



SPACE LAUNCH SYSTEM

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12/05/2023

Base Aerothermodynamics Post-Flight Reconstruction for Artemis I

Manish Mehta, Bud Smith
and Brandon Mobley

*Aerosciences Branch
NASA Marshall Space Flight Center*

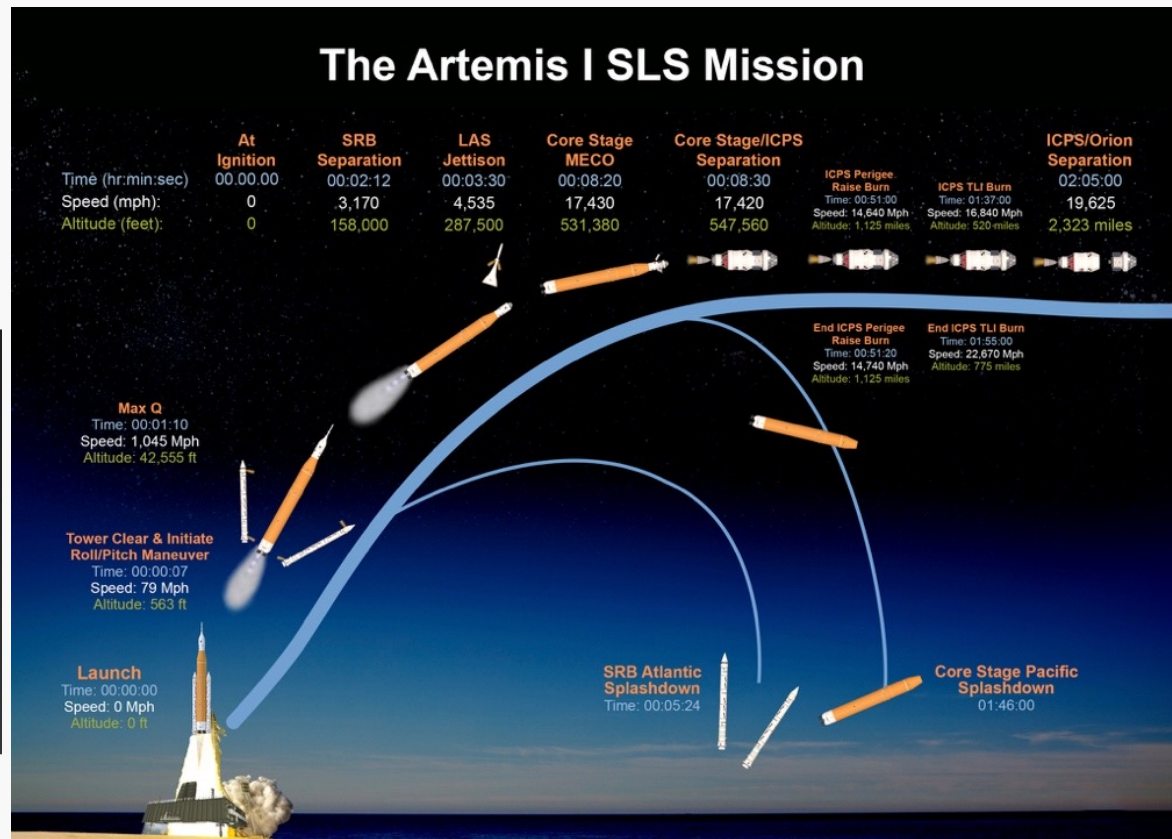
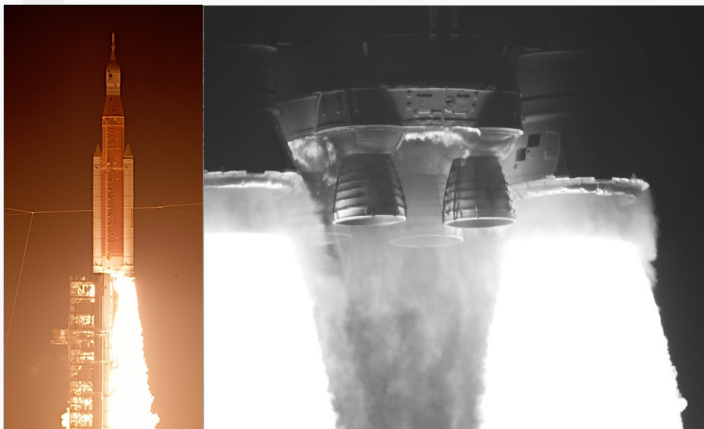


- **AR01 Flight Summary**
 - Mission Profile
 - Flight Reconstruction Approach
- **AR01 Core Stage (CS) Base Aerothermodynamics**
- **AR01 Solid Rocket Booster (SRB) Base Aerothermodynamics**
- **Conclusions**



AR01 Mission Profile

- No thermal anomalies observed due to plume-induced base environments
- All base environment model anchoring objectives satisfied





- **Compare calorimeter and radiometer Development Flight Instrumentation (DFI) data to pre-flight Best Estimated Trajectory (BET) models**
 - Determined plume induced radiative and total heating rates ($\dot{q}_{\text{Rad}}$, $\dot{q}_{\text{Tot}}$) utilizing serialized calibration for each sensor location (15 rads, 35+ cal/s along CS and SRB base regions)
 - Utilized collocated, symmetry DFI sensors to back-out the convective heat rate ($\dot{q}_{\text{Conv}}$) and heat transfer coefficient at respective DFI locations
 - Used T-0 as specified by Post-Flight BET and synced up all DFI using linear interpolation with BET
 - No correction applied on Gas Temperature Probes (GTPs)
 - Artemis I reconstructed environments were compared against post flight models that used BET inputs (e.g. motor conditions)
 - Base aerothermal environment reconstruction supported SLS Thermal and Stages

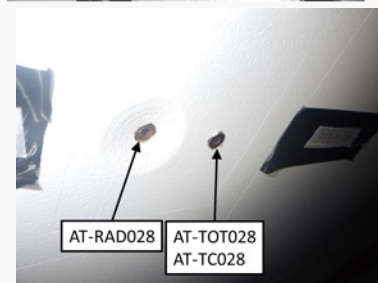
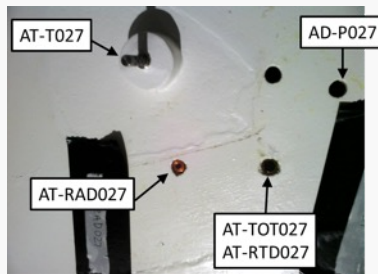
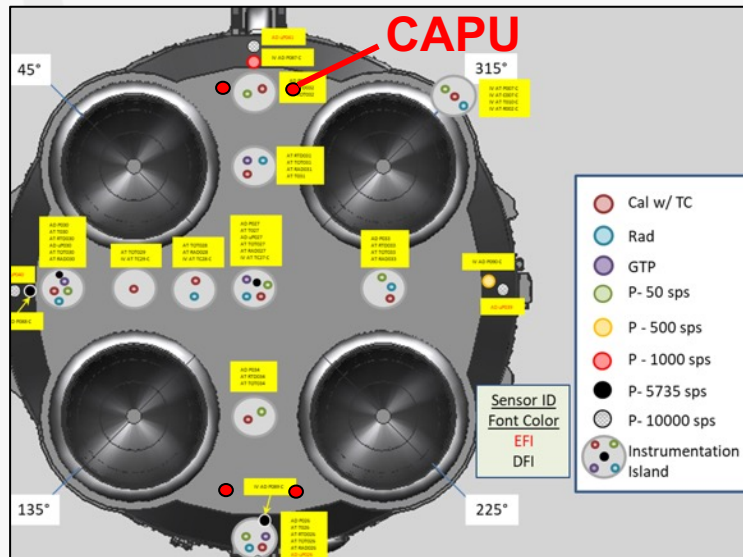
Summary

- **Core Stage**
 - **Radiation:** Plume radiative heating environments were bounding
 - **Convection:** Heat rate exceedances were observed at the base heat shield and RS-25 engine blankets, but total heat load bounding at the base heat shield
- **Booster**
 - **Radiation:** Plume radiative heating environments were bounding
 - **Convection:** Heat rate and total heat load exceedances were observed at the inboard aft skirt



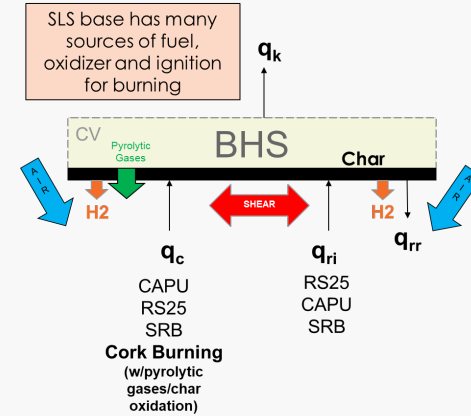
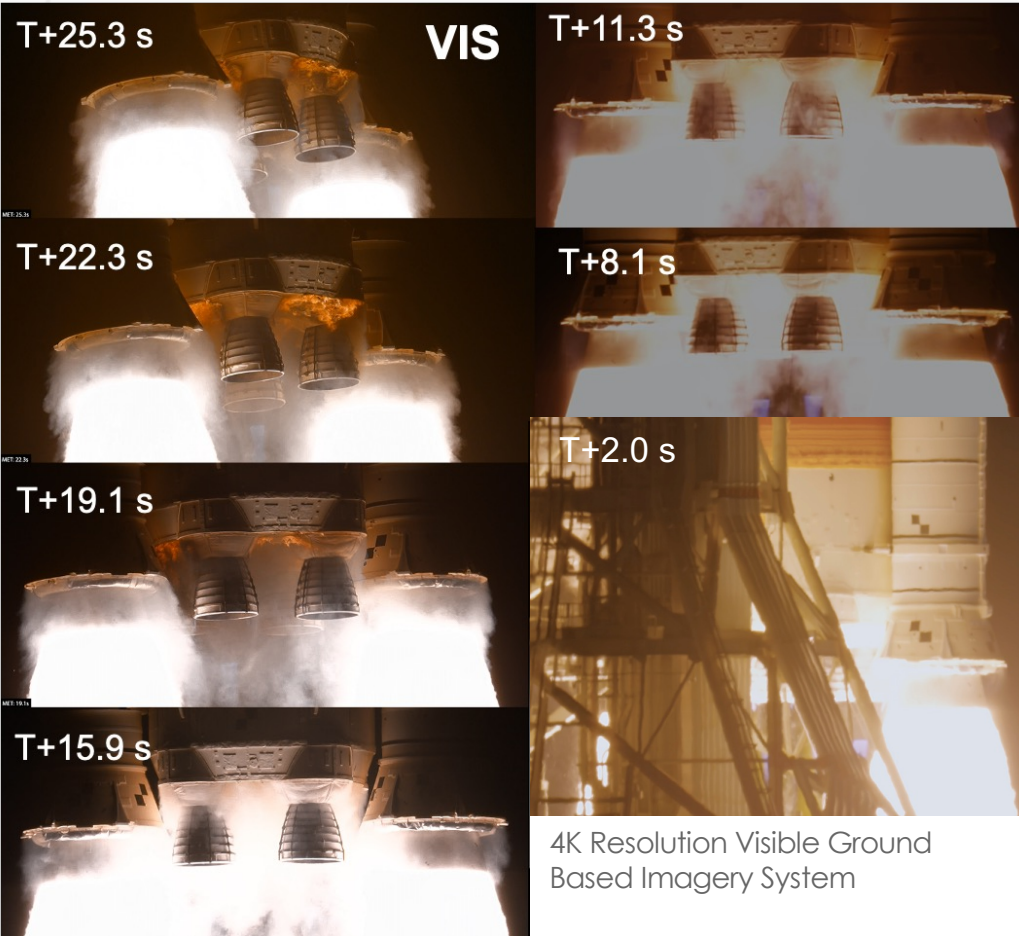
CS Base Aerothermal: Development Flight Instrumentation

- All AR01 CS base aerothermal DFI were nominal
- A total of 55 CS base aerothermal sensors (static pressure, calorimeters/w TC, radiometers and gas temperature probes) were used in base heating flight reconstruction of 16 DFI locations
- Enabled adequate assessment of the convective heat transfer coefficient, cold wall heating and base flow physics



Sensor	Type	Component	Sample Rate (Hz)	Status	Notes
AT-RAD026	Radiometer	Boat Tail	50	Good	PN: 22121-20
AT-RAD027	Radiometer	Base Heat Shield	50	Good	PN: 22121-16-1.425
AT-RAD028	Radiometer	Base Heat Shield	50	Good	PN: 22121-16
AT-RAD030	Radiometer	Base Heat Shield	50	Good	PN: 22121-16
AT-RAD031	Radiometer	Base Heat Shield	50	Good	PN: 22121-16
AT-RAD033	Radiometer	Base Heat Shield	50	Good	PN: 22121-16
AT-RTD026	Thermocouple	Boat Tail	50	Good	
AT-RTD030	Thermocouple	Base Heat Shield	50	Good	
AT-RTD031	Thermocouple	Base Heat Shield	50	Good	
AT-RTD032	Thermocouple	Base Heat Shield	50	Good	
AT-RTD033	Thermocouple	Base Heat Shield	50	Good	
AT-RTD034	Thermocouple	Base Heat Shield	50	Good	
AT-TC027	Thermocouple	Base Heat Shield	50	Good	
AT-TC028	Thermocouple	Base Heat Shield	50	Good	
AT-TC029	Thermocouple	Base Heat Shield	50	Good	
AT-T023	GTP	Aft Engine Compartment	50	Good	
AT-T024	GTP	Aft Engine Compartment	50	Good	
AT-T026	GTP	Boat Tail	50	Good	
AT-T027	GTP	Base Heat Shield	50	Good	
AT-T030	GTP	Base Heat Shield	50	Good	
AT-T031	GTP	Base Heat Shield	50	Good	
AT-TOT026	Calorimeter	Boat Tail	50	Good	PN: 22121-05KS
AT-TOT027	Calorimeter	Base Heat Shield	50	Good	PN: 22121-07KS-1.425
AT-TOT028	Calorimeter	Base Heat Shield	50	Good	PN: 20850E-07KS-1.15
AT-TOT029	Calorimeter	Base Heat Shield	50	Good	PN: 22121-07KS
AT-TOT030	Calorimeter	Base Heat Shield	50	Good	PN: 22121-07KS
AT-TOT031	Calorimeter	Base Heat Shield	50	Good	PN: 20850E-07KS-1.15
AT-TOT032	Calorimeter	Base Heat Shield	50	Good	PN: 20850E-07KS-1.15
AT-TOT033	Calorimeter	Base Heat Shield	50	Good	PN: 22121-07KS
AT-TOT034	Calorimeter	Base Heat Shield	50	Good	PN: 22121-07KS
IV-AT-C001-E	Calorimeter	E4	50	Good	PN: 22150-02
IV-AT-C002-E	Calorimeter	E4	50	Good	PN: 22150-02
IV-AT-C003-E	Calorimeter	E4	50	Good	PN: 22150-01
IV-AT-C004-E	Calorimeter	E4	50	Good	PN: 22150-01
IV-AT-C005-E	Calorimeter	E4	50	Good	PN: 22150-02
IV-AT-C006-C	Calorimeter	Engine Fairing	50	Good	PN: 22121-05KS
IV-AT-C007-C	Calorimeter	Engine Fairing	50	Good	PN: 22121-05KS
IV-AT-R001-C	Radiometer	Engine Fairing	50	Good	PN: 22121-16
IV-AT-R001-E	Radiometer	E4	50	Good	PN: 22151-01; FOV 79 deg
IV-AT-R002-C	Radiometer	Engine Fairing	50	Good	PN: 22121-16
IV-AT-R002-E	Radiometer	E4	50	Good	PN: 22151-01; FOV 79 deg
IV-AT-R003-E	Radiometer	E4	50	Good	PN: 22151-01; FOV 79 deg
IV-AT-T001-E	Thermocouple	E4	50	Good	
IV-AT-T002-E	Thermocouple	E4	50	Good	
IV-AT-T005-E	Thermocouple	E4	50	Good	
IV-AT-T006-C	Thermocouple	Engine Fairing	50	Good	
IV-AT-T006-E	Thermocouple	E4	50	Good	
IV-AT-T007-C	Thermocouple	Engine Fairing	50	Good	
IV-AT-T007-E	Thermocouple	E4	50	Good	
IV-AT-T008-E	Thermocouple	E4	50	Good	
IV-AT-T010-C	Thermocouple	Engine Fairing	50	Good	

CS Base Aerothermal: AR01 SLS Ascent Base Imagery Data



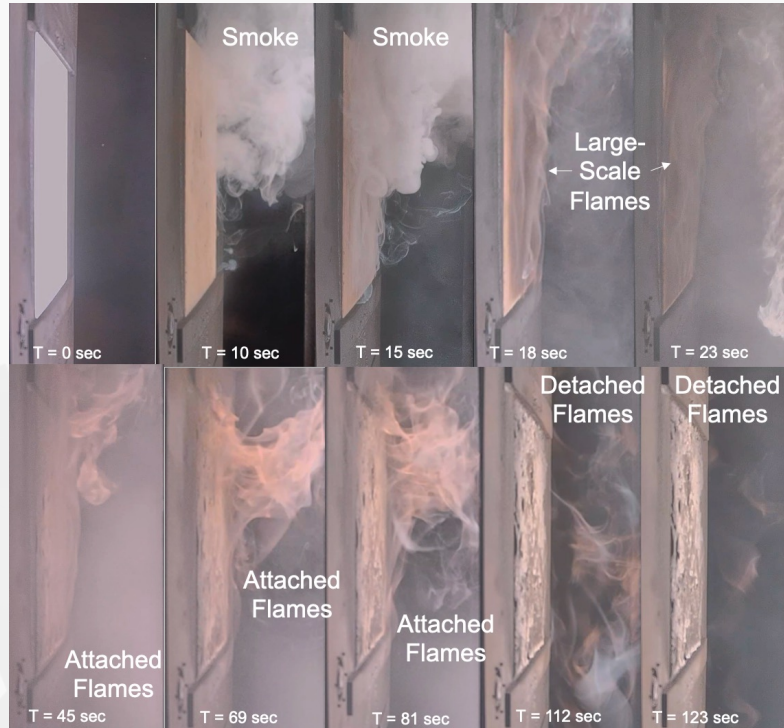
Led to the development of Post-Green Run (PGR) environments

- Strong evidence of TPS outgassing, cork combustion products and smoke entrainment
- Validation data that flight CS BHS cork combustion characteristics occurred **as predicted**
- Observe cork ablation products (dark soot) being entrained downstream of the engines
- BHS TPS extensively charred at T+40 s
- No flames propagated to boat tail/ES barrel and no charring observed there at T+40 s

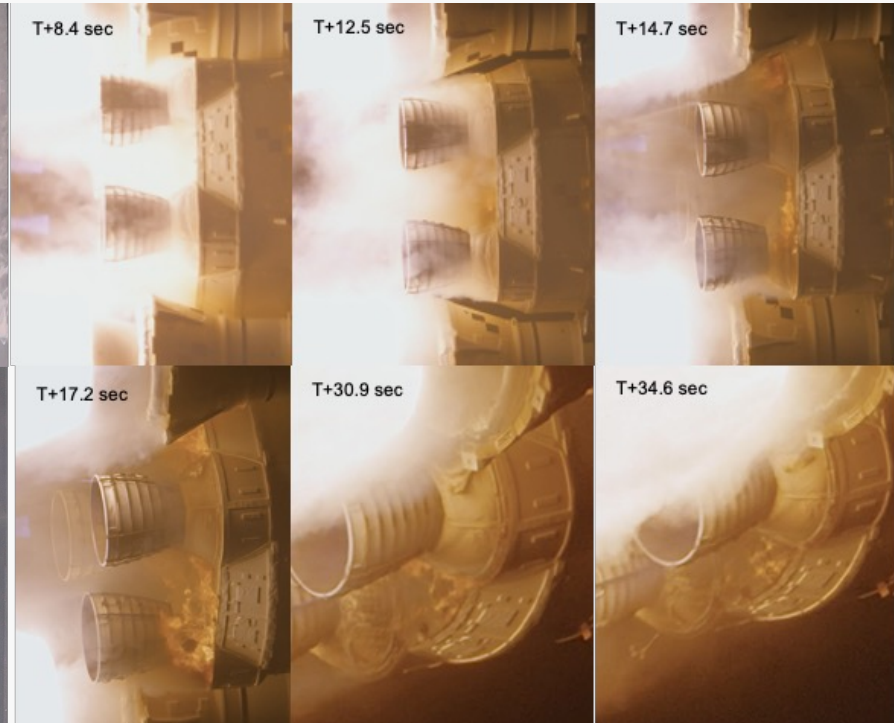


CS Base Aerothermal: Thermal Vac Chamber (TVC) vs. AR01 Imagery

TVC Hypalon/P50 Cork Data



AR01 Flight Data



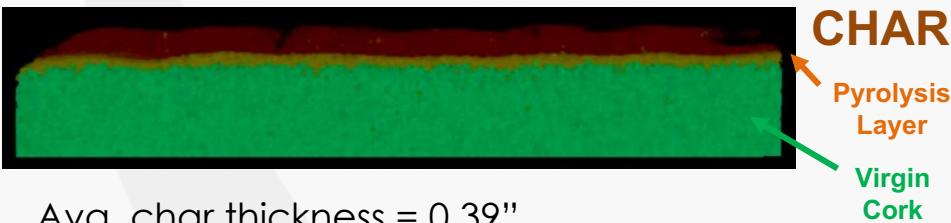
AR01 flight radiation much larger than ground test

CS Base Aerothermal: Post-Green Run (PGR) Environments

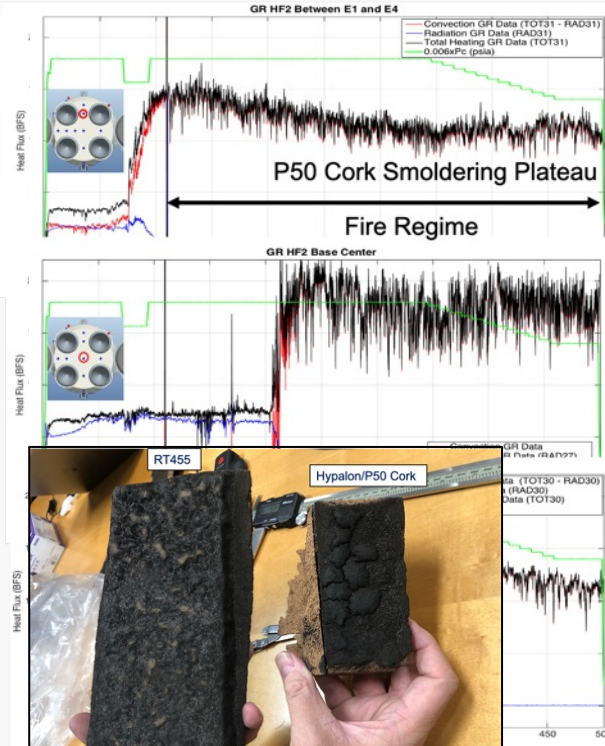
- SLS Aerothermodynamics Team conducted reconstruction of GR HF1 and GR HF2, investigated the GR base heating anomalies, determine mitigation plans and developed new flight environments prior to AR01 launch
- Leveraged GR data and pre-flight models to develop new base environments that accounted for cork TPS combustion during ascent

GR HF2

- GR HF2 BHS Sample
- X-Ray CT Reconstruction done by R. Beshears/EM21



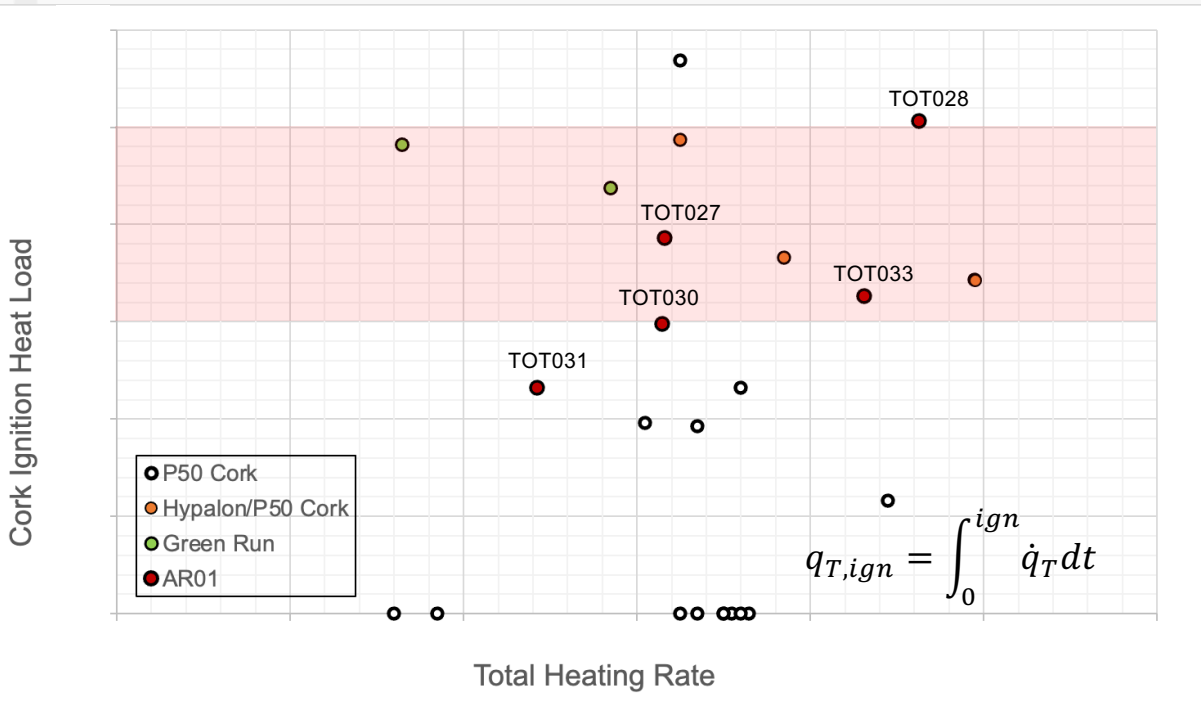
Avg. char thickness = 0.39"
 Avg. pyrolysis layer = 0.06"
 45% of TPS thickness burn effected during GR HF2





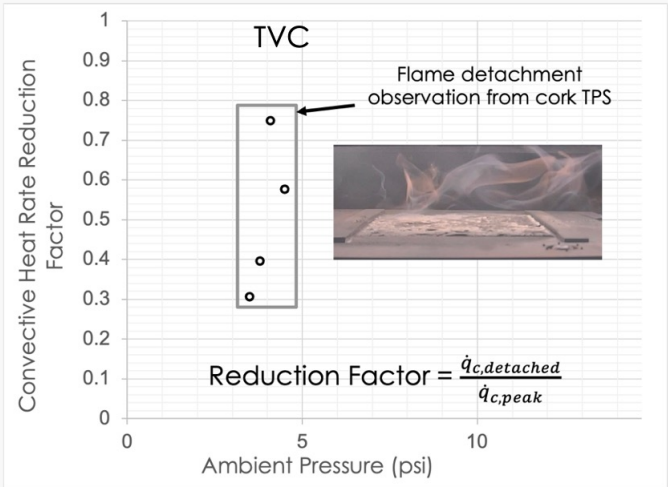
CS Base Aerothermal: AR01 Cork Ignition Heat Load & Flame-Out

- Based on the below cork ignition heat load vs. nominal total heating rate map, AR01 data shows good agreement with TVC and GR HF data for room temperature initial TPS surface temperature.



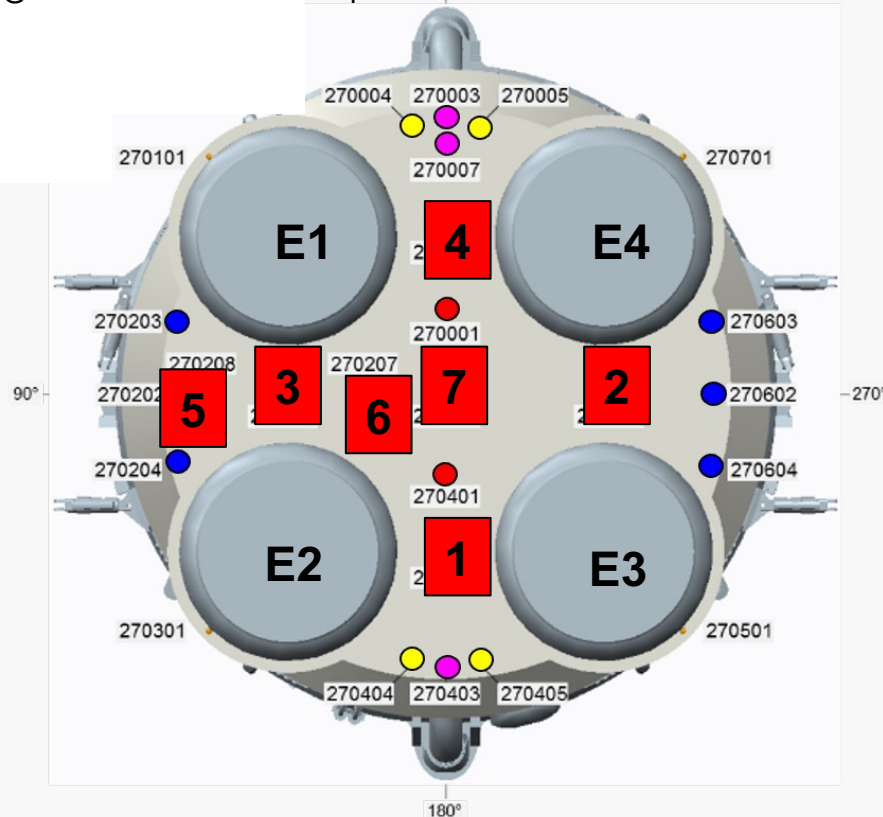
Detached Flame Onset		
Pressure (psi)	Altitude (ft)	DFI
2.95	40,283	TOT028
2.97	40,184	TOT031
5.64	25,618	TOT030
2.49	43,764	TOT032
3.1	39,300	TOT033
3.43	37,830	Avg

AR01 Flight Data



CS Base Aerothermal: AR01 Cork Combustion Ignition Onset

- Heat shield deflagration duration lasted anywhere from 60 s to 70 s depending on region
- Entire heat shield engulfed in flames as predicted



Onset Time

TOT033: T+13.8 s

TOT034: T+12.8 s

TOT031: T+17.3 s

TOT027: T+24.2 s

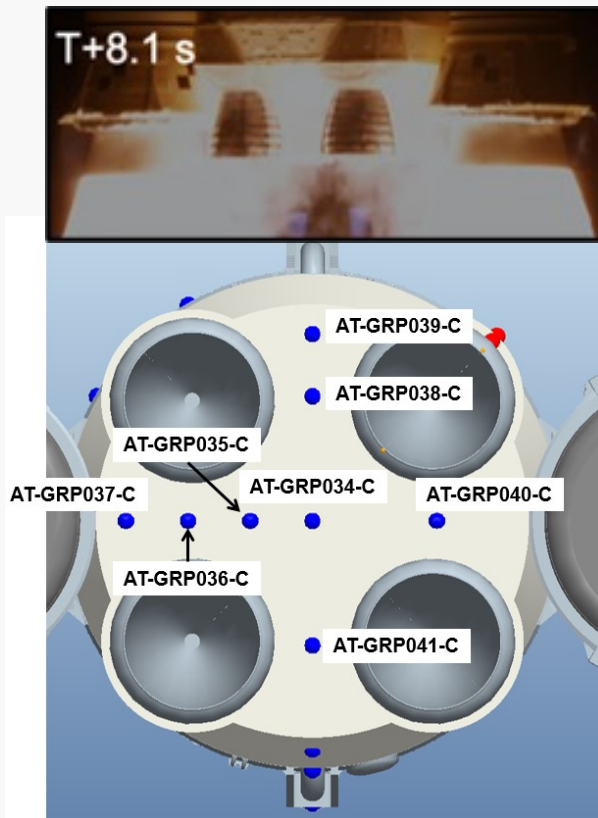
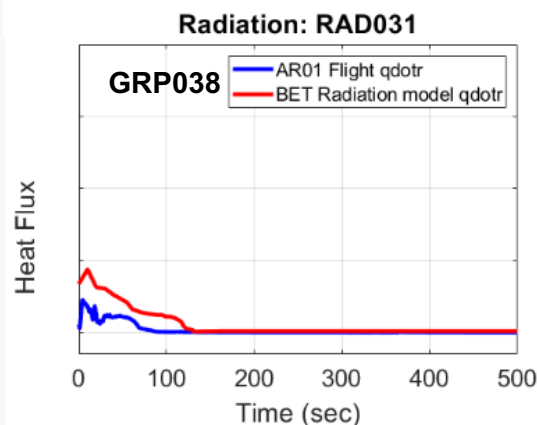
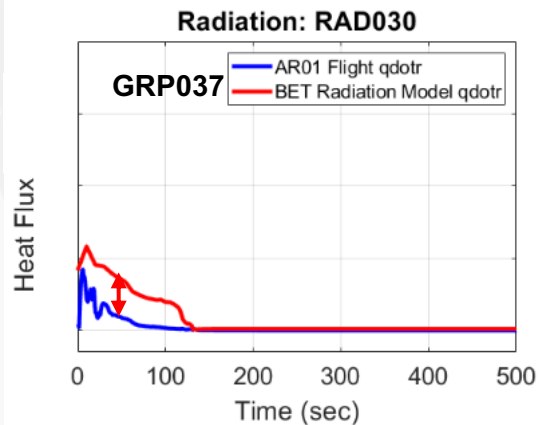
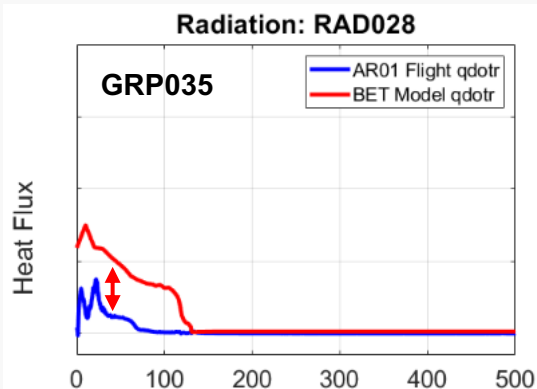
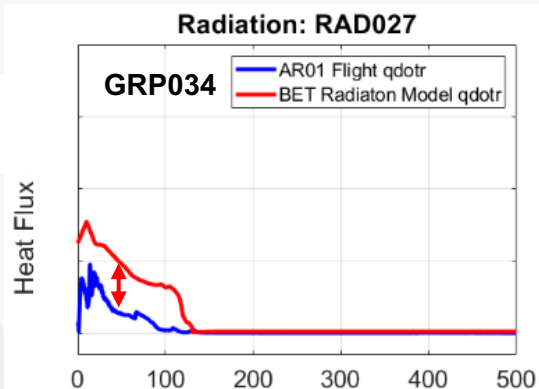
TOT028: T+21.0 s

TOT030: T+17.8 s

TOT029: T+14.1 s

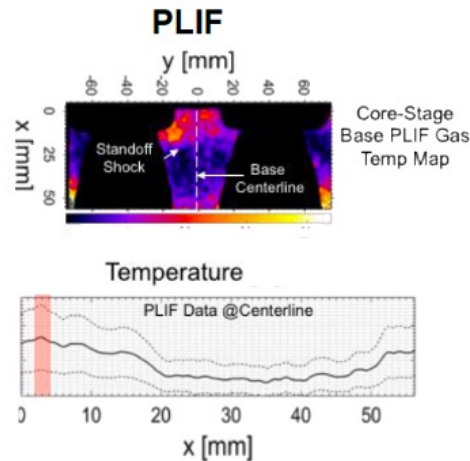
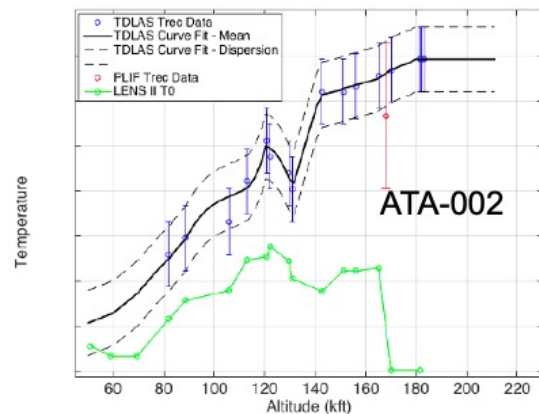
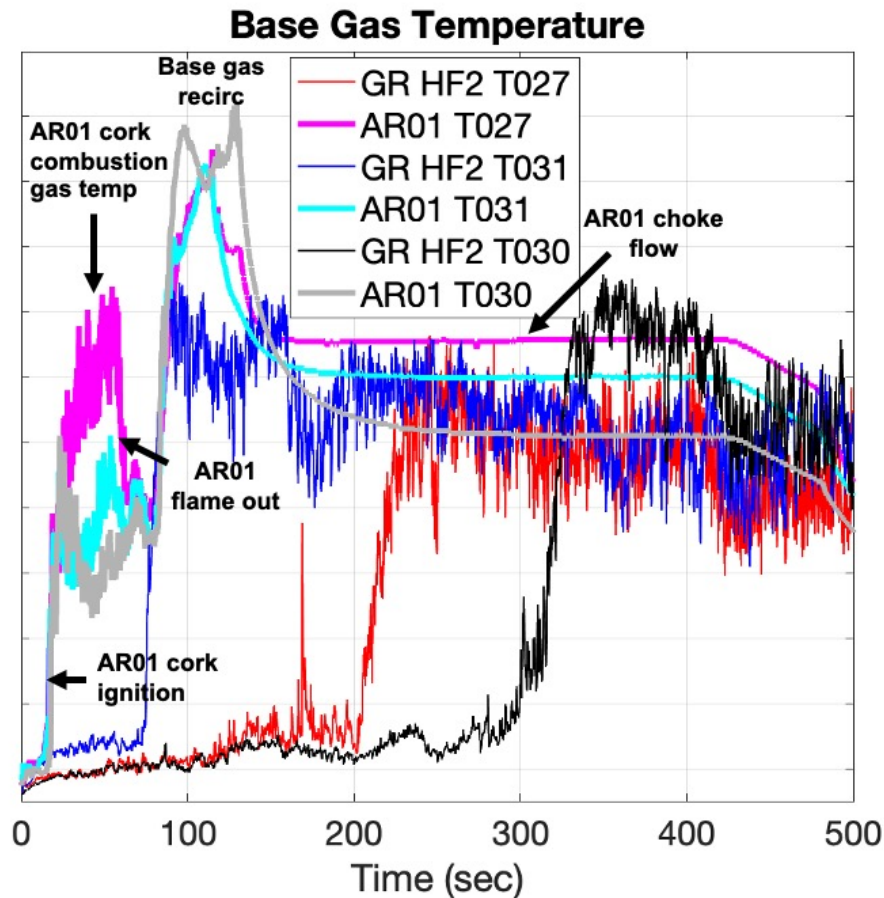
CS Base Aerothermal: Plume Radiation

- Consequences of BHS pyrolysis products lead to attenuation of plume radiation, as observed from radiation comparisons (fac.~2, over-predicted)



CS Base Aerothermal: Gas Temperature

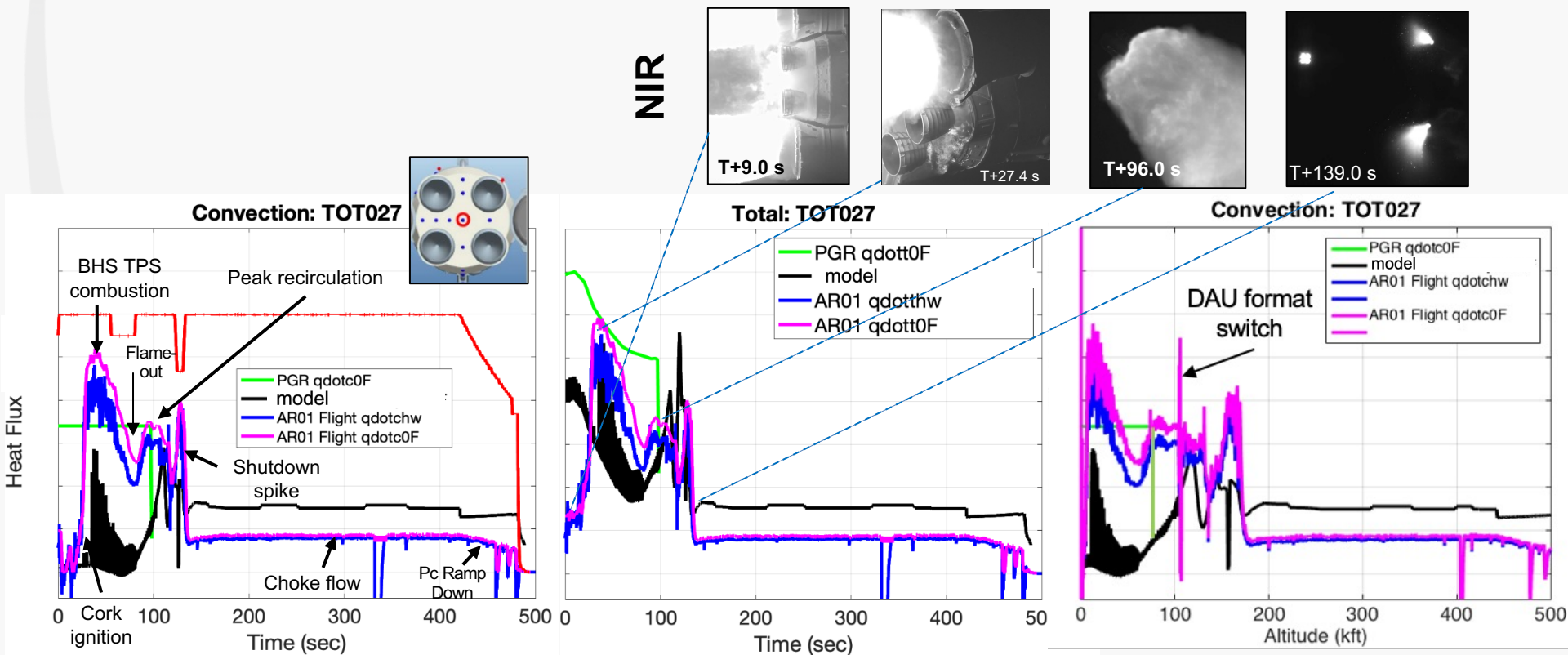
Gas Temperature



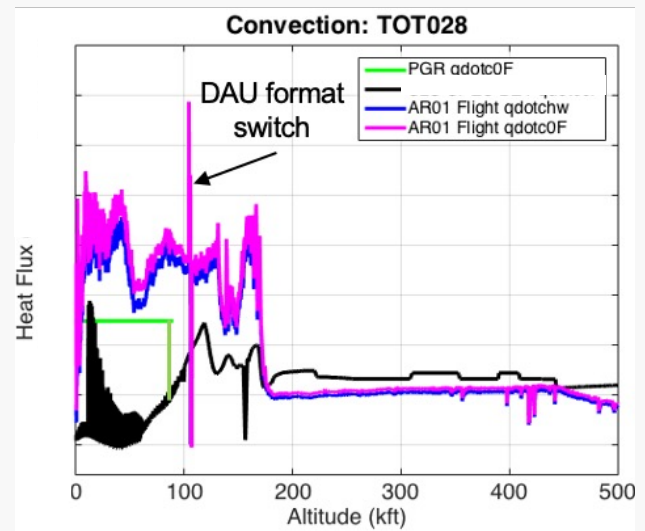
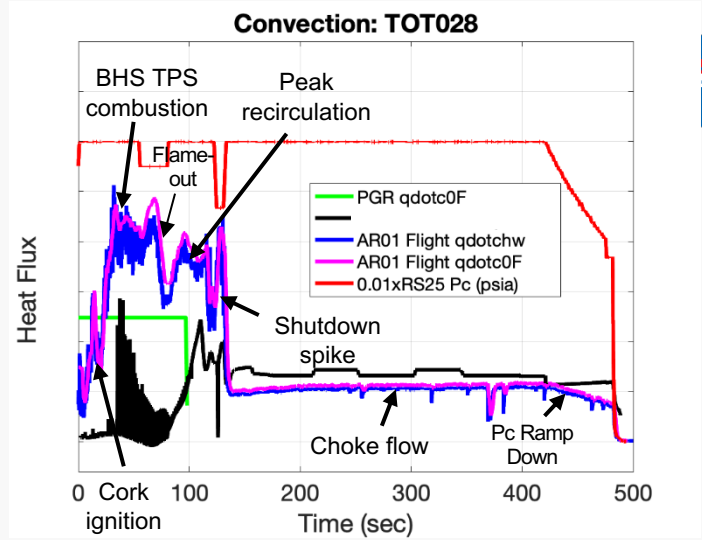
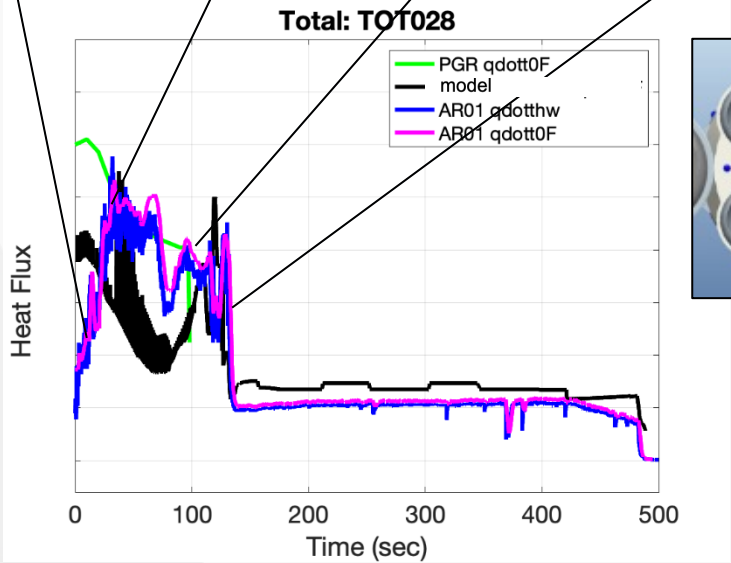
- Good agreement of cork combustion gas temperature between AR01 flight and GR HF2
- Good agreement with model of peak recirculation onset and temperature magnitude and trends below T+150 s
- Poor agreement at core-only flight regime

CS Base Aerothermal: Convection (TOT027)

- Prior to plume induced recirculation from RS-25 plume-plume interactions, $T < 75s$, PGR models showed better agreement with flight reconstruction than pre-GR models
- Once RS-25 plume recirculation began, $T > 75s$, good agreement was observed between BET models & reconstruction

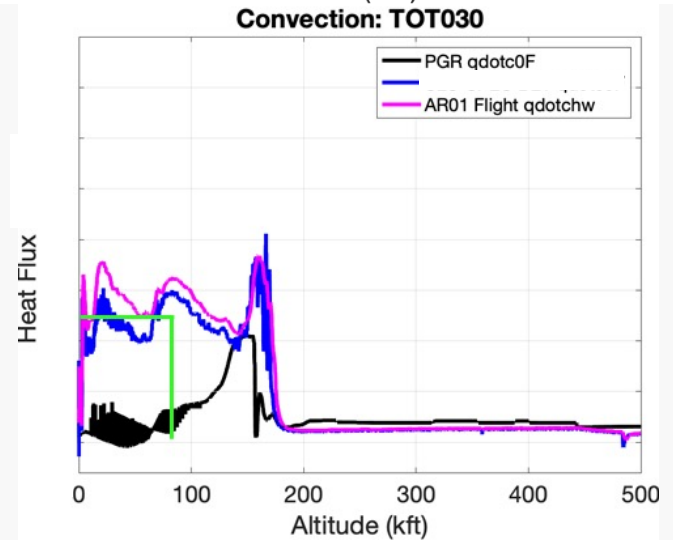
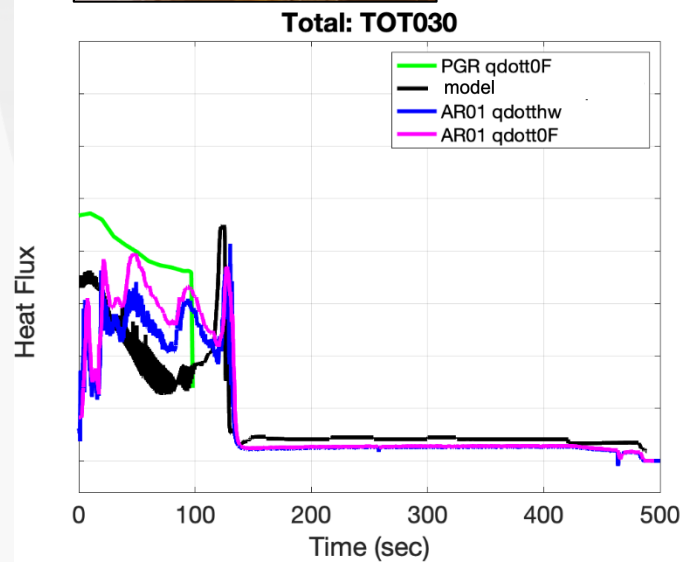
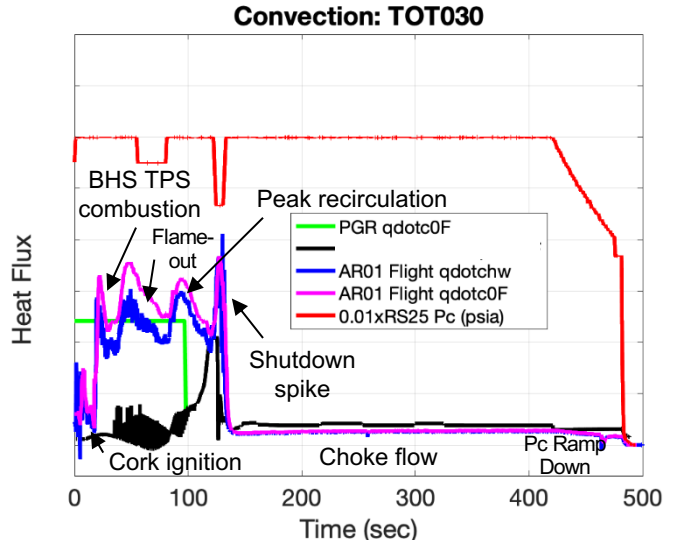
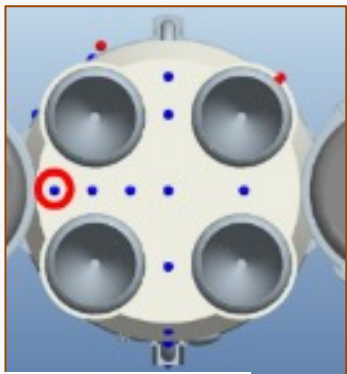
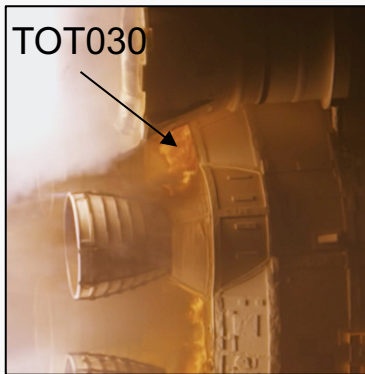


CS Base Aerothermal: Convection (TOT028)





CS Base Aerothermal: Convection (TOT030)



CS Base Aerothermal: Convection Model Validation

$$Nu_D = \frac{hD}{k} = C Re_D^m Pr^n$$

Reynolds
exponent
↓

$$Nu_D = \frac{hD}{k} = C \left(\frac{PUD}{RT\mu} \right)^m Pr^n$$

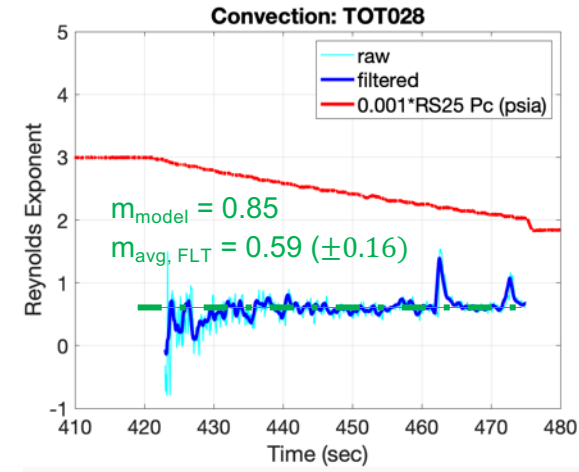
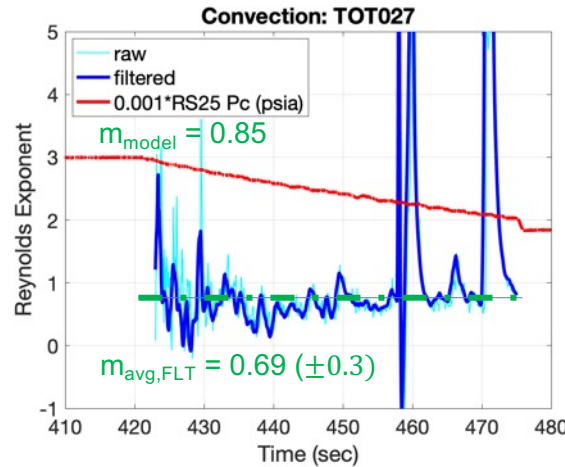
$$P_b \propto P_c^1$$

$$\frac{Nu_{D,0}}{Nu_D(t)} = \frac{\frac{h_0 D}{k}}{\frac{h(t) D}{k}} = \frac{C \left(\frac{P_{c,0} UD}{RT\mu} \right)^m Pr^n}{C \left(\frac{P_c(t) UD}{RT\mu} \right)^m Pr^n} = \left(\frac{P_{c,0}}{P_c(t)} \right)^m$$

$$m_{Re} = \frac{\ln \left(\frac{h_0}{h(t)} \right)}{\ln \left(\frac{P_{c,0}}{P_c(t)} \right)}$$

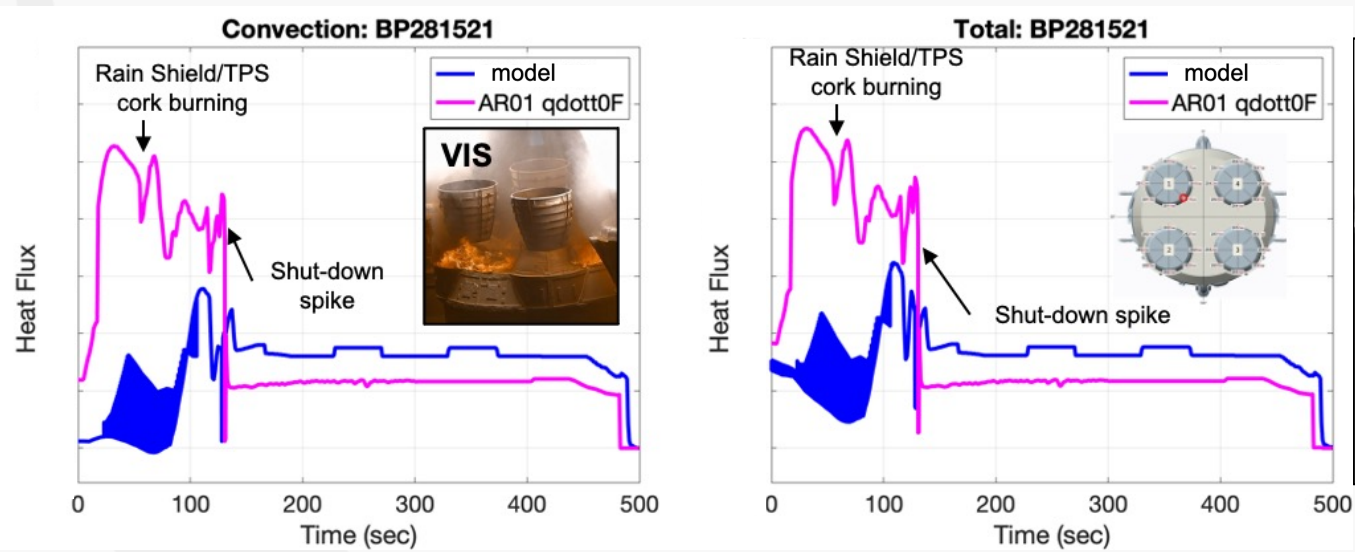
- CS choke base flow is between laminar and turbulent regimes
- DMM is conservative

- All at flight scales, so no differences in the following parameters:
 - D, k, Pr, μ, U, R, T
 - $h_0 = f(P_{c,0})$
- Only parameter varying is h and Pc as a function of time during **RS25 ramp-down phase**
- Analysis needs to consider P_b for future assessments

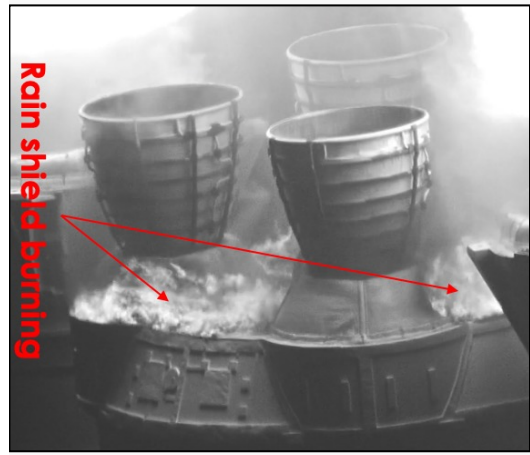


CS Base Aerothermal: Convection (Inboard Engine Blanket)

- **No DFI data available on the RS-25 nozzle close-out blankets (EMHS), reconstructed environments are shown:**
 - Observed cork and rain shield burning augmented convective and total heating rates ($T < 75s$) and leading to exceedances when compared to pre-flight BET models
 - Plume recirculation heating higher than prediction as observed for the base heat shield
 - Good agreement between the pre-flight BET model and AR01 flight-derived environment model during core-only flight



NIR





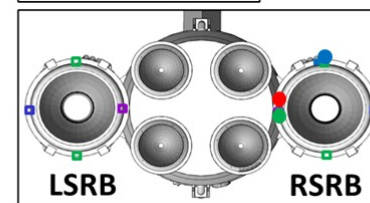
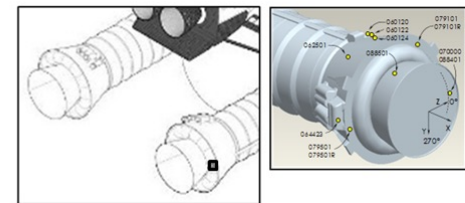
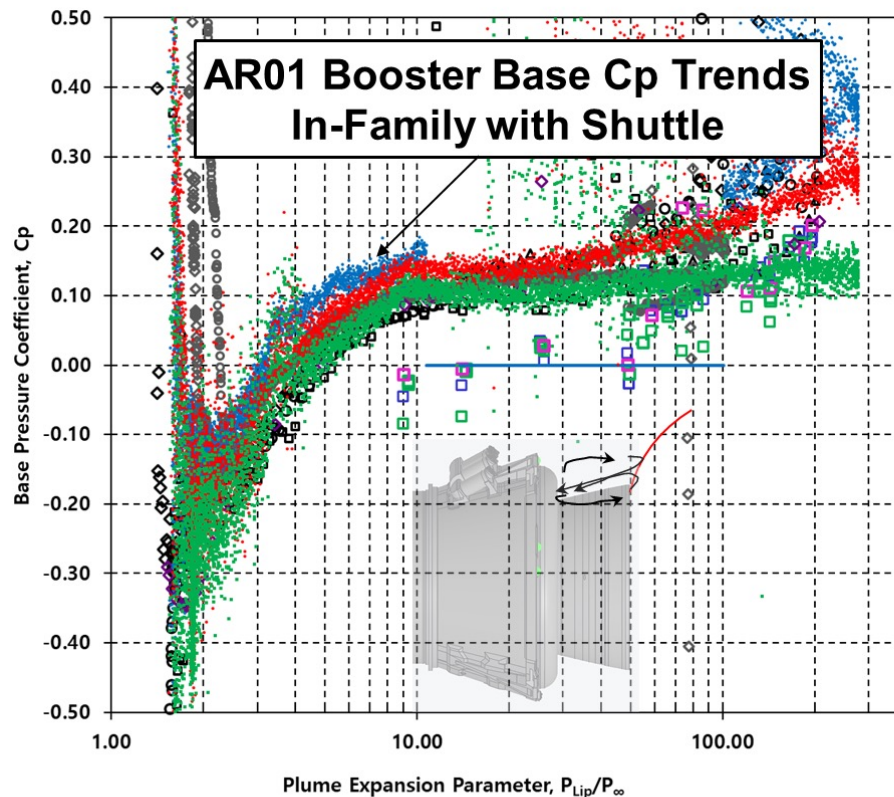
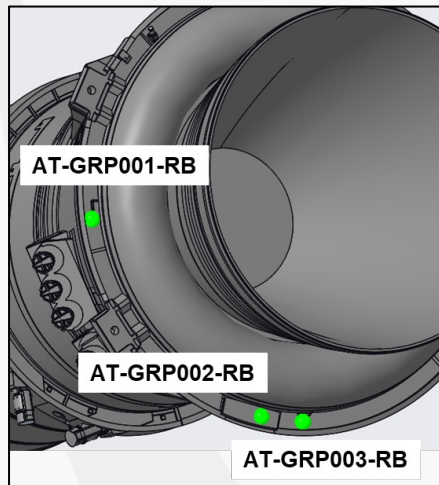
SRB Base Aerothermal: Environments

Transition from Aspirating to Recirculating Flow

- Booster observed similar base pressure trends as Shuttle RSRM, WRT to plume expansion

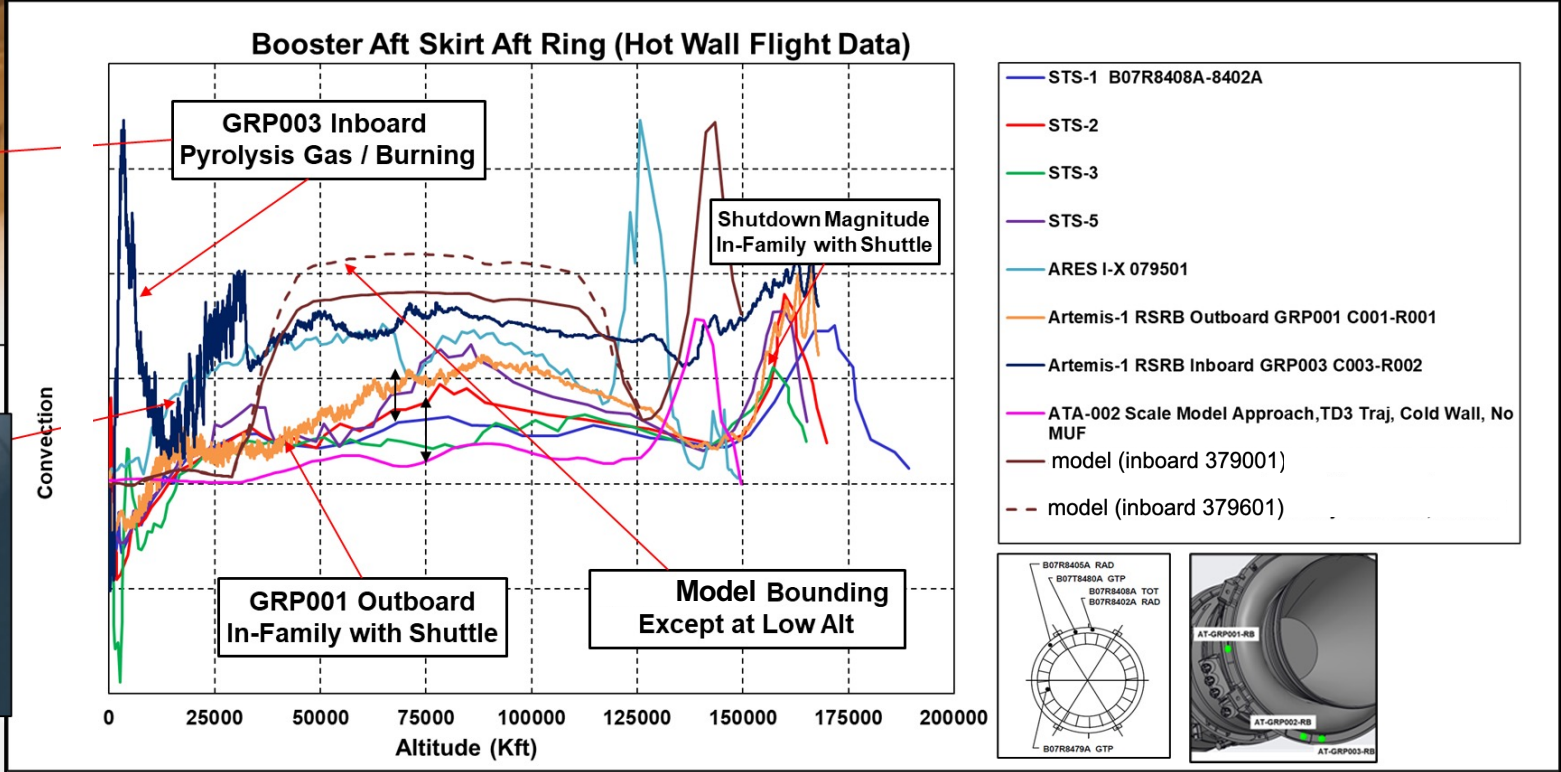
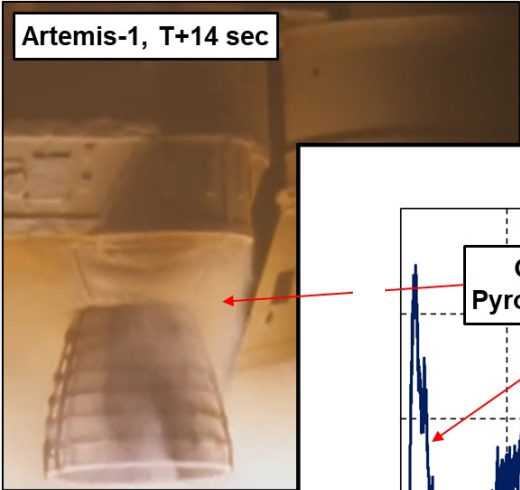
parameter, P_{Lip}/P_{inf}

- AR01, $P_{Lip}/P_{inf} \approx 3.5 - 4$
- 044-02 Used, $P_{Lip}/P_{inf} = 4$
- STS RSRM, $P_{Lip}/P_{inf} \approx 5-10$
- AR01 Trans. Alt. $\approx 25-30\text{Kft}$



- STS-2 RSRM Zone 27 B07P8352A Theta=77.6
- ▲ STS-3 RSRM Zone 27 B07P8352A Theta=77.6
- ◇ STS-5 RSRM Zone 27 B07P8352A Theta=77.6
- STS-6 RSRM Zone 27 B07P8352A Theta=77.6
- Ares I-X Aft Skirt 079101R
- ◇ Ares I-X Aft Skirt 079501
- ATA-002 LH SRB Outboard P30
- ATA-002 RH SRB Outboard P25
- ATA-002 LH SRB Top/Bottom P27,28
- ATA-002 RH SRB Top/Bottom P23,24
- ATA-002 LH SRB Inboard P29
- ATA-002 RH SRB Inboard P26
- ◇ Pre-AR001 SLS Semi-Empirical
- AR001 RSRB P001
- AR001 RSRB P002
- AR001 RSRB P003

SRB Base Aerothermal: Convection



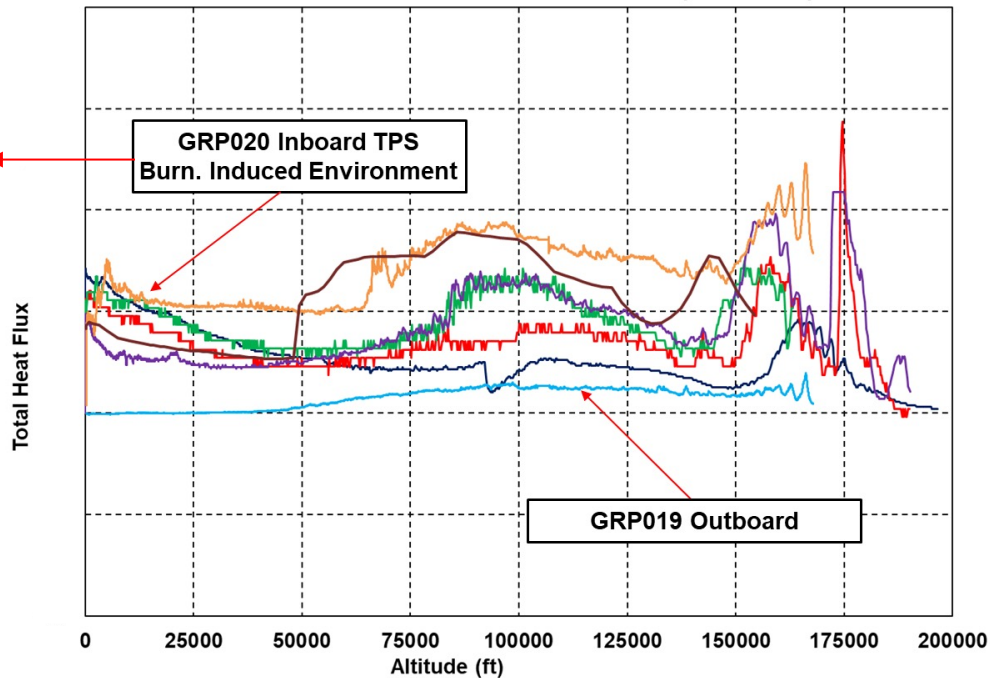
SRB Base Aerothermal: Convection



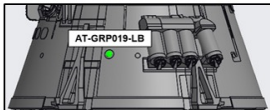
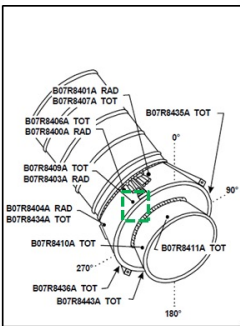
AR01, T+17 sec

Gauge GRP020

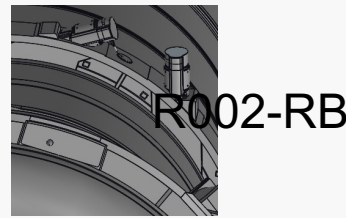
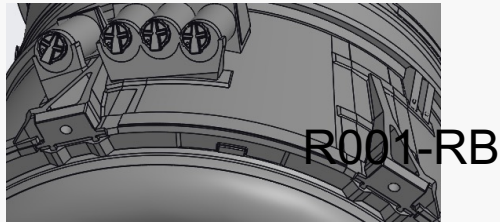
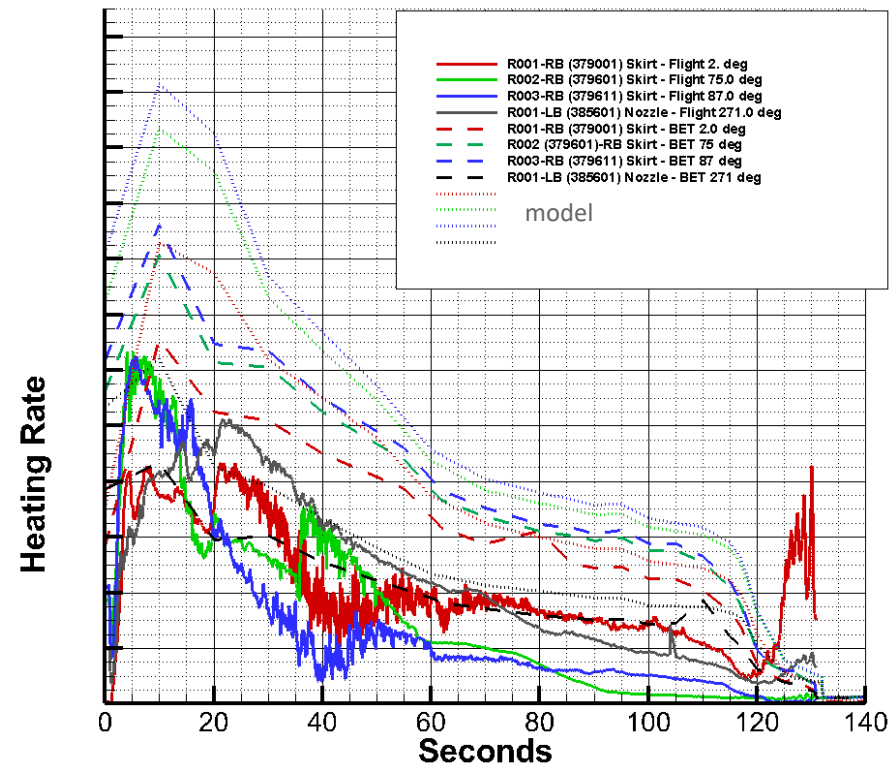
SRB Aft Skirt Inboard Total Heat Flux (Hot Wall)



- STS-1 B07R8409A
- STS-2
- STS-3
- STS-5
- Artemis-1 GRP020 C020 (Inboard)
- Artemis-1 GRP019 C019 (Outboard)
- model (inboard)



SRB Base Aerothermal: Radiation





Conclusions

- **Base heat shield (BHS) TPS cork combustion ignition and flame-out regimes occurred between $\sim T+14$ s and $\sim T+75$ s (below 48,000 ft); attributes to $<40\%$ of total heat load and highest rates; shows good agreement with Post-Green Run (PGR) models**
 - Peak cork combustion convective heat rates are greater than **5x** the non-TPS-burning (modeled) rate
 - Impacted inboard booster aft skirt heating
 - Base heat shield (BHS) plume-induced radiation partially attenuated due to high TPS outgassing, smoke and cork combustion products early in-flight
- **Peak base gas recirculation spans between $\sim T+95$ s and $\sim T+114$ s and shows good agreement with PGR/pre-GR BET models**
 - RS-25 – SRB plume recirculation at 40,000 ft ($T+60$ s) which led to high base pressure may have led to high heating, but believe the dominant mechanism is cork combustion
 - Peak recirculation regime spans an altitude between 86,000 ft and 128,000 ft
 - BET model shows peak recirculation at $T+110$ s (118,000 ft)
 - Few poke-outs where AR01 flight data shows higher convection than prediction
- **Constant convective heating observed in choked flow regime during core-only flight ($>T+130$ s); good agreement/conservatism observed between flight reconstruction and PGR/pre-GR BET models**
- **EMHS reconstructed environments are much higher than the BET models <75 s due to rain-shield and cork TPS burning; good agreement observed with BET models during core-only flight**
- **Booster shutdown environments at the core stage were much less than flight, in most cases unobserved in comparison to Shuttle environments**



- Need to compare EV33 CFD and ATA-002 test data with reconstructed flight environments to assess model accuracy
- Recommend updating the uncertainty quantification (UQ) using the flight and ground test data and incorporating flight-to-flight variations