External Tank Program
Legacy of Success

Chief Engineer's Council
Montreal
8/23-24/2010

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ET-138 Rollout 7/8/10

External Tank Legacy of Success

- ***Agenda***
  - *External Tank Overview*
  - *Super Lightweight Tank Verification*
  - *Return to Flight*
  - *Engine Cut-Off Sensor Circuit*
  - *ET-124 Hail Damage Recovery*
  - *STS-130 / ET-134 Launch*

STS-132/ ET-136
05/14/10

External Tank Legacy of Success Overview

- *Notable Events*
  - *ATP – 1972*
  - *1st Production Article – 1978*
  - *1st Flight Article Complete – 1979*
  - 1st SLWT Complete – Enabled access ISS – 1998
  - *TPS design changes implemented post-Columbia (RTF) to reduce debris - 2003*
  - *All manifested tanks completed and delivered to KSC – 2010*
  - *139 tanks manufactured in total*

2003 - 2009

Changes Implemented to Reduce Debris

1980's **1990's** **2000's** **2010**

Tank structure 'evolved' to improve payload performance and producibility

1981 - 1983

HWT

6 flown

1981 - 1998

LWT

86 flown

1998 - Present

SLWT

21 flown

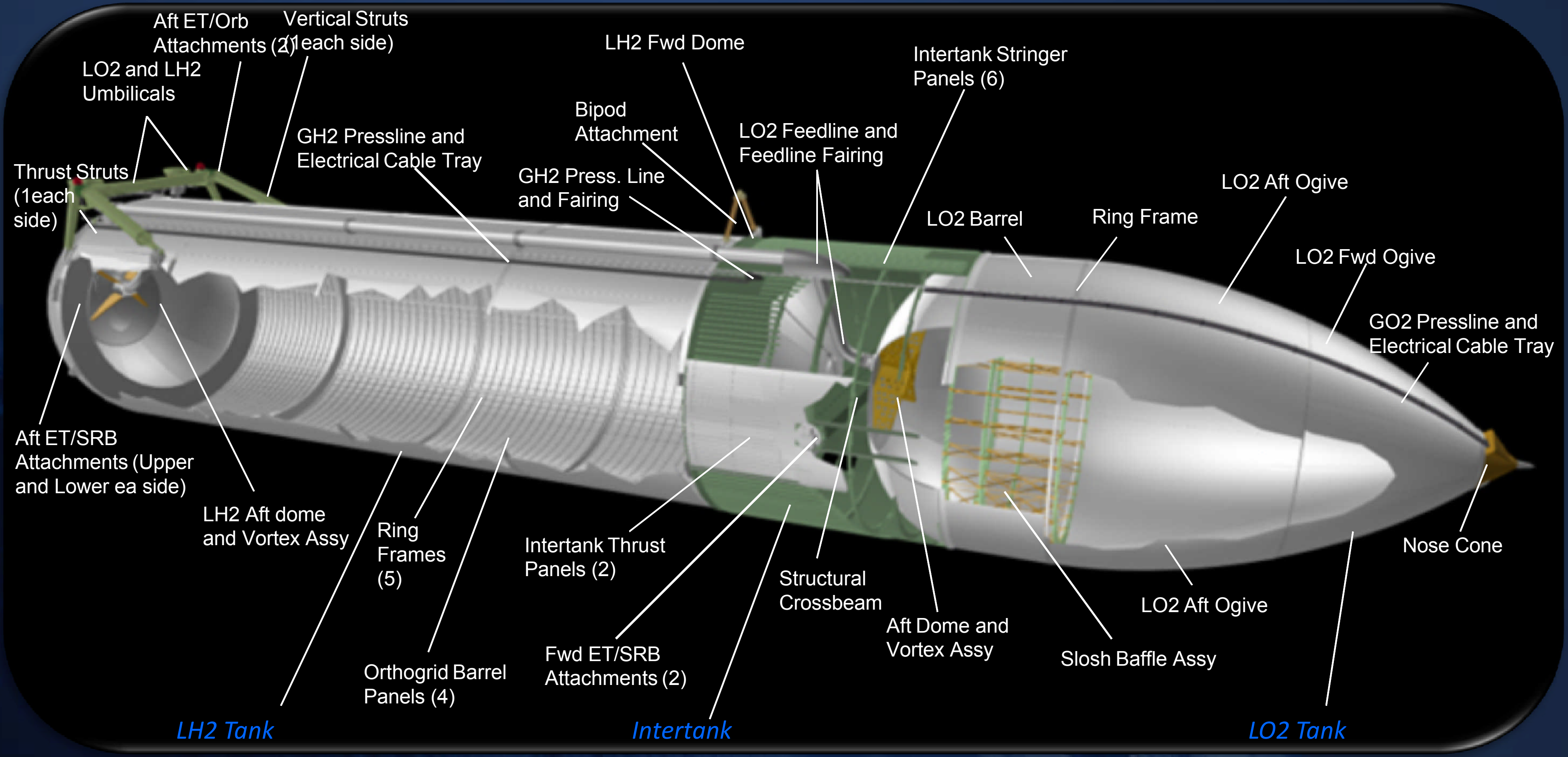
RTF

19 flown

External Tank Evolution / Weight

- *HWT (1981 – 1983): 77,086 lb. (6 flown)*
- *LWT (1981 – 1998): 66,000 lb. (86 flown)*
- *SLWT (1998 – present): 58,550 lb. (40 flown)*

External Tank Legacy of Success
Overview



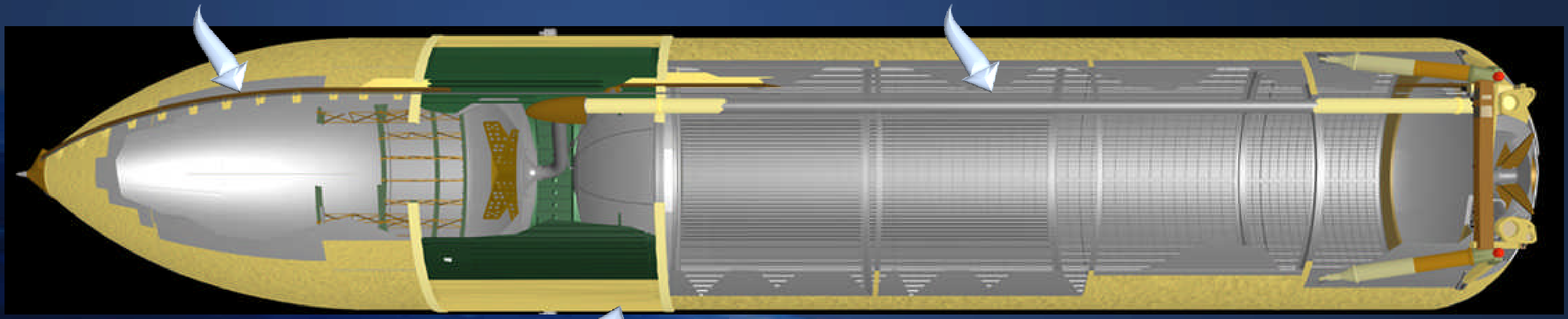
System	Structure	Propulsion	Electrical	Thermal Protection	Interface Hardware
	• LO2 Tank • Intertank • LH2 Tank	• Propellant Feed • Pressurization • Vent/Relief • Environmental Conditioning	• Instrumentation (sensors, heaters, and associated cabling) • Lightning Protection • ET Camera	• Foam (Spray and Pour) • Ablators (Spray and Molded) • Composites	• ET/SRB • ET/Orbiter • ET/Ground

External Tank Legacy of Success
Overview

- ***Interesting ET Facts***

Liquid Oxygen Tank
- 1,385,000 lbs. / 145,138 gallons Oxidizer
- -297°F

Liquid Hydrogen Tank
- 231,000 lbs. / 309,139 gallons fuel
- -423° F



Intertank
- Unpressurized Structure

- ~4,000 lbs. of thermal protection materials (16,750 sq. ft.)
- ~38 Miles of Electrical Wiring
- Length = 153.8 Feet
- Diameter = 27.6
- > ½ mile of pressure vessel welds

- Max TPS thickness - ~2.5" (LO2)
- Min TPS thickness - ~0.2" (Intertank)
- Max Al substrate thickness - ~2.0" (Intertank)
- Min Al substrate thickness - ~0.050" (Intertank)
- Max LO2 operating pressure - ~70 psig
- Max LH2 operating pressure - ~40 psig

External Tank Legacy of Success
Super Lightweight Tank

- ***Goal***
  - Optimize External Tank structural mass to support ISS construction
    - ~7500 lbm required to achieve 51.6° orbital inclination with ISS payload
    - Super Lightweight Tank (SLWT) program initiated to provide performance

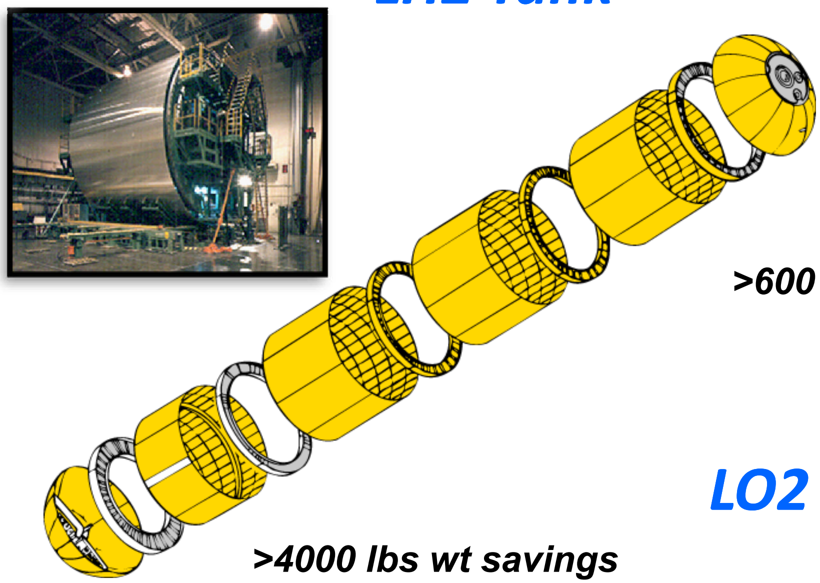
- ***Challenges***
  - Required parallel development of lightweight aluminum-lithium material, and associated manufacturing processes, and design
  - Aggressive schedule to support ISS program
  - Structural verification program constrained by funding and schedule
    - Dedicated full-scale, cryogenic STAs not planned
  - Significant production impacts caused by Al-Li alloy weld-related rework

- ***How'd We Do It?***
  - Leveraged government and corporate research with Al-Li alloys
  - Used new orthogrid design for LH2 tank barrels to optimize performance
  - Developed innovative design / material verification and acceptance test program
  - Fully engaged industry experts and technical community early in design verification
  - Evolved design to mitigate production issues

External Tank Legacy of Success
Super Lightweight Tank

- *Super Lightweight Tank (SLWT) Change from Lightweight (LWT)*

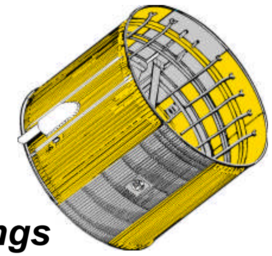
LH2 Tank

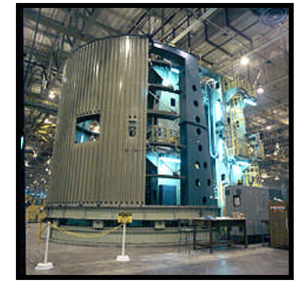


>4000 lbs wt savings

- Substitute Al 2195 for Al 2219
- Redesign to Orthogrid Waffle
- Optimize TPS Application

Intertank

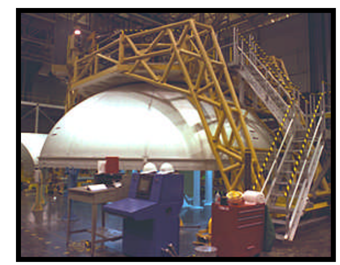




>600 lbs wt savings

- Substitute Al 2090 for Al 2024 and Al 7075

LO2 Tank



>1500 lbs wt savings

- Substitute Al 2195 for Al 2219
- Resize

= Al Li 2090, 2195

= Other Redesigned Parts

External Tank Legacy of Success
Super Lightweight Tank

- ***Major configuration change implemented on SLWT LH2 Tank barrels***
  - Was: Al 2219 T-stiffened
  - Now: Al 2195 Orthogrid
    - Required development of new manufacturing process for machining, forming, and welding

Standard Weight (SWT) and Lightweight (LWT) – Al 2219 alloy

Super Lightweight (SLWT) – Al 2195 alloy

External Tank Legacy of Success
Super Lightweight Tank

- ***Innovative structural verification plan established for SLWT***
  - An independent Verification Team was formed with industry experts
  - Verification Team established plan that verified each failure mode by either test, flight history, or independent analyses
  - Team utilized wealth of data from SWT and LWT heritage
    - STA, GVTA, MPTA, DDT&E and 90 flights

ET Structural Verification Approach

Design Verification

Partial / Complimentary

Existing Data Base

Component Tests (strength & stability)

Independent Analysis (stability)

Aluminum Lithium Test Article (ALTA)

Analysis

Total Tank

Proof Tests (strength, fracture)

Protoflight Tests (stability)

Verified SLWT

Acceptance Verification

Material Acceptance

Proof Tests

Protoflight Tests

Nondestructive Evaluations

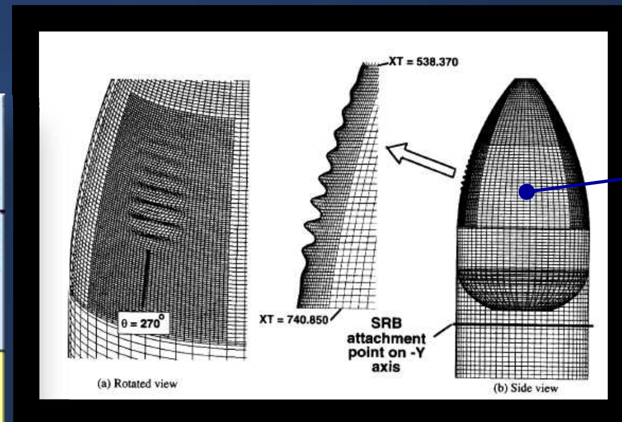
"Test what you fly – Fly what you test"

External Tank Legacy of Success
Super Lightweight Tank

- *SLWT Verification Process*

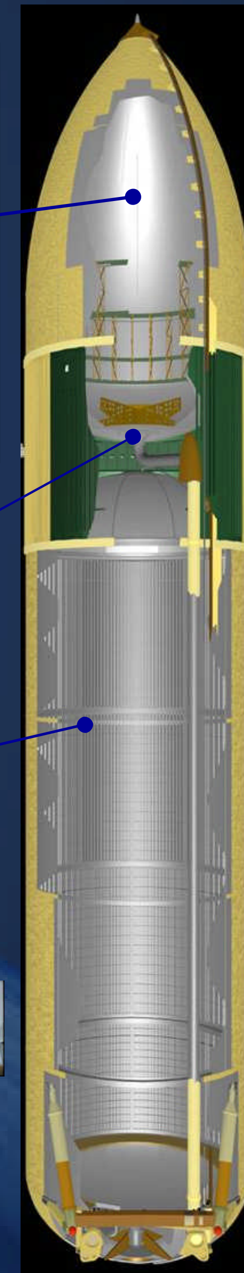
	Existing Data Base	Component Tests	Independent Stability Analysis	ALTA	Proof Tests	Protoflight Tests	Tanking Test	Engineering Analysis
LO2 Tank Structure								
Stability	x	x	x	x				x
Strength	x				x			x
Intertank Structure								
Stability	x	x	x					x
Strength	x							x
LH2 tank Structure								
Stability	x	x		x		x	x	x
Strength	x	x			x	x		x
Thermal Protection Systems	x	x					x	x
MPS / Electrical Systems		x					x	x
Interface / Component Hdwr	x							x

ALTA used to verify multiple hardware elements and failure modes
- - LH2 Barrel Panels, LO2 Dome, Fusion Welding



LO2 Tank Independent Stability Analysis (LaRC)

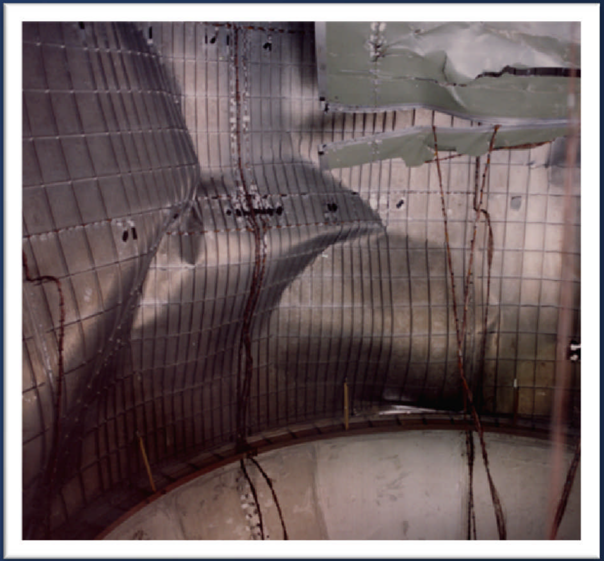
ALTA at MSFC

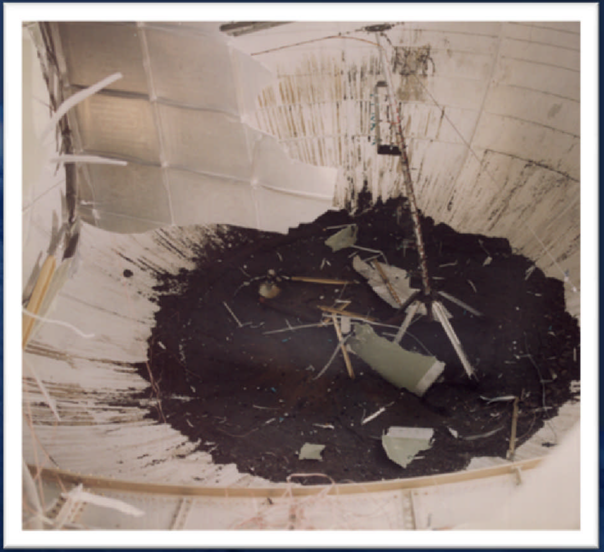


Test-based Verification Performed for All Hardware and Failure Modes
- - Program Mitigated Requirement for Full-scale Cryogenic Test

External Tank Legacy of Success
Super Lightweight Tank

- ***ALTA Capability Test***
  - Structure tested to demonstrated to > ultimate load





External Tank Legacy of Success
Super Lightweight Tank

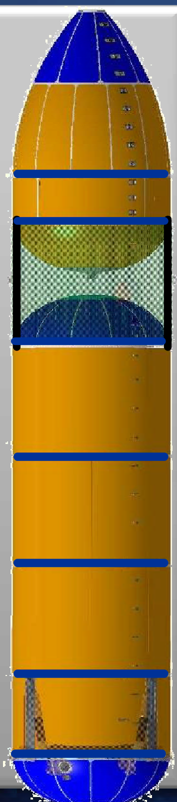
- ***SLWT design further evolved to mitigate production issues with fusion welding and maintain payload performance***
  - Reverted back to Al 2219 for domes / ogives with structural optimization (+wt)
  - Further optimized LH2 tank in areas with high margins (-wt)
  - Implemented Al-Li in non-welded application (Intertank thrust panel) (-wt)

ET-123 / STS-116 (first flown)

- Substituted Al 2195 LO_2 fwd ogive, LH_2 fwd & aft dome gores with Al 2219 / resize membrane
- Redesigned Intertank thrust panels

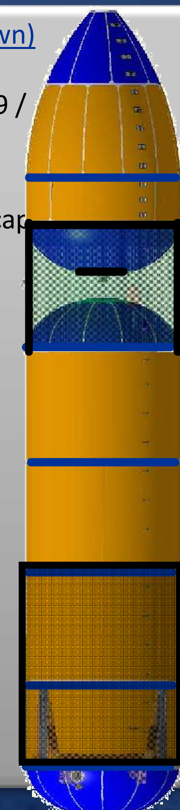
Legend

- Al 2195
- Al 2219
- Design changed (thickness optimized / material unchanged)
- Al 2297
- FSW on ET-132 & subs
- FSW on ET-134 & subs



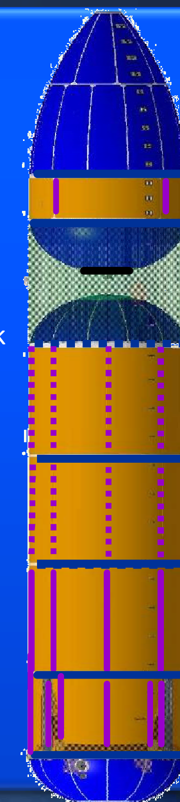
ET-127 / STS-119 (first flown)

- Substituted Al 2195 LO_2 dome gores with Al 2219 / resize membrane
- Resized LO_2 tank X_T 851 frame webs, LO_2 dome cap and LH_2 barrels 1 and 2



ET-134 / STS-130 (first flown)

- Implemented FSW on LO_2 & LH_2 Tank barrel longitudinal welds *(barrels 3 & 4 only for ETs 132 & 133)*
- Substituted Al 2195 LO_2 aft ogive with Al 2219 / resize membrane
- Substituted Al 2219 Intertank thrust panels with Al 2297



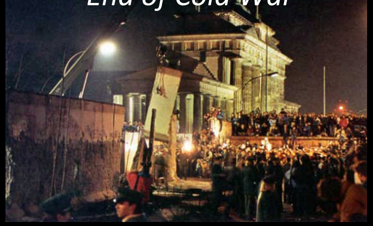
Design Changes Leveraged Data Developed during Baseline SLWT Certification - - Changes Mitigated Production Issues without Increasing Weight

External Tank Legacy of Success
Super Lightweight Tank

- ***Results***
  - 1st SLWT tank delivered in 44 months
  - SLWT tanks delivered on-time and within budget and have performed flawlessly
  - SLWT tank enabled ISS construction by improving Shuttle payload capability
  - ISS construction required international collaboration
  - SLWT tank + SSP + ISS = World Peace!!

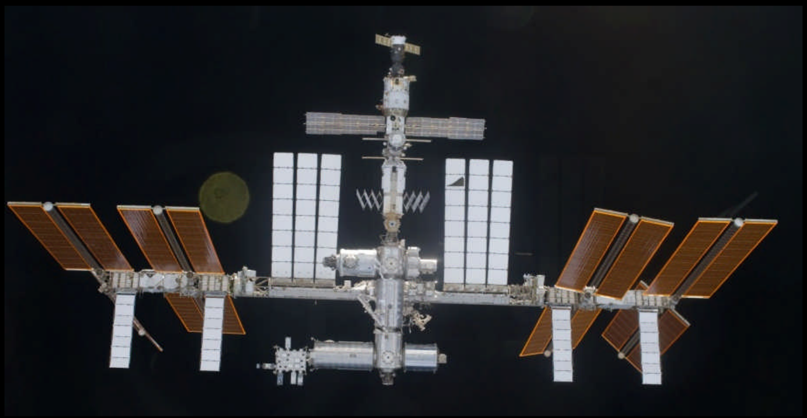
International Teamwork made possible by SLWT

End of Cold War



Improved Relations between Nuclear Super Powers

STS-91 / ET-96



International Space Station photographed by STS-132 crew

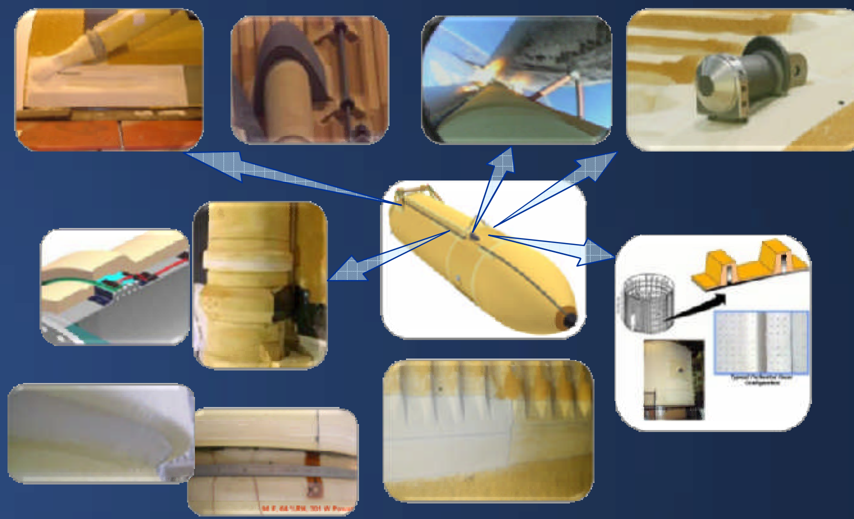
External Tank Legacy of Success
Super Lightweight Tank

Key Lessons Learned

- *Engage industry experts early in design verification cycle*
- *Verification program should be test-based and failure mode specific*
- *Tests to design capability are critical to understand margins*
- *Tests should be performed incrementally to reduce program risk*
  - *Component – Large scale – Acceptance*
- *Protoflight tests can be used when ultimate load tests not practical*
- *Independent analyses can be used to extend test-based data for similarity verification*
- *Leverage ALL previous test, analysis, and engineering experience data to the fullest extent to minimize risk*
- *Designs should 'evolve' to more exotic material and manufacturing*

External Tank Legacy of Success
Return to Flight

- ***Goal***
  - Post-Columbia ET Project directed to ***eliminate*** critical debris sources by redesign or provide flight rationale

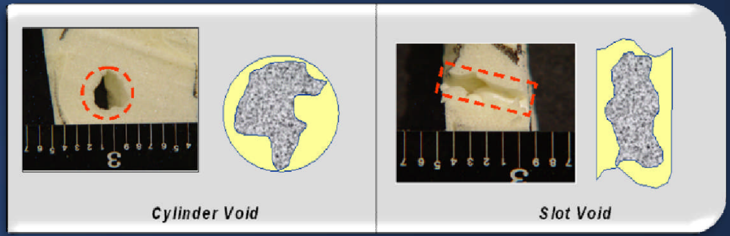


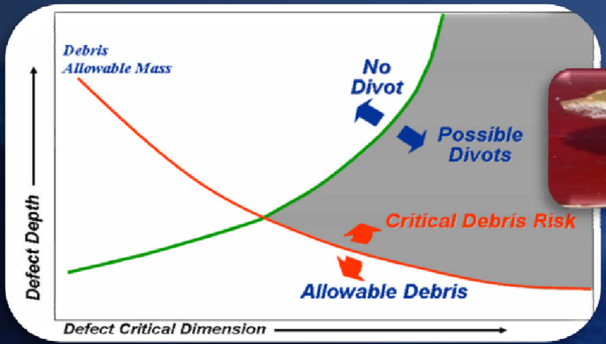
- ***Challenges***
  - Limited understanding of TPS material, failure modes, and analysis methods
    - TPS debris never considered a ‘safety of flight concern’ before STS-107
  - Extreme amount of distrust / anxiety within technical and programmatic communities
  - Schedule pressure to Return to Flight – 6 month target for RTF initially established…
  - Debris expectations not effectively communicated or understood coupled with unexpected foam loss on RTF I
  - Limited ability to effectively communicate integrated debris risk
  - TPS performance after RTF I resulted in stand-down to perform additional debris mitigations
  - Hurricane Katrina devastated south Louisiana following RTF I
  - TPS scope increase from RTF I and RTF II jeopardized ET’s ability to ‘Meet the Manifest’

External Tank Legacy of Success
Return to Flight

How'd We Do It?

Performed extensive test program to document and characterize TPS application process performance





Performed failure mode tests to relate process data to debris expectations

Enhanced flight imagery assets and post flight assessment process to further correlate understanding of failure modes

ET-120 dissection following cryogenic loading provided key insight into TPS failure modes

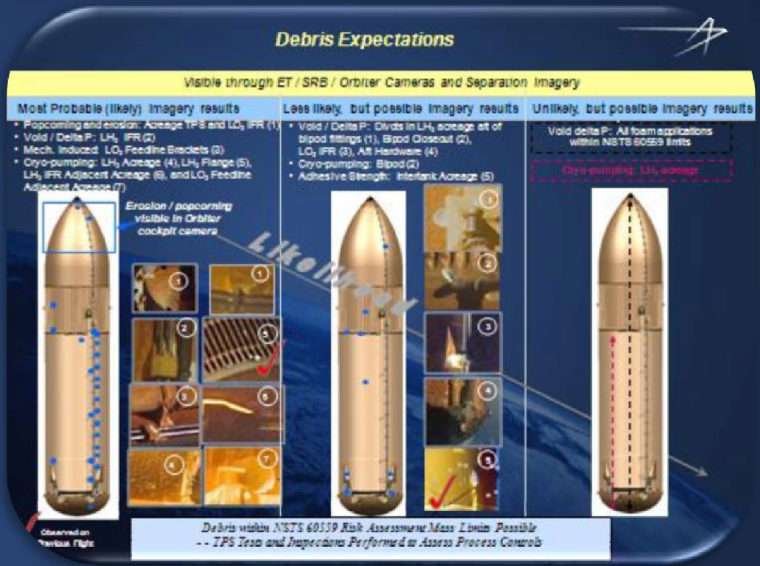
Significantly improved understanding and communication of debris expectations

- - Fully engaged technical community

External Tank Legacy of Success
Return to Flight

How'd We Do It?

Improved understanding of performance led to,
- *Improved communication of expectations*
- *Enhanced designs with improved process controls*
- *Design / process changes prioritized and implemented as soon as practical – Mod tanks and In-line tanks*



Outstanding dedication and perseverance in the face of extreme hardships

- *A section of eastern New Orleans after Hurricane Katrina*
- *Michoud Assembly Facility (green) is not flooded, while the surrounding neighborhoods (dark greenish brown) are extensively flooded*

ET Team become extremely resilient and efficient when confronted with difficult situations..

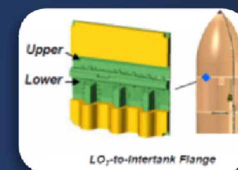
External Tank Legacy of Success
Return to Flight

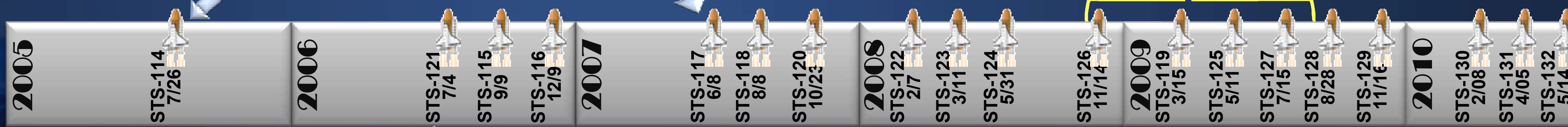
- ***Challenges and learning led to continuous improvements during RTF***

ET– 121 RTF Modifications
Bipod Fitting and Feedline Bellows Heater

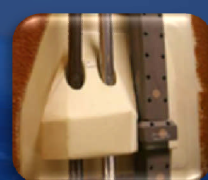
ET– 124
Hail Damaged Tank

ET -129/127/130/131
TPS Producibility Enhancements





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

Processing Improvements

- *Low Output Spray Guns*
- *Human Factors*
- *High Fidelity Mockups*
- *Video Review Of Sprays*
- *Improved Tank Access*
- *NDE*
- *Produciblity Enhancements*
- *GUCP Improvements*
- *Friction Stir Welding*

Design Improvements

- *Bipod Fitting*
- *Bellows Heater*
- *Feedline Camera*
- *PAL Removal*
- *LH IFR's*
- *LO2 Ti Brackets*
- *ECO Feed Through*
- *Sixth Buy Tanks*

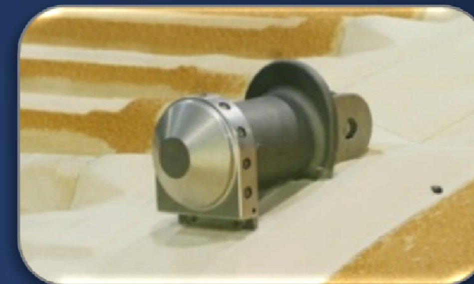
Post Flight Assessment

- *Imagery*
- *Failure Mode Assessment*
- *CAD Modeling*
- *EPAT Process*
- *Historical Data Base*
- *Statistical Assessments*

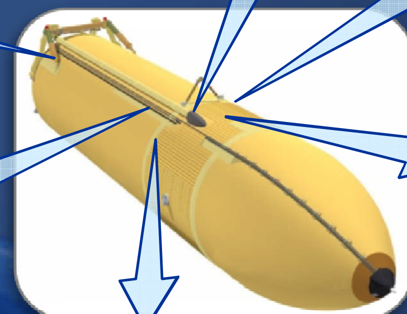
External Tank Legacy of Success
Return to Flight

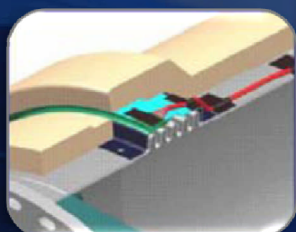
Remove/Replace Longeron Closeouts

Feedline Fairing Camera



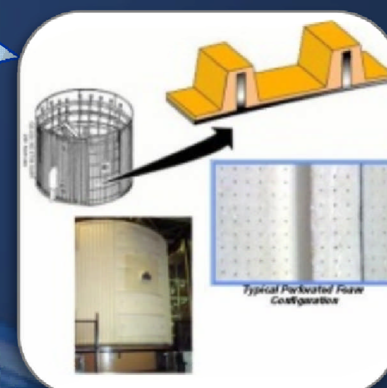
Bipod Fitting Closeout





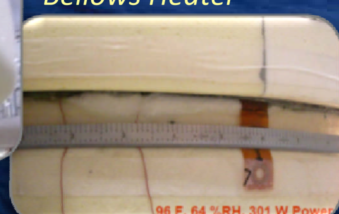
Feedline Bellows

Forward feedline Bellows Heater



Increase Area of Vented Intertank TPS

Without heater



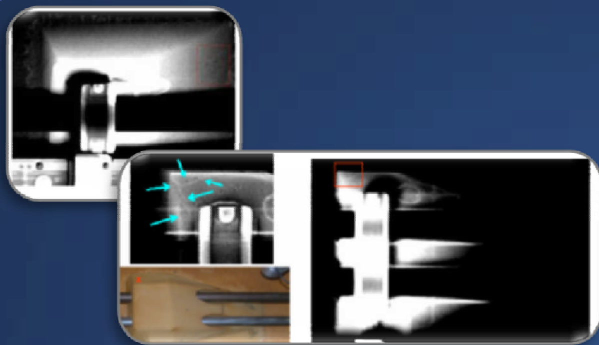
With Heater

Intertank/LH2 Tank Flange Closeout Enhancement

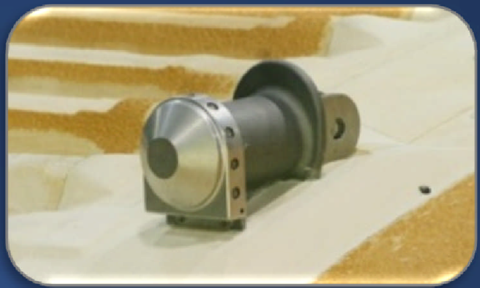
RTF I: ET-121 modifications to reduce foam and ice debris

-- Performance improved but 'unexpected' observations from the LH2 flange, bipod, and LH2 PAL ramp resulted in stand-down and RTF II

External Tank Legacy of Success
Return to Flight

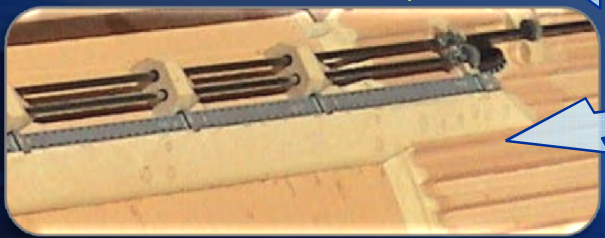


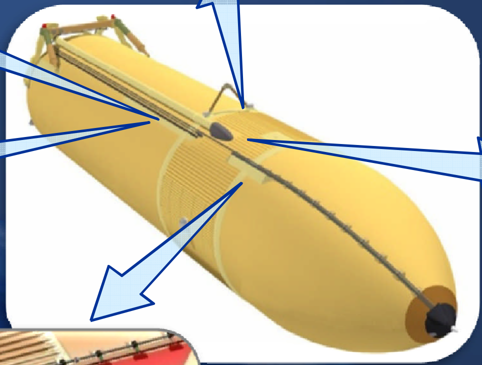
Development of NDE capabilities

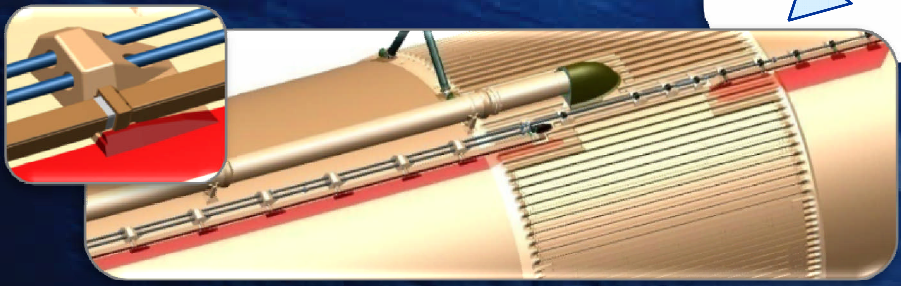


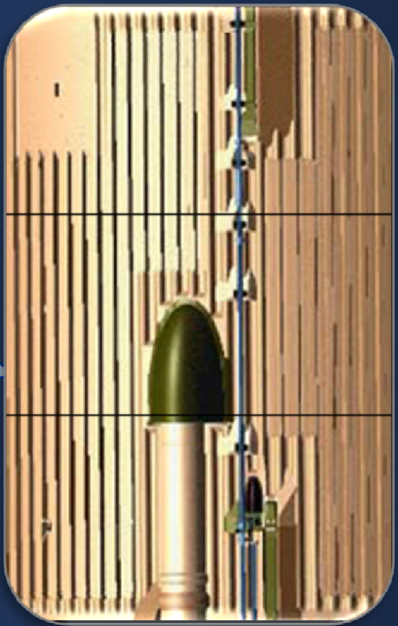
Bipod Harness Revisions

LO2 and LH2 PAL Ramp Removal









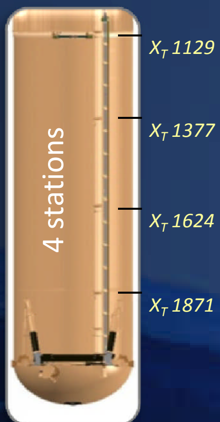
Increase Area of
Vented Intertank TPS

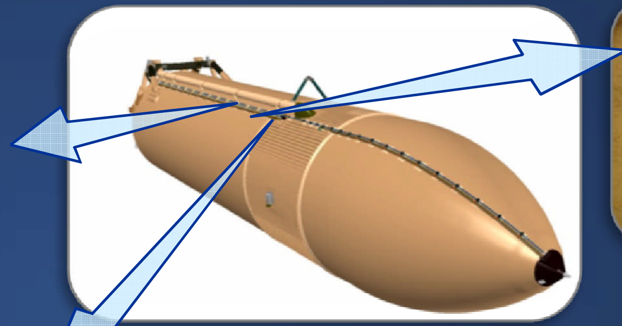
RTF II: Following STS-114, additional foam debris risk mitigation

-- Elimination of the PAL ramps and Bipod heater harness modifications were key changes

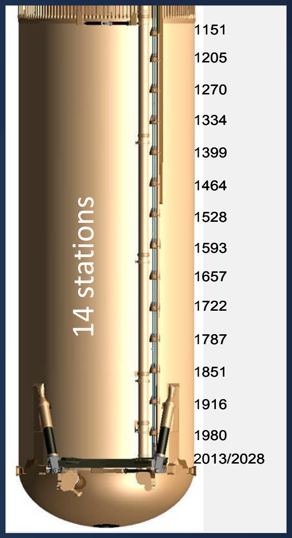
External Tank Legacy of Success
Return to Flight

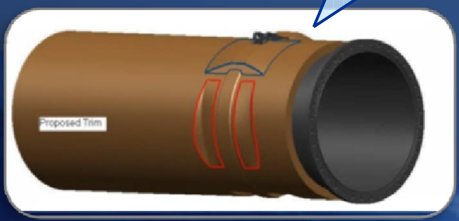
Titanium LOX Feedline Brackets





LH_2 Ice/Frost Ramps

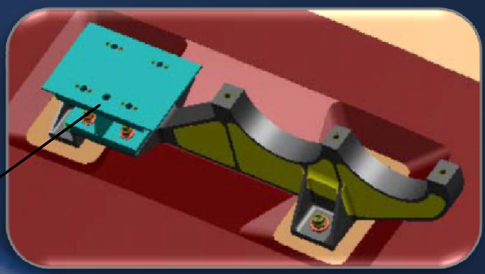




Zero Gap / Slip Plane (Teflon)

Aluminum Bracket

Titanium Bracket



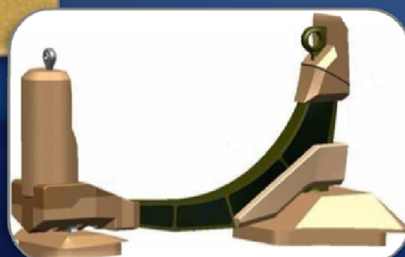
Cryopumping path along shear pin hole eliminated – Issue identified through ET-120 dissections and testing

Beginning with ET-128 additional 'in-line' changes implemented to further improve debris performance --LH2 IFR's and LOX feedline titanium brackets

External Tank Legacy of Success
Return to Flight

- ***Post-RTF process and design changes have increased work scope and complexity***

LO2 Feedline Support Bracket TPS



Redesigned Bipod Fitting & TPS Closeout

SSP Requirements and ET Planning					
ET	**STS**	**SSP Ship**	**Current ET DD250**	**Revised ET DD250**	**Improvement Challenges**
ET-127	125	07/02/08	07/24/08	07/15/08	-13
ET-129	126	08/04/08	08/18/08	08/09/08	-5
ET-130	119	11/15/08	12/05/08	12/22/08	-37
ET-131	127	03/11/09	03/23/09	04/03/09	-23
ET-132	128	05/11/09	06/05/09	06/03/09	-23
ET-133	129	07/14/09	08/24/09	08/25/09	-42
ET-134	130	09/14/09	11/03/09	10/09/09	-25
ET-135	131	11/14/09	01/21/10	01/05/10	-52
ET-136	132	01/20/10	04/05/10	02/25/10	-36
ET-137	133	03/23/10	06/04/10	04/26/10	-34
ET-138	LON	07/10/10	08/26/10	07/09/10	1

	HFPTA – RTF Requirement[1]			Production	
Application	**Proficiency # of Sprays**	**Proficiency Time Req**	**# of Sprays per Part**	**Sprays per tank RTF**	**Sprays per tank Pre-RTF**
Longeron	5	28 days[2]	3	10	2
LH2 Flange	4	28 days	56[3]	28	1
LO2 Flange	2	28 days	9	9	1
Bipod	2	28 days	4	4	2

1. Requires detailed dissection and data analysis
2. Recently changed from 28 to 90 days based on performance
3. Recently changed from 56 to 34 days by eliminating the leadout HFPTA's based on performance

117 Additional Sprays Performed Per Tank Since RTF - Proficiency Spray Requirement adds 13 Sprays (time dependent)

External Tank Legacy of Success
Return to Flight

- ***ET Project with the help of Shuttle community aggressively pursued changes to reduce scope without increasing debris potential***
  - — Leveraged improved understanding of physics and debris risk

Redesigned TPS Applications
27 days

Simplified TPS Trim Processes
5.5 days

KSC Deferred Work
8 days

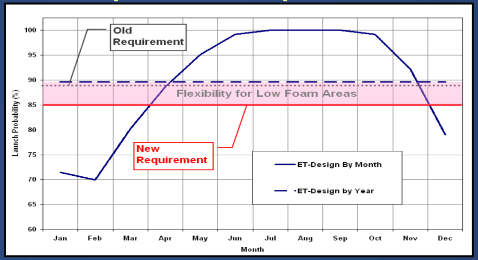
Expanded Acceptance Criteria
1.5 days

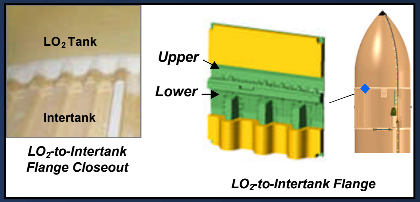
Streamlined Process Controls
1.5 days

Revised Inspection Requirements
4 days

SLA Deletions
1 day

Requirements Updates



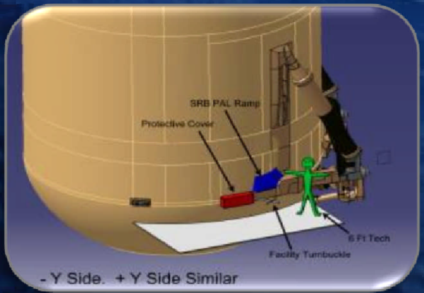


Process and Design Changes

Single Pass LO2/IT Flange Spray Reduced cycle-time by ~25 days in Cell G/H

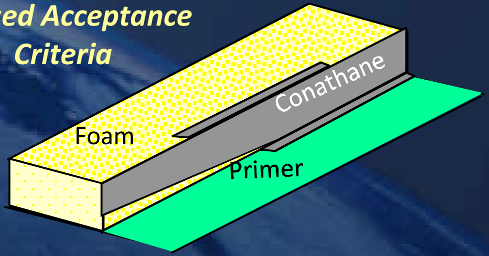
On-time Deliveries and Outstanding Performance

Deferred Work to KSC



Training / Certification for Deferred Work to KSC

Revised Acceptance Criteria

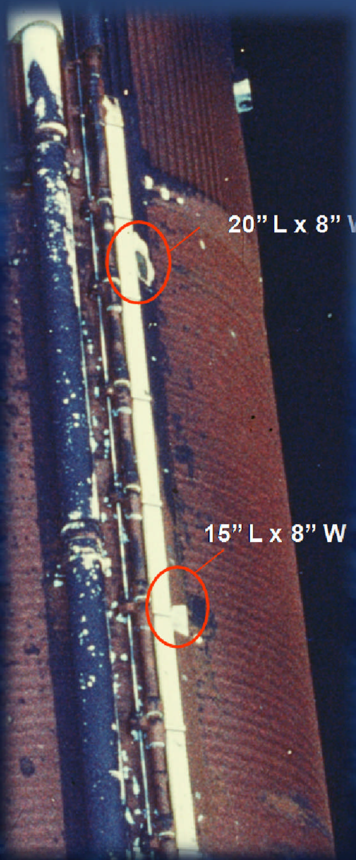


Revised Build Acceptance Criteria has Lowered NCDs

External Tank Legacy of Success
Return to Flight

- ***Post RTF TPS Performance Dramatically Better than Previous Designs***

STS-4/ET-4
06/27/82

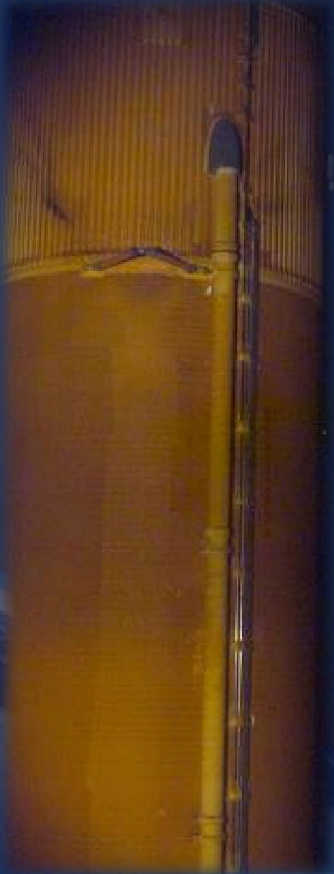


- LH2 tank PAL ramp loss

STS-26/ET-19
07/29/85

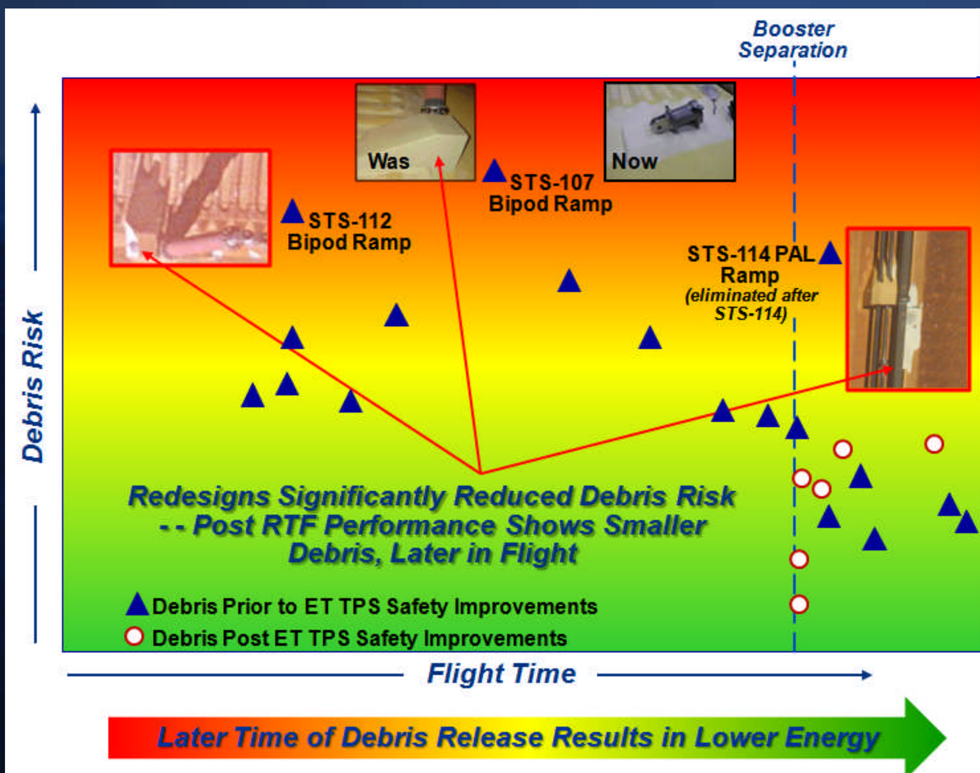
- Intertank foam loss (two tone acreage foam) 18 divots, 3" to 30" diameter

STS-126 / ET-129
11/14/08



External Tank Legacy of Success
Return to Flight

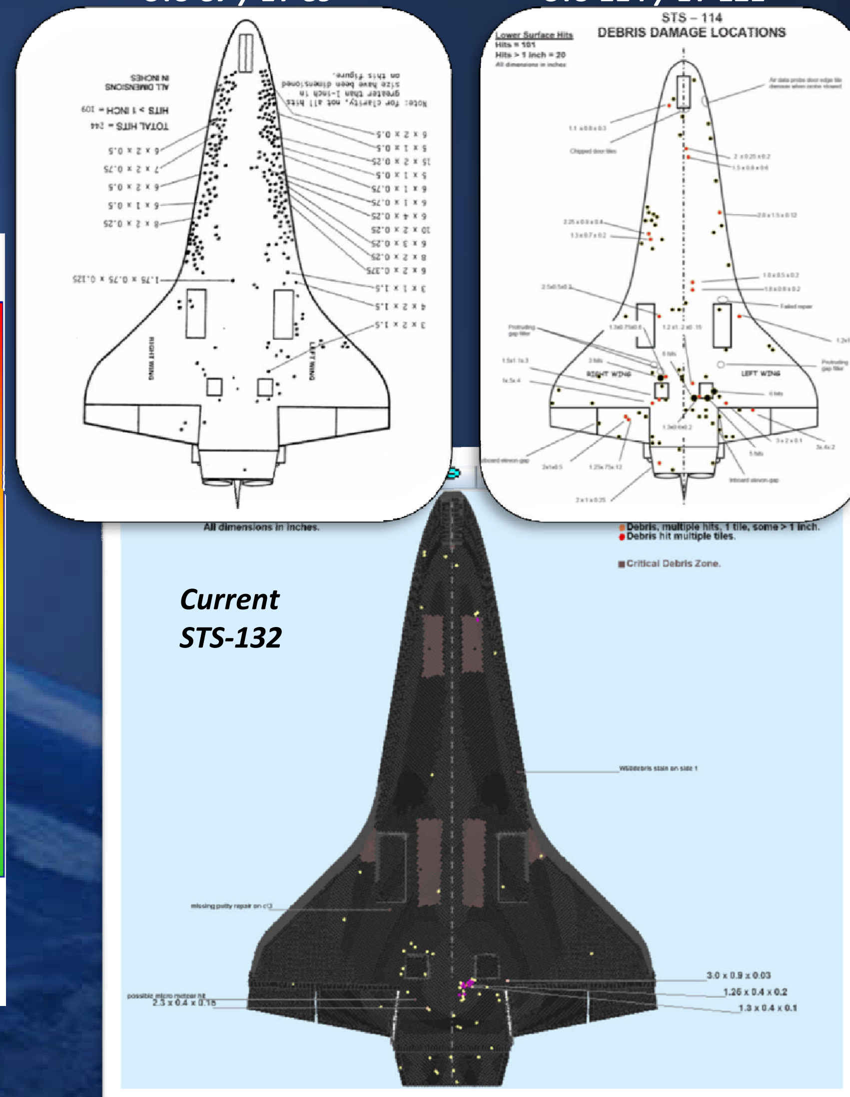
- ***Post RTF TPS Performance Demonstrates Reduction in Debris Risk***
  - Recent Orbiter tile damage maps show fewest and smallest impacts over life of program

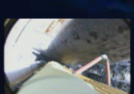


RTF I

STS-87 / ET-89

STS-114 / ET-121



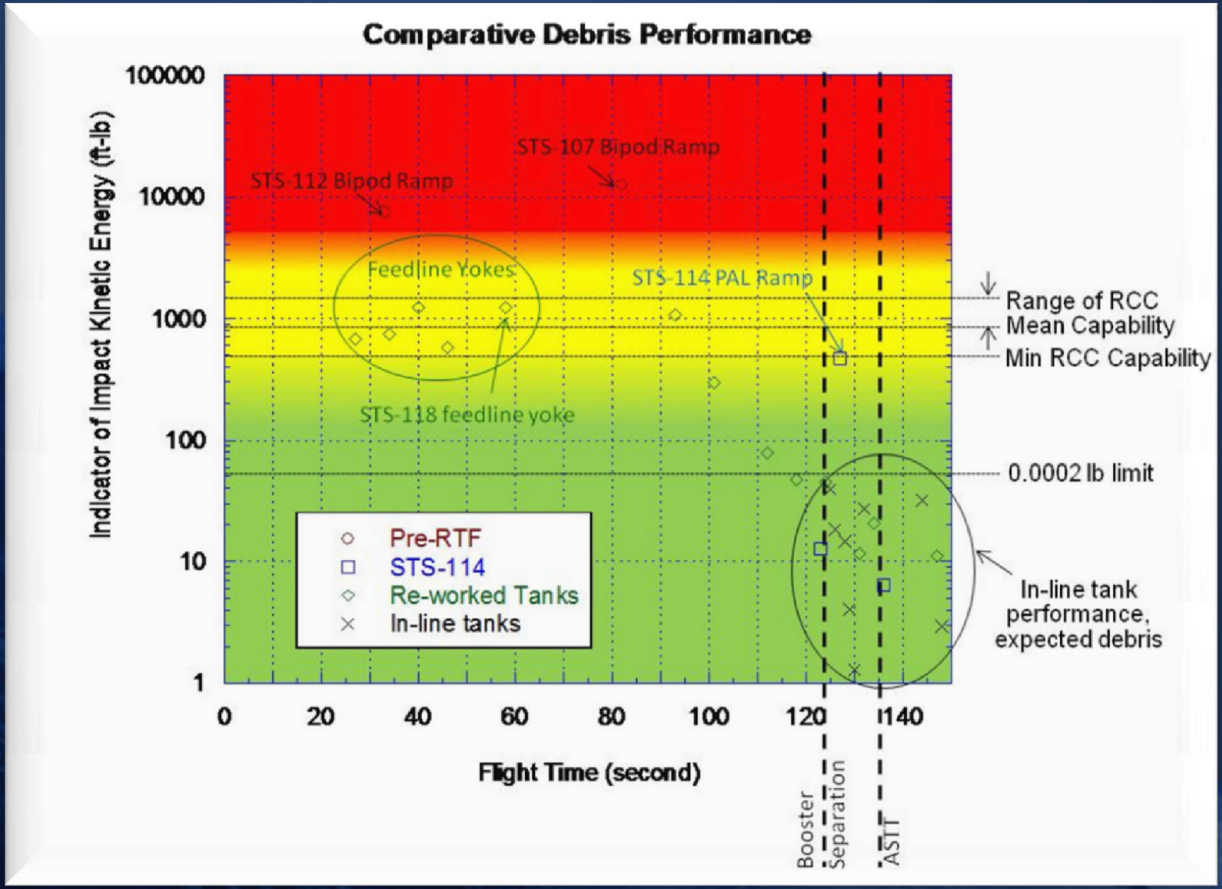


Post RTF Debris Performance Results in Smaller, Later Debris and less Orbiter lower surface damage

External Tank Legacy of Success
Return to Flight

- *Results*

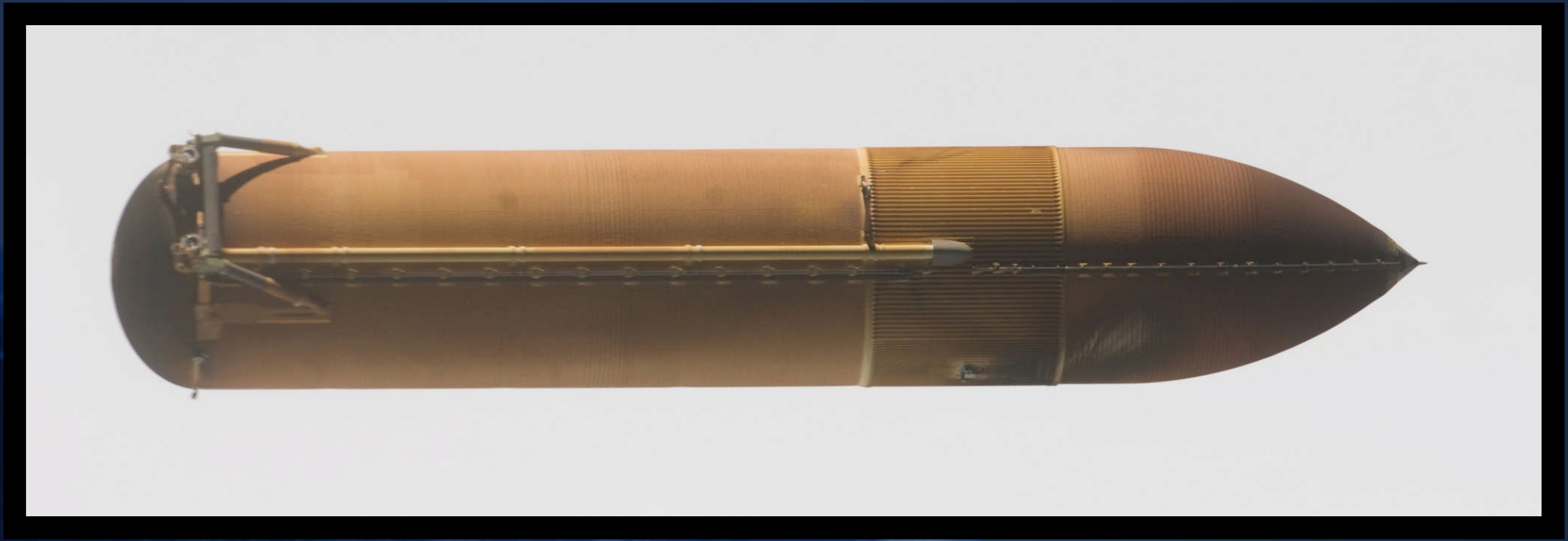
Comparison of all Return to Flight Missions



Impact energy continuously reduced as design improvements were implemented

External Tank Legacy of Success
Return to Flight

- *Results*



Outstanding External Tank Performance for STS-132
- - Orbiter lower surface damage was the lowest since Return to Flight

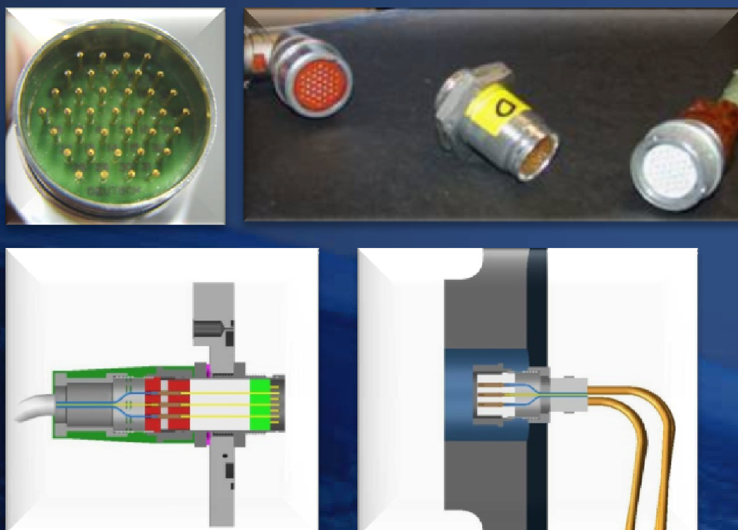
External Tank Legacy of Success
Return to Flight

Key Lessons Learned

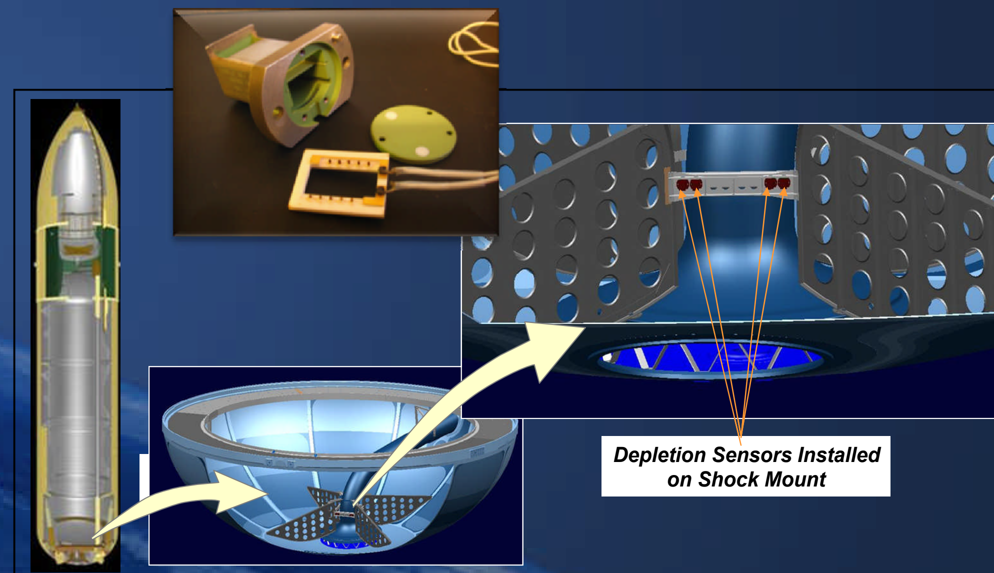
- *Ensure early and clear understanding of requirements*
- *Acknowledge verification limitations and effectively communicate risk to program management*
- *Ensure a strong physics-based understanding of failure modes with test-demonstration*
- *Be cautious of implementing excessive process controls without having a good understanding of failure modes*
- *Critical to communicate and educate all stakeholders early and often*
  - *Can be difficult but the payoff is HUGE!!*

External Tank Legacy of Success
ET-125 ECO Sensor Anomaly

- ***Goal***
  - Establish root cause and redesign solution to mitigate LH2 tank engine cut-off (ECO) sensor circuit anomalies
    - Anomalies resulted in multiple launch scrubs since RTF



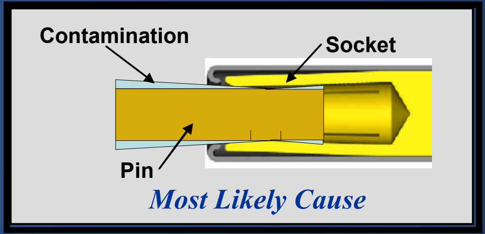
Feed Through Connector



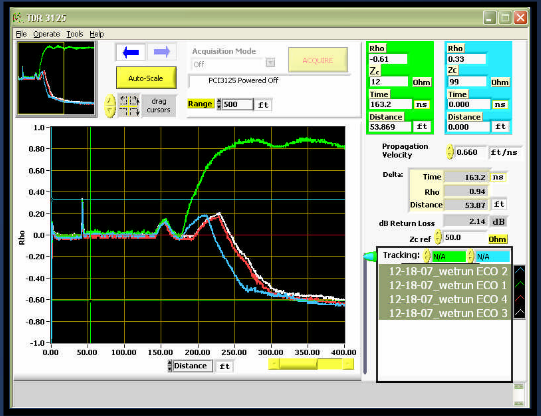
- ***Challenges***
  - Intermittent nature of failures and system complexity made troubleshooting difficult
  - Data set not compelling enough to focus community – many different opinions
  - Emerging data issues (feed thru glass cracks / pin contamination)
  - Launch pressure to support manifest / ISS construction

External Tank Legacy of Success
ET-125 ECO Sensor Anomaly

- ***How'd We Do It?***
  - Got Lucky??– Anomaly signature on ET-125 focused efforts on feed thru connector
    - Simultaneous failure of two sensor circuits and timing related to fill level
  - Strong Leadership – Decision made by Wayne Hale to stand-down and fix problem
  - Developed physics-based scenario to explain failure signatures

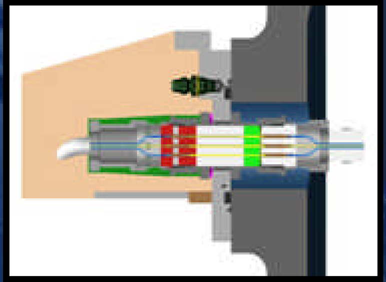


  - Outstanding teamwork to perform tanking test with instrumentation to confirm theory and isolate fault



Time Domain Reflectometry used to detect fault during tanking test

  - Leveraged previous experiences from Atlas / Centaur to develop rapid corrective action design solution



  - Developed innovative TPS analysis and repairs to minimize ablator applications
  - Outstanding teamwork to perform expeditious certification test program of redesign

External Tank Legacy of Success
ET-125 ECO Sensor Anomaly

- ***Results***
  - Design change successfully implemented and flown with no issues
    - Rock solid sensor circuit performance

- ***Key Lessons Learned***
  - Physics should drive the investigation and corrective action
    - Originally focused on sensor as source of fault
    - Physics and testing did not support scenario
  - Critical to learn from and incorporate lessons learned
    - Atlas / Centaur corrective actions not fully understood or investigated during initial phase of investigation

External Tank Legacy of Success
ET-124 Hail Damage Recovery

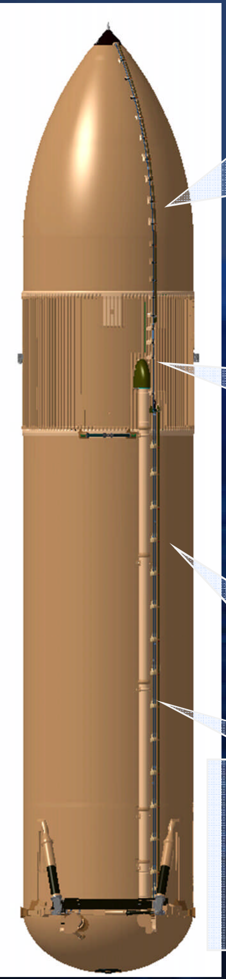
- ***Goal***
  - Extensive TPS damage caused by extreme hail storm
  - Repair plan required to restore TPS to minimize program manifest impacts

- ***Challenges***
  - Skeptical technical community – Concerned about interactions of damage with known / unknown failure modes
  - Schedule pressure to accommodate ISS program
    - Next tank still at MAF
  - Limited ET resources

- ***How'd We Do It?***
  - Developed unique engineering requirements and tooling to minimize repairs
  - Performed large amount of performance testing to demonstrate understanding of repairs and residual conditions
  - Effectively communicated results to technical community and management to instill confidence in expected performance

External Tank Legacy of Success
ET-124 Hail Damage Recovery

- ***How'd We Do It?***
  - Unique assessment process and repairs developed to efficiently disposition thousands of damage sites

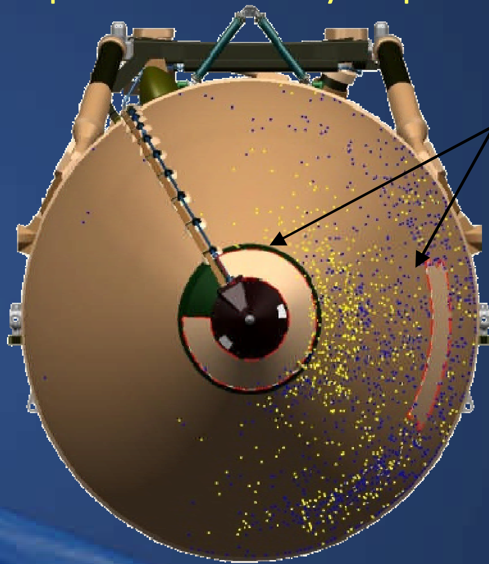


LO_2 Tank TPS
- Large concentration of dense damage in forward / aft ogive areas (>3400 sites)

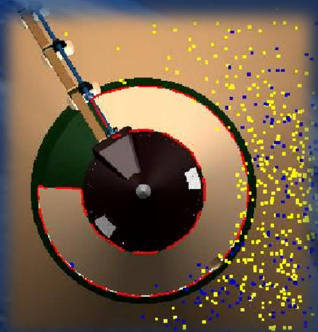
Intertank TPS
- 76 defects > 1"
- 3,265 defects < 1"

LH_2 Tank TPS
- Minimal damage recorded (22 items)

Component TPS (ice frost ramps, closeouts, flanges, etc.)
- ~200 items recorded
- Primarily superficial



LO_2 Tank Forward Ogive "Pencil Sharpened Area"



LO_2 Forward Ogive Area (pencil sharpened area)

External Tank Legacy of Success
ET-124 Hail Damage Recovery

- ***Results***
  - STS-117/ET-124 scheduled to Launch 03/15/07
    - Repaired and successfully launched 6/8/07
  - Post flight Assessment revealed no issues with any of the hail damage repairs
  - Success enables ET Project to improve ‘credibility’ within technical community
    - Very helpful with future changes to enhance producibility
- ***Key Lessons Learned***
  - Be creative in the face of adversity
    - Explore requirements to capitalize on any mission unique aspects
  - Tests are critical to demonstrate performance and minimize anxiety / chaos
  - Communicate early and often

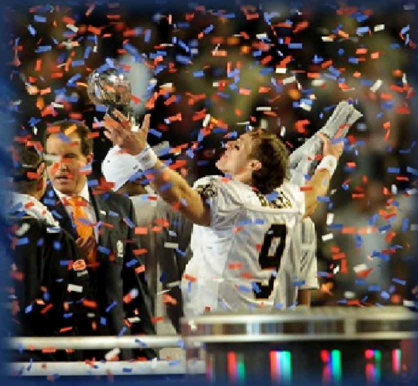
External Tank Legacy of Success
STS-130 / ET-134 Launch

- ***Goal***
  - Launch STS-130 / ET-134 – 2/8/10
    - 2/8 launch date required due to ‘suspicious’ launch delay from the previous day due to low ‘Colts blue’ debris clouds

- ***Challenges***
  - Saints in Super Bowl!!!!
  - Call to stations / launch support coincided with kick-off
  - Large group of ‘Who Dats’ required for launch support
  - Pressure to keep up with BCS champs Alabama!

- ***How’d We Do It?***
  - We did it – A day the ET Team will never forget..

Keep Your Teams Focused and FINISH STRONG



External Tank Program
Legacy of Success

[redacted]

ET-138 Rollout 7/8/10