



# SLS

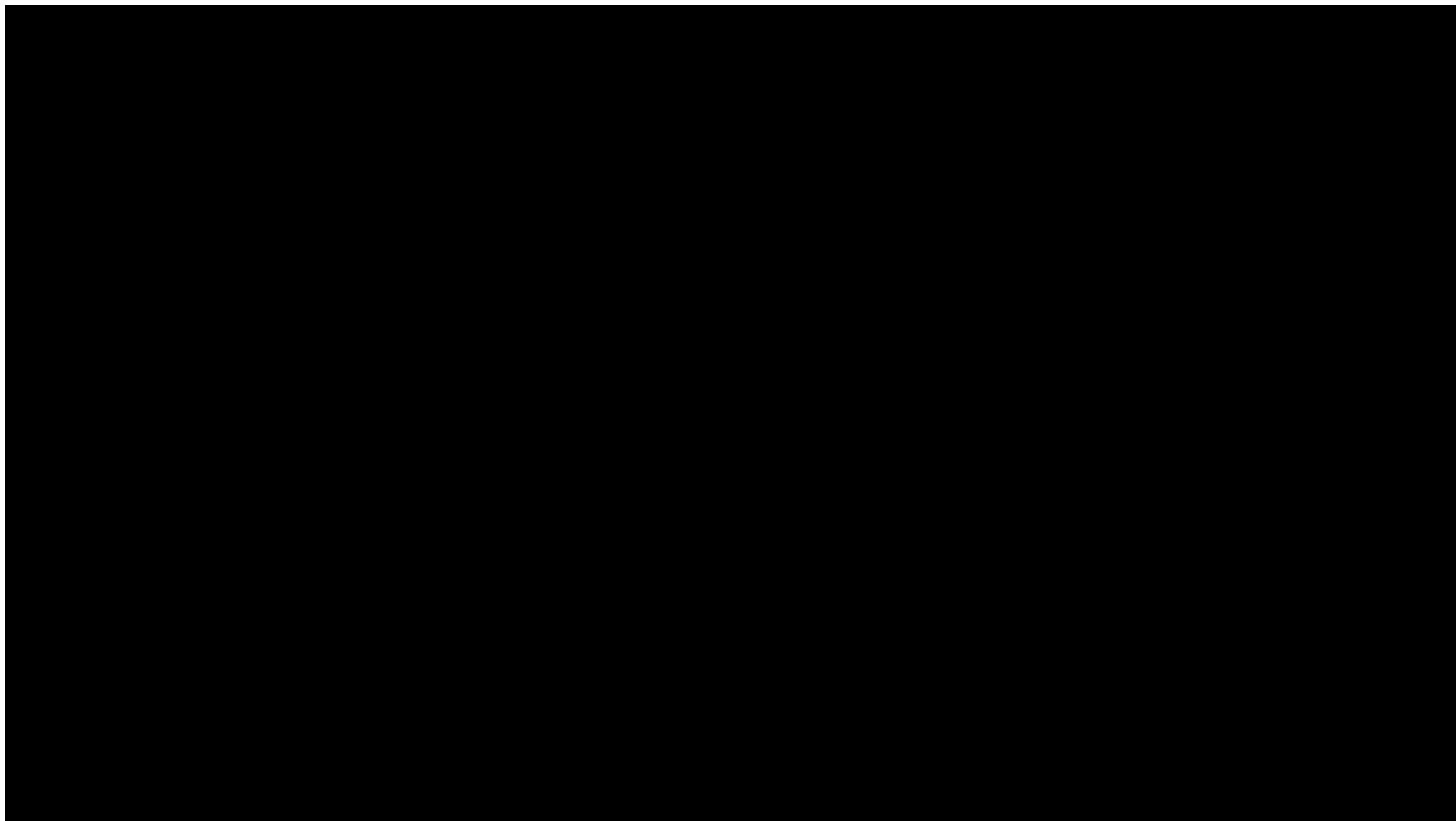
Space Launch System

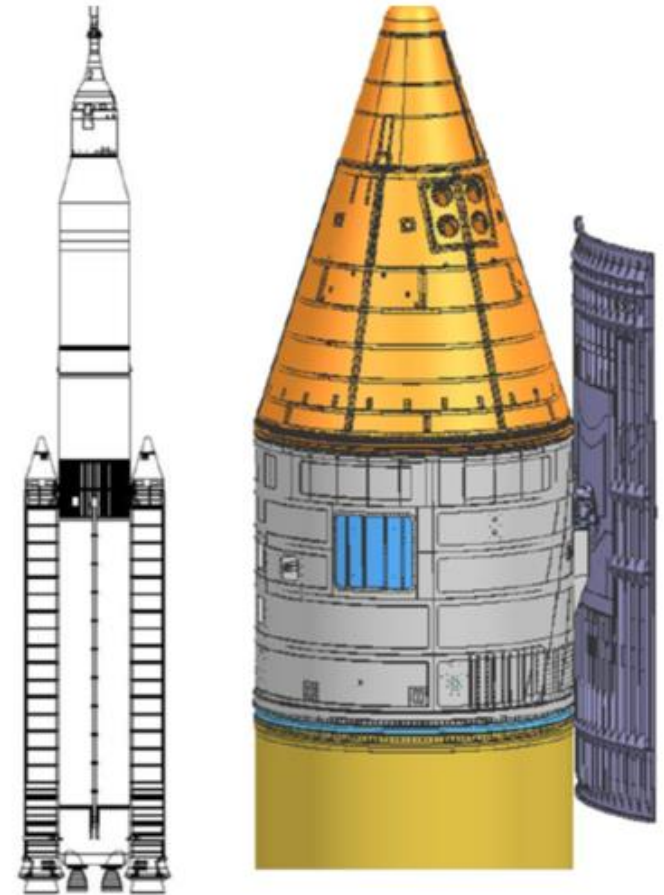
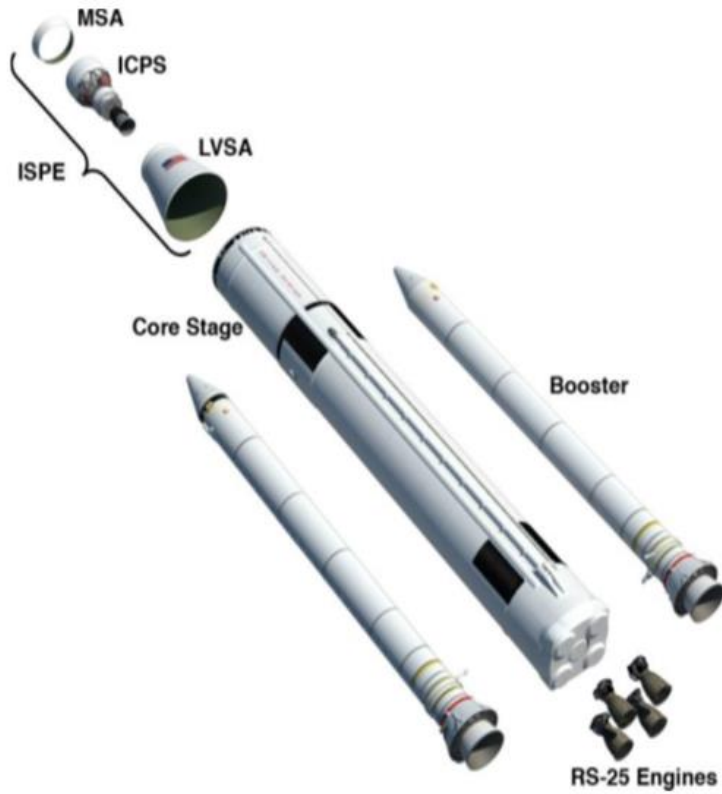
## Use of Shuttle Heritage Hardware in Space Launch System (SLS) Application – Structural Assessment

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- ◆ **We appreciate the work done by a team of engineers and technicians at MSFC and Orbital ATK in developing and executing the test and analysis to help establish the flight rationale for the shuttle heritage hardware for use on SLS. This paper takes advantage of reports published to document the test and analysis for developing the flight rationale and was not possible otherwise. However, these references are not cited herein due to potential conflict with International Traffic in Arms Regulations (ITAR)**

- ◆ **NASA is aggressively moving forward with development of the next generation human spaceflight system to meet the Nation's human space exploration goals as expressed in the 2011 NASA Strategic Plan**
  - Strategic Goal 1 – Extend and sustain human activities across the solar system
  - Strategic Goal 1.3 – Develop integrated architecture capabilities for safe crewed and cargo missions beyond low Earth orbit
  
- ◆ **To meet this goal with limited resources and with an expedited schedule, Affordability Safety, & sustainability are the key tenants**
  - Use of existing hardware in inventory from previous programs offers increased cost savings
    - i.e., **AFFORDABILITY**
  
- ◆ **The Space Launch System (SLS) is a heavy-lift launch vehicle currently being designed to meet these goals**
  - SLS Block 1 architecture is the configuration for the first flight: EM-1
  - Block 1 includes Heritage: Solid Rocket Boosters and RS-25 Engines, New: Core Stage, Integrated Spacecraft and Payload Element (ISPE), Launch Vehicle Stage Adapter (LVSA), Separation System, MPCV Stage Adapter (MSA) Cryogenic Propulsion Stage
  
- ◆ **Heritage Boosters, left over from the Shuttle Program, will be used to provide the major ascent thrust to the Vehicle**
  - Qualification of heritage hardware to all structural and functional requirements of the SLS program provided significant challenges ~ ensuring **SAFETY**





- ◆ **Use of heritage hardware in new applications requires special consideration and understanding of previous lessons learned**
  - Lessons learned should be carefully assessed and addressed in the design, development, qualification and validation/verification for use in new applications

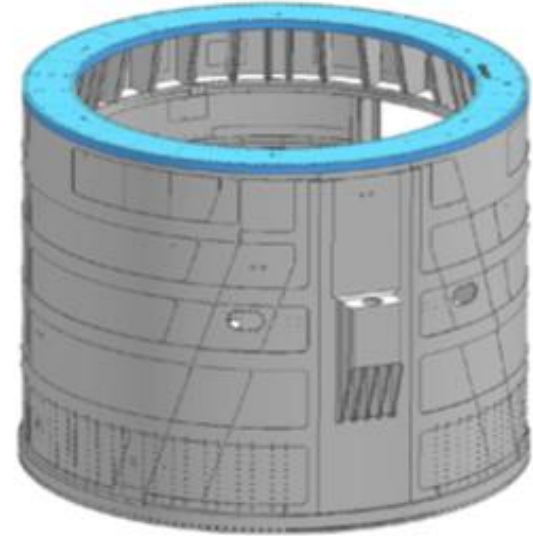
## Lessons Learned

External, independent review teams judging the flight readiness of a vehicle should keep in mind the following key lessons gleaned from the past 20 years of space launches:

1. Propulsion systems are the primary cause of all launch failures. All propulsion test and checkout anomalies/failures demand special attention and review.
2. Hardware built out of normal sequence and hardware that has been reworked are major causes of failures. The processes, procedures, quality inspections, and particularly the re-test results demand special review.
3. There are no small, inconsequential changes in flight-critical components or subsystems. Systems engineering and every affected technical discipline must be involved in the assessment of all new systems and their changes. If a change is not recertified by test, the rationale must be thoroughly examined.
4. Test results that are "in-family," but near the edge of the acceptable envelope, should be thoroughly examined. Usually there is a subtle message. Always believe test data until they are conclusively proved wrong beyond all doubt.
5. All test anomalies/failures must be thoroughly understood and convincingly explained. All hardware that is potentially related to an unverified system anomaly/failure must be purged from the system before launch.
6. The flight environments and dynamic loads that set the qualification and acceptance test levels of each flight-critical component must be rigorously validated by a continuum of flight measurements and analyses.

Charles Gun, Launch Space Magazine, January 1999

- ◆ **The SRB forward skirt structural assembly is an all welded, ring stiffened monocoque cylindrical shell, primarily manufactured from 2200 series Al alloy by McDonald Douglas between 1975 and 1984**
- ◆ **Located between the Nose Cap and Frustum**
- ◆ **The skin is machined to various thicknesses around the circumference of the shell with the forward ring, thrust post fitting and attach rings machined from special forgings.**
- ◆ **Primary purpose is to support the core vehicle prior to launch and act as the axial thrust take out point from booster to the core vehicle during flight**
- ◆ **Some structural modifications for SLS but majority is same as Shuttle configuration**



◆ **Forward Skirt Thrust Post carries axial and lateral loads at Solid Rocket Booster to Core interface**

- Prelaunch: rollout, on-pad stay and core engine build up
- Ignition up to Pre-Staging, where the SRB is pyrotechnically released
  - Critical load case

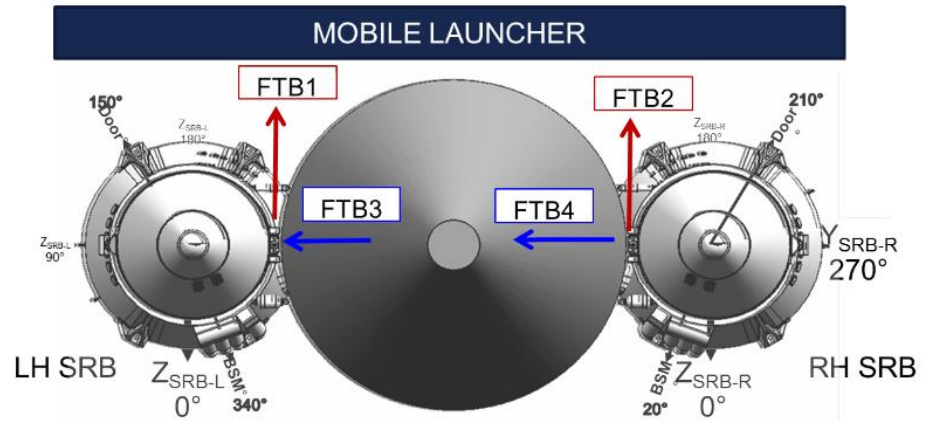
◆ **90% of thrust post ascent compression loading is due to statically determinant flight mechanics loads**

- Fwd Attach Load =  $\text{Booster Thrust} - \text{Booster Mass} * \text{Vehicle Accel}_x$

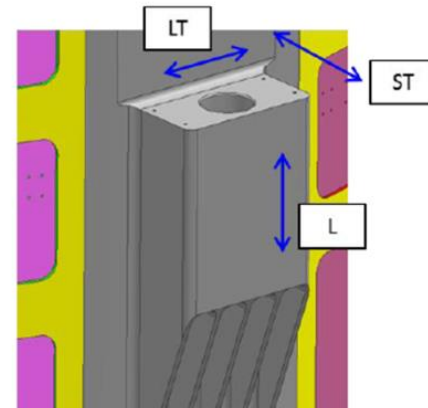
◆ **Due to the design of the interface, this axial load produces a large moment that is reacted over a relatively small fillet area that is machined into the forging**

◆ **SLS compression loads ~ 40% higher than Shuttle loads**

- Increase in loads too high to say qualified by similarity
- Finite element models used to validate Shuttle validated via linear test results. Updated models showed highly non-linear response
- Updated Testing required



Booster	Indicator	Direction	Description
Left	FTB1	Transverse	Toward the fwd skirt door is positive (+)
	FTB3	Radial	Radial inward is positive (+)
	FTB5	Axial	Compression is negative (-)
Right	FTB2	Transverse	Toward the fwd skirt door is positive (+)
	FTB4	Radial	Radial outward is positive (+)
	FTB6	Axial	Compression is negative (-)





◆ **Structural testing of the heritage forward skirt was performed for the SLS program in 2014.**

- Two skirts randomly selected from inventory
- Tested all critical loading conditions to 1.4 x limit loads
- Tested both skirts to failure

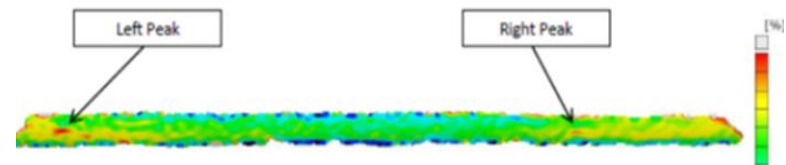
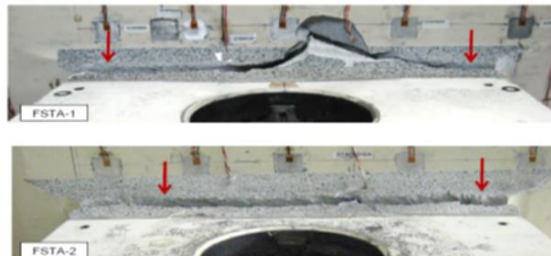
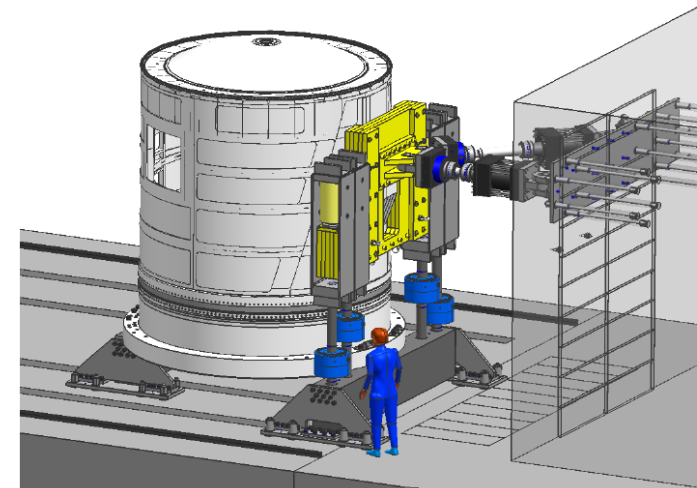
◆ **Extensive instrumentation was used to monitor the structural status of the hardware and determine failure location and time**

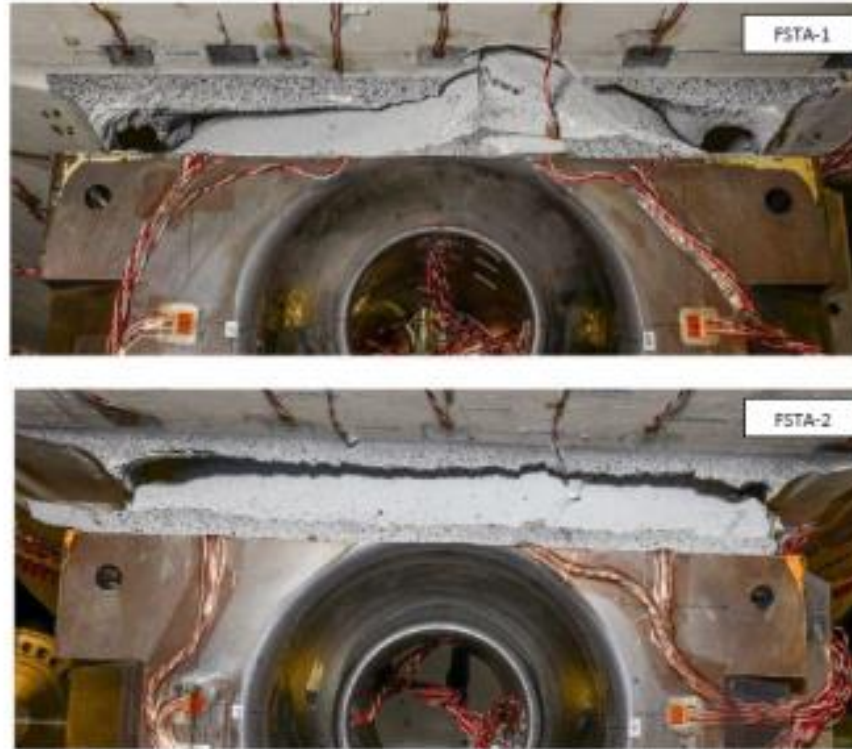
- Strain gauges
- ARAMIS digital photogrammetry system
- String potentiometers
- Acoustic emission detectors
- Instrumented pins

◆ **Strain gauges and ARAMIS located in region of failure**

- Compared well with each other
- Used to help Finite Element Model predictions

◆ **Both test articles failed well above the max predicted limit loads for SLS and pre-test analytical predictions due to crack initiation and growth across the fillet radius of the fitting**





◆ **Failure occurred in the primary load path**

- Initiated in fillet region
- Thrust Post gussets subsequently buckled

◆ **Structural acceptability of metal structures can be determined with linear-elastic or elastic-plastic finite element analysis**

- Linear-elastic analyses produce stresses that are compared to the material allowable ultimate strength
- Elastic-plastic analyses produce strains that are compared to the material allowable elongation

◆ **Majority of heritage Shuttle hardware designed to be evaluated in linear-elastic regime**

- Hardware that required elastic-plastic analysis traditionally evaluated using the Constant Critical Strain Criteria methodology, where failure occurs at the same critical strain, no matter the stress state

– Factor of Safety =  $\frac{e}{ETPO}$

– e = elongation strain from material testing

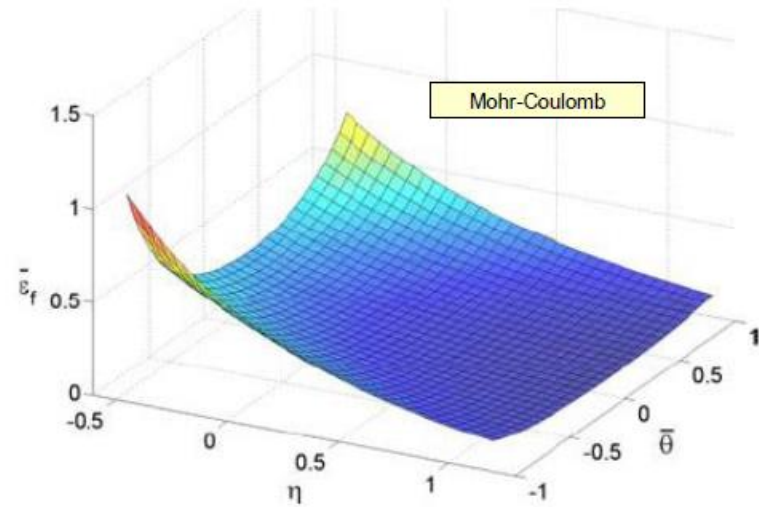
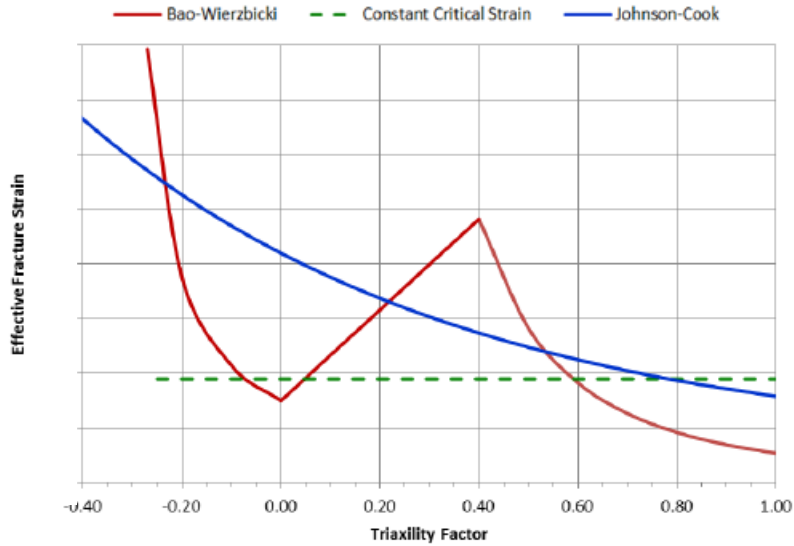
– EPTO = total equivalent strain determined at 1.4 x limit load from an elastic-plastic analysis with minimum required stress-strain curve

◆ **Approaches that utilized Triaxiality Factor employed**

- Triaxiality factor accounts for stress state
- Hydrostatic pressure divided by Von Mises stress
- Higher Triaxiality – lower strain to failure Lower Triaxiality – higher strain to failure

$$TF = \frac{\sigma_m}{\text{Von Mises stress}}$$

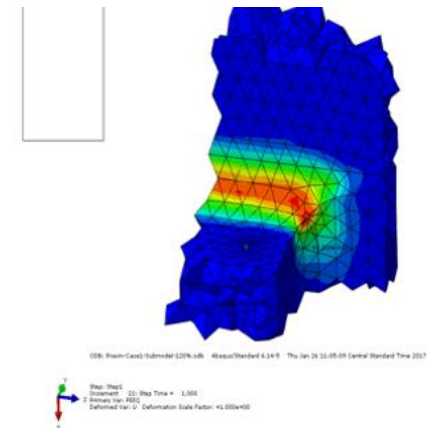
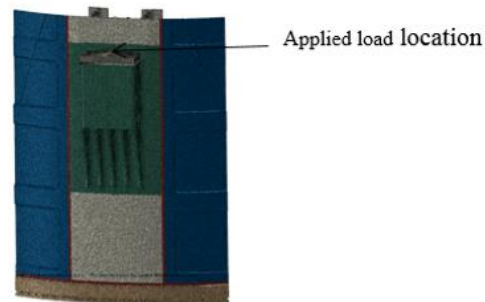
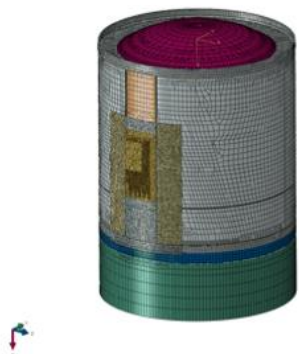
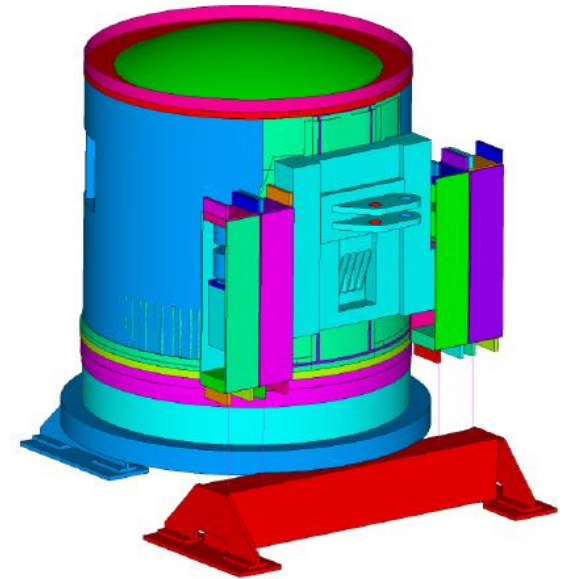
- ◆ **Research has shown that ductile failure of metallic structures consists of three phases**
  - Accumulation of damage caused by plastic strain
  - Initiation of fracture
  - Fracture propagation resulting in failure
  
- ◆ **Three Triaxiality based damage initiation criteria selected that had correlation with aluminum material testing**
  - Johnson-Cook
  - Bao-Wierznicki
  - Mohr-Coulomb
  
- ◆ **References listed in paper compares the constant critical strain, Johnson-Cook and Bao-Wierznicki criteria for aluminum 22xx-Txxx alloy**
  
- ◆ **Failure Curves developed by plotting effective fracture strain vs Triaxiality factor**

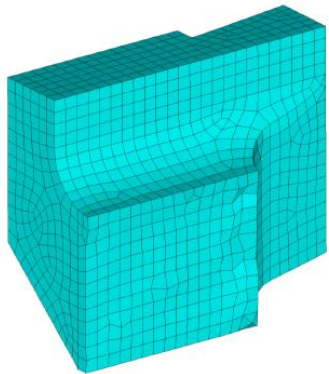


References for plots included in accompanying paper

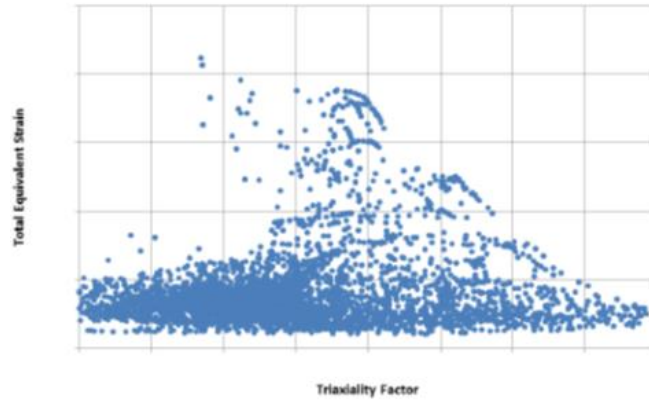
- ◆ **Bao-Wierzbicki chosen due to lack of influence of shear during thrust post failure and existence of test data with similar material**

- ◆ **Two independent models were developed at MSFC**
  - Utilized commercial codes ANSYS and ABAQUS
- ◆ **First step was to build model representing test setup**
  - Modeled test equipment and load sequencing
  - Used material data from post-test cut samples
  - Overall structure response was characterized and correlated with model
  - Detailed sub-models created to characterized failure
- ◆ **Develop Bao-Wierznicki failure curve for tested structures using material test data and analysis results**
- ◆ **Rerun analysis for flight conditions**

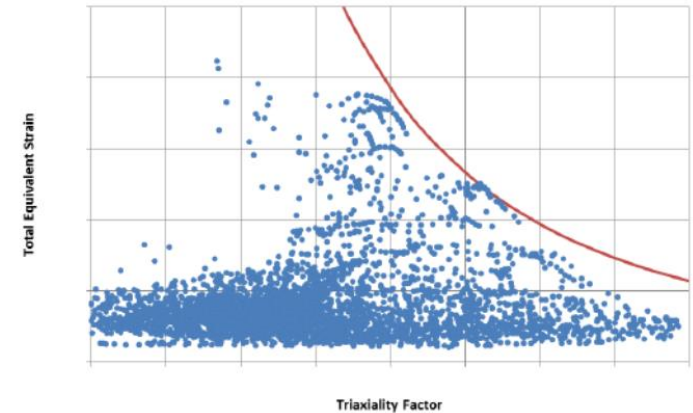




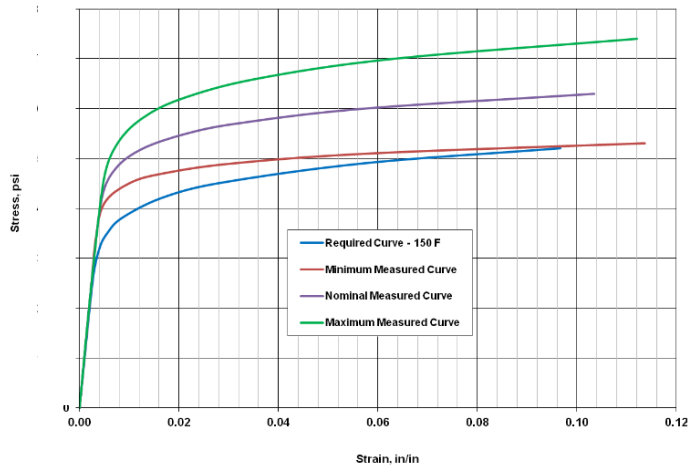
**Isolate failure location**



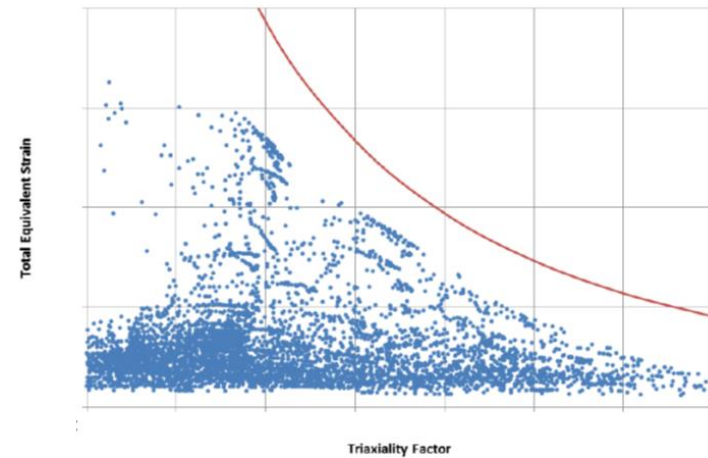
**Plot Eqv. Strain vs TF at test failure load**



**Adjust B-W curve until just touching  
This is failure curve**



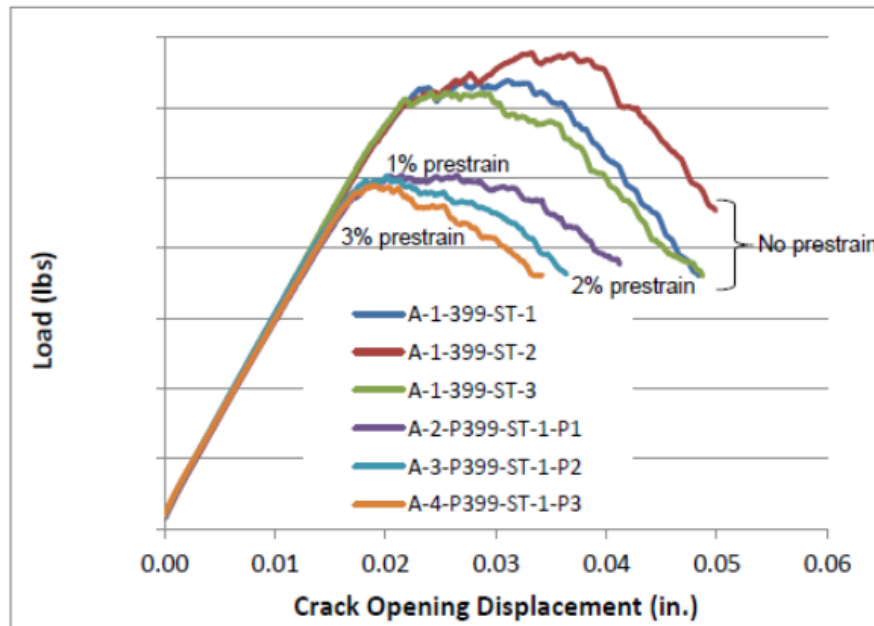
**Apply flight loads, adjust model for minimum conditions and tolerances**



**Plot Eqv. Strain vs TF at flight limit load  
Incrementally adjust until just touching failure curve  
Difference is Factor of Safety**

◆ **Traditional fracture assessment performed as well**

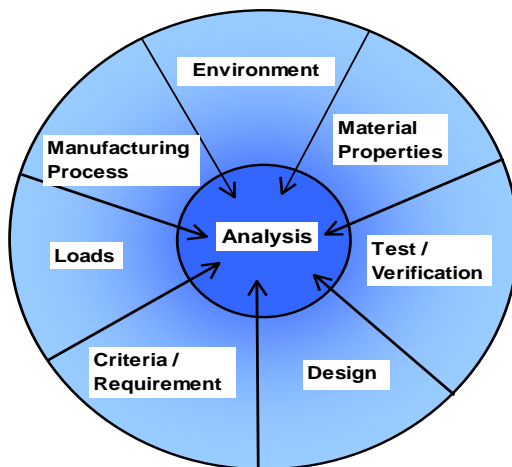
- Material samples taken from thrust post radius region to develop the fracture toughness properties
- Area experiences yielding very early in load sequence
- Samples pre-strained to different values and tested to determine worst-case fracture toughness





◆ **A high degree of confidence in understanding loads, material properties, failure phenomena anchored with analysis and flight-like testing instrumental in requalifying the heritage Forward Skirt for the SLS program**

- Well understood loads
  - Majority flight mechanic statically deterministic. Key contributors understood
- Detailed Finite Element Models
  - Independent Analyses
  - Correlated to test
  - Anchored to material test data & minimum geometric conditions
- Failure criteria based on Triaxiality approach using test established failure criteria
- Flight factors of safety incorporate minimum material properties, minimum drawing tolerances and refurbishment considerations



◆ **The execution of a detailed test/qualification program and use of a more advanced analysis methodology was directly responsible for saving the Program 10's of millions of dollars that it would have cost to design, develop and qualify a new forward skirt and expediting the schedule and meets NASA's two important tenants for the SLS program: Affordability and Safety**

## ◆ References cited in accompanying paper

1. ESD 10001, Revision D, "Exploration Systems Development Implementation Plan" (2015)
2. ESD 10013, "Exploration Systems Development Integrated Design Definition Document" (2015)
3. NASA-STD-5001, Revision B, "Structural Design and Test Factors of Safety for Spaceflight Hardware"
4. MMPDS-04, "Metallic Materials Properties Development and Standardization (MMPDS)" (2008)
5. NASA-SP-6105, "NASA System Engineering Handbook"
6. Wierzbicki, T., "Calibration and Evaluation of Seven Fracture Models," *International Journal of Material Sciences* 47 (2005), pages 719-743
7. Wierzbicki, T., "On Fracture Locus in the Equivalent Strain and Stress Triaxiality Space," *International Journal of Material Sciences* 48 (2004), pages 81-98
8. Wierzbicki, T., "Ductile Fracture Calibration and Validation of Anisotropic Aluminum Sheets," *Proceedings of the SEM Annual Conference, June 1-4, 2009*
9. Teng, X., and Wierzbicki, T., "Gouging and Fracture of Engine Containment Structure Under Fragment Impact," *Journal of Aerospace Engineering* 21 (2008), pages 174-186
10. Brar, N. S., "Constitutive Model Constants for AL7075-T651 and AL7075-T6," *American Institute of Physics* 978-0-7354-07354-1006-0 (2011)
11. Brar, N. S., "Anisotropic Effects on Constitutive Model Parameters of Aluminum Alloys," *American Institute of Physics* 978-0-7354-1006-0 (2011)
12. Danas, K., "Influence of the Lode Parameter and the Stress Triaxiality on the Failure of Elasto-Plastic Porous Materials," *International Journal of Solids and Structures* 49 (2012), pages 1325-1342
13. Bai, Y., "A New Model of Metal Plasticity and Fracture with Pressure and Lode Dependence," *Internal Journal of Plasticity* 24 (2008), pages 1071-1096
14. Bai, Y., "Application of Extended Mohr-Coulomb Criterion to Ductile Fracture," *International Journal of Fracture* 161 (2010), pages 1-20
15. Wierzbicki, T., "On The Cut-off Value of Negative Triaxiality for Fracture," *Engineering Fracture Mechanics* 72 (2005), pages 1049-1069
16. Xue, L., "Ductile Fracture Initiation and Propagation Modeling Using Damage Plasticity Theory," *Engineering Fracture Mechanics* 75 (2008), pages 3276-3293
17. Xue, L., "Damage Accumulation and Fracture Initiation in Uncracked Ductile Solids Subject to Triaxial Loading," *International Journal of Solids and Structures* 44 (2007), pages 5163-5181
18. ABAQUS Standard Finite Element Analysis Program, Version 6.14-5
19. ANSYS APDL Finite Element Analysis Program, Version 15.0
20. ARAMIS Digital Image Correlation System

- ◆ **Thanks for the opportunity to be part of this special session!**
  
- ◆ **Any questions?**