

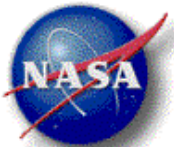


# Success Legacy of the Space Shuttle Program

## Changes in Shuttle Post Challenger and Columbia



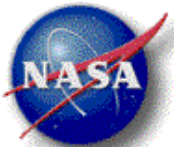




# Success Legacy of the Space Shuttle Program— Its DNA Markers



- **Agenda**
  - **Overview of Organizational Culture and Change**
  - **Shuttle Heritage—DNA Markers From Apollo**
  - **Challenger and Its Impacts on Shuttle Culture**
    - RTF Technical Changes
    - Impacts on Culture from Organizational changes
  - **Columbia and Its Impacts on Shuttle Culture**
    - RTF Technical Changes
    - Impacts on Culture from Organizational Changes
  - **Conclusions—Evidence of Change**
    - Post STS107 continuous improvement

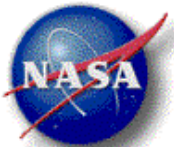


# Success Legacy of the Space Shuttle Program—Its DNA Markers



## Overview of Organizational Culture

- What is The Culture of an Organization
- Organizational culture is the common set of beliefs, values, and norms, together with symbols like dramatized events and personalities that represents the unique character of an organization.
- Culture provides the framework and context for behavior within and by it.
- It is not defined by the actions of a few, though their visibility may be high
- Culture guides the way individuals and groups in an organization interact with one another and with elements outside it.
- Need for a Cultural Change is most often recognized or considered after a significant event such as an accident
- Key to any change like this is for the individuals within the organization to decide to change their behavior
  - First , understand what the current behaviors are that lead to the undesirable event
  - Second, decide which of those behaviors need to be changed for success and
  - Third, implement activities/ structure that modifies those behaviors
- Presentation will examine some of those behaviors and let you be the judge of whether the cultural changes have occurred

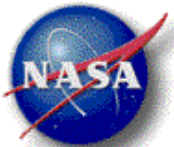


# Success Legacy of the Space Shuttle Program—Its DNA Markers



## Shuttle Heritage-- Its DNA Markers

- Shuttle Heritage began as early as 1967 with Apollo
- Apollo Technical Model for Spacecraft Development focused on four critical aspects
  1. Design
  2. Test
  3. Control of changes
  4. Interpretation of discrepancies
- Design principles
  - Build it simple then double up on redundant components or systems-- Make it fail safe
    - Use established technology for improved reliability
    - Examples: Hypergolic propellants, 3 fuel cells, series/parallel redundancy in valves, regulators, diodes and capacitors were no single failure would be catastrophic
    - Minimize functional interfaces between complex pieces of hardware—simple interfaces leads to individual contractor work packages without encumbering complex integration DDT&E
      - Wiring between Apollo spacecraft and Saturn V launch vehicle limited to 100 wires and between lunar and command and service module limited to 36 wires, mostly for redundancy needs
    - Closed loop accountability of change impacts



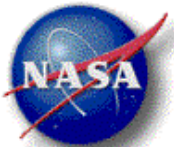
# Success Legacy of the Space Shuttle Program—Its DNA Markers



## Shuttle Heritage-- Its DNA Markers

- **Apollo Testing Philosophy**
  - **Flight “Qualify” Launch Vehicle, Spacecraft, and integrated Support System before “manned flight”**
    - **Example: Little Joe II vehicles (5 flights) used to qualify the Launch Abort System in cases from on pad to high “Q” to upper stage separation**
  - **Building Block Approach for each mission as well as each phase of the mission**
  - **Engineering Judgment was driving principle in testing, funding not available for Statistically significant reliability testing**
    - **Component testing emphasized rather than rely only on final system level**
    - **ATP testing was critical component of demonstrating reliability and screening all flight units for workmanship defects**
    - **Thermal cycling included on all ATP acceptances to screen marginal fabrication processes**
    - **Every Saturn V Booster was “full mission duration” hot fired at Mississippi Test Facility and retested at MAF before delivery to KSC**



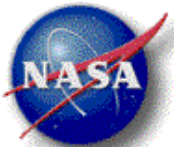


# Success Legacy of the Space Shuttle Program



## Shuttle Heritage--Its DNA Markers

- Testing has been considered the most important factor leading to the high degree of reliability of Apollo—Funding readily available
  - Single Prototype—Qualification level testing to demonstrate performance
  - Acceptance Testing—to assure no workmanship defects
  - Orbiter continued to use the same workmanship screening levels
- Flight History shows we have failures well before expected—failure modes not seen in qualification program
  - Frequently the cause is qualification testing not performed to combined flight environments
  - Qualification unit configuration different from flight hardware configuration
  - Unintentional Process changes evolved in the manufacturing process
  - Life used up on ground processing and not accounted for in operating life
  - Incremental life assessments not performed to verify performance—no real hardware tear down and analyses
  - Lack of trending data, missing subtle indicators or just not listening to the hardware
  - Normalization of deviances—seen so many times becomes fair wear and tear versus failure to be corrected before next flight

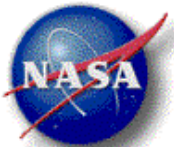


# Success Legacy of the Space Shuttle Program



## Shuttle Heritage-- Its DNA Markers

- Apollo heritage hardware selected for Shuttle included
- IBM Computers—AP 101's a derivative of the Apollo computer used in Skylab
  - AP-101's used in first Fly By Wire aircraft at Dryden—F-8 Crusader
  - First flight on 27 August 1976.
  - Used on the Corsair to validate the Shuttle flight control system before first atmospheric flight
- Fuel Cell Power plant
  - Additional sub-stack added (32 cells to power section) for additional capability to allow return on 1 FCP
  - Cryogenic tanks same as Apollo
- On-Orbit Digital Auto Pilot and Orbital Rendezvous guidance and navigation were adapted from Apollo
- Autonomous onboard navigation used Kalman Filtering developed for Apollo by MIT/Draper Labs used in Shuttle onboard navigation
- Descent Guidance and Mission Planning for Shuttle was expansion of the Gemini and Apollo systems
- ET Vent and Relief valves were from Saturn V hardware configuration



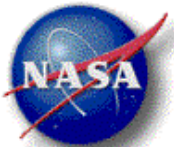
# Success Legacy of the Space Shuttle Program



## Shuttle Heritage--Its DNA Markers

- Apollo 1 Fire
- A spark caused by an electrical short in a 100% oxygen atmosphere set fire to an abundance of flammable material
- • Vulnerable design and material choices for wiring, atmosphere, cabin materials, and hatch door.
- Root Causes/Underlying Issues
  - Combustible Material in Crew Module.
  - Teflon-coated wiring susceptible to wear and collateral damage
  - Single gas (100% Oxygen) vs. two gas (Nitrogen and Oxygen)
  - Inward opening hatch door—Modified just prior to test from External opening door
- • Poor quality control and workmanship.
  - KSC Quality Inspector cited multiple deficiencies concerning equipment, parts, procedures, workmanship and contamination.
- • Inadequate provision for emergency response, rescue and medical assistance.
- • Budget and schedule pressures resulted in the over-prioritization of speed to completion.
- Cost overruns and schedule delays were acknowledged as contributing factors to the design, manufacturing, and quality control process issues.



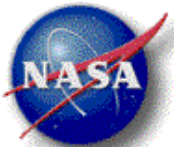


# Success Legacy of the Space Shuttle Program



## Shuttle Heritage-- Its DNA Markers

- Apollo Lesson to Learn
- Past successes do not obviate the need to continually reassess the rationale for accepted risks.
  - NASA had “successfully” logged over 1000 hours of flight time under the same conditions before the Apollo 1 fire.
- Expertise in materials properties throughout a defined and understood range of operating conditions in crucial.
  - Teflon may have been the correct choice for insulation and fire resistance, but it was the wrong choice for resistance to deformation and damage, leading to a string of cascading failure modes and effects.
- Every redesign or modification has unintended consequences
  - Modification of the Apollo Crew Hatch Latch was made prior to the fire in response to a previous failure when it failed to remain closed
  - We are never as smart as we think we are
- Lessons Learned captured in set of design standards for manned spacecraft design, Manned Spacecraft Center (MSC 08080, later captured as Shuttle Standards, NSTS-08080)
- Test philosophy fully vetted in SSME element and its test program at SSC

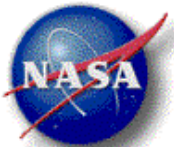


# Success Legacy of the Space Shuttle Program



## Challenger and Its Impacts on Shuttle Culture: Rogers Commission

- Redesign SRM Joints and sealing system, with procedures for assembly and inspection prior to next flight
- Consolidate decision making and review processes into Space Shuttle Program Organization instead of as individual Center efforts
- Complete review of Safety critical items and tighten procedures for granting waivers
- Establish an SR&QA Office reporting directly to NASA Administrator
- Improve Communications between Centers and make Crew Commander part of Flight Review Process
- Improve Landing safety, especially in Orbiter brakes and nose wheel steering
- Make effort to provide Crew Escape System for use during controlled, gliding flight
- Establish a flight rate consistent with resources
- Increase rigor in critical item installation, test, and maintenance procedures



# Success Legacy of the Space Shuttle Program

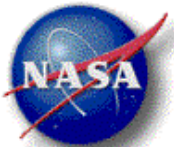


## Challenger and Its Impacts on Shuttle Culture

### **RTF—Post Challenger Program Recovery Actions--Technical changes**

- Program Level changes to CIL and Hazard documentation updated to provide more focus on risks and their controls, shortcomings in eliminating the risk, and methodology for approving residual risks in non-redundant, critical hardware
- Boiler room discussions provided forum for healthy debate on validity of assumptions of “credibility”, completeness of testing, and applicability of any optional workarounds available to mitigate consequences of failures, should they occur.
- Independent Contractor design assessments were performed to identify CIL criticality of each component
- Differences were resolved as part of Program Re-baselining Effort across all Elements
- Orbiter implemented 76 major redesigns, including robust improvements in Landing Gear Braking system, Drag Chute, Crew Escape Pole, and 17 Inch Disconnect Latch mod.



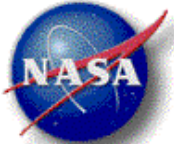


# Success Legacy of the Space Shuttle Program



## Challenger and Its Impacts on Shuttle Culture

- RTF—Post Challenger Program Recovery Actions--Technical changes
- Performed in-depth review and re-baselining of all Program Requirements
- For Orbiter and GFE, Two major milestones set up to define, assess and track this body of work were Design Requirements Review (DRR) and the Design Certification Review (DCR)
- A complete review of all the verification and validation documentation was performed, with representatives from astronaut, SR&QA, Mission Operations and KSC Shuttle Processing representatives participating
  - Focus was on the completeness of the testing and verification of all the hardware and software
  - Deficiencies in designs were identified, categorized for corrective action,
    - Redesign mandatory, constraints to first flight, or acceptable to fly until Fix can be implemented
    - Desirable, but not required for first flight—rationale included work around or alternative (scrub, etc) available
    - Desirable, but not sufficient value added—risk acceptable, can not be eliminated



# Post STS-51L RSRM / Return to Flight Configuration



- The key changes for RSRM include:
  - Improved case field joint with a capture feature and third O-ring
  - Improved field joint thermal protection with a rubber J-leg replacing putty
  - Added field joint heaters to ensure O-rings can track dynamic motions even under cold ambient conditions
  - Improved ply angles in nozzle phenolic rings to preclude anomalous pocketing erosion
  - More robust metal housings in the nozzle to increase structural margins and accommodate dual and redundant O-ring seals
  - An improved nozzle/case joint with 100 radial bolts to reduce the dynamic joint motion plus addition of a bonded insulation flap with a wiper O-ring in place of the putty thermal barrier
- Shortly after return to flight, an insulation J-leg thermal barrier was developed for the igniter inner and outer joints
- Subscale testing included a transient pressure test article and an nozzle joint environmental simulator
- Six static tests were conducted, including tests at hot and cold specification bounds with side loads applied to simulate those induced by the external tank attachments.
- The final static test Production Verification Motor No. 1 (PVM-1) prior to return to flight was a full-scale flaw test motor to verify the redundant features of critical seals

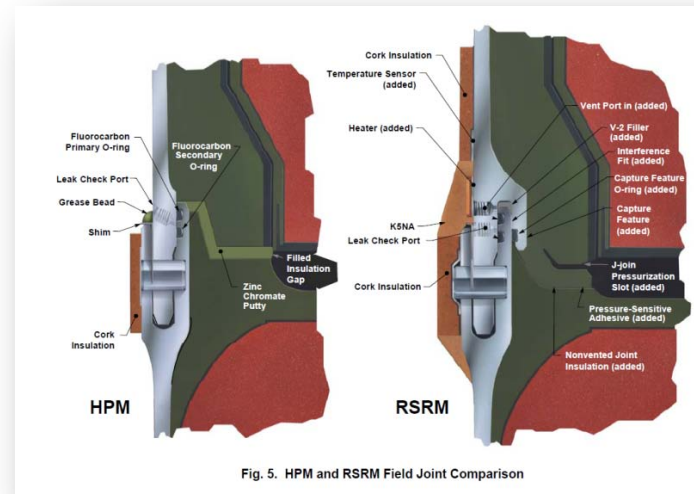


Fig. 5. HPM and RSRM Field Joint Comparison

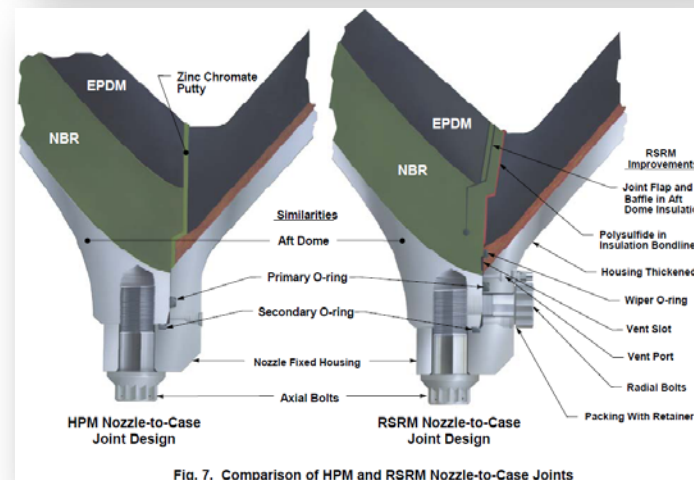
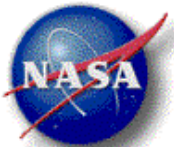


Fig. 7. Comparison of HPM and RSRM Nozzle-to-Case Joints

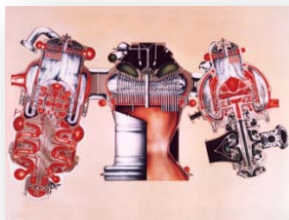


# Post STS-51L SSME Phase II / Return to Flight Configuration

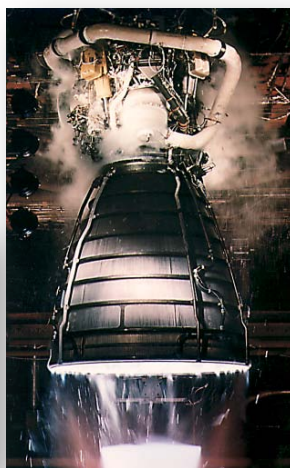


- SSME FMEA/CIL rewritten
  - New FMEA/CIL drove 18 mandatory changes to SSME before next flight
- Established an SSME Margin Improvement Board
  - Identified an additional 50 items as mandatory changes
- Additional 90,000 seconds of hot fire time accrued during RTF period, including full recertification to 104% RPL
  - Engine 2105 FCE (Flight Certification Extension)
    - Completed two successful Phase II FPL certification cycles
    - 23 test and 11,304 seconds was demonstrated for the FCE first segment
    - 64 tests and 30,799 seconds were completed with no engine malfunctions for the FCE
    - Engine modifications required by the next flight by the post Challenger review actions were added to 2105 for concurrent development and certification testing

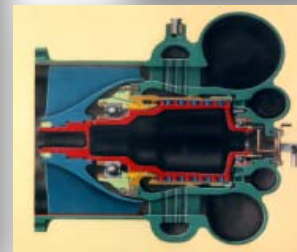
*Powerhead Improvements*



*Nozzle insulation*

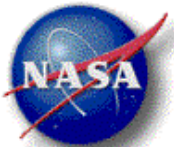


*Block II Controller*



*LPOTP thrust bearing improvements*



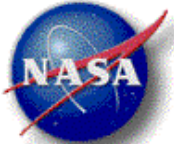


# Post STS-51L External Tank / Return to Flight Configuration



- No Major Design Changes (Light Weight Tank Configuration) following STS-51L
- External Tank FMEA/CIL and Hazards Assessments were rewritten
- Review of fracture control and NDE practices
  - Added post proof x-ray of all weld repairs
  - All indications go through MRB
- Changes added later include:
  - LO2 Pressurization System – fixed orifice flow control valve
  - Deletion of the External Tank Range Safety System
  - Development of load indicators to support DOLILU



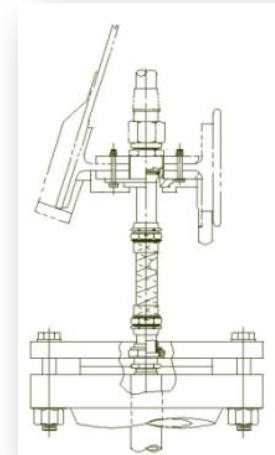


# Post STS-51L Solid Rocket Booster / Return to Flight Configuration

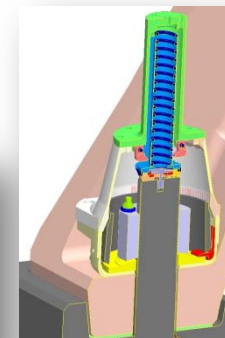


- SRB hardware changes for return to flight
  - ET attach ring design changed from 270° to 360°
  - T-O umbilical added to aft skirt
  - Aft skirt GN2 purge redesigned to redirect warm GN2 toward SRM aft bulkhead
  - SRB blast container on HDP was redesigned
  - Development flight instrumentation added
    - Nose assembly was redesigned for DFI
    - Added DFI to forward skirt
      - Added brackets for equipment mounting panels, connector plates, and approx 100 holes for misc. Brackets, clips, etc.
    - Systems tunnel redesigned to accommodate DFI and the SRM joint redesign
    - DFI added to aft skirt

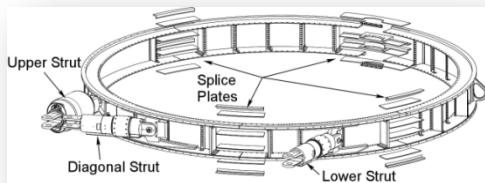
*GN2 Purge*



*SRB Blast Container  
On Hold Down Post*



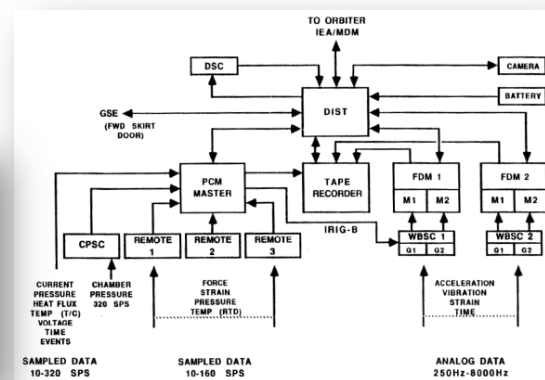
*ET Attach Ring*



*T-O Umbilical*



*Development Flight  
Instrumentation*





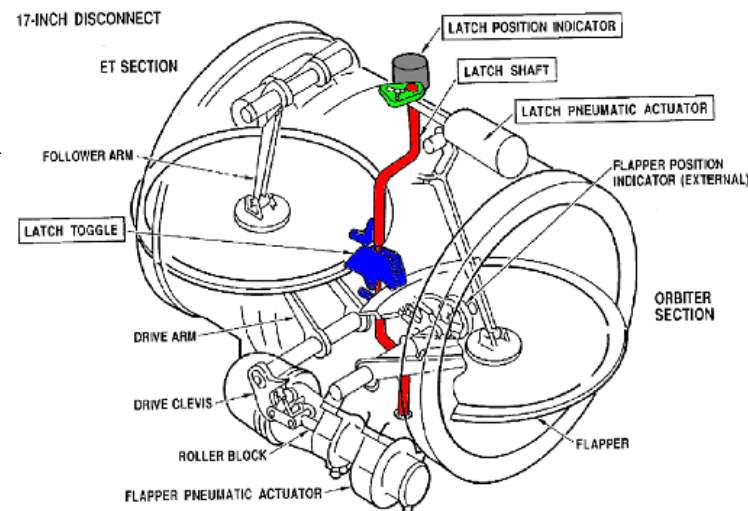
# Success Legacy of the Space Shuttle Program



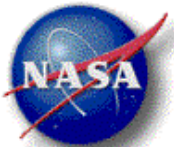
## Challenger and Its Impacts on Shuttle Culture

### RTF—Post Challenger Program Recovery Actions--Technical changes

- Redesigns were implemented where Mandatory Corrective Actions were identified—Example below
- MPS Modifications shown below
  - LH2/LO2 ET/Orbiter 17-Inch Disconnect : Addition of Latch Mechanism to valve visor to prevent flow forces from oscillating visor
  - LO2 Pre-valve: Filters added to Pneumatic actuator
  - LH2/LO2 Fill and Drain Valve: position indicator ,Fabrication upgrades
  - LH2/LO2 T-O Umbilical: Modified support plate to accommodate Debris plate.
  - New Critical 1 and 1R CIL's: 44 and 27, respectively
  - Total Waivers , all CIL's went from 46 to 270
- Ground rules changes in CIL classification caused most of the upgrades
  - Any Leakages of H2/O2 classified as Critical 1—considered as a hazard, but not automatically a CIL
  - Failure Modes considered credible without regard for likelihood.
  - Highlighted fact that “not all CIL's are of equal risk” but book kept as if they were
    - Impacts flowed down to OMRS New Requirements added as a result of CIL upgrades—85
    - Revised to include new criteria—192
    - New LCC's- 28, Revised 15





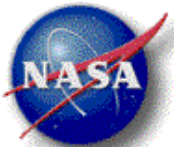


# Success Legacy of the Space Shuttle Program



## Challenger and Its Impacts on Shuttle Culture

- **RTF—Post Challenger—Technical changes**
  - Program Recovery Actions (cont'd)
  - Flight Operations approach similarly focused on adequacy of the Flight Rules and Crew Procedures
    - Participation in CIL and Hazard Boileroom reviews enabled flow-down of impacts into flight operations documentation
    - Format was upgraded for Flight Rules to capture Rationale for these rules, criteria for classifying a component failed, and options for flight workarounds where available
    - This structuring of documentation assured information would not be lost over time as workforce turnover occurs
  - Return to Flight required 974 days, with Discovery launching on 29 September 1988

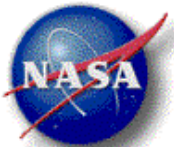


# Success Legacy of the Space Shuttle Program



## Challenger and Its Impacts on Shuttle Culture

- **RTF—Post Challenger Program Recovery Actions--Cultural changes**
  - **Program Approach to Recommendation to change Management Structure and eliminate tendency for management isolation included**
    - Director of NSTS filled with former shuttle Commander, reporting directly to Associate Administrator for Space Flight
    - Two Deputies to NSTS Director established at KSC and JSC responsible for operational aspects and day-to-day management, respectively
    - Director, Shuttle Projects Office at MSFC designated as NASA Headquarters position responsible for management and coordination of MSFC projects and reporting to NSTS Deputy Director
    - At KSC, Shuttle Operations and Engineering rolled up under Director of STS Management and Operations, reporting to KSC Center Director
    - Robust Flight Readiness Review and MMT processes included adding Director of Flight Crew Office and flight crew commander, along with formal records published of meetings
    - Space Flight Safety Panel set up to report directly to Associate Administrator for SR&QA
    - Office of SR&QA established at NASA Headquarters to report directly to NASA Administrator—provides dual path for elevating serious issues
    - Established NSRS Hotline for Anomalous reporting of issues to NASA HQ
    - Placement of Astronauts throughout management positions



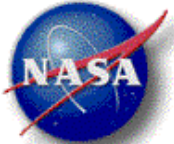
# Success Legacy of the Space Shuttle Program



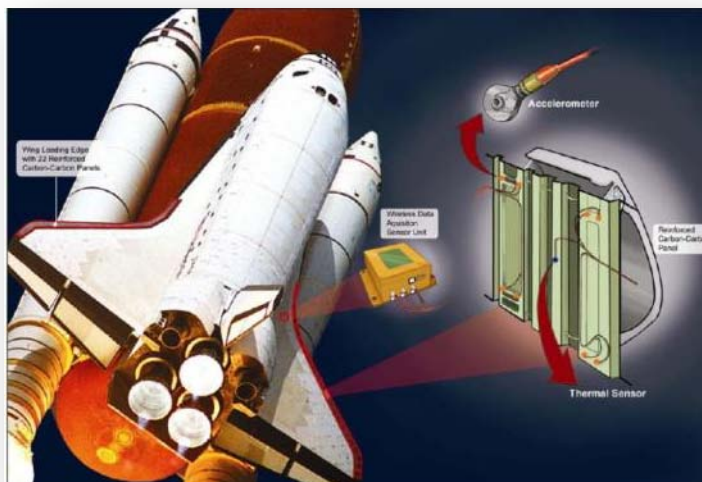
## Challenger and Its Impacts on Shuttle Culture

- **RTF—Post Challenger**
  - **Lessons to Learn**
  - **Qualification Program needs to demonstrate performance under realistic flight conditions and environments**
    - “Test what you fly, fly what you test”
    - Analysis tools must be test anchored—used to augment testing, not in lieu of testing
  - **Investigate and understand the physics of each failure, the risks should it occur in flight, and corrective action needed to fix the cause before flight if risk is unacceptable**
    - Do not let repeated non-conformances become acceptable as “normal performance”
    - Test when you do not have the knowledge of the physics
    - Believe the hardware, it does not know how to provide wrong data
  - **Reusable Solid Rocket Motor management culture change was dramatic**
    - Reliability via Process Control
    - Human Rating
  - **Did our Decision Making behavior Change?**

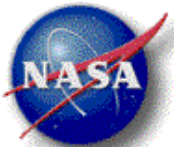




# Program Improvements during Post STS-107 Return to Flight



- Improvements In Tech Excellence, Communications & Decision-making
  - Space Shuttle Program Mission Management Team
  - NASA Engineering And Safety Center
- Space Shuttle Improvements
  - Reinforced Carbon-carbon Wing Panels And Nose Cap
  - Wing Leading Edge Structural Subsystem
  - Rudder Speed Brake
  - Foreign Object Debris
  - Closeout Photography Process
  - Launch Pad Ground Support Equipment
  - Fixed And Rotating Service Structures
  - In-flight inspection and repair

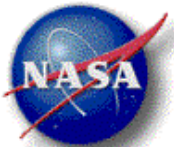


# Success Legacy of the Space Shuttle Program



## RTF—Post Columbia—Cultural changes

- Program Recovery Actions
- Improvements in MMT “decision making” skills
  - Outside Consultants contracted to provide operational and decision making training for Management Team, including mid and senior level managers
  - Independent consultants provided cultural and communications skills training with feedback recommendations from observations during meetings, boards and working groups
  - MMT membership now a Program certified position—minimum Training includes
    - MMT Simulation training
    - Review of LCC, OMRS, and Flight Rules and Tools to support launch decisions
    - Decision making and risk management, including studies of Challenger, Redundancy and Reliability
  - Increase focus on “Safety First,” elevating risks to Directorate, Project and Program level when required as integral part of Risk Management
  - Seek, Recognize, and deal with all dissenting or alternate views at all levels of program and project reviews

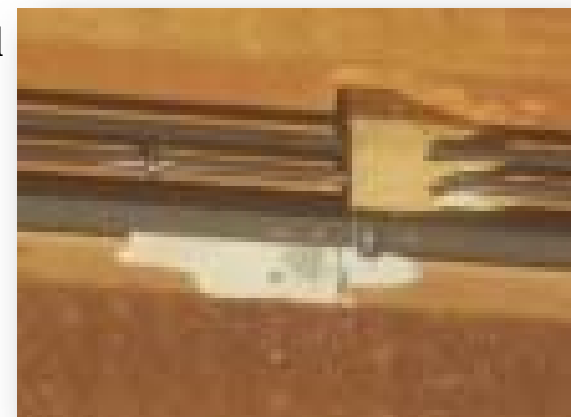


# Success Legacy of the Space Shuttle Program

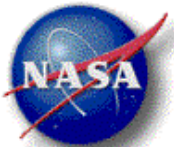


## RTF—Post Columbia—Cultural changes

- **Program Recovery Actions (cont'd)**
  - Increased robustness to processes for Project, Program and Agency FRR—increased level of detail for special topics and issues
- **Strengthen Engineering and Safety**
  - Established Independent Technical Authority (ITA) within Engineering and S&MA disciplines
  - Increased NASA system engineers oversight into contractor tasks
  - Established NESC for augmentation of independent technical expertise into special problems
  - Emphasized Resolving problems rather than resolve schedule impacts
  - Benchmarked and migrated best practices into NASA Safety Culture
  - Improved Risk Assessment tools
    - Debris liberation models based on additional NDE and imagery to better characterize physics of losses
    - Transport models
    - Impact prediction and capability models based on test
    - Rigorous ET Post flight review and assessments
    - Continuous Improvement, Modifications and Inline
  - Implemented broader use of Probability Risk Assessment Tools







# Success Legacy of the Space Shuttle Program



## Columbia and Its Impacts on Shuttle Culture

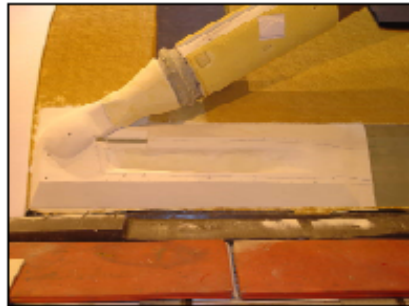
- **RTF—Post Columbia—Technical changes**
  - **Orbiter Changes, Major Examples**
  - **Eight Significant RTF Modifications, 36 additional Modifications to improve systems Reliabilities**
    - OBSS with its 2 Sensor packages
    - Wing Leading Edge Instrumentation
    - EVA Digital Camera
    - New ET Umbilical Camera
    - New Digital Crew Handheld Cameras with downlink for Orbiter post separation viewing of tank and for Viewing from ISS during RPM
    - WLE Spar Sneak Flow Protection
    - WLE Carrier Panel Horse Collar Gap Filler Redesign
    - SSOR and WVS Antenna Relocation to improve EVA Coverage
  - **Robust suite of Decision Making Tools**
    - RCC Damage Limit Analyses, high Velocity Impact Testing and Arc Jet Testing
    - Tile Impact testing and damage capability models,
    - Repair tools and materials tested for Tile and RCC with Man-in-the-loop procedures and entry conditions to characterize performance with limitations
  - **Technical Issues Resolved based on previous anomalies, inspections during downtime and reassessments of life limits**
    - Flex hoses inspected and replacements driven by damages detected
    - Point Sensor Box investigations based on STS-114 Tanking anomalies
    - COPV Life Limit methodology limitations and tiger team formed to resolve



# STS-114 External Tank – 121



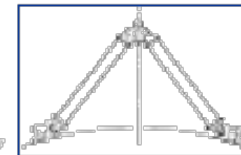
## RTF Modifications



*Remove/ Replace  
Longeron Closeouts*



*LO2 Feedline Bellows  
TPS Drip Lip and Fwd  
Bellows Heater System*



*Bipod Strut Hardware  
(Lubricated thru-bolts)*



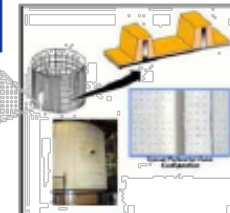
*Redesigned  
Bipod Fitting*



*Intertank / LH2 Tank  
Flange Closeout  
Enhancement*



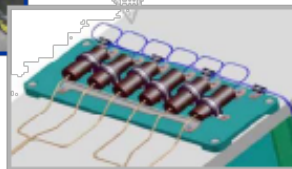
*Partial LH2 PAL Ramp  
Replacement*



*Increase Area of  
Vented Intertank TPS*



*ET Ground Umbilical  
Redesign*



*RTF  
Instrumentation*



*ET Camera in LO2  
Feedline Fairing*



*ET/SRB  
Bolt  
Catcher  
Inserts*

*Eliminated the proximate cause of STS-107 In-Flight Anomaly (STS-107-T-01)*

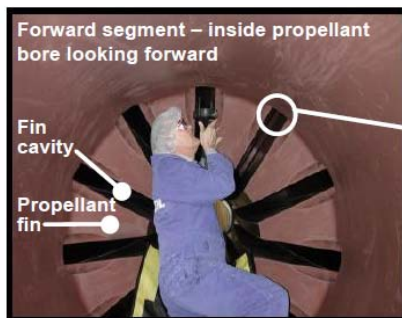


# STS-114

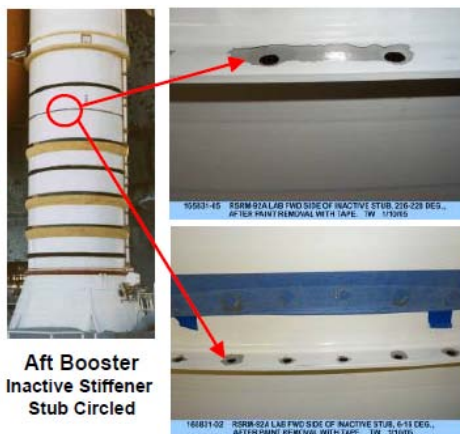
## Reusable Solid Rocket Motor— RSRM-92



### RTF Modifications

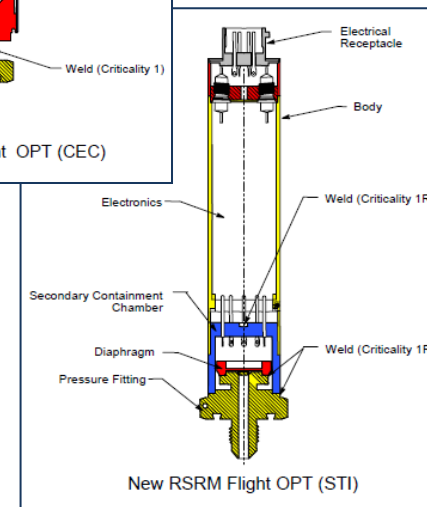
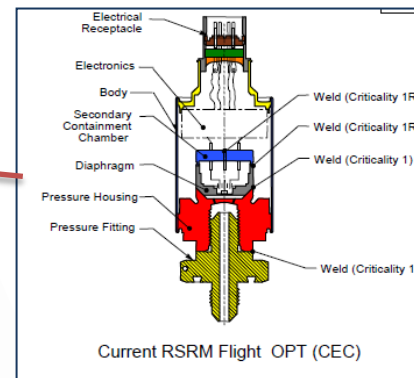
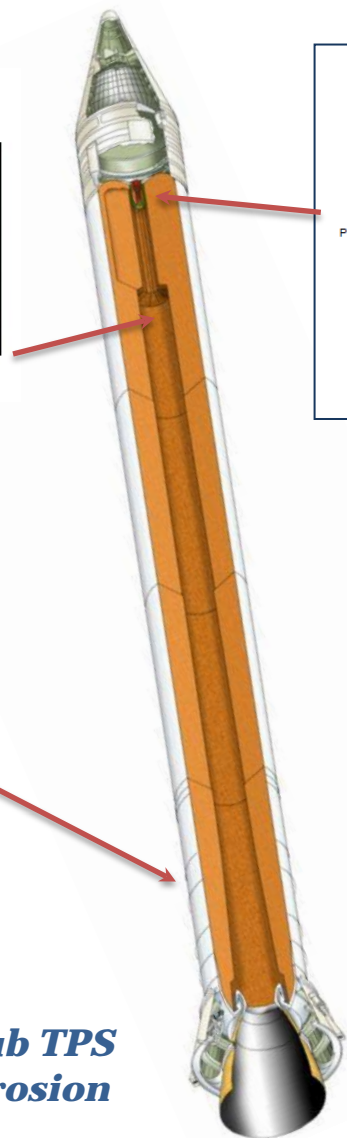


### Propellant Horizontal Storage Structural Safety Factor



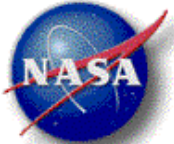
Peeling/Flaking Paint on STS-121 LH Inactive Stiffener Stub

### Inactive Stiffener Stub TPS Redesign Due to Corrosion



### New Stellar Technologies, Inc. (STI) Operational Pressure Transducer (OPT)





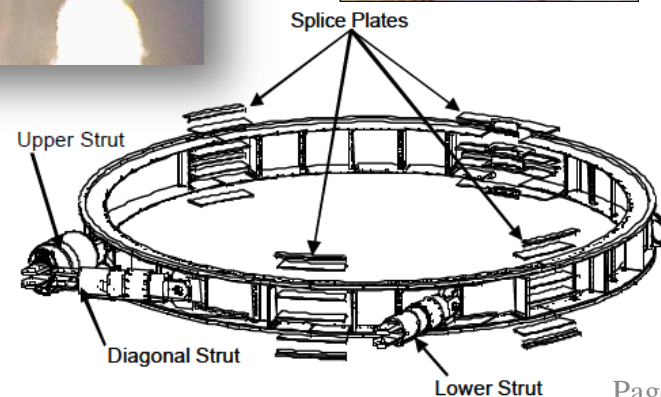
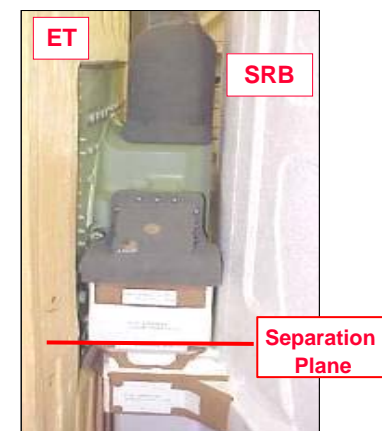
# STS-114

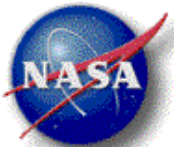
## Solid Rocket Booster– BI125



### RTF Modifications

- Separation/Deceleration
  - BSMs – Igniter, Aeroheat Shield, Plume, FOD, and Throat
  - Bolt Catcher/NSI PC
  - Forward/Aft Separation Bolts
  - Thruster Pressure Cartridge
  - Forward Skirt Aft Clevis
  - Ring/Lower Bay
- ET/SRB Attach
  - ET Attach Rings and Aft Struts
  - Diagonal Strut Restraint Cable
  - EPDM Covers
- Aft Assembly
  - FIV Connector and Backshell
  - Aft Skirt GN2 Purge (Prelaunch)
  - Blast Container





# STS-114

1 - 2057  
2 - 2054  
3 - 2056



## Space Shuttle Main Engine -

### RTF Modifications

#### Main Fuel Valve (MFV) End Cap

- *Eliminated Leakage and Improved Safety*

#### New Baseline Software

- *Increased Reliability and Supportability*

#### HPFTP Liquid Nitrogen Insulation

- *Increased Effectiveness in Prevention of Liquid Nitrogen Formation*

#### HPFTP -712 Configuration

- *Increased Life and Robustness*

#### HPOTP Upgrades

- *Reduced Maintenance*
- *Increased Margin*

#### Main Injector Solid Fuel Sleeves

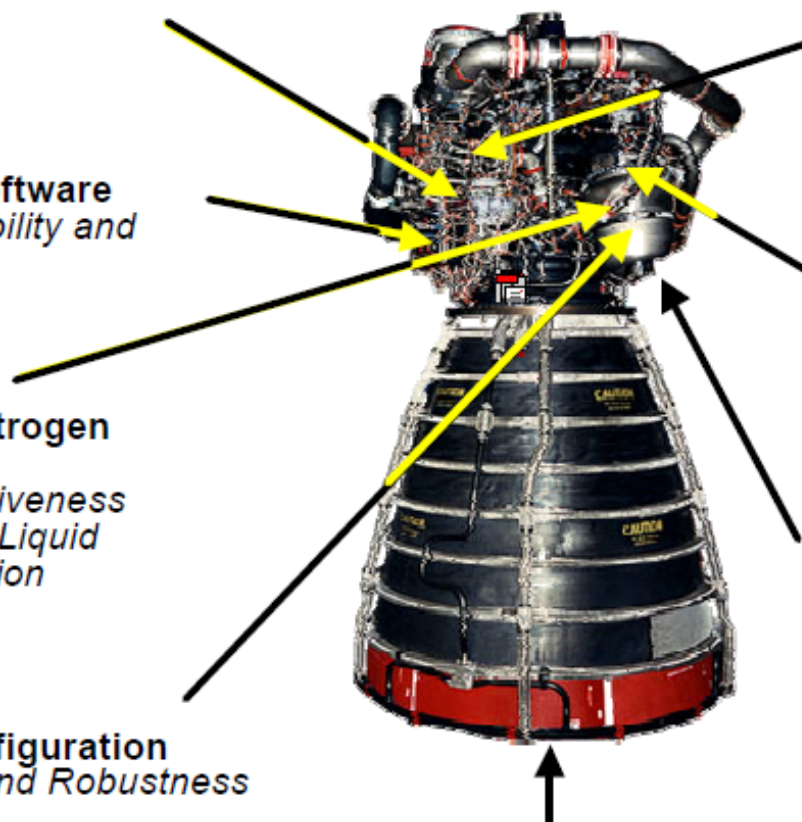
- *Increased Margin against LOX Post Tip and Face Plate Erosion (E2054 only)*

#### HPFTP Two Piece Speed Sensor & Retaining Bolts

- *Increased Reliability*

#### Nozzle Ablative Redesign

- *Increased Life*







# STS-114 Mission - Integration



## RTF Modifications

### Imagery Improvements



### WB-57 High Altitude Research Program



### Flowliner Placard



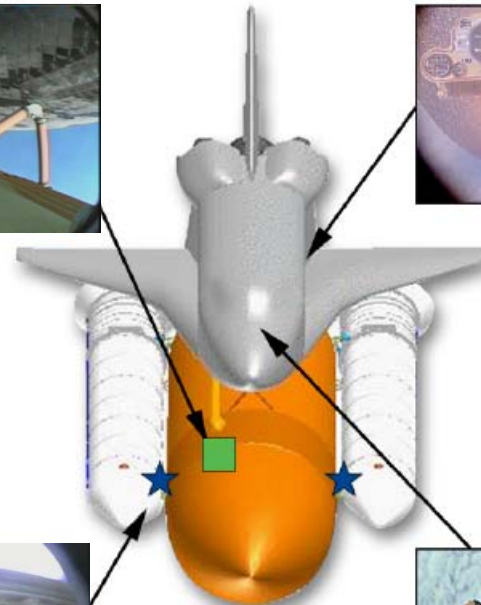
ET mounted camera

■ = Image for ET camera



Orbiter based cameras

35mm Umbilical well camera imagery



SRB mounted camera

★ = Image for SRB ET observation camera

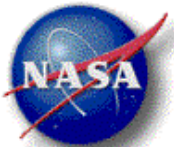


35mm External tank handheld imagery

RTF\_VI\_001.png

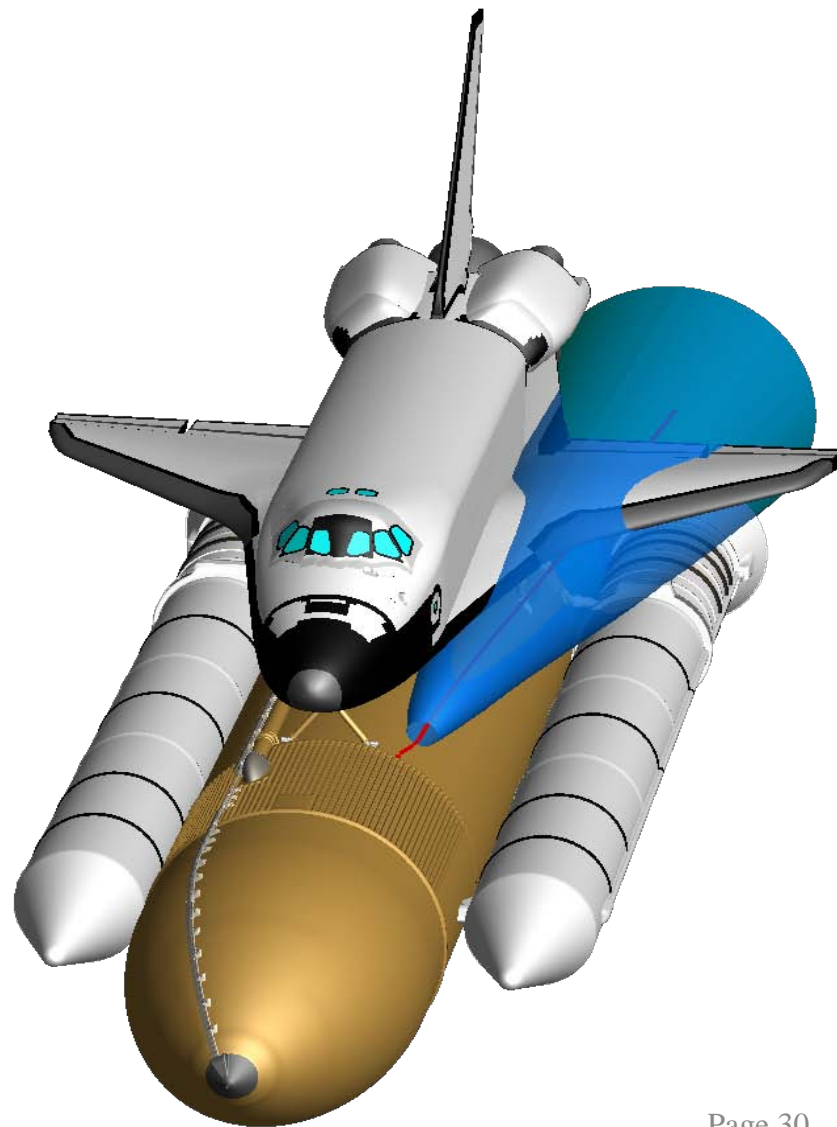
Cameras on the Space Shuttle boosters, External Tank and Orbiter

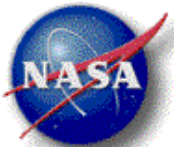




# Space Shuttle Debris Assessment History

Reynaldo J. Gómez III  
Mail Code EG3  
NASA Johnson Space Center  
[reynaldo.j.gomez@nasa.gov](mailto:reynaldo.j.gomez@nasa.gov)  
July 2010





# Success Legacy of the Space Shuttle Program



Liftoff and ascent debris has been a problem since STS-1. Several vehicle **modifications** were made to the tank and pad during the Operational Flight Tests to reduce this threat.

**No analysis capabilities.**

**Design changes included:**

- Removed ET lightning bands
- Removed ET anti geyser line
- Modified hold down post ablator and RTV minimized
- Modified beanie cap to reduce ice formation
- Foamed over multiple areas with thermal shorts.

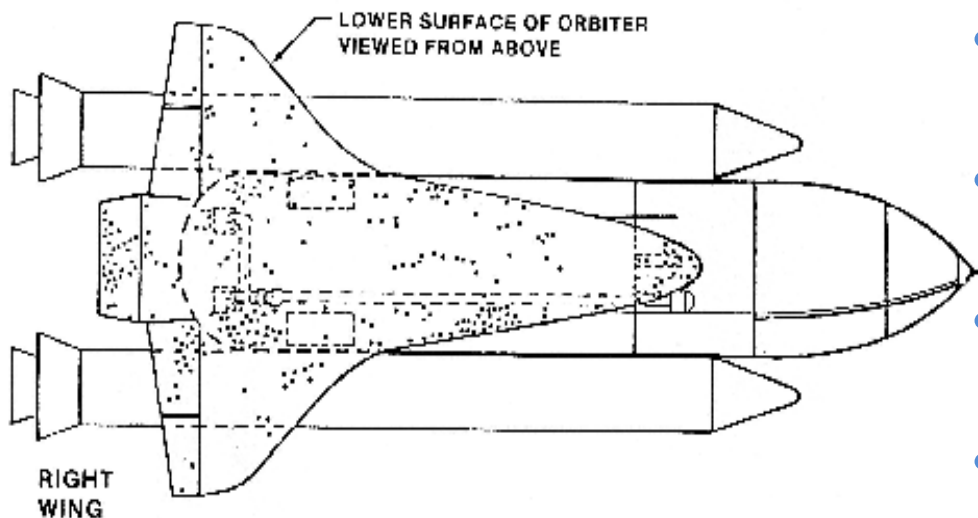
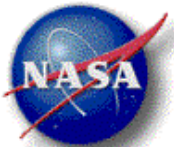


Figure 8.- STS-1 and STS-5 lower surface debris damage composite.

Craig, Mark K, "Shuttle Launch Debris - Sources, Consequences, Solutions," Space Shuttle Performance Lessons Learned Conference Report, NASA CP-2283, 1983, p. 159-185.



# Success Legacy of the Space Shuttle Program



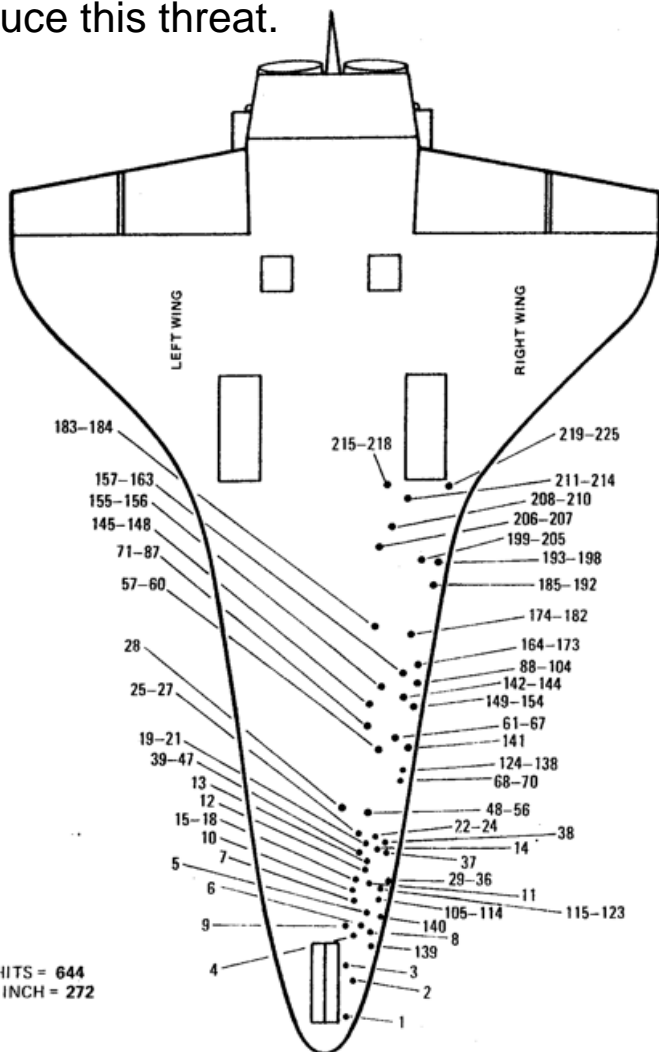
Liftoff and ascent debris has been a problem since STS-1. Several **vehicle modifications** were made to the tank and pad during the Operational Flight Tests to reduce this threat.

## Early debris transport

- No formal configuration control
- No debris release models
- Very limited transport & capability models. Foam and ice only.

## STS-27R

- 644 total hits, 244 > 1 inch
- Cause traced to SRB nosecone ablator

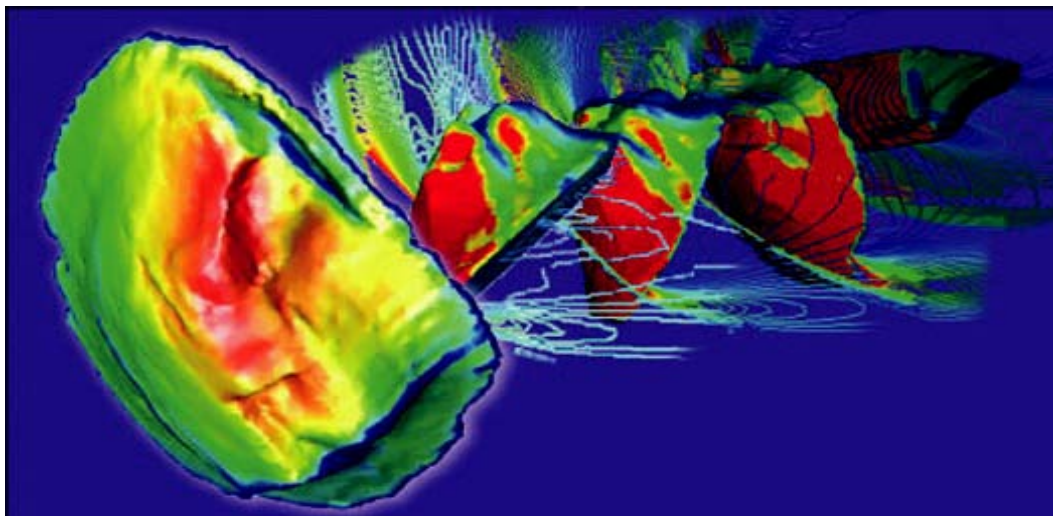
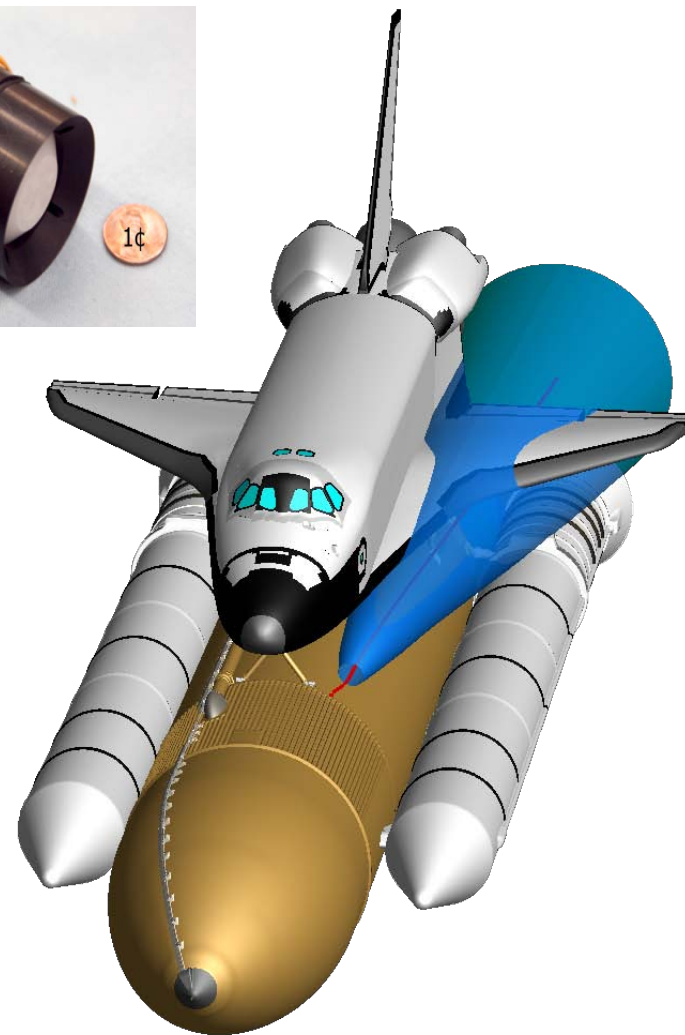
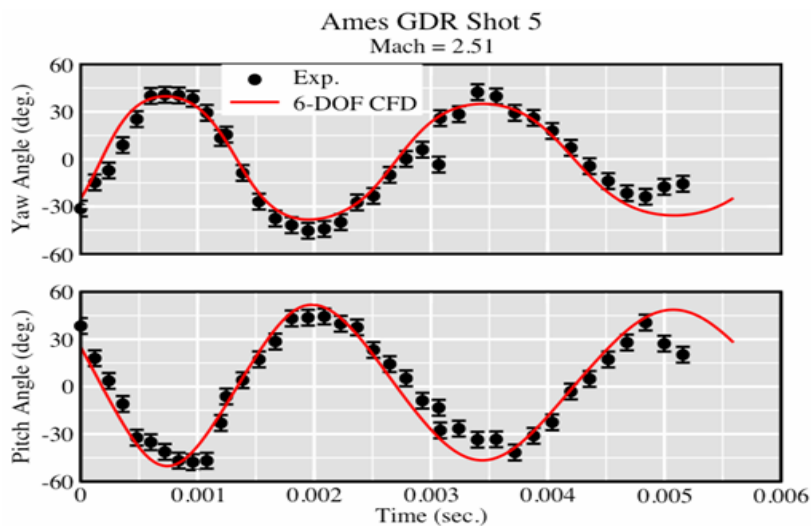


TOTAL HITS = 644  
HITS ≥ 1 INCH = 272



# Success Legacy of the Space Shuttle Program

Post STS-107 an extensive amount of development and testing was performed to improve debris models.

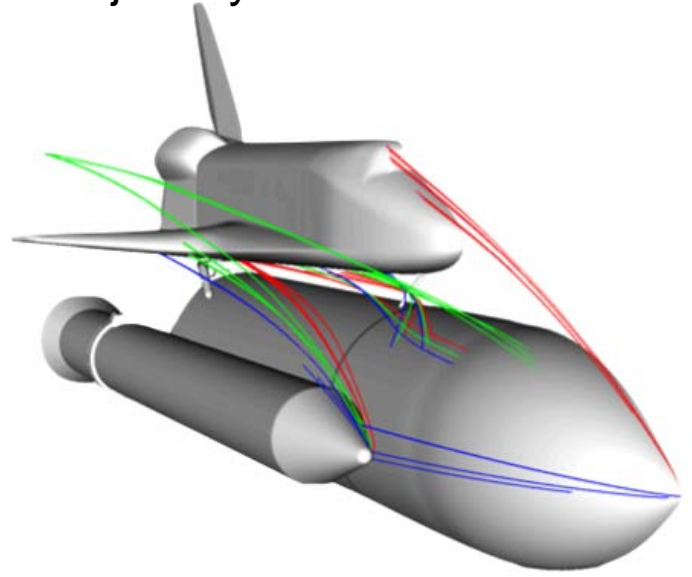




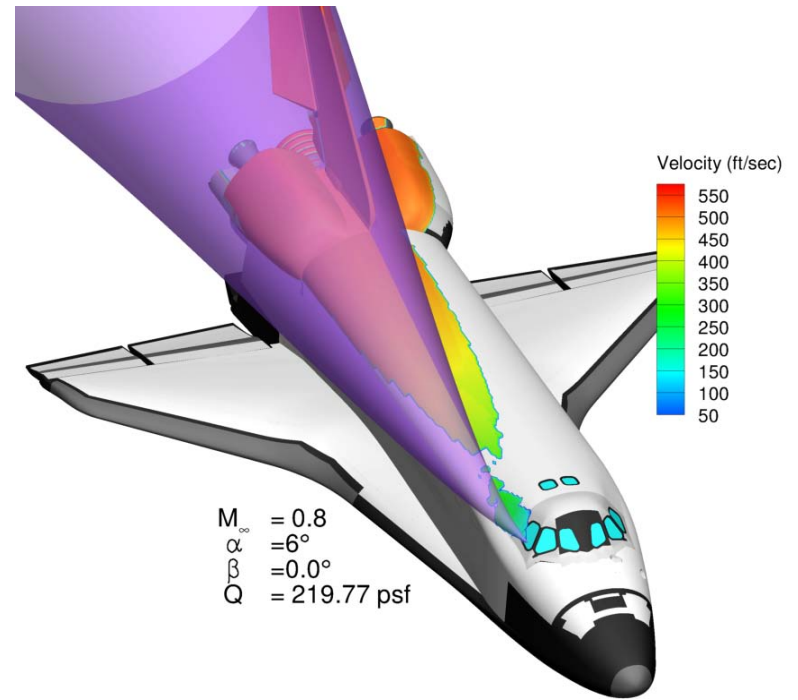
# Success Legacy of the Space Shuttle Program



### STS-27R simplified geometry & trajectory calculation

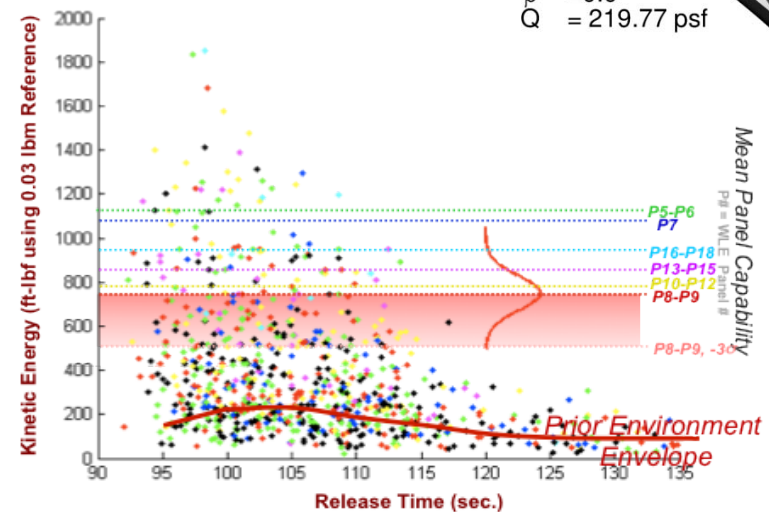


### STS-126 refined geometry & acreage impact predictions



$M_\infty = 0.8$   
 $\alpha = 6^\circ$   
 $\beta = 0.0^\circ$   
 $Q = 219.77 \text{ psf}$

### 2010 Aerospace Corporation probabilistic impact results





# Columbia Accident Investigation Board (CAIB)

## Two Decision Histories and the Normalization of Deviance

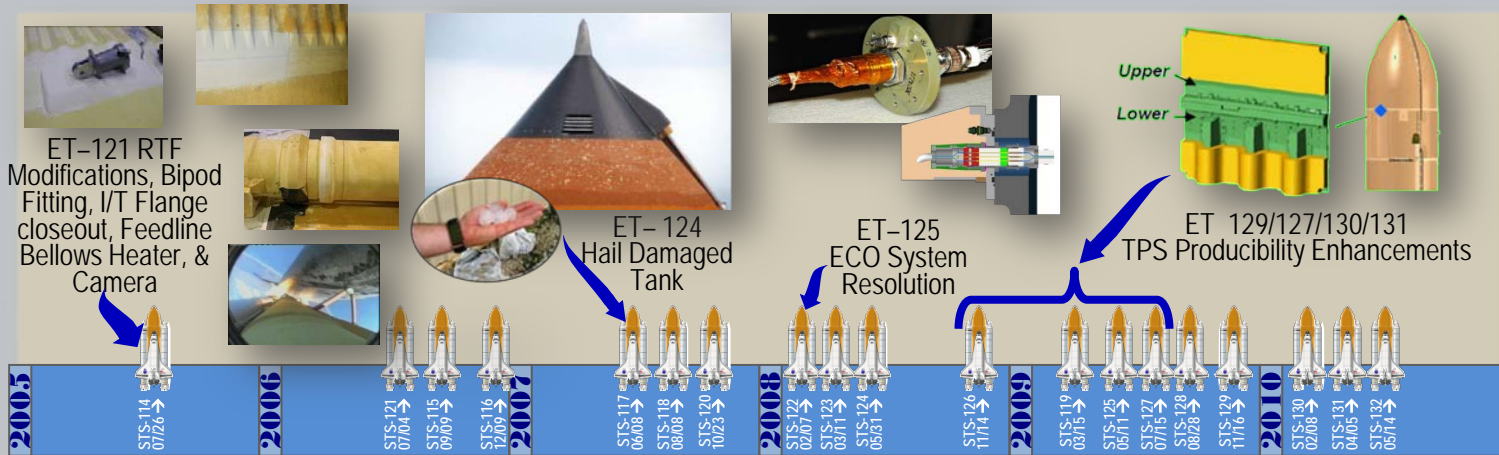


STS 51-L – O-ring Erosion	STS 107 – Foam Debris
<u>Wake up call</u> <ul style="list-style-type: none"> <li>• STS-51C, January 1985, cool weather launch               <ul style="list-style-type: none"> <li>• Primary o-ring erosion</li> <li>• Gas to secondary o-ring</li> </ul> </li> </ul>	<u>Wake up call</u> <ul style="list-style-type: none"> <li>• STS-112               <ul style="list-style-type: none"> <li>• Bipod ramp foam loss at 31 sec.</li> <li>• Impacted SRB aft ET attach ring</li> </ul> </li> </ul>
<u>Insufficient data</u> <ul style="list-style-type: none"> <li>• O-ring resilience at cold temperature</li> <li>• Poor trending of data</li> <li>• Engineers could not prove that cold temperatures were unsafe</li> </ul>	<u>Insufficient data</u> <ul style="list-style-type: none"> <li>• Affects of large foam debris impacts and RCC damage tolerance modeling</li> <li>• Imagery data not obtained</li> <li>• Engineers could not prove that foam strikes were unsafe</li> </ul>
<u>Pre-flight assessment</u> <ul style="list-style-type: none"> <li>• Acceptable risk – sealing system redundant</li> </ul>	<u>FRR assessment</u> <ul style="list-style-type: none"> <li>• Acceptable risk – in family</li> </ul>
<u>Workforce fatigue and schedule pressure</u> <ul style="list-style-type: none"> <li>• High flight rate – goal of 15/year in 1986, and 24/year by 1990</li> <li>• 4 scrubs for 61C (1/12/86) and 1 for 51L (1/28/86)</li> </ul>	<u>Workforce reductions and schedule pressure</u> <ul style="list-style-type: none"> <li>• Multiple (40%) reductions during 1990's</li> <li>• Mission content and schedule unchanged</li> <li>• Goal of achieving Node 2 launch schedule</li> </ul>
<u>Return to Flight – Redesign</u> <ul style="list-style-type: none"> <li>• Redesign and recertification of SRM joint sealing systems</li> </ul>	<u>Return to Flight – Risk Management</u> <ul style="list-style-type: none"> <li>• Selected redesigns, inspection and repair capabilities, and risk acceptance</li> </ul>

*“NASA managers believed that the agency had a strong safety culture, but the Board found that the agency had the same conflicting goals that it did before Challenger, when schedule concerns, production pressure, cost-cutting and a drive for ever-greater efficiency – all the signs of an “operational” enterprise – had eroded NASA’s ability to assure mission safety. “ CAIB Report*



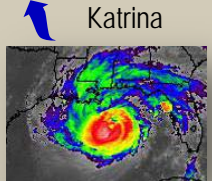
## External Tank



Enabling ISS High Inclination Payload Mass



Baseline SLWT AI-Li



Katrina



ET-119 RTF II Modifications PAL Ramp Removal



ET-120 LH2 IFR Redesign Demonstration



ET-128 First In-line Tank LO2 Feedline Brackets and LH2 IFR's

AI 2219 Complex Curvature Panels, and Friction Stir Welding fully implemented on ET-134



SLWT Mass Unchanged

- Processing Improvements**
- Low Spray Guns
  - Human Factors
  - High Fidelity Mockups
  - Video Review Of Sprays
  - Improved Access
  - Non Destructive Evaluation
  - Producibility Enhancements
  - GUCP Improvements
  - Friction Stir Welding

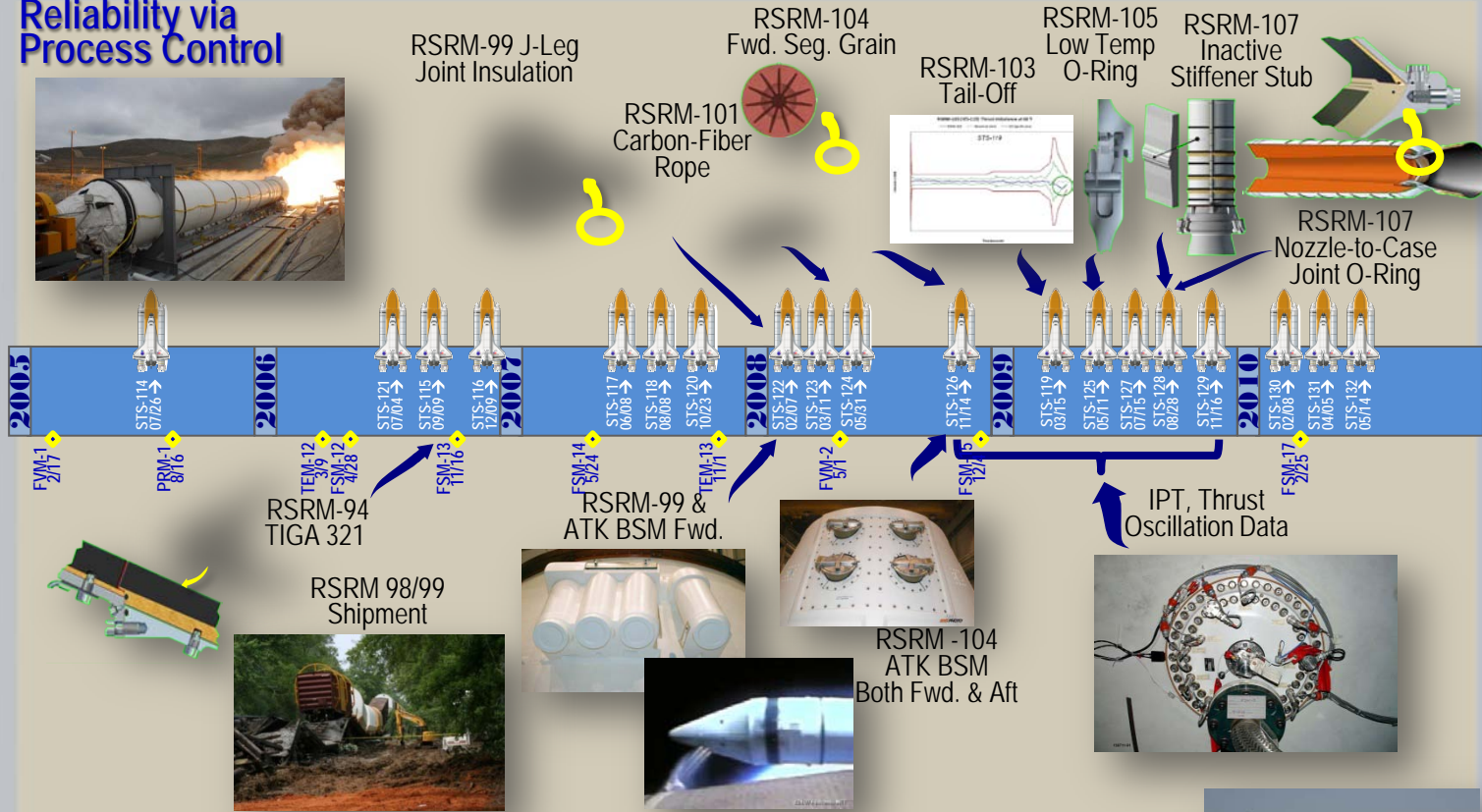
- Design Improvements**
- Bipod Fitting
  - Bellows Heater
  - Feedline Camera
  - PAL Removal
  - LH2 Ice Frost Ramps
  - LO2 Titanium Brackets
  - ECO Feed Through
  - Sixth Buy Tanks

- Post Flight Assessment**
- Imagery-Situational Awareness
  - Failure Mode Assessment
  - CAD Modeling
  - Post Flight Assessment Process
  - Historical Data Base
  - Statistical Assessments



## Reusable Solid Rocket Motor

### Reliability via Process Control



#### Design Changes

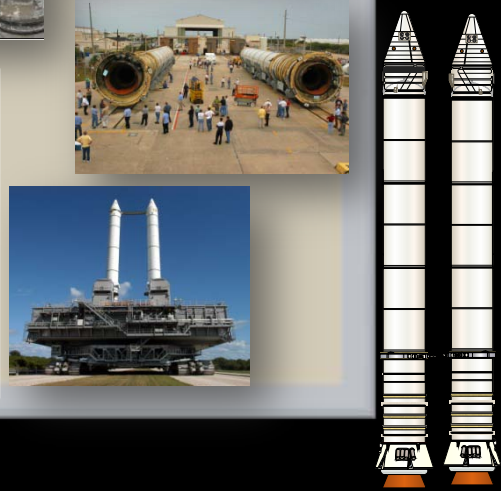
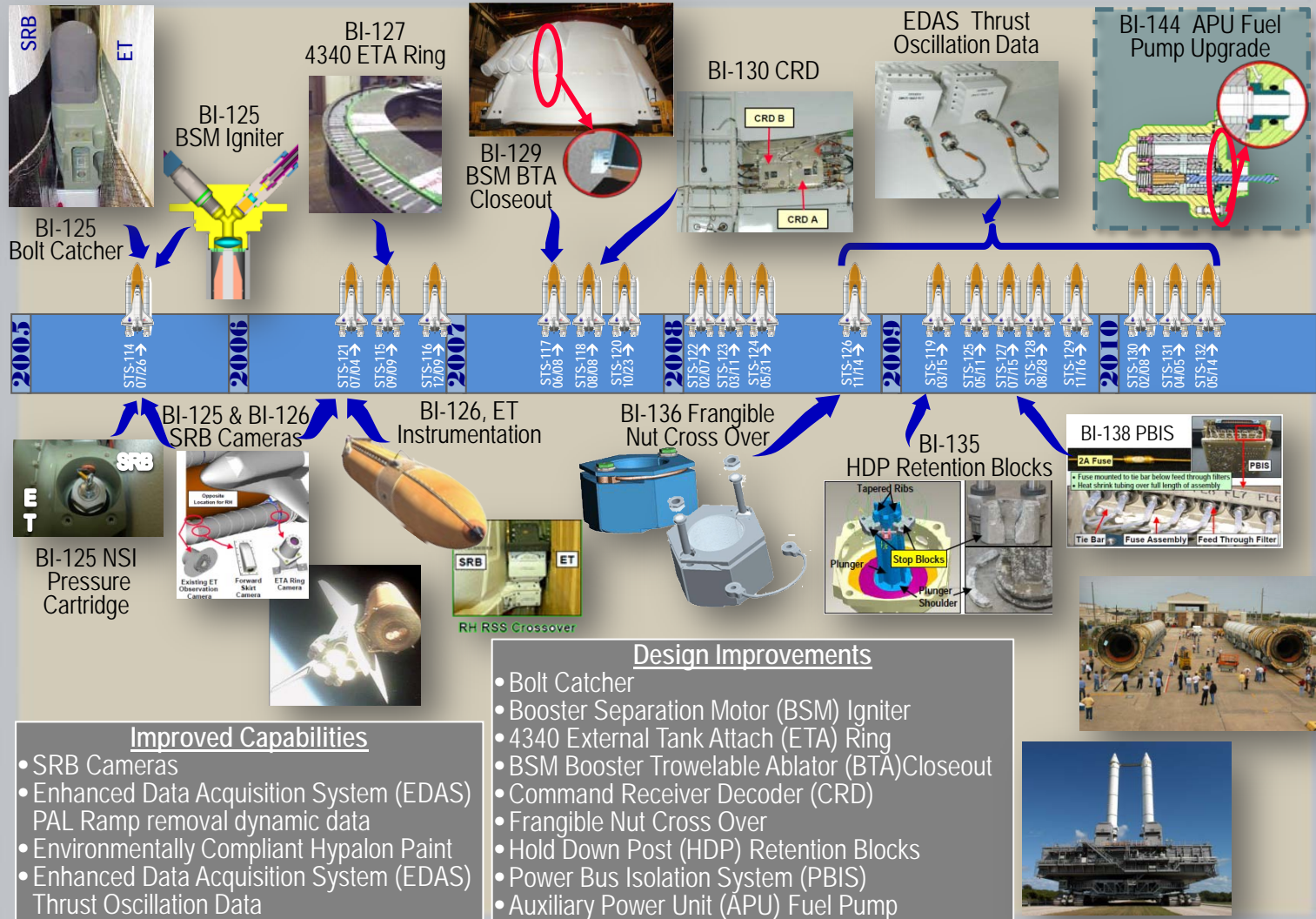
- TIGA 321 Adhesive
- ATK Booster Separation Motor's
- Carbon Fiber Rope
- Forward Grain Redesign
- Inactive Stiffener Stub Removal

#### Processing and Capability Improvements

- Nozzle-To-Case J-Leg Joint Insulation
- Intelligent Pressure Transducer (IPT)
- Age Life Extensions
- Low Temp O-rings

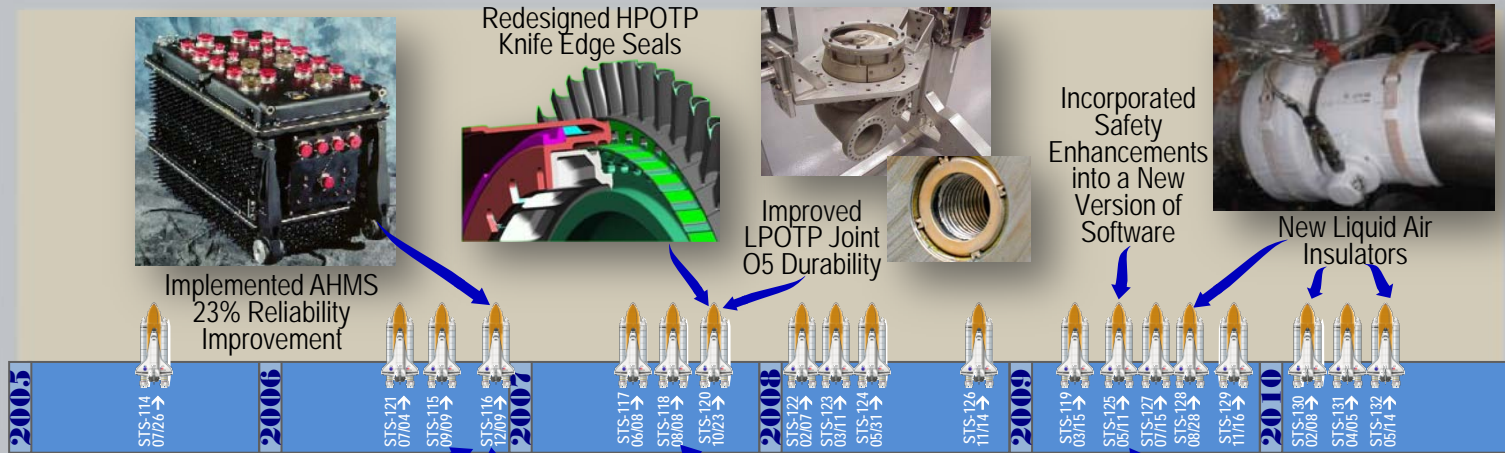


## Solid Rocket Booster





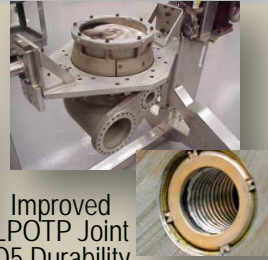
## Space Shuttle Main Engine



Implemented AHMS  
23% Reliability Improvement



Redesigned HPOTP  
Knife Edge Seals

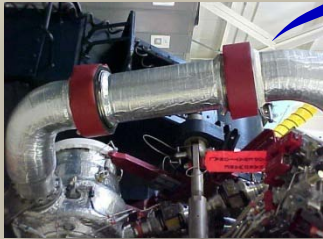


Improved  
LPOTP Joint  
O5 Durability

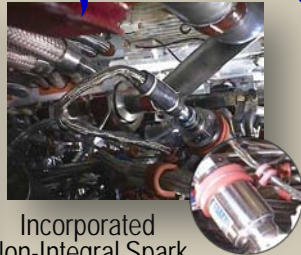
Incorporated  
Safety  
Enhancements  
into a New  
Version of  
Software



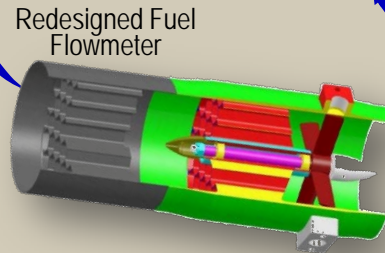
New Liquid Air  
Insulators



Implemented Kevlar  
Insulation



Incorporated  
Non-Integral Spark  
Ignition System



Redesigned Fuel  
Flowmeter



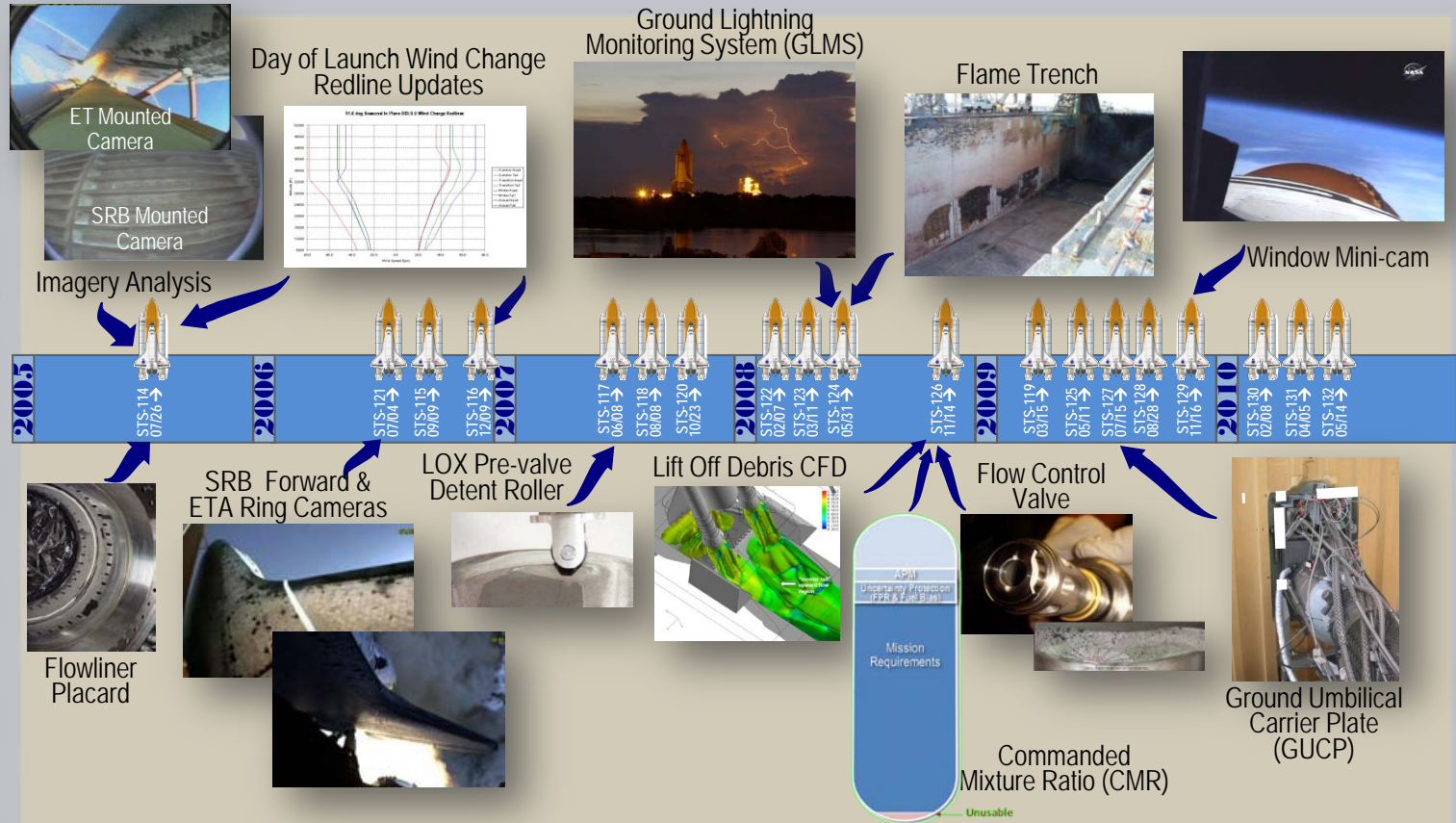
140% Nozzle Fabrication  
Performance  
Improvement

- Processing & Operations Improvements**
- Software Upgrades
  - Low-Pressure Oxidizer Turbopump (LPOTP) Joint O5 Enhancement

**Reliability Improved By A  
Factor Of 3 During The Program**

- Design Improvement Areas**
- Advanced Health Management System (AHMS)
  - Kevlar Insulation
  - Non-Integral Spark Ignition System
  - Fuel Flowmeter
  - High-Pressure Oxidizer Turbopump (HPOTP) Knife Edge Seals
  - Software
  - Rigid Fuel Bleed Duct
  - Liquid Air Insulators

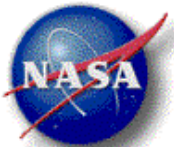




- ### New Capabilities
- Imagery Analysis
  - Risk Assessment Process
  - Lift Off Debris Computational Fluid Dynamics (CFD)
  - Ground Lightning Monitoring System(GLMS)
  - Day of Launch Wind Change Redline updates

- ### Solving Problems
- LOX Pre-valve Detent Roller Solution
  - Overboard Mixture Ratio (OBMR)
  - Flow Control Valve (FCV) Evaluation And Flight Rationale
  - Ground Umbilical Carrier Plate (GUCP)
  - Flowliner Placard





# Success Legacy of the Space Shuttle Program



## Conclusions

- Evidence of Cultural Change
- Level of Detail presented at Boards, Project and Program Reviews is significantly increased: Examples
  - Removal of PAL Ramps prior to next flight after STS-114 loss
  - Continued modifications to ET foam applications to reduce debris
  - Robusted EPAT assessment and reporting process
  - On-Orbit repairs of OMS Blankets
  - Bookkeeping time for Focused Inspection early in flight
  - Content and format of On-Orbit MMT structured to highlight significant issues requiring MMT decisions
  - Launch slips when decisions could not be supported by data
  - Combined Safety Review with NASA Chief Engineering and Chief, Safety and Mission Assurance
  - Level of detail required to disposition Launch constraint issues
  - Respect and dignity extended to individuals with alternate or dissenting opinion throughout FRR and MMT processes
- Clear and Irrefutable evidence our Shuttle Culture has made a positive behavioral change