SHUTTLE PROPULSION SYSTEM MAJOR EVENTS AND THE FINAL 22 FLIGHTS

James W. Owen, NASA, Marshall Space Flight Center

ABSTRACT

Numerous lessons have been documented from the Space Shuttle Propulsion elements. Major events include loss of the Solid Rocket Boosters (SRB's) on STS-4 and shutdown of a Space Shuttle Main Engine (SSME) during ascent on STS-51F. On STS-112 only half the pyrotechnics fired during release of the vehicle from the launch pad, a testament for redundancy. STS-91 exhibited freezing of a main combustion chamber pressure measurement and on STS-93 nozzle tube ruptures necessitated a low liquid level oxygen cut off of the main engines. A number of on pad aborts were experienced during the early program resulting in delays. And the two accidents, STS-51L and STS-107, had unique heritage in history from early program decisions and vehicle configuration. Following STS-51L significant resources were invested in developing fundamental physical understanding of solid rocket motor environments and material system behavior. And following STS-107, the risk of ascent debris was better characterized and controlled. Situational awareness during all mission phases improved, and the management team instituted effective risk assessment practices. The last 22 flights of the Space Shuttle, following the Columbia accident, were characterized by remarkable improvement in safety and reliability. Numerous problems were solved in addition to reduction of the ascent debris hazard. The Shuttle system, though not as operable as envisioned in the 1970's, successfully assembled the International Space Station (ISS). By the end of the program, the remarkable Space Shuttle Propulsion system achieved very high performance, was largely reusable, exhibited high reliability, and was a heavy lift earth to orbit propulsion system. During the program a number of project management and engineering processes were implemented and improved. Technical performance, schedule accountability, cost control, and risk management were effectively managed and implemented. Award fee contracting was implemented to provide performance incentives. The Certification of Flight Readiness and Mission Management processes became very effective. A key to the success of the propulsion element projects was related to relationships between the MSFC project office and support organizations with their counterpart contractor organizations. The teams worked diligently to understand and satisfy requirements and achieve mission success.

INTRODUCTION

The propulsion elements provided a remarkable, high performance, reusable rocket engine; evolved to provide highly reliable, large solid rocket motors; provided a fully integrated, recoverable and reusable booster system; and provided a structurally efficient propellant tank with truly significant debris risk reduction. Integration of the propulsion system enabled reliable earth to orbit performance with very small margins. We finished strong. The final 22 flights were not easy, but were a fulfilling contribution to human spaceflight, worthwhile work. STS-135 flown July of 2011 was a superb "completion of mission". In this paper the successes of the final 22 flights are discussed, followed by a discussion of the major events experienced by the propulsion elements during the program. This is followed by an assessment of issues worked during the last 22 flights, looking for recurring themes and lessons. Finally, observations concerning project management practices, and applicability of the propulsion elements to future launch systems are discussed.

During the final flights the propulsion elements embraced a culture of continuous improvement. This was evident in all the elements. Some design changes were implemented in response to the Columbia Accident Investigation Board findings, and many were initiated prior to STS-107 and implemented in the flight program during this era. Each element is discussed below.

SPACE SHUTTLE MAIN ENGINE

The space shuttle main engine implemented a number of design and processing improvements, as well as a major safety upgrade, the advanced health management system. Additionally the engine solved a life issue related to seals in the high pressure oxidizer turbopump with a redesign, and implemented a number of improved insulation systems intended to eliminate liquid air formation during prelaunch. A redesigned fuel flow meter was implemented which eliminated a fluid dynamic phenomena which had occasionally resulted in a slight shift in measured flow rate on the prior design. Manufacturing improvements were also noted in reduced time for nozzle fabrication, significant for reducing manufacturing costs. Additional operational improvements included upgrades to software, updates to the spark ignition system, and improved durability and margins to fasteners at one of the oxygen system joints. These upgrades are shown pictorially, in Figure 1 below, along a timeline illustrating the final flights of the Space Shuttle.

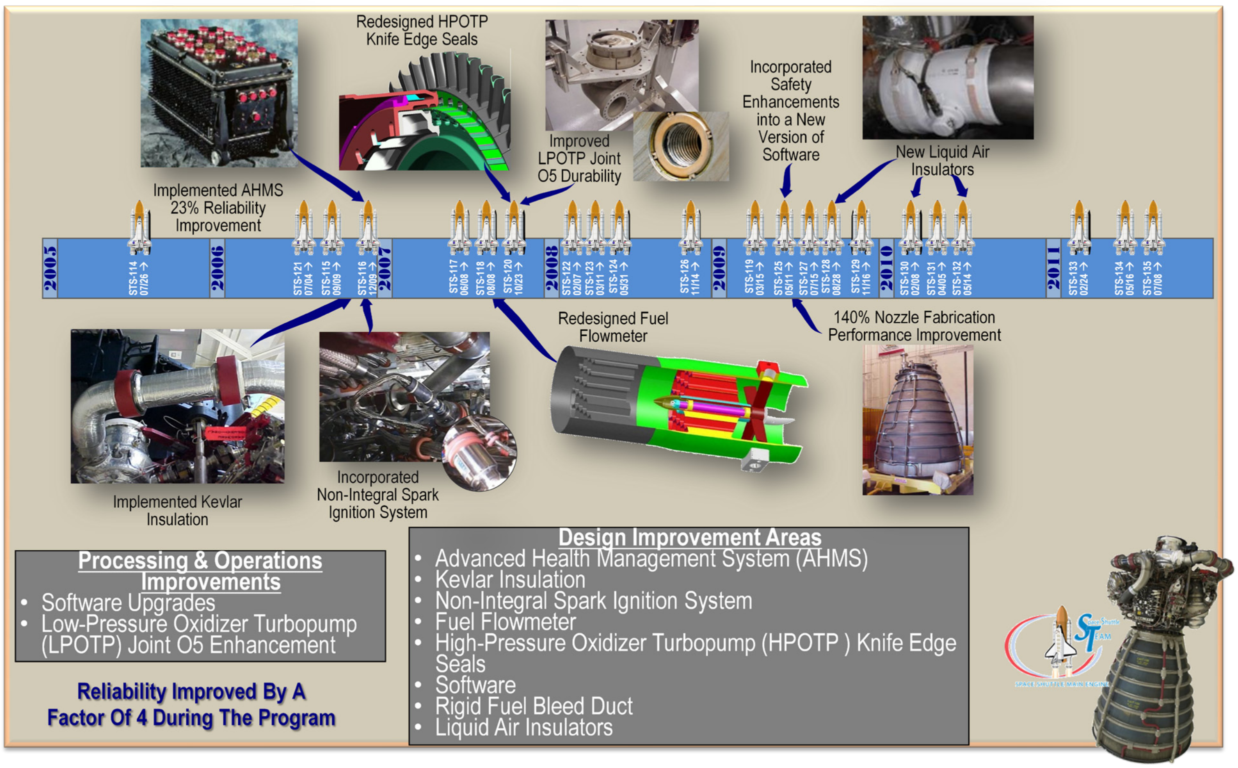


Figure 1. Space shuttle main engine improvements

EXTERNAL TANK

The External Tank project provided significant debris reduction redesigns and processing improvements during the final era of Shuttle flights. Additionally the tank transitioned to use of friction stir welding while implementing major structural upgrades in the manufacturing process. For an expendable element, the tank implemented a very effective post flight assessment process. The debris reduction efforts were implemented in a process of continuous improvement during this era of flight. Existing tanks (already manufactured) were retrofitted with redesigns in areas identified as high risk for debris generation. Eventually, for STS-124, the redesigns were incorporated as the tanks were manufactured, and additional redesigns were implemented. Processing improvements included use of low spray guns for thermal protection system application reducing the occurrence of flaws in the final product, additional attention to human factors for manual processing, use of high fidelity mockups during manufacturing to assess quality, video review of critical spray processes, and use of non destructive evaluation of the finished product. Design improvements included redesign of the bipod fitting foam closeout to eliminate a debris source, addition of a bellows heater within the liquid oxygen feedline to preclude ice formation (another potential debris source), addition of a feedline camera to observe debris performance during ascent flight, elimination and redesign of thick foam applications including protuberance air load ramps and ice frost ramps, and a very innovative ice reduction redesign changing the liquid oxygen feedline brackets from aluminum to titanium. The result of these debris reduction initiatives was roughly a two order of magnitude reduction in impact energy for observed debris events during the final flights. And during all this effort, the tank project successfully implemented friction stir welding in the manufacturing process and transitioned the structural configuration of several major components from aluminum-lithium to an aluminum alloy with better weld properties, to improve manufacturability. All these changes were accomplished without adding weight to the tank. And of great significance was hurricane Katrina, severely damaging the manufacturing facility, and a hail storm which severely damaged a tank while on the launch pad. Recovery from these major events, and implementation of all improvements was a remarkable accomplishment and are illustrated pictorially, in Figure 2 below.

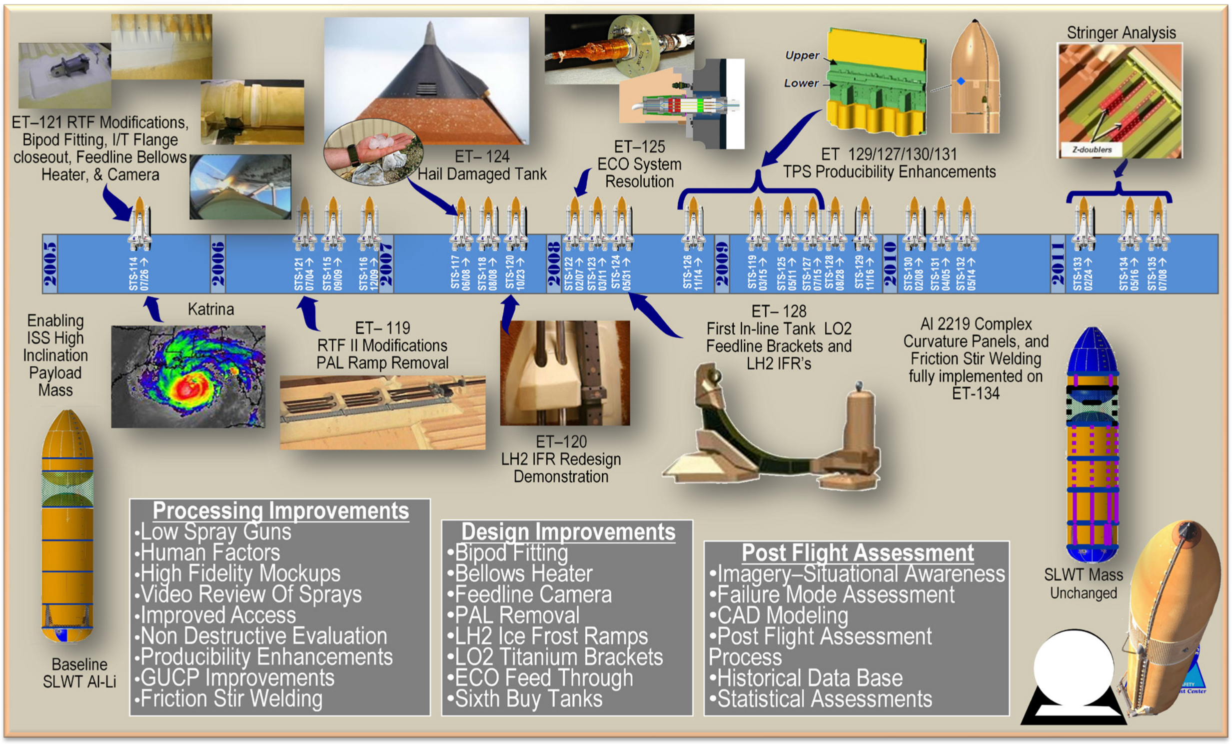


Figure 2. External tank improvements

REUSABLE SOLID ROCKET MOTOR

The redesigned solid rocket motor implemented a major booster separation motor redesign, and used an "intelligent pressure transducer" for flight data acquisition. The booster separation motor redesign was implemented due to the need to procure these components from a new vendor, as the previous supplier chose to discontinue production. Additionally, obsolescence drove re-qualification of an adhesive used in the nozzle. Several redesigns eliminated low design margins including elimination of an inactive stiffener ring and redesign of the propellant forward grain. Several innovative design improvements included use of a new o-ring material which had excellent elastomeric properties even at low temperature, and inclusion of thermal barrier material within nozzle joints called "carbon fiber rope" which absorbed heat and protected joint sealing materials. During this era the delays caused by STS-107 resulted in the solid rocket motor project assessing age life of previously built units to assure flight worthiness. Also during this timeframe a train trestle collapsed during a major hardware shipment, requiring extensive engineering evaluation both to recover the affected hardware from the scene of the accident, and to re-manifest other hardware to support the flight schedule. Performance of the motors was quite remarkable on each flight.

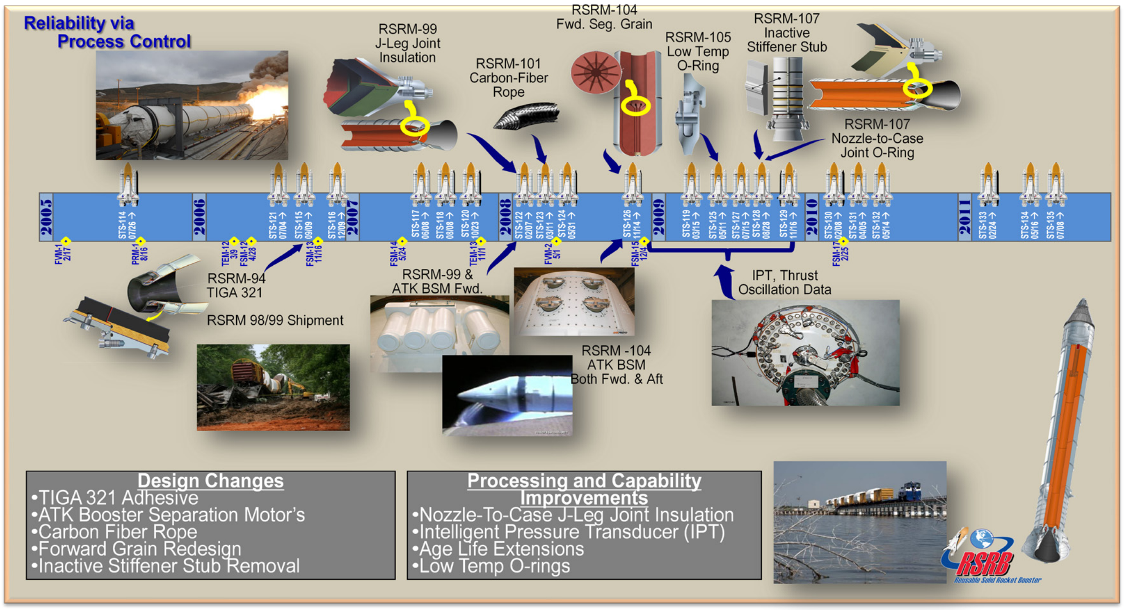


Figure 3. Reusable solid rocket motor improvements

SOLID ROCKET BOOOSTER

The solid rocket booster element implemented a frangible nut cross over feature and provided extraordinary in flight video and data recording. The frangible nut design change significantly reduced the risk of having a condition at lift-off called “stud hang-up”. This occasionally induced an undesirable load into the aft skirt during lift off from the pad. The in flight video implemented following STS-107 provided remarkable ascent videos to observe the vehicle’s potential for ascent debris. Additionally, because the boosters were recovered, they were an ideal platform for standalone data systems to record flight data. This was done on several occasions, and near the end of flight significant data was collected to investigate the potential for thrust oscillations within the solid rocket motor, and to record structural response of the hardware as well. Several redesigns were implemented including a change of material for the aft external tank attach ring to address a material condition and structural margin issue. And near the end of flights a redesigned auxiliary power unit fuel pump eliminated a critical failure mode within the pump, improving flight safety. Additional changes included a modification to the power bus isolation system to eliminate a failure mode and implementation of a new command receiver decoder, part of the range safety system. The solid rocket booster element performance was outstanding and provided significant data to resolve and evaluate system level issues.

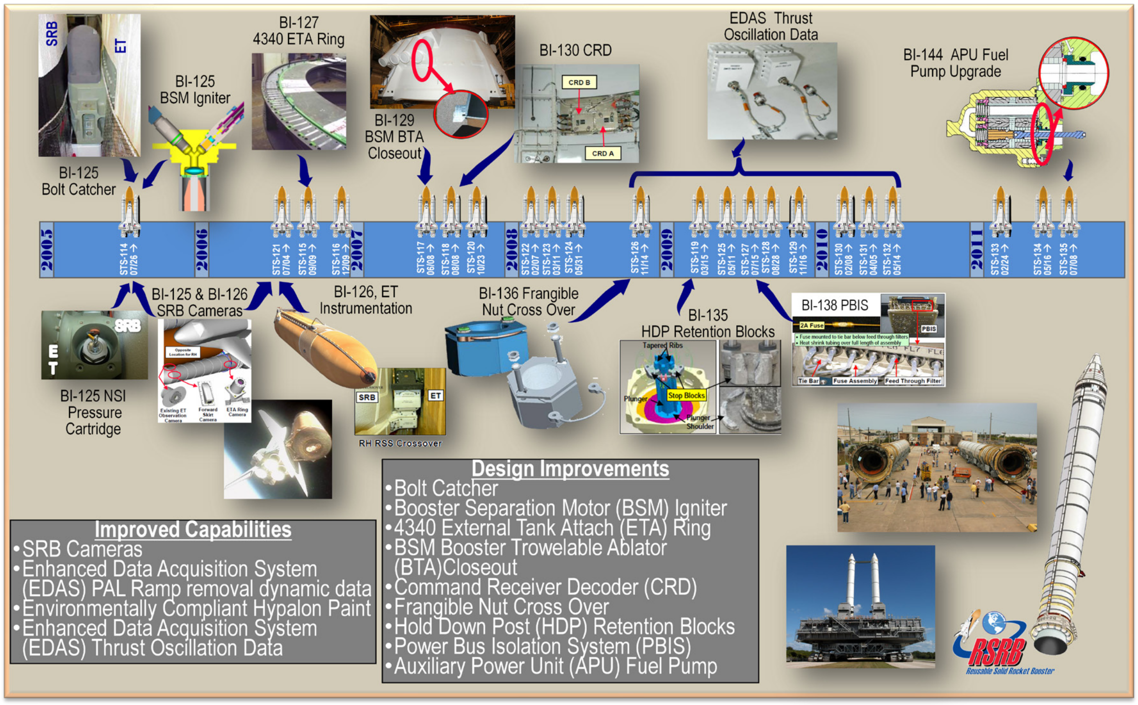


Figure 4. Reusable solid rocket booster improvements

PROPULSION SYSTEMS ENGINEERING AND INTEGRATION

And the Propulsion Systems Engineering and Integration project added new capabilities including imagery analysis, lift off debris assessment, mitigation of debris risk, and contributed to solutions of a number of problems. This included development of a flowliner placard to eliminate a flow induced dynamic environment (which could damage a bellows within the main propulsion feed system). This office was instrumental in evaluation of the newly acquired ascent imagery implemented following STS-107. Additionally, significant improvements in evaluation and control of lift off debris were implemented. These included numerous inspections of the pad, awareness of potential foreign object debris, corrective actions to abate possible debris sources where possible, and evaluation of an aging flame trench at the pad. These and many more are illustrated pictorially in Figure 5. Improvements were implemented in the assessment of day of launch wind constraints and the ability to monitor and evaluate lightning events at the pad. Main propulsion system personnel were essential in contributing to solutions for a liquid oxygen system pre-valve component which exhibited cracking, and for resolution of a flow control valve issue discovered when a valve poppet failed during flight of STS-126. To optimize propellant usage, the commanded mixture ratio was adjusted, based on system modeling. The integrated propulsion system exhibited remarkable success during the final 22 flights.

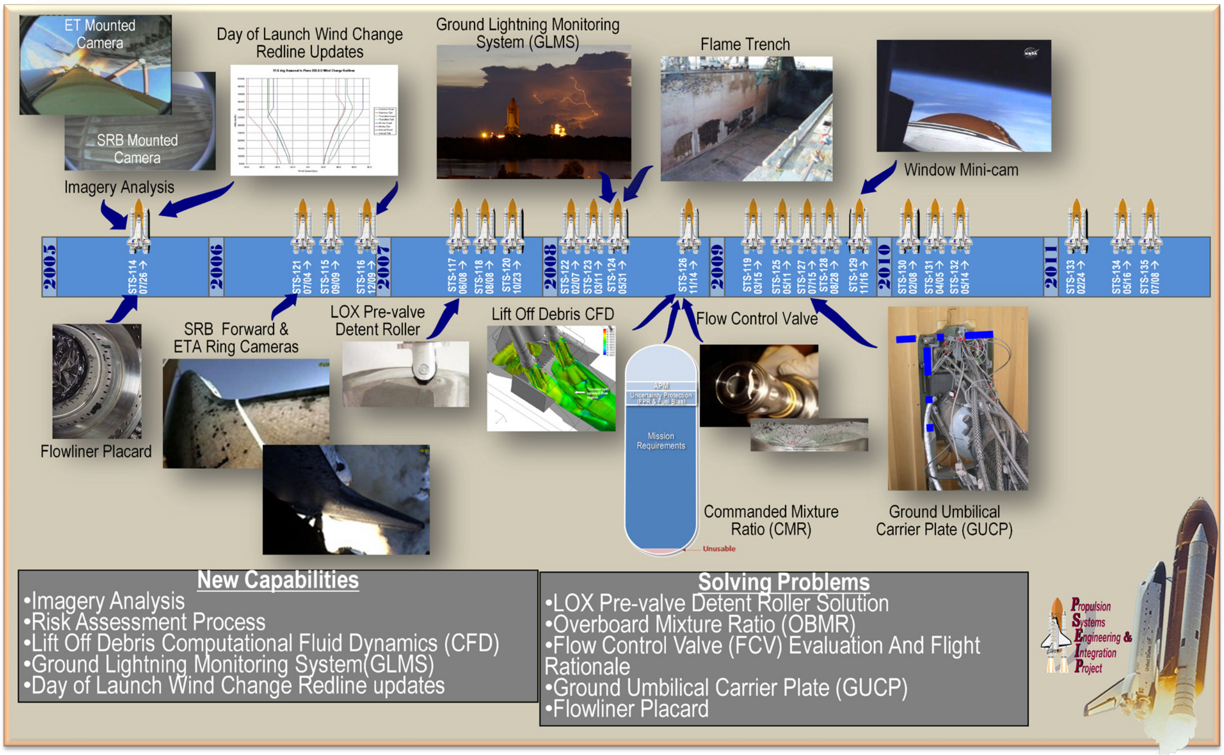


Figure 5. Propulsion systems engineering and integration improvements

DISCUSSION OF RECURRING THEMES

In reviewing lessons during the program experienced by the propulsion elements, and by examining problem resolution, it was useful to categorize contributors to root cause where possible. The first three categories chosen for study included deficiencies in design, inadequate verification of design, and/or escapes during manufacturing, processing, and operations. These can be thought of as encompassing the systems engineering life cycle for the program or project. The final major category chosen was management processes, which at times has been a contributor to poor decision making. The purpose is to look for recurring themes, useful for future consideration. These categories are further defined and discussed below (see Figure 6).

Design deficiencies can result in fundamental hardware problems, avionics design and software errors, or instrumentation system problems including instrument failure. Some issues can be a result of the top level system configuration and/or materials of construction choices made early in the program.

Inadequate design verification can be can result in consequences during the flight program from several sources. Inadequate definition of environments or failure to understand life limits for hardware in its use environment can be a contributor. Inappropriate or inaccurate design analyses (or uncorrelated analyses) can lead to failures in test or flight. Inadequate testing (hardware or software) for verification of requirements, or inability to accomplish adequate combined environment testing has been noted on occasion. This is especially true for space launch systems where the combined environments are complex (not possible to duplicate them accurately in ground testing). And finally the inability to identify interactions among hardware elements, failure to anticipate unintended consequences, or inadequate systems integration can lead to problems.

During manufacturing, processing, and operations, process escapes and human errors can lead to undetected issues. These may be traced to inadequate process controls, or problems traced to acceptance of discrepant hardware (which did not meet acceptance requirements). Inadequate sub-tier vendor controls indicated by inadequate process controls or design standards at a vendor (undetected by the prime) have been noted. Acceptance criteria alone may prove insufficient for parts procured from a vendor. And finally poor situational awareness where inadequate operational data is available to assess risks can lead to in flight issues.

Poor management processes can be manifested in poor communications where problems are a result of the inability to communicate accurate information, or provision of inadequate resources which may include factors leading to workforce fatigue. For multi-decade programs loss of corporate knowledge and retention of adequate technical skills (with knowledge of the design intent) is difficult. And finally, on occasion management processes which led to the acceptance of increasing levels of risk were observed. This may be accompanied by accepting deviations from the design intent without implementing corrective action, incorrect interpretation of a prior warning, inadequate interpretation of post flight conditions, or lack of adequate trend data.

These categories are summarized in Figure 6. As specific examples of problems experienced and solved during the space shuttle flight program are described, the matrix in Figure 6 is used to best characterize major contributors to root cause for each lesson or experience.

- **Design Deficiency**
    - Hardware – problem traced to a fundamental hardware (including avionics) design
    - Software – problem traced to poor software design or software errors
    - Instrumentation – problem traced to a failure of instruments
    - System Configuration – problem traced to “top” system level configuration deficiency, or inadequate systems integration
- **Inadequate Verification**
    - Environments – inadequate definition of environments or failure to understand life limits
    - Analysis Errors – problem traced to inappropriate or uncorrelated analyses
    - Inadequate Testing – problem traced to inadequate verification of requirements, inadequate level of testing (hardware or software),or inability to accomplish adequate combined environment testing
    - Interactions or failure to identify Unintended Consequence – design change causes an undesirable consequence within the system, not detected via the verification process
- **Inadequate Manufacturing, Processing, & Operations**
    - Process Escapes & Human Error – problem traced to inadequate process controls including manufacturing processes or incorrect human action
    - Hardware Acceptability – problem traced to acceptance of discrepant hardware
    - Inadequate Sub-tier Vendor Controls – problem traced to inadequate process controls or design standards at a vendor, undetected by the prime
    - Poor Situational Awareness – inadequate operational data to assess risks
- **Poor Management Processes**
    - Poor Communications – problem was a result of inability to communicate accurate information
    - Inadequate Resources (i.e. Faster, Better, Cheaper) including workforce fatigue
    - Corporate Knowledge & Technical Competence – problem could have been avoided if adequate design/verification expertise had been available (or critical knowledge was lost over time)
    - Escalation of Accepted Risk – normalization of observed deviation from design intent, incorrect interpretation of prior warning, inadequate interpretation of post flight conditions, or lack of adequate trend data

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

Figure 6. Recurring themes

PROPULSION SYSTEM MAJOR LAUNCH OPERATIONS OBSERVATIONS AND IN-FLIGHT EVENTS

Loss of both Solid Rocket Boosters (SRB’s) on STS-4 at water impact: Both SRB’s failed to decelerate properly after separation of the frustum from the booster. A change had been implemented to include explosive ordnance, designed to deflate the chutes at water impact (by separating half the parachute risers). This device activated prematurely at frustum separation. This caused the chutes to stream instead of filling, resulting in the loss (sinking) of both SRB's due to very high water impact velocities. The malfunctioning of the switch was due to shock loads induced from the pyrotechnics for frustum separation. The settings on the g-switch, intended to activate the chute deflation was found to be marginal for this induced shock load.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments	X	Process escapes		Communications	
Software		Analysis		Hardware acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences	X	Situational awareness		Escalation of Accepted Risk	

Hydrogen leakage in the aft compartment prior to STS-6: On the maiden flight of Challenger in 1982, a flight readiness test on the launch pad revealed a hydrogen leak. The launch was postponed. The source of the leak was difficult to identify post test, as it emanated from the high pressure portion of a main engine; the engine operation was required to experience the leakage. A second flight readiness test confirmed the leakage, and special testing was required to finally identify the source, a crack in a weld repair on part of the fuel line plumbing. The number one main engine, the one with the leak, was replaced. In this case, the hardware repair had been accepted per normal review processes, but the crack had grown in service to become an unacceptable condition.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes		Communications	
Software		Analysis		Hardware acceptability	X	Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

Abnormal solid rocket motor nozzle erosion on STS-8: During the flight of STS-8 the carbon/phenolic ablative rings on the forward nose of one of the nozzles exhibited a high rate of erosion, called pocketing erosion. These ablative rings form the interior contour of the nozzle and protect the nozzle's metal structure from the exhaust gases. The major contributor was determined to be high tensile strain in the plane of the carbon cloth fibers. This condition was induced by high thermal conductivity along the plies and thermal expansion normal to the plies. The corrective action included a ply angle change to the design to reduce the material stresses.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware	X	Environments		Process escapes		Communications	
Software		Analysis		Hardware acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

STS-51F Space Shuttle Main Engine Shutdown during ascent flight: On STS-51F a premature engine shutdown 350 seconds into flight was caused by the high pressure fuel turbopump discharge temperature measurements which both exceeded the redline. The other two engines operated longer than planned to obtain a successful "abort to orbit". Post flight inspection confirmed that both temperature sensors had failed and analysis of data showed that there was no problem with the engine performance. This was the only in-flight SSME shutdown of the Shuttle program. Following the center engine shut-down, a sensor in another main engine also failed at the high temperature limit. Premature shutdown of the engine was prevented when mission control instructed the shuttle commander to inhibit the protection circuitry. Post flight inspection showed that sensor failures were caused by element wire breakage. Sensors of a new improved design were used on subsequent flights. The lesson is that instrumentation systems can be less reliable than your hardware.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation	X	Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

STS 51-L Loss of Crew and Vehicle: The failure of the solid rocket motor field joint sealing system during launch of Challenger on January 28, 1986 has been well documented, and investigated by the Rogers Commission. The combination of a design which allowed the joint to open during motor pressurization coupled with extremely cold temperature on the day of launch resulted in hot gas leakage leading to structural failure of the vehicle and loss of the crew. The investigation revealed prior warnings of problems with the field joints, and an increasing acceptance of risk as flights proceeded. Redesign following the accident corrected the design's shortcomings, and produced a design that has multiple layers of protection. These improvements include a capture feature that greatly reduces gap opening, an innovative seal within the segment insulation called a j-leg, joint heaters, and improved assembly procedures. The redesign flew successfully throughout the remainder of the program, with no indications of sealing problems. A number of cultural, managerial, and decision making process improvements were implemented, and the government/industry team performed exceedingly well during the remainder of the program.

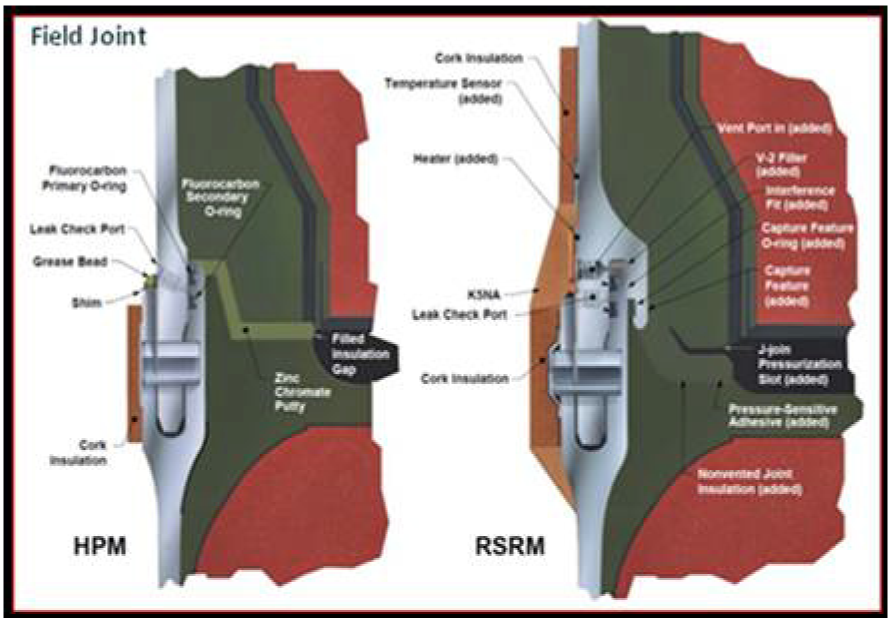


Figure 7. Solid Rocket Motor Field Joint Redesign

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware	X	Environments	X	Process escapes		Communications	X
Software		Analysis		Hardware Acceptability		Resources	X
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	X

On Pad Aborts: While preparing for STS-41D on June 26, 1984 the countdown for the second launch attempt for Discovery's maiden flight ended at T-4 seconds when the main engine controller detected a sluggish valve in main engine number three. The main engine was replaced and Discovery launched on August 30, 1984. This launch attempt marked the first time since Gemini 6A that a crewed spacecraft experienced a shutdown of its engines just prior to launch. During preparation for STS-51F on July 12, 1985, Challenger's countdown halted at T-3 seconds due to a problem detected with a coolant valve on main engine number two. The valve was replaced and Challenger was launched on July 29, 1985. And while preparing for the launch of STS-55 on March 22, 1993, Columbia's countdown halted at T-3 seconds when a problem was detected with a purge pressure reading in the oxidizer preburner on main engine two. All three main engines were replaced on the pad, and the flight was rescheduled after STS-56 and launched on April 26, 1993. In preparation for STS-51 on August 12, 1993 the countdown for Discovery's third launch attempt halted at the T-3 second seconds when a main engine controller detected failure of one of four sensors in main engine number two which monitor hydrogen flow. All three main engines were replaced on the pad, delaying the fourth launch attempt until Sept. 12, 1993. In preparation for STS-68 on August 18, 1994, Endeavour's countdown was halted at 1.9 seconds before liftoff when a higher than acceptable reading in one sensor monitoring the discharge temperature of a high pressure oxidizer turbopump was detected. A test firing of the engine at the Stennis confirmed a slight drift in a fuel flow meter in the engine that caused a slight increase in the turbopump's temperature. The test firing also confirmed a slightly slower start for main engine number three during the pad abort, which could have contributed to the higher temperatures. Following replacement of all three main engines in the Vehicle Assembly Building, Endeavour was launched on October 2. Launch commit criteria have been a key in detecting problems, prior to flight, contributing to mission success.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware	X	Environments		Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

Hydrogen leakage STS-35: The launch was first scheduled for May 16, 1990 but was scrubbed during tanking due to a leak in the external tank to orbiter 17-inch quick disconnect assembly. Hydrogen was also detected in orbiter's aft compartment but was believed to be associated with leak involving 17-inch umbilical assembly. This hardware was replaced in the vehicle assembly building and Columbia rolled out to Pad A for second time. During tanking, high concentrations of hydrogen were detected in orbiter's aft compartment, forcing another postponement. NASA managers concluded that Columbia had experienced separate hydrogen leaks from beginning; one from the umbilical assembly (now replaced) and one or more in aft compartment which had resurfaced. Suspicion focused on three hydrogen recirculation pumps in aft compartment. These were replaced and retested. However, the fuel leak in aft compartment resurfaced again during tanking and the mission was scrubbed. The STS-35 mission was put on hold until the problems were resolved by a special tiger team assigned by the space shuttle program. The hydrogen leak investigation team analyzed available data from previous tests and developed a fault tree which identified suspect joints for further test and inspection. In addition, leak check and gas detection methods were reviewed. A suspect joint list was developed based on the fault tree and each of these joints was repaired and/or re-torqued. Following systematic leak checks and another tanking test using special instrumentation the leak was finally eliminated and the mission proceeded. When dealing with hydrogen systems, processes must assure adequate sealing system performance.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes		Communications	
Software		Analysis		Hardware acceptability	X	Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

STS-78 Pressure Sensitive Adhesive: Hot gas penetrated past the tips of solid rocket motor j-legs (an innovative thermal barrier which inhibits gas flow to the motor case joints) on STS-78 launched in July 1996. A new environmentally friendly pressure sensitive adhesive was used for the first time on this flight. The new adhesive had worked well in static testing. Investigation revealed that the humid environment at Kennedy Space Center reduced the strength of the adhesive. The corrective action was to return to the baseline adhesive. Verification testing must include all operating environments and parameters.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments	x	Process escapes		Communications	
Software		Analysis		Hardware acceptability		Resources	
Instrumentation		Testing	x	Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences	x	Situational awareness		Escalation of Accepted Risk	

STS-91 SSME Chamber Pressure Channel A Failure: On 06/02/1998, during Discovery's ascent, the Main Combustion Chamber (MCC) Chamber Pressure Channel A sensor ceased to respond on main engine one. During throttle down, channel A exceeded the 200 PSID limit (the sensor did not follow the engine power level). Main Engine one was controlled by Channel B for the remainder of ascent. No engine problems were experienced and Discovery continued to a nominal orbit insertion. The channel A sensor, however, remained qualified for redline monitoring by the controller, since it was with reasonable limits. If the engine had experienced a real problem that drove the engine to a chamber pressure redline, sensor B (the good one) would have called for an over-speed shutdown which would have been ignored by the controller because sensor A (the bad one) remained qualified for redline monitoring. Hence redline protection had been lost. Contamination was found (post flight) to have plugged the chamber pressure port (a material from a leak check performed during engine manufacture). Control of foreign object debris is essential.

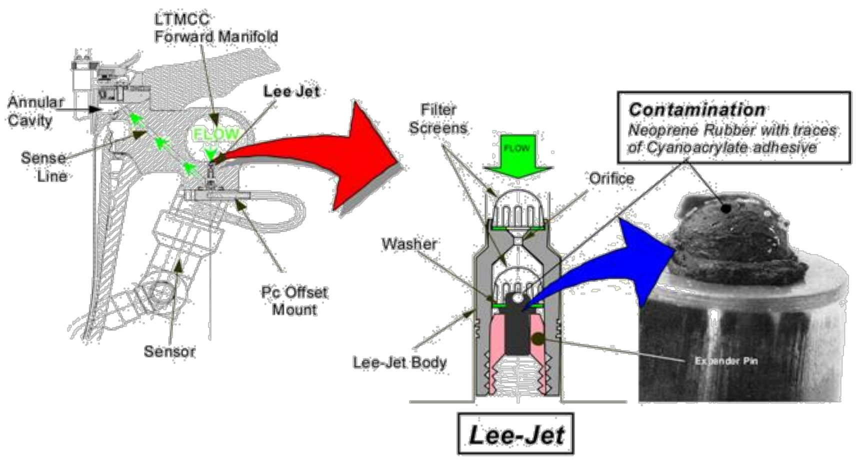


Figure 8. Contaminated Chamber Pressure port

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes	x	Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

STS-93 Orbiter wiring and Space Shuttle Main Engine (SSME) nozzle tubes punctured during ascent flight: Two serious in-flight anomalies occurred during ascent flight on STS-93. One main engine controller primary circuit, and one back-up circuit, on separate engines dropped offline when an Orbiter AC power bus experienced a short circuit 6 seconds after liftoff. The redundant controller circuits (one on each engine) worked throughout ascent, but redundancy had been lost on two engines. This flight observation initiated a system level inspection of all Orbiter wiring. Clearly redundancy management had been key to mission success. Additionally, on STS-93, a nozzle fuel leak on one engine resulted in a premature main engine shut down (low level liquid oxygen cutoff) due to an SSME liquid oxygen pin being ejected from an injector post in the main combustion chamber. The pin penetrated 3 nozzle coolant lines causing a hydrogen leak from the nozzle. The loss of fuel caused the main engine controller to increase power level (an increase in turbine power requires an increase in oxidizer flow) which depleted oxygen prematurely. Acceptable orbit insertion, or orbital velocity, was provided by the Orbiter Maneuvering System, post main engine shutdown. Corrective action called for elimination of pins used in the main combustion chamber liquid oxygen posts. Redline protection was essential in achieving mission success.

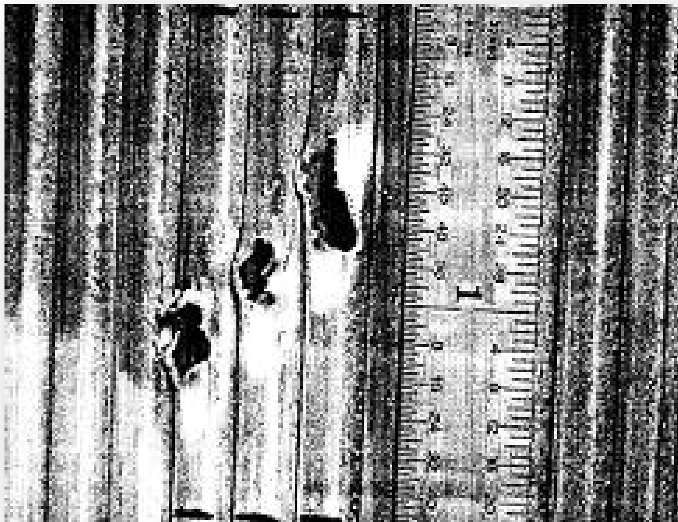


Figure 9. Punctured nozzle coolant tubes from STS-93

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes		Communications	
Software		Analysis		Hardware acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences	x	Situational awareness	x	Escalation of Accepted Risk	

STS 112 Pyrotechnic Initiator Controllers (PICs) did not discharge: On STS 112 in 2002, half the critical pyrotechnic systems, which release the shuttle from the launch pad, did not work. Post launch review indicated that the Pyrotechnic System A Hold Down Post (HDP) and ET Vent Arm System (ETVAS) Pyrotechnic Initiator Controllers (PICs) did not discharge. The most probable cause was narrowed down to loss of the fire command due to a single wire path failure at the T-0 interface. Solid Rocket Booster exhaust and salt-spray environment of the pad likely created corrosion on the connectors. This corrosion eventually interrupted safety-critical circuits. Because the systems had redundancy, the flight launched successfully. The connectors were inspected for corrosion on subsequent flights.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments	x	Process escapes		Communications	
Software		Analysis		Hardware Acceptability	x	Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

STS 107 Loss of Crew and Vehicle: The loss of crew and vehicle during entry of Columbia on February 1, 2003 was a result of debris damaging the Orbiter wing during ascent. This accident was well documented by the Columbia Accident Investigation Board report. Prior warnings of debris damage had been evident throughout the history of the program, but had usually been treated as a maintenance and refurbishment item. Following STS-107 corrective actions were implemented to remove sources of foam debris where possible, improve process controls, and preclude ice formation in selected components as well. The debris risk mitigation efforts continued as the flight program continued. Generally the effect of debris mitigation efforts during the final 22 flights resulted in a two order of magnitude reduction in possible impact energy. The program also implemented on orbit inspection to assess the Orbiter heat shield prior to entry, and developed a thermal protection system repair capability if needed during orbit.

The resulting redesigns and operational procedures enabled successful management of risk during the remainder of the flight program.

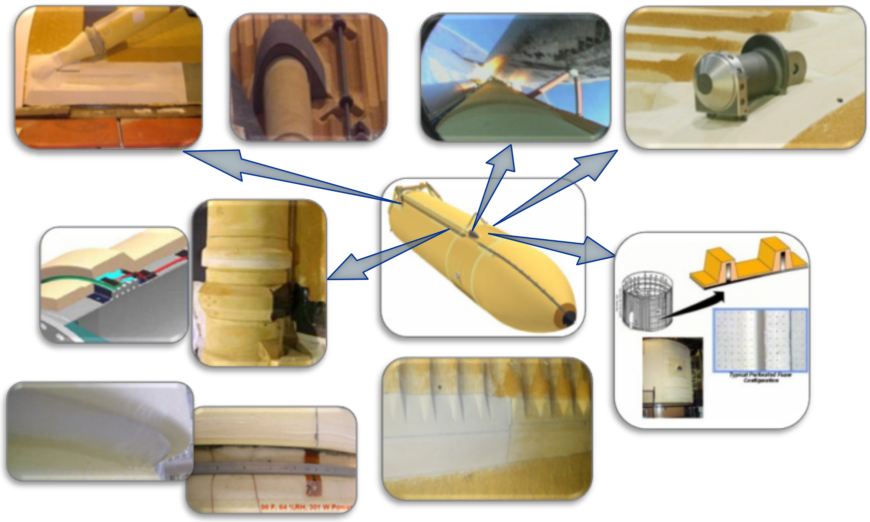


Figure 10. STS-114 External Tank Redesigns resulting in Reduced Ascent Debris Risk

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes		Communications	X
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration	X	Consequences		Situational awareness	X	Escalation of Accepted Risk	X

Summary from the major launch operations observations and in-flight events: It is apparent from the summary table below that a number of issues were related to design, verification, and processing. Design changes must always be assessed for unintended consequences, and require adequate certification. Redundancy management was a key to success on several occasions. Also, instrumentation systems can be less reliable than the hardware it is monitoring. Control of foreign object debris is essential. Wiring and connectors in a reusable system can be especially vulnerable to wear and collateral damage. The program's management processes were criticized following the major failures, as risks were poorly communicated, and increasing levels of risk were accepted without corrective action. Situational awareness, good communications, adequate resources, and a clear understanding of accepted risk are essential to success. The consequences of failure were severe, loss of life, loss of mission, and change of space policy. Where possible, drive out failures via ground testing or non crewed flight testing.

	Design Deficiency				Inadequate Verification				Inadequate Mfg., Proc., and Ops.				Poor Management Processes			
Major Events	Hardware	Software	Instrumentation	Sys. Configuration	Environments	Analysis	Testing	Consequences	Process escapes	Hardware acceptability	Sub-tier vendor controls	Situational awareness	Communications	Resources	Corporate knowledge	Escalation of Accepted Risk
Loss of both Solid Rocket Boosters (SRB's) on STS-4					X			X								
Hydrogen leakage in the aft compartment prior to STS-6										X						
Abnormal solid rocket motor nozzle erosion on STS-8	X															
STS-51F Space Shuttle Main Engine Shutdown during ascent flight			X													
STS 51-L Loss of Crew and Vehicle	X				X								X	X		X
On Pad Aborts	X															
Hydrogen leakage STS-35										X						
STS-78 Pressure Sensitive Adhesive					X		X	X								
STS-91 SSME Chamber Pressure Channel A Failure									X							
STS-93 Orbiter wiring and Space Shuttle Main Engine (SSME) during ascent flight												X				
112 Pyrotechnic System Pyrotechnic Initiator Controllers (PICs) did not discharge					X					X						
STS 107 Loss of Crew and Vehicle				X								X	X			X

The Final 22 Flights

Surprisingly, a number of design changes were made late in the program, to address known problems, or to implement planned upgrades. Several of these are briefly discussed here. While these are not major redesigns or block upgrades, all had to be evaluated for unintended consequences. Occasionally these consequences also had to be addressed. Additionally problems worked are summarized, best characterizing root cause as above. Issues involving design or design changes are discussed first, followed by issues related to processing. Finally, some items where new knowledge about the system was acquired after all these years are discussed, followed by some unique observations related to unexpected events.

ISSUES RELATED TO DESIGN OR REDESIGN, AND VERIFICATION

External Tank (ET) Liquid Hydrogen Tank (LH2) Ice Frost Ramps: A unique opportunity arose following STS-114, when an External Tank (ET-120) was returned to the manufacturing facility after undergoing two cryogenic cycles on the launch pad. Detailed inspection of a flight tank following partial operation had never been done before. Dissection data of the thermal protection foam material from ET-120 (post cryogenic cycling) revealed significant foam cracking and delaminations within the liquid hydrogen tank ice frost ramps and protuberance air load ramps (PAL). The PAL ramps were subsequently removed. Subsurface cracking and delaminations in the ice frost ramps, were believed to be linked to stresses induced by thick foam. Reducing foam thickness was thought to be a solution. However, reshaping the ramps revealed conflicting thermal and debris requirements and did not address root cause. Subsurface cracks and delaminations were later found to be caused by cryogenically induced liquid air intruding into “built-in” leak paths and reservoirs. Once the failure mode was fully understood, a redesign was initiated which met thermal and debris requirements. Additionally, identification of the correct failure mode enabled updated risk assessments showing greatly reduced ascent debris risk from these ramps. The lesson to remember is that failure modes and effects must be fully understood and characterized. The ability to get direct inspection of actual hardware after service is invaluable.

Figure 11. Liquid Hydrogen Tank Ice Frost Ramps

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware	X	Environments		Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

Redesign of the Liquid Oxygen Feed-line Bracket: A significant change implemented during the final 22 flights was the redesign of the feedline support brackets (from aluminum to titanium) greatly reducing the risk from ice debris, and eliminating a failure mode discovered at the bracket to feedline interface. The material change greatly simplified the foam closeout on the bracket, and dramatically reduced ice formation on the bracket. The initial redesign included a gap at the bracket to feed-line interface, susceptible to ice formation. Ice growth at these interfaces could bridge the gaps between the bracket and feedline, and subsequent articulation of the joints could cause the foam to crack. This could have resulted in ice and foam debris. Flight video data from STS-118 revealed the potential debris risk (from an aluminum bracket with a similar gap), and a slip joint was successfully added to the redesign, eliminating the gap (and ice). This design was extremely successful, flying on twelve of the final twenty-two flights.

Figure 12. Liquid Oxygen Feedline Titanium Bracket

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware	X	Environments		Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

Solid Rocket Booster (SRB) Pyrotechnic Cross-over Redesign and Debris Containment Plunger Failure: During launch of STS 126 video showed the SRB hold-down post (HDP) plunger spring, and plunger, extending during liftoff from the debris containment system. Concurrent with this launch a design change had been implemented to reduce the occurrence of a condition called “stud hang-up” a recurring anomaly during the program. A pyrotechnic crossover feature had been added to the SRB frangible nut, part of the system which released the Shuttle from the pad. The change enabled nearly simultaneous firing of two pyrotechnic charges in the nut. The crossover successfully mitigated the potential for stud hang up, but an unintended consequence was discovered. The decreased pyrotechnic skew time (the time between the two charges firing) increased the velocity of the debris containment system plunger, and increased the chance of a plunger being released. A design modification (called retention blocks) was successfully implemented within the debris containment system housing to address this issue for STS-119 and subsequent missions. All changes must be evaluated for potential unintended consequences.

Figure 13. Pyrotechnic cross over and plunger/spring released during lift-off

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences	x	Situational awareness		Escalation of Accepted Risk	

Ground Umbilical Carrier Plate (GUCP) Disconnect: A recurring problem during the program was leakage from the ground interface disconnect for the hydrogen vent line from the External Tank to the hydrogen burn stack. Leakage from the GUCP had been a nuisance occasionally during the program, and recurred on STS-119 and again on STS-127. Seals and interface hardware were replaced. The problem recurred on STS-133 and a detailed alignment procedure was developed to align the ground system interface to the flight seal with a high degree of concentricity. The corrective actions enabled process and assembly controls to be adequate to meet the design intent. One lesson is, if you are not able to identify root cause and implement corrective action, anticipate recurrence sometime in the future.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware	x	Environments		Process escapes	x	Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

Redesign of Space Shuttle Main Engine High Pressure Oxidizer Pump Knife Edge Seals: Inboard and outboard turbine exit knife edge seals in the High Pressure Oxidizer Turbopump (HPOTP) were redesigned in order to fix two different problems (one problem with each of the two seals). Changes were certified through analysis, component test, and engine testing. Significant testing was required to identify root cause and to certify the design change. The entire effort took three years to work the redesigned hardware into the flight program. The redesigned outboard seal incorporated damping to resolve a fluid-structure instability which was most likely induced by certain combinations of effects from the surrounding flow (certain flow rates, pressures, etc.). The redesigned inboard seal incorporated a single larger tooth to eliminate acoustic interactions. This design change was essential in eliminating a life limit on the pumps, which was a significant impact to flight operations.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware	X	Environments	X	Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

Solid Rocket Motor Operational Pressure Transducer (OPT) Redesign: During the final flights of the program a change was implemented to replace the flight OPT's with a newer design (from a new vendor because the original supplier had gone out of business), first implemented on STS-114. Twelve units of the new OPTs were successfully flown before an OPT failure occurred on STS-117 during the pre-flight Shuttle Interface Test (SIT). Workmanship and design deficiencies were identified via a failure investigation. It was determined that the circuit boards, as designed, did not meet design standards. Redesign and re-qualification of this design was completed but not flown. The remainder of the flight program was completed using the previous vendor's units. The redesigned units were held as spares. The key lesson is that sub-tier vendor design standards and process controls must meet flight standards, and the prime contractor must assure acceptability of their procured parts.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware	X	Environments		Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls	X	Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

ISSUES RELATED TO MANUFACTURING, PROCESSING, AND OPERATION

STS-114 Increased Number of LH2 Pre-pressurization Cycles: In preparation for STS-114 an increased number of cycles were noted during pressurization of the hydrogen tank to flight pressure levels. The cause was determined to be an out of configuration screen material for diffusers installed in the pressurization system. The condition was found to exist on several tanks. The screen material installed was not per engineering requirements (discovered at sub-tier supplier). A plain dutch weave wire was specified but a duplex dutch weave wire was used during manufacturing. This altered the pressure drop in the diffuser and changed the system response (pressure cycling). A redline on number of cycles was in effect, to attempt to detect hydrogen leakage from the vent valve, and this out of configuration part made violation of the redline a possibility. As corrective action all out of configuration diffusers were replaced. The lesson is that sub-tier vendor controls, and material acceptance inspections must insure proper configuration.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes		Communications	
Software		Analysis		Hardware Acceptability	X	Resources	
Instrumentation		Testing		Sub-tier vendor controls	X	Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

STS-133 External Tank Cracked Stringer: During preparations for launch of STS-133 stringer cracks were observed on the External Tank intertank liquid oxygen flange during propellant loading. Subsequent cracks were identified by nondestructive evaluation following roll back to vehicle assembly building. Extensive root cause investigation was performed and identified two primary contributors, first a material with low fracture toughness (isolated to two lots of material) had been used during assembly, and second loads and resulting residual stresses had been imparted during assembly of stringers due to tolerance stack up. A corrective action was successfully implemented by reinforcing the stringer feet near the end of the stringer. The lessons include the need for adequate sub-tier vendor controls, and material acceptance inspections must assure proper configuration. Also, design and assembly tolerances must accommodate the potential for residual stresses.

Figure 14. External Tank stringer cracks

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes		Communications	
Software		Analysis		Hardware Acceptability	X	Resources	
Instrumentation		Testing		Sub-tier vendor controls	X	Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

SRB Ordinance ring installation (linear shape charge rotation): During STS-120 the Linear Shape Charge (LSC) failed to cut 22 inches of the frustum to forward skirt attach ring. The frustum separated successfully, but concern existed for future flights. An investigation determined that the failure to cut resulted from a rotated LSC subassembly (i.e. the LSC angle was too great for jet penetration). Analysis determined that the subassembly rotation was possible, based on dimensional data measure from actual lots. The corrective action included enhanced LSC installation techniques to minimize the potential rotation. Also an additional inspection, via nondestructive x-ray, was developed and added on all ordnance rings post installation to assure the LSC position.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes	X	Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

Gas Generator O-ring Nondestructive Evaluation: During gas generator injector stem o-ring installation, in preparation for assembly of a solid rocket booster auxiliary propulsion unit, one of the rubber o-rings was rolled onto the installation bullet and the o-ring broke in half. The cause was determined to be use of a new x-ray machine at the vendor. The power level was sufficient to cause the o-ring material to become brittle. Corrective actions included test demonstration that the new machine could be programmed to prevent degradation of the O-ring material.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls	X	Corporate knowledge	
Sys. Configuration		Consequences	X	Situational awareness		Escalation of Accepted Risk	

Space Shuttle Main Engine Powerhead missed post-proof Nondestructive Evaluation: It was discovered that several powerhead welds had not received penetrant inspection after the final top assembly proof pressure test. The planning paper for the proof test of powerheads had been modified to eliminate interim powerhead proof pressure tests. The planning modification did not appropriately incorporate the post-proof penetrant requirements for the welds. An investigation began after first escape was noted in order to determine scope and number of units affected. All hardware was assessed for acceptability and several inspections were conducted in the field. Inspection requirements must not be lost when processing changes are made.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes	X	Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

Operational Pressure Transducers (OPT) Configuration Management: It was discovered during preparations for STS-119 that twelve of twenty-five Operational Pressure Transducers, OPT's that had been designated "non-flight" (because they had experienced test environments exceeding flight environment), were flown on the Shuttle. The configuration management process should have prevented these OPTs from entering into flight inventory, but did not. The corrective actions included review of drawings to verify that all discrepant hardware was removed from flight inventory. All STS-119 OPT's were removed and replaced. The lesson here is that flight hardware configuration and inventory control must be strictly maintained.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes	X	Communications	
Software		Analysis		Hardware acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

Weatherseal Debris – Missed Removal of Polyethylene Ply Backing: A thin Silica Filled Ethylene Propylene Diene Monomer (SF-EPDM) cap ply is placed over the butt joints of the RSRM factory joint extruded SF-EPDM weather-seal. The cap ply comes from the vendor with a poly backing on it and is supposed to be removed before assembly. A small piece of missing SF-EPDM weather-seal was found during STS-122 post-flight inspection. Further investigation determined that the poly backing on the cap ply had not been fully removed prior to application. This posed the potential to become a debris source and led to inspection of all accessible hardware in the fleet. A risk assessment was required prior to flight.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes	X	Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

RepliSet Contamination: RepliSet contamination was found in Engine 2058, after its maiden flight, during post flight inspections. The source was identified as a flowliner mold material from molds taken prior to STS-121. These inspections were to check for cracks in the flowliner bellows. The concern was raised for foreign object debris in all engines since molds were taken on all flow-liners. It was found that the repliset application and removal techniques did not guarantee all molds were removed intact. This was an oversight resulting from the flow-liner investigation by instituting an inspection without considering potential unintended consequences. The corrective actions included engine inspections and the elimination of repliset molds. Processing inspections must be evaluated for unintended consequences. Foreign object debris must be controlled. Everything that touches the flight hardware must be controlled.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes	X	Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences	X	Situational awareness		Escalation of Accepted Risk	

Main Injector Face Nut Staking: Engine inspections noted two face-nuts improperly staked in the main combustion chamber. The concern was that the Main Injector LOX Posts could become loose during engine operation. The face-nuts had been replaced due to minor erosion during routine processing in the engine shop at the launch site. Review of staking procedures showed that tooling used during manufacturing was different from that used in the engine shop for the staking procedure. Additional tools were created and sent to all sites where face nut staking might be required. Procedures and tooling should be consistent across multiple sites.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes	X	Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

STS-127 and STS-128 Nozzle Hotwall Leakage: A post-flight hotwall leakage increase on two nozzles was noted. Inspections showed presence of high levels of chloride ions which is well known corrosion accelerant. Investigation also found that the sponges used to apply corrosion inhibitor contained high levels of chloride ions. Use of these sponges was discontinued. The affected nozzles were repaired, cleaned and dry purges were implemented to protect against any future occurrence. Further investigation showed that a change in the procurement specification had allowed the sponges to become available in inventory. Interestingly, a similar condition had been identified years earlier during external tank manufacturing. A timeline is shown in Figure 15 below. Lessons are that adequate specifications are necessary for everything that touches the flight hardware and that process controls must be assured for multi-decade, multi-element programs. Implementation of effective problem reporting and corrective actions systems across a multi-element program, with multiple prime contractors and independent reporting systems, is quite a challenge.

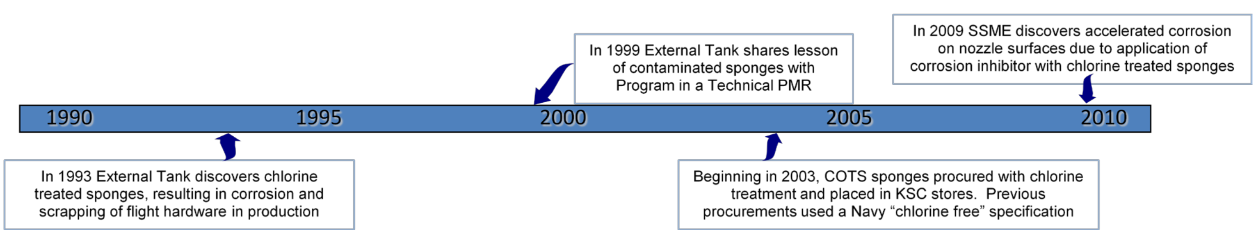


Figure 15. Timeline describing unrelated corrosion events.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes	X	Communications	X
Software		Analysis		Hardware acceptability	X	Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

External Tank (ET) Inter Tank Foam Loss: Unexpected foam losses occurred from the ET Intertank during ascent of STS-127. Imagery indicated visible areas of shiny primer from loss sites, indicating adhesion failures. Although the root cause could not be determined, most probable cause was inadequate cleaning of the surface prior to foam application. This was the first intertank to be processed following the plant shutdown after STS-107 and also following hurricane Katrina and damage to the plant. Since all remaining intertanks had already been sprayed at the time of STS-127, corrective action consisted of performing bond adhesion testing (sampling) on future intertanks. Since it is not over 100% of the area, the sampling could only provide confidence that the cleaning anomaly was not widespread or systemic. Unexpected events (i.e. Katrina) can lead to consequences revealed only in flight performance. Ensure that adequate controls/verifications are in place for critical processes. If you are unable to implement corrective action, anticipate recurrence in the future.

Figure 16. Example of inter tank foam losses due to poor bond adhesion

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments		Process escapes	X	Communications	
Software		Analysis		Hardware Acceptability	X	Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

STILL LEARNING AFTER ALL THESE YEARS

Dynamic Environments: Amazingly, environments were updated throughout the program. Even during the final 22 flights a number of assessments were required to respond to changes in system level environments. Captured here are element level dynamic environments which were updated several times during these flights. In 2005 a review of RSRM static firing motor case measurements (random vibration environments) indicated that vibration criteria did not encompass the worst case environment. The result of the review required an instrumented system tunnel and linear shape charge, during a static motor firing. The new environments derived necessitated delta qualification for the range safety system (RSS) liner shape charge (LSC). For STS-124 a pyrotechnic shock waiver was required, when it was discovered that an anti-alias filter was not used during safe and arm (S&A) pyrotechnic shock testing. Delta qualification for the S&A device was required prior to STS-119. Additionally shock load testing was required for the aft booster separation motors. For STS-125 a motor ignition shock environment was defined, which again necessitated delta qualification for the new environments. Ignition shock loads were assessed for the aft exit cone LSC and operational pressure transducer, and delta qualification for this nozzle severance LSC was required. In 2010 in preparation for STS-130, development of random vibration criteria for the Ares five-segment motor highlighted an observation that RSRM full-scale static test random vibration data exceeded requirements at discreet frequencies and motor locations. All components were reassessed, and the range safety system LSC required lot acceptance delta qualification testing. All of these environment updates required extensive engineering analysis and testing for component re-qualifications, but no hardware modification was ever required. These assessments also required extensive integration with the range, for range safety system components. Additionally, as late as STS-130, the orbiter became concerned with ignition overpressure environments in the base region of the vehicle due to main engine ignition. Accelerometers and acoustic microphones were added to better characterize the environment and reduce the uncertainties applied to the loads analyses. Clearly dynamic environments should be understood and quantified such that hardware certification is not repeated.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments	X	Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

External Tank external feed through connector – Engine Cut off Circuits: Beginning at STS-114, the frequency of liquid hydrogen engine cut off circuit failures increased. These failures seemed random, “healing” after the tank was drained and often did not recur on subsequent tank loadings. These remained unexplained and seemed to have stopped failing after sensors improvements were implemented. Following another failure on STS-122, however, the problem was finally isolated to the feed-through connector on the LH2 tank. The root cause was determined to be an open circuit at the pin/socket interface caused by relative motion in the presence of cryo-induced contamination (solidified air). The connection was redesigned to solder the sockets directly to the pins. The increased failure rate was likely caused by a subtle change to the socket design combined with extended connector durations in the mated condition (years vs. months). Interestingly, a similar problem and identical corrective action had been noted on the Atlas/Centaur program. Lessons include; ensuring that hardware is adequately qualified for its usage environment and the expectation that failures involving contamination will be random. Be aware of age life issues and pay attention to vendor/sub-tier vendor changes. Assess the effects of phase change when using liquid hydrogen, and treat frozen gases as potential contaminants. If you are unable to identify root cause and implement corrective action, anticipate recurrence in the future.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware	X	Environments	X	Process escapes		Communications	
Software		Analysis		Hardware acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls	X	Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

Solid Rocket Booster Aft Booster Separation Motor Debris: During STS-116 imagery captured a Booster Separation Motor (BSM) heat seal Thermal Protection System (TPS) debris impact on orbiter during ascent. Debris from this area was previously believed to have no transport potential to the orbiter vehicle. The Booster Trowelable Ablative (BTA) closeout was subsequently modified to mitigate debris liberation. The design modification significantly reduced debris mass while maintaining thermal and structural requirements. Analysis showed that the design modification was acceptable, eliminated the failure mode, provided consistent aft heat seal separation, and minimized possible debris. Demonstration testing was accomplished which verified the predicted failure region and limited debris size. Here, imagery collection during flight was invaluable in identification of unexpected failure modes and consequences.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware	X	Environments		Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness	X	Escalation of Accepted Risk	

Power Bus Isolation Supply (PBIS) Transformer: Testing and evaluation determined that the Integrated Electronic Assembly (IEA) PBIS transformer solder joints were susceptible to fatigue due to a potential for inadequate strain relief combined with exposure to thermal and vibration environments of flight. Even though this device was criticality 3 (data only), a thorough investigation was accomplished to assess the potential for failure propagation. Evaluation indicated that an open circuit in this non-critical device could potentially result in a current draw that might result in loss of a solid rocket booster power bus (loss of critical redundancy). An innovative external fuse design was implemented which isolated the PBIS. Testing verified other systems were not affected by operation of the PBIS fuse. The fuse removed the critical failure mode. Don't just remove and replace "non-critical" devices, follow thru on failure investigations and with corrective actions where needed.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware	X	Environments		Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

Flow Control Valve Failure: During ascent flight of STS-126, a main propulsion system flow control valve poppet broke, potentially allowing excess gaseous hydrogen to enter the External Tank (ET) ullage. Because there were three flow control valves, adequate pressurization was maintained during this flight. The crack initiation was most likely generated during ground processing. Lack of adequate pre-flight inspection methodology allowed for unchecked crack growth during flight, leading to failure. The most probable contributor to the failure was a high frequency acoustic environment induced uniquely during ground testing. The corrective action included enhanced inspections using several non destructive methods for the remainder of the program. All environments, including ground processing, must be assessed during hardware verification.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware	X	Environments	X	Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration		Consequences		Situational awareness		Escalation of Accepted Risk	

Lift Off Debris: For each mission beginning with STS-114, liftoff debris has been generated that has required assessment. Liftoff debris can be the result of the aging structure characteristics (rust), process escapes (forgotten tools/hardware), ice generation, and a result of the launch the environment. Examples of expected liftoff debris include rust, ice, frangible nut fragments, range safety coax cable remnants, and others. Mitigations included periodic pad walk downs and known debris source mitigations such as rust removal and painting. Aging facilities must be assessed for structural integrity and debris risk.

Design Deficiency		Inadequate Verification		Inadequate Mfg., Proc., and Ops.		Poor Management Processes	
Hardware		Environments	X	Process escapes		Communications	
Software		Analysis		Hardware Acceptability		Resources	
Instrumentation		Testing		Sub-tier vendor controls		Corporate knowledge	
Sys. Configuration	X	Consequences		Situational awareness		Escalation of Accepted Risk	

Unexpected Events can dramatically affect Programmatics: Unexpected events can affect the program in numerous ways. On the launch pad wind and lightning events can result in the need to reassess hardware configuration. A hail storm badly damaged an external tank prior to STS-117, requiring repair resulting in schedule delays. Launch delays in turn lead to longer exposure to the natural environment. In a very unexpected event, a train wreck including a trestle collapse occurred during shipment of solid rocket motor segments requiring urgent attention. And hurricanes including Katrina and Frances damaged critical manufacturing and assembly facilities. Unusual events require unique responses and diligence in implementing a recovery process.

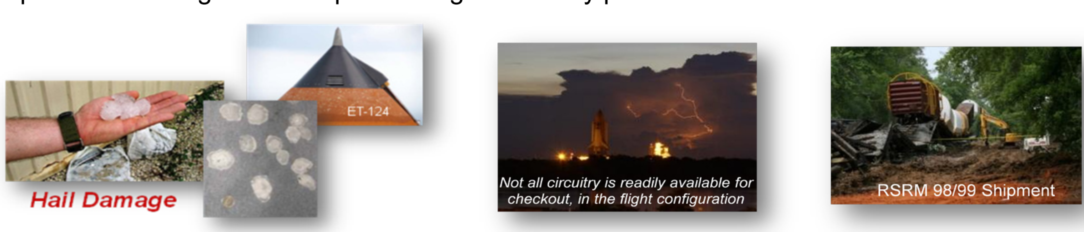


Figure 17. Unexpected Events

Affect of Launch Scrubs: Shuttle launched only about 50% of the time the tank was loaded during the final flights. Roughly 50% of scrubs were due to weather and the others were hardware issues. Launch scrubs can cascade into a sequence of unintended or unexpected events (wind, lightning, rain, hail, and additional hardware problems), and can lead to workforce fatigue. The table below summarizes the launch history for the final 22 flights.

	TANKING TEST	FRF	SCRUB - Weather	SCRUB – Hardware	ON PAD ABORT	LAUNCH	TOTAL
STS-114*	2			1		1	4
STS-121			2			1	3
STS-115				1		1	2
STS-116			1			1	2
STS-117						1	1
STS-118						1	1
STS-120**						1	1
STS-122	1			2		1	4
STS-123						1	1
STS-124						1	1
STS-126						1	1
STS-119				1		1	2
STS-125						1	1
STS-127	1		2	2		1	6
STS-128			1	1		1	3
STS-129						1	1
STS-130			1			1	2
STS-131						1	1
STS-132						1	1
STS-133	1			1		1	3
STS-134			1			1	2
STS-135	1					1	2
SUM	6	0	8	9	0	22	45

** ET-119 replaced ET-120*
*** ET-120 tanked twice for STS-114, then returned to MAF*

Table 1. Launch scrub history for the final 22 flights

Summary from the Final Flights: The final flight era certainly had issues to address. Remember this is the same complex vehicle architecture envisioned in the 1970's. The Shuttle system was complex and choice of configuration and material systems led to operational impacts. Integration of the vehicle was difficult. The missions were far from routine. Issues ranged from design, to environments definition, and unintended consequences. As you would expect a number were related to processing during this era. And a key message is that sub tier vendor controls are important, and difficult to implement. Control of sub tier vendors varies across multiple prime contractors so this requires management awareness and attention. But also apparent from the summary table below, is that the management processes were excellent during this era of the program. Management of risk, acknowledgment of accepted risk and situational awareness improved dramatically. When problems arose the leadership team enabled collection and assessment of pertinent data, and management made informed decisions. Some items to remember are summarized below.

- Be aware of all changes, and assess all changes for unintended consequences
- Assess phase change when using liquid hydrogen, and treat frozen gases as potential contaminants. Expect failures involving contamination to be random
- Be aware of age life issues and vendor/sub-tier vendor changes

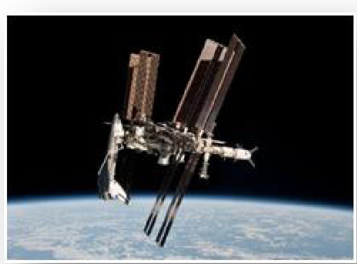
- If you are not able to identify root cause and implement corrective action, anticipate recurrence sometime in the future
- Multi-decade programs are rife with opportunities for configuration escapes
- Adequate specifications are necessary for everything that touches the flight hardware
- Not all circuitry is readily available for checkout, in the launch configuration
- Shuttle launched only 50% of the time the tank was loaded with propellants, roughly 50% of the launch scrubs were due to weather, the rest were hardware related
- Launch scrubs can lead to a sequence of unexpected events (further exposure to wind, lightning, rain, hail, and additional hardware problems) and can lead to workforce fatigue
- Expect unexpected events requiring unique responses
- Situational awareness is essential during critical operations
- Imagery collection during flight is invaluable in identification of unexpected failure modes

	Design Deficiency				Inadequate Verification				Inadequate Mfg., Proc., and Ops.				Poor Management Processes			
Issues during the final 22 flights	Hardware	Software	Instrumentation	Sys. Configuration	Environments	Analysis	Testing	Consequences	Process escapes	Hardware acceptability	Sub-tier vendor controls	Situational awareness	Communications	Resources	Corporate knowledge	Escalation of Accepted Risk
External Tank (ET) Liquid Hydrogen Tank (LH2) Ice Frost Ramps	X															
Redesign of the Liquid Oxygen Feed-line Titanium Bracket	X															
Solid Rocket Booster (SRB) Pyrotechnic Cross-over Redesign and Debris Containment Plunger Failure								X								
Ground Umbilical Carrier Plate (GUCP) Disconnect	X								X							
Redesign of Space Shuttle Main Engine High Pressure Oxidizer Pump Knife Edge Seals	X				X											
Solid Rocket Motor Operational Pressure Transducer (OPT) Redesign	X										X					
STS-114 Increased Number of LH2 Pre-pressurization Cycles										X	X					
STS-133 External Tank Cracked Stringer										X	X					
SRB Ordinance ring installation (linear shape charge rotation)									X							
Gas Generator O-ring Nondestructive Evaluation								X			X					
Operational Pressure Transducers (OPT) Configuration Management									X							
RepliSet Contamination								X	X							
Main Injector Face Nut Staking									X							
STS-127 and STS-128 Nozzle Hotwall Leakage									X	X			X			
External Tank (ET) Inter Tank Foam Loss									X	X						
Dynamic Environments					X											
External Tank external feed through connector – Engine Cut off Circuits	X				X						X					
Power Bus Isolation Supply (PBIS) T2 Transformer	X															
Flow Control Valve Failure	X				X											
Lift Off Debris				X	X											

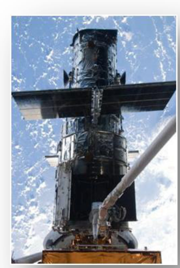
PROJECT MANAGEMENT BEST PRACTICES

The conclusion of the program resulted in successful completion of the International Space Station and the final servicing mission for the Hubble Space Telescope. The final flights were among the best in debris performance, and the propulsion element performance was superb.

ISS configuration, STS-114



ISS configuration, STS-135



HST servicing, STS-125

During the program a number of project management processes were implemented and improved. Technical performance, schedule accountability, cost control, and risk management were effectively managed and implemented. Award fee contracting was implemented to provide performance incentives. The Certification of Flight Readiness and Mission Management processes became very effective. Risk management, as depicted in Figure 18 became routine within the program and propulsion elements.

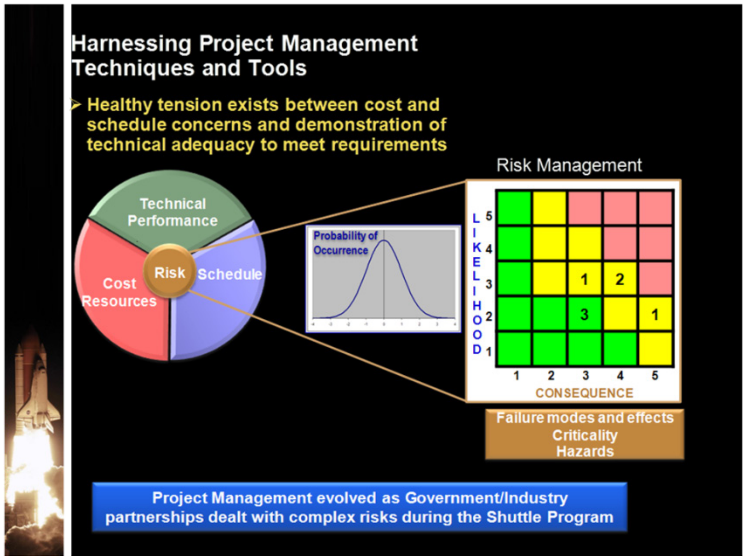


Figure 18. Management of Risk evolved during the Program

Perhaps the most important aspects of success were related to relationships developed with the prime contractors, which evolved to become very successful government/industry partnerships. A key to the success of the propulsion element projects was related to relationships between the MSFC project office and support organizations, with their counterpart contractor organizations. The teams worked diligently to understand and satisfy requirements of the project. Frequent team building, daily communications, continuous feedback, and operating with openness created a climate where teams cooperatively resolved challenges and continually looked for ways to learn and improve. Even at the material suppliers and their sub-tier suppliers periodic visits were made to improve understanding and importance of space program requirements, and their impact on mission success. Teams used visits, presentations, videos, symposiums, seminars, other events to share the importance of product consistence. Trust and development of personal relationships were key features of the strong government/industry teaming, to solve problems, and complete the mission.

Engineering also evolved during the 30 year program. As difficult problems were solved, engineering disciplines improved and evolved. New computational capabilities evolved and analysis tools were developed to address specific problems. Advanced computer aided design and manufacturing, new non destructive evaluation techniques, advanced materials including composites, and advances in fracture mechanics and failure analysis all contributed to hardware evolution and problem resolution. Figure 19 illustrates the improvement in engineering capability as new techniques became available and as they were applied to solutions of difficult problems. The government/industry teams were especially effective in accomplishing failure analysis, as both teams brought unique and complementary skills. The management and engineering teams evolved to a culture of continuous improvement and were very effective in completion of the program.

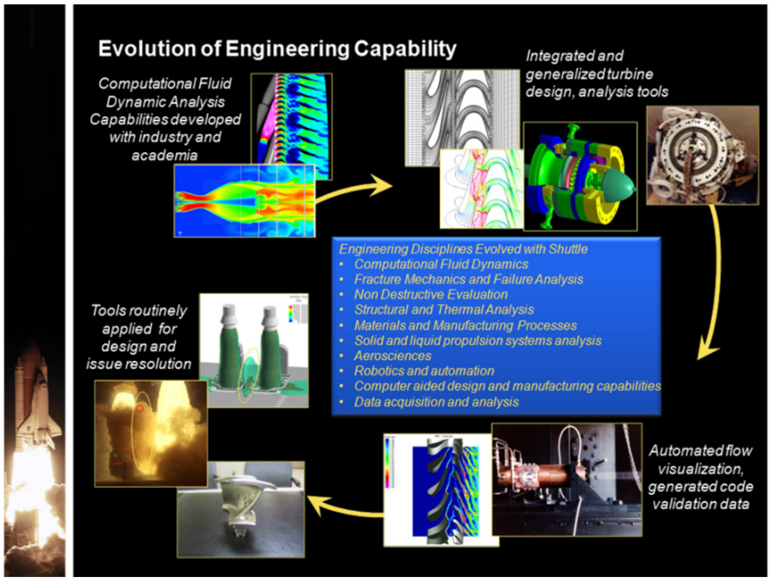


Figure 19. Evolution of Engineering Capability

Summing this up into major categories and recommended practices, the table below captures major items described in this paper. The propulsion elements and the Shuttle Program evolved during the flight program and in the final era of flight implemented excellent management and engineering practices, and exhibited many of these attributes.

	Desirable Attribute
Design	Block upgrades are an effective method to incorporate design changes
	Redundancy management is essential in critical systems
	Assure that instrumentation systems are more reliable than the hardware it is monitoring
	Design and assembly tolerances must accommodate potential for residual stresses
	Thoroughly assess the choice of configuration and material systems for operational impacts
Verification	Seek to drive out failures via ground testing or non crewed flight testing
	Imagery collection during flight is invaluable in identification of unexpected failure modes
	Dynamic environments should be properly understood and quantified
	All environments, including ground processing, must be assessed during hardware verification
	Where simulation of combined flight environments in ground test is not possible, collect flight data
	Be aware of all changes, assess design changes for unintended consequences, and require adequate certification
Manufacturing, Processing, and Operations	Control of foreign object debris is essential
	Wiring and connectors in a reusable system can be especially vulnerable to wear and collateral damage
	Assess phase change when using liquid hydrogen, and treat frozen gases as potential contaminants
	Expect failures involving contamination to be random
	Be aware of age life issues and vendor/sub-tier vendor changes
	Adequate specifications are necessary for everything that touches the flight hardware
	Flight hardware configuration and inventory control must be strictly maintained
	Appropriate launch commit criteria are essential
	Redline protection is essential in achieving mission success
	If you are not able to identify root cause and implement corrective action, anticipate recurrence sometime in the future
Management Processes	Seek to develop strong government/industry partnerships with a culture of continuous improvement
	Utilize the best combination of engineering resources including government and industry, expecially for failure analysis
	Pay attention to suppliers and sub-tier vendors with visible visits from management
	Seek to assure situational awareness, good communications, adequate resources, and a clear understanding of accepted risk
	When problems arise enable collection and assessment of pertinent data to make informed decisions
	Expect unexpected events, unusual events require unique responses and diligence in implementing a recovery process

SUMMARY – EVOLVING TO FUTURE LAUNCH SYSTEMS

The Shuttle Propulsion elements evolved to become highly reliable, flight proven systems which offer the opportunity for evolution to heavy lift, beyond low earth orbit, flight capability. The solid rocket booster and solid rocket motor can be configured in a five segment configuration developed during the Constellation program, currently in development testing. The Space Shuttle Main Engines exhibit the proven reliability from 135 flights and 35 years of ground testing, and exhibit the highest performance of any earth to orbit liquid rocket engine. The engine can be configured in a reusable or expendable configuration, with a goal of reduction in manufacturing cost for the expendable system. The External Tank structural efficiency can be extended to in-line launch vehicle configurations and, for a 27.5 foot diameter vehicle, tooling is available for manufacturing with state of the art processes. System studies indicate that payload to orbit can be achieved in the range of 70 to 130 metric tons. The building blocks for upper stages and earth departure stages are in development. The modifications to ground support systems are understood. This approach, adopted by the Space Launch System, toward development of a heavy lift system represents a cost effective approach for achieving a human exploration capability beyond earth orbit.

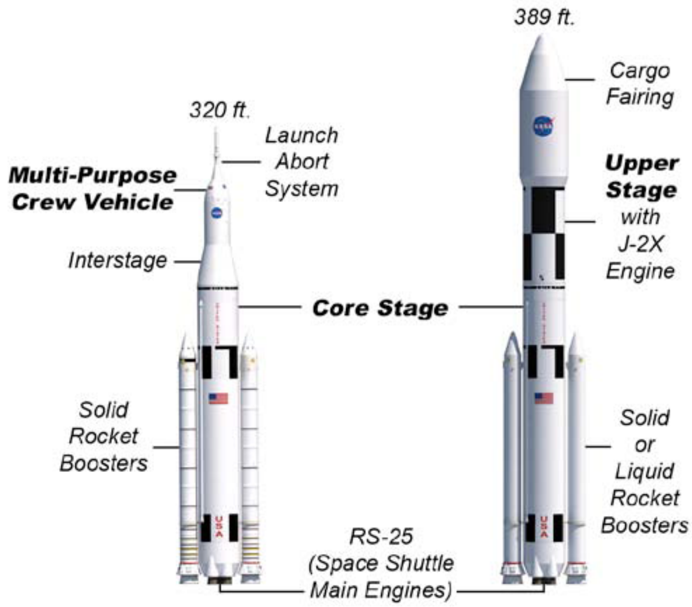


Figure 20. Space Launch System Concept

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