Alternate Methods in Refining the SLS Nozzle Plug Loads

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ABSTRACT

Numerical analysis has shown that the SLS nozzle environmental barrier (nozzle plug) design is inadequate for the prelaunch condition, which consists of two dominant loads: 1) the main engines startup pressure and 2) an environmentally induced pressure. Efforts to reduce load conservatisms included a dynamic analysis which showed a 31% higher safety factor compared to the standard static analysis. The environmental load is typically approached with a deterministic method using the worst possible combinations of pressures and temperatures. An alternate probabilistic approach, utilizing the distributions of pressures and temperatures, resulted in a 54% reduction in the environmental pressure load. A Monte Carlo simulation of environmental load that used five years of historical pressure and temperature data supported the results of the probabilistic analysis, indicating the probabilistic load is reflective of a 3-sigma condition (1 in 370 probability). Utilizing the probabilistic load analysis eliminated excessive conservatisms and will prevent a future overdesign of the nozzle plug. Employing a similar probabilistic approach to other design and analysis activities can result in realistic yet adequately conservative solutions.

1.0 BACKGROUND

The Space Launch System (SLS) booster nozzle plug will be located near the nozzle throat and will act as an environmental barrier to seal and protect the propellant against random debris and pre-ignition caused by the heat and debris from the RS-25 core vehicle engines start up. Seven seconds after the RS-25 startup, the five segment reusable solid rocket motor (RSRMV) booster ignites, which causes the nozzle plug to be rapidly expelled. Figure 1 shows the plug installation location, material composition and overall dimensions for the SLS design. The SLS nozzle plug design was carried over from the Ares program, which was an enlarged version of the heritage reusable solid rocket motor (RSRM) nozzle plug design.
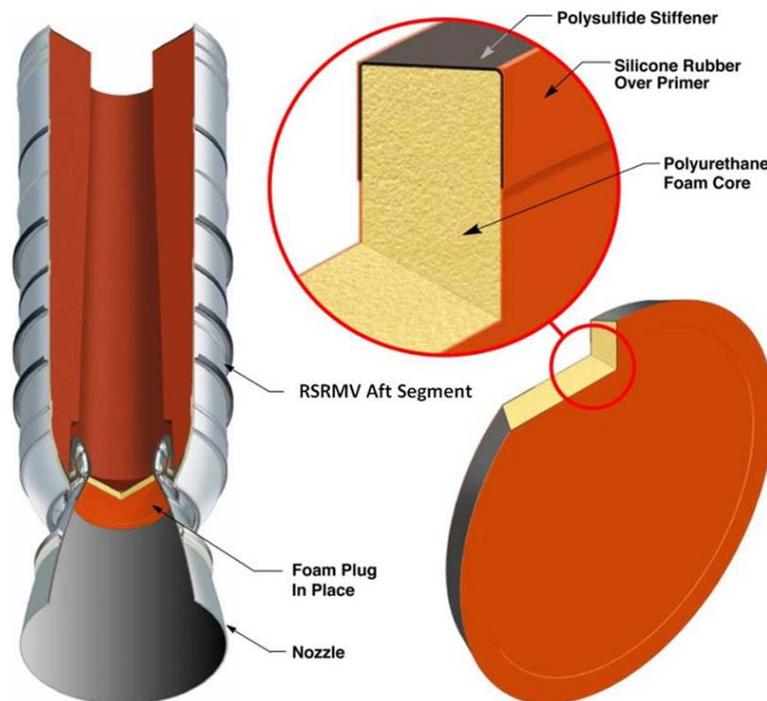

Figure 1. Nozzle plug installation location and material composition.

Based on a previous analysis of the nozzle plug, prelaunch, defined as the seven seconds between the RS-25 main engine startup and booster ignition, will be the most sever loading event (1). A numerical model of the heritage design incorporating the SLS prelaunch loads showed a safety factor of 0.31, which would not meet the required safety factor of 1.4 (2).

Two different approaches could mitigate the nozzle plug design inadequacy. One approach would be to increase its capability. This would involve an expensive redesign process which would likely include material modifications, manufacturing process adjustments and design requalification testing. The alternate and preferred approach would be to refine the predicted loads by eliminating excessive conservatisms. This could potentially lower the loads enough to show positive margins with the current design. The following sections will investigate the second approach by discussing the two prelaunch loads acting on the nozzle plug and the efforts made to eliminate conservatisms.

2.0 ENVIRONMENTAL LOAD

The skin differential pressure is an environmentally induced pressure which develops as a result of differences in the ambient and internal motor bore environments. The pressure occurs over the time period between booster assembly at the vehicle assembly building (VAB) and booster ignition, and can act as either a positive (burst) or negative (crush) pressure.

Skin differential pressure predictions typically assume the worst possible conditions for both booster assembly and prelaunch as discussed in section 2.1. The probabilistic approach in section 2.2 utilizes a statistical analysis to determine a 3-sigma skin differential pressure which eliminates unrealistic environment combinations. A Monte Carlo simulation was also performed to verify the statistical analysis.

2.1 Worst Case Approach

Assuming there is no leak through the nozzle plug, the RSRMV bore will be a sealed compartment of approximately constant volume and the internal pressure will change only as the temperature of the air inside the bore warms or cools after the RSRMV segments are assembled inside the VAB. Using the ideal gas law and assuming an ambient pressure of P_1 and ambient temperature in the bore of T_1 during segment assembly, the pressure inside the RSRMV bore during prelaunch with bore air temperature of T_2, will equal P_2 in Equation 1.

$$P_2 = P_1 \frac{T_2}{T_1} \qquad [1]$$

The skin differential pressure across the nozzle plug is the difference between air pressure inside and outside the RSRMV bore. Equation 2 defines the skin differential pressure as dp, where P_{out} is the pressure of the air outside the RSRMV bore during prelaunch. Equations 1 and 2 use absolute temperatures for T_1 and T_2.

$$dp \equiv P_2 - P_{out} = P_1 \frac{T_2}{T_1} - P_{out} \qquad [2]$$

The worst case approach assumed the worst possible combination of ambient pressure and temperature. Eleven years of historical atmospheric pressure data from Patrick AFB (located near the VAB) ranged between 14.13 psia and 15.05 psia (3). The ambient temperature varied between a minimum 3-sigma value of 39.7 ºF (499 R) in January and a maximum 3-sigma value of 90.3 ºF (550 R) in July and August. Temperature data was from five years of VAB historical measurements from 1992 through 1996. Analytical models predicted the temperature of the air inside the RSRMV bore during prelaunch to be between 36.1 ºF (496 R) and 83.3 ºF (543 R) (4)(5). Because the internal bore temperature could be 90.3 ºF from the VAB, this was the assumed highest internal bore temperature during prelaunch.

The burst case corresponds to maximum internal pressure and minimum external pressure. Therefore, the burst skin differential pressure across the nozzle plug was calculated from Equation 2 to be 2.44 psid using P_1 =15.05 psia, T_1 =499 R, T_2 =550 R and P_{out} =14.13 psia.

The crush case corresponds to minimum internal pressure and maximum external pressure. Therefore, the crush skin differential pressure across the nozzle plug was calculated from Equation 2 to be -2.31 psid using P_1 =14.13 psia, T_1 =550 R, T_2 =496 R and P_{out} =15.05 psia.

2.2 Probabilistic Approach

The skin differential pressures discussed above are applicable only if a worst case assembly event is followed by a worst case prelaunch event, which is highly unlikely. In an effort to assess more realistic loads, a collaborative cross discipline team of engineers and statisticians at ATK used a statistical analysis to estimate a 3-sigma skin differential pressure.

The ambient pressure used for P_1 and P_{out} was assumed to have a normal distribution with ±3-sigma values of 14.13 psia and 15.05 psia. The average was 14.59 psia with a standard deviation equal to 1/6 of the range or 0.15 psia. Using the average (μ) and the standard deviation (σ), the coefficient of variation (CV) was calculated from Equation 3 to be 1.05%.

$$CV = \frac{\sigma}{\mu} \qquad [3]$$

In the 5 years of temperature data, there were 84,528 temperature readings with an average of 74.0 °F (534 R), a standard deviation of ±7.8 °F and a coefficient of variation of 1.47%. To simplify the calculations, the VAB temperature limits were assumed to also represent those inside the RSRMV bore during prelaunch, so the VAB distribution was used for all temperatures. It was also assumed that the ambient pressure and temperature inside VAB and air temperature inside the bore were uncorrelated.

Equation 1 showed the average of P_2 to be 14.59 psia with a coefficient of variation of 2.33% as determined by Equation 4. The standard deviation of P_2 was the product of the CV and the average, or 0.34 psia.

$$CV(P_2) = \sqrt{CV(P_1)^2 + CV(T_1)^2 + CV(T_2)^2} \qquad [4]$$

The average skin differential pressure (dp) was the difference between P_2 and P_{out}, or 0 psia, and the standard deviation of dp was 0.37 psia from Equation 5. A "3-Sigma" estimate of the skin differential pressure was then calculated to be ±1.11 psia using Equation 6.

$$\text{Std Dev (dp)} = \sqrt{Std\ Dev(P_2)^2 + Std\ Dev(P_{out})^2} \qquad [5]$$

$$\text{3-Sigma Condition} = \mu \pm 3\sigma \qquad [6]$$

A Monte Carlo simulation (MCS) was performed to randomly select temperature and pressure values from historical data to generate 10,000 skin differential pressures. The plot in Figure 2 shows the normally distributed skin differential pressures which have a +3-sigma value of +1.1 psid. Even using the non-normal historical distributions of temperature and pressure over a broad range of years, the MCS results verify and support the results of the probabilistic analysis. Further details of the simulation and probabilistic analysis can be found elsewhere (6)(7).
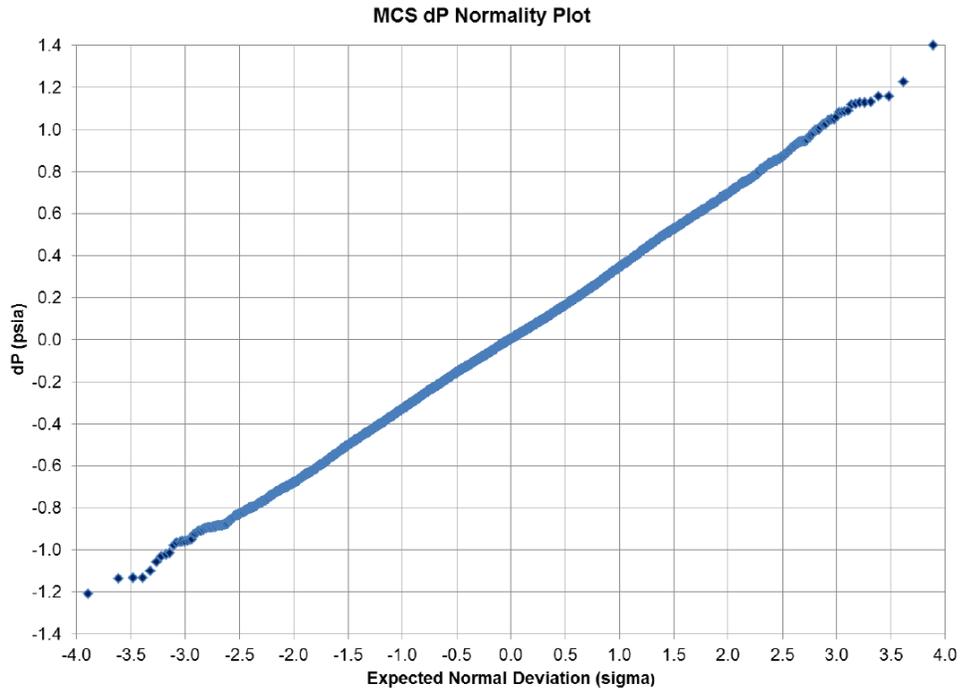
Figure 2. Distribution of 10,000 skin differential pressures calculated with temperatures and pressures randomly selected form historical data.

2.3 Discussion

The probabilistic approach resulted in a 54% reduction in the skin differential pressure while still maintaining an acceptable level of conservatism. Employing a probabilistic approach to other engineering design and analysis activities has the potential to trim designs and improve margins by eliminating over conservatisms resulting from highly improbable conditions. It also promotes cross-discipline collaboration.

3.0 MAIN ENGINE STARTUP LOAD

Startup of the RS-25 main engines will generate a plume of hot exhaust and debris which the nozzle plug will experience as a dynamic pressure wave. The transient dynamic pressure, shown in Figure 3, is typically simplified to a static pressure for use in a static numerical analysis by viewing it in either the frequency domain as a static equivalent fluctuating pressure (SEFP), or in the time domain as an ignition over pressure (IOP). Both SEFP and IOP use the natural frequency and damping ratio of the nozzle plug to determine the equivalent static pressure. Because the SEFP and IOP are two representations of the same event, only the worst of the two is applied. For the nozzle plug, the SEFP was ±3.7 psi and the IOP was ±2.8 psi based on a natural frequency of 38 Hz and damping ratio of 4%.

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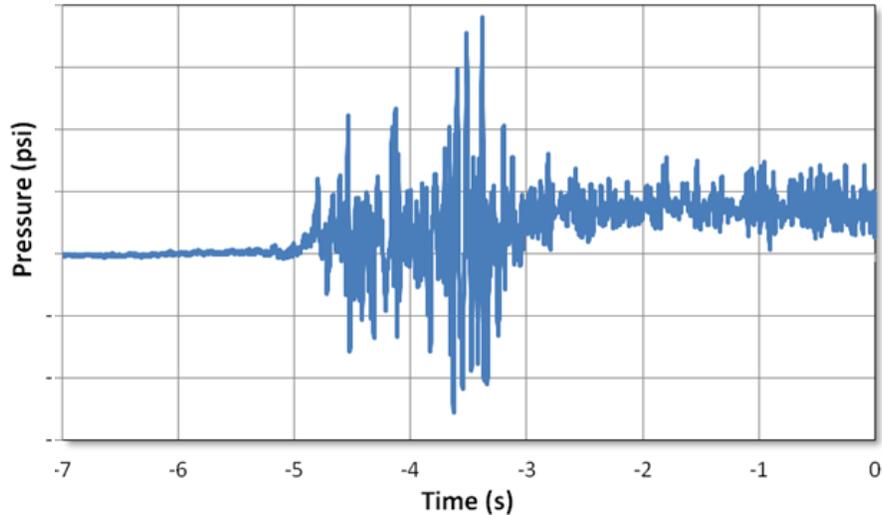
Figure 3. Dynamic main engine startup load.

3.1 Dynamic Analysis

An approach to reduce the main engine startup loads eliminated the conservative simplification of representing the dynamic pressure as a static equivalent pressure. While a detailed description of the dynamic analysis is beyond the scope of this publication and is discussed elsewhere (8), a brief summary is presented herein.

The dynamic implicit nozzle plug analysis was performed in Abaqus 6.11-1 using a 2-D axisymmetric model which used material properties obtained by material property testing conducted at ATK. The natural frequency and damping ratio of the nozzle plug were experimentally determined by impact hammer modal tests on a full-scale plug and were tuned numerically by adjusting material damping coefficients. To represent the prelaunch event, the dynamic load in Figure 3 was directly applied to the model along with the probabilistic environmental load discussed in section 2.2.

Simulations at various temperatures showed that the highest stresses were in response to the highest dynamic pressure, which occurred at approximately T-minus 3.4 seconds. The lowest safety factor (0.45) occurred at the highest temperature (115°F), which was a 31% improvement over the previous static analysis safety factor of 0.31. The previous static analysis also included the probabilistic environmental load discussed in section 2.2.

3.2 Discussion

Unfortunately, the main engine startup load would still need significant reduction to meet the required safety factor of 1.4. In addition to the marginal results improvement, the cost and complexity of validating the dynamic analysis through testing does not make the dynamic approach a viable design solution.

Unfortunately, no combination of the explored loads reduction methods provided the relief needed to meet requirements with the current nozzle plug design. Because the loads could not be sufficiently lowered, the structural capability must increase. The lower skin differential pressure will, however, prevent the nozzle plug form being overdesigned in a future redesign effort

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4.0 CONCLUSION

An effort was made to lower the two dominant loads for the SLS nozzle plug. Applying a transient main engine dynamic pressure instead of the standard static equivalent pressure improved stress levels by 31%. The dynamic simulation incorporated the probabilistic environmental load, but the safety factor (0.45) was still well below the design limit (1.4). In addition, the cost and complexity of pursuing dynamic validation testing did not make the dynamic approach a viable design solution. A probabilistic analysis of the environmentally-induced skin differential pressure, assuming a 3-sigma condition, reduced the load by 54% to ±1.1 psid. This was compared to the standard worst-case approach of ±2.44 psid. A Monte Carlo simulation supported the results of the probabilistic analysis, indicating the predicted load is reflective of a "3-sigma" condition. Utilizing the probabilistic load eliminated excessive conservatisms and will prevent overdesign of the future nozzle plug. Employing a similar probabilistic approach to other engineering design and analysis activities can result in realistic yet adequately conservative solutions.

5.0 ACRONYMS

IOP   Ignition Over Pressure

MCS   Monte Carlo Simulation

RSRM   Reusable Solid Rocket Motor

RSRMV   5-Segment Reusable Solid Rocket Motor

RTV   Room Temperature vulcanized rubber

SEFP   Static Equivalent Fluctuating Pressure

SLS   Space Launch System

VAB   Vehicle Assembly Building

6.0 REFERENCES

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ATK

- Prelaunch Nozzle environment for SLS will be more severe than Space Shuttle.

  - SLS will have 5 main engines. Shuttle had 3. These ignite 7 seconds before launch.

  - SLS main engines and booster nozzles will be on the same plane.

  - Shuttle engines were canted away from booster nozzles.
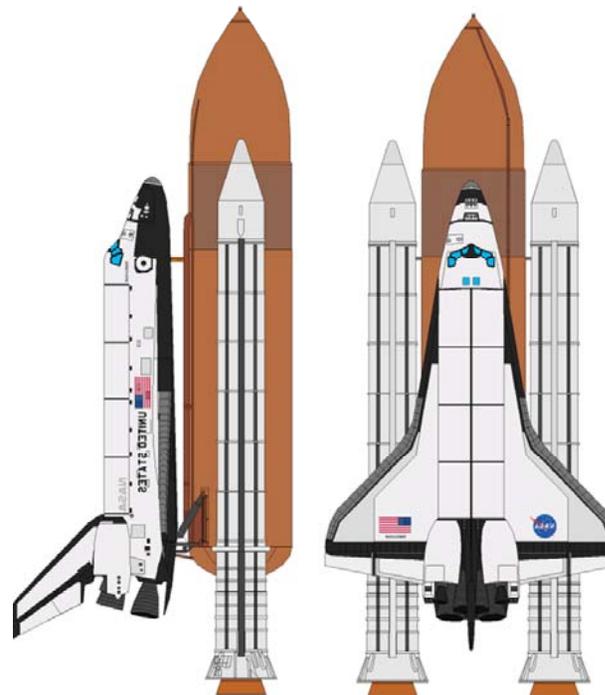
The proximity and number of main engines increased the prelaunch nozzle environment severity
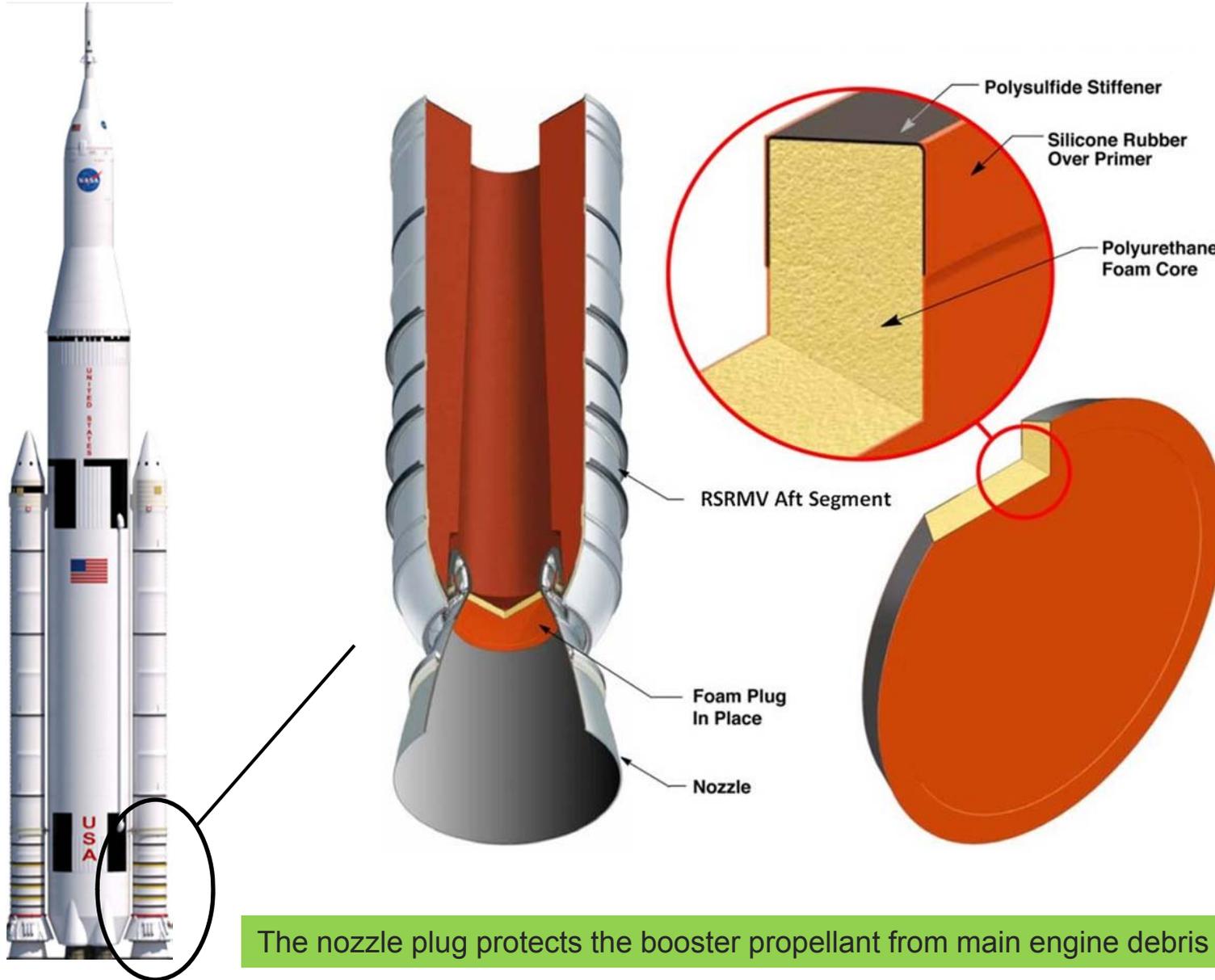
The nozzle plug protects the booster propellant from main engine debris and exhaust

Overview

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Issue: Heritage nozzle plug design is inadequate for SLS loads.

- Analysis showed a prelaunch safety factor of 0.31 (Required 1.4).

- Premature failure of the nozzle plug could allow booster propellant pre-ignition.

Solutions:

1) Increase the design capability (redesign)

- Cost $1 million (material formulation, testing, analysis).
- Tight schedule to get new design on QM-2 in 2014.

2) Refine the loads estimate

- Keep current design (certified/qualified)
- Method: Eliminate conservatisms
    1) Environmental pressure
    2) Main engine startup pressure

Lowering the loads could prevent an expensive redesign

Environmental Load Overview

- Installing the nozzle plug isolates the air inside the motor.

- Pressure develops as the ambient and internal bore environments change between booster assembly and launch.

- Could be either a positive or negative pressure.

- Historical data

  - Atmospheric pressure (11 years of data)

    - Ranged between 14.13 psia and 15.05 psia.

  - Temperature (5 years of hourly measurements at the VAB)

    - Ranged between 40.0 °F and 93.9 °F.

- Analytical model predicted internal bore temperature for launch to be between 36.1 ºF and 83.3 ºF.
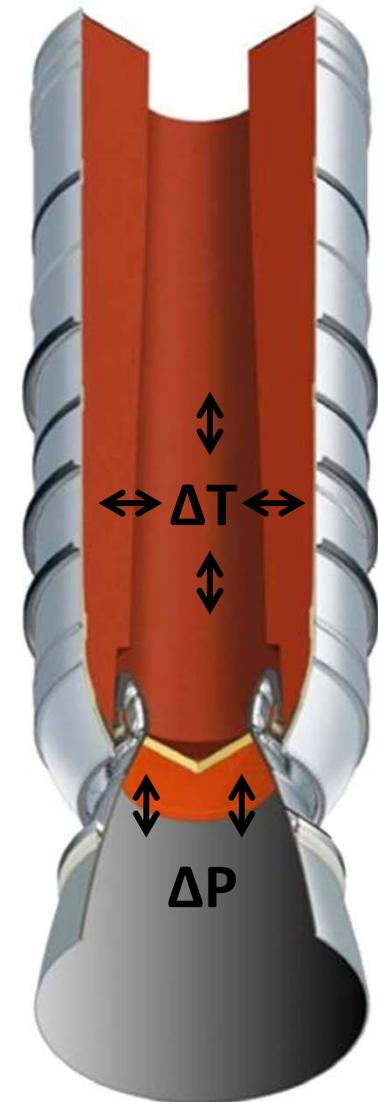
The environmental pressure is caused by changes in ambient temperature and pressure

Environmental Load: Typical Approach

- Assume the worst possible conditions for both booster assembly and launch

- Ideal Gas Law

$$P_2 = P_1 \frac{T_2}{T_1}$$

  - Assembly pressure of P_1
  - Assembly temperature of T_1 (Rankine)
  - Launch bore temperature of T_2 (Rankine)
  - Launch bore pressure of P_2
  - Launch environmental pressure of P_{out}
  - Environmental pressure on nozzle plug of dp

$$dp \equiv P_2 - P_{out} = P_1 \frac{T_2}{T_1} - P_{out}$$

- Results

  - Maximum internal and minimum ambient pressure: +2.44 psia

  - Minimum internal and maximum ambient pressure: -2.31 psia

- Realistic?
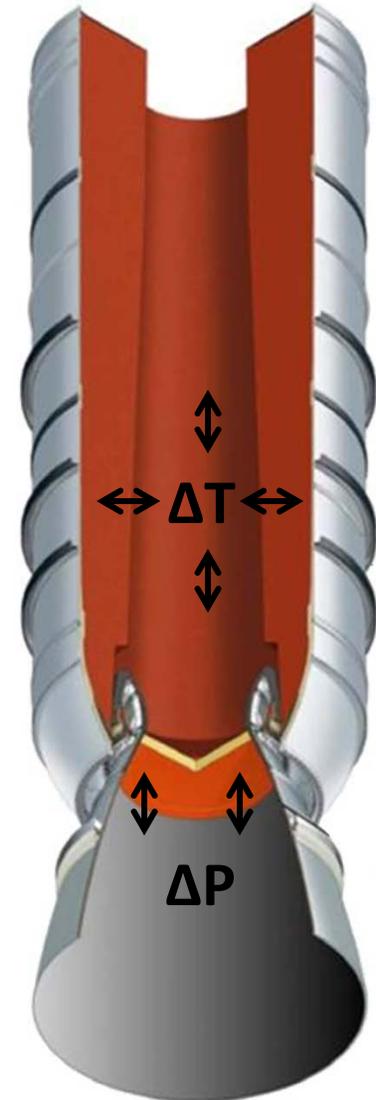
The typical approach uses unrealistic combinations of temperature and pressure

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Booster Assembly Temperature

Standard Dev.	Probability
1σ	1 / 3.1
2σ	1 / 22
3σ	1 / 370
4σ	1 / 15,787
5.8σ	1 / 250,000,000

Chart: Booster Assembly Temperature. Y-axis: Temp (°F) from 35 to 95. X-axis: Expected Normal Deviation (sigma) from -5.0 to 4.0. Labels: 87.5°F, 75.5°F, 46.0°F.
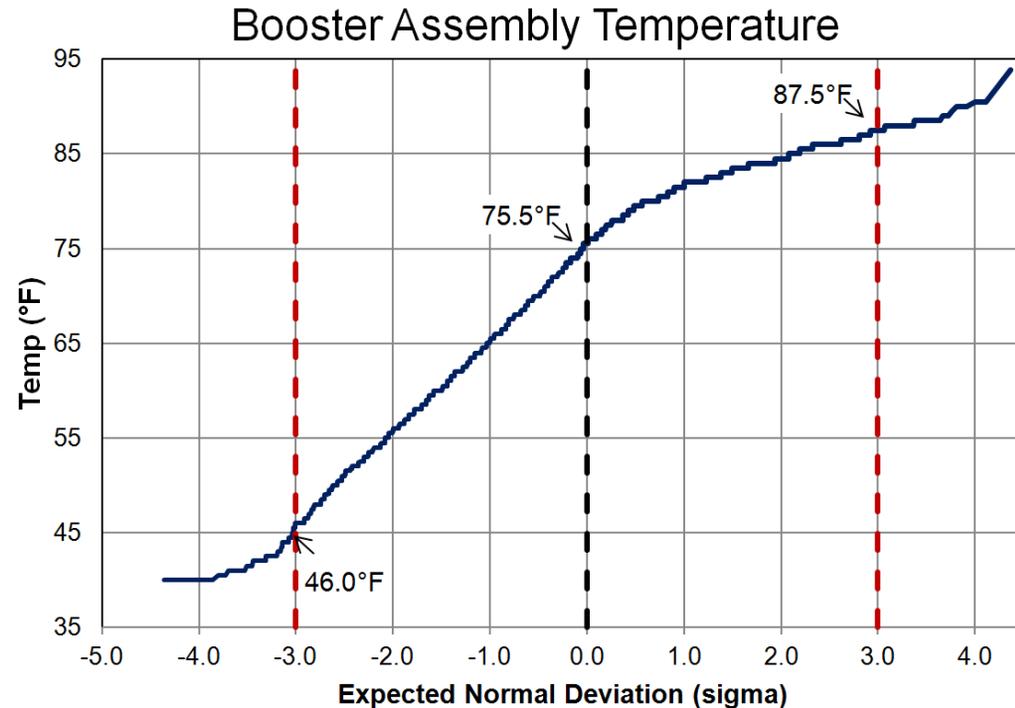
- **Issue:** Two 4σ events occurring together has a probability of 1 in 250 million.

- **Goal:** Make the load more realistic, maintain reasonable conservatism.

- **Solution:** Use cross discipline collaboration between engineers and statisticians to identify a 3σ environmental pressure on the nozzle plug.

$$3\sigma \text{ Condition} = \mu \pm 3\sigma$$

A 3σ load will occur in 1 out of every 370 launches

Environmental Load: Probabilistic Approach

Define μ and σ for P_1 and P_{out}

- μ = 14.59 psia
- σ = 0.15 psia
- CV = 1.05%

Define μ and σ for T_1 and T_2

- μ = 75.5 °F
- σ = ±7.8 °F
- CV = 1.47%

- **Define μ and σ for P_2**
  - $\mu(P_2) = \mu(P_1) * \mu(T_1) / \mu(T_2) = 14.59$ psia
  - $CV(P_2) = \sqrt{CV(P_1)^2 + CV(T_1)^2 + CV(T_2)^2} = 2.33\%$
  - $\sigma(P_2) = CV(P_2) * \mu(P_2) = 0.34$ psia
  - Assumption: Pressure (P_2) is uncorrelated with Temp (T_1, T_2)

$$CV = \frac{\sigma}{\mu}$$

- **Define μ and σ for environmental pressure dp**
  - $\mu(dp) = \mu(P_2) - \mu(P_{out}) = 0.0$ psia
  - $\sigma(dp) = \sqrt{\sigma(P_2)^2 + \sigma(P_{out})^2} = 0.37$ psia

- **3σ Condition for environmental pressure dp**
  - Upper 3σ = +1.11 psia
  - Lower 3σ = -1.11 psia
  - **Environmental pressure reduced by 54%!**

The probabilistic approach was more realistic, yet still conservative

Environmental Load: Monte Carlo Simulation

- Temperatures and pressures randomly select from historical data.
- 10,000 random environmental pressures were generated. 3σ load was 1.1 psid.
- The simulation results verify and support the probabilistic analysis.
- This method could benefit other engineering activities (realistic yet conservative).
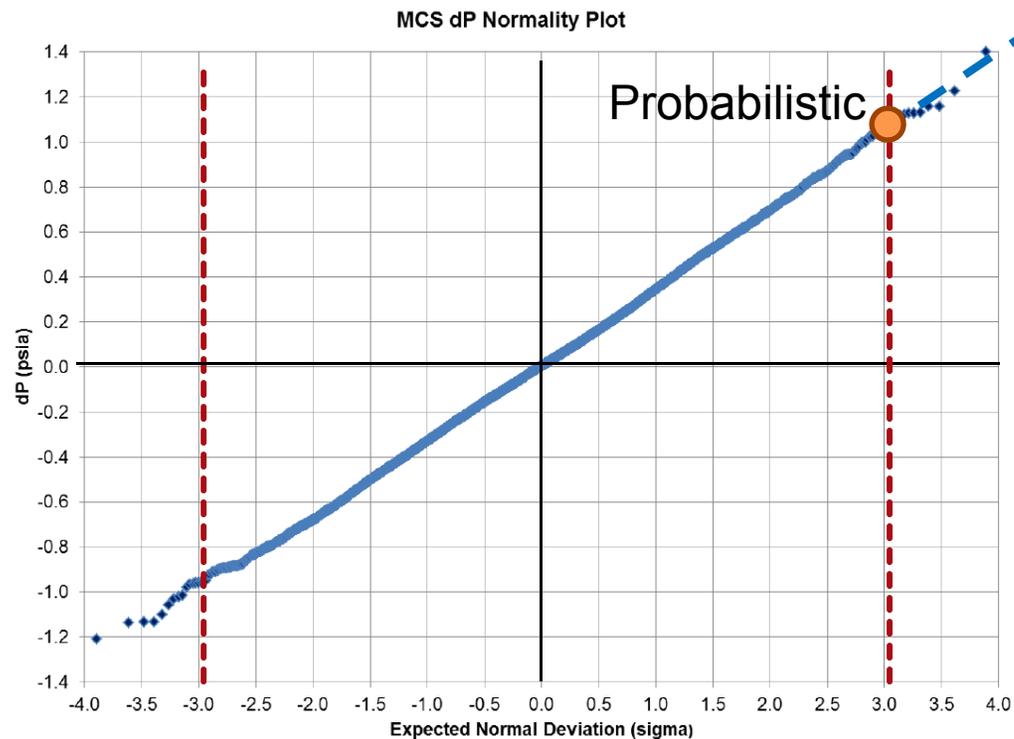
The Monte Carlo simulation verified that the environmental load had a 1/370 probability

Main Engine Startup Load

- Main engines start up 7 seconds before booster ignition.

- Main engine plume is experienced by the nozzle plug as a transient dynamic pressure.

- Dynamic pressure is simplified to a static pressure for use in static analyses.

  - Simplification introduces conservatisms.

- **Solution**: Directly apply the transient main engine startup pressure in a dynamic analysis.
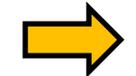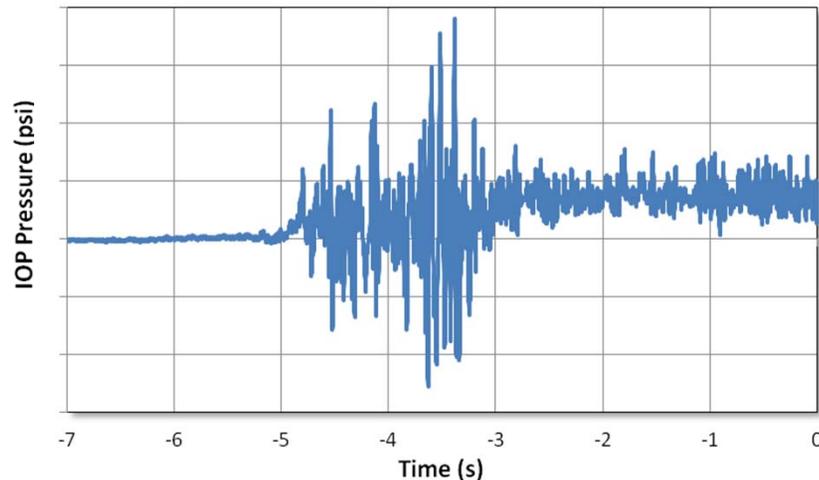

Transient Dynamic Pressure → Static Equivalent Pressure
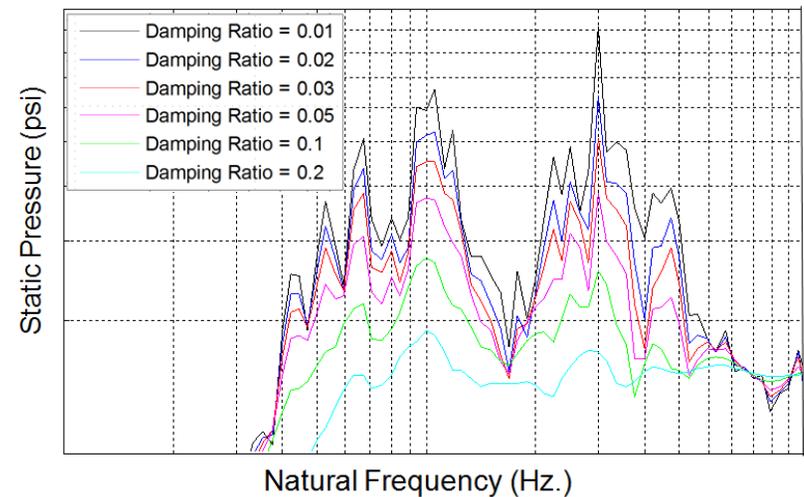
"Dumbing down" the main engine startup load introduces conservatisms

Tuning the Dynamic Model

Experiment

Method

- Tap a mounted, full scale nozzle plug.
- Measured vibration ring down with accelerometer.

**Results**

- Natural frequency = 38 Hz
- Damping Ratio = 4%

Accelerometer

Technician "taps" nozzle plug with hand
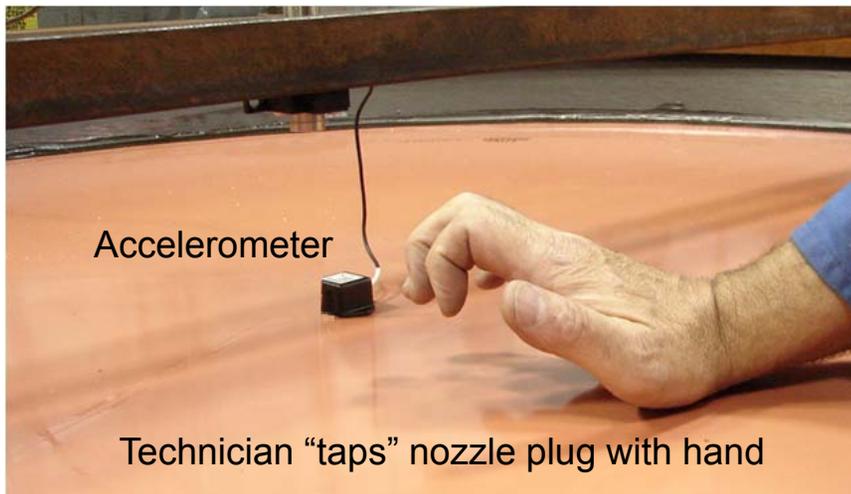
Dynamic Simulation

Method

- Apply a pressure pulse to a simulated nozzle plug and track ring down.
- Tune material damping to match experiment.

Results

- Natural frequency = 38 Hz
- Damping Ratio = 4%
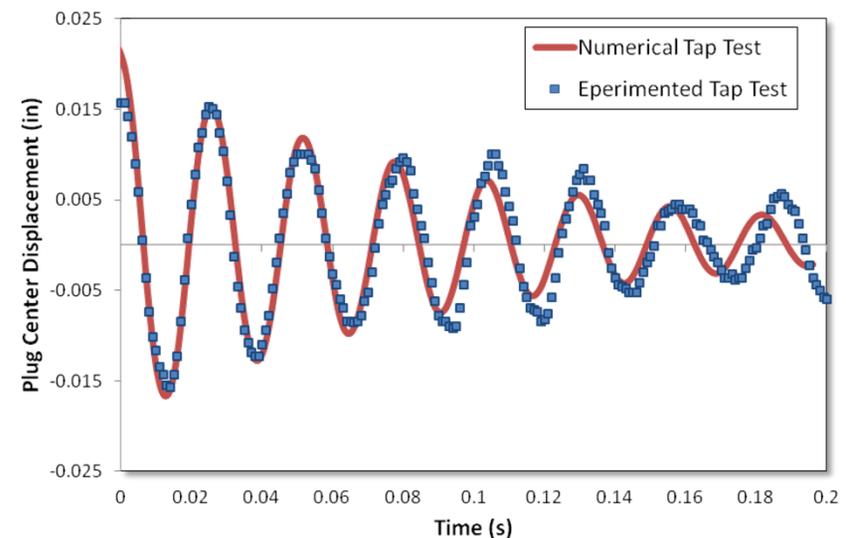
Natural frequency and damping ratio affect dynamic behavior and were tuned

Dynamic Analysis Setup

- **Model:** 2D Axisymmetric using a dynamic implicit step in Abaqus

- **Failure Criteria**: Max principal σ

- **Material properties**: Based on ETP70236

- **Temperature**: 20°F, 70°F or 115°F

- **Output**: Every millisecond

Environment (Static 1.1 psi)

Fixed Edge

IOP (Dynamic)
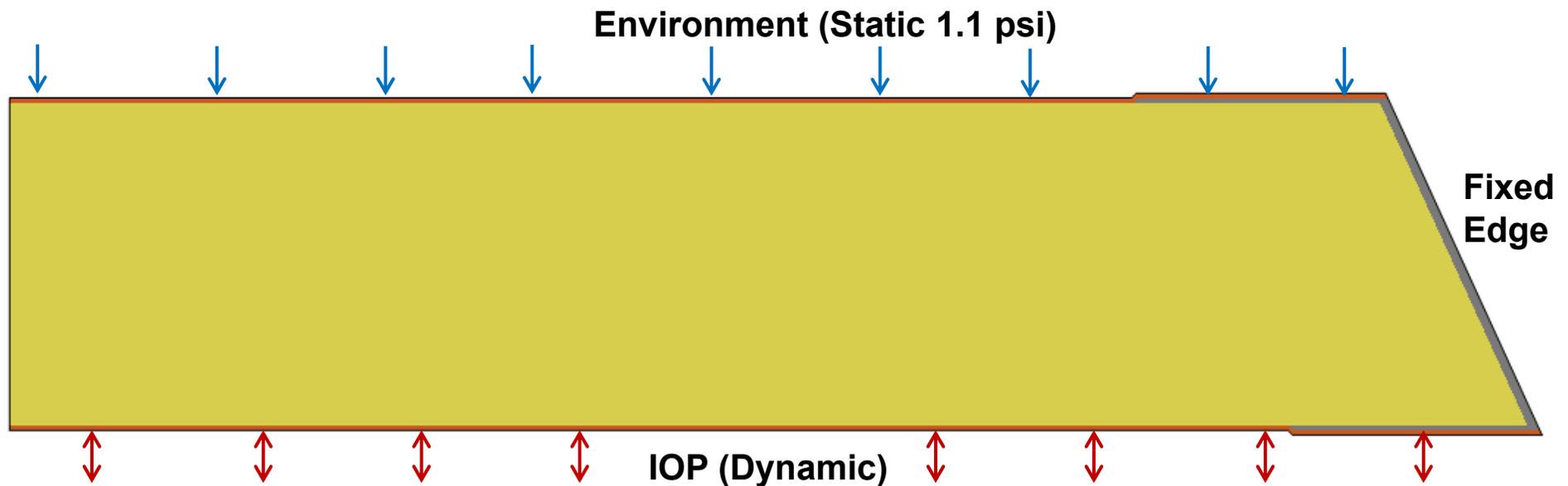
The dynamic analysis setup was similar to previous static analysis
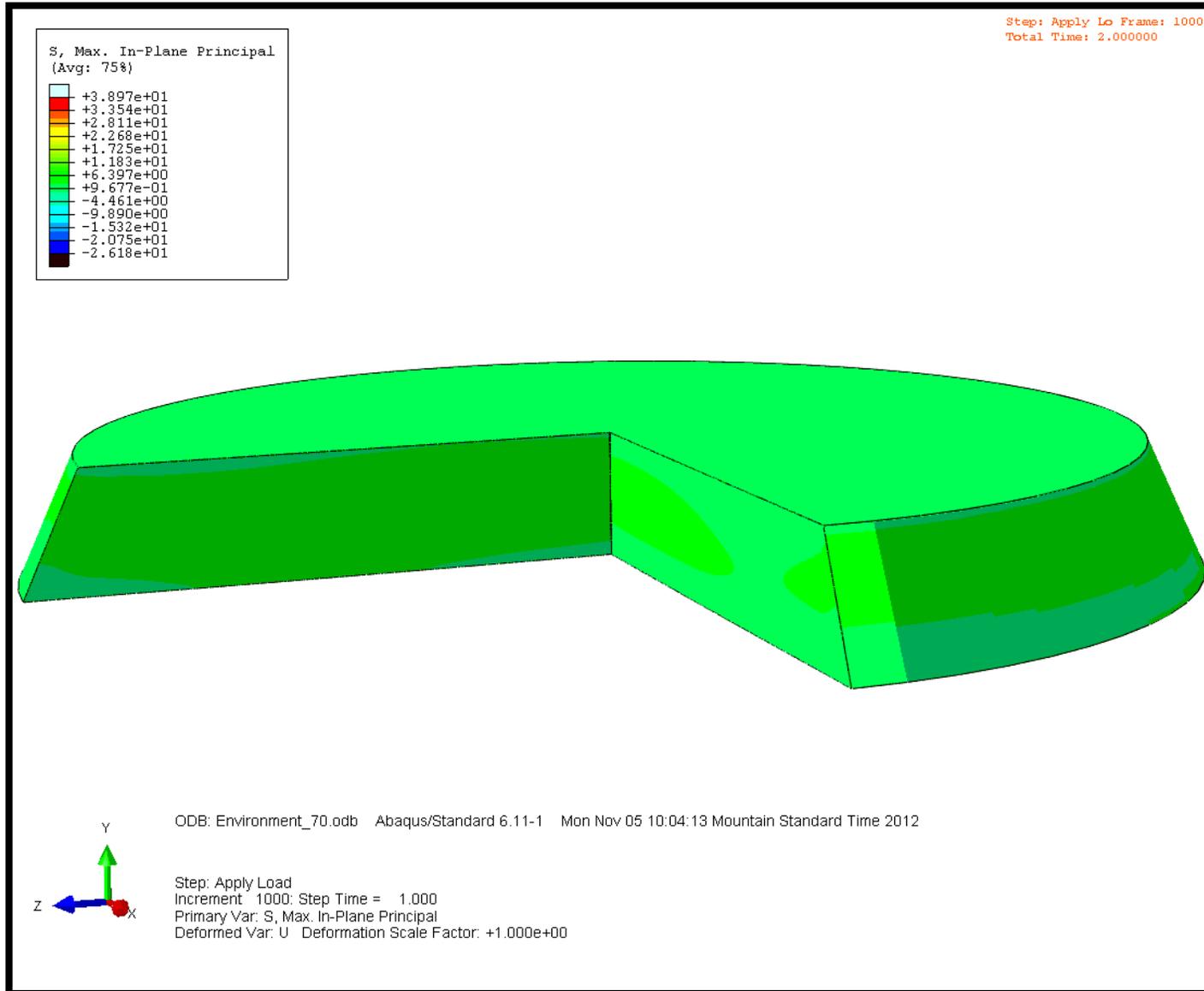
Dynamic Analysis Results

- The dynamic analysis reduced peak stress by 31% compared to static analysis.
- All cases had safety factors below the required 1.4.
- The lowest was 0.45 in the foam at 115°F.
- Stresses were higher than the foam capability by a factor of 2.2.

Max: +1.217e+002

Dynamic Analysis

```
S, Max. In-Plane Principal
(Avg: 75%)
     +1.217e+02
     +3.897e+01
     +3.513e+01
     +3.128e+01
     +2.744e+01
     +2.359e+01
     +1.975e+01
     +1.591e+01
     +1.206e+01
     +8.218e+00
     +4.374e+00
     +5.304e-01
     -3.314e+00
     -7.158e+00
```

Max: +1.734e+002
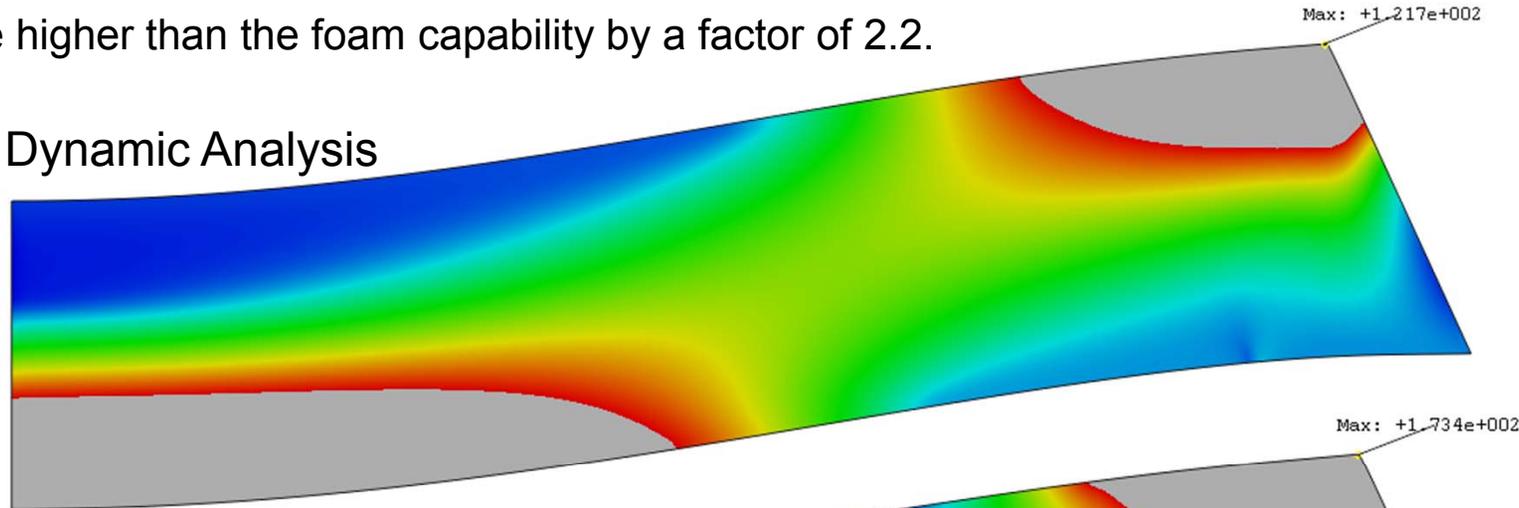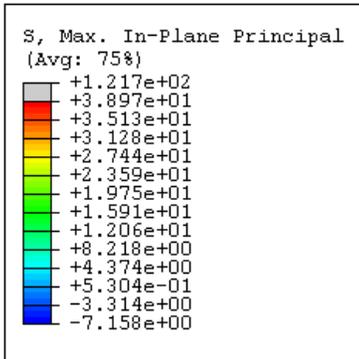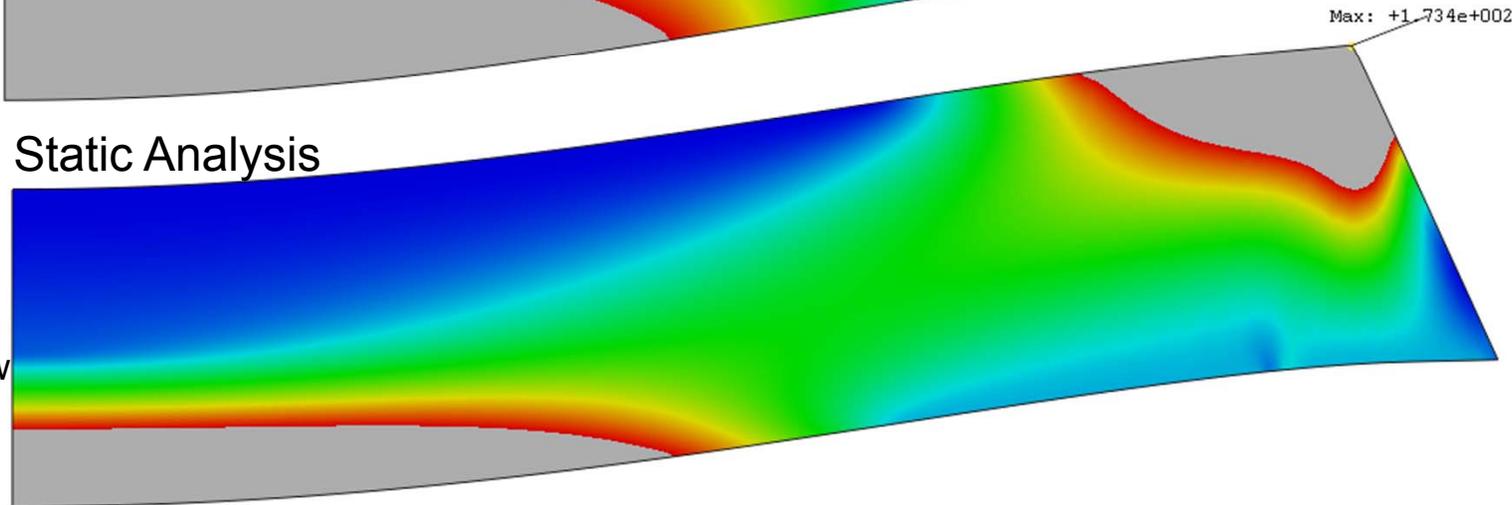
Static Analysis

Same color scale.
Gray regions are below
a safety factor of 1.4.

The dynamic analysis did not sufficiently reduce stress

Summary

ATK

Both loads were refined

- *Environmental Load*

  - Probabilistic approach reduced the load by 54%.

  - Results were validated by a Monte Carlo Simulation.

  - A probabilistic approach to other design and analysis activities could be beneficial.

    - Realistic yet conservative results
    - Promote cross-discipline collaboration

- *Main engine startup load*

  - Dynamic approach improved 31% over static approach.

  - Stresses were still higher than material capability by a factor of 2.2.

The nozzle plug must be redesigned

- Increase density and thickness to increase capability and reduce stress.

The redesigned nozzle plug will not be overdesigned as a result of the refined loads