National Aeronautics and Space Administration

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SPACE LAUNCH SYSTEM

1-24-2022

Core Stage Green Run Base Heating: Anomaly, Mitigation and Flight Redesign

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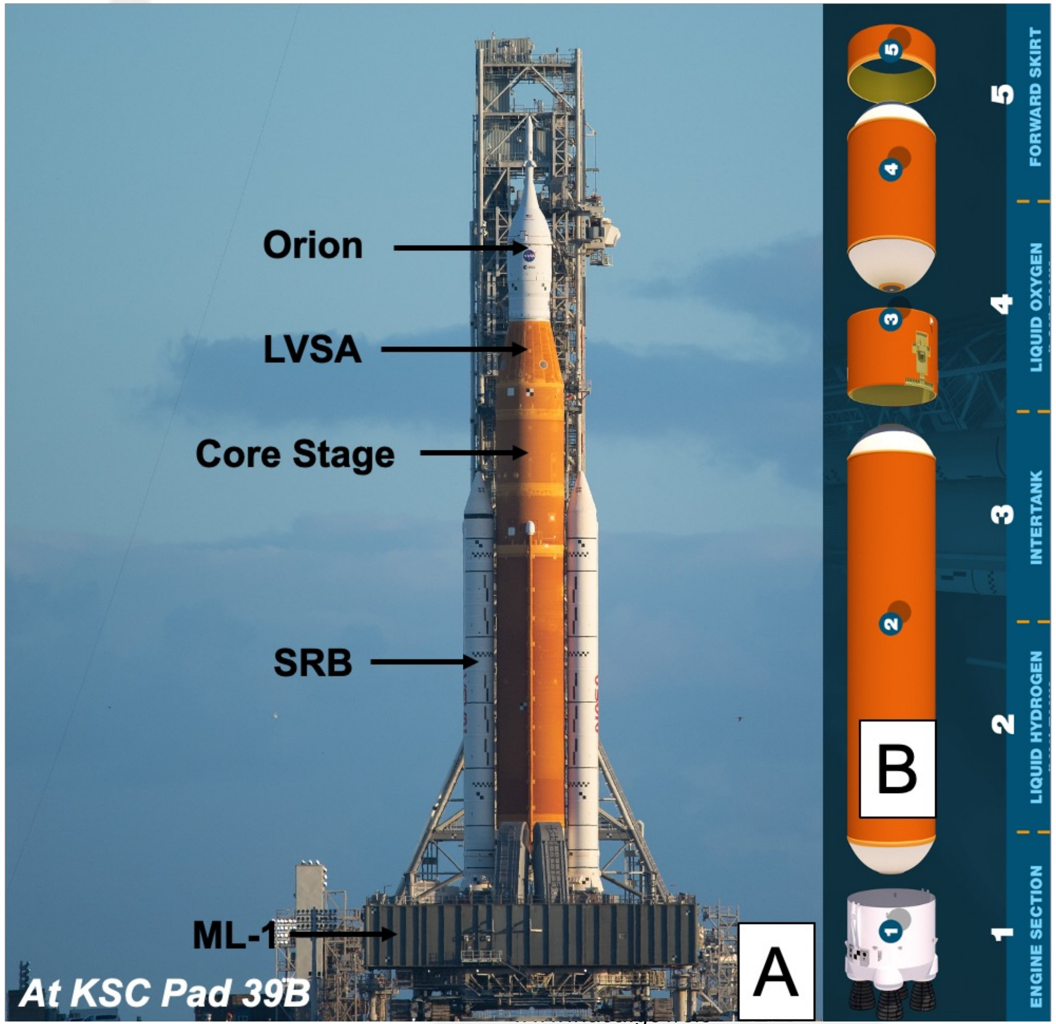
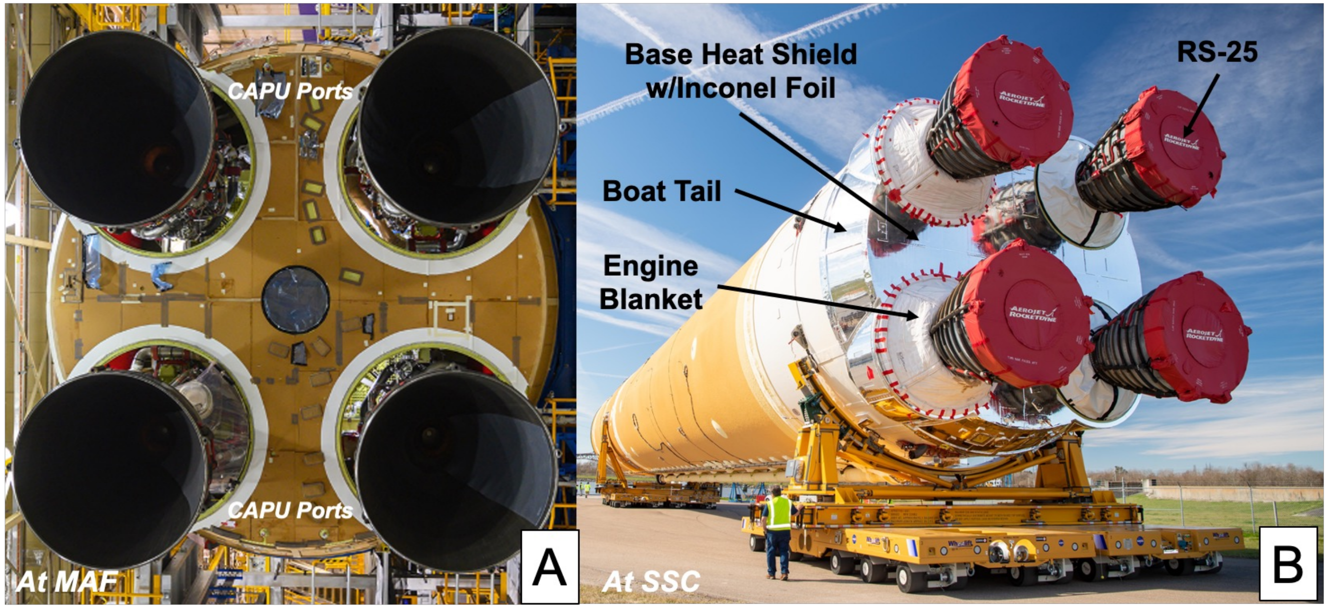
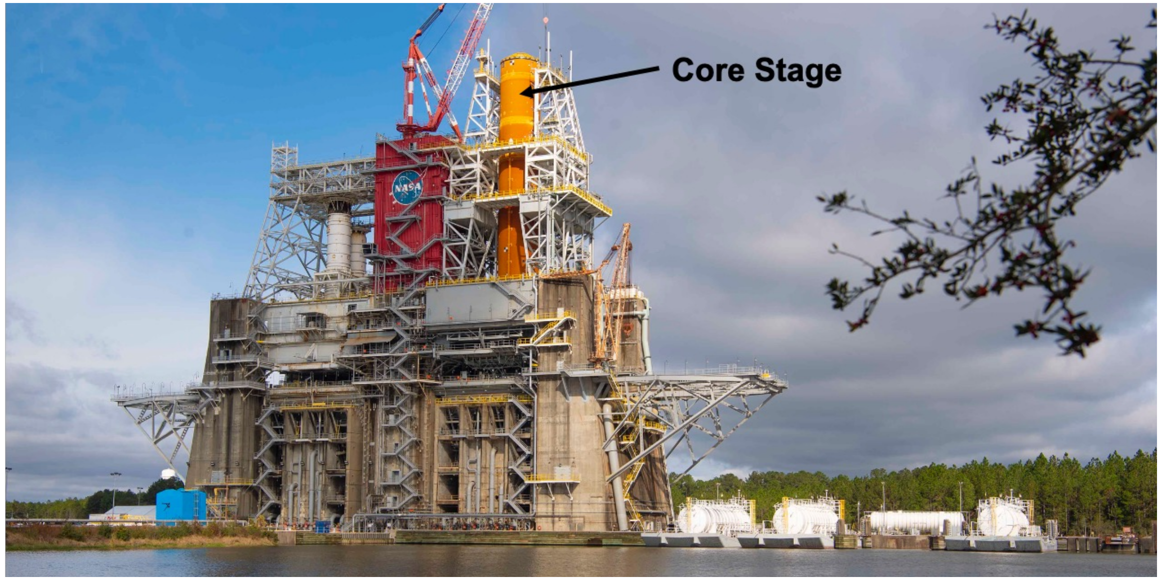
SLS Core Stage, BHS and Green Run

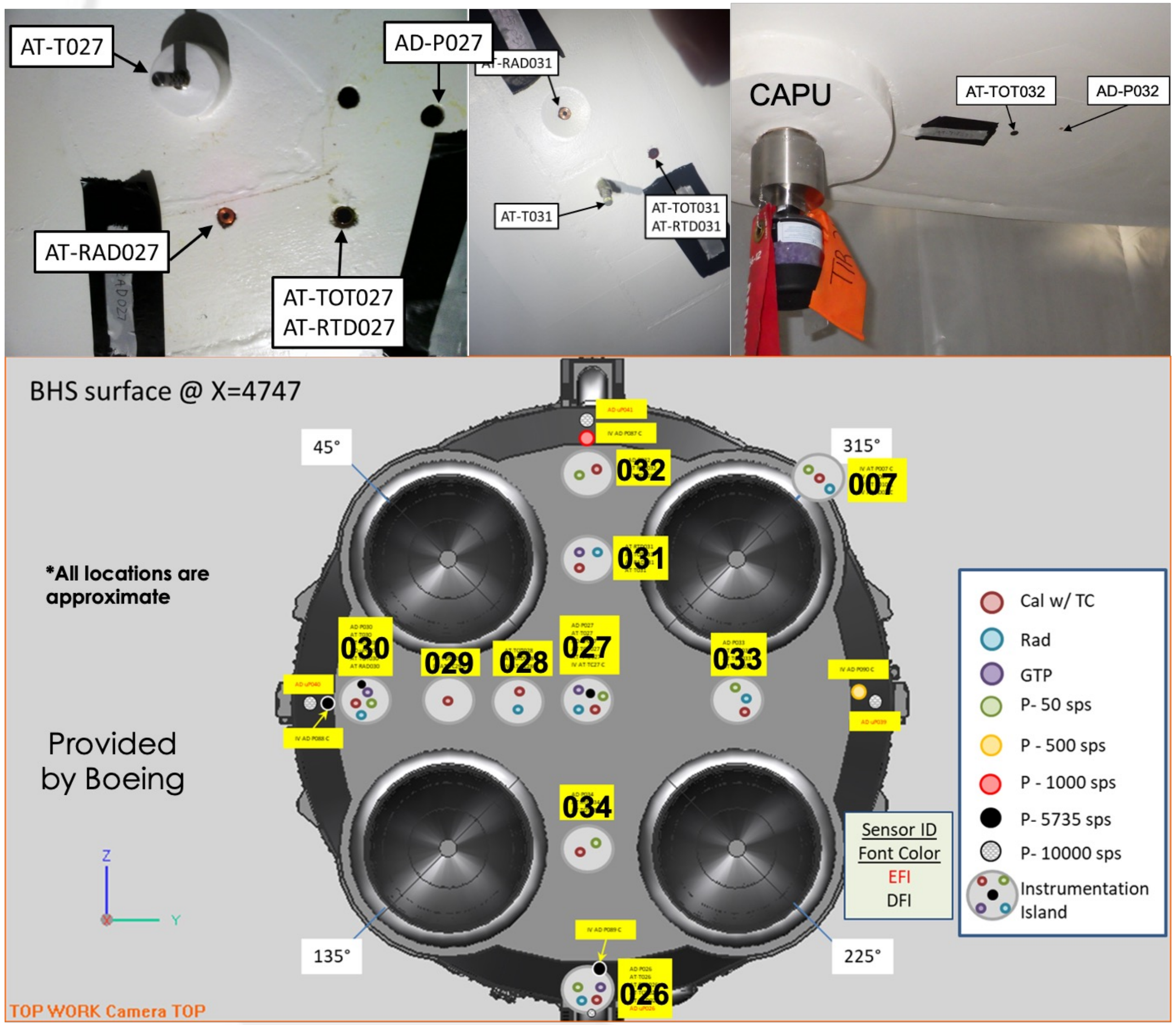
- **Focus here is the Core Stage base heat shield Green Run environments & TPS observations**







Base Heat Shield (BHS) DFI

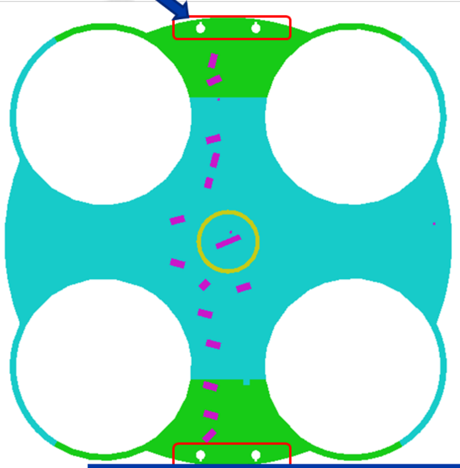


- 10 DFI Islands were installed to determine BHS aerothermal environments for ascent
- Calorimeters, radiometers, calorimeter embedded TCs, gas temperature probes and static pressure sensors were collocated where possible
  - 45 sensors were used to reconstruct GR CS base environments
- DFI sensors were collocated or symmetry was used to measure the convective heat transfer coefficient and assess the Reynolds Analogy and Colburn Turbulent Flat Plate Theory
- All DFI sensors on the BHS were flush with the TPS

GR HF1 Pre and Post-Test Observations

Flight CAPU Ports

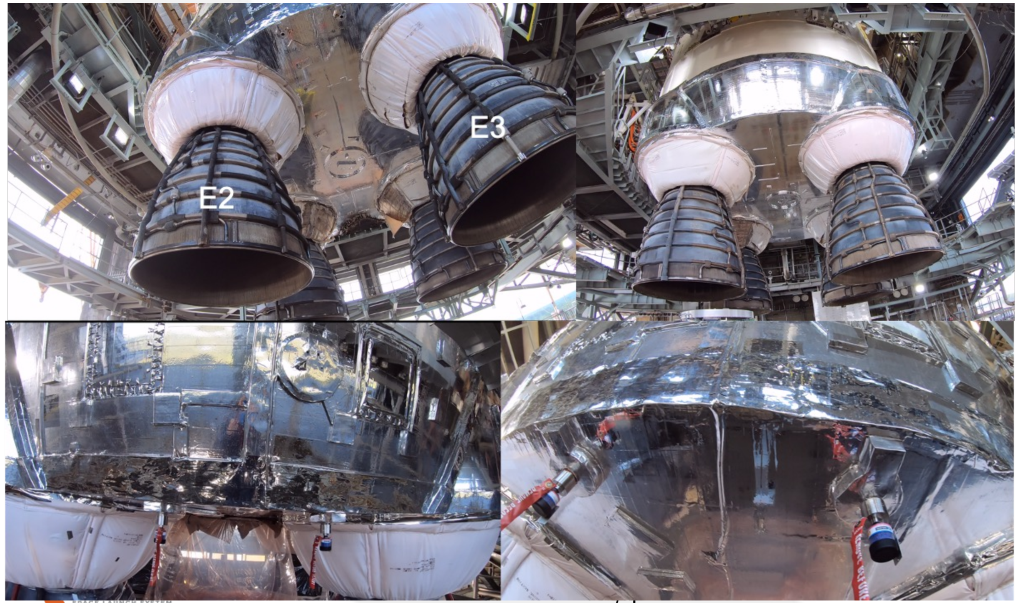
2.4" RT455 at CAPU Exhaust Ports



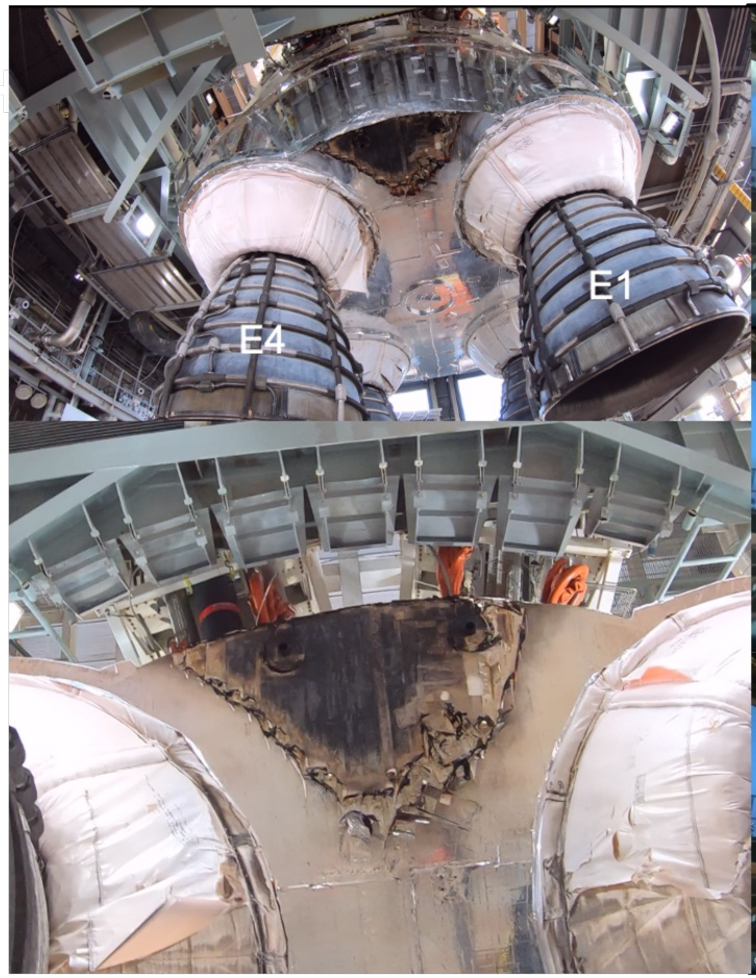
- **Not flight configuration**
- Applied Nexolve Reflective Tape over entire base heat shield

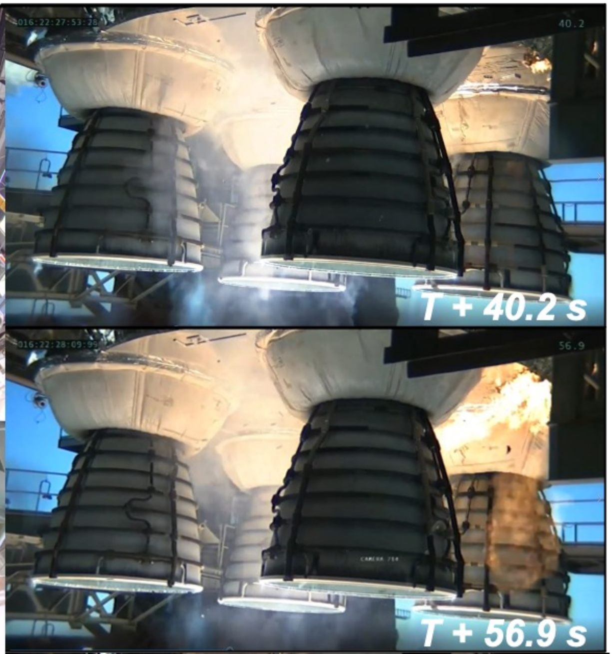
Material	Notes
1" Cork (green)	Ablative Materials (can handle high heating)
0.7" Cork (cyan)	Ablative Materials (can handle high heating)
1.25" RT455 (magenta)	Ablative Materials (can handle high heating)
1.25" S180 Foam (yellow)	- NOT AN ABLATOR Used for Ease of Removal Post GR

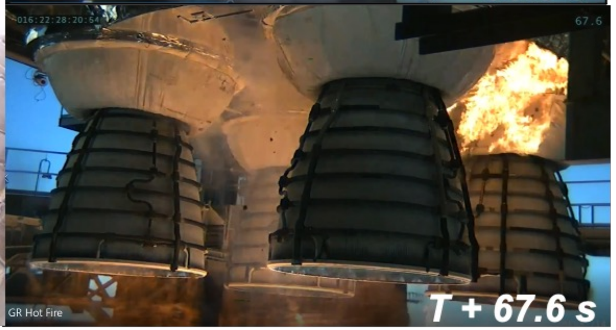
TPS Thicknesses Designed for Flight Environment; Exception Being Manhole Cover Closeout



- **Localized tape adhesive and TPS cork burning observed**
- **Led to localized tape removal and BHS charring**

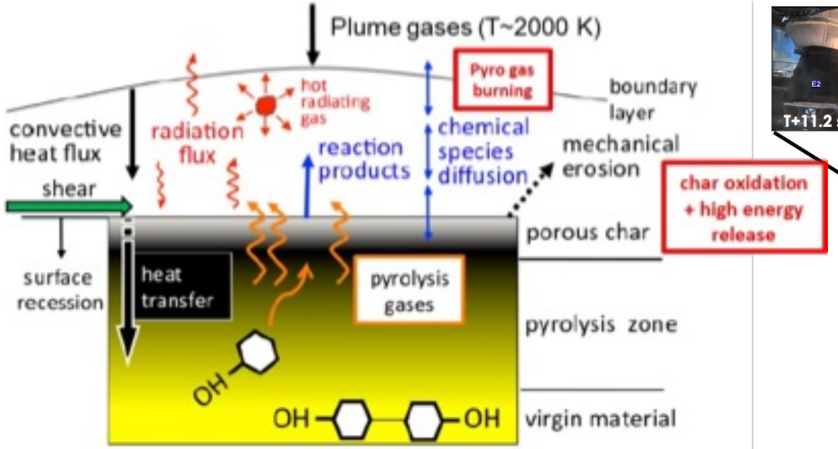


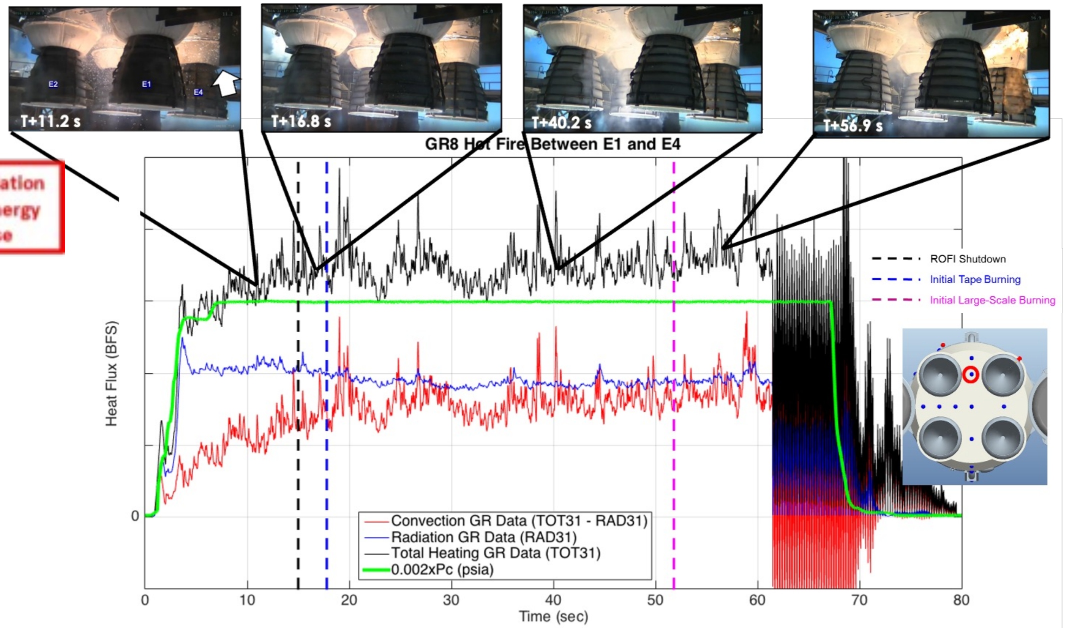


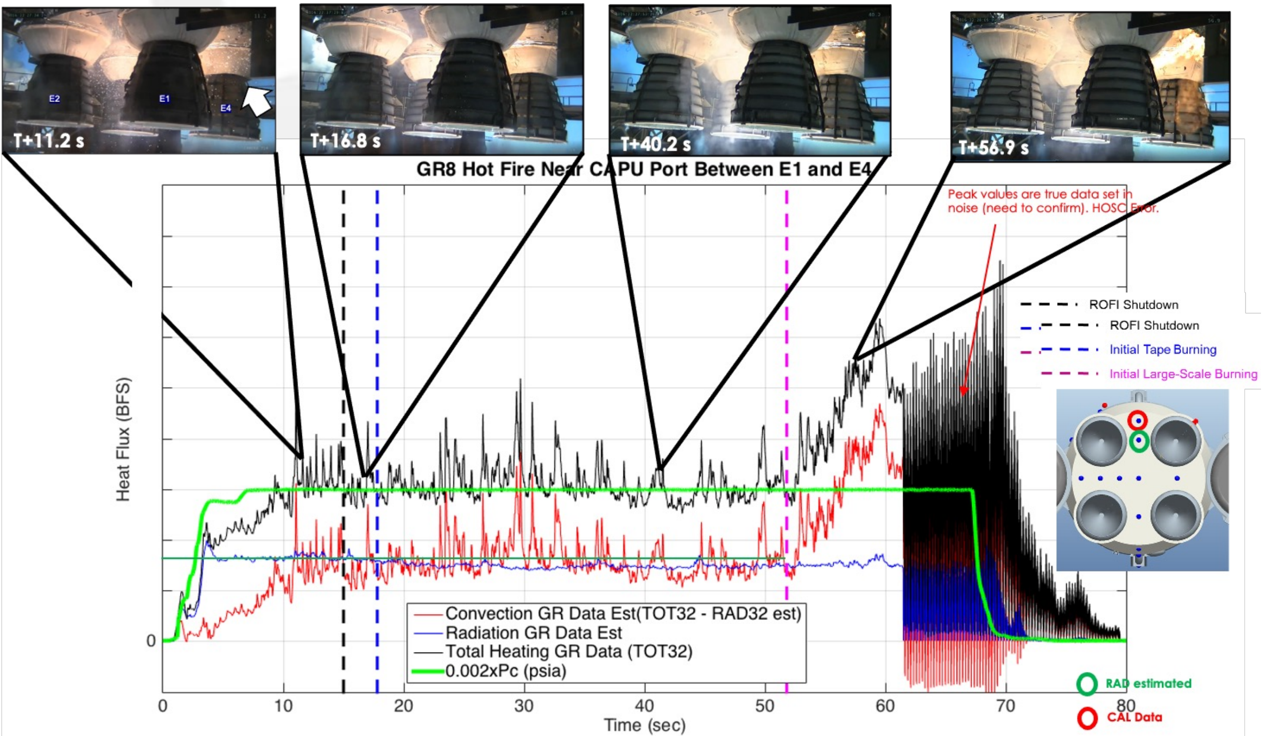


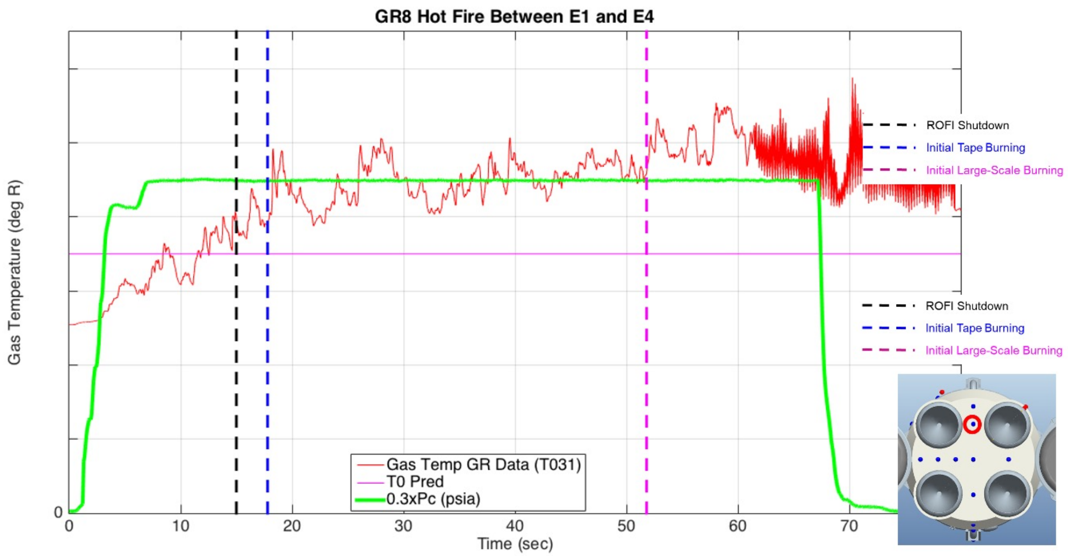
GR HF1 BHS Aerothermal Reconstruction

- Localized tape adhesive and TPS cork burning observed near the CAPU ports between E1/E4 led to significant increase in convective heating and gas temperature



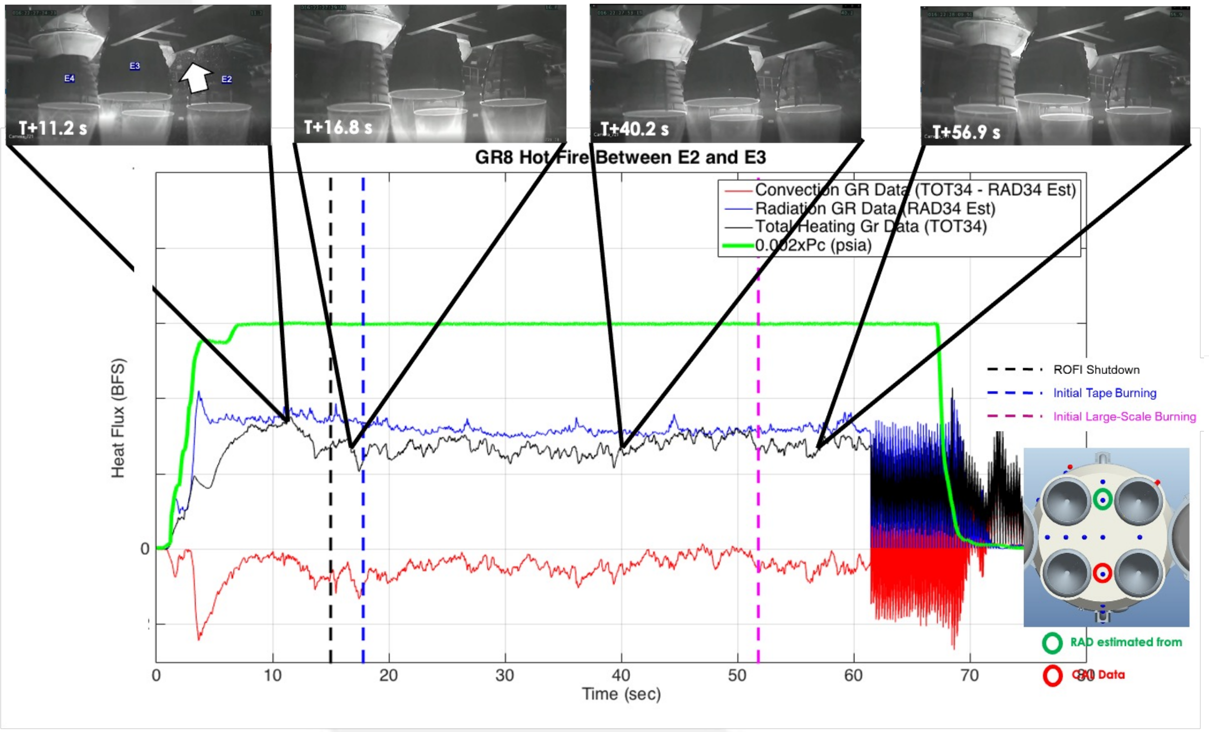


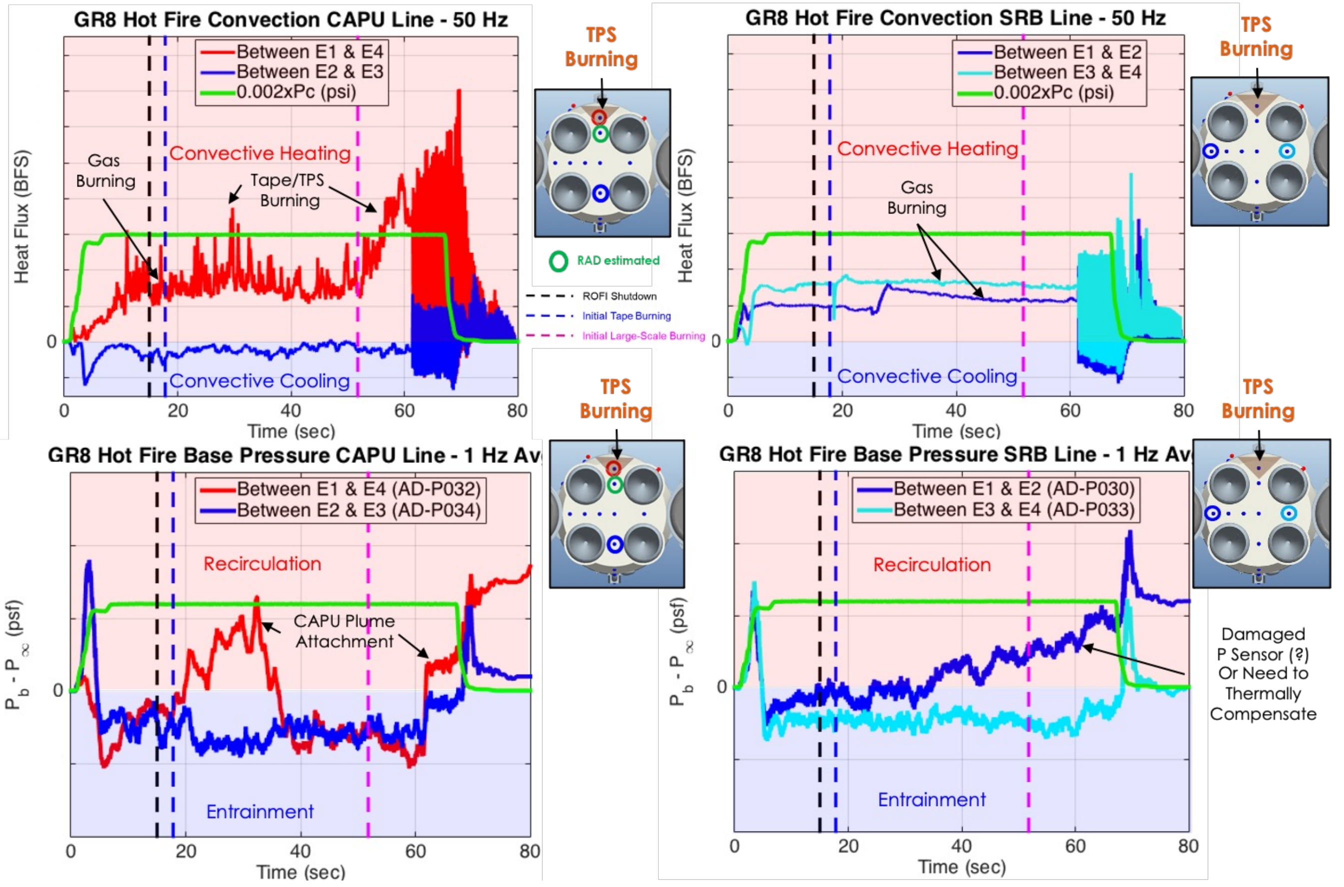




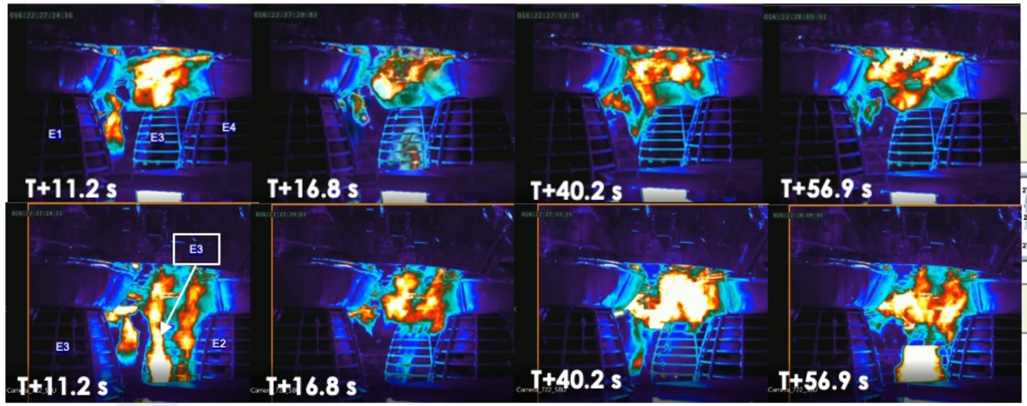
GR HF1 BHS Aerothermal Reconstruction

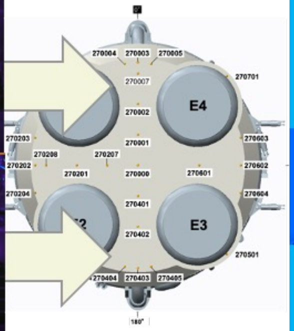
- No burning event observed between E2/E3
- Localized TPS cork convective cooling observed near the CAPU ports between E2/E3
- Negative base pressure and convective heating observed between E2/E3 shows flow entrainment effects

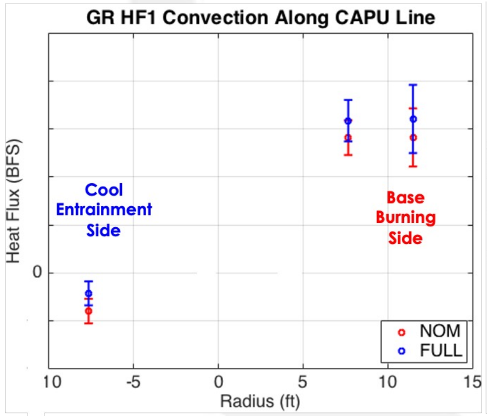


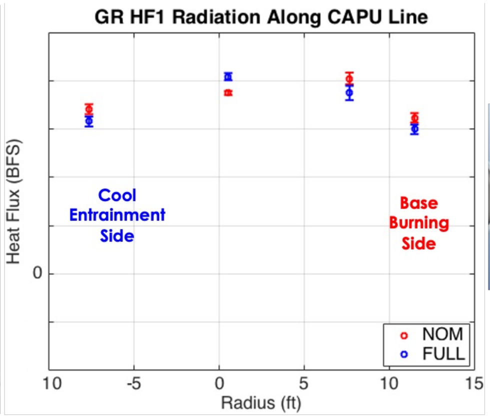


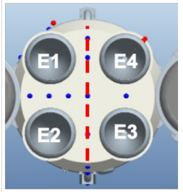
GR HF1 BHS Aerothermal Reconstruction

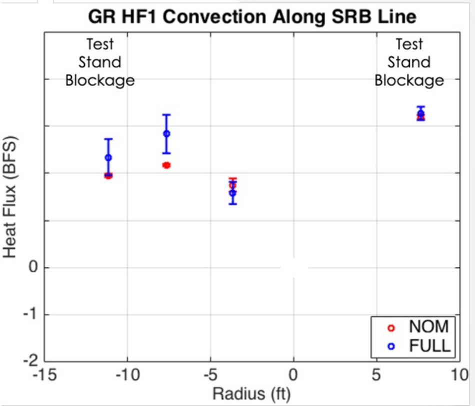


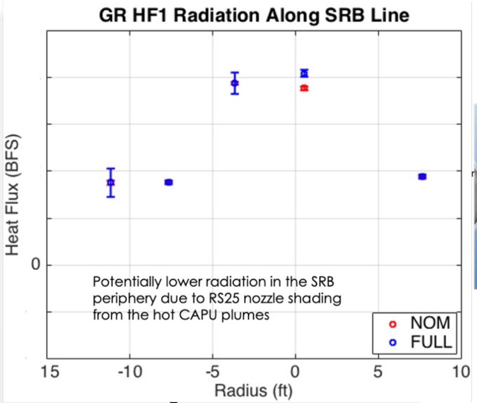


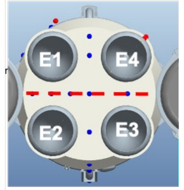


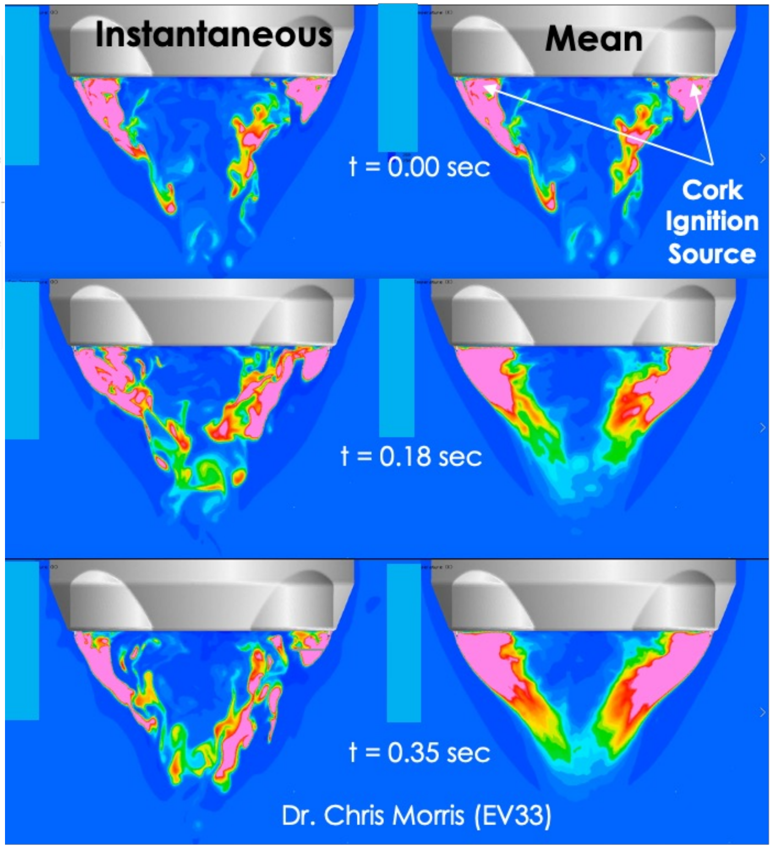


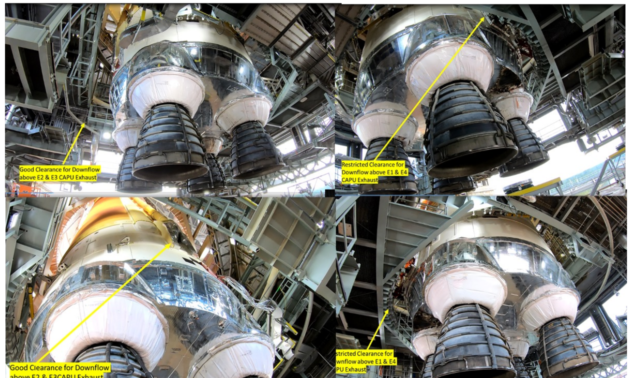












- IR imagery, convective heating and base pressure data and CFD analysis show that in the low CAPU flow state, H_2 flame attachment to the BHS in the E1/E4 region due to freestream flow obstruction
- Test fixture may have led to the flow obstruction

Mitigation Approaches for GR HF2

- **Theoretical analysis done to determine CAPU design**
- **GR HF1 reconstructed data used to size sacrificial TPS**

Reference: Feikema, Chen & Driscoll, Combustion & Flame (1991)
Turns, S.R. Introduction to Combustion (2012)

Air blow off velocity

$$U_{a,BO} = U_f \left\{ \frac{\left[\left(C_2 \frac{U_f}{d_f}\right)^{-2/3} - 1\right]}{\left(\frac{d_a}{d_f}\right)^2 - 1} \right\}^{1/2} \quad (1)$$

Flame length

$$L_f = d_f \left(\frac{L_f}{d_f}\right)_0 \left\{1 + \frac{\rho_a}{\rho_f}\left(\frac{U_a}{U_f}\right)^2\left[\left(\frac{d_a}{d_f}\right)^2 - 1\right]\right\}^{-1/2} \quad (2)$$

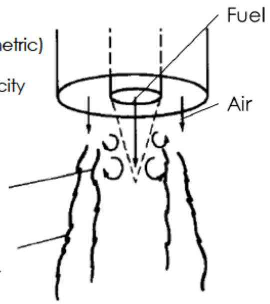
Thermal Diffusivity

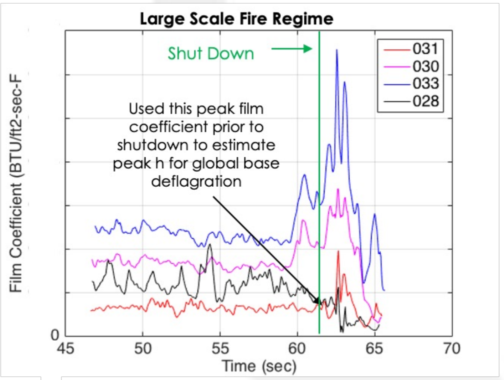
$$C_{2,H2} = 4.8\frac{\alpha}{S_{L,H2}^2}(1+AF^{-2})\left(\frac{\rho_f}{\rho_a}\right)^{-1/2} = 0.95\mu sec \quad (3)$$

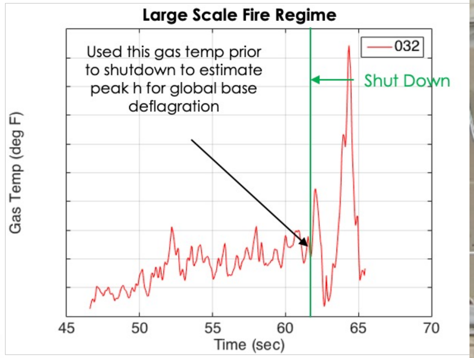
Normalized flame length for **no** coaxial air flow

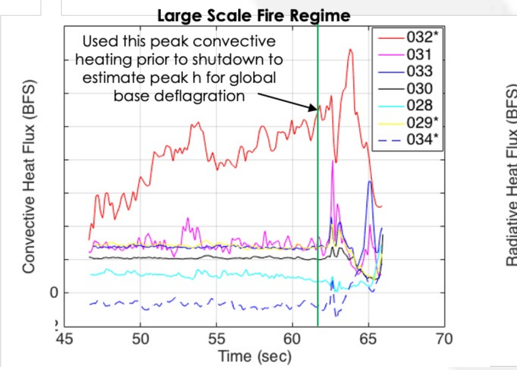
$$\left(\frac{L_f}{d_f}\right)_{0,H2} = f\left(Fr, AF, T_{ad,f}, T_\infty, U_f, \left(\frac{\rho_f}{\rho_a}\right)\right) \quad (4)$$

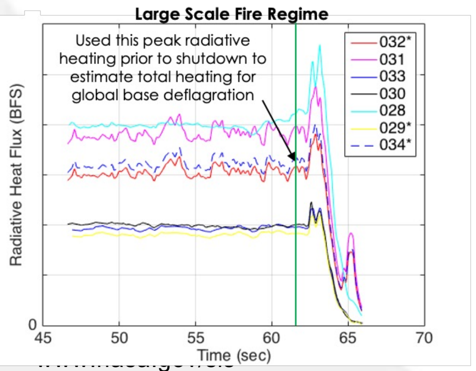
U = velocity
d = diameter
AF = air to fuel ratio (stoichiometric)
ρ = density
S_L = max laminar burning velocity
f = fuel
a = air
0 = no coaxial air

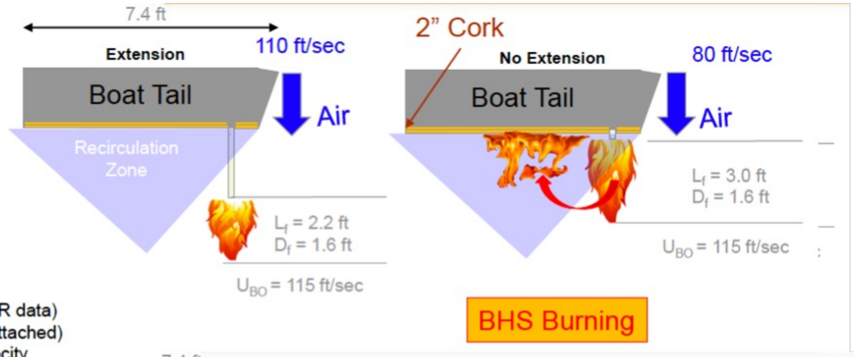








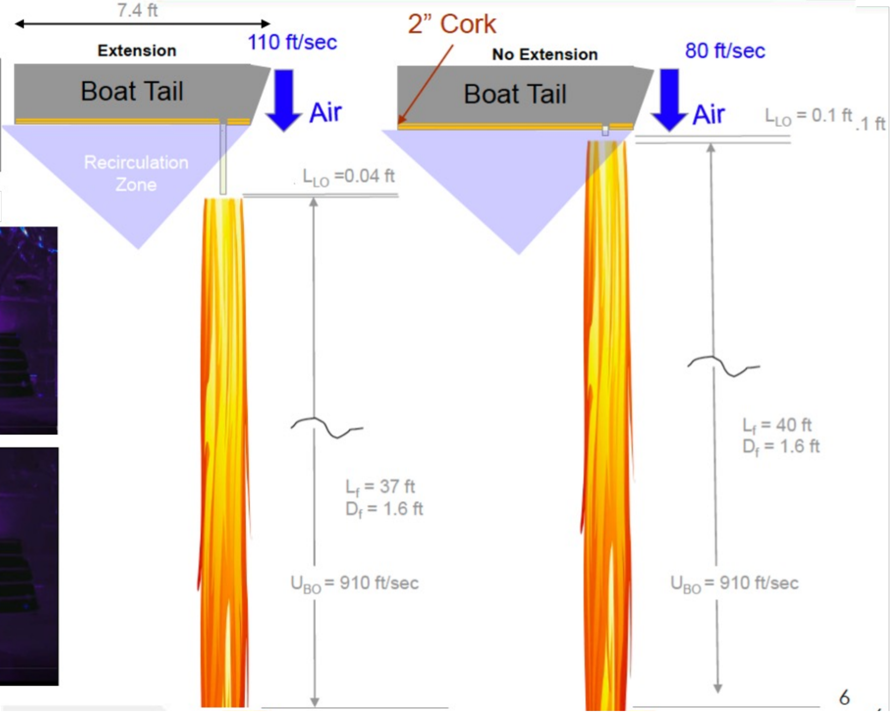


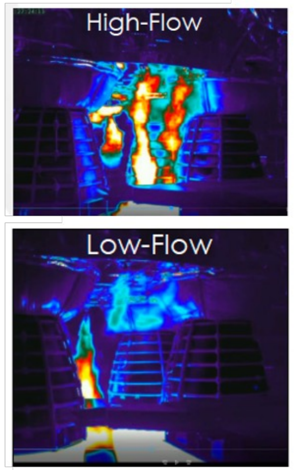


Note: To Scale

L_f = Flame Length
D_f = Flame Diameter (IR data)
L_{LO} = Lift-Off Height (attached)
U_{BO} = Blow-off Air Velocity

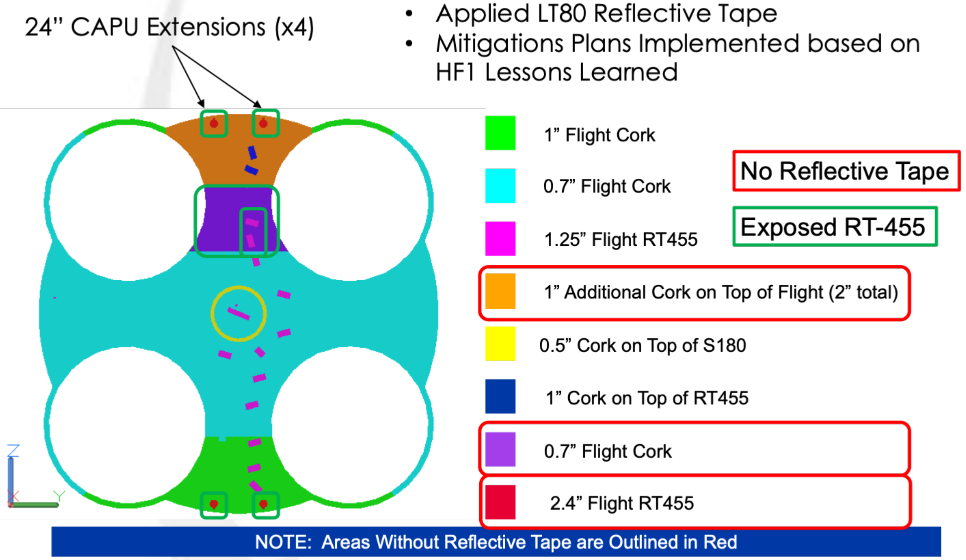
Assumed boat tail shear layer behavior similar to initial GR predictions

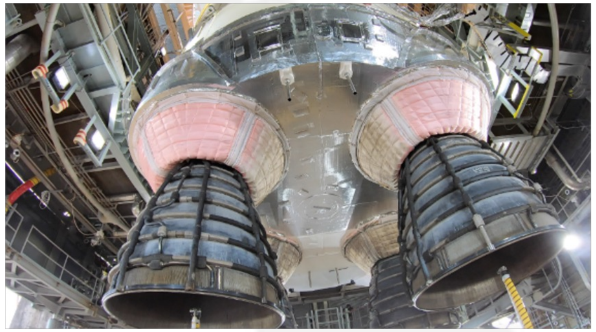


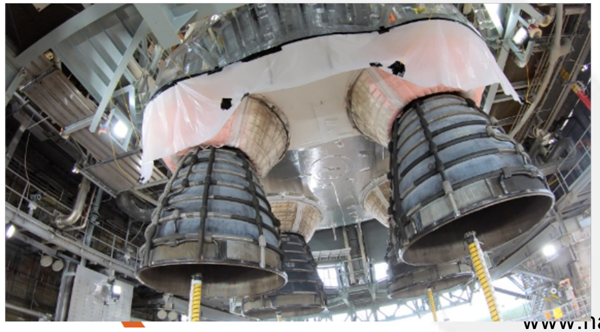


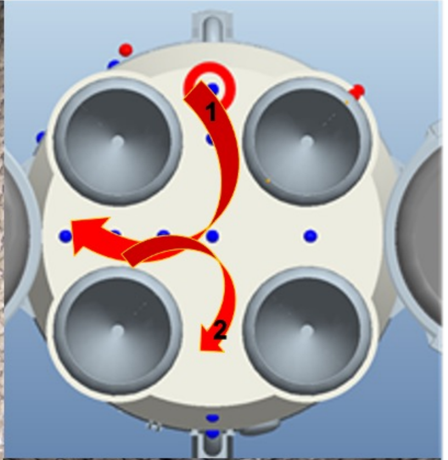
GR HF2 Pre and Post-Test Observations

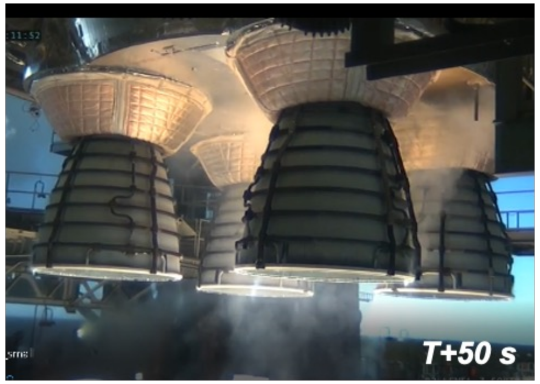
- **Not flight configuration**
- Applied LT80 Reflective Tape
- Mitigations Plans Implemented based on HF1 Lessons Learned



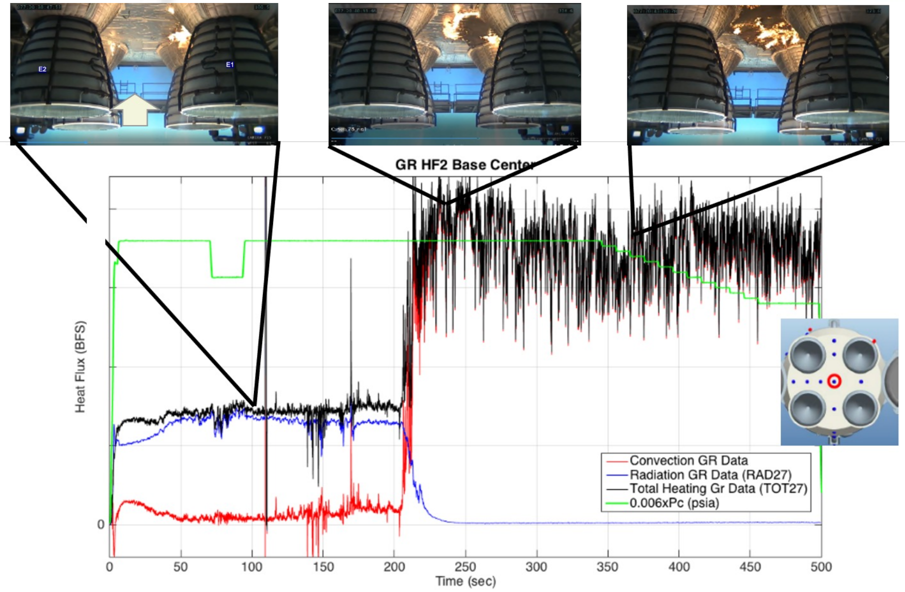


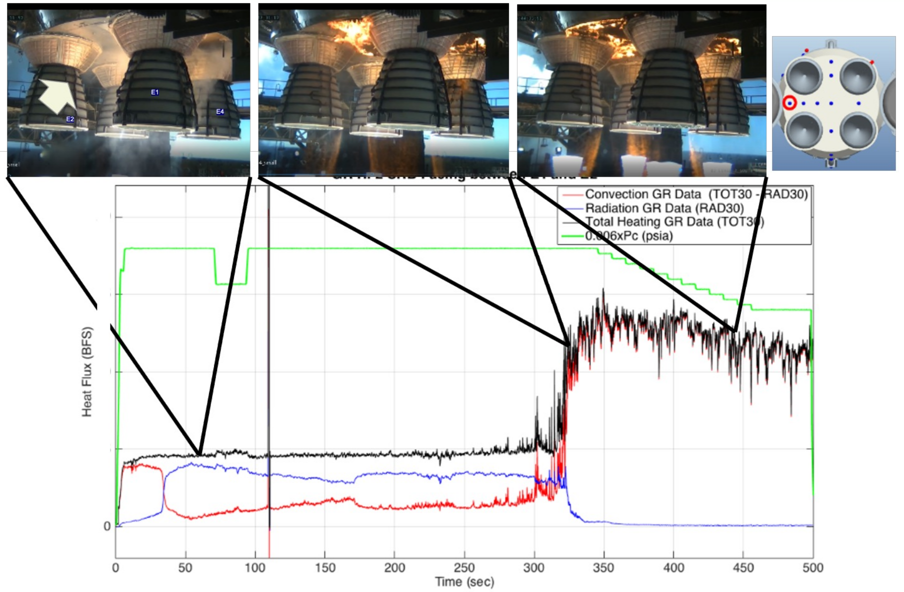


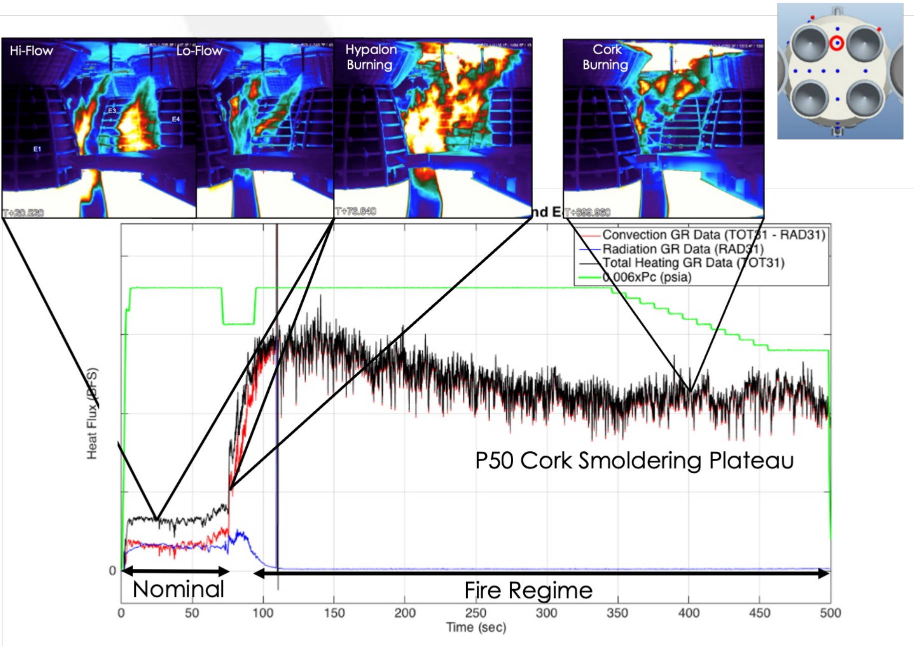


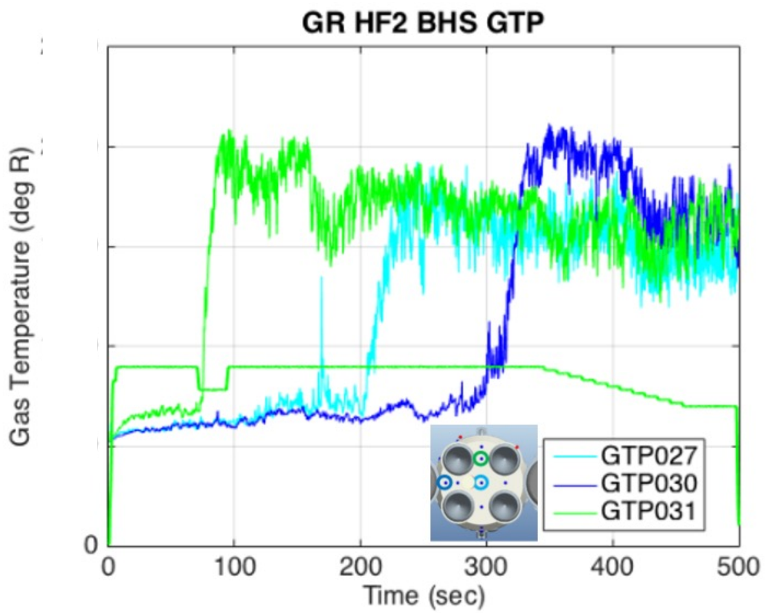


GR HF2 BHS Aerothermal Reconstruction





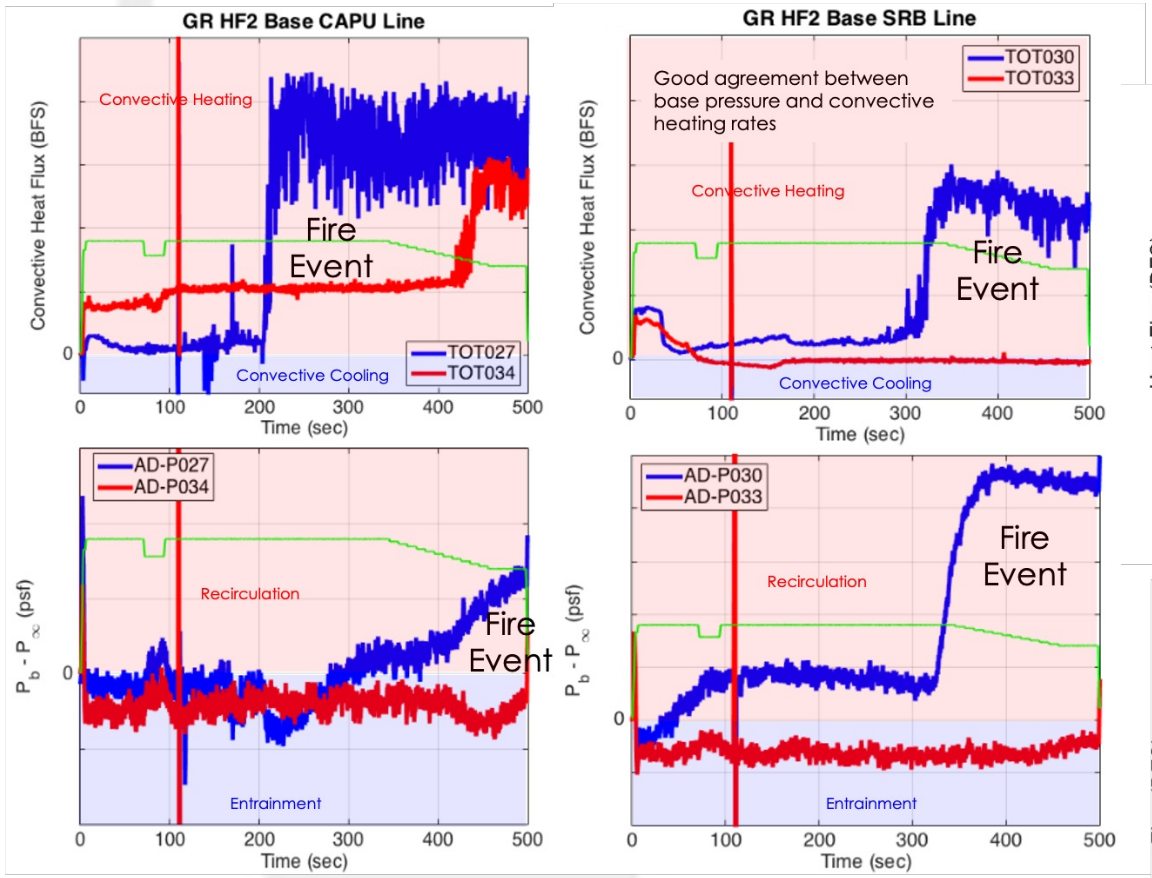




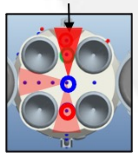
- Upon reaching the cork ignition heat load, large increase in total and convective heating observed
- Cork combustion first occurred near the CAPU ports between E1/E4 due to the exposed TPS and then large-scale flames propagated through most of the heat shield
- Cork combustion supported by high convective heating and high gas temperatures
- Radiation nominal and close to prediction prior to cork ignition, but not measured during cork combustion due to soot covering the radiometers

GR HF2 BHS Aerothermal Reconstruction

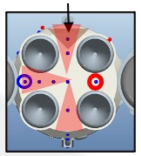
- Large-scale BHS deflagration leads to increases in base pressure and convective heating



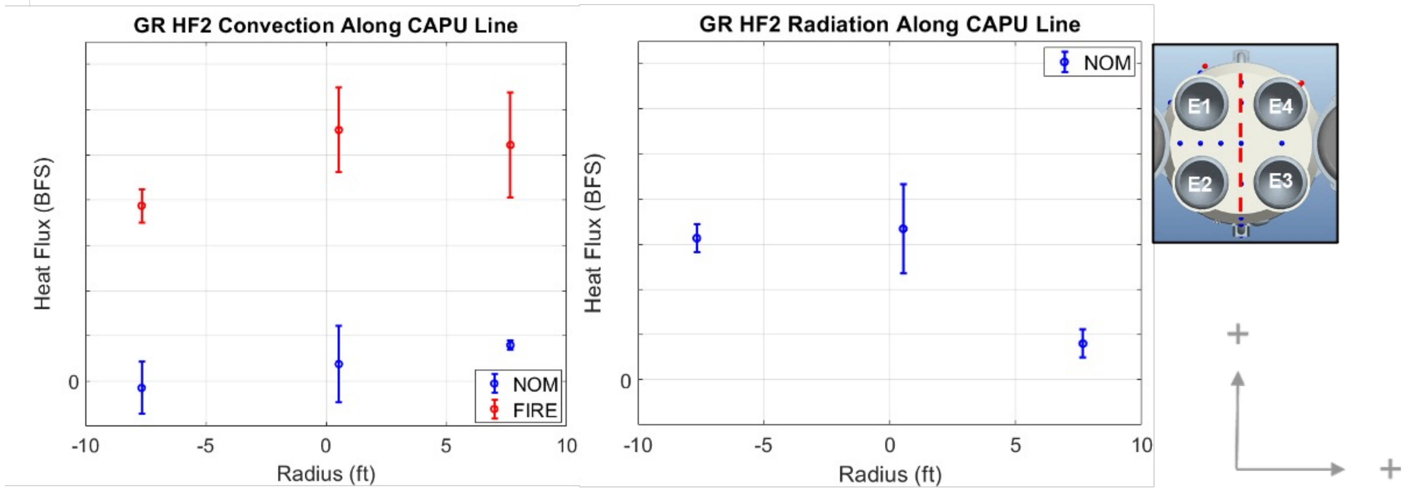
TPS Burning

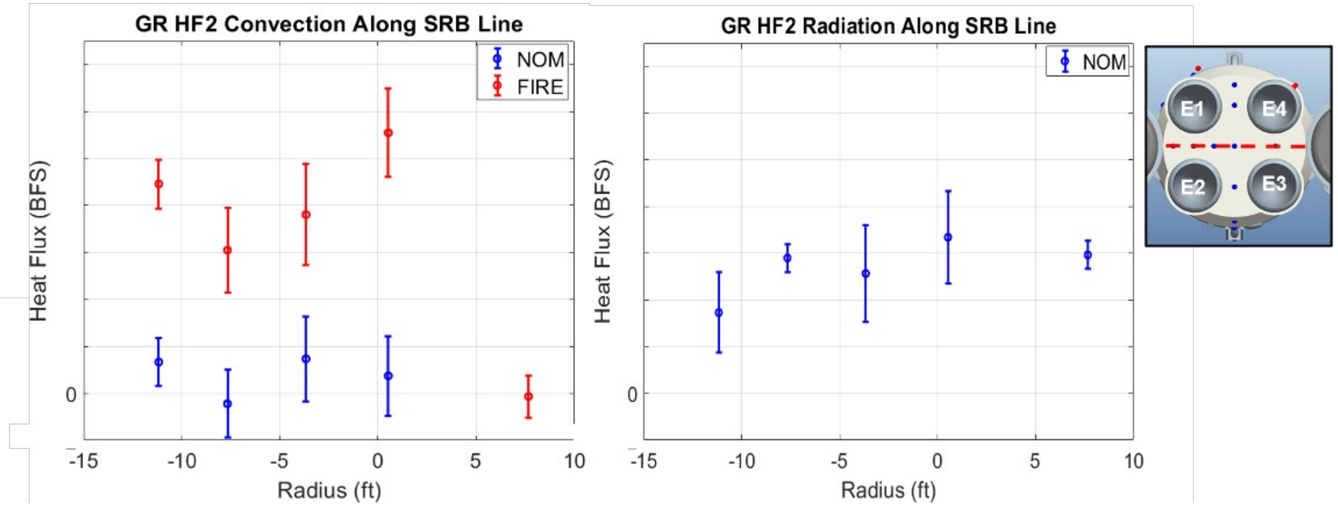


TPS Burning

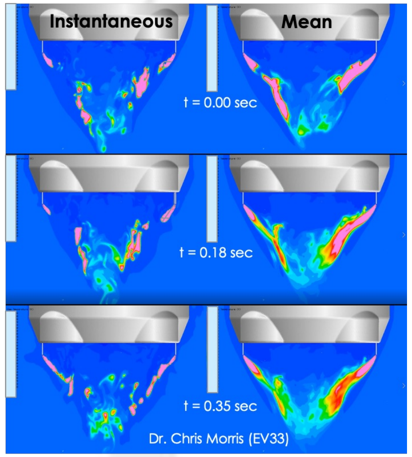


- Large-scale BHS deflagration leads to up to an order of magnitude increase in convective heating over the whole heat shield from nominal (unknown impact to radiation)



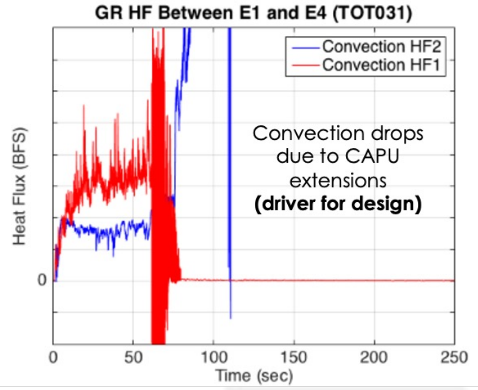


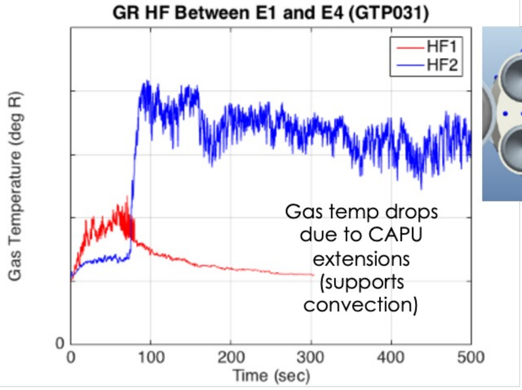
GR HF2 BHS Aerothermal Reconstruction

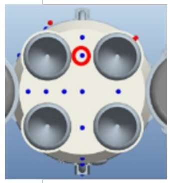


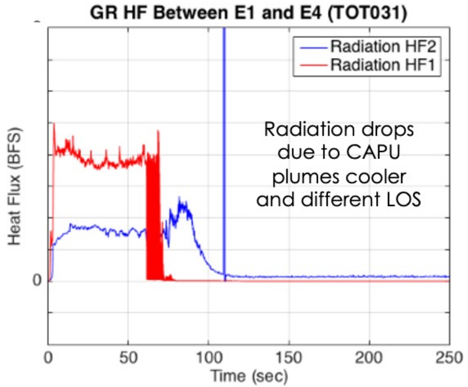
- CAPU extensions have shown to substantially decrease local convection as observed from DFI data, IR imagery data and as predicted by engineering and computational analysis (performed as designed)

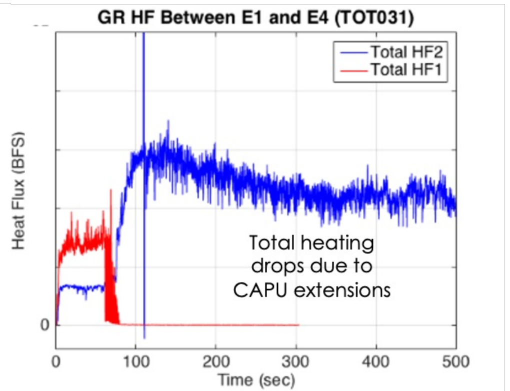
- Radiation environments were still high and led to P50 cork TPS combustion





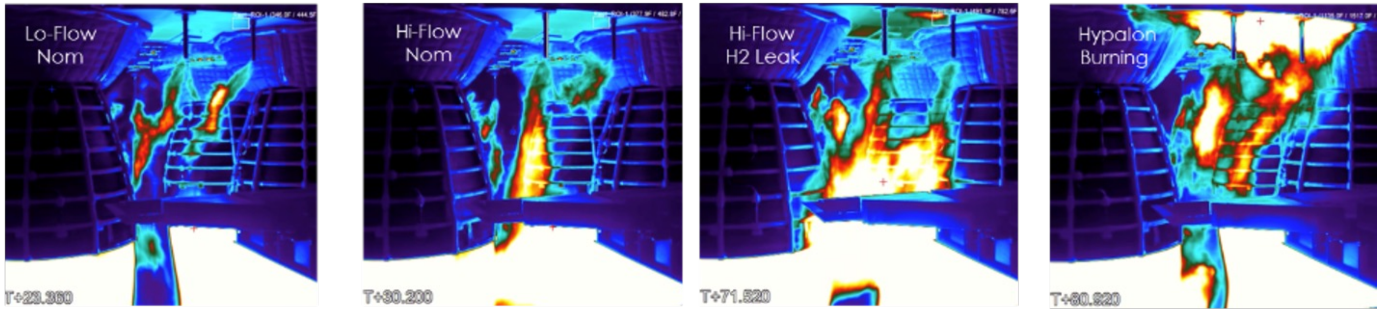




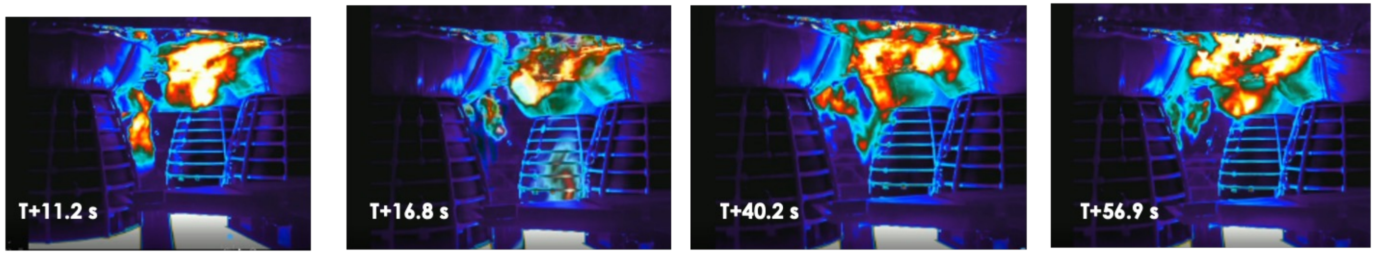


- Based on IR imagery data and DFI convective heating environments, CAPU extensions performed as designed

HF2 (CAPU Extension Design & Other Mitigation Plans)



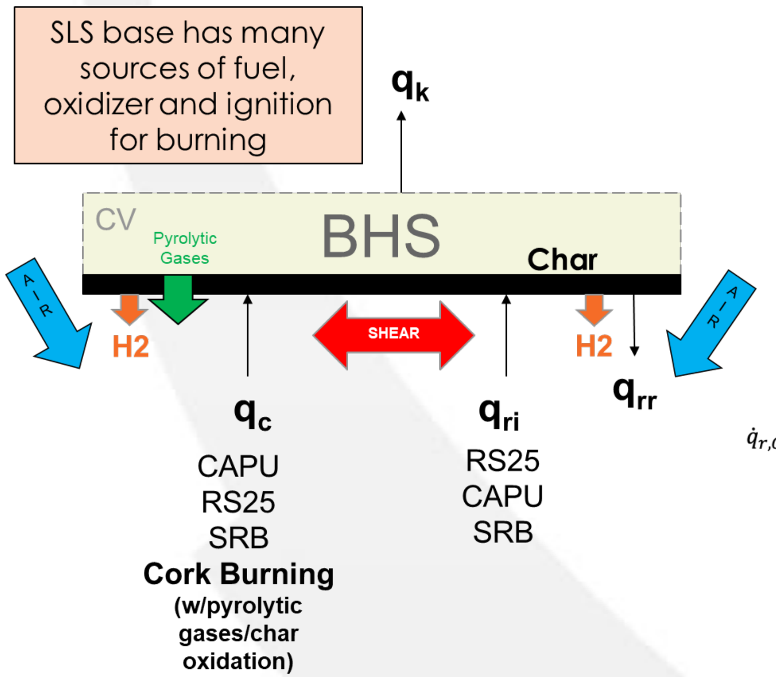
HF1 (Nexolve Tape in Flight Configuration)



All IR/VIS imagery provided by Darrell Gaddy (ER43)

BHS PGR Heating Models

- **BHS has multiple sources of fuel, oxidizer and ignition for burning**
- **Applied methods in deriving equations and constraints for the base heat shield post-Green Run (PGR) heating models**



- All DFI Co-located

HF2 Fire DFI; RS25/CAPU HF2 Fire DFI; HF2 Fire DFI; HF2 Fire DFI

$$h_{c,f,TOT027} = \frac{\dot{q}_{t,f,TOT027} - \bar{\dot{q}}_{r,n,RAD027}}{T_{g,f,GTP027} - T_{w,f,TOT027}} \quad (1)$$

$$\bar{\dot{q}}_{r,n,RAD027} = \frac{1}{n}\sum_{i=0}^{i=n} \dot{q}_{r,RAD027} \quad (2)$$

RS25/CAPU

GR HF2 Fire CW Convective Heat Flux

$$\dot{q}_{c,f,0F,TOT027} = \left. h_{c,f,TOT027}\left(T_{g,f,GTP027} - 459.7\right) \right|_{t=0s}^{t=103s} \quad (3)$$

$$\sigma^2_{c,f,0F} = \left(\frac{\partial q_{c,f,0F}}{\partial q_{t,f,0F}}\right)^2 \sigma^2_{t,f,0F} + \left(\frac{\partial q_{c,f,0F}}{\partial q_{r,f}}\right)^2 \sigma^2_{r,f}$$

HF2 Fire DFI

$$1\sigma_{\dot{q}_{c,f,0F}} = \sqrt{\sigma^2_{t,temp} + \sigma^2_{t,G} + \sigma^2_{r,temp} + \sigma^2_{r,G}} \quad (4,5)$$

$$\bar{\dot{q}}_{c,f,0F,TOT027} + 1\sigma_{\dot{q}_{c,f,0F}} = \frac{1}{n}\sum_{i=0}^{i=n} \dot{q}_{c,f,0F,TOT027} + 1\sigma_{\dot{q}_{c,f,0F}} \quad (6)$$

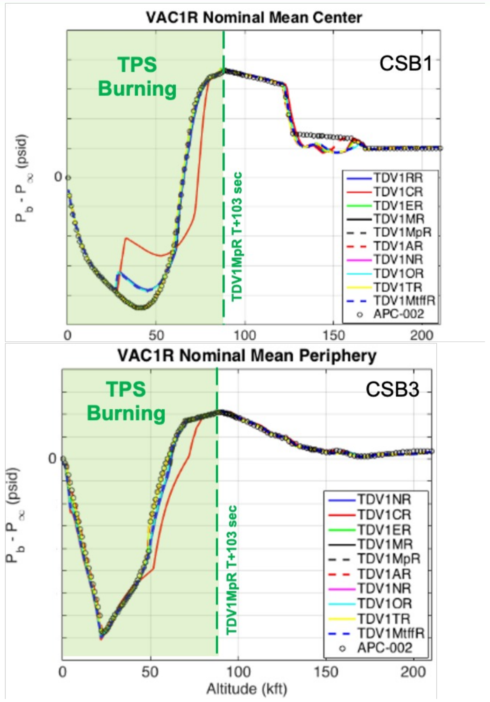
GR HF1 Scaled – Flight RS25/CAPU Radiation; HF1 Nominal DFI; DAC3R GasRad Files; GR HF Predictions

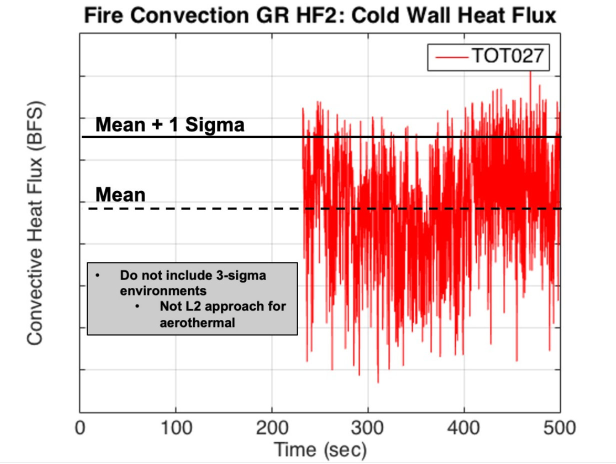
$$\dot{q}_{r,GR\ LL\ FLT,RS25-CAPU,RAD027} = \left. \left[\frac{\bar{\dot{q}}_{r,n,RAD027}}{\bar{\dot{q}}_{r,n,GR\ RS25,GASRAD} + \bar{\dot{q}}_{r,n,GR\ CAPU,GASRAD}}\right] \dot{q}_{r,FLT,RS25/CAPU,RAD027} \right|_{t=0s}^{t=103s} \quad (7)$$

DFI; DFI-Scaled; Prediction

$$\dot{q}_{t,GR\ LL\ FLT,TOT027} = \bar{\dot{q}}_{c,f,0F,TOT027} + 1\sigma_{\dot{q}_{c,f,0F}} + 1.25\dot{q}_{r,GR\ LL\ FLT,RS25-CAPU,RAD027} + 1.25\dot{q}_{r,FLT,SRB,RAD027} \quad (8)$$

Total Heating during TPS burning regime (varies w/altitude); Constant during TPS burning regime (HF2); GR HF1 Scaled – DAC3R Flight RS25/CAPU Radiation (varies w/altitude); DAC3R Flight SRB Radiation (varies w/altitude)

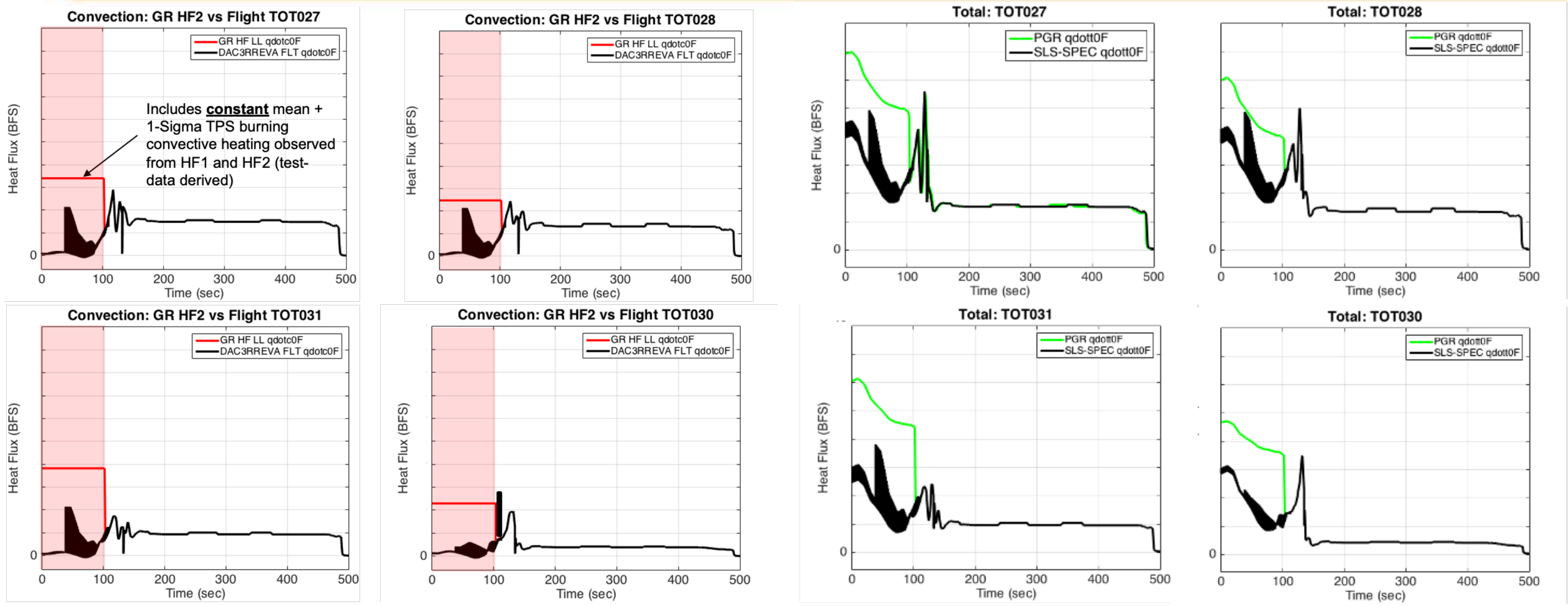




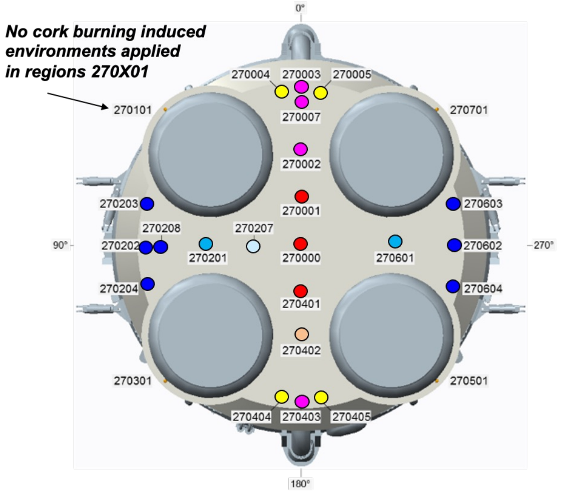
BHS PGR Models

- BHS PGR heating models show a significant increase in both convective heating (red line) and total heating (green line) as compared to the baseline SLS-SPEC models (black line) prior to T+103 s due to P50 cork combustion

- 7 DFI island GR test data reconstruction was incorporated to all the body points in the BHS either through zonal or symmetry approximations

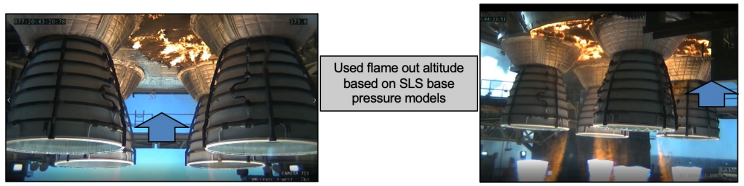


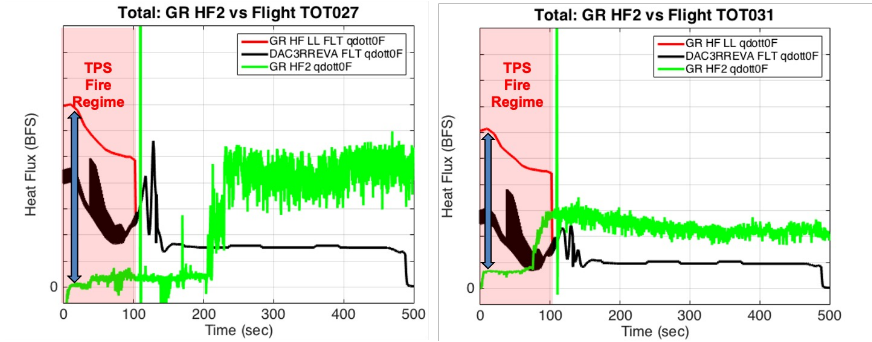
Convective Heating Map



CAPU Line – Hot Zone
SRB Line – Cool Zone

- BP270087 (TOT031)
- BP270077 (TOT027)
- BP270477
- BP270297 (TOT030)
- BP270277 (TOT028)
- BP270287
- Incorporate CAPU Heating

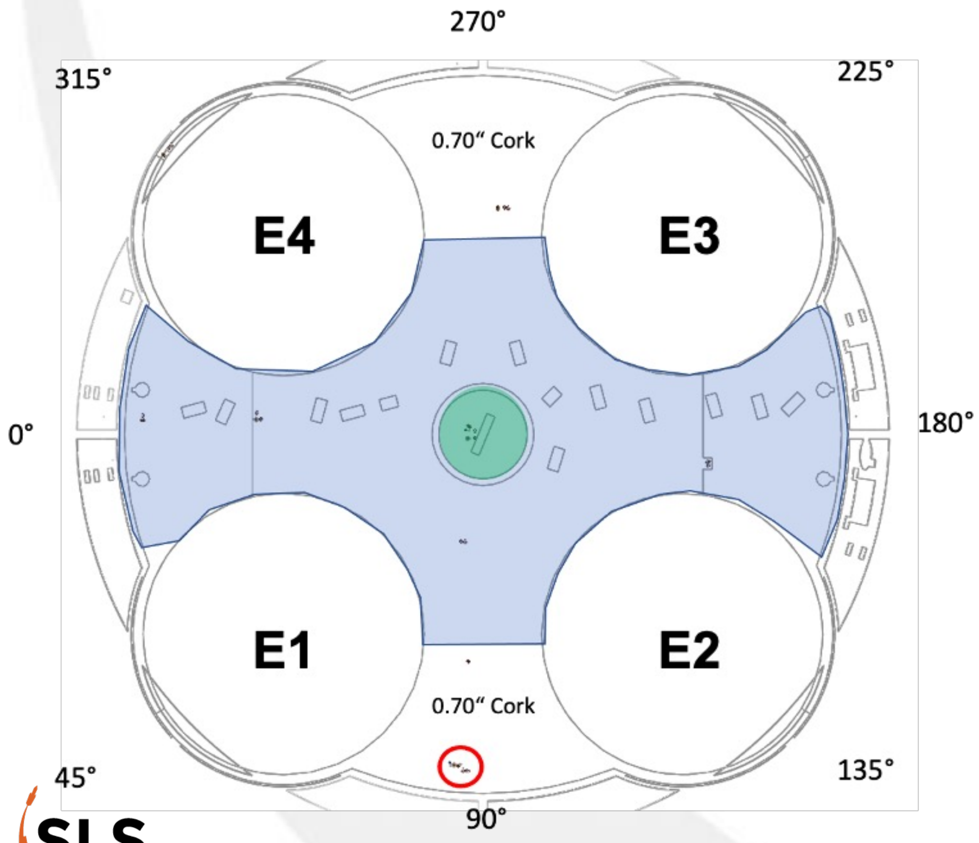




AR01 BHS TPS Flight Redesign

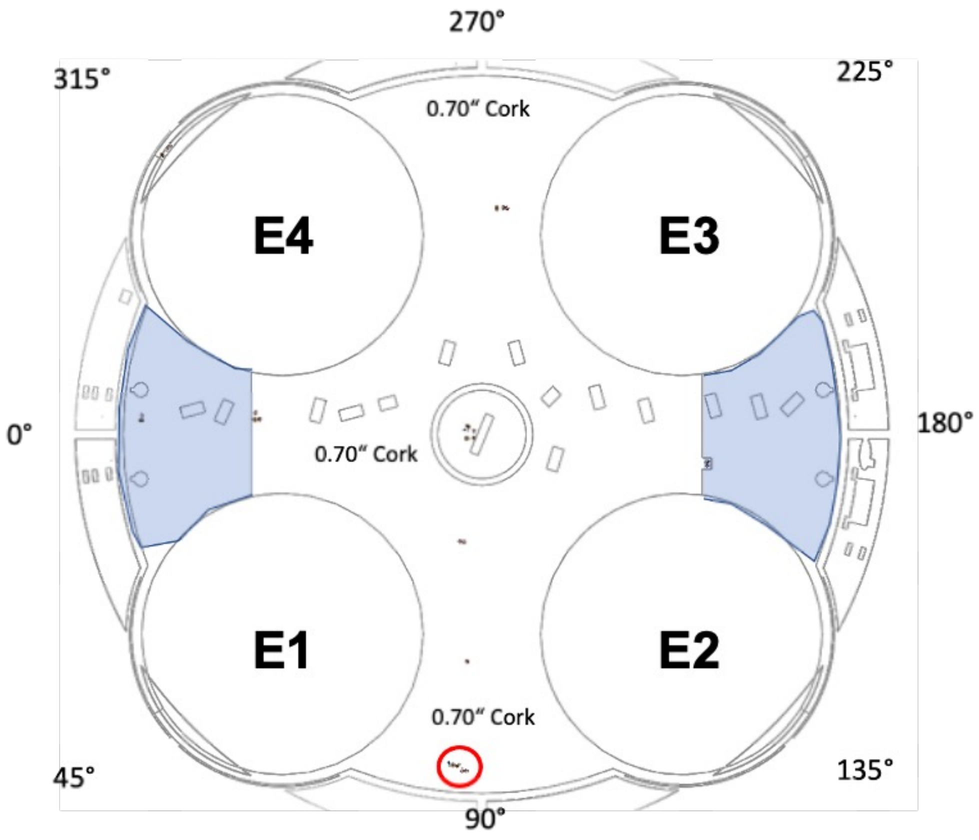
- CS BHS TPS redesign required an increase in TPS thickness anywhere from 140% to 200% from the baseline due to the updated PGR heating models
- Required full removal and reapplication of new TPS prior to launch

CS BHS Configuration– PGR Model



Legend
1.00" Hyp/P50 cork area
1.312" Hyp/P50 cork area
0.700" Hyp/P50 cork area

CS BHS Configuration– SPEC Model



Conclusions

- Completed base heat shield environment reconstruction and TPS observations for both GR HF1 and HF2
- Quantified critical Hypalon/P50 cork TPS combustion environments from GR HF1 and HF2 that led to the development of PGR models
- Completed mitigation approach analysis that both protected the Stage from heat shield burn through and showed optimal performance for GR HF2
- Updated PGR base heating models led to significantly higher heating than the baseline SPEC models which would result in a heat shield burn-through if no TPS redesign occurred
- BHS TPS redesign occurred about 1 year prior to launch