple of a payload in the payload bay and maneuver around the bay to assess the payload bay environment, singularity management tests, PRCS/SRMS interaction with an unloaded SRMS and with the payload on the SRMS.

STS-7: Release and capture of a light-weight payload (SPAS-01). Multiple releases in different EE modes were performed to evaluate residual rates imparted on the payload by the release. Track and capture was performed with the arm in manual mode and also single mode. Maneuvers were also performed to provide data for simulation validation.

STS-8: Grapple of a medium weight payload (Payload Flight Test Article) and extensive maneuvering around the payload bay to provide data for SRMS capability checkout and simulation validation. Two grapple fixtures were used. One simulated the inertia of an 8K payload and the other simulated the inertia of a 16K payload.

IV. Lessons Learned

A. Off Nominal Operations:

The primary mission of the SRMS was to deploy and retrieve payloads; however one of the key lessons learned during the life of the Shuttle program is how useful a robotic arm can be for off-nominal and contingency operations. As the missions and additional hardware developed, unique uses of the arm emerged. Over the life of the program, the SRMS allowed the mission management team to deal with a variety of unforeseen problems encountered on orbit. The reach and force capability of the SRMS provided an operational flexibility that was not available with any other shuttle system. A robotic arm provides an effective solution for many tasks that formerly either could not be performed or required EVA to perform. Some unique operations performed were applying force to a satellite antenna to lock it in place (see Figure 15), supporting an EVA crewman performing a repair on Thermal Protection System of the Shuttle (see Figure 16), "ice busting" on STS-41D to remove a large icicle that formed on the shuttle's waste nozzle; and "fly swatting" on STS-51D to engage a switch lever on a satellite that had been incorrectly positioned.

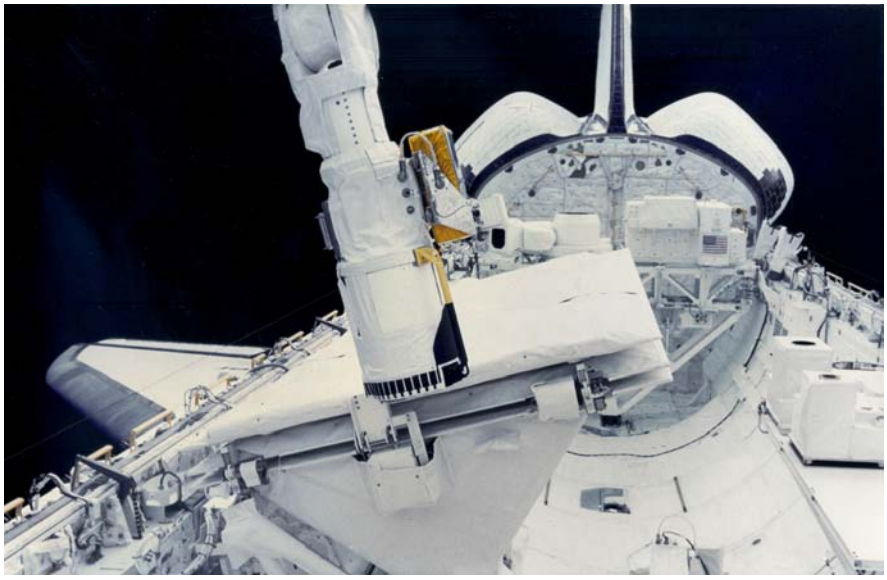


Figure 15: STS-41G Latching Down the SIR-B Antenna (Source- Reference 1)



Figure 16. STS-117 - Positioning an EVA crewman to repair the OMS POD for Re-entry (Source- Reference 1)

B. Position Orientation Hold Sub-mode:

A key lesson learned during the SRMS program was the improvement in arm performance that could be achieved with the addition of Position Orientation Hold Sub-mode (POHS) to control un-commanded motion. During STS-8 while the SRMS operator was maneuvering the PFTA payload, he noted that many corrections were needed to control un-commanded motion. During the LDEF un-berthing on STS-41C, crew started the un-berthing with a pure z command, as shown in Figure 17. This provided very clear data on un-commanded motion. As seen in the figure, the only command is a THC z-command, but at about 11.5 inches of z translation, x moved about 2.5 inches (about 22% of the motion in the commanded direction), roll moved about 1 deg, pitch moved about ½ deg (after first moving a small amount in the opposite direction), and the other axes moved by smaller amounts. Un-commanded POR motion is caused by a number of factors including torque disturbances due to dynamic coupling between the joint, friction, etc. In particular, when any joint rate crossed zero and friction torque changed sign, the un-commanded motion increases. This un-commanded motion was more significant when the commanded rate is low, and it became particularly objectionable for the deployment of heavy telescopes in the early 90's. During the HST deployment on STS-31 in April 1990, crew commented on the heavy workload due to the un-commanded motion. Figure18 shows the THC commands and the resulting translational motion, and Figure 19 shows the same data for the rotational axes. The unberthing command is a pure z, but that command stops and starts and many commands are also seen in all other axes.

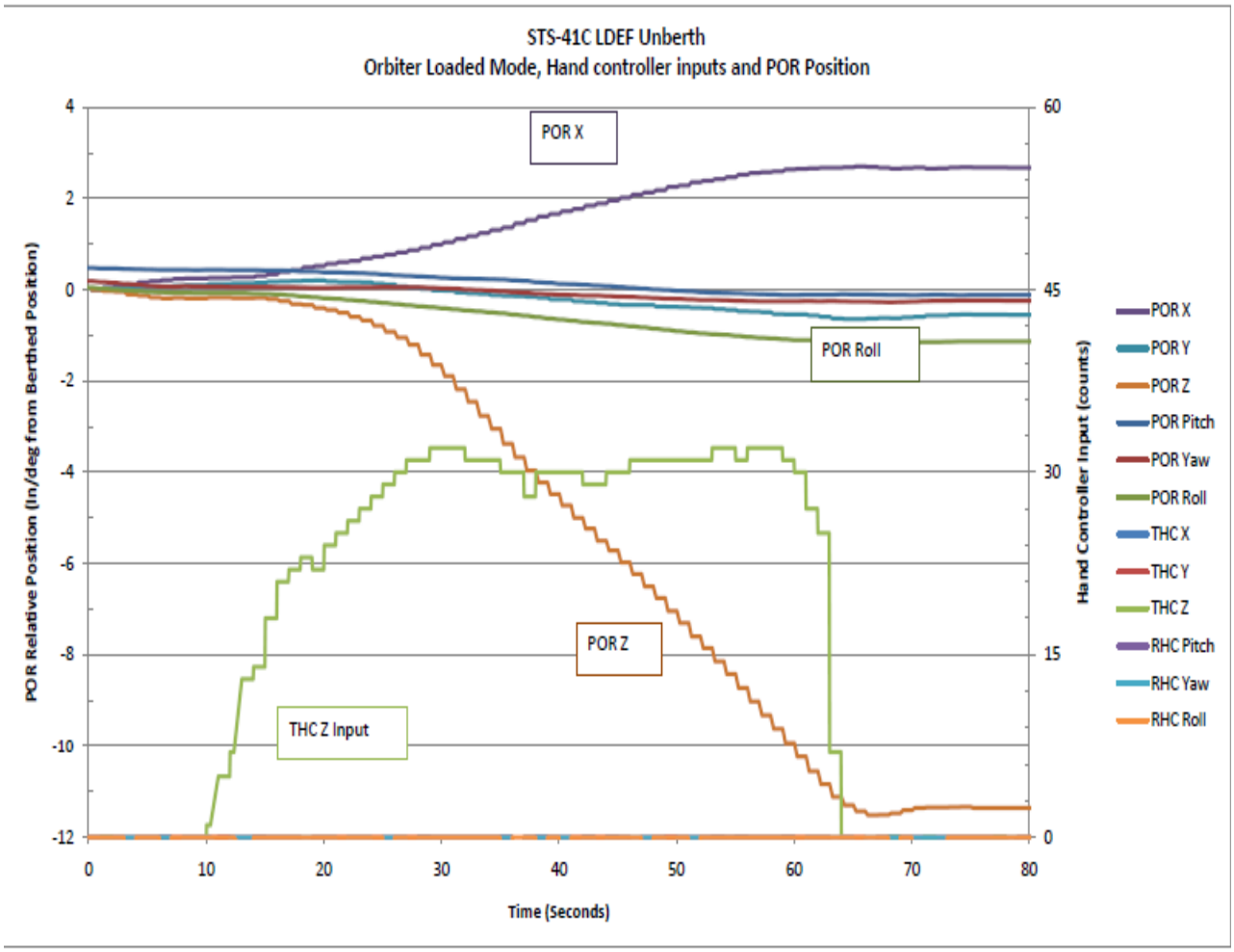


Figure 17. POR commands and POR actual motion during the first part of LDEF unberthing on STS-41C

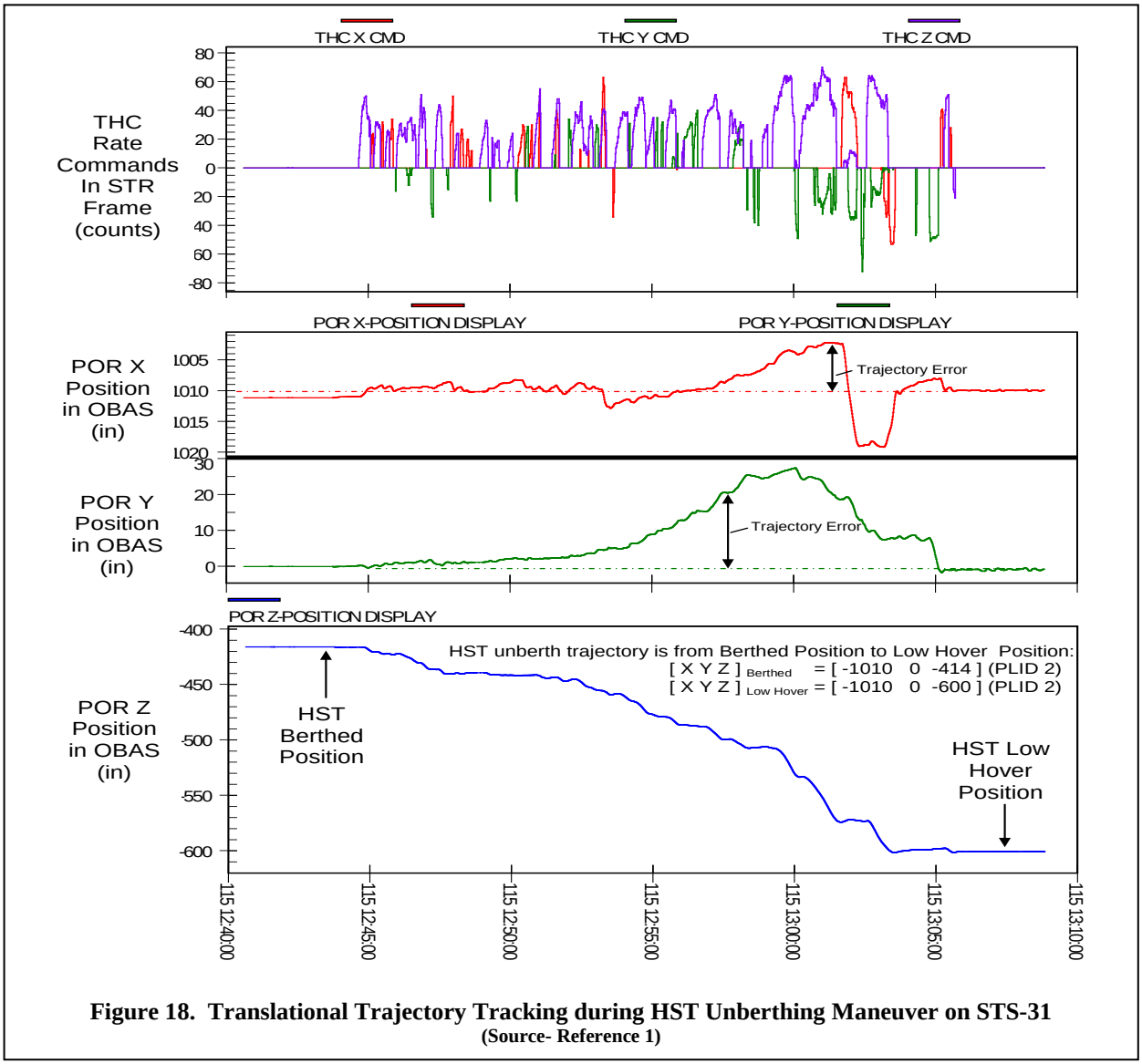


Figure 18. Translational Trajectory Tracking during HST Unberthing Maneuver on STS-31
(Source- Reference 1)

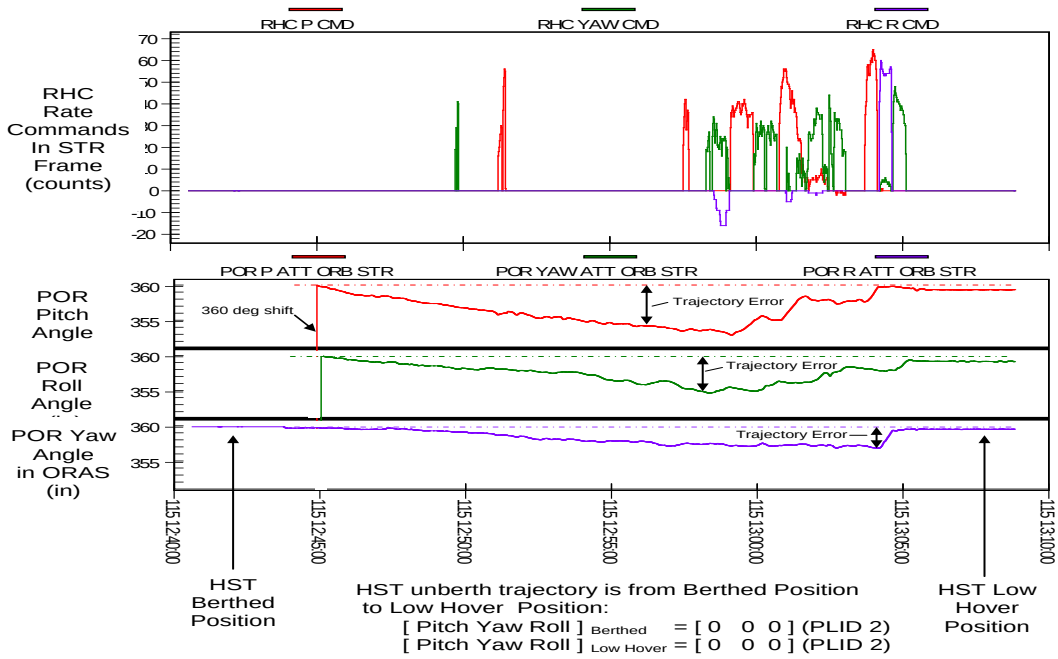


Figure 19: Rotational Trajectory Tracking during HST Unberthing Maneuver on STS-31

(Source- Reference 1)

To address this issue, POHS software was developed. The SRMS is a rate command system, and prior to the implementation of the POHS software, POR position and attitude were computed for display only. The POHS software uses the POR position and the commanded rate as shown in Figure 20. The figure shows two periods of rate command with a period of null command between them. When the SSRMS is at the initial POR position, the operator puts in the command V_1. The POHS software projects a reference trajectory and at each software update cycle (80 msce) compares the actual POR position to the projected position at that same time. The error perpendicular to the reference trajectory is used to generate POHS commands that will bring the actual position back to the projected position. When the operator command is nulled, the reference trajectory is projected based on the last command until the rates drop below a defined threshold value. At that point POHS goes into position hold and commands are generated

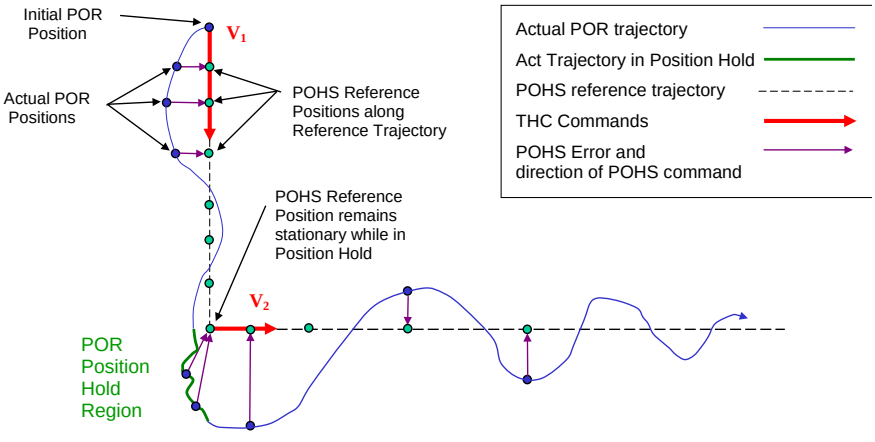


Figure 20: POHS Control of POR Trajectory

(Source- Reference 1)

to return the SRMS to that point if any un-commanded motion occurs. Figure 20 shows one axis of the POR computation for position; for attitude, the POHS software uses a total angle deviation from the projected attitude to generate the POHS commands.

POHS software was available for the HST servicing missions after STS-64, and the reduction in workload was very striking during HST unberthing operations. During the missions the HST is unberthed when it is vertical in the payload bay and it was horizontal in the bay during the STS-31 unberthing, but the unbething rates were similar for both unberthings and commanded rate is the major driver for uncommanded motion. Figures 21 and 22 show the hand controller commands and actual POR motion for the STS-103 HST unberthing. These figures show deviations of less than 1 inch and ½ degree. STS-31 deviations were larger than 25 inches and almost 10 deg. There were also no operator corrections during the STS-103 unberthing with POHS. There was one roll correction before the unberthing started, but no attitude or position corrections during the unberthing.

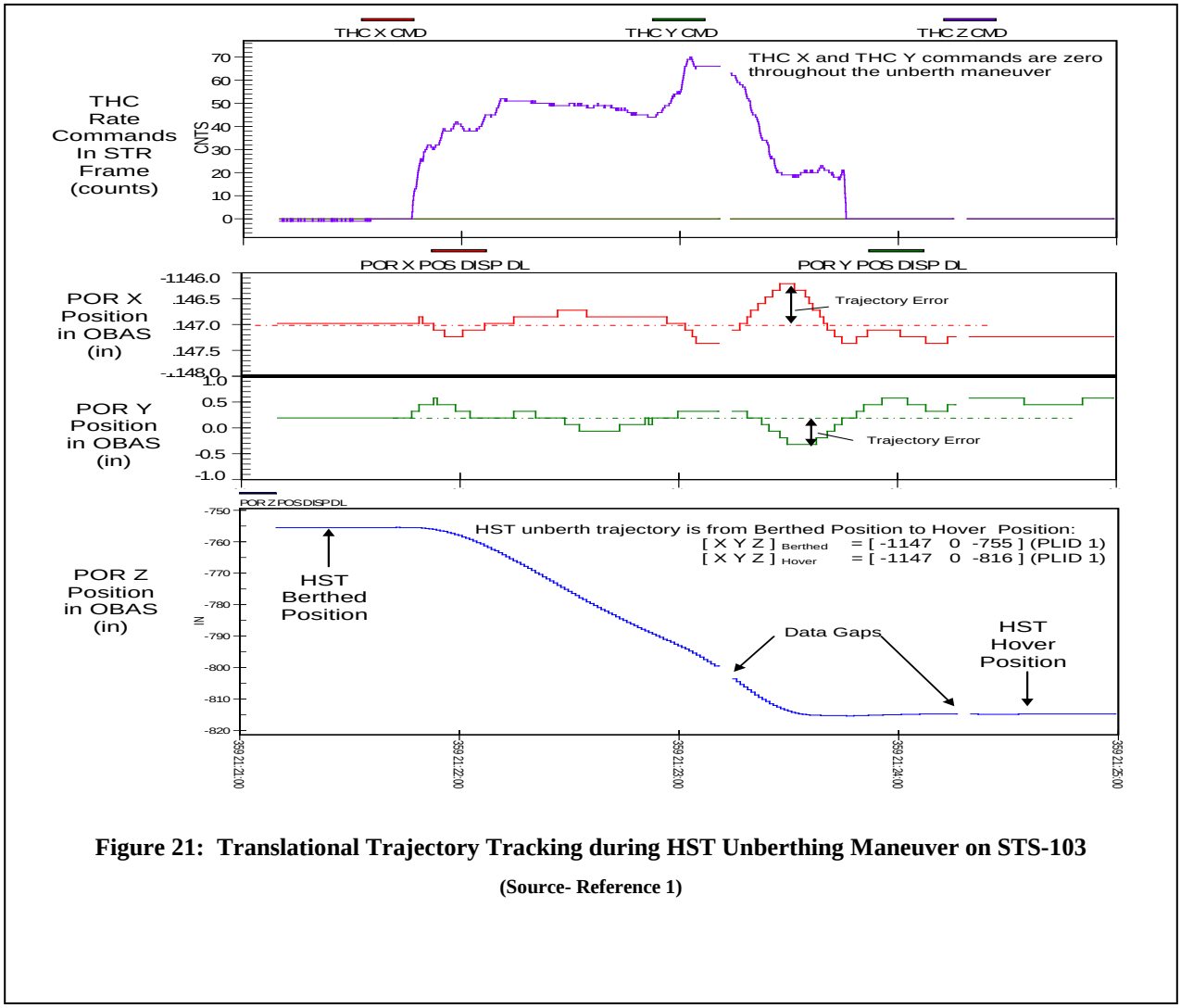


Figure 21: Translational Trajectory Tracking during HST Unberthing Maneuver on STS-103

(Source- Reference 1)

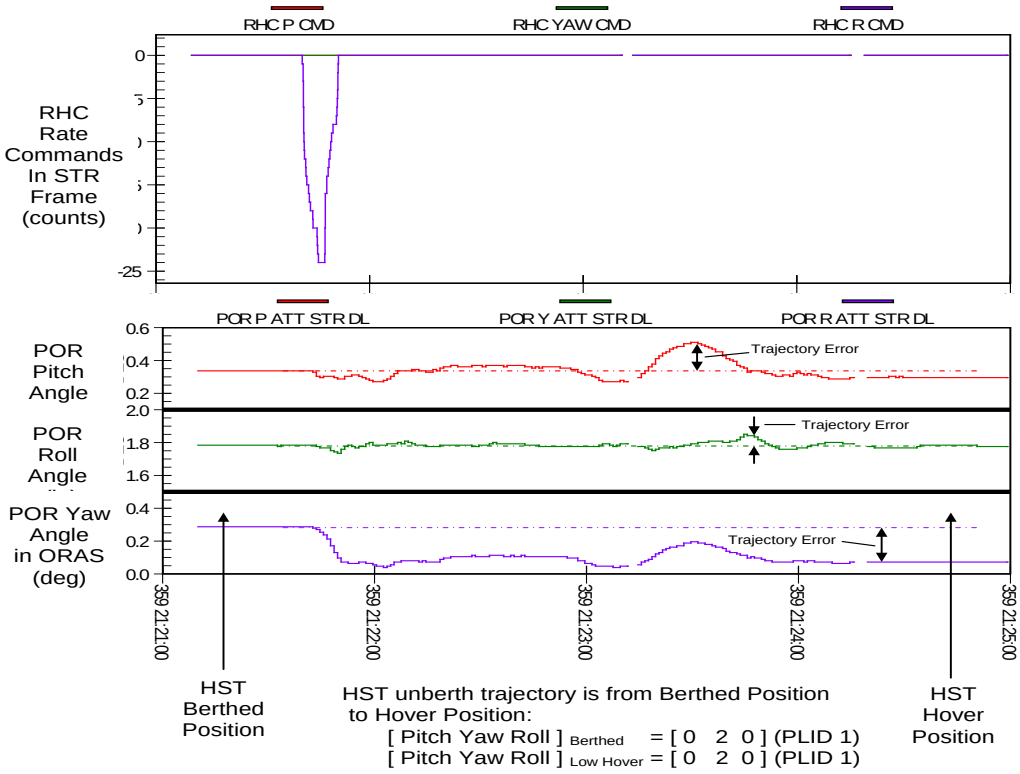


Figure 22: Rotational Trajectory Tracking during HST Unberthing Maneuver on STS-103

(Source- Reference 1)

The POHS software was first implemented in Manual Augmented modes to address the operator workload issue. When Auto modes were used for Orbiter tile inspection after the Columbia accident, the operator had limited ability to monitor the OBSS while the boom was under the orbiter. To address this, the POHS controller was added to auto modes. However, an undesirable attitude oscillation was noted in position hold when the sensors on the OBSS scanned a specific point. This was traced to GPC precision for the very small angles seen during position hold, and the algorithm for calculating attitude error was changed to use a function that was less sensitive to the small angles.

The value of POHS was reinforced during ISS assembly operations when the SRMS unberthed heavy modules and truss segments from the shuttle payload bay, often with small clearances between trunnions and the OBSS or other elements in the payload bay..

C. Command Wash-in in Auto Mode:

Auto modes and single joint mode both command to a single rate, but they start the commands differently. In single joint mode the commands are ramped up over several computer cycles but in the auto modes the full command is put in instantaneously. After the Columbia accident, wash-in was also proposed for auto modes to improve the transient response, as discussed below. The existing and proposed auto mode command profiles are shown in Figure 23. In both single joint and auto modes the command is washed out as shown in Fig 23, because abrupt nulling of command would cause the flexible SRMS to have significant overshoot and oscillations in POR and POR rate. There are similar overshoots and oscillations with a step input, and these were

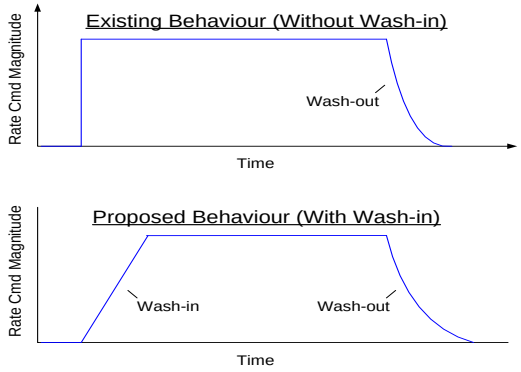


Figure 23: Comparison of Existing and Proposed Wash-in Rate Command Profiles for Auto Mode

(Source- Reference 1)

sufficiently objectionable in single joint mode to force wash-in of commands. For auto modes, the commands were initially started far enough from structure that the oscillations were not objectionable.

When auto modes were used for OBSS inspections, the sensors had rate limits above which the images were not adequate for clearing tile for entry. The rate overshoots then drove reductions in the command rates to meet sensor requirements. Wash-in of the auto mode was proposed at this time, but it was decided that the reduction of command rate was an adequate solution. The effect of wash-in for a TPS inspection auto sequence is shown in Figure 24, which compares the rates at the start of the same auto mode with and without wash-in. The sensors had requirements to find 0.25 inch and 1.00 inch damage at different parts of the survey. For 0.25 in damage the existing software requires a POR translation rate of 0.5 meter/minute and with wash-in the rate could have been increased to 0.6 meter/minute. For 1 inch damage, the translation rate must be 1.4 meter/minute with the step input; with wash-in the translational rate limit could have been 2.7 meter/minute.

While wash-in was not considered necessary for the SRMS, it is an improvement that should be considered seriously for any future space robotics.

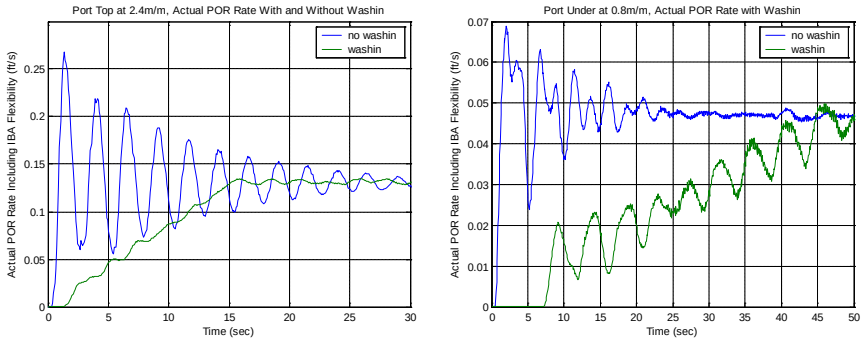


Figure 24: Effect of Wash-in on Actual Rates at Start of Auto Maneuver

(Source- Reference 1)

D. Value of Open Review of Simulation Models:

At the start of the SRMS program, several different implementations of the SRMS equations of motion were developed by organizations including Spar, Rockwell Downey, JSC, and CS Draper Labs. At the time modeling a robotic space-based robotic system with the many degrees of freedom of the SRMS was a significant technical challenge for each organization. Early in the program, the model developed by the hardware provider Spar was designated as the "truth" model by the Program Office; however, the simulation was considered proprietary and the model and implementation were not disclosed. The truth sim, and all other sims, did not always match well with hardware data and sim responses did not match each other well. These differences between sim responses were a major topic of discussion in SRMS forums for 20 years. Even comparison to flight data did not resolve the issue since the errors from all sims were about equal, particularly for loads. As discussed in the section "Enhanced Instrumentation", this was due to limitations of the flight data.

Little progress was made in resolving model/implementation differences until 1999 when the SRMS Program office insisted on development of a "common" SRMS model and chartered the SRMS Math Model Working Group (MMWG) to coordinate open discussion of all model features and implementation. This resulted in co-development of an SRMS model that was accepted as the standard for the remainder of the Shuttle program.
For any system used in a Program, a single model and implementation that is open for review and well grounded in ground testing and flight data should be provided for use throughout the Program

E. Load Relief of Space Based Robotics:

The SRMS was designed with relatively weak brakes at the wrist, a stronger brake at the elbow, and even stronger brakes at the shoulder. As a result, the wrist brakes slip under high load, and the orbiter does not see high loads at the longeron. The RMS for the ISS (SSRMS) made a different design choice to allow inchworm capability for the

SSRMS. Either end can be the shoulder, so all joints have high strength brakes. As a result, the SSRMS can transmit a high load to the base, a feature that has required operational workarounds, particularly to avoid potential high loads if the SSRMS brakes come on as a result of a safing event while a berthing mechanism is pulling an element held by the SSRMS. For berthing with the element held by the SRMS, the brake torque scaling avoided this problem.

A potential solution that would allow inchworm capability and also load relief would be use of dual brakes at each of the three end joints, with one set scaled to allow load relief, and a second brake to bring the total torque up to the shoulder value. Positive lockout of the second brakes at the joints that are acting as the wrist must be provided. The elbow joint brake torque could be scaled as the SRMS elbow brake torque was.

Dual brakes on each of the three end joints would add mechanical complexity and weight to the robot; these need to be weighed against the reduction in operational complexity when load relief is important.

F. Enhanced Instrumentation:

The SRMS electronics provided motor rate and joint position data to the operator, and a later upgrade to the Arm Based Electronics added motor current data that was available for viewing on the ground. The original arm had a set of strain gauges, called Development Flight Instrumentation (DFI), installed however the data was of limited usefulness due to factors such as low resolution, poor calibration and the difficulty of retrieving the data. These limitations were largely due to the state of the technology at the time of development. After the Columbia accident one of the arms was instrumented with strain gauges and a test was performed on orbit with a crewman on the end of the OBSS to simulate a repair scenario. This data was useful, however the test was limited to this one scenario only. No data was ever collected when the arm was maneuvering large payloads, or when the arm was operating in a constrained motion scenario.

As the SRMS was utilized for more varied tasks as the program progressed, including manipulating much larger payloads, it became clear that force and moment data would be very useful. Examples of this include using the OBSS on the SRMS as an EVA platform for repair of the shuttle thermal protection system, and certifying the SRMS to grapple the ISS and maneuver the entire Shuttle. This data would allow engineers to understand the loads the SRMS was exposed to which would aid in life cycle estimates. In addition, loads data would be very valuable for simulation. Several simulators of the SRMS were developed over the life of the program and these simulations played an integral part in certifying SRMS/payload operations. The major difficulty encountered was validating the various models that were developed for the arm. Due to the uncertainty in models developed from analysis only, conservative assumptions were made to ensure the uncertainty was bounded. Proper instrumentation on future robotic systems would aid greatly in the development of accurate models and limit the amount of analysis required.

Additionally, significant analysis has been devoted to analyzing situations when loads can buildup due to contact with a berthing mechanism, grapple fixture, etc. This analysis is required because the only times that the SRMS was instrumented, the loads were not recorded when there was contact between the SRMS or payload and hardware attached to the Orbiter. The complexity of modeling contact surfaces has raised many questions that increased the analysis impact. Adding load instrumentation to a future robot would allow validation of contact load models with flight data.

G. Force Moment Accommodation:

Deploying and retrieving payloads primarily involves maneuvering payloads that are unconstrained. Since this was the mandated task of the SRMS it was designed for pure coordinated joint rate control. However, for constrained motion when the payload can contact external structure, coordinated joint rate control is no longer possible. In this scenario, the direction of the applied tip force/moment will be altered and will not be as commanded by the operator hand controllers. This will result in motion of the arm tip in un-commanded directions. This makes constrained motion activities more difficult for the SRMS operator. Force moment accommodation (FMA) can greatly facilitate SRMS tasks involving constrained motion operations.

The lack of FMA during the construction of the ISS underscored how useful it could be. The SRMS operational requirements expanded to include assembly tasks involving the mating of modules during the ISS construction. For these operations the limitations of velocity control became apparent. Mating operations required force application between surfaces that had to be correctly aligned for proper mating. Since misalignments are inherent in space robotic operations with limited visibility, this alignment uncertainty had to be addressed. Sophisticated visual aids were required for the SRMS operator to place the mating surfaces within a predefined capture envelope, and active

mating latches were required to provide the force necessary to overcome the remaining misalignments within this envelope. Additionally, extensive preflight analysis of all the potential contact conditions during misalignments was necessary to ensure load limitations of the SRMS were not exceeded.

Force and moment data displayed to the operator would provide enhanced situational awareness thus improving positioning accuracy. The increased positioning accuracy of the payload/mating interface would reduce the reliance on visual cues. The sensed force and moment data implemented in a feedback loop would control contact forces improving constrained motion operations. By controlling contact forces, FMA would allow the SRMS/payload to adapt to uncertainties in the contact environment, safe guarding against damage caused by excessive loads. This minimizes the need for pre-mission loads analysis. With the capability to apply constant, pre determined forces in a given direction, the SRMS can be used to activate berthing and latching devices. Active mating mechanisms would not be necessary, simplifying the mating interface design.

Additionally, FMA can extend the capability of a robotic arm to perform complex and delicate tasks needed for satellite servicing. These tasks include refueling, module change outs, cleaning of surfaces, electrical connector mate/de-mates, and thermal blanket change outs.

H. Expansion Capability:

The SRMS end effector was designed with an electrical connector called the Special Purpose End Effector (SPEE) connector. This was envisioned as a means of providing power and data to future specially designed end effectors that were grappled by the standard SRMS End Effector. This connector could also electrically mate with a special grapple fixture called an electrical flight grapple fixture (EFGF). Payloads with this grapple fixture could utilize the sixteen power and data lines that ran the length of the arm in conjunction with switching panels in the orbiter that were configured preflight as needed. When the OBSS was developed, it utilized an EFGF to provide power and a data path for the cameras and lasers on the end of the boom. During the design phase it became clear that the existing SPEE cables could not provide the required electrical current needed by the sensors at the Shuttle bus voltage of 28 Volts. The work around was to use a 120 volt power source in the shuttle that was designed for use on the ISS.

The limited capability of the original design of the SPEE wiring harness was a lesson learned for robotics on future space vehicles. Robotic systems of the future should be designed with future growth in mind. While it is difficult to predict future requirements, and cost limitations may restrict the amount of enhancements, it is still prudent to provide additional power and data paths that can be utilized for future capabilities.

V. Conclusion

The Shuttle Remote Manipuilator System represents one of the many great legacies of the Space Shuttle. Its unique capabilities were recognized as the program developed, and it evolved into much more than just a means of deploying and retrieving satellites. From an EVA platform, to satellite rescue and repair, to the inspection of the thermal protection system of the shuttle, it met the challenges of ever more complex space missions. Its success was a major driver in developing the Space Station Robotic Manipulator System on board the International Space Station today, and it will serve as the foundation for all future space robotic systems.

References:

1. MDA-RMS-R.10786 “SRMS Technical History and Lessons Learned”
2. “Wings in Orbit – Scientific and Engineering Legacies of the Space Shuttle” (NASA)
3. Space Shuttle Orbiter Operational Level C Functional Subsystem Software Requirements Remote Manipulator System (RMS)
4. NSTS 07700, Volume XIV “System Description and Design Data- Payload Accommodations”, Appendix 8 “Payload Deployment and Retrieval System Description”

Acknowledgments

The authors would like to acknowledge the excellent work McDonald Dettweiller Associates (MDA) has performed in documenting the history of the SRMS program in reference 1.

References

The following pages are intended to provide examples of the different reference types, as used in the AIAA Style Guide. When using the Word version of this template to enter references, select the “references” style from the drop-down style menu to automatically format your references. If you are using a print or PDF version of this document, all references should be in 9-point font, with reference numbers inserted in superscript immediately before the corresponding reference. You are not required to indicate the type of reference; different types are shown here for illustrative purposes only.

Shuttle Remote Manipulator System History, Evolution and Lessons Learned

Elizabeth Bains
Glenn Jorgensen

Outline

- SRMS Overview
- SRMS History
- Unique challenges
- Lessons Learned

SRMS Overview

Requirement

- Deploy and retrieve satellites from payload bay
  - 50 foot long anthropomorphic arm
  - Teleoperated from aft crew cabin

Manipulator Arm

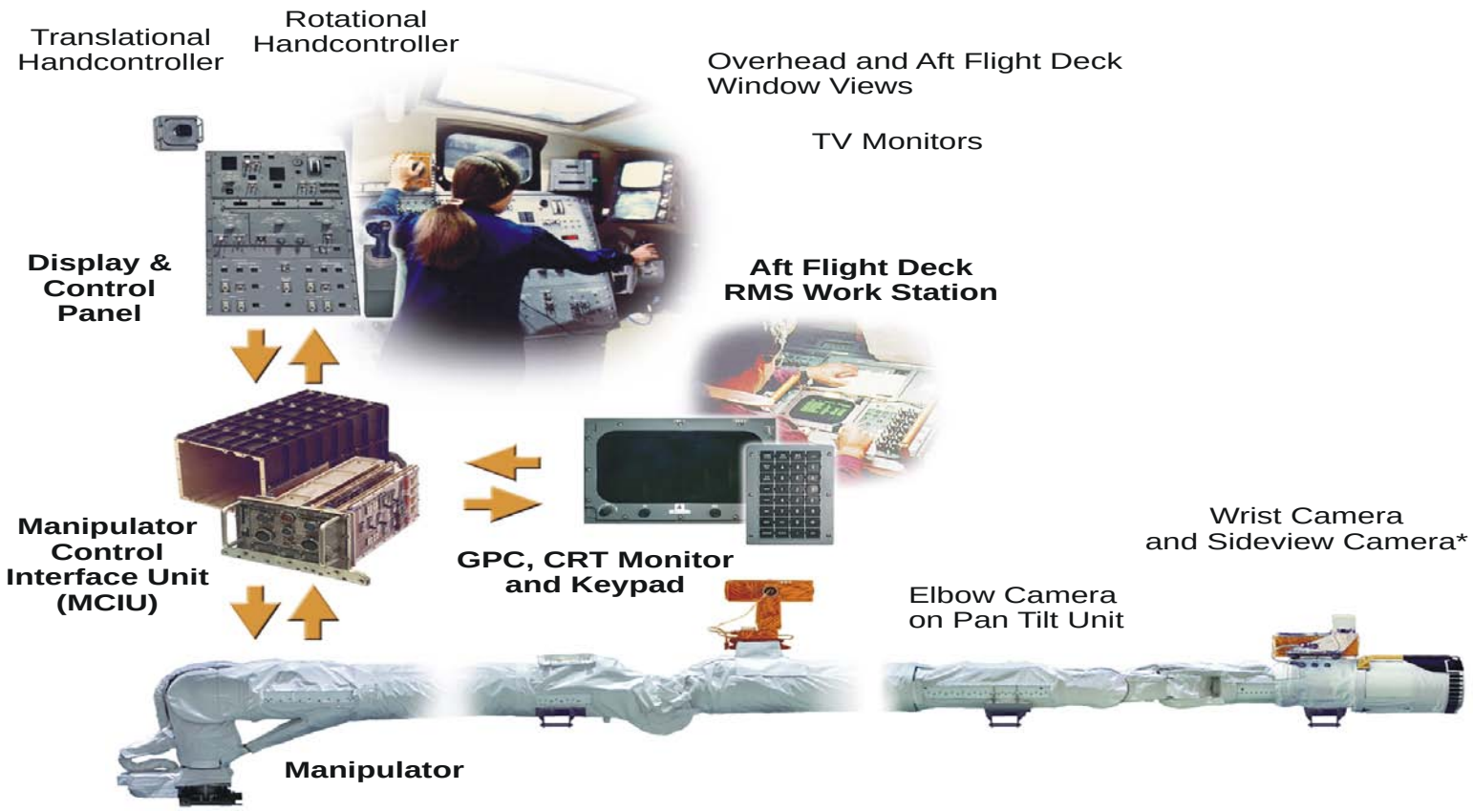
- 3 joints – 6 DOF
- 2 arm booms
- End Effector
- Three camera assemblies
- Thermal protection system

Cabin Equipment

- Displays and Controls panel with rotational and translational hand controllers
- Manipulator Controller Interface Unit – interface between Shuttle GPC, D&C panel, and Manipulator Arm electronics



SRMS Overview

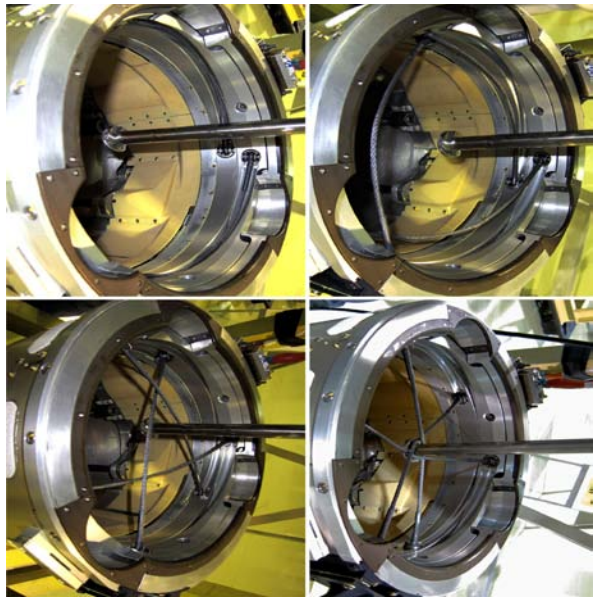


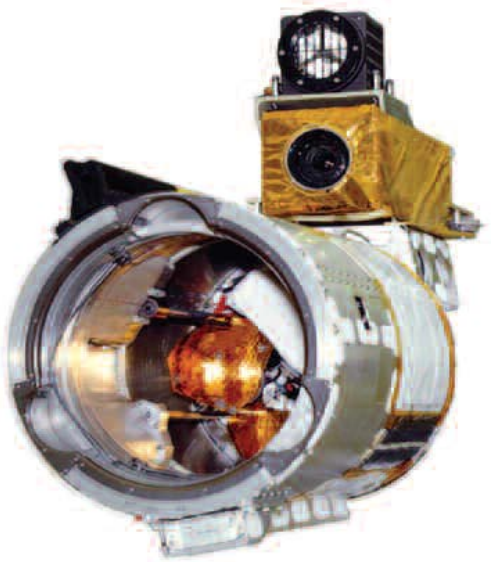
SRMS Components

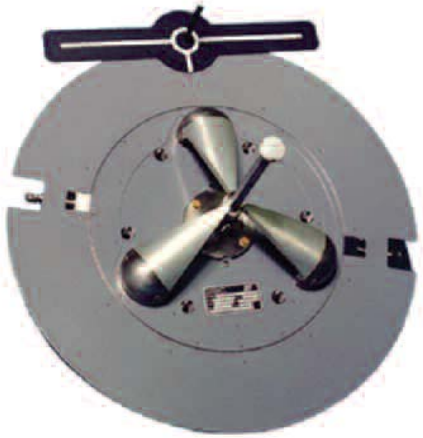
SRMS Overview

SRMS End Effector

- 3-Cable mechanism snares a grapple fixture on payload
- Snare mechanism is retracted to “rigidize” payload to End Effector
- Grapple target used with Wrist camera







SRMS Overview

SRMS Operating Modes

- Primary Modes
  - Computer Supported Modes
    - Coordinated servo rate control – rates are pre-programmed
    - Automatic Sequences - Pre-programmed and Operator commanded
    - Manual Augmented Modes
      - Point of Resolution control via RHC and THC commands
      - POR and Co-ordinate axes based on one of five modes chosen by operator
      - Payload POR determined pre-flight
    - Single Drive
      - Single Joint Driven – other joints in position hold
  - Direct Drive Mode
    - Single joint driven with a fixed voltage – no servo rate control
- Back-Up Drive
  - Separate electronic drive
  - Single joint driven with a fixed voltage – no servo rate control

SRMS History

Satellite Deployment

- Gamma Ray Observatory (GRO) on STS-37
- Earth Radiation Budget Satellite (ERBS) on STS-41
- Upper Atmosphere Research Satellite (UARS) on STS-48.
- **Satellite Deployment and Retrieval**
- SPAS-1 satellite on STS-7 –first free flyer capture
- Long Duration Exposure Facility (LDEF) - deployed on STS-41C, and retrieved on STS-32
- Solar Maximum Mission satellite (Solar Max) on STS-41C
- Hubble Space Telescope (HST) – deployed on STS-31, retrieved on 4 missions for repair





SRMS History

EVA Platform

- Developed over life of the program as an important use of SRMS for both pre-planned and contingency operations
- Crewman mounted on foot restraint at End Effector – SRMS provided a platform to react forces
- Communication from crewman to SRMS operator allowed quick and easy positioning
- Tool stanchions and holders developed to aid in repairs

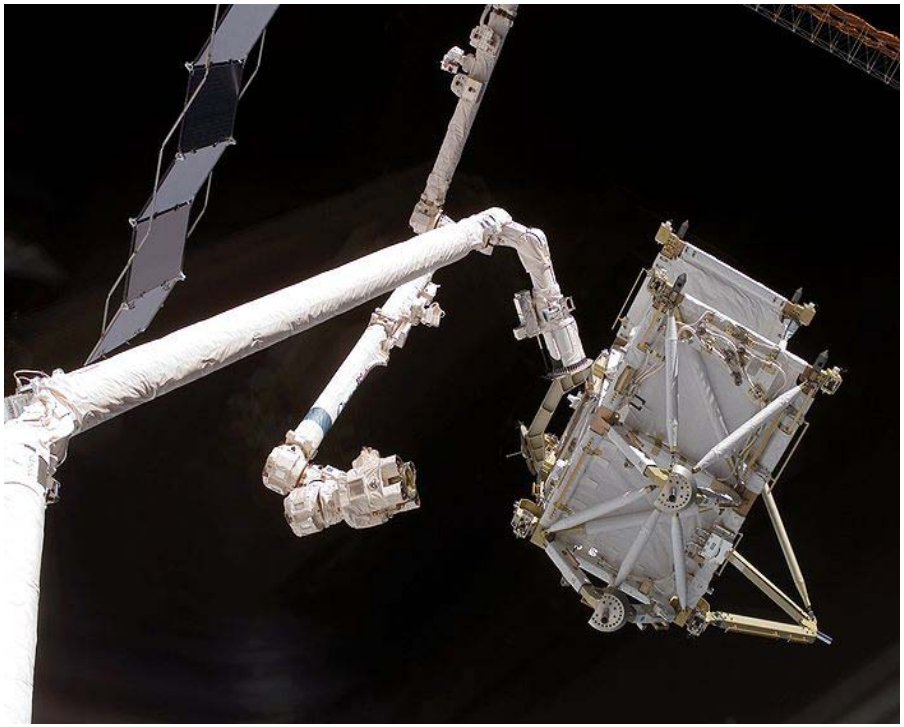


STS-61 EVA Hubble Repair

SRMS History

Space Station Construction

- Primary mechanism used for early ISS construction
  - Nodes
  - US Lab
  - Truss segments
  - Russian Zarya Module
- Later stages – used with the SSRMS to complete construction
- Servo Electronics upgraded to improve controllability of heavier payloads



P5 Handoff from SRMS to SSRMS

SRMS History

Post Columbia - The Orbiter Boom Sensor System

- OBSS developed to scan the Shuttle Thermal Protection System
  - 50 foot boom with Cameras and Laser Sensors
- Robotically compatible with the SRMS – Electrical connector on End Effector provided path for power and data to Sensors
- EVA repair of TPS – 2 Scenarios
  - Orbiter Repair Maneuver – SRMS grapples ISS and moves Orbiter to position where EVA on SSRMS can repair
  - Crewman on the OBSS – DTO on STS-121 showed feasibility of repair with crewman on OBSS

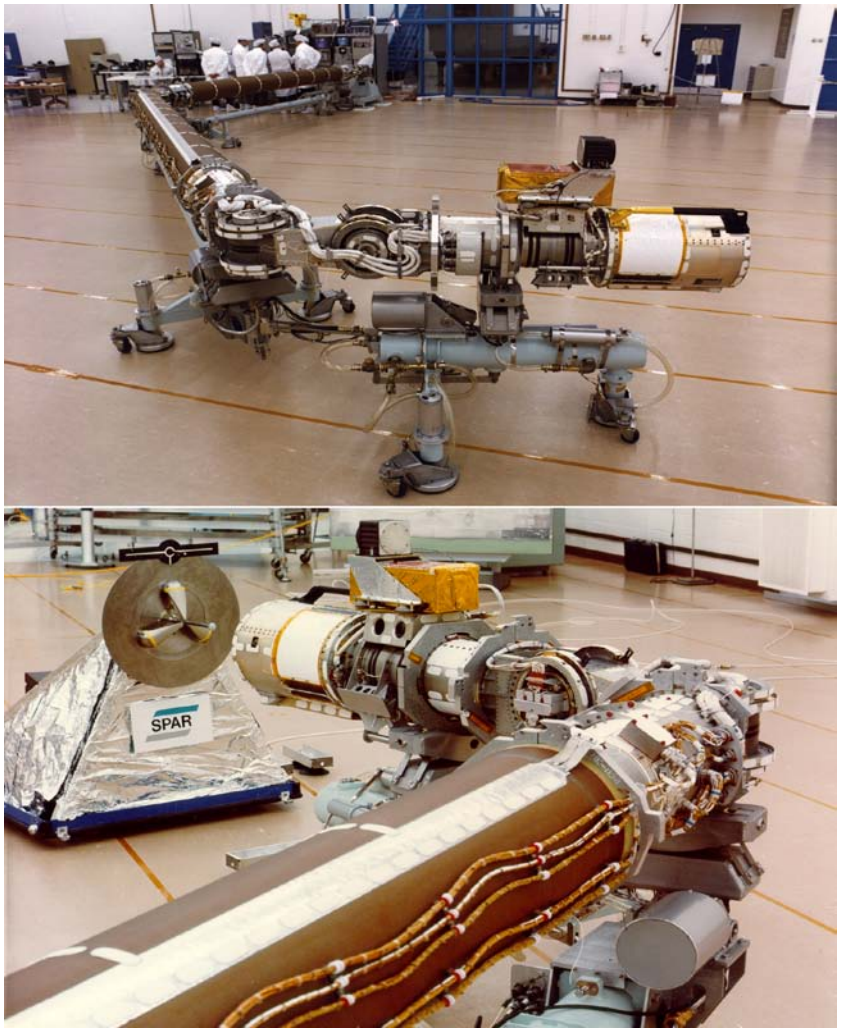


OBSS Grappled by SRMS

Unique Challenges

Test and Verification – Air Bearing Test Rig

- 1-G environment required unique test method to verify multi-joint point of resolution control
- Air Bearing test rig developed to allow motion in pitch plane or yaw plane
- Parameters Verified:
  - Straight path Arm Control
  - Tip accuracy
  - Tip force
  - Response to misalignments
  - Current Limit testing



Lessons Learned
Enhanced Instrumentation

History

- SRMS electronics provided motor rate and joint position data to operator and down listed to ground
- Upgrade electronics added motor current data (down listed at 1 Hertz only)
- STS-2,3 ,4, 7 and 8 had a set of strain gauges that collected loads data (Development Flight Instrumentation) – this was of limited usefulness due to the state of the technology
  - Low resolution
  - Poor calibration
  - Difficult to retrieve data
  - Limited number of payloads – no heavy payloads
  - No constrained motion data
- Wireless Strain Gauge Instrumentation System installed on STS-121 – DTO 849 tested SRMS/OBSS response to crewman applying loads to simulate a repair – limited data

Lessons Learned
Enhanced Instrumentation

Consequences of limited loads data

- difficulty in validating simulation models
- Tremendous effort spent in developing models and running simulations over the life of the program
- Several models developed by different organizations that did not match – truth model was difficult to find
- Life assessment was difficult
- Due to uncertainty of models – conservative assumptions had to be made

Lessons Learned
Enhanced Instrumentation

- Lesson: Implement force and moment sensors in future space robotic systems
- Benefits:
  - Accurate model development
  - Less analysis required – more confidence in simulations leads to less conservatism
  - Better assessment of Arm capability – payload handling, constrained motion operations, life
  - Enables Force Moment Accommodation to be implemented

Lessons Learned
Force Moment Accommodation

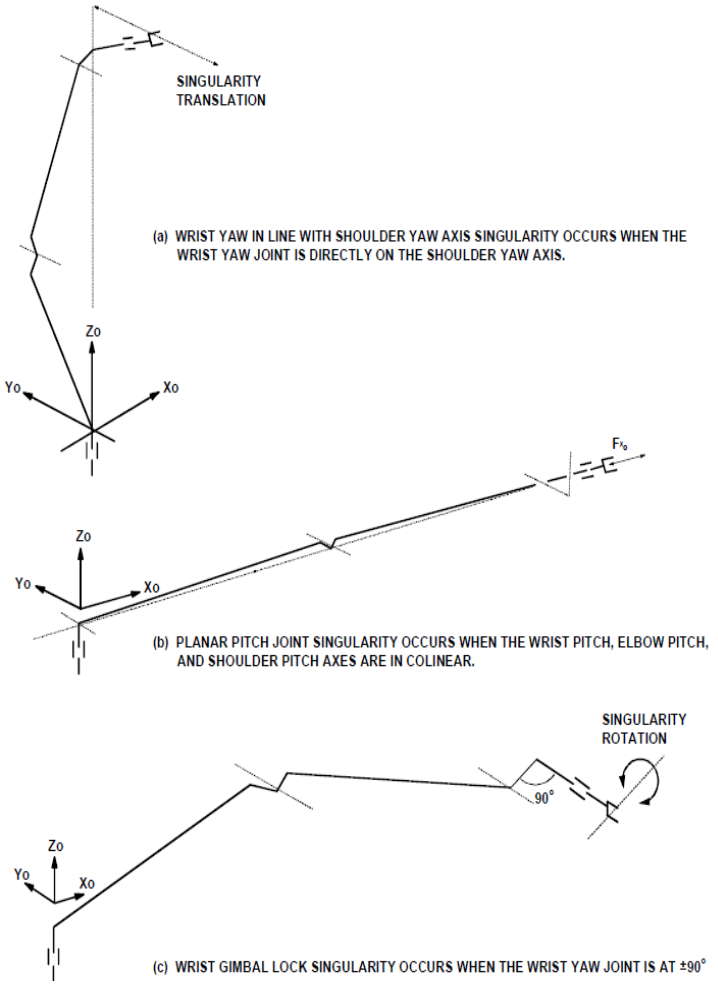
- SRMS designed for coordinated joint rate control only
- Rate control not possible during constrained motion operations – results in un-commanded motion of arm tip
- Lack of FMA noticeable during ISS construction
  - Alignment difficulties during mating of modules – sophisticated visual cues required
  - Pre-flight analysis of load conditions during mating was required to ensure structural loads were not exceeded

Lessons Learned
Force Moment Accommodation

- Lesson: Implement FMA in future robotic systems
- Benefits:
  - Better positioning accuracy during mating operations – less reliance on visual cues
  - Adaption to external contact forces – lower loading conditions and reduces need for pre-mission analysis
  - Ability to activate berthing and latching devices by applying pre-determined forces in commanded direction
  - Complex satellite servicing tasks can be performed; refueling, module change outs, connector mate/de-mates

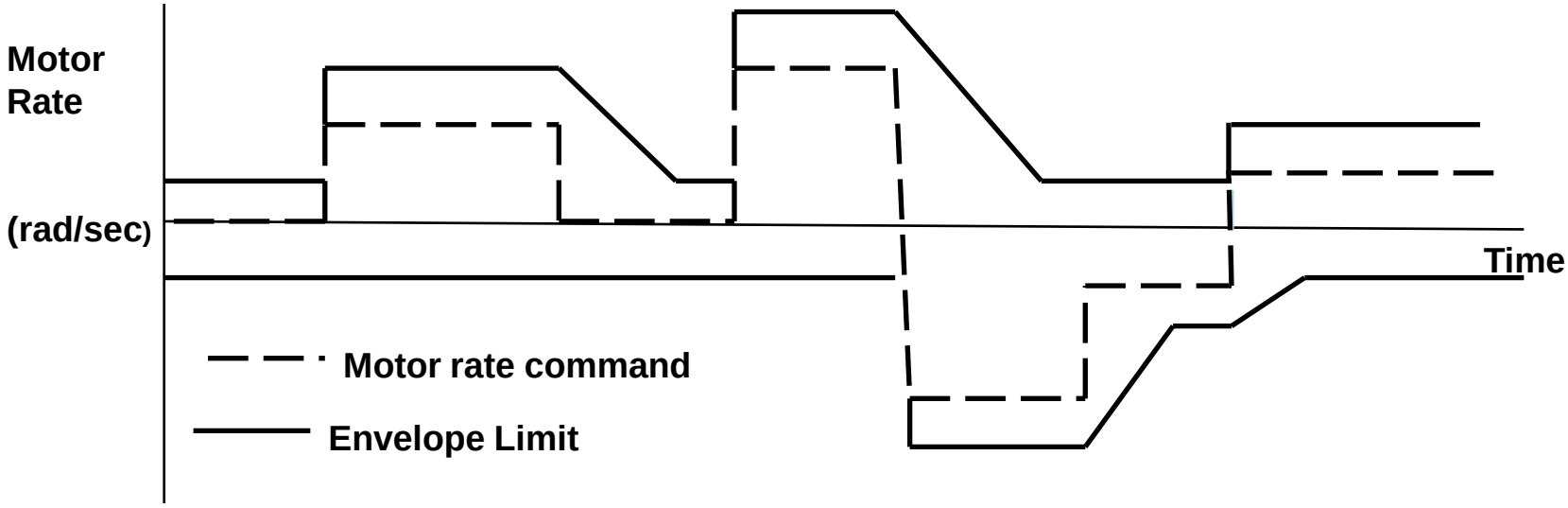
Unique Challenges: Software Singularity Management

- There are 3 SRMS control singularities due to zeroes in the joint rate to tip rate Jacobian
  - Shoulder singularity: wrist yaw joint directly over shoulder joint no +/- y translation control
  - Elbow singularity: all pitch joints are colinear: no +x control
  - Wrist singuarity: wrist yaw joint at +/- 90º: limited roll control
- Software control may cause unexpected motion
  - Shoulder singularity: 3 feet from Wrist yaw directly over shoulder yaw, wrist yaw is reconfigured to opposite side of singularity zone
  - Elbow singularity: No change in motion
  - Yaw singularity: roll motion continues at a reduced rate



Unique Challenges: Software Consistency Check

- Runaway of an SRMS joint due to a fault that applies unlimited current to the motor would potentially drive a payload through orbiter structure and required special protection
  - No runaway ever occurred during the 30 year Shuttle program
- The software consistency check monitored actual motor rate for each joint against an envelope around the motor rate command
  - If the actual motor rate for any joint was outside its envelope for more than 4 consecutive GPC cycles (to allow for motor dynamics), the SRMS brakes are applied



Unique Challenges: Simulation

- Simulation provided solution to inability to fully test SRMS in 1-g but also provided challenges with computers of ‘70’s and 80’s
  - Real-time simulation computers did not have both speed and high precision required by SRMS model; approximations eliminated in 2004
  - Testing flight software running in Orbiter computers required special purpose hardware boxes to connect Orbiter computer with simulated SRMS
- JSC’s Systems Engineering Simulator (SES) combined SRMS simulation with 6 DOF dynamic motion of two vehicles
  - Vehicles subjected to orbital mechanics, aerodynamics, orbiter jet thruster firings, payload control system, RCS plume impingement, berthing contact forces
  - Functionally equivalent orbiter aft cockpit mockup provides displays and controls for SRMS and for orbiter Digital Autopilot (DAP)
  - Scene generators provide out the window and CCTV views



Unique Challenges: Simulation

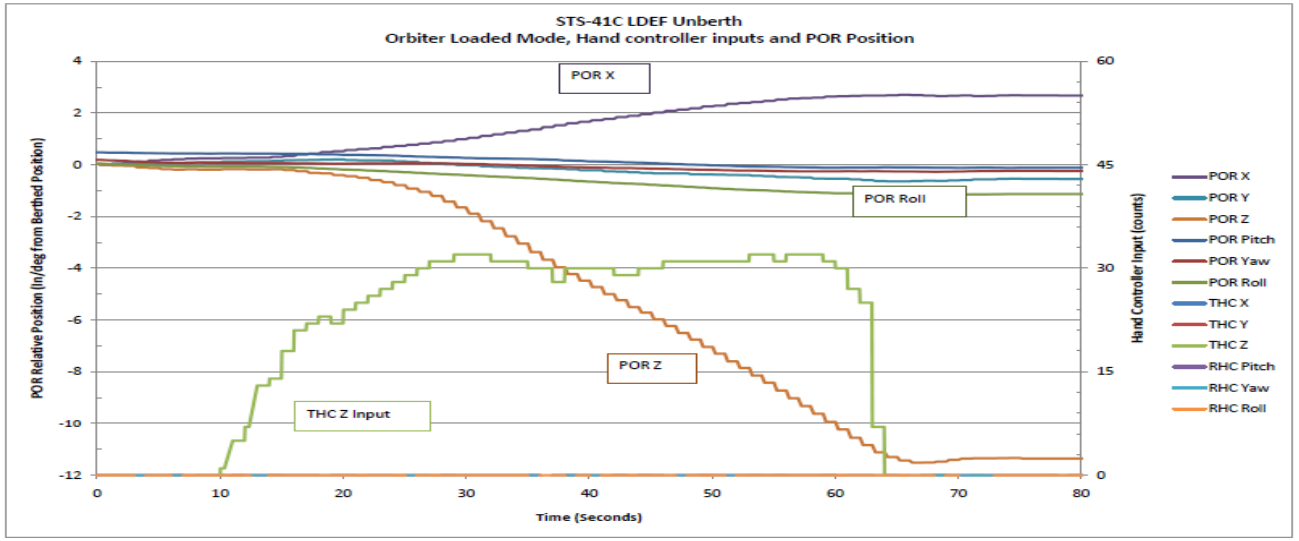
Uses of SES

- SES provided capability to test SRMS operations that require operator in the loop and also integrated SRMS and Orbiter DAP operations (such as approach to free flying payload and capture with SRMS)
- SES was used throughout the Shuttle program for engineering evaluation and also used by Mission Operations personnel for procedures development and crew training
- Uses of SES included assessment of:
  - Procedures for operations on early flights that tested SRMS
  - Track and capture of first payload released and recaptured by SRMS and of rotating payloads
  - Uncommanded motion and software used to control it
  - Berthing payloads to various latching mechanisms on ISS and shuttle
  - Proposed Orbiter repair techniques
  - Interaction of DAP firings in different modes and SRMS holding various payloads

Lessons Learned:
Position Orientation Hold Submode

The Problem

- The SRMS was initially purely a rate command system
- Early operators noted uncommanded motion that required significant correction commands
- During LDEF unberthing on STS-41C, crew did not correct uncommanded motion during 11 inches of unberthing (z) motion
  - Most significant uncommanded motion was 2 inches x and 1 deg roll

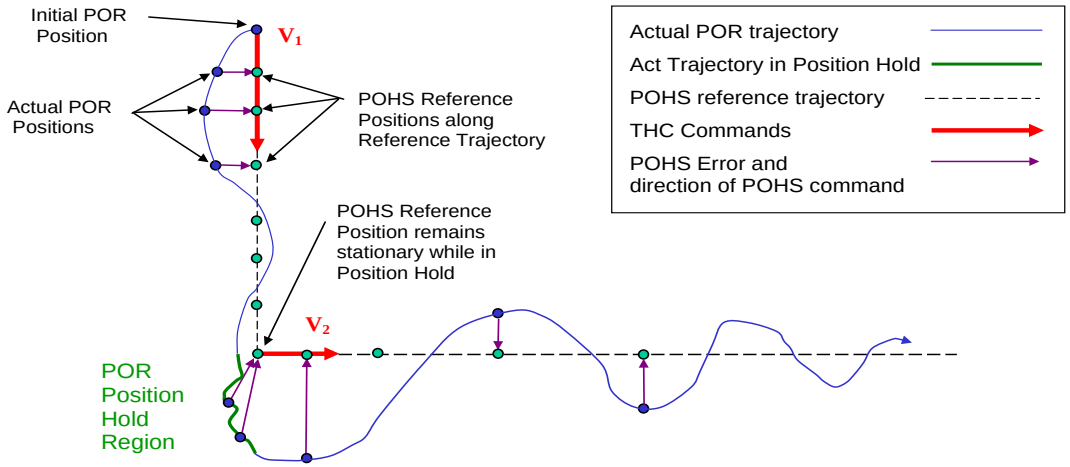


- In the early 90's, when large telescopes were unberthed the uncommanded motion became very objectionable

Lessons Learned:
Position Orientation Hold Submode

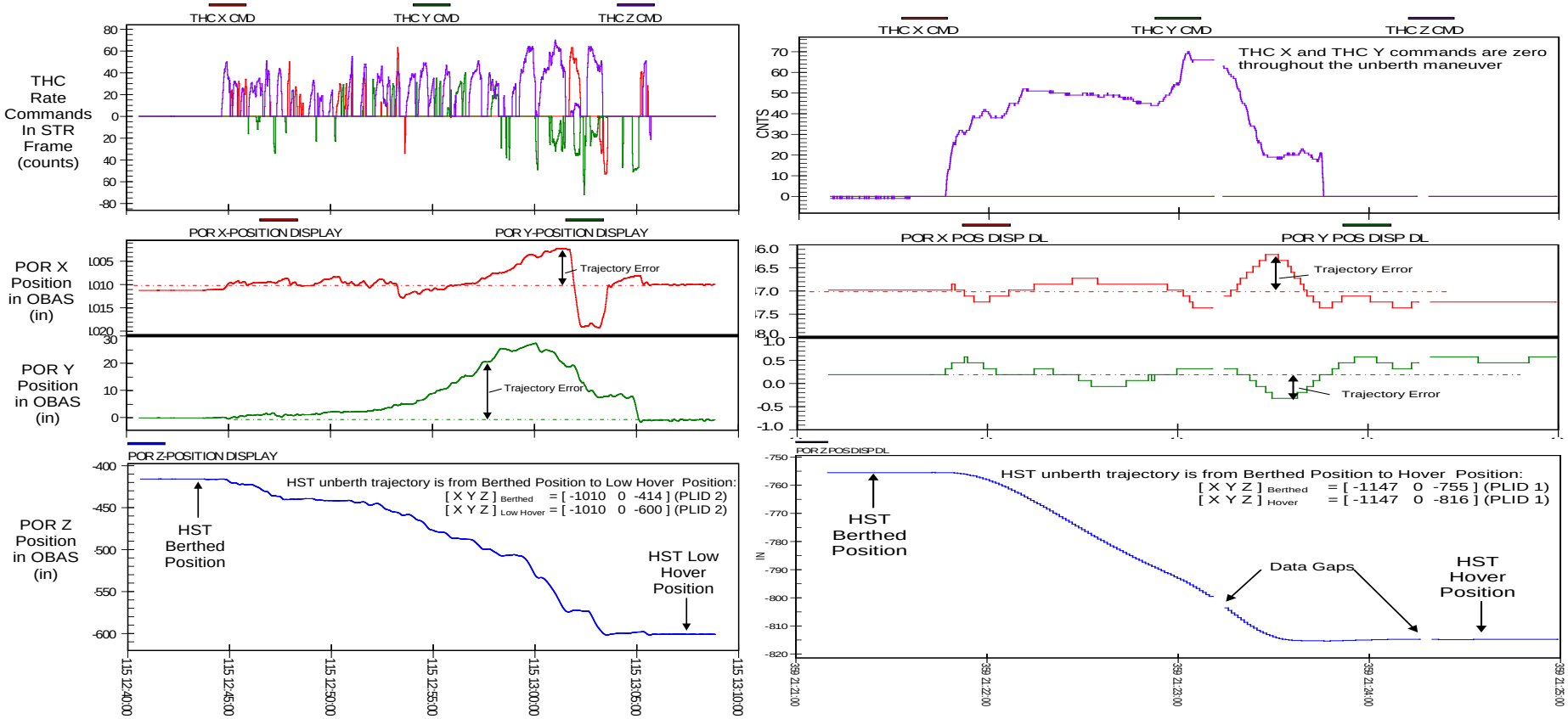
The Solution

- POHS software was developed that added position correction commands to the rate commands, based on the actual motion of the commanded point
  - Initial position and command used to generate projected trajectory
  - At each computer cycle, actual position compared to projected position and error perpendicular to reference trajectory used to generate POHS commands to bring actual position back to projected position



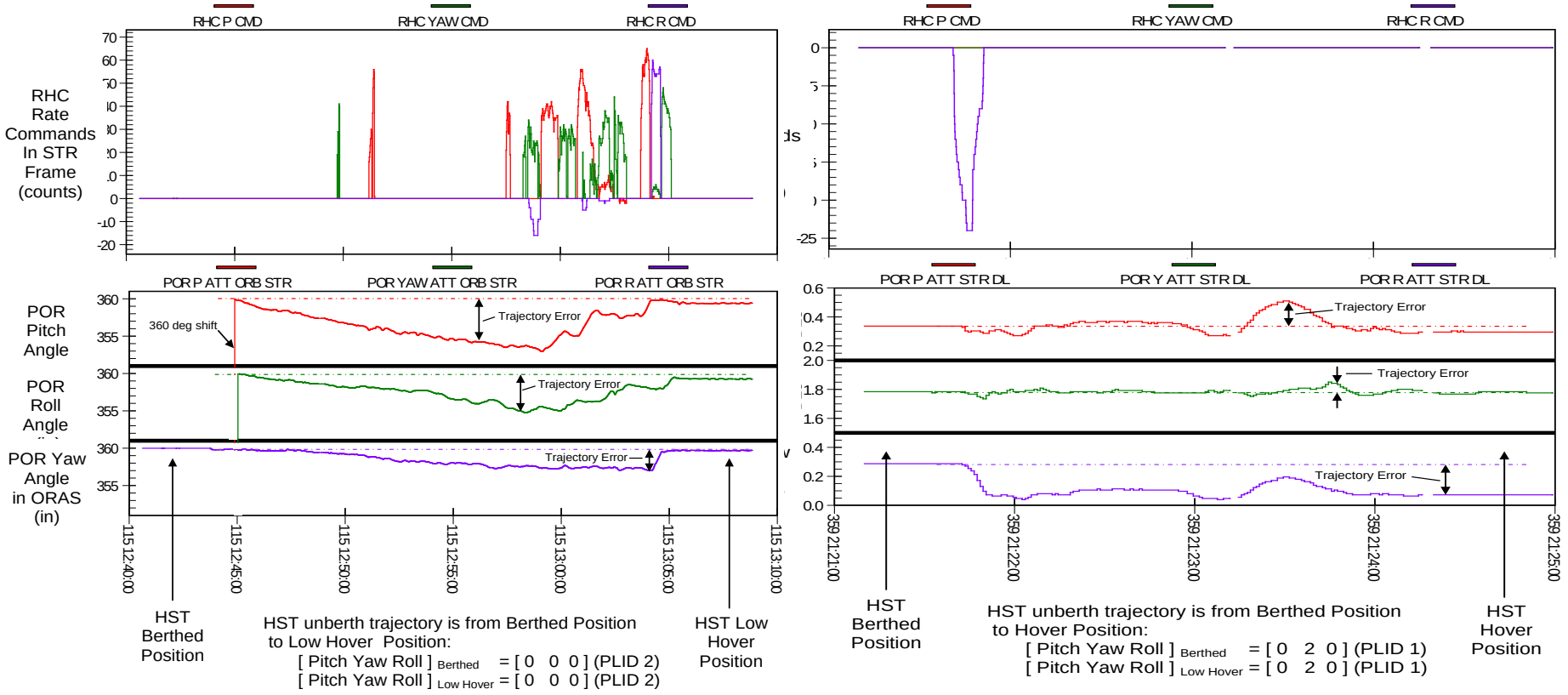
- The following charts show the difference between the translation/rotation commands and motion for Hubble Space Telescope unberthings on STS-31 (no POHS) and STS-103 (POHS active)

Lessons Learned:
Position Orientation Hold Submode



SRMS translation commands and command point motion for STS-31 (left) and STS-103 (right)

Lessons Learned:
Position Orientation Hold Submode



SRMS rotation commands and command point motion for STS-31 (left) and STS-103 (right)

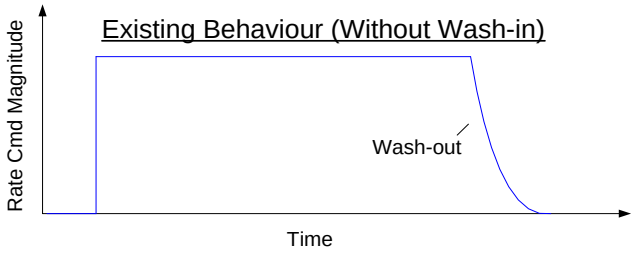
Lessons Learned:
Position Orientation Hold Submode

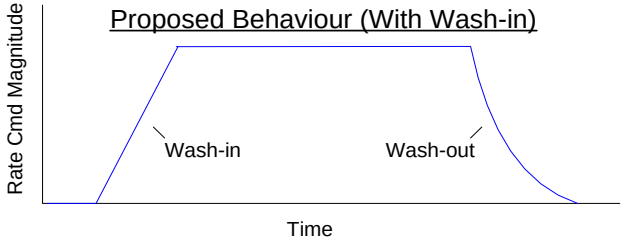
Uses of POHS

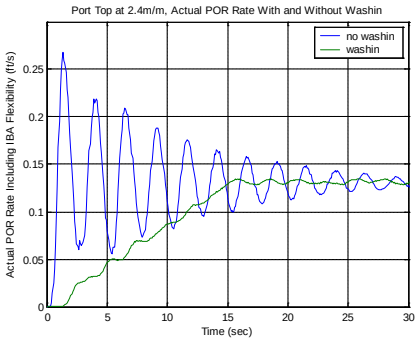
- POHS was initially developed for manual modes to alleviate operator workload controlling uncommanded motion, as shown in STS-31 and STS-103 unberthings
  - STS-31 had multiple rotation and translation commands during unberthing
  - STS-103 had one roll command before the unberthing command; no commands in other axes during unberthing
  - Uncommanded motion on STS-31 (no POHS) was over 25 inches and almost 10 deg; for STS-103 (with POHS) it was less than 1 inch and about ½ deg.
- After Columbia accident when OBSS was used in auto mode to inspect Orbiter tile and crew had limited visibility of OBSS under orbiter, POHS was added to auto modes
- POHS was very valuable during unberthing of large ISS modules and truss segments for ISS assembly
  - Many cases of close clearance with OBSS or other elements in the Orbiter Payload Bay during unberthing

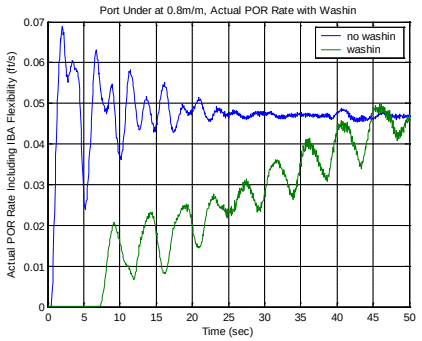
Lessons Learned: Command Wash-in in Auto Mode

- SRMS Auto mode commands a constant rate from start point to near end point
  - Command washes out to prevent overshoot of end point and rate oscillations
- After Columbia accident wash-in was also proposed for start
  - Rate oscillations at start forced reduction in commanded rate so oscillations did not exceed sensor limits for damage detection
  - NASA elected to reduce commanded rate instead
- Bottom figure compares rate oscillations with and without wash-in for 2.4 and 0.6 meters per minute









Lessons Learned:
Value of Open Review of Simulation Models

History

- When the SRMS program started, modeling a 6 DOF space based robotic system was a technical challenge for all organizations
- Multiple organizations developed models independently
- Model developed by hardware provider defined as “truth” model but considered proprietary so model and implementation not disclosed
- Responses of models had differences
  - With each other
  - With truth sim
- All sims, including truth sim, had about equal errors with:
  - Ground test data
  - Flight data
- Accepted model only defined after SRMS Program Office required development of “common” model and chartered MMWG to facilitate open discussion of model and implementation details (completed 2004)

Lessons Learned:
Value of Open Review of Simulation Models

Consequences of limited insight into proprietary model

- 20 years of discussion of model/response differences at different forums without resolution
- Operations designed conservatively to cover model uncertainties

Lesson Learned

- Models used by a program should be open for review and well grounded with ground test data and flight data

Benefits

- Avoids duplication except when necessary (necessary if modeling a system at the limit of standard practice)
- Less time trying to understand differences
- Accurate model developed early in program

Lessons Learned: Load Relief in Space Based Robotics

History

- SRMS has scaled brakes: weaker at wrist, stronger at elbow, strongest at shoulder
  - Wrist brakes slip under high load and orbiter does not see high loads at longeron
- SSRMS design choice was to use equal strength brakes at all joints
  - Provides inchworm capability
  - Requires operational workaround to avoid potential high loads if brakes come on while berthing mechanism is pulling element held by SSRMS
- Proposed design to allow both inchworm capability and load relief would use two brakes at end joint and reduced strength brakes at elbow
  - First brake scaled to provide load relief when that end is used at tip
  - Second brake adds torque to make total torque adequate for shoulder
  - Requires positive lockout of second brake at tip joints
- Dual brakes add mechanical complexity and weight
  - Need to weigh against gain in load relief, if important

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Team Collaboration: Lessons Learned Report

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January 2005

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January 2005

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This report contains preliminary findings, subject to revision as analysis proceeds.

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Team Collaboration:
Lessons Learned Report

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Executive Summary

An Agency team collaboration pilot was conducted from July 2002 until June 2003 and then extended for an additional year. The objective of the pilot was to test a set of tools and supporting processes to be considered as a team collaboration service for the Agency. In an effort to share knowledge and experiences, the lessons that have been learned thus far are documented in this report. Overall, the pilot has been successful. An entire system has been piloted: tools, adoption, and support. The pilot consisted of two collaboration tools, a virtual team meeting capability and a team space. For the virtual meeting capability, we used WebEx Meeting Center application (WebEx Communications, Inc., San Jose, CA). For the team space capability, we used the eRoom Hosted Enterprise Service application (eRoom Technology, Inc., Cambridge, MA).[1] Of the two tools that were evaluated, the team meeting tool has been more widely accepted. Though the team space (eRoom) tool has been met with a lesser degree of acceptance, the need for such a tool in the NASA environment has been evidenced. Both adoption techniques and support were carefully developed and implemented in a way that has been well received by the pilot participant community.

The pilot administration team members have had much experience conducting similar pilots. Because of this experience, several of the lessons reported in this document were not newly learned but simply reconfirmed. More than a year into the pilot, we have also learned many new lessons. While they are captured in detail in this report, the major ones fall into three categories: (1) Collaborative tools enable NASA virtual teams to work more efficiently, (2) Adoption (change management) planning and implementation are critical to the successful use of the tools, and (3) Issues unrelated to the technology or its acceptance have significant impact on the pilot. The top 10 lessons learned from the pilot are listed below.

Collaborative Tools Enable NASA Virtual Teams

(1) A virtual meeting solution is quickly accepted by teams and provides immediate value. The fact that this type of application fits existing meeting norms most likely contributed to its high acceptance.

(2) A team space enables virtual team processes to be completed much more efficiently than sole reliance on typical mechanisms such as telephone and e-mail. However, team spaces had a lower acceptance rate than the virtual meeting solution. This can be attributed to the significantly larger time investment and change of work habits the team must make at the onset of utilizing this type of tool.

[1] Application's company and name at time of pilot. Presently eRoom Enterprise from Documentum (Pleasanton, CA).

(3) Web-based tools provide the accessibility needed for collaboration amongst NASA centers and their external partners. Barriers such as client software, network configurations, or specific hardware requirements can prohibit potential collaborators from fully participating thereby minimizing true collaboration.

(4) Application service providers (ASPs) provide excellent operational capability as well as security—even though team members may perceive security issues with the use of ASPs since data may reside outside of the NASA domain.

Adoption Planning and Implementation

(5) The team coordinator (TC) role is crucial in the adoption process of tools, especially a team space. The TC should be IT (information technology) savvy and must be engaged so that he or she can serve as a team champion as well as an early adopter. This allows the person to motivate and support the team. Pilot participants with team vision, goals, and deliverables have greater probability of engagement. When these items are known, work processes and views of how the tools enable those processes are much clearer.

(6) A team space needs to address a "pain point" that the team is experiencing. Perhaps it is a process that is not as efficient as could be. An example of that might be assuring that team members are reviewing the same version of a document.

(7) The pilot administrators must be engaged with the pilot participants. Various mechanisms can be used to cultivate the exchange of information between the two groups. Proactive facilitation, communication, and customer-focused support are all methods of supporting the administrator-participant relationship.

Pilot Issues

(8) Executive and management sponsorship and support must exist. Workers tend to adopt tools and processes utilized by management. Management support also creates a higher level of visibility of the new way of doing business.

(9) Teams are reluctant to heavily invest in a tool or process that will exist for a short duration (1 year), particularly if there is a large initial time investment as is the case with a virtual team space.

(10) The limited scope (and funding) of a pilot results in limiting the community of people with access to tools (especially where tools require per-seat licensing). This impedes the adoption of those tools.

Pilot Overview

Shortly after the events of September 11, 2001, the NASA Administrator asked the NASA Chief Information Officer (CIO) to improve the ability for NASA teams to accomplish work with less reliance on travel. NASA has many teams that are distributed across NASA centers and external partner locations. There is currently no NASA standard method for basic collaboration beyond teleconferences and e-mail. However, commercial tools exist for increasing the richness of virtual team meetings, supporting virtual team processes, and sharing information. Best-practice companies have realized corporate value by deploying and adopting these tools across the organization. It was felt that NASA would benefit by establishing a common language and standard methodology for collaboration.

Purpose

Extensive collaboration amongst NASA personnel was inhibited since NASA has many teams that are geographically distributed across NASA centers and external partners. While it has always been somewhat difficult to accomplish work without travel, the events of September 11, 2001, and additional travel restrictions that followed have made it even more challenging. It has become more evident that NASA needs a corporate capability for its "virtual teams," and it was strongly felt that successful deployment of team collaboration tools could make a difference at NASA. In addition, both electronic Government (eGOV) and OneNASA objectives included improving collaboration via information technology. The goals of the team collaboration pilot were

(1) To assess the value of commercial collaboration tools applied to NASA teams
(2) To refine NASA requirements for team collaboration tools
(3) To provide a valued service to pilot participants and exceed their expectations by emphasizing facilitation change and adopting new work processes
(4) To serve as a first step towards a corporate capability for team collaboration at NASA

Business drivers and functional requirements for NASA team collaboration had been identified over the preceding years and updated after discussions with a sampling of potential users of this technology. This information then served as the basis for the selection of the tools. It was determined that a team collaboration capability should

(1) Reduce reliance on travel to get work done
(2) Enable collaboration between NASA centers
(3) Enable collaboration between NASA and its external partners (industry, academia, other government agencies, and international partners)
(4) Be easy to learn and use (usability)
(5) Be operational and deployable in a short (1- to 2-month) time frame
(6) Appeal to a broad-based audience (scientists, engineers, technicians, managers, and administrators)
(7) Be secure—all users shall be authenticated and all communication shall be private
(8) Have high availability and performance
(9) Have a reasonable cost of implementation

Process

The process of conducting the pilot consisted of (1) recruitment and selection of pilot teams, (2) selection and deployment of collaborative technology, (3) development and application of team adoption strategies, and (4) measurement of results.

Recruitment and selection of pilot teams.—The pilot was planned for a population of about 500 people, and participation would be based on selecting a set of virtual teams representing a cross section of NASA project and work areas. As we considered recruitment and selection of pilot teams, we first defined criteria we felt were essential for a team to be successful in the pilot. Specifically,

(1) The team must be geographically distributed and actively working on team tasks.
(2) The team and team leader must be willing to adopt new work methods and ideally be somewhat frustrated with current distributed work methods.
(3) The team must have a leader who is committed to actively leading the adoption of new work methods and tools.

(4) The team must name one of its members as a pilot focal point who will be responsible facilitating the setup and adoption of tools.

(5) The team should be no larger than 25 people in size.

Next, the NASA CIO sent a call for participation memo to the Agency inviting all centers and Enterprises to submit candidate teams for pilot participation. A selection process was performed to select teams that represented NASA mission-oriented and administrative areas. To account for the pilot capacity of approximately 500 seats, 25 teams were selected for the pilot.

Selection and deployment of collaborative technology.—One of the main objectives of the pilot was to sell the concept of using collaborative technology to enable distributed teams, more so than a particular product or service. Thus, we did need to select collaborative applications for the pilot. This selection was guided by the NASA business drivers and functional requirements that had been identified. Key areas of consideration for pilot product selection included

(1) Features: The pilot focus was to enable virtual team meetings and virtual team spaces. Data conferencing was the key feature intended to enable virtual team meetings. Data conferencing enables people to share presentations and live applications running on their computers with all meeting participants. The virtual team space required basic asynchronous features including file sharing, discussion lists, action item management, calendars, and workflow features.

(2) Usability: The ease of use of collaborative technology is very important for NASA teams. People realize that if tools are difficult to use, team adoption will not likely occur. Teams are already stressed by lack of time and information overload. While usability can be rather subjective, it is a key requirement that came directly from NASA customers.

(3) Ubiquitous access: A key business driver is to enable collaboration across NASA centers and external partners. Lessons learned from previous pilots reveal significant problems when special firewall ports must be open and/or when desktop client software (especially if it must be licensed and maintained) must be installed. Our vision was to allow collaborators to participate from anywhere using the Internet and common network and desktop configurations. No special rooms or network configurations should be required; tools should be accessible from any office, hotel room, telecommuting site, partner location, and so forth.

(4) Security: It is vital that the privacy of NASA team information and processes be maintained. All team members must be authenticated and all communication must be private. All support processes must work in concert with the guidance from NASA's standards for information technology security.

(5) Multiplatform functionality: NASA (and some of its partners) has a heterogeneous computing environment consisting of Windows, Macintosh, Linux, and Unix workstations.[2] It is essential that collaborators be able to participate using their normal work environment, since this is where their work (applications and data) resides.

Other issues considered include product maturity, vendor viability, training alternatives, cost, and deployment options. With respect to deployment options, the NASA CIO and the team at Glenn Research Center were interested in pursuing the option of providing the pilot infrastructure via an application service provider (ASP) rather than deploying in house. The ASP model is being driven by fundamental enabling trends in network services; specifically, the relentless increase in network bandwidth. From a Government perspective, the ASP model provides a provocative option for information technology (IT) outsourcing. ASPs can give NASA access to the identical services that are competing for customers in the commercial marketplace. In addition, since this was intended to be a pilot, we were interested in both a

[2] Windows is owned by Microsoft Corporation, Redmond, WA; Macintosh by Apple Computer, Inc., Cupertino, CA; Linux by Linus Torvalds, San Jose, CA; and Unix, by The Open Group, San Francisco, CA.

short deployment time and avoiding capital costs (e.g., purchasing and installing servers and software applications).

Finally, with inputs from Gartner Consulting (Gartner, Inc., Stamford, CT) and the META Group, Inc., (Stamford, CT) and from previous piloting and standards work at Glenn, we recommended a pilot of two ASP-hosted capabilities:

(1) Virtual team meetings via the WebEx Meeting Center service
(2) Virtual team space via eRoom Hosted Enterprise Service

To help assure a short deployment time, support processes and plans were developed and implemented. These included e-mail, phone, and online assistance, documents such as a pilot frequently asked questions (FAQ), customer support documents, and on-line help, as well as other important elements such as hours of operation and maintenance, priority levels and response time, and points of contact databases.

Development and application of team adoption strategies.—Realizing it would be a significant challenge to transition pilot teams to new ways of working, a tool adoption plan was developed. We also set realistic customer expectations and planned for customer-focused technical and administrative support.

The adoption plan focused on the following techniques:

(1) Defining key roles: Key roles and responsibilities of pilot personnel were defined prior to the creation of the adoption plan. The three key roles were the team leader (TL), team coordinator (TC), and team facilitator (TF). A critical success factor for a team to adopt collaborative technology is that one team member must become an active proponent of the required change in work habits and use of tools. A key role then was that each team must have a defined TL who accepted the responsibility of actively leading the team into the ongoing application of team collaboration tools. In addition to the TL, each team was to name a person on the team to act as the team tool expert (or TC), who would be responsible for identifying opportunities to apply tools, tool setup (i.e., directory structures), and immediate assistance to team members. A member from the Glenn team was assigned to serve as the TF for each team. The TF would be responsible for developing a relationship with and checking in on the TL and TC to assist with the team adoption of tools.

(2) Providing proactive facilitation: From past pilot experiences, we learned that simply giving people access to collaborative technology usually resulted in the tools not being effectively used, if used at all. We decided that active facilitation with the teams would go a long way in the adoption of the tools being provided. TFs would proactively monitor teams by checking in with teams on a regular basis, attending team meetings when appropriate, and monitoring the team space. TFs would then be in a good position to encourage and assist in tool adoption.

(3) Facilitating monthly pilot forums: One way to encourage adoption is to facilitate sharing of results and best practices among all the teams participating in the pilot. Each month, we scheduled a virtual meeting with all of the team leaders and team coordinators. The forums were used to obtain feedback as well as share team information and best practices of tool use. The best practices shared at these forums included the use of WebEx to host a large international conference, the use of WebEx to collaborate on video content, and the use of eRoom to create a project operating plan with multiple authors. The forums were also used to provide technology briefings such as tool tips and features of new software versions.

(4) Providing tool technology training: An understanding of the use and purpose of all tool features can facilitate adoption of tools. We planned for vendor-supplied tool training, both instructor-led as well as self-paced. eRoom training was completely led by an instructor and was provided at the onset of the pilot. Further into the pilot, it was provided on an as-needed basis by the pilot administrators. WebEx offers virtual instructor-led training sessions and self-paced instruction on an ongoing basis at no additional cost.

Measurement of Results.—A key objective of the pilot was to assess the value of team collaboration tools as applied to NASA teams. To that end, we decided to administer two surveys to pilot participants—one before the application of team collaboration tools and another after the teams had used the pilot tools

for a fairly significant period of time—about 9 months. The focus of the first survey was to both measure the prepilot state of each team's ability to get distributed work done and to assess basic team collaborative skills (e.g., trust, communication, etc.). The focus of the second survey was to measure each teams' ability to get distributed work done while using the pilot tools and to gather additional feedback on the pilot such as how well business drivers were met.

In addition to the surveys, customer feedback was collected by team facilitators and at the monthly pilot forums.

The survey distributed before the pilot is found in appendix A, and the survey given after the pilot is found in appendix B. To aid the reader, a list of acronyms used in this report is found in appendix C.

Lessons Learned

The pilot administrators brought to this pilot experience and knowledge from conducting past IT pilots. The lessons learned during those earlier pilots aided in the success of the team collaboration pilot. Realizing the importance of documenting those lessons, it is with forethought that we provide a summary of the lessons learned during this pilot. This section is divided into three major areas: (1) adoption issues, (2) technology issues, and (3) general pilot issues. Requirements for team collaboration are also listed.

Adoption Issues for Team Collaboration at NASA

Tool adoption is key to obtaining value from collaborative technology. Technology is only half the battle. It is difficult for one person to change habits, let alone getting 10 to 25 people to change them together. Executive acceptance is also critical to success. The success of any project initiative is shown to be directly linked to the degree of executive acceptance, and as such it is absolutely necessary that senior management have a comprehensive understanding of the business benefits of the system that is being evaluated. Upper management support, TL involvement, and forming a critical mass of team members with technological skills are all methods that contribute to the likelihood of tool adoption.

Lessons were captured regarding overall tool adoption as well as each of the specific pilot applications.

Overall.—The following were learned about adopting tools for team collaboration in general.

Lesson: The team must be committed to working differently. The TL in particular must commit and actively lead the group into new ways of working. If there is not a commitment to work differently, real or perceived barriers to adoption grow both in number and size and seriously jeopardize the possibility of incorporating the tool into a team's normal workflow.

Lesson: Key pain points or impediments for the team must be identified. Identification of pain points focuses application of team collaboration tools on areas of maximum benefit. Expected results of utilizing the toolset must be clear and valued by the team. Valuation is directly related to the number and size of the impediments. Greater value is perceived when impediments are reduced.

Lesson: A system for how team work will be automated by technology must be established. On a personal level, people create a system for themselves, often enabled by their personal computer, including folder structure, method of tracking their actions, and in some cases establishing processes. Likewise, a team system must be established to organize team information, actions, and processes. Each team must designate a coordinator (TC) to ensure that the team makes use of the tool as appropriate, to implement and maintain the structure for the team's information according to agreed upon criteria, and to be the primary team contact for issues regarding the use of the tools. Without a person who is dedicated and available for this function, most teams do very poorly in adoption of the tools. There needs to be

executive support of the TC to empower him/her to get a team to incorporate the collaborative tools into the team's normal work patterns. As an example, The Payload Safety Review Panel (PSRP) successfully adopted WebEx in part because of a very engaged TC. The TC (1) developed a training program for all team members, which included PSRP and support engineers as well as payload organizations, (2) effected cultural change throughout the team, one person at a time, and (3) developed a process for the scheduling and notification of WebEx meetings.

Lesson: Team acceptance of the new system must be established. Team members must feel vested in the system and actively use it for team work. They must also have an agreement among themselves for how they will work together using the new system. Though the entire team must buy into the new system, cultural change often occurs with one individual at a time.

According to one TC's philosophy, there are several roles as it pertains to the adoption of a new system: innovators, hesitators (perfectionists and procrastinators), and resisters. The innovator thrives with the new system as their motto is "Change can be fun!" Hesitators include both perfectionists who are uncomfortable with displaying their lack of knowledge and procrastinators who often proclaim that they are too busy for training. Resisters feel that change is bad, and often management support is needed to reinforce the need for change.

Team Meetings.—The following lessons were learned about the tool applied for team meetings.

Lesson: Conferencing (e.g., WebEx for the pilot) is quickly accepted by teams and provides immediate value. Meetings are a common process at NASA. Enriching the meeting experience with a tool like WebEx fits fairly simply into this existing process. The ability to share live content from any computer in a meeting significantly increases the richness of the communication. Several teams eliminated travel due to this increase in communication. For example, the Stennis Space Center Office of Technology Transfer (OTT) successfully utilized WebEx to conduct two very high level and sensitive meetings in place of traveling to Washington, DC. The OTT managers from all NASA centers participated in the meeting. A significant amount of time was saved using WebEx—4 to 6 hours versus 3 days.

Note: See the Post-Pilot Survey (appendix B) for additional points.

Virtual Team Space.—The following lessons were learned about the tool applied for team space.

Lesson: Teams are reluctant to heavily invest in a tool/process that will only exist for a short duration (1 year). Since team space does not fit into an existing work pattern (as compared to conferencing), more time is needed for teams to adopt. There was reluctance to heavily invest in a tool that might be available for the short term.

Lesson: Training should be provided just in time for active use of the tool. If training is offered before individuals are ready to use the tool, its usefulness is minimized. Training should cover the features of the tools, but just as importantly, training needs to demonstrate how the tool can effectively be incorporated into automating a team's existing processes.

Lesson: Piloting a team space is better accomplished by targeting an entire user segment (i.e., the entire project, program, or enterprise), rather than distributing seats to small teams at the working level. The training and needs assessment should be done with the targeted group so that they learn the common language of using the tool, thereby having a better chance for broader acceptance since everyone will be on the same page regarding how the tool is going to be incorporated into their work processes.

Note: See the Post-Pilot Survey (appendix B) for additional points.

Technology Issues for Team Collaboration at NASA

Technology has been an incredible enabler for distributed teams to get more work done. High-speed network connectivity and feature-rich applications allow virtual teams to accomplish their work remotely in a very efficient manner. For the technology selected as part of this pilot, particular attention was paid to selecting tools that supported two critical requirements for NASA: ease of use and interoperability in a multiplatform environment. Other areas that were very important were availability, security, and service delivery. While the tools generally worked as advertised, there were a few technology issues that surfaced during the course of performing this pilot. We felt the issues were grouped somewhat into four topic areas of (1) application service providers, (2) multiplatform issues: operating systems and browsers, (3) security issues, and (4) ubiquitous access: browsers and Internet.

Application service providers.—The pilot was conducted using application service providers (ASPs). So while we piloted the tools and their adoption, we also piloted the mechanism for offering the service. A driving force for using ASPs was the short turnaround time needed to initially offer the services. Our experience using ASPs was mostly a positive one. Generally, operations and support have been excellent for both tools. Software updates took place with little or no disruption to the end user. Performance of the tools (e.g., end-user response time) was generally very good. Pilot participants were inconvenienced on a few occasions when there were problems with the tools. There also were some unresolved problems that were due to limitations with the operating systems, browser applications, and firewall restrictions in the systems NASA used to access the services.

While WebEx had a couple of operational incidents, they were addressed in a timely manner by WebEx support staff. There were numerous software updates that occurred over the course of the pilot. These updates would have taken more administrative resources if the Web-conferencing service were offered in-house, since we would have needed to install and test in a development environment and then move them to a production system. It was also very helpful to have access to beta sites with the next release of the tool to test and evaluate any impacts before it was moved into the production environment. The overall availability of the service was very good as was the response time of WebEx ASP support.

We experienced literally no down time on eRoom. However, on the occasion that we needed assistance, response time for eRoom ASP support was poor.

Lesson: ASPs provide excellent operational capability as well as security. However, team members may perceive security issues with the use of ASPs since data may reside outside of the NASA domain.

Lesson: ASPs allow for virtually trouble-free software upgrades and reduce need for in-house resources.

Lesson: Operating systems, browser applications, and firewall restrictions can pose problems for ASPs in the NASA environment.

Multiplatform issues: operating systems and browsers.—Multiplatform access is needed but is also a challenge. Both eRoom and WebEx support Windows, Mac OS 9/X, Linux, and some Unix variants, but you still find more issues and functionality gaps on the non-Windows platforms. This is somewhat hard to overcome in a Windows-dominated world. However, we believe we are as close to full interoperability as possible considering there are many Windows-only applications that were purposely avoided. There is also a challenge with multiple browser types (Netscape, Internet Explorer, Mozilla, and Safari) and versions in use.

Because of the platform diversity within NASA, it would be useful to know which operating systems and browsers are currently being used and which ones are in the queue for future deployment. Likewise, consideration must be given to the NASA environment when a new release of software is made available. As with any other software, the benefits of a release must be weighed against any complications it might bring to our desktop environment. So it is important that thorough testing occur before a decision is made

to deploy the software. It is also worth noting that the tool feature set may vary from one platform to the next.

Lesson: Multiplatform goes beyond types of desktop (PC, Mac, Unix, etc.) and must include versions of operating systems and browsers.

Security issues.—This pilot surfaced many IT security issues that had to be addressed. It was imperative that a security plan be developed to cover matters such as NASA Procedures and Guidelines (NPG) 2810 conformance and in particular the Business and Restricted Technology (BRT) data category that is of interest to many customers. Some customers expressed interest in collaborating on International Traffic in Arms/Export Administration Regulations (ITAR/EAR) data. Additionally, the service was provided beyond NASA proper since collaboration often extends to external partners in industry, academia, and other Government agencies. As a result of that, it became clear that a process must be developed to address external partners agreeing to the service providers' and data owners' rules and regulations on the use of a Government service. All of these security issues were managed by working cooperatively with the NASA Information Technology Security (ITS) personnel and the pilot vendors (WebEx and eRoom).

Pilot participants stated a desire for stronger authentication. However, they also wanted an easy way to securely access systems, such as the RSA SecurID (RSA Security Inc., Bedford, MA) tokens, so that they would not have to remember yet another username and password.

Lesson: A balance must be struck between security and information sharing through collaboration. There are tradeoffs between the usability of a service and making it too restrictive. A tiered approach for various security levels should be developed.

Ubiquitous access: browsers and Internet.—Access via ubiquitous infrastructure is a big win. We chose products that work with in-place network and desktop configurations so that no real infrastructure changes were required (e.g., we did not require additional firewall ports open; we used SSL, and we did not require any active installation of special or licensed desktop software—just quick downloads when accessing services). And because most teams need to interact both across NASA centers and with external partners, ubiquitous access was a key enabler.

The tools operated well in a wide range of firewall and proxy server implementations and configurations. With WebEx, there was only one unresolved firewall and proxy server issue with one NASA center at the conclusion of the first year of the pilot.

Lesson: Web-based tools provide the accessibility needed for collaboration amongst NASA centers and their external partners.

Conducting Pilots

Just as knowledge was acquired with respect to the adoption (change management) issues and technological issues involved in piloting the two collaborative tools, we also gained knowledge about conducting IT pilots. The lessons captured below will hopefully aid in conducting more efficient and effective pilots in the future.

Lesson: Executive sponsorship and support must exist.

Lesson: Develop and adhere to criteria for team selection. If a team is participating in a pilot simply because they were told by management "thou shall participate," the chance of engagement is greatly reduced. Team members—in particular the TLs—need to see the value of adoption.

Lesson: Pilots need to be customer focused. Both communication and support should be just as people centered during a pilot as it is in a production environment. Multiple methods can be utilized to share information as well as to receive feedback. A pilot Web site, e-mail, surveys, a discussion area, and monthly forums were all used to communicate during the pilot. Monthly forums were also useful for pilot participants to share best practices, ideas, and concerns with fellow pilot participants. A support plan should include necessary elements such as pilot FAQs, on-line help, problem escalation and resolution, and customer support documents.

Lesson: Customer expectations must be defined. What you expect from customers and what they should expect from you must be clear. This includes the duration of pilot, service levels, and so forth.

Lesson: Pilot participants with team vision, goals, and deliverables have greater probability of engagement. Knowing one's goals and/or objectives is sometime difficult because of fairly broad Agency shifts. Also, participating in a pilot is often viewed as a layered add-on. Therefore engagement in the pilot can be superficial.

Lesson: Plan beyond a successful pilot. Be prepared for a larger scoped service if the pilot is successful. This includes procurement, infrastructure, security, and other areas.

Key Requirements for Team Collaboration at NASA

One of the first steps in defining the pilot was to draft business requirements (or drivers) for a team collaboration service at NASA and verify them with NASA focus groups. Those requirements have been further verified by our pilot participants. Key requirements have been developed. Some critical requirements are listed below. The team collaboration service must

(1) Enable NASA teams to participate from any NASA desktop computer
(2) Enable external partner participation without requiring reconfiguration of existing network perimeters
(3) Be easy to learn and use
(4) Be based on a leading commercially available Internet service
(5) Conform to NASA NPG 2810 IT security guidelines
(6) Provide multiplatform support (Windows, Macintosh, Linux, and Unix) in combination with NASA-recommended Web browser applications

Survey Results

Surveys were conducted as part of the pilot to assess the value of team collaboration tools. There were two major surveys conducted during the pilot: a Pre-Pilot Readiness Assessment (appendix A) conducted at the start of the pilot and a Post-Pilot Survey (appendix B) conducted 9 months into the pilot.

Both surveys measured the ability to get distributed work done. The Pre-Pilot Readiness Assessment was focused on evaluating the work environment and benefits of collaborative work. Issues such as trust and motivation were queried. The Post-Pilot Survey was more focused on the use of the pilot tools. As a result, only a limited cross analysis between the two has been done. Another limitation that prevented greater analysis of the two sets of data was the different audiences for the two surveys because a number of teams did not participate for the duration of the pilot. There were several reasons why teams did not participate for the duration: (1) Projects and programs were cancelled; therefore teams were disbanded,

(2) A team's work processes were unknown or did not lend themselves to virtual collaboration, and (3) The abundance of team responsibilities did not allow adequate time to learn and incorporate new tools into their work processes. In addition, other teams entered the pilot midyear through the pilot. Yet another difference in the survey audience was the first survey was distributed to all known pilot participants whereas the second survey was distributed only to team leads and coordinators.

The Pre-Pilot Readiness Assessment consisted of three major sections: demographic, social aspects of collaboration, and lastly the current state of the collaborative tool environment for virtual teams. The rate of return for the survey was 23 percent (137 out of 593 responded). Summarizing the data returned from the survey:

- Respondents represented a cross section of NASA and its external partners. In fact, representatives from all the NASA centers responded to the survey.
- A high level of trust among workgroups existed, and fellow workgroup members were motivated and adequately engaged in the work.
- Workgroup members openly communicated, and to a lesser degree managed knowledge.

Complete details of the Pre-Pilot Readiness Assessment can be found in appendix A.

The Post-Pilot Survey (found in appendix B) yielded more information about the technology and the implementation of the pilot. The Post-Pilot Survey had a 24 percent rate of return (126 out of 517 responded), and again all centers were represented in the survey responses with 41 percent of the respondents being a support service contractor (SSC) or external partner. While the majority of the respondents used a PC-Windows platform, just under 25 percent of them used Mac or Linux platforms.

From the results of the survey in the table below, it appears the original business drivers were met. Highlights from the survey include

- Teams that had a clear mission, schedule, and deliverables more readily embraced the pilot tools and had greater success using them.
- Individual responses were aligned with their respective team response (i.e., not many outliers).
- Collocated teams that had access to WebEx still received benefit from the tool.
- Teams with access to both eRoom and WebEx often only used one of the tools.
- Pilot participants using eRoom were often collocated and able to meet face-to-face. This might have resulted in less of a need to participate in virtual meetings.
- Pilot participants using WebEx often utilized asynchronous tools with which they already had access and familiarity (and not eRoom).

Business requirement	Applicable post-pilot survey question number(s)	Requirement met?	
		eRoom	WebEx
Tools shall reduce the reliance on travel to get work done	3, 10	Not necessarily	Yes
Tools shall enable collaboration between NASA centers	4, 11	Yes	Yes
Tools shall enable collaboration between NASA and its external partners	4, 11	Yes	Yes
Tools shall be easy to learn and use	5, 12	No	Yes
Tools shall appeal to a broad-based audience (scientists, engineers, managers, and administrators)	NA	Yes	Yes

Concluding Remarks

Conducting this pilot has proven to be valuable to the Agency in many ways. While sharing the aforementioned lessons learned is intended to broaden the knowledge within the Agency, we also feel that the pilot served to yield the following discoveries and confirmations:

Increased productivity and efficiency are better proved by pilots as opposed to paper studies. Vendors often tout their ease of use, reliability, full feature sets, and so forth. However, it is not until customers use a product that these characteristics can be verified.

Requirements can only be validated through the actual use of a product. Often an initial set of requirements evolve as a tool is used in one's work processes. Requirements are updated—deleted, modified, and added—as the tool is used. The pilot then serves to yield a better set of requirements. Lastly, the experience gained during a pilot is valuable as one plans for transition to an operational state.

Appendix A
Pre-Pilot Readiness Assessment

The survey presented in this appendix was administered by the Principal Center for Workgroup Hardware and Software at the NASA Glenn Research Center. It was distributed to the participants of the team collaboration pilot to assess their proficiency in collaborative skills and practices before the pilot took place.

Pre-Pilot Readiness Assessment

The Survey

Collaboration is a socio-technical process that involves social processes and technology to achieve high levels of workgroup performance and productivity. To help workgroups better exploit their collaboration skills throughout the course of the pilot activity, each workgroup was surveyed to assess their current strengths in the four key skill areas that are considered important to effective collaboration in a virtual workspace. While this survey instrument is by no means a comprehensive cultural assessment, it does provide general insight into the workgroups' skill proficiency so that any necessary incremental changes can be implemented. The survey was conducted via the Internet using Facilitate.com.

General data was collected from 137 (out of the 593 mailed) respondents from various Centers throughout the Agency. The survey questionnaire consisted of three parts:

> Part I of the questionnaire asks for user demographic information. This information will be used to identify the participating workgroups. This information will also help in defining the type of work that workgroup members are actively engaged in.
>
> Part II contains questions relating to the social aspects of utilizing collaborative workgroup technology. The questions in this section are specifically focused on the core skills, attitudes, and behaviors that are essential to successful collaboration in a virtual environment. Responses obtained in this section will give a general view of the workgroup's skills for effective collaboration.
>
> Part III contains questions about the state of the current virtual team/collaborative tool environment. These questions will help assess the efficiency and effectiveness of current collaborative workgroup technology and will provide a baseline for documenting any changes in workgroup productivity.

Survey Limitations

The data collection tool was not robust enough to provide adequate error checking and exception handling. Consequently, scores from two non-responsive respondents had to be eliminated. In some cases, survey respondents did not answer all of the questions. Total responses will therefore vary from question to question.

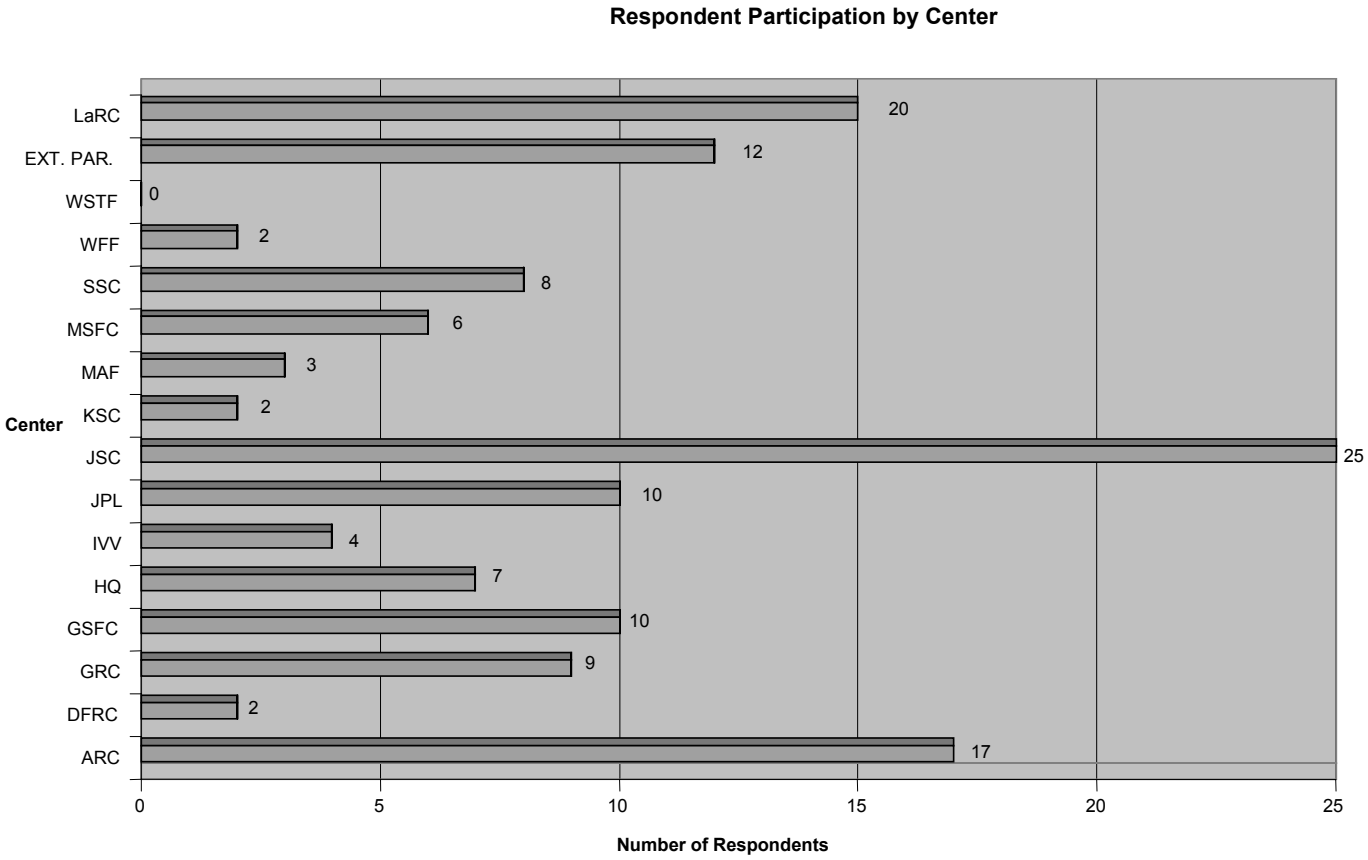
A statistically-significant number of respondents (approximately 20%) did not select the proper workgroup (question 2). As a result, the survey results could not be analyzed and reported for each workgroup (sample population - pn). The results discussed herein are the results for the entire group of survey respondents (population P). This is probably the most unfortunate limitation of the survey.

Survey Results

The survey results are provided in this report, which is organized according to the survey layout. Part I of this report provides demographic information such as Center location, workgroup name, and workflow type. Part II provides the results of the collaborative skill assessment. The four skill dimensions are trust, motivation, open communications, and knowledge management. Part III contains the results on the respondents' experience with their current virtual environment.

Part I - Demographic Information

Center Participation



Return Rates

Analysis

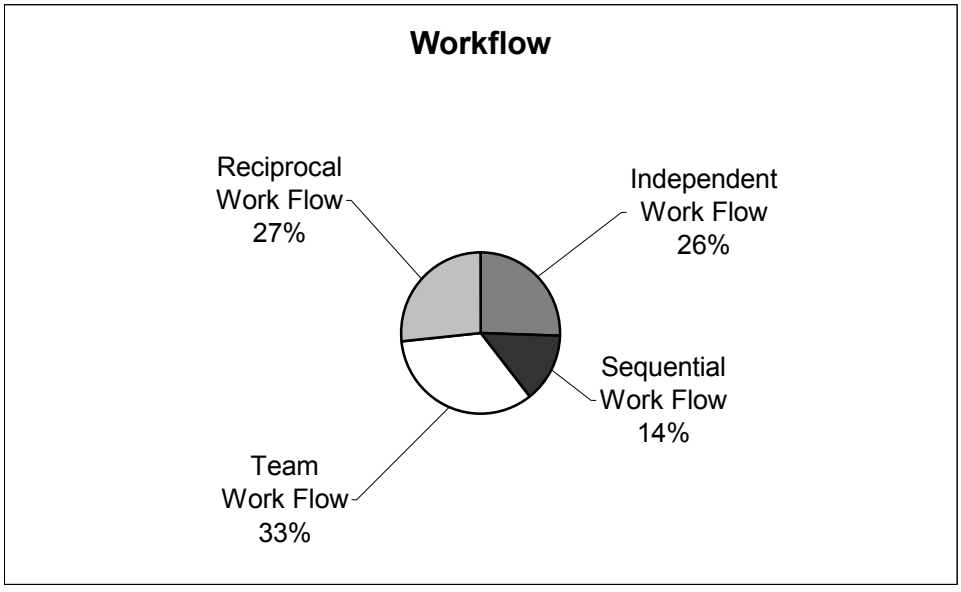
A 23% return rate (137/593 = 23%) provides a significant statistical sampling for this assessment. The return rate is slightly higher than the typically-accepted return rate for web-based surveys (20%). This suggests that participants care about collaboration and are willing to explore alternative ways to enhance and improve their collaboration skills and abilities.

Benefits

Benefits Respondents Would Like To Receive Through Pilot Participation

Stated Benefit	Frequency
Make group information more accessible	115/137 = 84%
Provide a virtual context for meetings	98/ 137 = 71%
Provide a means for problem solving	93/137 = 68%
Identify project issues	89/137 = 65%
Encourage all members to contribute	80/ 137= 58%
Enhance team building	76/137 = 55%
Maintain historical project records	74/ 137= 54%
Make lessons-learned more accessible	71/137 = 52%
Increased creativity	66/137 = 48%

Current Workflow



Analysis

Survey respondents spend slightly over one-third of their time working in a team environment where they collaborate to solve problems and share information to fulfill the charter of the group. In this arrangement, all share in the responsibility of the work. Respondents spend slightly more than one-quarter of their time in reciprocal work arrangements where the work and activities are exchanged back and forth. In this work flow format, responsibility for the work may shift as the work is passed among group members. Respondents spend one-quarter of their time working independently. Respondents spend the remaining time in an arrangement where work and activities flow between group members in one direction.

Part II - Collaborative Skills Results: All Workgroups

Introduction

Research on virtual teams and workgroup collaboration shows that there is a connection between collaboration and workgroup culture. This study specifically examines the social aspects of organizational culture that have a significant impact on workgroup collaboration. Drawing upon the literature, four key competencies are identified and assessed, namely, trust, open communications, motivation (engagement), and managing knowledge.

Central to this research is the premise that workgroups with high competencies in these major collaborative skills are most likely to succeed in transferring these competencies to a virtual environment using virtual team collaboration technology. See the white paper entitled, The Affects of Workgroup Culture on Collaborative Tool Adoption, for a comprehensive discussion of this research.

Overall mean average scores for each skill category are based on a Likert scale where 1 = Strongly Disagree and 5 = Strongly Agree

Trust

Question: I trust my fellow workgroup members:

Trust	
Category Description	**Frequency of Responses Over 3**
Are competent in performing their jobs	123/134 = 92%
Respect authority when appropriate	122/134 = 91%
Will generally keep the promises they make	119/134 = 89%
Feel free to contribute to the success of the group	119/134 = 89%
Express their true feelings about important issues	113/134 = 84%
Have a high level of trust and respect for each other	111/134 = 83%
Collaborate on projects and tasks even when it takes time away from other duties	92/133 = 69%
Will openly acknowledge their own mistakes	83/134 = 62%

Overall Mean Average Score: 4.06

Analysis

The results reveal that the respondents collectively hold a high level of trust among members within their respective workgroups. Respondents trust that workgroup members:

- Are competent in performing their jobs,
- Respect authority when appropriate,
- Will generally keep the promises they make,
- Feel free to contribute to the success of the group,
- Express their true feelings about important issues, and
- Have a high level of trust and respect for each other.

Respondents reported slightly lower perceptions of trust in workgroup members' willingness to collaborate on projects and tasks when it takes time away from other tasks and duties. Respondents also reported slightly lower perceptions of trust that workgroup members will openly acknowledge their own mistakes. In a collaborative environment, individual needs must often compete with the needs of the workgroup. In most cases, individuals will protect their personal interests unless they realize a greater benefit in doing otherwise. For these reasons, it is not surprising to find a reluctance to trust that workgroup members will subordinate their individual interests to the overall needs of the group. Nonetheless, it is important to note that high trust scores were not anticipated.

High levels of trust increase the likelihood that workgroups will experience and realize the full benefits of team collaboration. These high scores suggest that workgroup members are willing to trust the information they share because they trust the competency and integrity of each other.

These scores also suggest that despite the fact that Centers often ‘compete’ for the same program dollars and other resources, a high level of trust and respect still exists amongst team members. While spirited competition among Centers may exist, team members are willing to work collaboratively and cooperatively for the good of the whole team. When a program is operating across Center boundaries, workgroup members still want to succeed, for themselves and the program.

Motivated/Adequately Engaged

Question: I am confident that my fellow workgroup members:

Motivated/ Adequately-Engaged	
Category Description	**Frequency of Responses Over 3**
Are generally motivated to succeed	123/132 = 93%
Are involved in making appropriate decisions that affect their work	117/132 = 88%
Generally have a sense of belonging to the workgroup	110/132 = 83%
Consider the success of the workgroup as their success	108/132 = 82%
Understand the overall mission and strategy of the workgroup and how their work supports it	103/131 = 79%
Feel adequately-engaged in shaping the outcomes and deliverables of the workgroup	103132 = 78%
Clearly understand their role in, and responsibilities to, the workgroup's effort	96/132 = 73%
Understand how the outcomes and deliverables of the workgroup are tied to the business strategy and objectives of the organization	83/131 = 63%

Overall Mean Average Score: 4.00

Analysis

The results suggest that the respondents collectively believe that workgroup members are highly-motivated to succeed and take ownership for the overall success of the workgroup. Respondents are involved in making decisions that affect their work and feel a sense of ownership for their products and deliverables.

Respondents have a sense of belonging to the workgroup and this suggests that there is a high degree of comfort with the identity of the workgroup. It is not unlikely that this strong sense of belonging is a motivating factor in workgroup members' willingness to contribute their best effort and take ownership for the success of the group.

While respondents generally understand the overall mission and strategy of the workgroup, nearly 30% indicated that they were unclear on their individual role and responsibility to the workgroup's efforts. Moreover, nearly 40% indicated they were unclear on how outcomes and deliverables are tied to the overall business strategy and objectives of the organization.

Clarity of purpose is among the best predictor's of team success. Role clarity is important to collaboration activities because individuals will put forth their best effort when they understand what they are expected to do and why they were selected to do it (Santous, 1993) (Fullan, 2001). Individuals will have an intrinsic caring about their tasks and embrace the importance of their cause.

Individual workgroups participating in this study would do well to take the extra time to map the current roles of each workgroup member to the charter and then to the mission. This activity will help clarify how these individuals contribute to the mission and business of the overall organization they serve.

Open Communications

Question: My fellow workgroup members:

Open Communications	
Category Description	**Frequency of Responses Over 3**
Pass on new or useful information as appropriate	111/131 = 85%
Actively listen to the thoughts, feelings, and ideas of others	108/131 = 82%
Provide timely information about changes in current plans	96/132 = 73%
Have easy, rapid access to key information	83/131 = 63%

Overall Mean Average Score: 3.88

Analysis

Respondents report that they experience meaningful communication as workgroup members pass on useful information and actively listen to the thoughts, feelings, and ideas. Nearly 30% of the respondents indicate that they are not informed about changes to current plans in a timely manner. This is a common dilemma of distributed workgroups and, in most cases, can be addressed by providing more frequent meetings, either face-to-face or virtual. Another way to increase communication is the use of web-based news sources like eRoom, Livelink, and similar tools that have event-based email notification and places project information in a single location. This type of technology will only work if the project members are disciplined enough to create a record of the changes. Nonetheless, workgroups would benefit from identifying a method for communicating project information as well as a communication plan for ensuring the timely release of news to all parties that will be affected by the information.

Nearly 40% of the respondents indicate that they do not always have easy, rapid access to critical information. Workgroups are already intuitively aware of this dilemma as one of the primary benefits they hope to realize through this pilot is gaining more access to group information.

It is nearly impossible to isolate the root causes of this dilemma without further investigation. However, social structure, technology limitations, and/or organizational structure may contribute to the problem. In many cases, knowledge and information is closely held by tightly knit group or subgroups, making it nearly impossible to obtain unless members sanction its release. Cultural norms and organizational design can also impact accessibility to information - it may not be an acceptable practice to cross organizational lines to access information. This may be particularly true for workgroups that function in a hierarchical organization. Also, employees may not be adequately compensated to share information, since their performance evaluations are based on individual, not team performance.

While technology such as email and document management tools play a major role in storing and exchanging information, other tools may be needed to harvest the full potential of that information. Tools such as Expert Locator and Tacit Knowledgemail which identify likely experts based on topics within a common directory or based on email content.

A legitimate reason for inaccessibility to key information may be poor assimilation of knowledgeable members into the workgroup. These individuals are not sure what type of information to share and how to share what they know, especially if communication processes are loosely followed. Another reason might be the lack of knowledge or experience, which may make an individual deliberately avoid situations to share what they know in order to save face. Each of these reasons requires a different coaching process.

Workgroups may benefit from providing more opportunities for members to interact - whether via web-based newsletter or web pages, face-to-face meetings, or frequent teleconferences. Workgroups may also benefit from understanding which of its members are central or core and which are considered peripheral and why. Workgroup leaders may need to reconstitute these sub-groups especially if it would increase accessibility to information and knowledge.

Managing Knowledge

Question: Mark the answer that represents your level of agreement with the statement provided:

Managing Knowledge	
Category Description	**Frequency of Responses Over 3**
We frequently collaborate and share information within our workgroup	110/133 = 83%
Creative ideas are given support and recognition within our workgroup	107/133 = 80%
We produce quality deliverables	107/133 = 80%
Our workgroup knows how to apply what we learn toward improving what we do and how we do it	96/132 = 73%
We are able to solve complex problems effectively because we get the right people involved at the right time	95/133 = 71%
Our workgroup actively applies what we learn toward improving what we do and how do it	94/133 = 70%
We systematically document and distribute our knowledge	80/133 = 60%
We have mechanisms built into our workgroup processes to ensure that we learn from previous success and failures	73/133 = 55%

Overall Mean Average Score: 3.83

Analysis

The key purpose of collaborating is to produce something, whether it is solving a problem or creating something new. Over 80% of the respondents report that they frequently collaborate and share information within their workgroups. Respondents are adept at exploiting their collaborative synergy to solve complex problems and produce quality deliverables. This suggests that the majority of the participating workgroups value knowledge sharing and are accustomed to collaborating and that sharing knowledge is widely practiced and supported.

While the results indicate that the survey respondents are apparently effective at collaborating and managing their knowledge, the results also show that more than of the workgroups are limited in their ability to learn from previous experiences. Of those who do harness key learning from their previous experiences, only 70% actively apply this learning toward process improvement.

Furthermore, only 60% of the respondents indicated that they systematically document and distribute knowledge, which may be contributing to their inability to gain access to critical knowledge in a timely manner as indicated in the previous section. While these indications are not alarming, they do suggest that workgroups may benefit from revisiting their continuous improvement strategies and processes for gathering and distributing lessons learned in order to get the most out of the pilot.

Part III - Current Collaborative Environment: All Workgroups

Virtual Team Meetings

Question: Mark the answer that represents your level of agreement with the statement provided:

Virtual Team Meetings	
Category Description	**Frequency of Responses Over 3**
Attending virtual meetings is a simple process	95/134 = 71%
Scheduling virtual meetings is a simple process	63/131 = 48%
Communication in virtual meetings is adequate	61/133 = 46%
Sharing electronic information in virtual meetings is simple to do and effective	56/132 = 42%
Consensus is easily reached in virtual meetings	40/133 = 30%

Overall Mean Average Score: 3.35

Analysis

While over half of the respondents experience some degree of difficulty in scheduling virtual meetings, most respondents perceive their overall experience in attending virtual meetings as relatively simple. More than half of the respondents indicate that communicating and sharing electronic information in virtual meetings is less than adequate. Only 30% find group consensus easy to reach.

Since WebEx is a tool designed specifically to facilitate scheduling, communicating, and sharing documentation during virtual meetings, workgroups should see marked improvements as they become more adept at using this tool throughout the pilot.

Virtual Team Information Sharing

Question: Mark the answer that represents your level of agreement with the statement provided:

Virtual Team Information Sharing	
Category Description	**Frequency of Responses Over 3**
Team members are aware of their actions	87/133 = 65%
I am aware of my team's schedule of events	83/133 = 62%
Actions items are effectively documented and tracked	73/133 = 55%
Sharing team information is simple and effective	71/133 = 53%
I can always find the current version of team documents	56/133 = 42%
Team leaders can easily track progress on actions	53/133 = 40%

Overall Mean Average Score: 3.43

Analysis

Nearly 40% of the respondents are not aware of their workgroup's schedule of events and actions. Much worse, almost half of the respondents report that action items are not effectively documented and tracked. Respondents, in general, do not find information sharing simple. These findings are consistent with those in the Open Communication section of this report, which showed that nearly 40% of the respondents found access to information is difficult and complex. Clearly inaccessibility to basic and critical information is the most recurrent theme.

In light of these findings, workgroups would do well to embrace eRoom as a mechanism to reach out and communicate with each other. Workgroup facilitators must look for ways to encourage members to use eRoom as a central hub for communicating between face-to-face meetings and/or teleconferences. Workgroup members must gain enough experience beyond the training exercises in order to realize the full value and benefits of the tool.

Productivity

Question: How likely would you be to adopt for regular use software/services that:

Productivity	
Category Description	**Frequency of Responses Over 3**
Allows you to enhance your virtual meetings by keeping discussions focused and actively engaging members	63/73 = 86%
Allows your virtual team members to simultaneously mark up a drawing or document on your desktop	63/78 = 86%
Allows you to make team documents and records available to the workgroup at all times	54/67 = 80%
Allows you to reduce or eliminate the need to travel to other destinations to make presentations	59/83 = 71%

****Responses indicate level of agreement**

Analysis

Most of the respondents indicated that they would adopt collaborative software or services that enhance the richness of virtual meetings. Not only would the respondents appreciate software that would allow them to simultaneously modify or edit a document, but also archive that document and make it accessible to others at all times. These requirements overshadow the respondents need to adopt collaborative tools that would reduce the need for travel.

Again, eRoom and WebEx are excellent tools that will allow pilot participants to enhance meeting activities and the flow of work products.

Collaborative Tool Use

Nearly 90% (119/135) of those that responded to this set of questions indicated that they were actively seeking new collaborative tools to improve productivity. The collaborative tools that workgroups reported using are:

eRoom	NetMeeting	Livelink	Docushare	WebEx	Telecons	ViTS	PBMA and other Intranet Websites	*Other
2	20	13	3	4	7	8	7	19

*Other tools include:
Government Off The Shelf (GOTS) product VSDE (1)
Meeting Maker (1)
Windchill (3)
CUCMe (3)
I-TIPS (1)
Email (5)
Smartboads (1)
Productview (1)
Science Organizer (1)
Postdoc (1)
PDS (1)

Part IV - Summary

Respondents care about collaboration and are willing to work on improving their collaborative capabilities. Respondents are skilled in the four core collaborative competencies: trust, open communications, knowledge management, and motivation. Respondents have a high degree of trust in each other as competent professionals and their ability to perform in the best interest of the group. Respondents are motivated to do a good job and take pride in the outcomes and deliverables of the workgroup.

While workgroup members practice and enjoy active listening and information exchange, many have difficulty accessing basic and critical project information. Like most teams and groups, survey respondents do not have continuous improvement processes.

Respondents realize that better access to project information would enhance their performance and collaborative capabilities as a team. In fact, the most recurrent theme in the analysis of responses was inaccessibility to project information. Fortunately, the respondents are motivated to explore new collaborative technologies that enhance virtual meetings by keeping members actively engaged. For these reasons, participants will benefit from the tools being piloted in this study.

Appendix B
Post-Pilot Survey

Overall Pilot Questions

1) Which Team Collaboration tool(s) did you attempt to use during this Pilot?

	Number of Responses	*% of Total*
eRoom and WebEx	27	21%
WebEx only	99	79%
Total	126	100%

2) Which platform(s) did you use for the Team Collaboration tool(s)?

	Number of Responses	*% of Total*
Macintosh	21	17%
PC/Windows	97	80%
Linux	3	2%
Unix/HP	1	1%

(Note: Some responses had more than one system type indicated; some responses did not make a selection).

eRoom Related Questions

3) eRoom has enabled my team to get work done with less reliance on travel.

Negative	28%
Neutral	32%
Positive	**40%**

4) eRoom has enabled collaboration among team members distributed across NASA Centers and external partners.

Negative	4%
Neutral	32%
Positive	**64%**

5) eRoom was easy to learn and use.

Negative	12%
Neutral	38%
Positive	**50%**

6) Considering the application of eRoom, check all that apply:

Sharing team information is simple and effective.	88%
I am aware of my team's schedule of events.	38%
Team members are aware of their action items.	25%

Action times are effectively documented and tracked.	19%
Team leaders can easily track progress on actions.	19%

7) Considering the capabilities you consider essential for a NASA Virtual Space service - please rate the importance of the following capabilities on a 1-5 scale where (1) is 'Not Important,' ... (5) is 'Very Important.'

Rank	
1	Multi Platform Support
2	Action Tracking
3	Team Calendar
4	Email Alerts/Notifications
5	Coordination of document changes (Check In/Out)
6	Threaded Discussions
7	Databases
8	Drag and Drop from Windows Desktop
9	Polling/Voting

8) If your team did not successfully adopt eRoom - please check your top 3, or so, primary reasons why.

Rank	
N/A	We did successfully adopt eRoom! (4 responses)
1	Unclear (and perhaps undocumented) team organization and/or processes
2	Did not want to take the risk of putting all the energy into shifting to this tool - and then not have it be adopted as a corporate solution – and have to transition all our data out
3	Lack of commitment by the team and team leader to employ a new tool
4 tie	Unidentified 'pain points' that team is attempting to address with collaborative tools
4 tie	Lack of commitment by the team and team leader to alter work habits
5 tie	Unclear (or changing) team goals and deliverables
5 tie	Lack of tool training
5 tie	Tool did not do what I needed it to do - it did not deliver on needed functionality
6 tie	Tool too difficult
6 tie	Already have this functionality - so don't want to switch from the tool we use now
7 tie	Lack of collaborative tool facilitation assistance from outside the team
7 tie	Lack of collaborative tool adoption assistance (internal resources) within the team
7 tie	Duration of the pilot not long enough to get started
8	Lack of executive sponsorship (support)

9) Overall, our team successfully used eRoom.

Negative	30%
Neutral	**43%**
Positive	26%

WebEx Meeting Center Related Questions

10) WebEx Meeting Center has enabled my team to get work done with less reliance on travel.

Negative	9%
Neutral	18%
Positive	**73%**

11) WebEx Meeting Center has enabled collaboration among team members distributed across NASA Centers and external partners.

Negative	5%
Neutral	13%
Positive	**82%**

12) WebEx Meeting Center was easy to learn and use.

Negative	4%
Neutral	17%
Positive	**79%**

13) Considering WebEx Meeting Center to conduct virtual meetings, rate all that apply:

Rank	
1	Attending virtual meetings is a simple process.
2	Attendees are able to participate effectively in virtual meetings.
3	Sharing electronic information in virtual meetings is simple to do and effective.
4	Scheduling virtual meetings is a simple process.
5	Consensus is easily reached in virtual meetings.

14) Considering the capabilities you consider essential for a NASA Virtual Meeting service - please rate the importance of the following capabilities on a 1-5 scale where (1) is 'Not Important,' ... (5) is 'Very Important.'

Rank	
1	Presentation Sharing
2	Simple attendance by external partners
3	Application Sharing
4	Multi platform support
5	Integration with telephone based voice conferencing
6	Desktop Sharing
7	Meeting recording and playback
8 tie	Polling
8 tie	Video
9	VoIP

15) Overall, our team successfully used WebEx Meeting Center.

Negative	7%
Neutral	14%
Positive	**79%**

General Pilot Questions

16) Our team has a clear mission, schedule, and deliverables.

Negative	10%
Neutral	16%
Positive	**74%**

17) My team embraced the Team Collaboration Tool(s) offered by the pilot.

Negative	8%
Neutral	24%
Positive	**68%**

18) Considering the ingredients you consider essential to successful team adoption of collaboration tools - please rate the importance of the following ingredients on a 1-5 scale where (1) is 'Not Important,' ... (5) is 'Very Important.'

Rank	
1	Easy to use tools
2	Commitment by the team and team leader to alter work habits and employ new tools
3	Corporate commitment to tool support and availability
4	Executive Support
5	Collaborative tool adoption assistance from inside the team
6	Clear team goals and deliverables
7	Clear (and perhaps documented) team processes
8	Collaborative tool facilitation assistance from outside the team
9	Clear team vision/mission statement
10	Agreed to “pain points” (most pressing problems) that team is attempting to address with collaborative tools
11	Critical mass of NASA people already using tools

19) Please list any challenges that made adoption of the pilot’s collaborative tools difficult, check all that apply:

Rank	
1	N/A
2	My team members were not able to commit enough time to learn features of the application
3	My team relied on, and only required, traditional/basic forms of communication - phone, email, fax
4	The leadership of my team changed
5	My team was reorganized
6	Our project lost funding
7	My team members do not see the value of using collaborative tools

20) Please rate the Support that you received during the Team Collaboration pilot.

Negative	2%
Neutral	30%
Positive	**76%**

21) A standard set of tools for team spaces and virtual team meetings (e.g., eRoom and WebEx) would benefit NASA.

Negative	2%
Neutral	12%
Positive	**86%**

22) My team/project/program/Center/enterprise would likely be willing to pay for these types of capabilities.

Yes	48%
No	52%

Appendix C
Acronyms

ASP	application service provider
BRT	Business and Restricted Technology Information
CIO	Chief Information Officer
EAR	Export Administration Regulations
eGOV	electronic Government (initiative)
FAQ	frequently asked questions
GOTS	Government off-the-shelf (software)
IT	information technology
ITS	Information Technology Security
ITAR	International Traffic in Arms
NPG	NASA Procedures and Guidelines
POC	point of contact
PSRP	Payload Safety Review Panel
SSC	support service contractor
SSL	secure sockets layer
TC	team coordinator
TF	team facilitator
TL	team leader

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13. ABSTRACT ***(Maximum 200 words)***

An Agency team collaboration pilot was conducted from July 2002 until June 2003 and then extended for an additional year. The objective of the pilot was to assess the value of collaboration tools and adoption processes as applied to NASA teams. In an effort to share knowledge and experiences, the lessons that have been learned thus far are documented in this report. Overall, the pilot has been successful. An entire system has been piloted—tools, adoption, and support. The pilot consisted of two collaboration tools, a team space and a virtual team meeting capability. Of the two tools that were evaluated, the team meeting tool has been more widely accepted. Though the team space tool has been met with a lesser degree of acceptance, the need for such a tool in the NASA environment has been evidenced. Both adoption techniques and support were carefully developed and implemented in a way that has been well received by the pilot participant community.

14. SUBJECT TERMS

Computer conferencing; World wide web; Information management; Communication

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X-43A
Lessons Learned

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Chief Engineer
NASA Langley Research Center

Brad Neal
Chief Engineer
NASA Dryden Flight Research Center

Hypersonic Lessons Learned Workshop
December 10, 2013
Arlington, VA

Program Objectives



- **X-43A project was designed to be the first ever flight demonstration of an airframe-integrated, hydrogen fueled, scramjet powered, hypersonic vehicle**
- **Gather flight data to validate the tools, test and analysis techniques, and methodology for designing scramjet powered, hypersonic vehicles**
- **Verify predicted scramjet performance**
- **Collect propulsion, aerodynamic, thermal, and structural data for future hypersonic vehicle design**

2

Project Overview

- Designed to be High-Risk/High-Payoff
- Three-flight Project
  - » 2 at Mach 7
  - » 1 at Mach 10
- Scaled version of a Mach 10 "cruise" configuration
- Air launched on a highly modified Pegasus booster
  - initially using same Orion 50S motor to minimize booster modifications
- 7 year project (1996 – 2004)
- ~ $230M investment
- ~ 220+ people worked the project at any given time



3

Project Team



4

Risk Management Approach

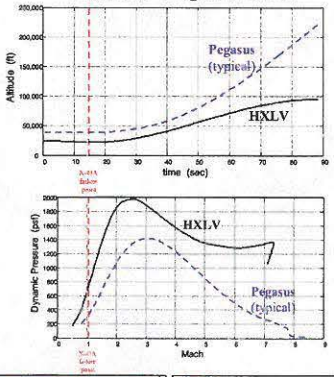
- Doing things that had never been done before
  - Many before we got to the experiment
- The program/project took all practical steps to minimize risks
  - Significant risks remained that were "inherent"
  - Most systems were single string
- Risks were mitigated to maximum practical extent by
  - Alternative approaches with down selection
  - Design for robustness
  - Extensive testing
  - Multiple internal and independent checks

5

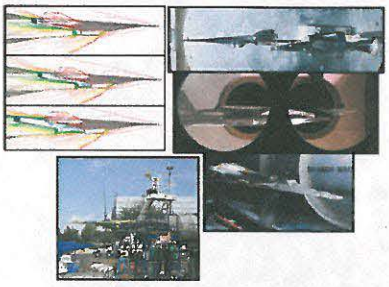
Risk Management Approach

Applied to…Never Done That Before!

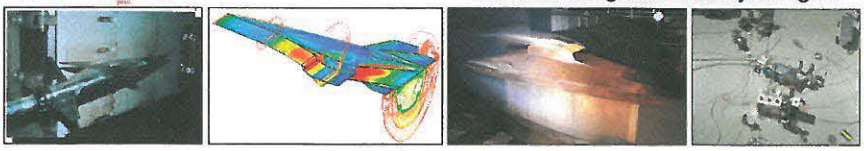
Booster Operation Outside "Normal" Flight Profile



High Mach/High q Non-axisymmetric Separation



Hypersonic Flight Powered by an Airframe-integrated Scramjet Engine



6

System Integration

Propulsion
- Fuel system
- Scramjet engine
- Propulsion control laws
- Environmental system



LV, Sep. & RV Sims
- GNC & PSC design & testing
- Monte-Carlo analyses
- Vehicle performance
- S/W & H/W testing
- HIL/AIL testing
- Mission control room training

Stage Separation
- Never been done
- High q, asymmetric bodies

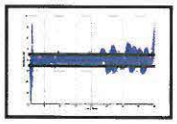


Systems
- Flight computers
- Actuators
- Power
- Software
- V & V testing





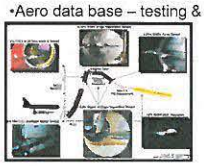
GNC
- LV, Sep. & RV control laws



Structures
- Aero & thermal loads
- FEM modeling
- Structural analysis & design



Aerodynamics
- Outer mold line design
- Aero data base – testing & CFD



Flight Operations
- Puts it all together
- Vehicle integration, fueling, flight, ground, & control room ops

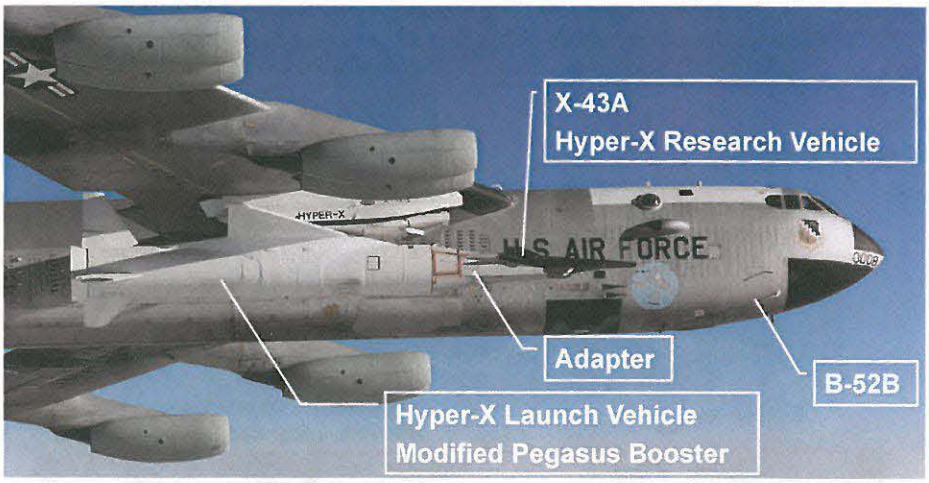


Launch Vehicle
- The ride to Mach 7 and 10
- Modified Pegasus booster



7

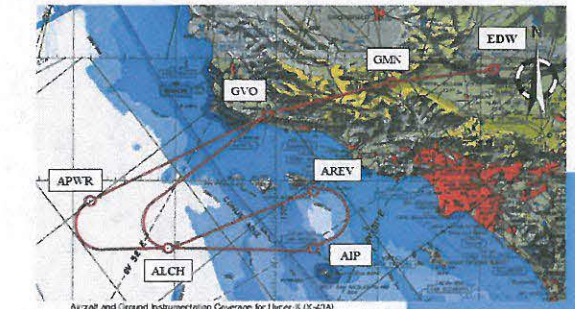
Flight Test System

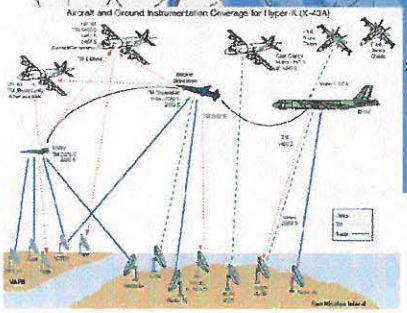


Stack = HXLV + Adapter + HXRV

8

Mission





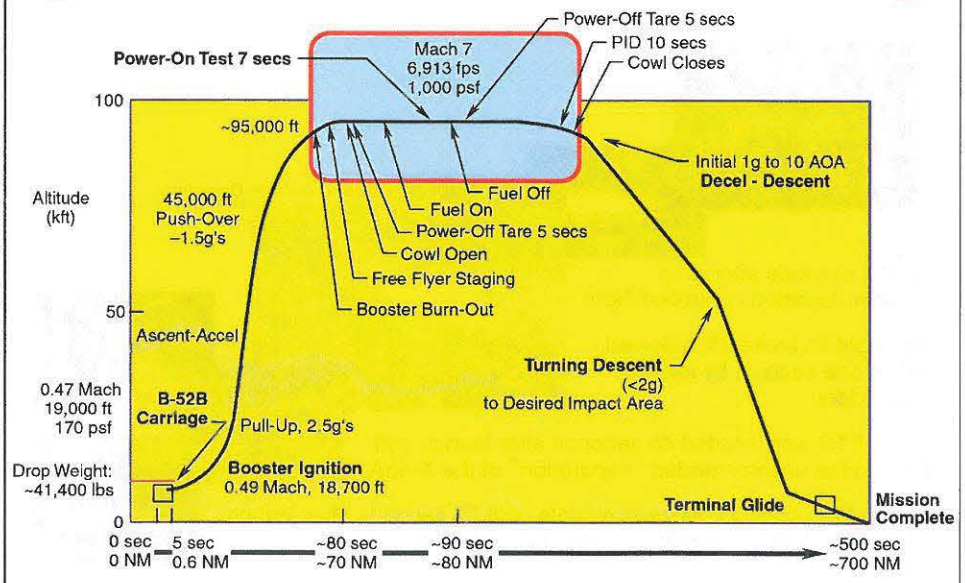


- 11 organizations
- 6 aircraft + Hyper-X Stack
- 2 ranges + FAA controlled space

- Days of Ground Ops and Coordination
- An hour plus to get to the launch point

9

Flight 1 Mission Profile

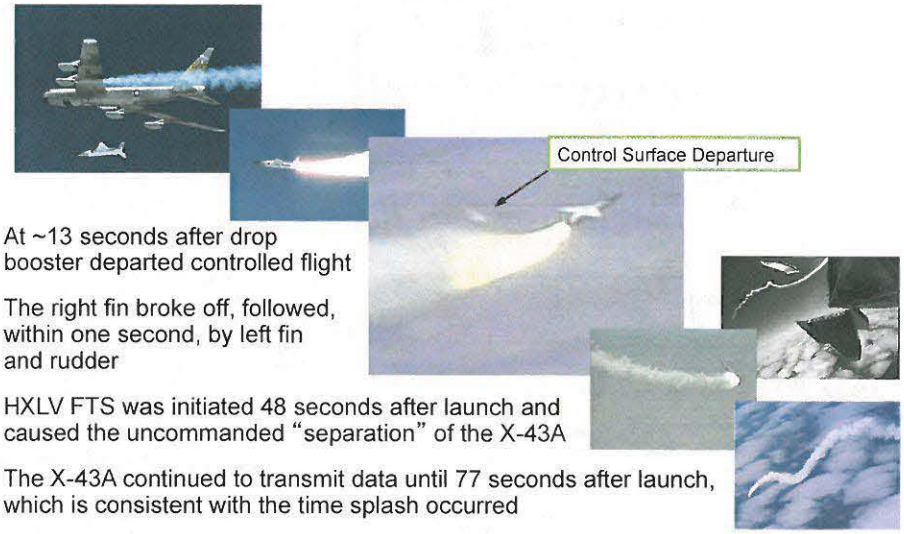


10



11

Flight 1 – June 2, 2001



At ~13 seconds after drop booster departed controlled flight

The right fin broke off, followed, within one second, by left fin and rudder

HXLV FTS was initiated 48 seconds after launch and caused the uncommanded "separation" of the X-43A

The X-43A continued to transmit data until 77 seconds after launch, which is consistent with the time splash occurred

12

Lesson Re-Learned

No matter how often you've done something...

No matter how experienced you are...

Things can go wrong!!!



* No actual beavers were harmed in the making of this slide

13

...9 months later

- Following the incident, the X-43A Mishap Investigation Board (MIB) was convened June 5, 2001 and ended March 8, 2002

"The X-43A HXLV failed because the vehicle control system design was deficient for the trajectory flown due to inaccurate analytical models which overestimated the system margins"

-- Root Cause MIB Report dated 3/8/2003

- Modeling deficiencies caused an over-prediction of autopilot stability margins:
  - Fin Actuation System Compliance
  - Launch Vehicle Aerodynamics
  - Mispredicted roll inertia (I_{xx})
- Over-prediction of fin actuator torque margin
  - Misprediction of aerodynamic hinge moments
- Other areas for improvement
  - Validation/Cross Checking/Reviews
  - Documentation
  - Workforce

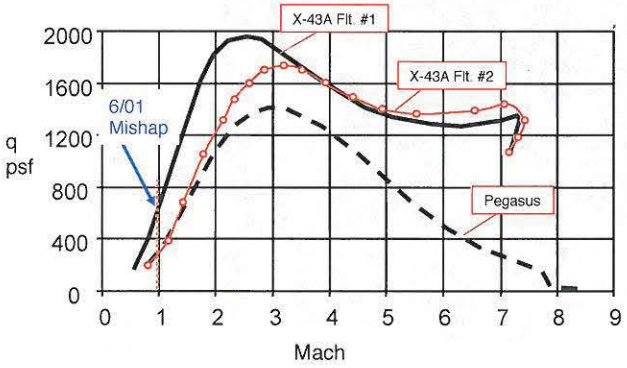
Additional detail on Flight 1 failure, mishap investigation and return to flight available at:
http://nescacademy.nasa.gov/video_catalog.php?catid=7 (search for X-43)

14

Return to Flight Approach

- **Review / improve all models for LV, Sep, & RV**
  - » Emphasis on the aero and FAS models
  - » 12 additional wind tunnel test runs
  - » Independent Simulations

More Pegasus Like Trajectory
40 kft and Mach 0.8



Too Little Torque



Dual Motor Actuator

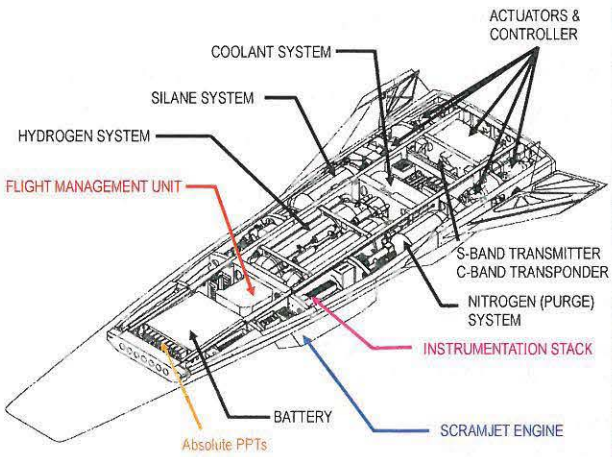
Too Much Energy



Propellant Offload

15

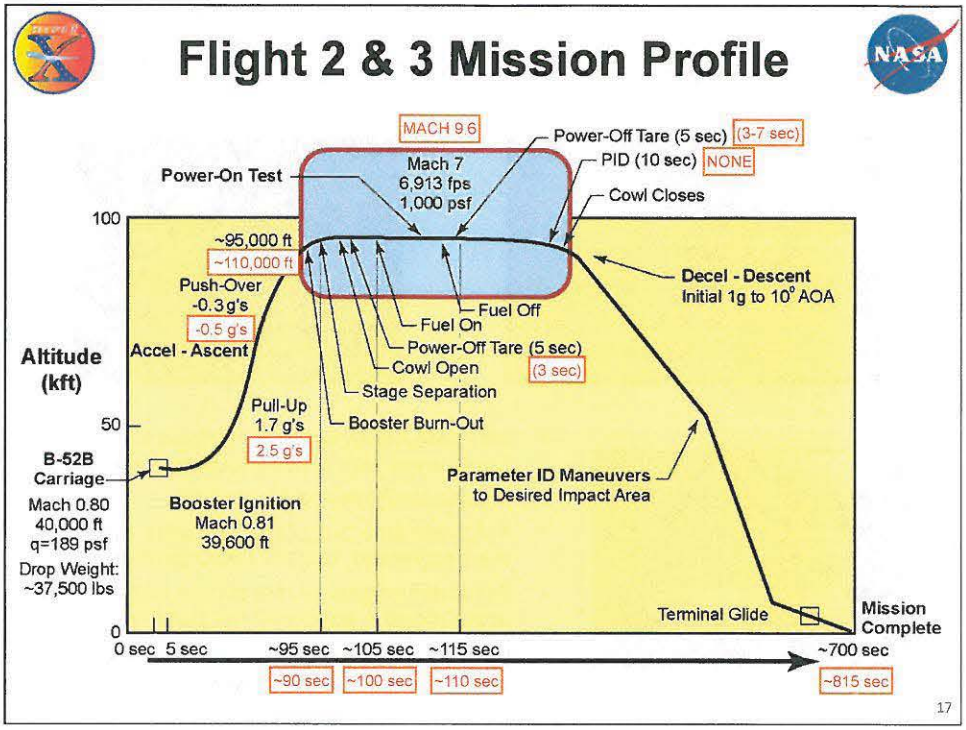
Return To Flight Approach



Research Vehicle

- Higher fidelity models
- Increase AOA for flameout robustness and greater thrust
- Upgrade engine control logic for unstart robustness
- Adapter fluid systems improvements
- Redesign of wing control horns
- Aircraft-in-the-loop timing tests
- Independent Simulation Review

16


Flight 2 & 3 Mission Profile
MACH 9.6
Power-Off Tare (5 sec) (3-7 sec)
PID (10 sec) NONE
Mach 7
6,913 fps
1,000 psf
Power-On Test
Cowl Closes
100
~95,000 ft
~110,000 ft
Push-Over
-0.3 g's
-0.5 g's
Decel - Descent
Initial 1g to 10° AOA
Fuel Off
Fuel On
Power-Off Tare (5 sec)
(3 sec)
Cowl Open
Stage Separation
Booster Burn-Out
Altitude
(kft)
Accel - Ascent
Pull-Up
1.7 g's
2.5 g's
50
B-52B
Carriage
Mach 0.80
40,000 ft
q=189 psf
Drop Weight:
~37,500 lbs
Booster Ignition
Mach 0.81
39,600 ft
Parameter ID Maneuvers
to Desired Impact Area
Terminal Glide
Mission
Complete
0
0 sec 5 sec
~95 sec ~105 sec ~115 sec
~700 sec
~90 sec
~100 sec
~110 sec
~815 sec
17


18

Flight 2 – March 27, 2004



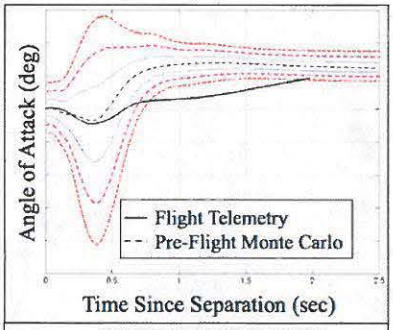


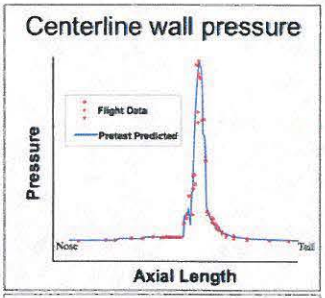


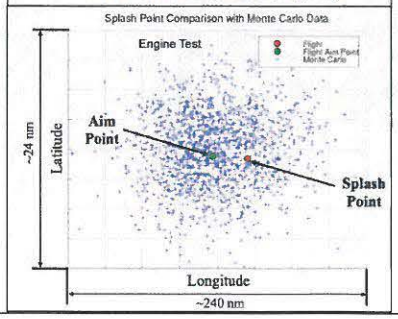
- All systems on both the LV and X-43A functioned well throughout the flight
- Maximum Powered Mach 6.83
- X-43 airframe drag (and lift) were higher than expected, but w/i uncertainties
- Scramjet engine performance within 3% of predictions – achieved net positive thrust
- Data quality was very good and acquired all the way to splash down

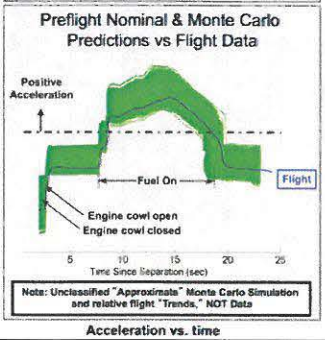
19

Mach 7 Flight Data









20

Flight 3 Approach

- The Flight 3 hardware was worked in parallel with Flight 2
- Final models and analysis were not available until after Flight 2 and initial post-flight analysis was complete
- Quick turnaround, goal for flight was 6 months after initial model release in early April
  - Capitalized on recent Flight 2 experience and Return-to-Flight Approach
  - Team remained mostly intact
  - Tests and procedures went faster than they did for flight 2
- Assumptions
  - Do very little independent analysis (i.e. no duplication of effort)
  - Look at Flight 2 data to determine what Flight 3 modification would be necessary for success
  - Models would not be updated based on flight data. The flight data would be used for guidance for modifications and for stress cases
  - Engine test region was primary objective and therefore was the highest priority
- Flight 3 approach was success oriented and assumed no major issues

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Flight 3 – November 16, 2004









- **All systems on both LV and X-43A performed well throughout the flight**
- **Maximum powered Mach 9.68**
- **During engine operation the vehicle achieved cruise condition, sustained thrust equal to drag**
- **The data collected during the engine test was by far the largest amount of data acquired for a Mach 10 scramjet. The quantity, quality, and type of the data acquired is well beyond what had been acquired in wind tunnels**

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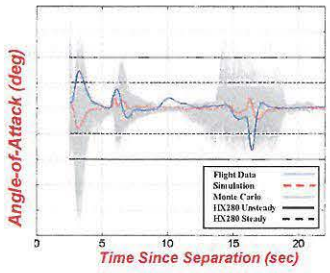
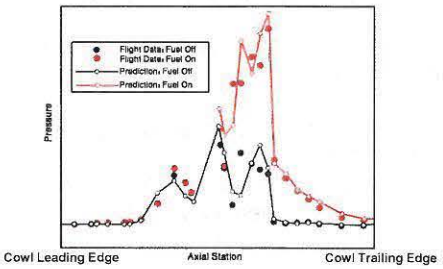
Mach 10 Flight Data

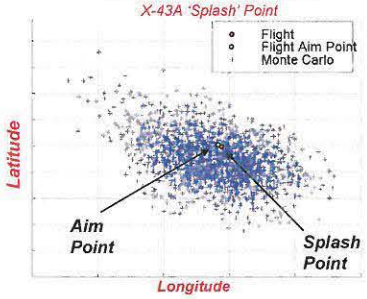
Angle-of-Attack During the Engine Test



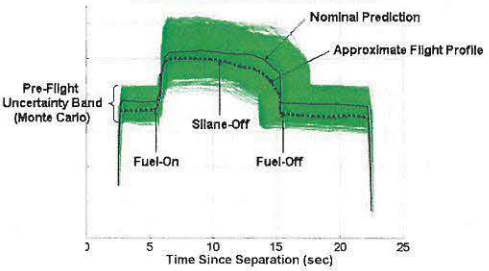
Flight vs. Pre-flight Propulsion Database



X-43A 'Splash' Point



Axial Acceleration Profile During Engine Test



23

Programmatic Lessons

- Development Program?
  - 2 (initial cost) and π (initial schedule)
- Communicate, communicate, communicate
- Define and agree to organizational roles and responsibilities before activity begins
  - The more organizations the more important this becomes
- Define and agree to program objectives and success criteria early
  - However review them regularly as you do learn things along the way

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Programmatic Lessons

- Co-locate a core team of key stakeholders
  - The location(s) may change throughout the life of the program
  - More information transfer tends to happen in the hallway than on telecons
- Strive to maintain the team
  - Replacing team members in the middle of a smaller, fast moving program will have impact
- Use established program management tools and processes
  - Innovation here AND with the technology makes life really difficult
  - Remember…They work for you, Not you for them

25

Systems Engineering Lessons

- Define and agree to design and operational standards early
- Ensure appropriate focus at the interfaces
  - Hardware
  - Disciplines
- COTS
  - For a development program there is no shelf
  - Heritage parts used outside of their intended/proven application - even slightly - don't have a heritage
  - Arrange for vendors of critical hardware/software to be on site during testing

26

System Engineering Lessons

- Identify test and flight safety requirements early and integrate them
  - Remember the unmanned system may not always be unmanned
- Test what you fly…Fly what you test
  - But try not to use the flight hardware as the test article
  - Ground tests can be more strenuous to the hardware than the flight
- Define and agree to clear test and success requirements
- Review ALL test data
  - You may learn things even in a nominal test

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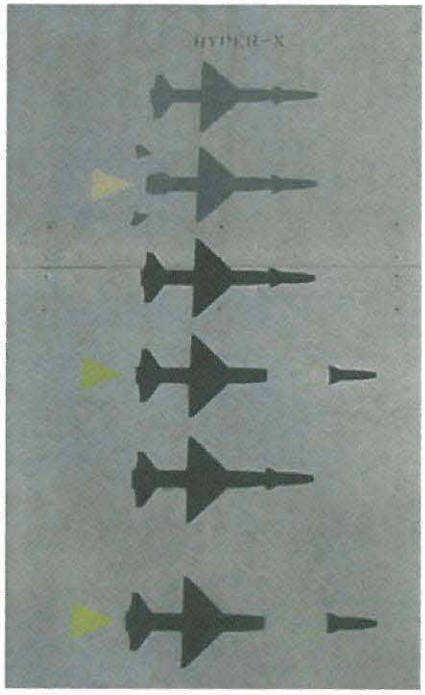
Operations Lessons

- Plan for vehicle maintenance
  - Removing all vehicle systems to work on the top of the engine is not efficient
  - Spares can make you or break you
- Maintenance and operations procedures are also a development effort…treat them as such
- When you have limited operations using all system assets with "Feast or Famine" timelines
  - Plan for dedicated training opportunities
  - Treat every system test as a mission training opportunity
  - Conduct nominal and off-nominal Missions simulations with all organizations

28



Questions ?

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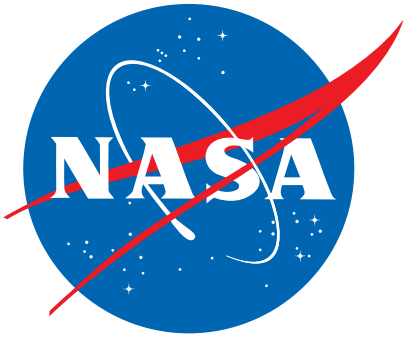

National Aeronautics and Space Administration

Armstrong Flight Research Center
Edwards, CA 93523-0273

X-57 Maxwell

Lessons Learned Report

LL-CEPT-025

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Date: December 20, 2024

Approved By:

Heather Maliska AFRC / 310 Date
X-57 Subproject Manager

Vincent Schultz 02/11/2025

Vincent P. Schultz LaRC / E1A Date
X-57 Deputy Subproject Manager



X-57 Lessons Learned

Revision History

REV	DATE	DESCRIPTION	AUTHOR
-	2/23/2024	Initial internal release	Vincent Schultz, Herb Schlickenmaier
A	12/20/2024	Editorial changes and cleanup for public release, updated scope statement and introduction, added best practices for knowledge transfer.	Heather Maliska, Vincent Schultz, Sean Clarke, Nick Borer

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1 Introduction

1.1 Scope

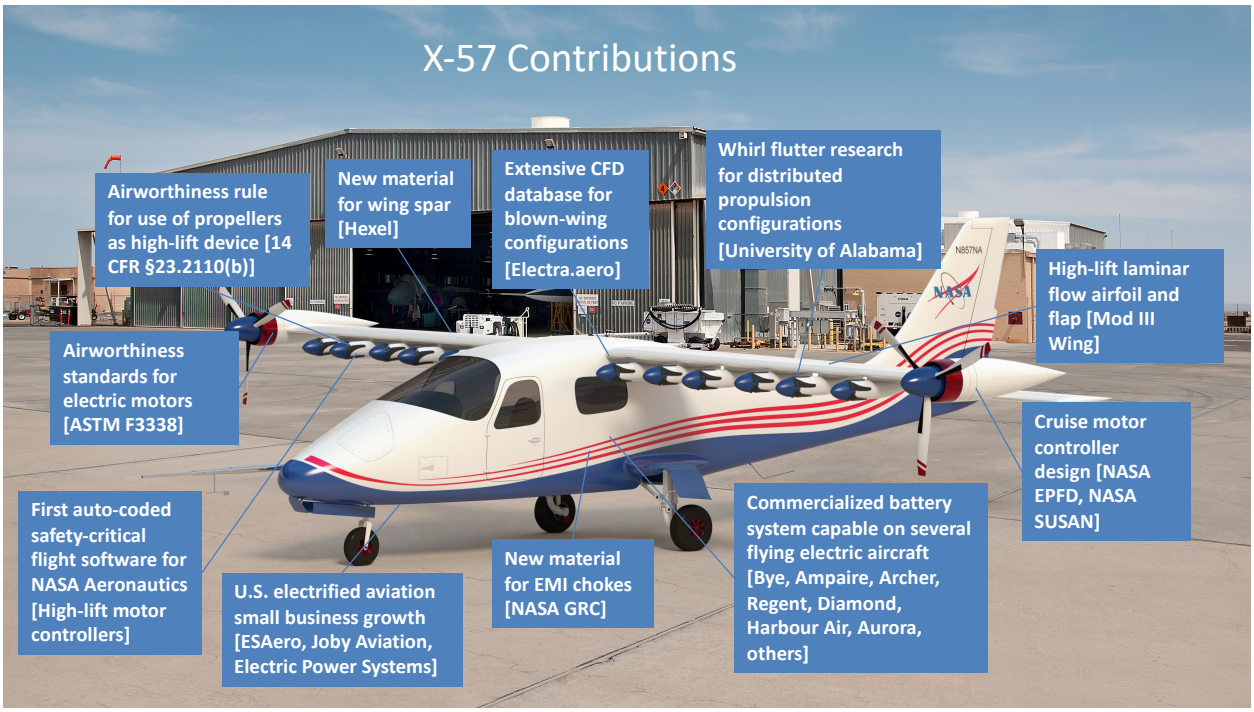
HS Advanced Concepts LLC was contracted to conduct in-person and remote interviews with subproject team members and key stakeholders to collect Lessons Learned and Recommendations related to the technology development challenges encountered during the development of the X-57 subproject. After conducting the interviews, HS Advanced Concepts provided a report and summary of the findings to the X-57 subproject leadership team. The X-57 team took the report and distilled it into the lessons learned and recommendations documented in this report. As the X-57 subproject has closed out, carefully collecting and cataloging key Lessons Learned within the technology maturation process used during X-57 execution is critical to inform future project management best practices and advance standards development in support of electric propulsion.

1.2 Lessons from Ten Years of X-57-Related Research

The goal of the X-57 subproject was to advance the Nation's ability to design, test, and determine airworthiness of distributed electric and aero-propulsive coupling technologies, which are a critical enabler of emerging, advanced air mobility markets. The value of X-57 lies in advancing the Nation's ability to design, test, and certify electric aircraft, which would enable entirely new markets. Mods III and IV had the intention of exploring the benefits of Distributed Electric Propulsion (DEP) which would revolutionize aircraft architecture and performance. Despite not achieving flight, the focus of achieving flight enabled the team to gather and share relevant lessons and data with industry and regulators. Maintaining flight as an objective drove testing and analysis rigor that led to more discovery. The impact of the X-57 lay not in what was originally set out to achieve but was evidenced by the identification of technology and certification gaps in industry and the need then to address those gaps. The identification and resolution of addressing gaps allowed for lessons to be shared early and often with industry and standards bodies and these lessons have been foundational to electrified propulsion. The X-57 subproject had aided in building the US electrified aircraft industry and has enabled commercial products. Figure 1 provides a summary of a handful of the contributions that X-57 has made to electrified aviation[1].

[1] H. Maliska, S. Clarke "X-57 Subproject Overview and Evolution," Spring meeting of ASTM Committee F44 on General Aviation, Cologne, Germany, April 2024. Available at https://ntrs.nasa.gov/citations/20240003363

Figure 1, X-57 Contributions



As compared to the level of NASA investment, the X-57 contributions have been substantial. The subproject elevated the Technology Readiness Level (TRL) of components leading to integration with flight performance specifications. By taking the publishing approach of 'early and often', the subproject shared design tools, component and subsystem test data and operational lessons learned with academia and industry. The X-57 published architecture is a principal reference for academia and standards development. The design and test standards and lessons learned are being adopted and the impact on regulations and standards is ongoing as operational constraints drive further learning. Additionally, the X-57 contractor and subcontractors grew, in part, because of X-57. With this, the X-57 has achieved the goal of advancing the Nation's ability to design, test, and determine airworthiness of electrified aircraft technologies.

The X-57 subproject began by leveraging NASA's Leading Edge Asynchronous Propulsion Technology (LEAPTech) effort, which was funded under an Aeronautics Research Mission Directorate (ARMD) Team Seedling award. LEAPTech focused on a ground test of the low-speed aerodynamic qualities of a wing designed for a uniquely novel vehicle concept of Distributed Electric Propulsion (DEP) to enable a more efficient cruise design. The X-57 subproject began in NASA's Convergent Aeronautical Solutions (CAS) project of the Transformational Aeronautics Concepts Program (TACP) with the goal of completing the LEAPTech ground test and advancing the DEP concept into a flight vehicle. This activity was known as the Scalable Convergent Electric Propulsion Technology and Operations Research (SCEPTOR) effort within CAS, which included flight of vehicles using a spiral development process in what were known as Mods I through III. As the scope of the effort grew, the activity transitioned to become a subproject of the Flight Demonstrations and Capabilities (FDC) Project within the Integrated Aeronautics Systems Program (IASP) and became known as the X-57 flight research vehicle. Mod IV, which integrated all the DEP concepts into a flight vehicle, was

added to the FDC X-57 subproject in 2017. An overview of the planned test vehicles associated with each of these activities is shown in Figure 2, and a timeline of the X-57 subproject is shown in Figure 3.

Figure 2, Test Vehicle Scope for X-57 Subproject and Precursor Activities

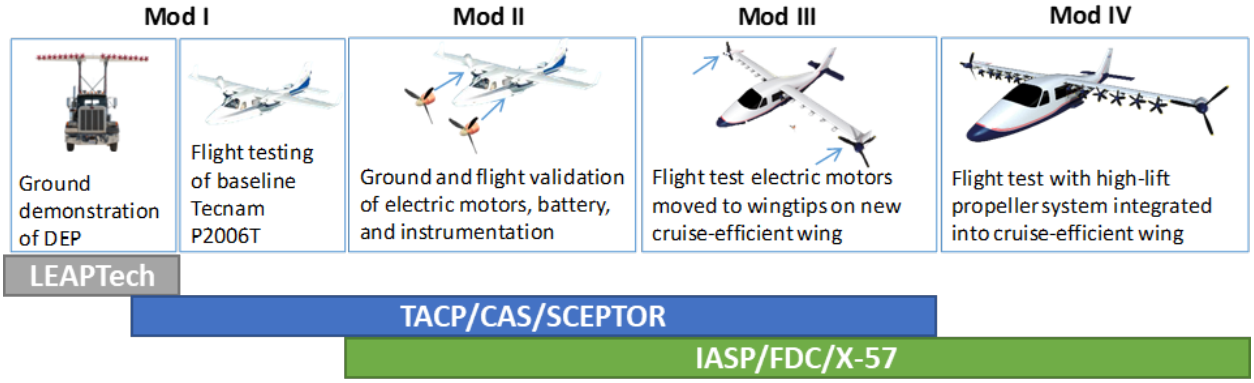
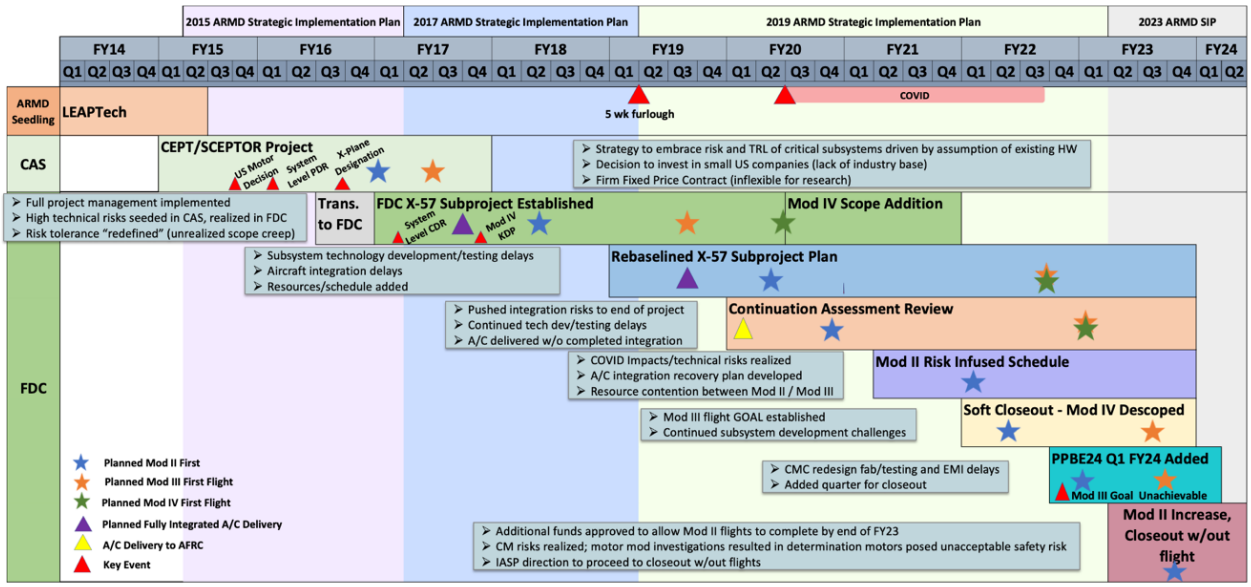


Figure 3, X-57 Timeline from LEAPTech to Close-Out

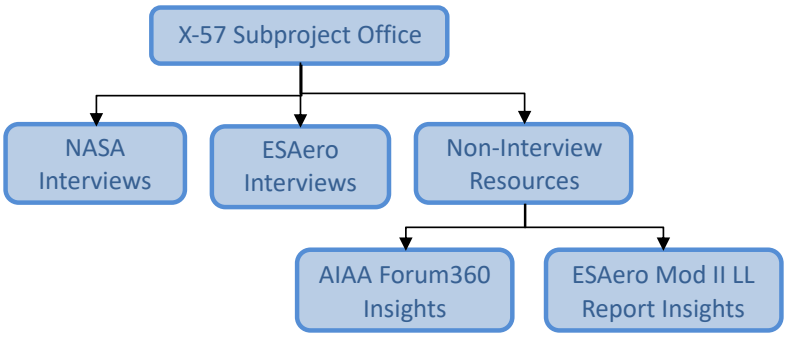


The X-57 subproject scope evolved throughout the lifecycle due to technical challenges, resource limitations, and changing stakeholder and industry needs. Throughout the effort, the team worked diligently to advance the state of knowledge and technology of electric aircraft subsystems and DEP, principally aiding in the development of industry standards.

1.3 Overview of the Lessons Learned Approach

Interviews were conducted with X-57 staff, both past and present staff members. These interviews were augmented through the extraction of lessons gathered from relevant reports (e.g., the AIAA AVIATION 2023 Forum 360 Panel on Lessons Learned, which discussed at a high level several lessons learned). Figure 4 illustrates the breadth of the approach used.

Figure 4, The X-57 Lessons Learned Approach



Consolidating the comments and insights from the breadth of interviews led to a recognition of common themes across the set of interviews. To help organize the key takeaways from the interviews, the team decided to organize around the following approach:

- Identify a key event and its resulting impact on the subproject.
- Document the key lesson or takeaway.
- Identify a relevant and actionable recommendation.

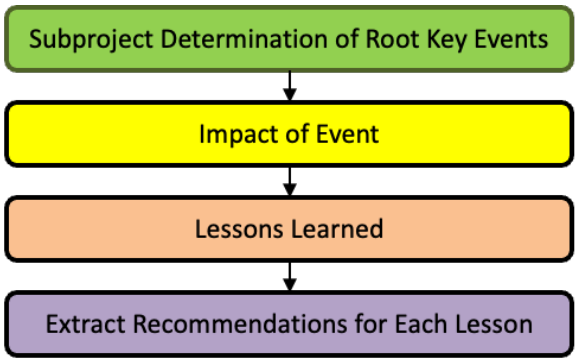
This resulted in the flow as outlined in Table 1.

Table 1, Terminology Used to Organize the Lessons

Term	Description
Driving Events:	A situation or decision leading to the lesson.
Impact of Event:	Consequences of event (things to avoid or embrace in the future).
Lesson Learned:	Lessons learned based on events and the associated ramifications of the events.
Recommendation:	An actionable proposal to address the lesson learned.

Figure 5 illustrates the hierarchy of the four terms starting with the driving event, to impact of the event, the lesson, and its recommendation. It also shows the color coding used throughout this report for the four characteristics.

Figure 5, Terminology Flow Down and Color Coding Used in This Report



2 X-57 Subproject Key Events, Impacts, Lessons Learned, and Recommendations

There are nine root key events that were distilled from the interview data by the X-57 subproject leadership team. The key events are listed in approximate chronological order.

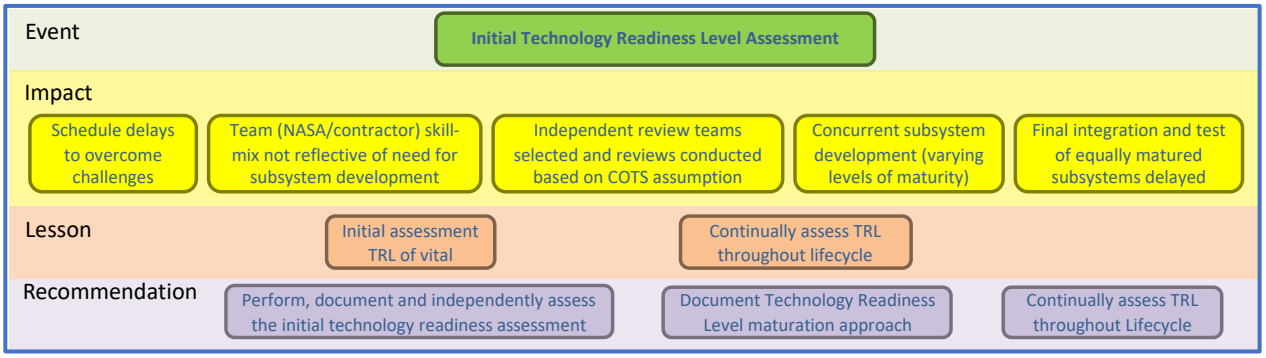
- Initial Technology Readiness Level Assessment
- Firm-Fixed Price (FFP), Phase III Small Business Innovative Research (SBIR) Contracting Mechanism
- Directed to Use US-Based Companies
- Using Small Companies with Limited Experience in Manned Flight Projects
- Subproject Transition from CAS to FDC
- Evolution of Advanced Air Mobility Community Needs
- Always a Year from Flight
- X-Plane Designation
- Take More Risk

In the following sections, each event, followed by the event's impacts, lessons, and recommendations will be described.

2.1 Initial Technology Readiness Level Assessment

At the start of this effort the Technology Readiness Level (TRL) of subsystems necessary and available to NASA to electrify the aircraft was assessed to be at a much higher level than they were in practice. Figure 6 summarizes the Impacts, Lessons, and Recommendations associated with the "Initial Technology Readiness Level Assessment" Event.

Figure 6, Initial Technology Readiness Level Assessment



2.1.1 Initial Technology Readiness Level Assessment Event

The initial NASA technical team was comprised of Subject Matter Experts (SME) in the development of Distributed Electric Propulsion (DEP) technology. The original approach planned to use "best-in-class" available components, as the project was not seen as a technology development effort, but rather an integration effort.

The initial assessment of the TRL for the required subsystems became a foundational cause and driving event for how the X-57 subproject was communicated, scoped, and formulated throughout its development. The initial assessment of TRL implied subsystem development did

not need to be accomplished as part of the execution plan, largely based on the existence of and assumed ability to access overseas flight-proven hardware. Therefore, a baseline plan for cost and schedule was developed, assuming that funding and time were not needed to develop subsystems. The schedule and budget were formulated under this overarching assumption. Likewise, the subproject personnel were selected to develop and integrate a wing featuring a Distributed Electric Propulsion (DEP), not to develop the individual subsystems necessary to electrify an aircraft. As a result, few risks relating to subsystem development were identified. Accordingly, no mitigations or reserves were identified.

However, the direction from senior ARMD leaders at NASA HQ was for the subproject to use technology available from the US industry only ("buy American"). When that direction was given, the project may have benefitted from reassessing the TRLs of American components (see the "Directed to Use US-Based Companies" event). During subproject execution, it became apparent that the actual TRL for the subsystems was significantly lower than anticipated, and recovering from this mismatch in planned versus actual TRL resulted in significant challenges for the subproject. This had a lasting impact that led to schedule delays and cost impacts throughout the lifecycle of the subproject.

2.1.2 Impacts of the Initial Technology Readiness Level Assessment Event

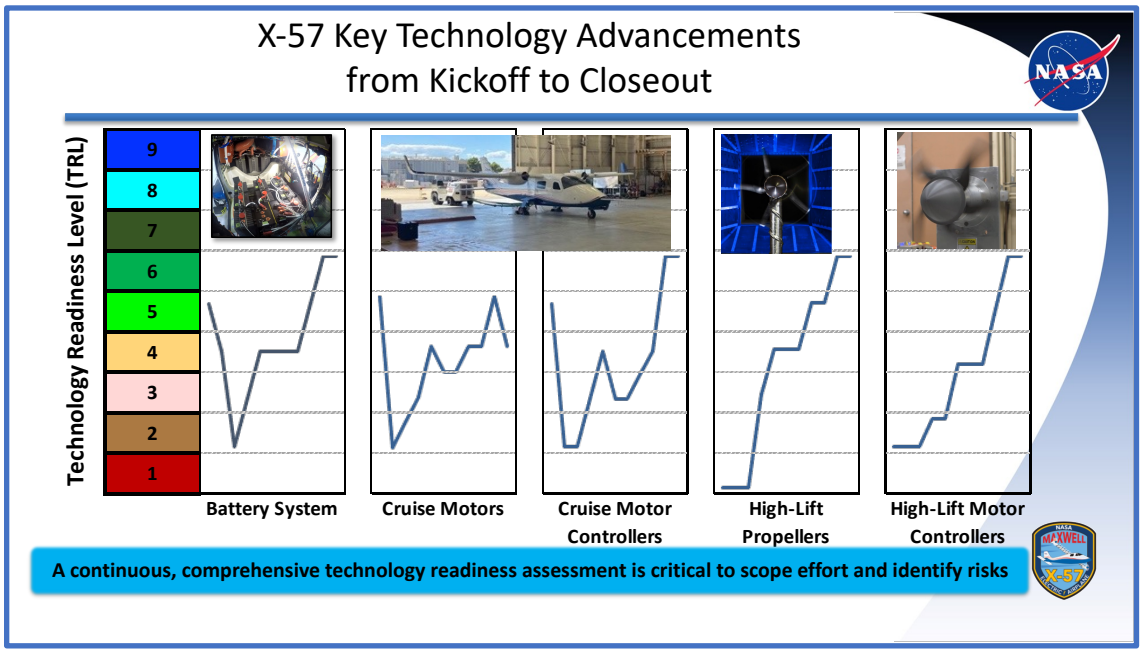
The subproject experienced schedule delays in overcoming technical challenges encountered due to lower-than-assessed TRL for major components of the Traction System - Cruise Motors / Cruise Motor Controllers; Battery Control Modules; and Mod IV High-Lift Motor Controllers (HLMC). Each of these subsystems had to be redesigned as the hardware and software either delivered or planned to be delivered were not at a sufficiently high TRL to support integration and test, let alone flight.

In addition, the team skillset was not originally scoped to resolve subsystem development challenges. The NASA and contractor skillsets were aligned to support the integration of market-available DEP components. There was a recognition of the need to design and fabricate a revolutionary new wing design to support DEP, and those skillsets were made available to the team early on. However, initial expertise was also needed for what turned into major subsystem development.

Independent review teams were selected, and reviews were conducted, but these reviews assumed that existing technology/hardware was already available for use. As a result, subsystem design reviews were not conducted, and independent assessments of Technology Readiness Levels (TRL) were not conducted following the realization of technical challenges.

To address the challenges associated with the TRL Assessment event, the project embarked on development of several subsystems, first serially and then in parallel as the scope of the challenges became evident. The required parallel development of several subsystems increased the technical risk and impacted the readiness of other mature subsystems. Figure 7 below indicates the progression of TRL on each of the indicated subsystems over the life of the subproject. While it was intended to develop the high lift systems for Mods III and IV, the development of battery systems, cruise motors and cruise motor controllers was not intended at the start of the subproject.

Figure 7, X-57 Technology Readiness Level Advancements



As a result of the unplanned subsystem development work, the final integration and test of matured subsystems was delayed, which increased the probability of additional schedule and cost impacts being realized late in the subproject with an inability to overcome realized integration risks (as no additional schedule or funds were available). Specifically:

- The Battery Control Module (BCM) redesign and delivery delays delayed key ground testing on internal power, which did not begin until mid-way through 2021.
- The Cruise Motor Controller (CMC) redesign delayed discovering and understanding the extent of the on-aircraft EMI challenges.
- On- and off-aircraft testing of the Cruise Motors identified further design deficiencies.

2.1.3 The Lessons Learned from the Initial Technology Readiness Level Assessment

Initial assessment of TRL is vital to scope and baseline the subproject approach and resources properly, as it sets the baseline risks, informs cost and schedule, and is foundational for formulation.

Continually assessing TRL throughout the subproject lifecycle provides an opportunity to assess health and adjust to challenges that occur. It should be triggered after technical challenges and at each lifecycle review.

2.1.4 The Recommendations Resulting from the Initial Technology Readiness Level Assessment Event

It is recommended that the initial technology readiness assessment be performed, documented and independently assessed. It is critical to assess where the technology is starting from (baseline) and have that assessment independently reviewed.

Document a technology readiness level maturation approach. One key to project success is to develop an achievable approach that couples with and accounts for airworthiness requirements with the intent to level-set the programmatic, technical, and safety risks. It is also important to

maintain and control the configuration of the technology readiness level maturation approach and update it when TRLs are changed or in some way impacted.

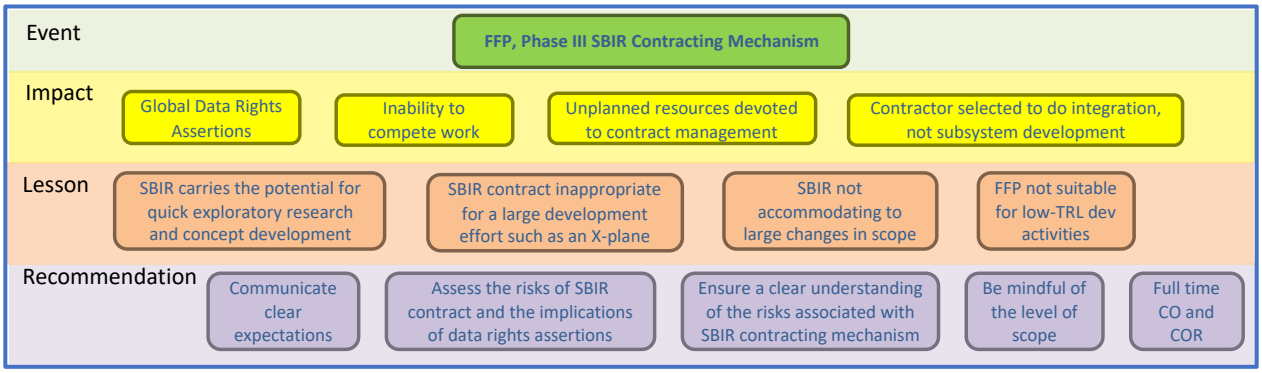
Continually Assess TRL Throughout the subproject Lifecycle is further recommended. At a minimum, the TRL assessment should occur at each subproject lifecycle review, assessing its impact on cost and schedule. At lifecycle reviews, the project team should consider the following questions and recommendations, at a minimum:

- Have subsystem development tasks been added that imply that a critical subsystem is at a lower level of maturity than was in the previous plan?
- Is there an impact on integration and test plans?
- How do the programmatic risks change as a result of changes to TRL?
- Does the skill mix of the team reflect the current TRL and any potential impacts on other subsystems?
- In addition to assessing TRL at the Lifecycle Reviews, be attentive to changes that occur due to technical challenges that arise during a subproject's lifecycle.
- For both the lifecycle review and changes due to technical challenges, the TRL assessment should be independently reviewed, and an assessment of the impact of changing TRL on one subsystem to the resulting TRL of the integrated system.

2.2 Firm Fixed Price, Phase III SBIR Contracting Mechanism

Use of the Firm Fixed Price (FFP), Phase III Small Business Innovative Research (SBIR) contracting mechanism provided access to technology quickly and provided a faster contracting mechanism. Figure 8 summarizes the Impacts, Lessons, and Recommendations associated with the "Firm Fixed Price, Phase III SBIR Contracting Mechanism" event.

Figure 8, Firm Fixed Price, Phase III SBIR Contracting Mechanism



2.2.1 The Event that Triggered the Firm Fixed Price, Phase III SBIR Contracting Mechanism Lesson

SCEPTOR's selection as a "directed" activity in CAS (noting CAS itself was a new ARMD project in 2015 looking into new business models at NASA favoring venture capitalist-style approaches to selecting a portfolio of high-risk/high-reward efforts) did not allow time to accommodate a full and open procurement. Furthermore, the nascent stage of the U.S. market in electrified aircraft meant that the established domestic supplier base did not yet have the capability and/or interest in such a procurement. A sole source Phase III SBIR following the sole

source Phase II SBIR was therefore appealing and favored the intent to build up the US small business electric aircraft industry.

The SBIR Phase III Indefinite Delivery Indefinite Quantity (IDIQ) Contract was awarded to the contractor as a follow-up to the Phase II effort. The FFP contract mechanism did not provide sufficient incentives for on-time deliverables.

2.2.2 The Impact of Experiencing the Firm Fixed Price, Phase III SBIR Contracting Mechanism Event

Data rights became an increasing challenge as the subproject progressed and as challenges (both contractual and technical) arose. The contractor did not initially choose to assert SBIR data rights on most deliverables, and NASA was able to share the information freely with the public or other support contractors without issue. Later, the contractor chose to assert SBIR data rights for all deliverables. This caused tension with the contractor when the NASA team opted to bring some work in-house, since this occasionally required NASA to share marked data with NASA support contractors. NASA's legal team determined that NASA could share SBIR data with support contractors who could then, in turn, support the X-57 subproject. This was at odds with the contractor's legal interpretation, which led to continued tension when working with internal NASA support contractors.

This evolved into challenges to compete or publish work due to concerns associated with data rights and derived data rights. The SBIR data rights limited NASA's ability to engage other external contractors to mitigate subsystem development risks. This resulted in an inability to maintain a flexible contracting approach to solving problems. NASA could either add scope (funding/time) to the contract (task order) or do the work in-house - both options of which posed challenges. Either the contractor did not have the expertise to do the work, and they would need to subcontract the work out (additional funding), or NASA did not have the skill set available within the X-57 workforce to solve the problem and would need to find additional funding to add the skill sets needed to the subproject and the time to find the appropriate personnel. The best solution, from a funding and schedule standpoint, would have been for NASA to find an external contractor with the appropriate expertise to solve the problem. The application of SBIR data rights and issues with derived information associated with these data rights limited this option.

The subproject realized more resources were necessary (from both NASA and the Contractor) to provide detailed Statements of Work (SOW), which were used to communicate detailed requirements and expectations. The Performance Work Statement (PWS) based task orders did not result in hardware that met the project needs, but SOWs were difficult to write for fundamental research when the requirements are not known *a priori*. Additionally, the contractor's minimal experience with aircraft hardware development drove a need to define requirements that reflected a developed subsystem. Later NASA SOWs that attempted to reconcile this lesson documented not only detailed requirements but also the means to meet these requirements.

The subproject conducted an acquisition strategy meeting to investigate potential new contracting mechanisms. Because of the contractor's SBIR data rights, contracting options were limited. An open competition for a new contractor was not an option. Thus, it was recommended and approved to allow for the contract to expire but to maintain the remainder of work on open task orders and potential new work to complete the contract via a new time and materials task order.

2.2.3 The Lessons Learned from the Firm Fixed Price, Phase III SBIR Contracting Mechanism

An SBIR contract carries the potential for quick exploratory research and concept development, but an SBIR contract is inappropriate for a large development effort such as an X-plane. For example, an SBIR may be a great opportunity for a small company to develop a sensor, leverage data rights protections to perfect that sensor, and later patent the sensor. NASA benefits from the ability to collect the data and publish what is collected from the sensor. In the case of X-57, the subsystem development needed to electrify the aircraft became the focus of lessons that the subproject wanted to share with regulators and the industry. The SBIR contract hindered the ability to share those developmental lessons.

SBIR contracts do not accommodate large changes in scope. Large changes in scope can reach beyond the SBIR contractor's ability and may drive the contractor to subcontract which will incur additional overhead and funding from the government. SBIR data rights of the original contractor do not allow the government the ability to seek a new contractor to resolve or accommodate changes in scope.

A Firm Fixed Price (FFP) contract is unsuitable for low-TRL development activities that are doing fundamental research. In the case of X-57, the subsystem development was not a part of the original objective of the subproject and became a necessity as the subproject worked to achieve the goal of DEP in flight.

2.2.4 The Recommendations Based on the Lesson from the Firm Fixed Price, Phase III SBIR Contracting Mechanism

Communicate clear expectations. Understand and provide clear expectations as to contracting mechanisms and their limitations. Although an SBIR contract, this Phase III SBIR held FFP task orders that required deliverables and deliverable dates based on requirements. The risk then falls on the contractor to estimate the work required to meet requirements at the proposal phase and then stay within their estimate. If the scope of work to meet the requirement exceeds their estimate, the contractor assumes that increase within the firm fixed price of the task order. NASA selected the SBIR contracting mechanism due to the perceived ease of making changes to accommodate shifting requirements. NASA needed to make clear to the SBIR contractor that NASA continued to expect the contractor meet the requirements of all tasks, even in the face of challenges.

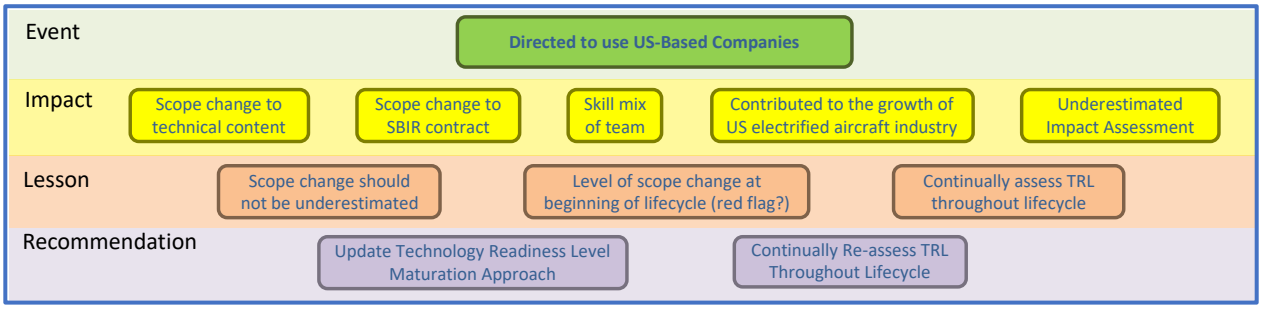
Consider generating a NASA document that clearly outlines data rights and data rights management at the time of subproject formulation. Establishing clear criteria for marking documents with the appropriate data rights – both from the contractor and any subcontractors – is best done at the beginning of the subproject, and periodically revisited for every major deliverable. Both NASA and the contractor should know and expect which elements of contractor-delivered and derived data should be marked, and how. "Proprietary" vs. "SBIR data rights" have different applications and management requirements.

2.3 Directed to Use US-Based Companies

SCEPTOR, under CAS, planned to use existing Cruise Motors (CM), Cruise Motor Controllers (CMC) and batteries from European manufacturers that had the highest technology readiness level aviation electric propulsion units in existence at the time. However, shortly into subproject execution, the team was directed not to purchase major subsystems from overseas manufacturers but rather to help build a U.S. industrial base in aviation electric propulsion. Figure 9

summarizes the Impacts, Lessons, and Recommendations associated with the "Directed to Use US-Based Companies" event.

Figure 9, Directed to Use US-Based Companies



2.3.1 The Event that Triggered the Directed to Use US-Based Companies Lesson

The CEPT team formulated the CAS activity with the assumption of reasonably mature aviation electric propulsion subsystems (CM, CMC, batteries) that had already been flight-proven, and were at a TRL of 5-6. The CEPT team's original tasks and composition were focused on integration of these systems to develop a DEP aircraft. The direction to source U.S. subsystems was intended by NASA senior management to better the US electric aircraft industry. However, the U.S. aviation electric components were generally at TRL 3, which meant they required technology development and aircraft integration technology development. This direction came after the prime contractor had been selected and the SBIR Phase III contract had already been put in place.

The unintended consequence led to substantial technology development efforts that the subproject was not scoped to handle. In addition, the SBIR contractor was challenged by a skill mix mismatched to developing/maturing new technologies vs. a heretofore expected technology integration effort.

2.3.2 The Impact of Experiencing the Directed to Use US-Based Companies Event

There was a major scope change to the technical content of the SBIR contract during execution. With the prime contractor having originally been selected for its integration experience, the change in scope reflected a new need for a capability that included subsystem development. The contractor did not initially have the capabilities necessary to resolve the technical challenges that were encountered.

The team did not have the necessary skill mix nor the appropriate plan and funding to support a development effort and had to quickly create a plan with very limited budget and schedule options while already in execution. For example, the plan to develop the CMs and CMCs – major subsystems – was developed and approved within about one month.

The initial impact assessment was underestimated on both cost and schedule, as well as both programmatic and safety risks. These impacts were compounded by other events described later in this document, such as the risk posture of the parent project (CAS) at the time of this decision that encouraged more aggressive and/or lean approaches to development.

2.3.3 The Lessons Learned from the Directed to Use US-Based Companies

Impacts of scope change should not be underestimated particularly early in the lifecycle of a project. The direction to use US-Based companies required a thorough review of its effect on the assumptions made within CAS, where a turnkey delivery of CMs and CMCs to be integrated on a novel DEP aircraft had assumptions about its technical objectives, schedule, and cost estimates. The change to a technology development effort for CMs and CMCs required a fundamental assessment of the impact of this change on technical, schedule, cost, and risks. A bottoms-up assessment of the effort to pivot to a US-based motor company was not done.

Continually assess TRL throughout the subproject lifecycle. A drop in TRL was an opportunity to reassess TRL and the impact of the change across the entire system. It was also a missed opportunity to revisit the acquisition strategy that had originally assumed global flexibility to use mature technology sources.

2.3.4 The Recommendations Based on the Lesson from the Directed to Use US-Based Companies

A change in scope that occurs during subproject execution should trigger a pause in execution and a thorough re-assessment of the impact of the scope change before proceeding. As noted later in this document, the rapidly evolving needs of an emerging market segment can lead to changes in subproject scope. Though it can be tempting to apply a "quick fix" to largely maintain previously approved schedule and budget estimates to completion, such large changes in scope warrant a pause in execution and re-evaluation of the project plan, and if necessary, the objectives to meet changing goals and needs.

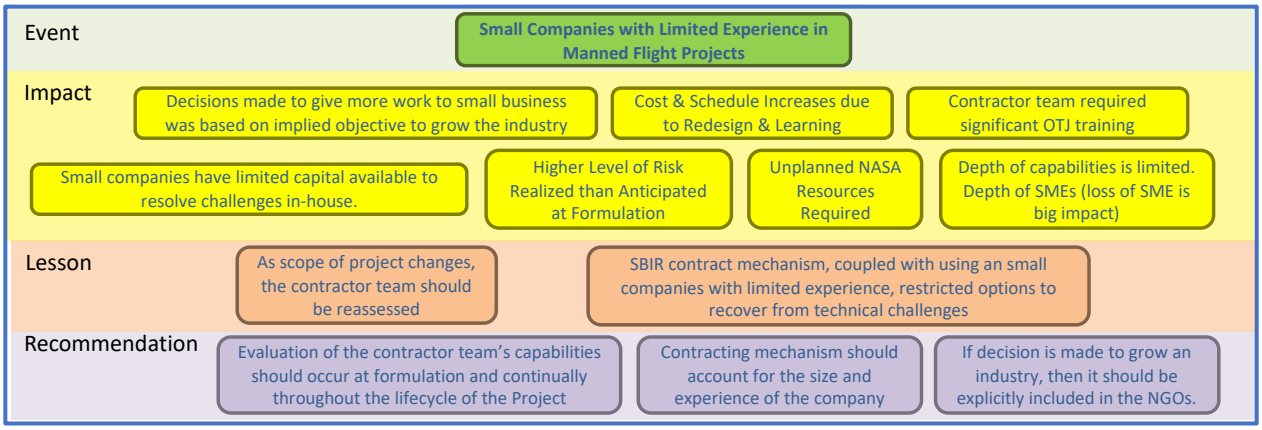
Continually assess TRL throughout a subproject's lifecycle. Reassess TRL and how the TRL maturation approach is affected. Revalidation of assumptions is a key to success (see more discussion of this in section 2.1, and specifically the associated recommendations in section 2.1.4).

Update the technology readiness level maturation approach as will be further discussed in section 2.1.4.

2.4 Small Companies with Limited Experience in Manned Flight Projects

In 2014 there were no mainstream US companies developing electrified aircraft concepts. A decision was made to use small businesses for the X-57 subproject. Figure 10 summarizes the Impacts, Lessons, and Recommendations associated with the "Small Companies with Limited Experience in Manned Flight Projects" event.

Figure 10, Small Companies with Limited Experience in Manned Flight Projects



2.4.1 The Event that Triggered the Small Companies with Limited Experience in Manned Flight Projects Lesson

NASA selected small companies with limited aerospace development experience to design, analyze, and integrate the aircraft. However, aerospace subsystem design, analysis, fabrication, and testing of manned flight vehicles is a domain where experience can be critical.

In addition to technical expertise, a company that is expected to develop, test, and provide a flight-worthy vehicle to NASA airworthiness standards needs solid quality assurance (QA) expertise. X-57's use of small companies without this expertise, although a great learning opportunity for the contractor, required a lot of support from NASA both in mentoring and development of a QA process which took time and impacted contracting.

2.4.2 The Impact of Experiencing the Small Companies with Limited Experience in Manned Flight Projects Event

The contractor required on-the-job training for technical and programmatic tasks. The contractor ran into challenges executing multiple task orders with similar periods of performance, particularly early in the project when the contractors had not built-up sufficient staffing in critical management areas. Additionally, while the recognition of working for NASA brought in additional business to the contractor team, this growth negatively impacted X-57 by drawing the contractor's and subcontractors' priorities away from X-57.

Out of necessity, NASA brought increased levels of subsystem development in house to meet schedule and budget. This induced additional cost and schedule increases to allow for redesign and learning.

The contractor's limited experience with flight systems suitable for manned flight drove the need to provide defined requirements that reflected a developed subsystem. This led to defining not only what work needed to be performed, but also "how" to do that work.

This level of engagement required more resources for the NASA team. Examples of these resources were not restricted to funding, but the application of QA by NASA to ensure quality of the developed subsystems as prototype vs. flight hardware. The result was that the contractor built up QA capabilities with NASA's mentoring. But the additional insight, oversight, mentoring, and training required more personnel. Additionally, the NASA subproject workforce

had to develop test capabilities to augment or establish capabilities that could not otherwise be met by the contractor.

Through the course of subproject execution, decisions were made to give more work to small businesses because there was a stated objective from NASA senior leadership to grow the electrified aircraft industry in the U.S., which, as an emerging market, was largely comprised of small businesses. Although not a formally documented objective of the subproject, the benefit of building up this domestic industry base was communicated by FDC/IASP/ARMD management to the X-57 team to be an unwritten objective.

The use of a small company had the side-effect that limited capital was available for that company to resolve challenges in-house. Additionally, the smaller workforce limited the depth of capabilities in each subject area. The loss of Subject Matter Experts (SME) by attrition proved to hinder the contractor as they worked to develop a recovery plan to backfill their loss.

The impact of using small companies with limited experience in manned flight projects drove a higher level of risk to be realized during execution of the subproject than was initially anticipated at the time the subproject was baselined within FDC.

2.4.3 The Lessons Learned from the Small Companies with Limited Experience in Manned Flight Projects

First, as the scope of a subproject changes, the contractor team should be reassessed. The X-57 contractor team was selected based on assumptions made during SCEPTOR formulation in CAS based on experience with electrified system integration and not subsystem development. The large change in scope to include development of critical subsystems should have led to a re-evaluation of the contractor team, subproject scope and resources and overall acquisition strategy.

Secondly, the SBIR contract mechanism restricted options to recover from technical challenges. Smaller companies do not tend to have access to funding reserves to recover from these challenges, and attrition within the company can leave it without a necessary skillset. Furthermore, by definition, the small company may not be able to access needed subject matter expertise from within when technical challenges arise in a new domain.

2.4.4 The Recommendations Based on the Lesson from the Small Companies with Limited Experience in Manned Flight Projects

It is recommended that an evaluation of the contractor team's capabilities occur at formulation and continually throughout the lifecycle of the subproject.

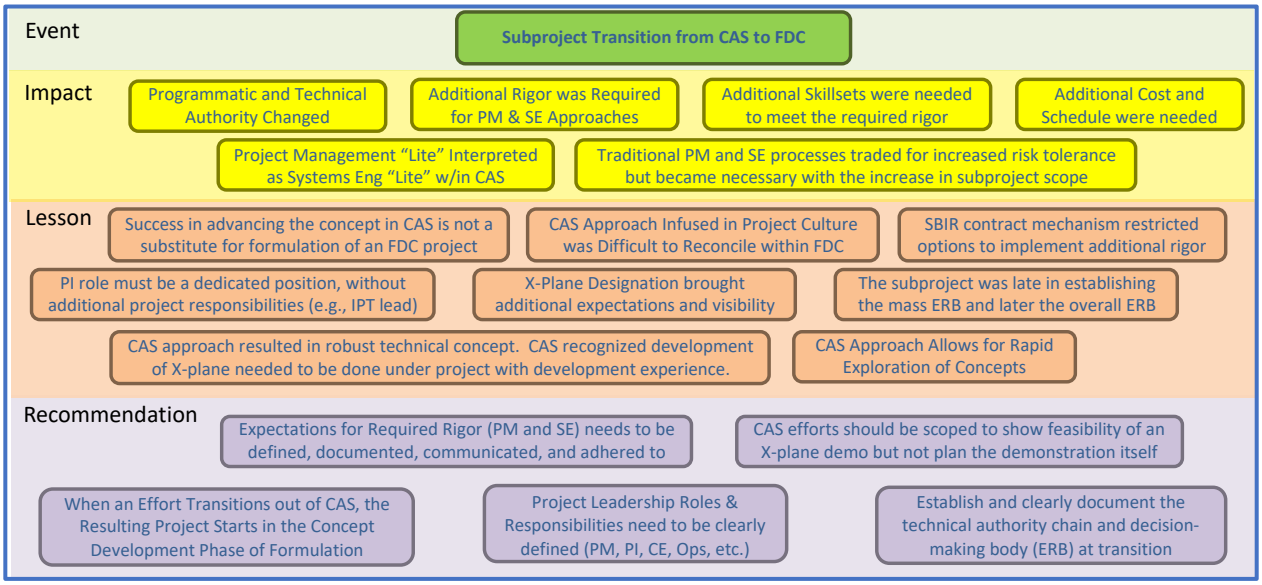
It is also recommended that the contracting mechanism chosen consider the size and experience of the company commensurate with the complexity of the technical challenges that will need to be overcome. For example, if a company does not have a quality assurance process, care should be taken in how the contracting mechanism is set up to work with this company and consideration given for how the lack of a quality assurance process affects the project's requirements.

If a decision is made to grow an industry, then it should be explicitly included in the subproject's Needs, Goals, and Objectives (NGO).

2.5 Subproject Transition from CAS to FDC

The SCEPTOR activity was developed within CAS in FY2015. CAS was a new ARMD project that was patterned after venture capitalist (VC) models of funding activities, in which multiple activities with higher levels of risk were encouraged in the hope that one would be successful. SCEPTOR was the first CAS activity to transition out of CAS into FDC and therefore it served as a pathfinder for transition of CAS activities into other programs and projects. After the CAS preliminary design review the subproject transitioned from CAS to FDC. The changes in project scope necessitated more resources than CAS could provide. FDC stepped through an assessment process and applied additional rigor and resources through a "Baseline Review" (using a bottoms-up approach). In 2017, a year into the execution of X-57 within FDC, Mod IV was baselined. The subproject was designated as an X-plane during the transition, which significantly raised its profile and visibility. Figure 11 summarizes the Impacts, Lessons, and Recommendations associated with the "Subproject Transition from CAS to FDC" event.

Figure 11, Subproject Transition from CAS to FDC



2.5.1 The Event that Triggered the Subproject Transition from CAS to FDC Lesson

The CAS project portfolio was inspired by VC models of development, in which prospective activities are "pitched" to CAS management rather than flowed down through the programs from NASA ARMD strategy (as is typical for other projects). This VC mindset extends to embracing risk. CAS management accepts high risk from a portfolio of several individual activities in the hope that one succeeds, whereas the traditional NASA process manages risks at the subproject level with the goal of ensuring every subproject succeeds. These differing risk postures pose challenges when transitioning from one risk posture to another. The management and mitigation of risks within FDC incurred a new level of scope and rigor that was not originally realized or accounted for at the time of transition. The technical and programmatic risks seeded in CAS were realized in FDC. The transition of a manned X-Plane into a flight subproject within FDC reset or "redefined" the risk posture to one of ensuring airworthiness of a manned X-Plane which, in turn, introduced additional programmatic rigor. The magnitude of scope, and thus rigor, was not initially identified at transition but was rather realized (i.e. scope creep) out of necessity

as challenges were encountered and plans to overcome the challenges were generated during subproject execution within FDC.

With the VC model in mind, CAS allowed its activities to streamline NASA processes in a way that likely increased programmatic and technical risk while maintaining the necessary level of safety. The SCEPTOR activity under CAS sought to develop a flight demonstrator with aggressive technology development assumptions, with zero reserves and tight resources, leveraging prime- and sub-contractors as the integrator of an electric aircraft with existing products. The X-57 risk posture under CAS accepted the approach of striving to fly lower TRL subsystems (TRL of 4 or 5), which further compounded risk when the initial, higher TRL electrical subsystems selected by the team became inaccessible early in the execution of the CAS portion of the project (see "Directed to Use US-Based Companies"). Other X-planes have advanced a handful of key technologies from TRL 5 or 6 to TRL 6 or 7. Ultimately, the X-57 subproject within FDC encountered several subsystem challenges that led to subsystem redesigns. Transitioning to FDC and having to meet its risk posture drove the need to develop the subsystems to a TRL 5 or 6 to accomplish flight.

2.5.2 The Impact of Experiencing the Subproject Transition from CAS to FDC Event

At transition, programmatic and technical authority changed. As in the approach in CAS the activity was focused on demonstrating the feasibility of the DEP novel concept vehicle. The CAS activity was led by a Principal Investigator (PI) who was responsible for (1) establishing and managing the project vision and objectives; (2) project planning, resource and contract management, and teaming; and (3) overseeing the technical decisions. In legacy NASA models, these roles are taken by three individuals, respectively: a PI, a Project Manager (PM), and a Chief Engineer (CE). For an effort as comprehensive as a manned flight demonstrator, reconciling these generally full-time roles to a single individual can lead to a "light touch" on traditional NASA PM and CE approaches. In the case of SCEPTOR, this led to a significant reduction in emphasis on the use of NASA legacy project management (project management "lite") and systems engineering (systems engineering "lite") tools and methods[2]. The transition from an integrated product team (IPT) based structure with decisions led by a PI to a traditional technical authority (that was CE-led) was slow and not well communicated within the team. Further, the technical authority chain was not clearly understood or communicated until much later in the subproject lifecycle (2020). Furthermore, throughout both the CAS activity and FDC subproject, the PI also held IPT lead roles, further diluting time and attention away from either leadership role.

It was found that although additional rigor in the areas of Project Management (PM) and Systems Engineering (SE) was applied at the time of transition from CAS to FDC, the scope (or magnitude) of that rigor increased further (out of necessity) as the subproject was executed within FDC. The level of rigor, amount of margin, and reserve allowance in cost and schedule estimates under the CAS subproject was not appropriate for an FDC flight project. The initial lean cost and schedule estimates set early expectations that followed the activity well after its transition to FDC. When a PM estimated cost in transition to FDC, the cost estimate doubled, which was hard for NASA senior management to accept. Similarly, the level of rigor applied to defining the Needs, Goals, and Objectives of the subproject was not appropriate for an FDC

[2] L. Kushner, T. Holtz, E. Baumann, C. Sales, "X-57 Systems Engineering Lessons Learned," AIAA Aviation Forum, Las Vegas, NV. Available at https://ntrs.nasa.gov/citations/20240006845

flight project and likewise impacted the system-level requirements. Although SCEPTOR's scope was a manned flight demonstrator, it was communicated as a lean and agile path to flight; during the initial CAS kickoff of the project, the PI indicated that the approach outlined by the SCEPTOR team could "streamline NASA design-to-flight process while maintaining safety."

As the risks assumed in CAS were realized within FDC (contracting, unplanned subsystem development), additional rigor (i.e. engineering review board, risk informed budget/schedule margin) was required for project management as well as systems engineering approaches to meet FDC expectations and requirements. Additional skillsets were then needed to meet this required rigor, ultimately requiring additional schedule and funding.

The VC approach within CAS fostered a project management "lite" path of management that was, as is discussed above, the responsibility of the PI. While a good approach for smaller scoped or unpiloted activities, for X-57 this project management "lite" approach led to a "lite" approach to systems engineering. Traditional PM and SE processes were traded for an increased risk tolerance but became necessary with the increase in subproject scope and change in subproject risk posture under the FDC project. It was difficult to insert traditional program management and SE processes at the critical design review phase of an "SE lite" subproject; the risk of scope increase was realized as FDC was executed and practiced with more rigor.

2.5.3 The Lessons Learned from the Subproject Transition from CAS to FDC

The CAS approach allows for rapid exploration of concepts.

The SCEPTOR management approach approved by CAS resulted in a robust concept; however, it was inadequate to apply this management approach to the development of a manned NASA flight demonstrator in FDC. Documenting and agreeing on a "tailored" airworthiness process at the start of the subproject helps baseline the scope of an effort required to prove the airworthiness of a piloted experimental aircraft.

Document the review process up front.

Clearly define the "tailoring;" and take a realistic approach to assessing the feasibility of the tailoring process to flight. This process allows for a baselining of what "…Take more risk…" means from a technical, programmatic, and airworthiness (safety) standpoint.

The CAS approach was infused into the subproject culture and was difficult to reconcile within FDC. Cost and schedule estimates in FDC should be developed by a subproject manager, who provides an "independent" assessment as well as the necessary experience to estimate what it takes to bring research objectives to reality. Even with a different risk posture, it would have been helpful to track risks within CAS activities to help aid in the transition to other larger subprojects, so that the appropriate level of mitigation planning can occur. This would have helped scope the subproject's schedule and cost estimates.

There was a recognition that getting a manned X-57 to flight and proving airworthiness combined with subsystem development was a much larger scope than CAS was chartered to handle. Thus, the decision was made to transition X-57 out of CAS and into FDC, which would implement more rigor and resources appropriate for a manned flight demonstrator development. The budget was adjusted to reflect schedule, labor, risk reduction, and subcontractor changes (reference section 2.3, "Directed to Use US-Based Companies"). However, they did not validate the transition assumptions from one subproject to another.

The success in advancing the vehicle concept in CAS is not a substitute for formulating an FDC subproject that includes the required artifacts for a manned NASA flight demonstrator. The SCEPTOR activity in CAS clearly had a lot of success early on when proving the feasibility of DEP within CAS. The transition to FDC may have benefitted from going through a true project formulation Key Decision Point (KDP). A KDP is a decisional review that serves as a gate through which programs and projects need to pass to continue through their life cycle.

Implementing additional rigor was further restricted because of the SBIR contract mechanism that was selected. This induced scope creep and, although intended as mentoring, was interpreted by the contractor as unwanted oversight and incurred additional documentation.

The PI role must be a dedicated position without additional subproject responsibilities (e.g., also being an IPT lead). This split of attention did not provide adequate time for the PI to advocate for the research both "up and out" of the subproject and "down and in" within the subproject. The added visibility brought on by the X-Plane designation, along with the evolving landscape of industry (needs of industry) and changes to the ARMD Strategic Implementation Plan (SIP) required a full-time effort of the PIs to advocate and communicate the ever-changing relevance of the X-57 subproject in a rapidly evolving market segment. Impacts of a changing SIP will be discussed within the "Evolution of Advanced Air Mobility Community Needs" event.

The subproject was late in establishing the hardware mass Engineering Review Board (ERB) and even later establishing the overall ERB. These changes occurred because the team needed a forum to manage the mass of the aircraft that was growing as the team resolved development challenges. Likewise, the general ERB was added out of necessity to resolve technical challenges or disagreements and make recommendations to the subproject manager (assuming they impacted cost and schedule). The subproject may have benefited from these forums being instituted at the transition into FDC.

2.5.4 The Recommendations Based on the Lesson from the Subproject Transition from CAS to FDC

When developing a manned flight demonstrator that will be subject to NASA airworthiness requirements, it is recommended the activity transition out of CAS start at the concept development phase of formulation (KDP A). It is difficult to reconcile the differences in execution philosophy for agile, lean approaches like CAS and more traditional approaches that are required for other NASA projects. By transitioning after concept development, these traditional approaches to project management and systems engineering can be costed and scheduled as appropriate.

Building off the strengths of CAS, it is recommended that research activities associated with manned flight demonstrators be scoped to show the feasibility of such a demonstrator, but it may not be appropriate to plan the demonstration itself when the receiving project has a different risk posture than CAS. It is recommended that the planning of how to execute the effort fall on the receiving subproject.

Define, document, communicate, and adhere to expectations for required level of rigor for FDC (e.g., project management and systems engineering).

Establishing and clearly documenting the technical authority chain and decision-making body (such as an Engineering Review Board, ERB) at transition, and explicitly note changes in

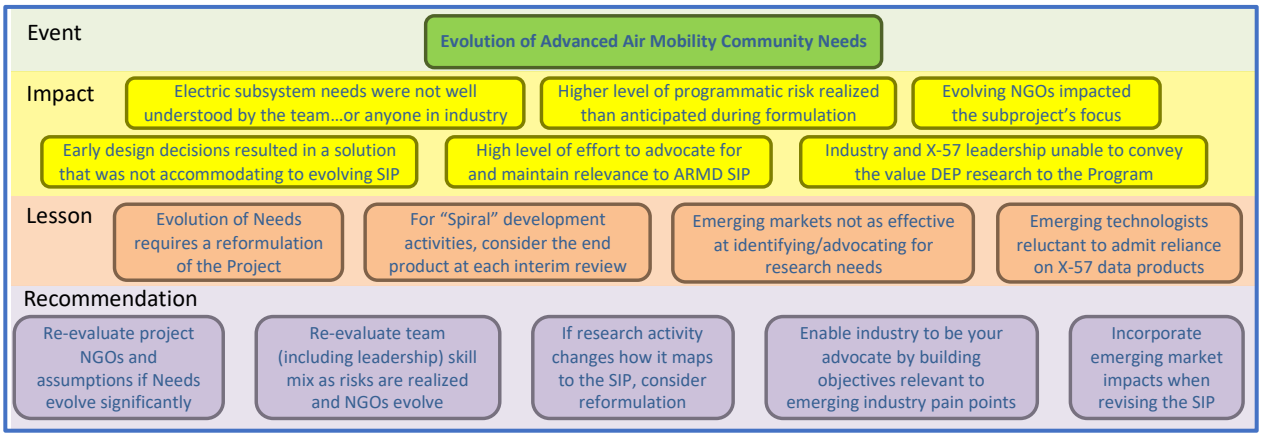
technical authority if the authority moves from one individual or group to another is also recommended.

It is recommended that subproject leadership roles and responsibilities be clearly defined (Project management, Principal Investigator, Chief Engineer, Operations, etc.) and any changes in titles or authorities be communicated at transition.

2.6 Evolution of Advanced Air Mobility Community Needs

Because X-57 was a flight research subproject in an emerging field, the needs of the aviation community and the response of the ARMD Strategic Implementation Plan (SIP) changed throughout the lifecycle of the subproject. Figure 12 summarizes the Impacts, Lessons, and Recommendations associated with the "Evolution of Advanced Air Mobility Community Needs" event.

Figure 12, Evolution of Advanced Air Mobility Community Needs



2.6.1 The Event that Triggered the Evolution of Advanced Air Mobility Community Needs Lesson

Electrified propulsion technologies and distributed propulsion architectures for manned aircraft were not established at formulation of the X-57 activity. As these technologies and designs began to be adopted in industry in parallel and in response to the progress of the X-57 systems development, the gaps in adopting these technologies changed, and the X-57 research products needed (e.g., data sets, lesson presentations, technical papers, system models) changed as well. In parallel, the ARMD SIP was also reacting to the research needs of industry, albeit at a broader level, and its goal to balance NASA aeronautics research across industries resulted in a different emphasis. With stakeholder needs changing more frequently and more drastically in these research areas than would be typical there was a mismatch between the formal Needs and subsequent Goals and Objectives driving the X-57 subproject activities. Accordingly, the subproject needs, goals, and objectives (NGOs) evolved to remain relevant to the evolving community and to the strategic thrusts identified in the ARMD SIP.

2.6.2 The Impact of Experiencing the Evolution of Advanced Air Mobility Community Needs Event

Electric subsystem needs were not well understood. Initial technology surveys found that there were few high-TRL components upon which to base system designs, so there was heavier

reliance on parametric scaling to extrapolate to the component sizes that would be needed for the Maxwell aircraft. Specific design features required for the safety needs of manned were not yet established for these technologies so identifying manned aircraft safety needs was a product of the X-57 activity.

The evolution of advanced air mobility community needs led to a higher level of risk than anticipated. As development of individual components progressed and prototypes were produced, many gaps between the expected technical maturity and what was readily available from US aircraft manufacturers were identified. These potential shortcomings in the state of the art had been highlighted as risks to the subproject execution plan, and over the course of development of multiple core subsystems it became clear that these risks were being realized. Each of these risk areas required additional resources to close to develop components and subsystems that could be candidates for flight readiness.

Evolving NGOs impacted focus. While the project team revised the NGOs to maintain alignment with the rapidly changing stakeholder needs, this had a side effect of shifting the emphasis of the project activities which is time consuming and distracting to the team developing the aircraft systems. The original objectives were adapted into "design drivers" which were intended to establish that the built-to requirements of the aircraft systems were not modified, but there were still impacts as the publication products changed from specific design data to focus more on the process artifacts and lessons learned such as design reviews and the airworthiness approach details.

Early design decisions did not accommodate later revisions to the SIP. The subproject was formulated to build a vehicle with a "5x improvement in efficiency" as responsive to Thrust 4 (Transition to Low-Carbon Propulsion) of the ARMD SIP. As the SIP evolved to emphasize focus on vertical takeoff and transport-class aircraft, the research focus of X-57 on enabling technologies on what would become known as Regional Air Mobility (RAM) was not directly related to the new Research Thrusts.

A high level of effort was required to map to the revised ARMD SIP. The process to update the research activity of the X-57 subproject to map to the revised Strategic Thrusts at each round of continuation assessments was time consuming and impacted the research focus. The day-to-day activities on the project did not always clearly trace to ARMD's vision while reformulating the X-57 NGOs.

The X-57 team struggled to convey the value of DEP research to the Program. As this research area and industry segment was new as the project was forming, there were no legacy advocacy channels within NASA (researchers to Projects and Programs) or in industry (to NASA or to other agencies or legislators). This made it difficult to substantiate the technology gaps in the state of the industry, and for NASA to identify which gaps were appropriate for NASA investment.

2.6.3 The Lessons Learned from the Evolution of Advanced Air Mobility Community Needs

Changing Needs may require reformulation. The disruption caused by changing the root of the requirements traceability network could be avoided by halting project execution and reformulating to a clean sheet of updated Project Needs and then deriving fresh Goals, Objectives, Mission Concept, and System Requirements. This would also be disruptive but

would make subproject activities explicitly aligned with the external stakeholders driving the changing Needs such as a revised SIP or industry evolution.

"Spiral" development activities should reduce the risk surrounding an end product much like traditional technology maturation approaches. Spiral development can rapidly iterate through component challenges, but system integration complexities are easy to miss and also impactful, especially for new technologies. As the NGO environment evolves, the risk driving the "spirals" may need re-evaluation to ensure that the "spiral" is still reducing the risk of the end product.

Emerging markets are not as effective at identifying/advocating for research needs. The X-57 research leads were tightly embedded with industry counterparts including civil aviation authorities, consensus standards developers, and academics. This gave the subproject team detailed insight into the industry needs and technology gaps that were most pressing, but that perspective was not well understood in the larger aeronautics research and technology community at NASA.

Emerging industry leaders were reluctant to admit reliance on X-57 data products. There is a fundamental tension for early adopters of emerging technology to publicly amplify the potential benefits and optimistic roadmaps even when there remain critical obstacles that require research investment. These barriers are often freely discussed in private when investors or regulators are not in the room but that limits the visibility of NASA's contribution. In the case of X-57, many companies are building upon the electric and distributed propulsion research produced by this subproject activity, but they did not effectively communicate that to NASA leadership at the Program and Directorate levels and did not understand that their reliance on continued X-57 progress was not accounted for in NASA portfolio management. This, coupled with the "lower volume" of an emerging industry's voice, is not heard as much as the "higher volume" of an established, larger market.

2.6.4 The Recommendations Based on the Lesson from the Evolution of Advanced Air Mobility Community Needs

Re-evaluate Goals, Objectives, and assumptions when Needs evolve: Large shifts in high-level subproject Needs or in the subproject risks must be accompanied by a re-evaluation of the rest of the subproject activity that flows from the Objectives. Needs will need more frequent review when supporting emerging aeronautics markets, and technology development risks will be more common during spiral development activities of fundamental technology.

Re-evaluate team (including leadership) skill mix as risks are realized and NGOs evolve: The type of expertise to conduct integration and aerodynamic research is obviously different than that required to develop high voltage electronics, but there was not a clear signpost in the case of X-57 for when the project focus changed from the former activity to the latter. More frequent review of the skill mix in comparison to the expected work would help identify these gaps.

If research activity changes how it maps to the SIP, consider reformulation: If the project relevance to industry changes enough, it may be time to reset and reformulate. While this might be disruptive in the short term, it could result in better alignment and products in the longer term when accompanied by systems engineering validation.

Enable industry advocacy with objectives relevant to emergent pain points: The close interaction between the technology gaps in industry and the X-57 publication and sharing was highly effective and actionable. As the project activity responded to the needs of adopters being

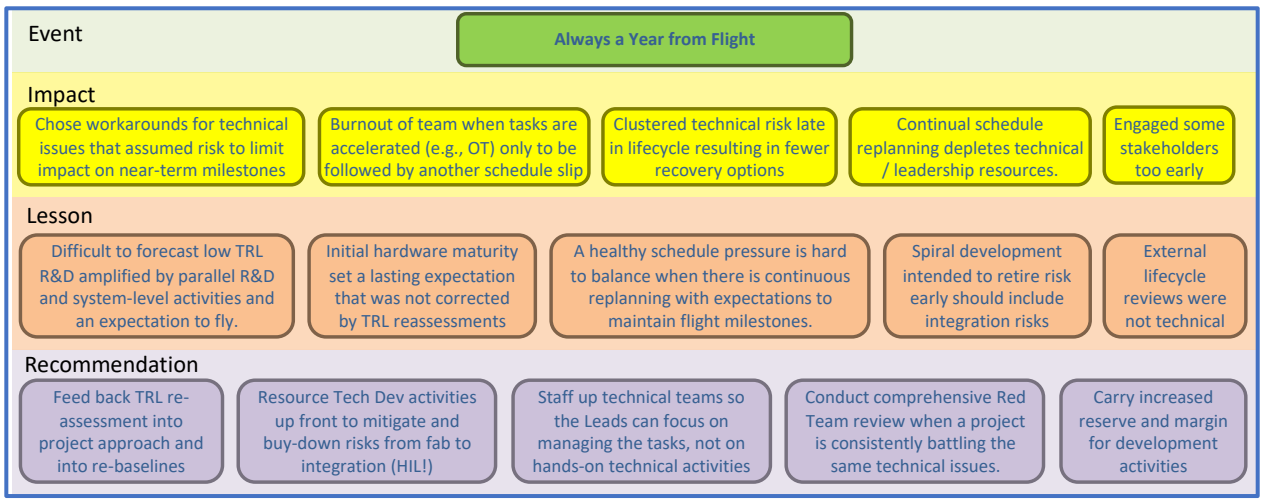
expressed in private and small group settings, the industry groups began to build their development plans around the published X-57 researched plans. When this could be documented and reported within NASA it was valuable.

Incorporate emerging market impacts when revising the SIP: When forming the SIP, industry views from *EMERGING MARKETS* should also be considered. The SIP lagged the needs of the industry in this emerging market space, and the X-57 struggled to map to the SIP because it was targeting research thrust gaps that had not yet been identified in the SIP. Industry wants to rely on NASA to close technology gaps, but emerging companies soliciting investment capital can't admit it publicly. The volume of the industry's voice in a small emerging market is less than that of a large market.

2.7 Always a Year from Flight

As mentioned in other events, the culture of CAS (VC-like investment decision-making and spiral development vs. defined technology maturation plans) instilled a schedule pressure, or pace, early in the life of X-57 that became an expectation that was hard to overcome after transitioning to a project (FDC) that requires additional rigor to get a manned X-Plane to flight. As integration and unplanned subsystem development challenges hindered the ability to maintain steady progress to first flight the subproject found themselves continually one year from flight for the last six years of the ten-year lifecycle. Figure 13 summarizes the Impacts, Lessons, and Recommendations associated with the "Always a Year from Flight" event.

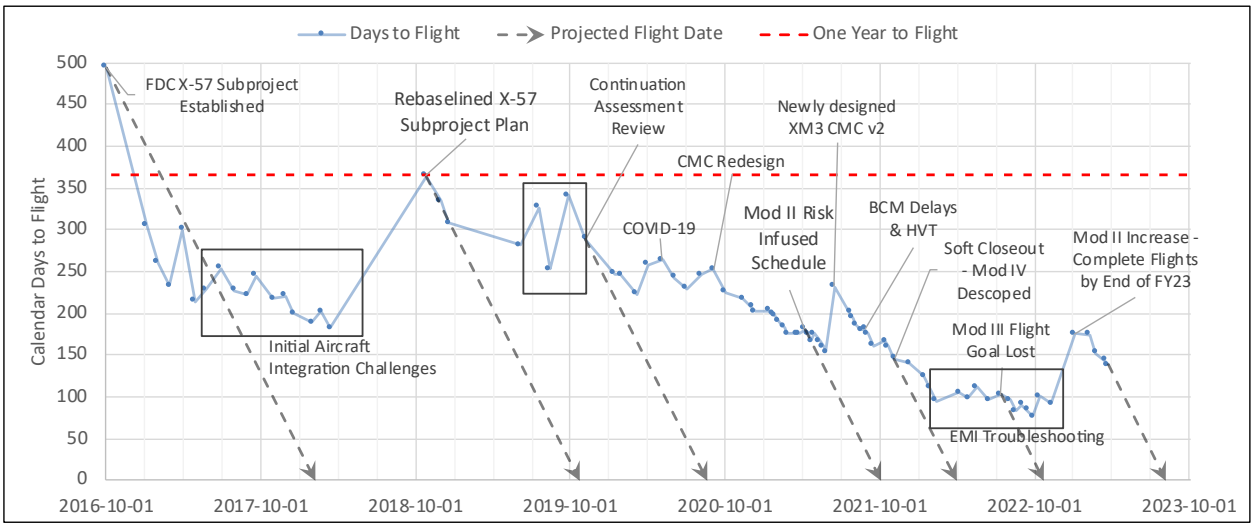
Figure 13, Always a Year from Flight



2.7.1 The Event that Triggered the Always a Year from Flight Lesson

This event is, perhaps, an impact of the collective "Events" reported in this document. There was pressure to hold the flight milestone while addressing challenges without reducing the subproject scope. The initial assessment of higher TRL was a foundational contributor to this event. Through the course of the subproject, it was as though the team was always one technical challenge away from flight, in other words, "…this is the last thing to resolve." Figure 14 shows the days forecasted to X-57's Mod II first flight. The first forecast in October 2016, is reflective of when the FDC subproject for X-57 was established, indicating 500 days to the first flight of Mod II.

Figure 14, X-57 Mod II First Flight Forecast from 2016 through 2023



2.7.2 The Impact of Experiencing the Always a Year from Flight Event

When an issue was encountered, with the milestone of the first flight in the perceived near term, the subproject chose workarounds to overcome technical issues that assumed either programmatic or technical risk to limit the impact on the near-term milestones. These workarounds were vetted within the project to be feasible stand-alone solutions that were assessed from both a programmatic risk perspective and an airworthiness perspective (system safety) perspective. As an example, given the amount of time it would have taken to stop redesigning and test a CM, the team chose a progressive approach to operationally mitigating hazards (i.e., additional inspections, limiting ground testing prior to hardware replacements) when hardware issues arose in 2018, 2021 and 2023. The battery defect was discovered early enough in the lifecycle that there was time to redesign it. Hindsight tells us that redesign time placed an increased risk on the subproject, such that there would not be time later in the lifecycle to overcome additional subsystem development challenges. The high-lift (HL) systems had time for technology maturation mostly because of Mod II subsystems slipping, allowing schedule for the dedicated HL team to mature the HL system. Given the perceived near-term Mod II flight milestone, decisions were made to mitigate challenges rather than stop to redesign and test individual subsystems. Pausing to redesign these systems would have allowed for more sustained development of the technology that was on the critical path to the Mod II flight.

This approach to mitigating challenges by introducing workarounds placed technical risk late in the lifecycle of the subproject, resulting in fewer recovery options due to the lack of time to execute those recovery options. For example, the CM rotor issues were “resolved” operationally which delayed a root cause discovery until years later in the subproject when there was little appetite for additional schedule.

The subproject was continuously reacting to technical or subsystem development challenges and could not pause to assess the collective impacts of challenges. A constant “push to flight” schedule can’t be endured long-term, and the interview data indicated that this was extremely hard on the team. Burnout of team members is a high risk when tasks are accelerated, or specific teams are asked to work overtime to make up the schedule only to be followed by another slip to the schedule because of a new subsystem development challenge. Interview data showed that

personnel were discouraged when asked to work overtime on their tasks when they believed that another subsystem was at a high level of risk of not meeting their optimistic schedules. It was difficult to communicate the integrated workflow to the entire team in a way that expressed the need for prioritization and conveyed importance. As an example, the operations team is, by the nature of a development effort, on the critical path at the end of the task lifecycle conducting aircraft integration and testing, and when risk reduction is not conducted early, the expectation of success during final integration and test is placed on the operations team.

Early in the subproject, no funding was available for an "iron bird," which would have allowed for off-aircraft testing, thus mitigating risks early and off the critical path of testing on the aircraft. The residual risk of not investing in an "iron bird" was accepted by the subproject. This lack of an "iron bird" did not allow for early risk mitigation with developmental components. This forced integration testing to be conducted using flight components on the flight vehicle, and did not address a full system integration risk or allow for incremental development and testing.

*"*It's a lot of work to be behind.*"* With the schedule slipping so often, re-planning to move resources to parallel tasks or accelerate or delay efforts to use the available bandwidth was time-consuming for the leadership team Uncovering one subsystem development challenge at a time also resulted in engaging some stakeholders too early which resulted in losing time on premature planning. For example, the Flight Readiness Review (FRR) for Mod II was rescheduled three times, and team members had to develop and update material for the FRR each time. Additionally, engaging the systems integration team at a point where progress toward flight was being made only to encounter a new subsystem development challenge resulted in this systems team being underused while the needed development team was understaffed.

Comprehensive replanning was challenging. Technical teams were saturated with the need to address subsystem development challenges and tended to have the resources and personnel to resolve these one at a time. This serial, reactionary response consumed more time and resources than a top-down technology maturation approach.

2.7.3 The Lessons Learned from the Always a Year from Flight

It is difficult to forecast the effort required to mature low TRL subsystems to a TRL suitable for a manned flight demonstrator. This is further amplified when executing parallel subsystem development and system-level activities with an expectation to fly. This is an example of compounding risk.

The initial hardware maturity set a lasting expectation that was not corrected by TRL reassessments. If the TRL drops, it is important to reassess the TRL and the system-wide impacts actively. The team needed to look across the entire system rather than triaging one thing at a time. The team did not have time to pause and be deliberate. Additionally, the team would have benefitted from considering how a drop in TRL impacted the airworthiness approach and likewise the impact to cost and schedule.

A healthy schedule pressure is hard to balance when there is continuous replanning with expectations to maintain flight milestones. Often times maintaining pace and progress toward a milestone as documented by a schedule is a difficult balance between applying an appropriate amount of pressure to continue efficient forward progress that applies a tolerable level of stress on the team and applying heavier pressure that, although it may continue forward progress, induces an unhealthy level of stress on the team which in the long run may hurt the quality of the

work. Not only will it hinder the efficiency of forward progress, but it weighs on team morale. Repeated replanning without allowing relief in the schedule or relief in scope introduces a high risk of team burnout.

A spiral development approach, intended to retire subsystem development risk using an iterative approach, should also include a scalable approach to addressing integration risks, including integration testing using development hardware in an appropriate environment (e.g., an "iron bird"). Expectations of the propulsion system TRL at CAS baseline (flying products quickly adaptable) were not reset when the subproject scope changed to develop US-based products from scratch.

External lifecycle reviews were not focused on assessing the technical state of the subsystems. While "red team" reviews/continuation assessments were performed, the technical and development challenges continued to hinder the subproject. The red team reviews conducted for the X-57 subproject did not assess TRL and what was left to mature the subsystem. They looked closely at the schedule and documented risks related to the schedule.

2.7.4 The Recommendations Based on the Lesson from the Always a Year from Flight

It is recommended that TRL re-assessments be incorporated into the subproject approach and fed into re-baselines.

Technical development activities should be afforded appropriate up-front resources to mitigate and buy down risks from fabrication to integration (e.g., an "iron bird" is critical to eliminate early integration risk for newly developed components).

It is also recommended that technical teams be staffed to allow for the lead to focus on managing and leading the work and development within their discipline as opposed to doing the technical work. Having a dedicated lead focused on managing affords the leadership team an additional team member to manage tasks and schedule down-and-in as well as communicate up-and-out to the leadership team. This may help communicate within the discipline teams the integrated approach of the overall schedule and alleviate some team stress when asked to work over-time to complete a task. Additionally, it will provide bandwidth of the lead to support schedule replanning efforts without impacting technical work that would need to continue in parallel with replanning.

Conducting comprehensive "red team" reviews when a project is consistently battling the same type of technical issues is also recommended. Additionally, conduct deep-dive TRL re-assessments at baseline updates, such as program transitions and continuation assessments. A project team should consider verification by an independent red team or board of SMEs.

Apply reserve at formulation commensurate with the risks that are identified. As the subproject encounters new or realizes existing risks, reassess the reserve posture and determine whether reserves should be adjusted or if descoping is needed. An independent assessment of the project scope and plans may aid in determining an "adequate" level of reserve.

2.8 X-Plane Designation

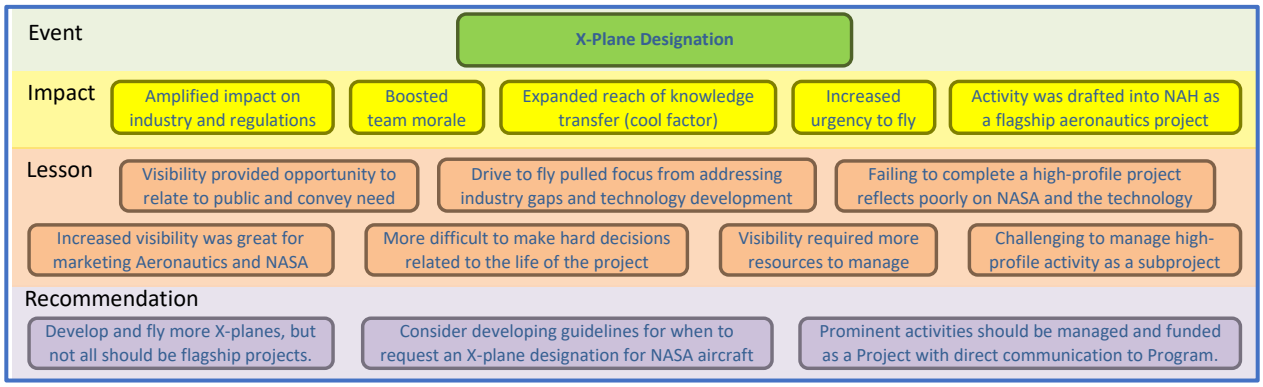
The SCEPTOR project was awarded an X-Plane designation, X-57, in June of 2016. Separately, in 2017, the New Aviation Horizons (NAH) Initiative was developed in parallel and ultimately added the X-57 subproject to the initiative. Figure 15 illustrates the breadth of the NAH. Figure

16 summarizes the Impacts, Lessons, and Recommendations associated with the "X-Plane Designation" event.

Figure 15, New Aviation Horizons Initiative



Figure 16, The X-Plane Designation



2.8.1 The Event that Triggered the X-Plane Designation Lesson

The "X" designation for X-57 was announced while the subproject was transitioning into FDC and out of CAS. This process, although approved and granted through the Air Force process and vetted within AFRC, was not coordinated with ARMD. In addition to gaining the X-Plane designation, which alone attracts additional visibility, that visibility, was amplified by NAH, which stated: "the centerpiece of NASA's 10-year acceleration for advanced technologies testing is called New Aviation Horizons, or NAH. It is an ambitious plan to build a series of five mostly large-scale experimental aircraft – X-planes – that will flight test new technologies, systems, and novel aircraft and engine configurations."[3]

2.8.2 The Impact of Experiencing the X-Plane Designation Event

The X-plane designation further catalyzed the aerospace research community's interest in electrified propulsion seriously and amplified the impact on industry and regulations. The X-57

[3] *New Aviation Horizons Initiative and Complementary Investments* (NP-2016-06-2167-HQ). (2017). National Aeronautics and Space Administration. Available at https://www.nasa.gov/wp-content/uploads/2017/11/nasa-aero-10-yr-plan-508-reduced.pdf (last accessed 2 December 2024)

was featured in several AIAA events, and the work of the X-57 team received greater influence in the development of the Advanced Air Mobility (AAM) market. The AIAA partnered with IEEE and formed the Electrified Aircraft Technology Symposium, which continues today, and the ARMD established the AAM Mission Office.

The designation boosted team morale and induced excitement not only within the team but also externally. The X-designation brought attention from the public in a way that the public could relate to the need for an electric aircraft. There was an expanded reach of knowledge transfer brought on by the "cool factor" of an X-plane. This amplified visibility and increased NASA's urgency to fly the aircraft in the context of the NAH initiative.

The inclusion in NAH was unexpected by the subproject team. The added visibility of the designation and inclusion in the NAH initiative resulted in an undocumented impression of the X-57 becoming a flagship X-plane for NASA.

2.8.3 The Lessons Learned from the X-Plane Designation

The increased visibility provided an enhanced opportunity to relate to the public and convey the need of the X-57 subproject. Similarly, the visibility provided great marketing for the good work of Aeronautics within NASA.

The drive to get to flight pulled focus from addressing industry gaps and conducting technology development that X-57 uncovered out of a necessity to electrify the aircraft.

The added visibility resulting from the X-plane designation required more resources to manage. With added visibility comes added reporting and status briefings to many layers of management. Therefore, information was filtered through several layers of management that provided opportunities to introduce gaps in communication. As a subproject it was challenging to manage a high-profile activity.

Additionally, failing to complete a high-profile project reflects poorly on NASA as well as on the technology.

2.8.4 The Recommendation Based on the Lesson from the X-Plane Designation

NAH noted that NASA should develop and fly more X-planes, but not all X-planes are necessarily flagship projects. Pushing the realm of possibility should accommodate failure in a way that does not reflect poorly on the agency.

Consider developing guidelines for when to request an X-plane designation for NASA aircraft to ensure the project is scoped, funded, and staffed appropriately to meet expectations and requirements.

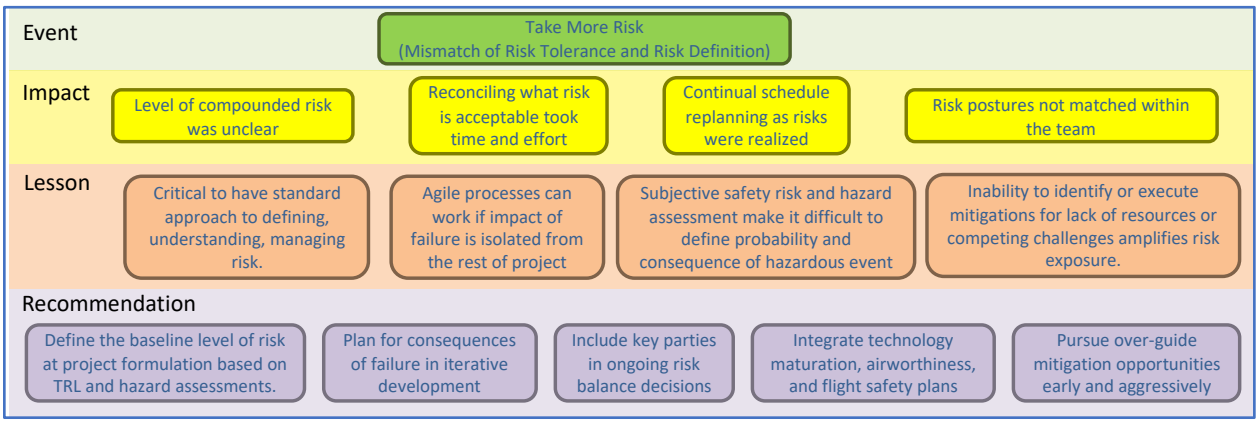
It is recommended that prominent activities be managed and funded as a Project with direct communication to the parent Program to avoid opportunities to introduce gaps in communication.

2.9 Take More Risk

The X-57's origins within the CAS subproject embraced a higher programmatic and technical risk tolerance than traditional NASA flight projects, which led to a team and management culture to "take more risk." The transition to a more traditional NASA flight project structure in FDC introduced a mismatch in risk tolerance and definition within the X-57 team and among

subproject and center leadership. Figure 17 summarizes the Impacts, Lessons, and Recommendations associated with the "Take More Risk" Event.

Figure 17, Take More Risk



2.9.1 The Event that Triggered the Take More Risk Lesson (Mismatch of Risk Tolerance and Risk Definition)

Throughout the subproject's lifecycle it became apparent there was a mismatch of risk tolerance and risk definition with the implicit direction to "take more risk" from external leadership. The message of "take more risk" was instantiated under CAS. As part of CAS, the subproject was formulated with a "high-risk/high-reward" approach that encouraged taking technical and programmatic risks to meet ambitious goals. Part of this approach under CAS was encouraging the team to reimagine how to accomplish the mission, not just tailor existing processes. As noted in the Project Transition from CAS to FDC event, CAS followed a VC model where failure was expected of a number of activities within its portfolio, so higher risk was to be expected from an individual activity like SCEPTOR. The transition from CAS to FDC did not establish a clear change in risk tolerance under the FDC project which led to confusion within the team. Following the transition to FDC, the message from external leadership to "take more risk" was intended to push the team to get to flight as soon as possible while meeting the airworthiness needs required of a flight project. Throughout the subproject's lifecycle, the meaning of "take more risk" was not documented and not understood within the team or with external stakeholders.

The "take more risk" message affected all aspects of the subproject's approach to programmatic, technical, and safety risk management. Without a clear understanding of what "take more risk" meant, the subproject's risk tolerance was continually misunderstood both internal and external to the team. It was unclear to team members if the "take more risk" approach applied to the Risk Management Process (RMP) used to manage the programmatic and technical risks, or if it applied to the System Safety process, or both.

2.9.2 The Impact of Experiencing the Take More Risk Event

The "take more risk" message resulted in some technical and programmatic decisions that resulted in compounding risk. It was difficult to evaluate the compounded level of risk on the subproject when a baseline understanding of risk tolerance was unclear and had changed from the formulation and initial execution under the CAS project to later execution under the FDC project.

Significant time and effort were spent reconciling and communicating the different perceptions within the subproject team and with NASA Leadership regarding what level of risk was acceptable. In addition, "take more risk" was understood by some team members to include omitting some processes for faster execution in lieu of the assurance the process might provide. This led to conflicts within the team as the subproject moved to incorporate more of the legacy NASA airworthiness processes vs. the "high-risk" plan formulated early in the subproject's life cycle.

Risk postures were not matched within the team. For example, the team was challenged during system safety discussions associated with defining an acceptable failure rate and failure outcome of the experimental X-57 propulsion system. Some team members perceived a lakebed landing following an engine failure as an unacceptable safety risk as well as programmatic risk (loss of program due to mishap investigations, etc.) whereas other team members considered this to be a low-impact event. There was no consensus on the subproject and statements by external leadership were unclear in terms of providing guidance. Neither the subproject nor NASA leadership shared a common understanding of how to define an acceptable level of safety, programmatic, or technical risk.

2.9.3 The Lessons Learned from the Take More Risk Event

It is critical for a subproject team to have a standard approach to defining, understanding, and managing risk. The X-57 subproject team began to more formally track risks partway into execution as an FDC subproject, and in doing so, the team was better able to identify and mitigate programmatic and technical risk. However, the very high level of risk load realized early on, particularly when the team was required to shift from subsystem integration to actual subsystem development for so many critical subsystems, meant that risk was often realized despite mitigations and planning.

The "take more risk" approach did pay off with the agile approach used for battery development. The subproject chose a startup manufacturer with little experience for this scale product, and they saw the original design fail, only to be iterated, and a year later, they produced battery storage modules that changed the state of the art for the entire market. A more traditional development approach would likely have taken longer and consumed more resources, though the result would be more assured.

Subjective (in lieu of quantitative) safety risk and hazard assessment make it difficult to define the probability and consequence of a hazardous event occurring. A qualitative hazard assessment is possible when all involved in the process share a common understanding of the hazards and what is an acceptable level of safety risk. Without that common understanding, there is no consensus and endless debate as to what risks are acceptable.

The inability to identify or execute mitigations for lack of resources or competing challenges amplifies the risk exposure. For example, an electromagnetic interference (EMI) and electromagnetic compatibility (EMC) risk could have been mitigated early in the project by conducting subsystem development and integration activities with an "iron bird" lab setup. This mitigation approach was not taken as the team did not have the resources to develop these test setups, nor was the level of risk fully understood. As a result, significant resources were expended during aircraft integration testing to identify and address the EMI challenges.

2.9.4 The Recommendations Resulting from the Take More Risk Event

It is recommended that the baseline level of risk be defined at subproject formulation based on TRL and initial hazard assessments. A technology readiness assessment will allow for all stakeholders to understand what development tasks are required along with the scope of the efforts. An understanding of the hazards will allow for the stakeholders to define what constitutes an acceptable level of safety risk. With an understanding of the required development efforts and a common safety definition, the stakeholders can have a realistic discussion as to what level of baseline risk the subproject should work to.

It is further recommended to plan for consequences of failure in iterative development. Challenges inevitably arise when developing and integrating subsystems, and the subproject should be scoped to include adequate schedule and budget reserves to account for these challenges. An independent assessment of the subproject scope and plans should be conducted by independent personnel to aid in determining what level of reserves are "adequate." This assessment should examine not just the schedule and budget reserves, but also the subsystem TRL and maturation plans.

Include key parties in ongoing risk balance decisions. A common definition of risk along with ongoing discussions are necessary to ensure all stakeholders understand the risks that a subproject is operating with.

Integrate technology maturation, airworthiness, and flight safety plans. Following the initial technology readiness and hazard assessments, it is recommended the formulation team develop a plan to mature the technology and demonstrate airworthiness and flight safety. This integration effort should lay out required subsystem TRL maturation at key project milestones and detail how airworthiness and flight safety requirements will be met.

Pursue over-guide mitigation opportunities early and aggressively. Project resources tend to be fixed and lagging in terms of matching additional mitigations to realized risks. Over-guide opportunities can be an effective means of supplementing project resources to buy down technical risk.

3 Recommendations

The X-57 subproject has developed three recommendations from the lessons learned exercise. These recommendations are related to overarching takeaways associated with Compounding Risk, Subproject Formulation and Execution, and Knowledge Transfer.

3.1 Compounding Risk

Risks are not necessarily stand-alone, and they tend to interact in complex ways. The compounded level of risk is difficult to fully assess, but it is certainly greater than the sum of the individual risks. As detailed throughout this report, the X-57 subproject carried many risks with few mitigation options. Figure 18 illustrates how five of the events discussed in this report combined to create compounding risk to the project. Individually, each of these events and their associated risks presented a challenge, and the magnitude of that challenge only increased when the project was forced to address all of them simultaneously. The subproject has concluded that the current risk management process as identified by FDC and IASP and the associated risk matrix does not provide an effective mechanism to communicate compounded risks.

Figure 18, The Overarching Lesson of Compounding Risk



To communicate the impact of compounded risks more effectively on project execution, the "Project Manager's Assessment" summary chart as developed for and briefed at the integrated Center Management Council briefings is a good example of a way to assess an overall risk level that the project is running. This summary chart provides a snapshot of the project cost, schedule, technical, management issues, and overall risk level that can be used in conjunction with the programmatic risk matrix to communicate the magnitude of the compounded challenges. Figure 19 shows the X-57 subproject Manager's Assessment Chart, dated May 17, 2023.

This example clearly shows the subproject was experiencing several challenges at the time, but what is not clear is the level of compounded risk that was exacerbating the project's abilities to address these challenges. The addition of an **overall risk assessment** to the chart would provide the subproject a forum to communicate the compound nature of the programmatic risks alongside the individual risk matrix.

Figure 19, X-57 subproject Manager's Assessment Chart

X-57 Project Manager's Assessment

Program/Project: IASP/FDC/X57
Status as of: 5/17/23

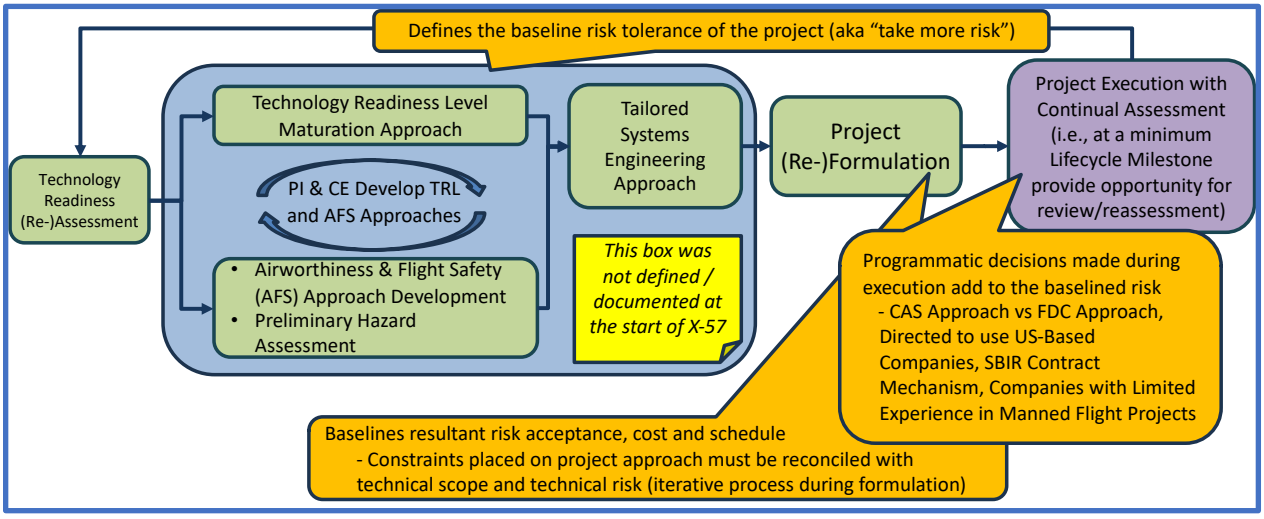
	Mar	Apr	May	Jun	
Cost	Y	Y	R	R	Mod II flight schedule impacted by cruise motor (Mod/Config 0) hazard assessment not to fly Mod/Config 0 motor. Generating cost/schedule/benefit to get to Mod II flight with modified cruise motor that addresses NESC/subproject findings.
Schedule	R	R	R	R	Mod II flight schedule impacted by cruise motor (Mod/Config 0) hazard assessment to not fly Mod/Config 0 motor. Generating cost/schedule/benefit to get to Mod II flight with modified cruise motor that addresses NESC/subproject findings.
Technical	R	R	R	R	Cruise Motors (in Mod 0 Configuration) deemed to be an unacceptable risk for flight. AFSRB concurrence received. Currently working toward CDR of modified cruise motor for flight (Mod/Config Z)
Mgmt. Issues	R	R	R	R	Delays to Mod III CN/Wing delivery and Mod IV hardware delivery putting task order closeout by end of FY at risk.

G	Progress according to plan. Meeting management plans or commitments. No action required.	R	Significant problem. Deviating from plans or commitments, with insufficient approved contingency/reserves to recover and successfully complete the program/project as approved. Needs action. Help required beyond the reporting organization to address the problem.
Y	Area of concern. Deviating from plans or commitments, but approved contingency/ reserves exists to recover and successfully complete the program/project as approved. Needs attention. Problem can be resolved within the reporting organization.	B	Restructuring to Establish Baseline

3.2 Subproject Formulation and Execution

In hindsight, many of the events and impacts experienced by the X-57 subproject may have been mitigated during formulation or by implementing a robust assessment and feedback process during subproject execution. With this in mind, the first step of formulating a new manned flight subproject should be to complete a detailed technology readiness assessment as this defines the starting point of the project. This assessment should then be reviewed by independent subject matter experts to provide a verification of the assessment. The next step is an iterative development of a defined TRL maturation plan, an Airworthiness & Flight Safety (AFS) approach, and a preliminary hazard assessment are necessary steps to develop a tailored systems engineering process. These iterative steps are where the baseline risk tolerance of the subproject is defined, and this definition is used to set what "take more risk" means for the subproject. Once the preferred technical approach and risk tolerance is defined, the subproject undergoes formulation where the contracting approach, cost, schedule, and resources are estimated based on the technical approach and proposed risk tolerance. Key to a successful project formulation is having a good understanding of the technical approach and the associated risks. During the project formulation step, constraints will be placed on the subproject in terms of schedule, resources, and other necessary elements, all of which must be reconciled with the technical scope and baseline risk as part of an iterative process to arrive at a viable subproject plan. The subproject formulation plan should also be reviewed by independent personnel. Once a subproject has transitioned to execution, a continual assessment of the subproject's progress, scope, and technology readiness is required by both subproject personnel, stakeholders, and independent subject matter experts. This assessment should be completed at a minimum at lifecycle milestone reviews and whenever there is a change in scope or significant development challenges arise. Figure 20 illustrates a recommended formulation and execution approach for future NASA manned flight projects based on the lessons learned by the X-57 subproject.

Figure 20, Continual Assessment Throughout the subproject Starting with a Solid Baseline



3.3 Knowledge Transfer

The enduring legacy of the X-57 subproject is the vast amount of technical information produced by the team associated with distributed electric propulsion technology. This information has been

widely shared through many dozens of public documents and presentations[4] at technical conferences and workshops, most of which are available on the NASA Technical Report Server (NTRS). Beyond this, the X-57 subproject engaged in detailed interactions with other U.S. government agencies and directly participated with regulatory and standards bodies associated with determining the airworthiness and operational requirements for electrified aircraft. These publications and engagements were not a byproduct; these were deliberate objectives that drove the subproject activities.[5]

As discussed in the Evolution of Advanced Air Mobility Community Needs lesson, the X-57 subproject was executed during a time of transient technology development associated with electrified propulsion as used for Advanced Air Mobility operations. As other electrified propulsion technologies were developed and operated outside of the X-57 subproject, the subproject objectives pivoted from demonstrating that distributed electric propulsion aircraft were possible to the use of the X-57 as a public reference platform for new analysis tools, assurance methods, and test techniques associated with distributed and electric propulsion technologies. A challenge with any new technology effort in aerospace lies in safety assurance – regulators and operators do not have a broad enough historical database to inform necessary changes in certification approaches. By establishing detailed public data on the X-57, regulators and standards organizations could access this data without running afoul of ongoing proprietary efforts to develop similar technology. This, in effect, enabled concurrent development of technology by Advanced Air Mobility manufacturers with assurance methods used by standards organizations and regulators. The data, experiences, and participation of X-57 team members within standards organizations were a small but important part of bringing nascent electrified aircraft propulsion technology into more widespread public use.

These interactions and publications were targeted based on persistent involvement of X-57 team members in the Advanced Air Mobility space. Rather than focus on static objectives, the team members were highly active in conferences, workshops, and consensus standards organizations associated with Advanced Air Mobility. This enabled the X-57 subproject to identify which of its ongoing activities associated with the design, development, and airworthiness assurance of the X-57 aircraft could have the most impact in the Advanced Air Mobility space. In fact, the X-57 subproject elevated knowledge transfer discussions and status as part of the overall project meetings, and had personnel dedicated in part or whole to survey this emerging technology landscape and manage involvement associated with development of consensus standards for distributed and electrified aircraft propulsion technology, integration, and flight performance.

A final recommendation of this section is that future NASA flight projects emulate this highly successful model for effective knowledge transfer. This is not simply an objective for a static project or report as a milestone, but rather a comprehensive and "living" approach for continuous engagement with the community of interest. Without this continuous engagement, the X-57 subproject would not have been even modestly impactful. However, through continued publication, engagement, and re-assessment of targeted community needs (in this case, the Advanced Air Mobility community), the X-57 subproject was able to influence the appropriate

[4] Many of these papers and presentations can be found at https://www.nasa.gov/x57/technical/ (last accessed 18 November 2024).

[5] S. Clarke, N. Borer, V. Schultz, "X-57 Knowledge Transfer and Wrap-Up," Spring meeting of ASTM Committee F44 on General Aviation, Cologne, Germany, April 2024. Available at https://ntrs.nasa.gov/citations/20240003422 (last accessed 18 November 2024).

research community even with the absence of flight and remains an ongoing and powerful influence on advancing key standards to enable electric propulsion.

4 Conclusion

It should be noted that although the X-57 subproject did not achieve flight, the focus on achieving flight enabled the team to gather and share relevant technical and operational lessons and data with industry and regulators. Maintaining flight as an objective drove testing and analysis rigor that led to more discovery. The impact of the X-57 lies not in what was originally set out to achieve, but that the subproject identified and addressed technology and certification gaps in industry that needed to be filled. The lessons learned were foundational to electrified propulsion and built up electrified aircraft US small businesses and enabled commercial products. The X-57 subproject advanced the Nation's ability to design, test and determine airworthiness of distributed electric and aero-propulsive coupling technologies, which is a critical enabler of emerging advanced air mobility markets. The subproject had a significant impact on industry and standards/regulations despite the absence of flight.

The X-57 subproject contributions have been substantial, especially compared to the level of investment. The subproject elevated the electric propulsion TRL of components leading to integration testing of hardware with flight performance specifications. The publishing approach of the subproject was early and frequent and included the sharing of design tools, component and subsystem test data, and operational lessons learned with academia and industry.

The X-57 subproject prime contractor and their subcontractors grew, in part, because of X-57. The motor subcontractor is currently working through certification of a full-scale flight demonstration. The battery system subcontractor commercialized the X-57-series battery systems and continues to advance the product line, and the prime contractor grew substantially during execution and has integrated quality assurance practices (AS9100 certification) into their company.

Additionally, the subproject had a wider impact across the electrified aviation space, including industry, regulators, and academia. The published architecture is a principal reference for academia and standards development. The design and test standards and lessons learned are being adopted, with the impact on regulations and standards ongoing as operational constraints drive further learning.

In short, the X-57 subproject ***HAS*** advanced the Nation's ability to design, test, and determine airworthiness of electrified aircraft technologies. The X-57 subproject produced significant technical insights and developed and established best practices that will significantly benefit future electric aircraft research and technology flight research projects. The subproject also learned hard lessons from its inception as a CAS effort and its transition into a FDC subproject. The lessons learned and associated recommendations are documented in this report, along with the driving events and their impacts, which led to the formulation of the lessons and recommendations.

Appendix A – Acronyms and Abbreviations

Acronym	Defined
AAM	Advanced Air Mobility
AFRC	Armstrong Flight Research Center
AFS	Airworthiness & Flight Safety
AFSRB	Airworthiness and Flight Safety Review Board
AIAA	American Institute for Aeronautics and Astronautics
ARMD	Aeronautics Research Mission Directorate
BCM	Battery Control Module
CAS	Convergent Aeronautical Solutions
CDR	Critical Design Review
CE	Chief Engineer
CM	Cruise Motor
CMC	Cruise Motor Controller
COTS	Commercial, off the shelf
DEP	Distributed Electric Propulsion
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
ERB	Engineering Review Board
FDC	Flight Demonstrations and Capabilities
FFP	Firm Fixed Price
FRR	Flight Readiness Review
FY	Fiscal Year
GRC	Glenn Research Center
HL	High Lift
HLMC	High-Lift Motor Controllers
HQ	NASA Headquarters
IASP	Integrated Aviation Systems Program
IDIQ	Indefinite Delivery Indefinite Quantity
IEEE	Institute for Electrical and Electronics Engineering
IPT	Integrated Product Team
KDP	Key Decision Point
LaRC	Langley Research Center
LEAPTech	Leading Edge Asynchronous Propeller Technology
NAH	New Aviation Horizons
NASA	National Aeronautics and Space Administration
NGOs	Needs, Goals and Objectives
PDR	Preliminary Design Review
PI	Principal Investigator
PM	Project Manager or Project Management
POP	Period of Performance
PWS	Performance Work Statement
QA	Quality Assurance
RAM	Regional Air Mobility

Acronym	Defined
RMP	Risk Management Process or Risk Management Plan
SBIR	Small Business Innovative Research
SCEPTOR	Scalable Convergent Electric Propulsion Technology and Operations Research
SE	Systems Engineering
SIP	Strategic Implementation Plan
SME	Subject Matter Expert
SOW	Statement of Work
TACP	Transformational Aeronautics Concepts Program
TRL	Technology Readiness Level
US	United States
VC	Venture Capital

Armstrong Flight Research Center

X-Plane Structures Challenges/Lessons Learned

Briefing to the 2016 NESC Structures TDT F2F Meeting

Randy Thompson, Chief, Aerostructures Branch

May 2016



Outline

- X-planes introduction
- Recent (30 years) of structures related X-planes and research aircraft
- ARMD New Aviation Horizons Plan
- Structures lessons learned (four of many)
- Summary

X-Plane Designation



- **70 years of X-planes (Bell X-1 First flight – 19 Jan 1946)**
- **Original designation – “XS” for eXperimental Supersonic**
- **“X” identifies research craft designed for experimental and developmental research programs which are not intended for production beyond a limited number built solely for flight research**

“Recent” Research Aircraft



- **Flight research just not with X-planes**
- **Research aircraft include purpose-built aircraft without an “X” designation and aircraft (significantly) modified for specific research**


NEW AVIATION HORIZONS

ARMD New Aviation Horizons Plan

- **2014 → 2034 (est) Global Aviation Industry**
  - 3.3B → 7B Passenger Trips; 58M → 105M Jobs; $2.4T → $6T GDP
- **ARMD 10 Year X-Plane Plan**
  - Research/Demonstrate new airframe and propulsion technologies
  - Distributed ~$4.25B budget increase over next 10 years
- **Ultra-Efficient Subsonic Transports (UEST)**



D-8: Prop/AF integration enables reduced drag

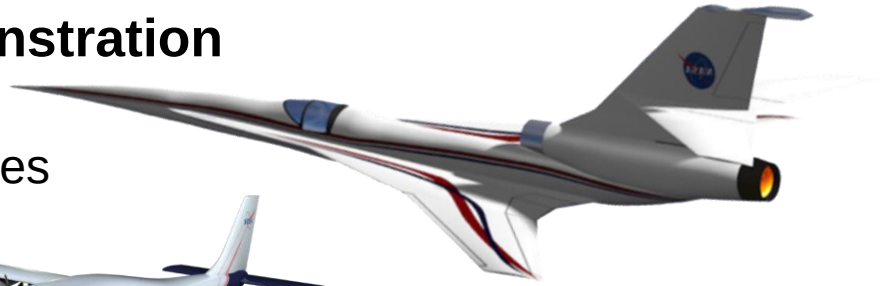


HWB: Aerodynamically efficient shape enables reduced drag



TBW: Very high AR substantially increases wing efficiency

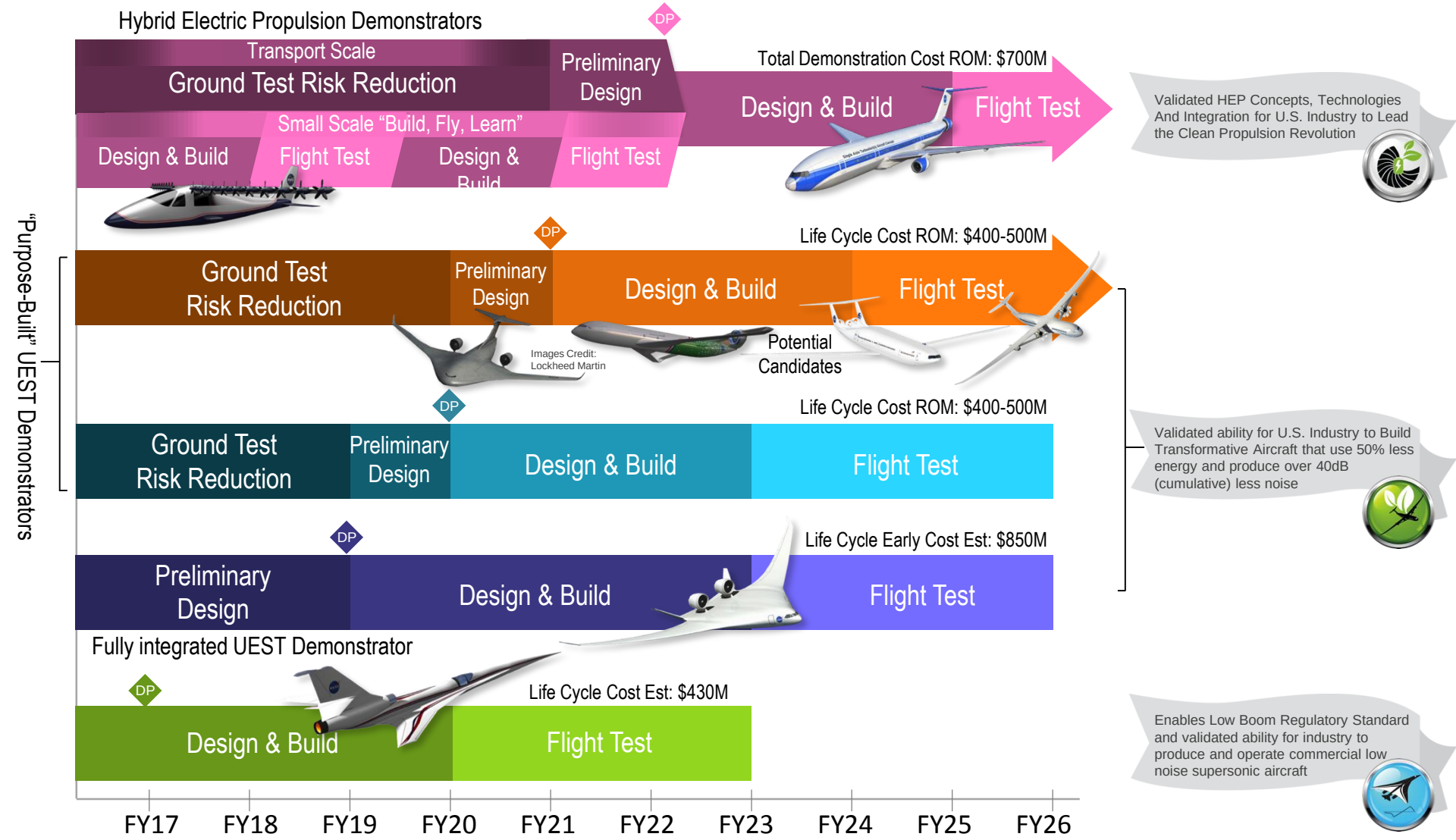
- **Supersonic Low Boom Flight Demonstration**
  - Demonstrate boom noise reduction
  - Support international regulation changes



- **Hybrid Electric Propulsion**
  - Integration and demonstration



New Aviation Horizons Flight Demo Plan



Structures Lessons Learned

- Executing fwd → Remembering the past to succeed in the future
- Lessons learned from programmatic to technical



X-3 (center), and clockwise from left:
X-1A, D-558-I, XF-92A, X-5, D-558-II, and X-4



Flight-Research vs. Developmental T&E

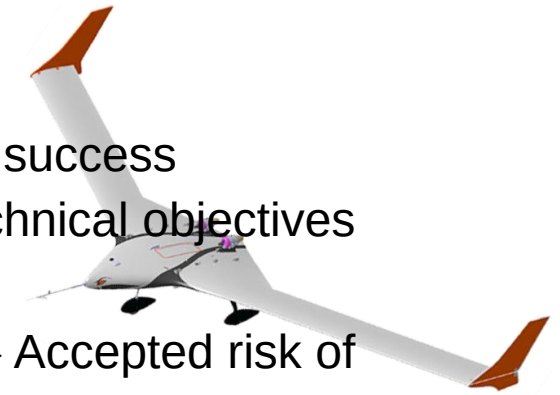
	Flight Research	DT&E
Purpose	Discover something new or validate a theoretical principle	Verify and validate proper operation in flight environment to show works as designed
Predicted outcomes	Typically high uncertainty	Typically high confidence
Measure of Success	Quality of data produced	Match predictions and validate operation

- **Changes perspective on technical risk →Take it! (more on that later)**
- **Changes perspective on "failure" → "Fail early, fail often."**
- **Changes perspective on scope → Limited vs. Complete**
- **Changes perspective on expected results → Data is key**
- **"Learn by doing" → Build, fly, learn…**

  "We will ask big questions, seek multi-disciplinary solutions, and demonstrate their feasibility in 18-36 months" – ARMD AA

Take the Right Kind of Risk

- **Programmatic Risk**
  - Unacceptable to fail due to inadequate planning, management, etc.
- **Technical Risk**
  - Technical failure is OK
  - Can learn as much from technical failure as technical success
  - Lean forward and accept risk of failing to meet the technical objectives
  - Take the right technical risk
  - Example: First X-56 flex-wing flight takeoff mishap → Accepted risk of mishap due to flutter, but not takeoff mishap



- **Safety Risk**
  - Edwards AFB, street names, conference room names, etc.
  - Hazards must be identified, mitigation implemented, and risk assessed and accepted
- **Misconception of taking risk in Convergent Aeronautics Solutions (CAS)**



Capt Glenn Edwards
Sat, 5 June 1948, AM
YB-49



Judson Brohmer
Tues, 17 July 2001, 0700
F-16

Understand Airworthiness

- **NASA granted authority to conduct airworthiness and safety review processes for "Public Use" aircraft outside of FAA regulations**
- **NPR7900.3C (Aircraft Operations Management Manual)**
  - 2.3.2 Center Directors shall establish airworthiness, flight safety, mission readiness, and configuration control review processes and procedures to identify any hazards, to manage the risks associated with flight programs, to ensure safe flight operations, to manage and thoroughly document aircraft configurations, and to ensure that flight objectives satisfy programmatic requirements.
- **Airworthiness = Capability of an aircraft to be operated within a prescribed flight envelope in accord with the project's safety risk posture**

Understand Airworthiness (Cont)

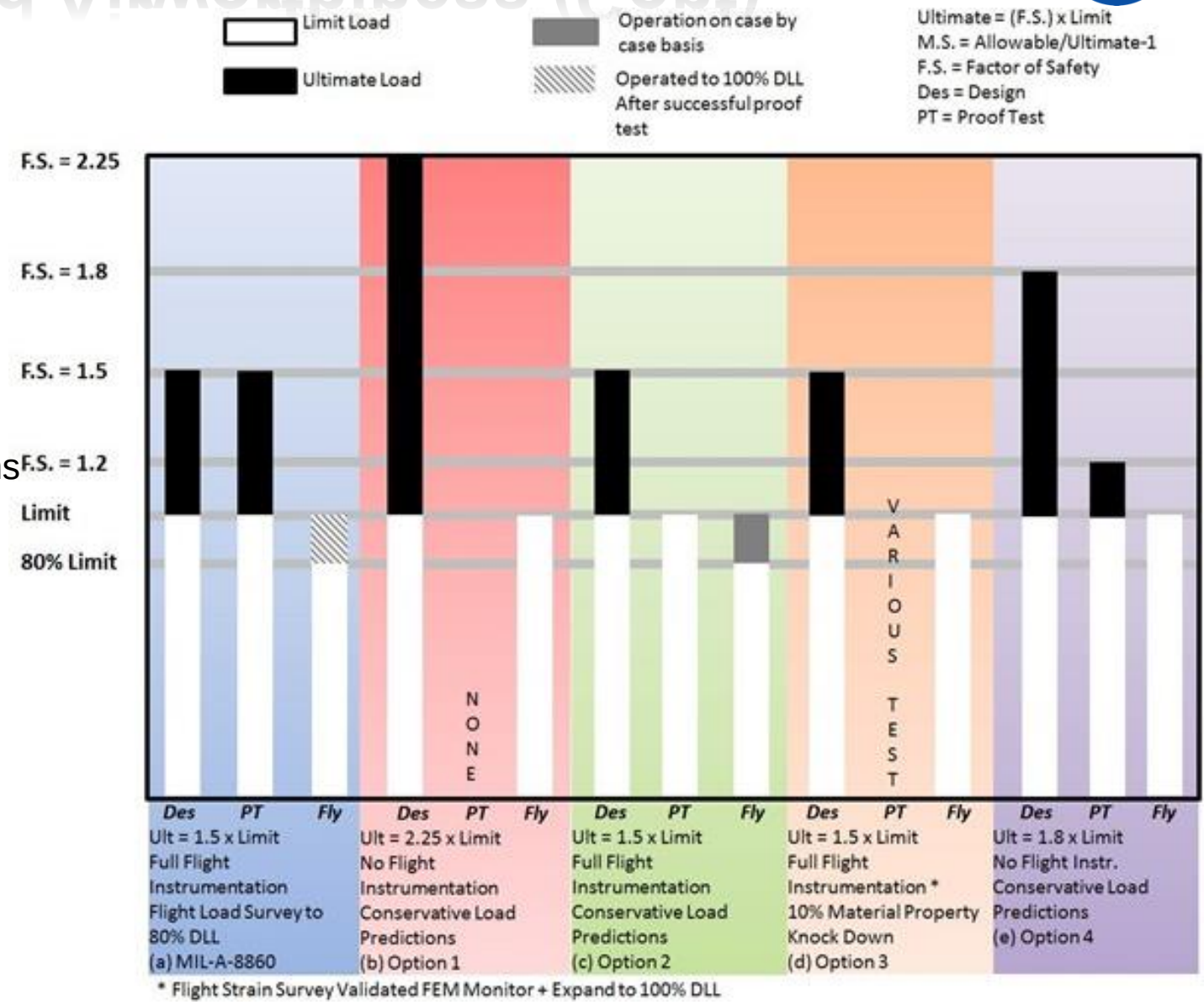
- **Big picture: Understand loads / Understand strength**
- **To support the airworthiness process, Structures Engineers gather airworthiness evidence through analysis and ground/flight-test to increase airworthiness confidence in accord with a project's safety risk posture**
- **X-planes and research aircraft are not normally "certified" operational systems (either FAA or DoD)**
  - Airworthiness guidelines are tailored to meet mission requirements
  - Multiple paths to airworthiness
  - Can accept higher risk (in many cases the higher risk is mitigated through shorter life, more inspections, instrumentation, ground test, etc.)
  - Can trade envelope for margin
  - Can trade real-time monitoring for margin
  - Can disregard (in many cases) fatigue concerns
  - Example:

Quiet SuperSonic Technology (QueSST) Aircraft (LBFD)	vs	Convergent Electric Propulsion Scalable Technology and Operations Research (SCEPTOR)

Understand Airworthiness (Cont)

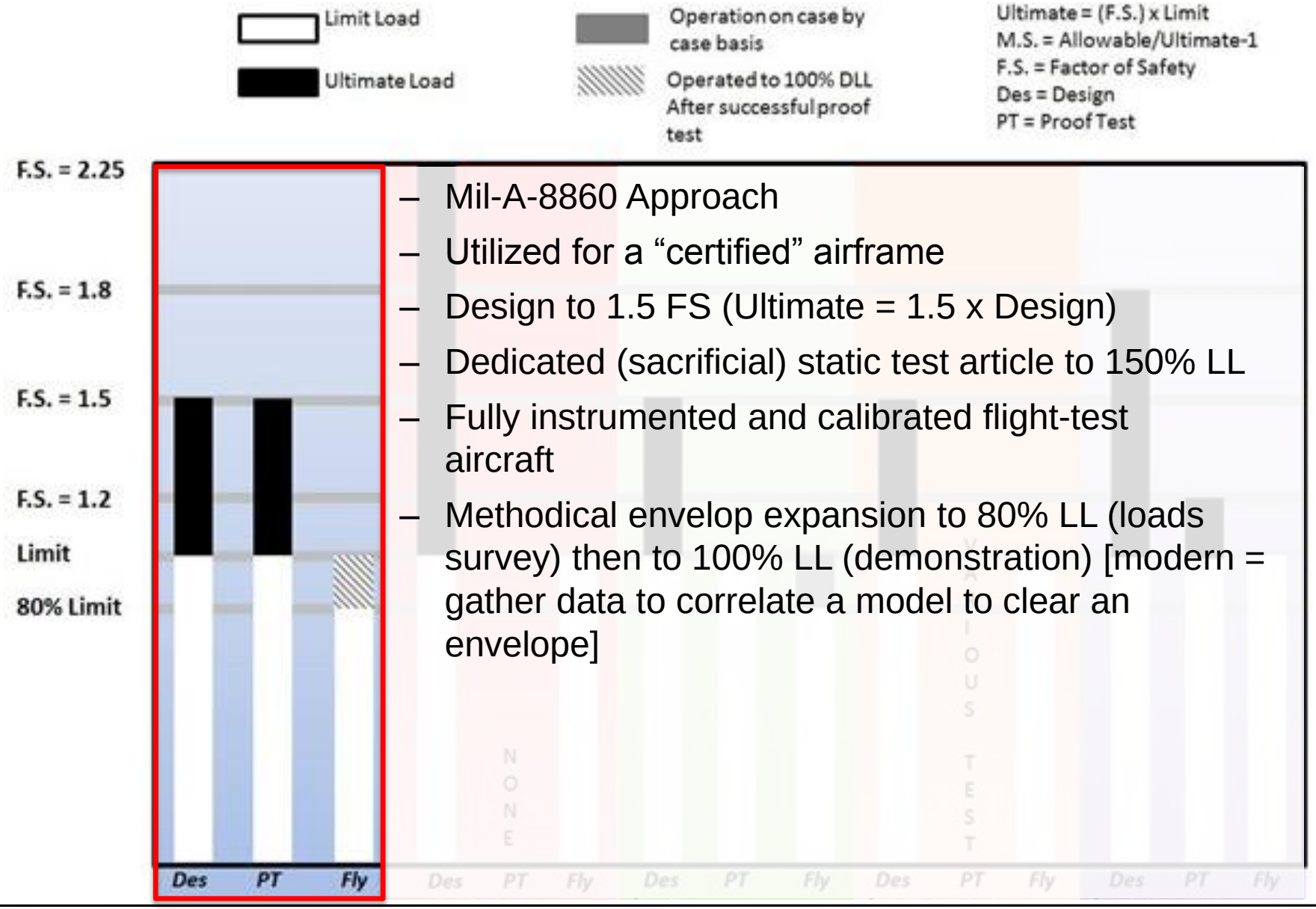
Considerations

- Design FS
- Confidence in external, internal, and thermal loads analysis
- Instrumentation ?
- Ground/flight testing
- Structural inspections (type & intervals)
- Flight envelope limitations
- Flight environment limitations
- Control law tailoring
- Fatigue considerations (usually of little concern)



Ref: G-7123.1-001B2 (Aircraft Structural Safety of Flight Guidelines)

Understand Airworthiness (Cont)



- Mil-A-8860 Approach
- Utilized for a “certified” airframe
- Design to 1.5 FS (Ultimate = 1.5 x Design)
- Dedicated (sacrificial) static test article to 150% LL
- Fully instrumented and calibrated flight-test aircraft
- Methodical envelop expansion to 80% LL (loads survey) then to 100% LL (demonstration) [modern = gather data to correlate a model to clear an envelope]

Understand Airworthiness (Cont)



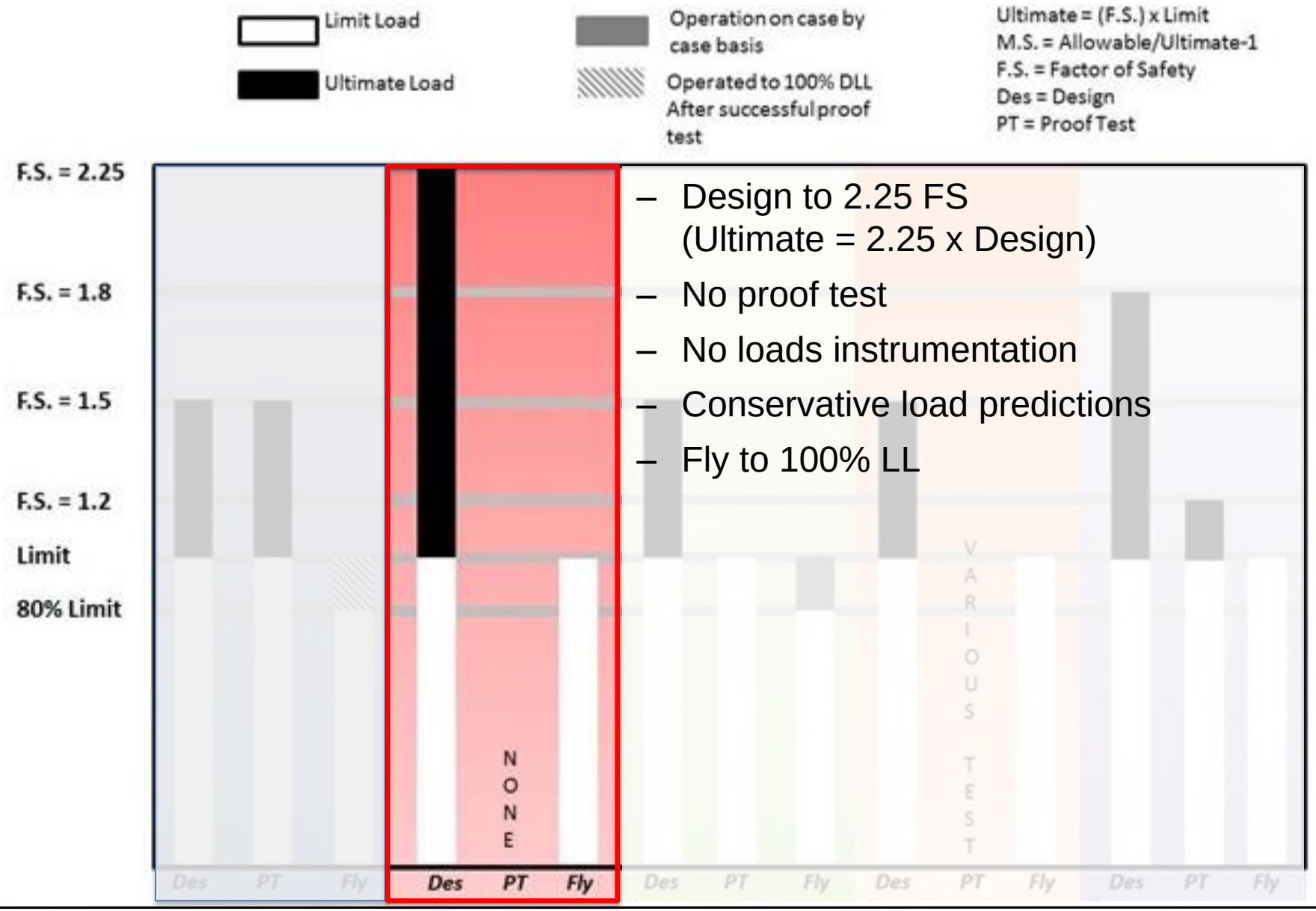








Understand Airworthiness (Cont)



- Design to 2.25 FS (Ultimate = 2.25 x Design)
- No proof test
- No loads instrumentation
- Conservative load predictions
- Fly to 100% LL

Understand Airworthiness (Cont)





AFTI/F-11 Mission Adaptive Wing (MAW)
Variable camber LE & TE



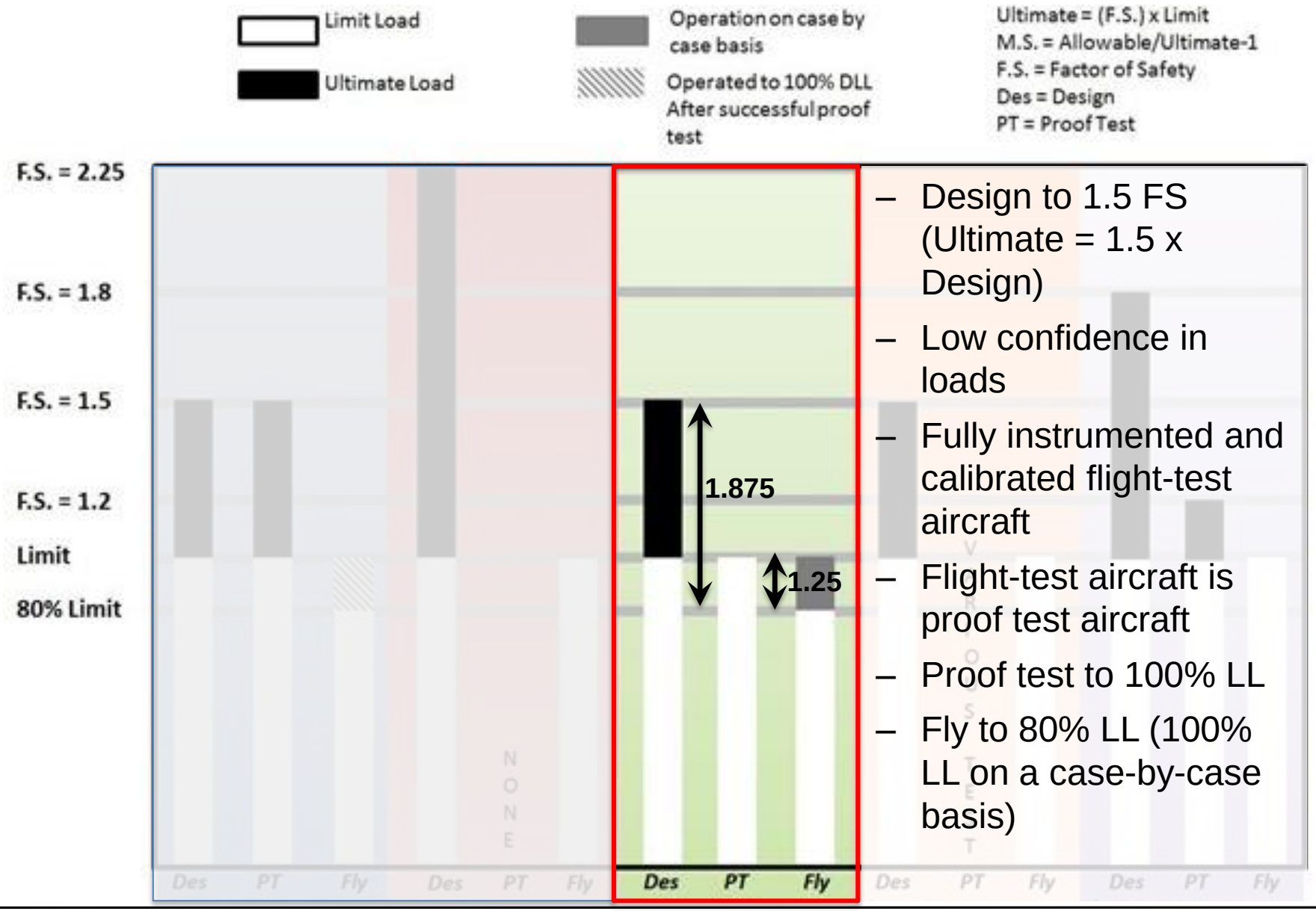


AFTI/F-16XL2 Supersonic Laminar Flow Control Glove and Attachments



F-106/C-141 Tow Launch Demonstration

Understand Airworthiness (Cont)



- Design to 1.5 FS (Ultimate = 1.5 x Design)
- Low confidence in loads
- Fully instrumented and calibrated flight-test aircraft
- Flight-test aircraft is proof test aircraft
- Proof test to 100% LL
- Fly to 80% LL (100% LL on a case-by-case basis)

Understand Airworthiness (Cont)



F-8 Supercritical Wing Research Aircraft



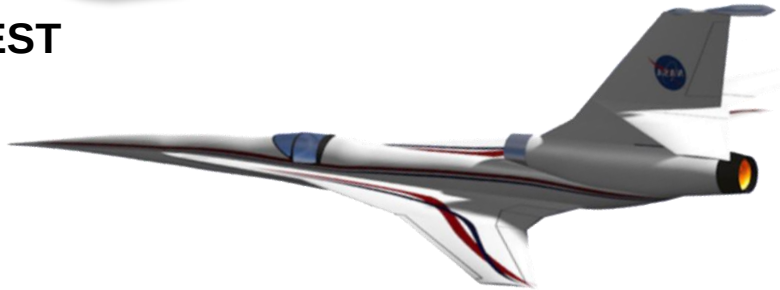
X-29 Advanced Technology Demonstrator



D-8 UEST

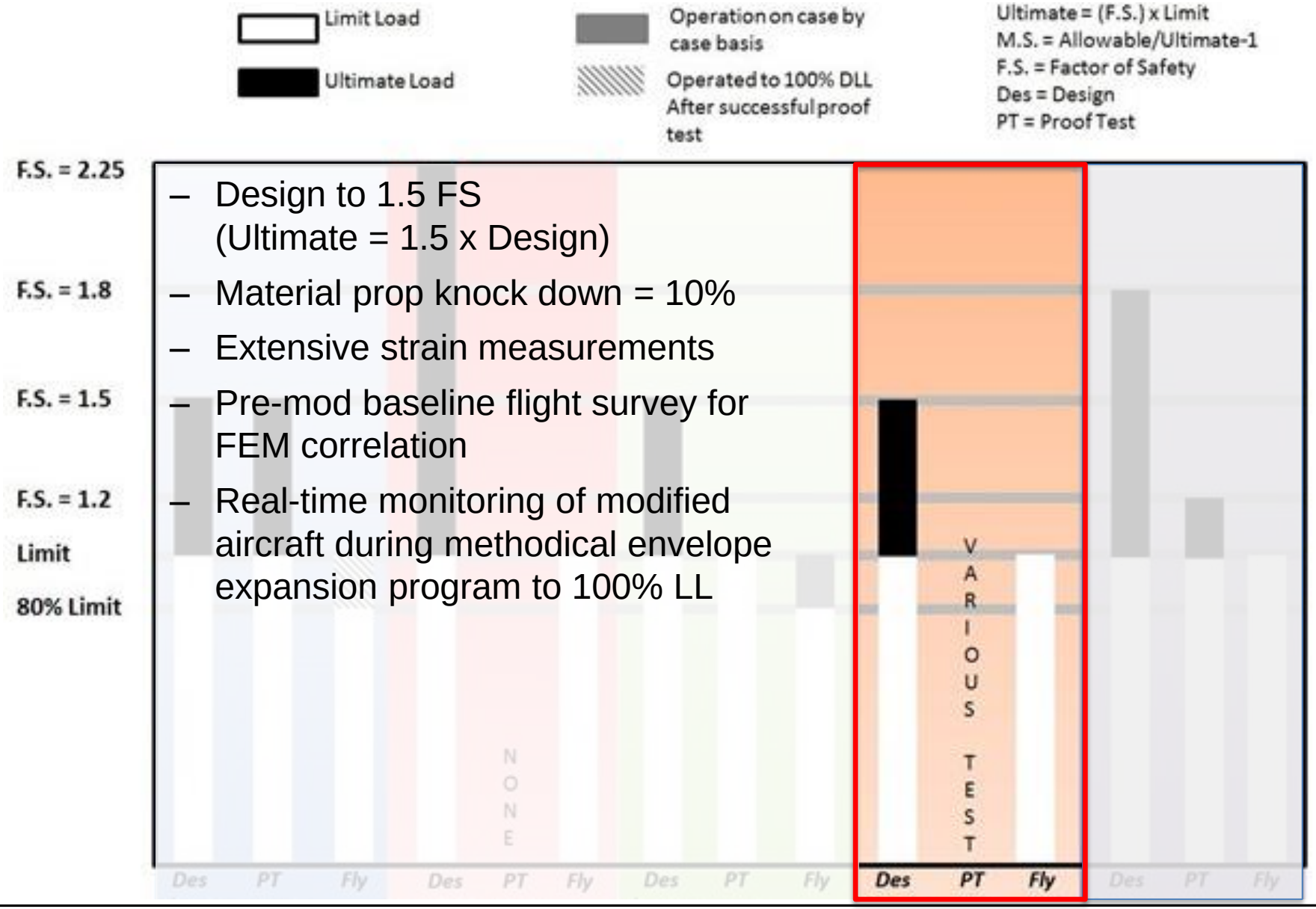


Scalable Convergent Electric Propulsion Technology and Operations Research (SCEPTOR)



Quiet SuperSonic Technology (QueSST) Low Boom Flight Demonstrator (LBFD)

Understand Airworthiness (Cont)



Understand Airworthiness (Cont)

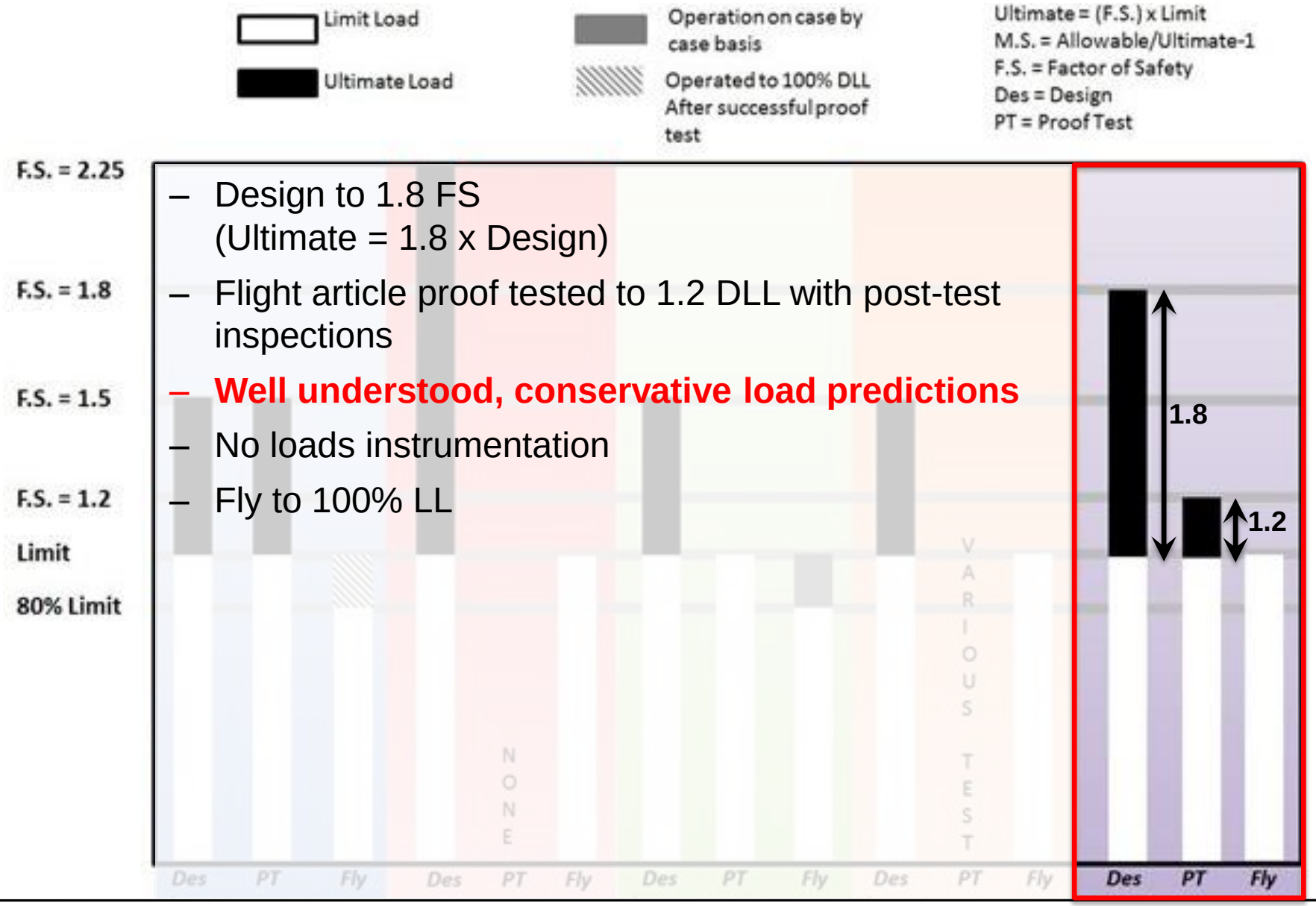






Stratospheric Observatory for Infrared Astronomy (SOFIA)

Understand Airworthiness (Cont)



- Design to 1.8 FS (Ultimate = 1.8 x Design)
- Flight article proof tested to 1.2 DLL with post-test inspections
- **Well understood, conservative load predictions**
- No loads instrumentation
- Fly to 100% LL

Understand Airworthiness (Cont)



Understand Airworthiness (Cont)

- **A Word About Composites…**
- **Difficulty of Composites**
  - Mechanical performance VERY dependent upon Materials and Processes (M&P)
  - Variance of material properties
  - Requires characterization of material properties and structural features
- **AFRC Aerostructures Philosophy**
  - Airworthiness requires a close link between design, analysis, and manufacturing (including material perf) to understand “as built” performance
  - Relationship easier to establish when working with high pedigree OEMs
    - Proven processes and ability to leverage design databases
  - Employ a “building block approach” appropriately scoped for prototype flight
  - Many paths to airworthiness → Tailorable based on risk posture, M&P, etc.

Understand the Requirements

- **X-planes/Research aircraft have unique requirements**
  - Unique research
  - Unique mission
  - Unique flight envelope
  - Unique airframe and systems
- **Design and airworthiness methodology should be tailored to meet unique research/mission requirements**
  - Not held to Federal Aviation Regulations (FAR), Joint Service Specification Guides (JSSG), etc.
- **Structures design and airworthiness methodology needs to be technically adequate (not technically meticulous) to meet the experiment's intent in accord with the project's safety risk posture**
- **Example**
  - SCEPTOR – An electric-aero-propulsion integration experiment; Expected flight time of 30 min within EDW restricted area with EDW lakebed as landing mitigation
  - QueSST – Expected flight time of 90-120 min over multiple CONUS metro areas including ferry to those locations (ferry OCONUS???)

Have the Ability to Learn the Right Info

- **"Everyone" thinks Developmental Flight Instrumentation (DFI) is important**
- **"Everyone" wants DFI (Eng/Res always want more data)**
- **Projects need DFI (Eng/Res need some data)**
- **However …**
  - Instrumentation development is often a project's afterthought and/or the last thing identified in the budget
  - Projects often want the minimum amount of DFI thus limiting understanding of **nominal** and **off-nominal** events
  - Projects want other projects to pay for their DFI development → Bad assumption that someone else is developing what you need
  - Projects often only want COTS DFI, but right DFI for the project's application does not exist (because no one paid for it to be on the shelf & ready to use)
- **Early involvement integral to experiment success**
  - DFI can be long-lead procurement item
  - Design in structurally imbedded DFI
  - DFI development time/effort needed (sensors and packaging)
    - Example: Hypersonics – High temp sensors for flight → New sensor, minimum form factor, minimum weight, severe environment

Learn the Right Info (Cont)

- **Lucky or Good?**
  - Structural DFI needed to understand performance impacting experiment
    - Example: QueSST/LBFD – Primary experiment boom reduction/characterization → Need to understand airframe deflection to understand impact on boom → FOSS deflection and twist determination → Roadmap developed to meet project requirement while leveraging other efforts
  - Structural DFI needed to understand performance in event of mishap
    - Example: Hypersonics experiments where additional info would have been helpful in understanding event
- **Purposed and opportune → Need big picture view to develop meas and test technology/techniques as a priority for future NASA efforts**



Highly Maneuverable Aircraft Technology (HiMAT)

Strain gage loads measurement techniques on composites proven on HiMAT then utilized on X-29

Electro-optical Flight Deflection Measurement System (FDMS) developed for HiMAT then utilized on AFTI/F-111 MAW, X-29, and X-53 AAW







Summary

- **Proposed budgets and research acknowledges need for USA to lead in aeronautics research – for nation and world**
- **If proposed budgets become reality → Very exciting time for NASA to significantly impact our nation's economy for years to come**
- **Lessons Learned**

  #1 – Understand the uniqueness of flight research vs. DT&E

  #2 – Understand risk; Take technical risk; Do not compromise on safety risk

  #3 – Understand tailorable/adequate airworthiness processes applicable to aeronautics research

  #4 – Make sure you have the ability to learn the right information from the research; Work DFI development early