



VALIDATION OF ARTEMIS I AEROTHERMAL DESIGN MODELS USING DEVELOPMENTAL FLIGHT INSTRUMENTATION

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Thermal & Fluids Analysis Workshop

TFAWS 2024

August 26-30, 2024

NASA Glenn Research Center

Cleveland, OH



Notice to the Reader



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BLUF



The Aerosciences Branch at NASA MSFC had the responsibility to develop aerothermal environments for the ascent portion of the Artemis I mission

Purpose:

1. Overview of the aerothermal measurements collected during the Artemis I launch
2. Compare flight data against aerothermal design models

Goal:

1. Validate aerothermal ascent design environments and models
2. Make model refinements based on flight observations



Aerothermal Instrumentation Summary



Orion Multi-Purpose Crew Vehicle (MPCV)

- 22 Calorimeters with embedded sensor thermocouples
- 22 Static pressure gauges
- 6 Radiometers
- 90 combined thermocouples and resistance temperature detectors embedded in TPS

Integrated Spacecraft and Payload Element (ISPE)

- 3 Calorimeters with embedded sensor thermocouples
- 3 Static pressure gauges

Core Stage (CS)

- 38 Calorimeters with embedded sensor thermocouples
- 27 Static pressure gauges
- 8 Radiometers
- 7 Gas temperature probes

Core Stage Engines

- 5 Calorimeters with embedded sensor thermocouples
- 3 Static pressure gauges
- 3 Radiometers
- 2 Gas Temperature Probes

Solid Rocket Booster (SRB)

- 24 Calorimeters with embedded sensor thermocouples
- 24 Static pressure gauges
- 4 Radiometers
- 3 Gas Temperature Probes
- 2 Flow direction probes



Why These Gauges?

Main measurement is heating rate

$$\dot{q}_{total} = \underbrace{h_c (T_{rec} - T_{wall})}_{\text{gaseous convection}} + \underbrace{\dot{q}_{rad}}_{\text{radiation}}$$

Parameter

$\dot{q}_{total}, T_{wall}$

T_{rec}

\dot{q}_{rad}

h_c

Measured by

Calorimeter, Thermocouple

Calculated or Gas temperature probe

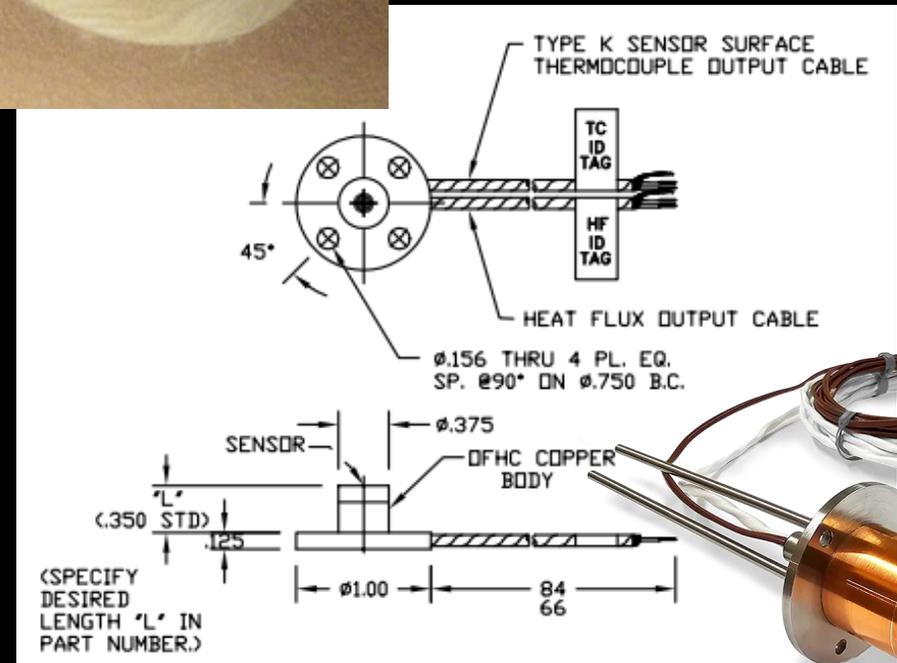
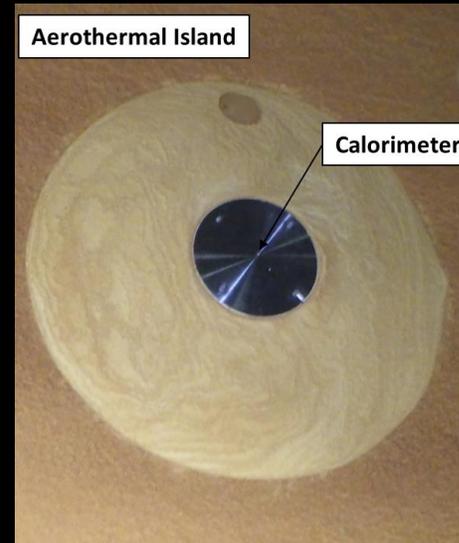
Radiometer

Calculated

Flow direction probes characterize plume induced flow separation region

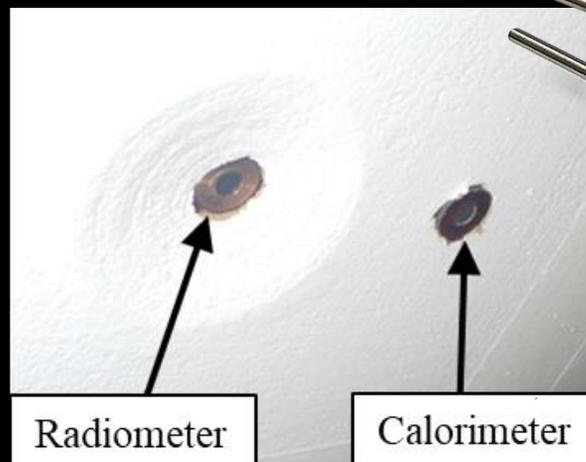
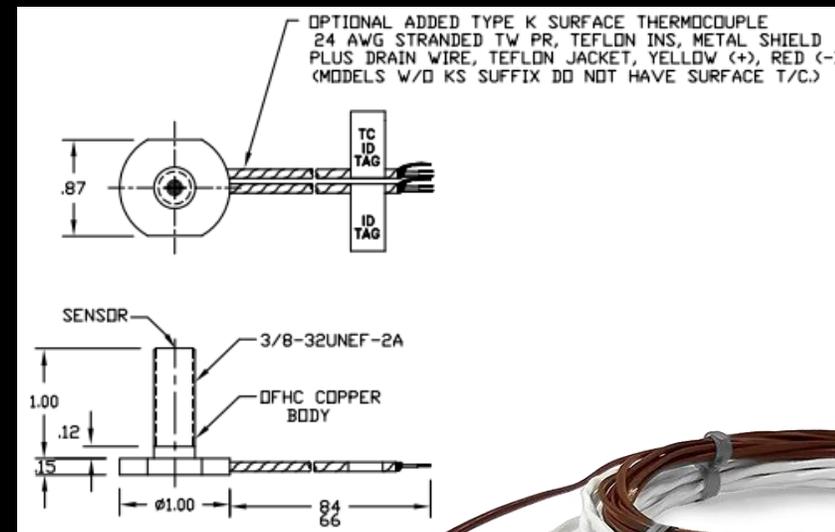
Static pressures provide local flow conditions and CFD validation data

- Schmidt-Boelter type calorimeter with embedded thermocouple (two-channel)
 - Medtherm model 20850
- Performance
 - 90 out of 92 calorimeters provided data
 - 88 out of 92 thermocouples provided data
- Lessons Learned
 - Frost built up on sensors near/on cryogenic tanks
 - Filtering caused a delay in response and magnitude clipping
 - Gauge surface re-radiation not negligible during Rarefied and Free Molecular regimes



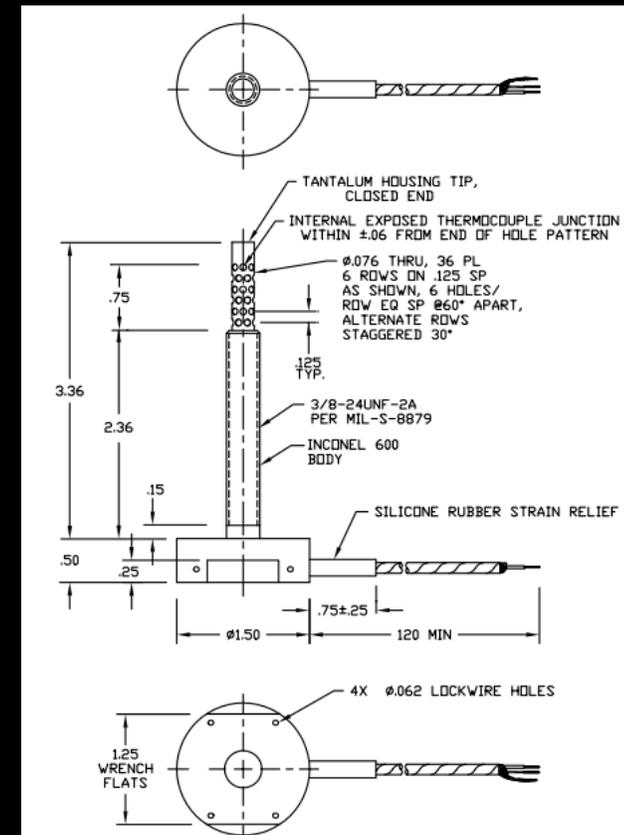
<https://raptor-scientific.com/about-us/medtherm-corporation/>

- Calorimeter with a sapphire window
 - Medtherm model 22121
- Performance
 - 21 out of 21 provided data
- Lessons Learned
 - Filtering caused a delay in response and magnitude clipping
 - Line of sight and FOV limitations
 - High concentration of surface contamination
 - Attenuation from the cork combustion



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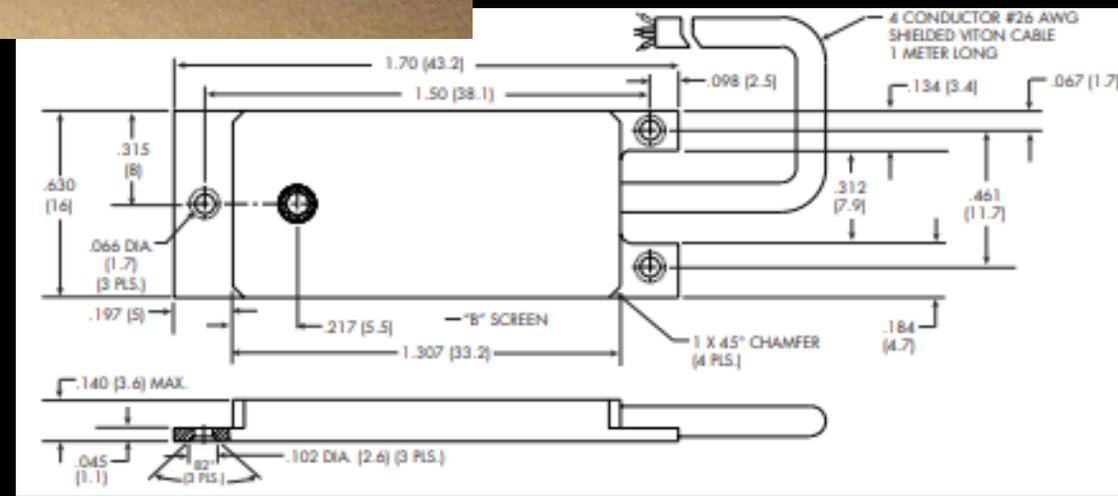
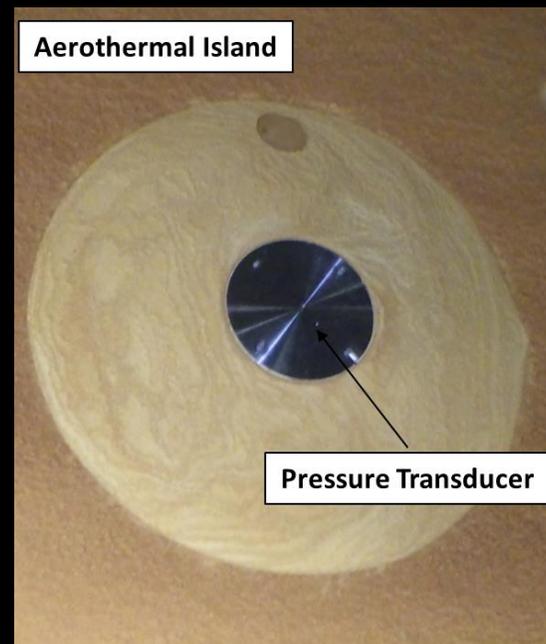
- Base Gas Temperature Probe
 - Medtherm model 11290
- Performance
 - 10 out of 12 provided data
- Lessons Learned
 - Thermocouple junction was fragile and prone to damage
 - Local to P50 cork and RT455 offgas
 - Faster response time provided better synchronization of environment events, to assist determination of the convective film coefficient in time (from calorimeter data)



<https://raptor-scientific.com/about-us/medtherm-corporation/>

Static Pressure Gauges

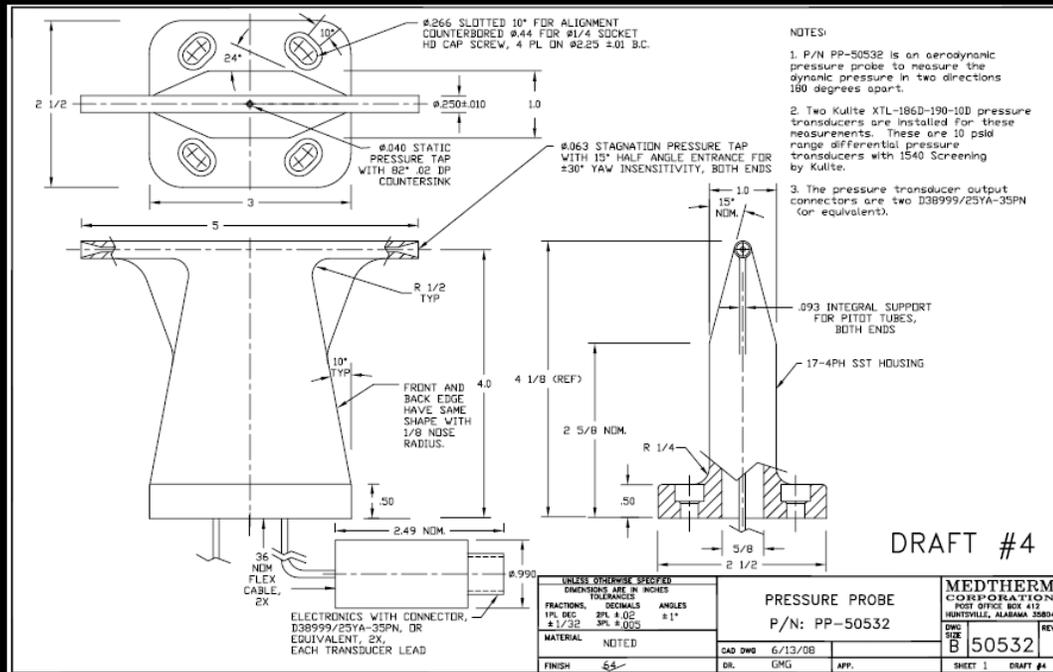
- Pressure Transducer
 - Kulite Model LLE-17DC-500
- Performance
 - 80 out of 82 provided data
- **Lessons Learned**
 - Not all gauges read ambient pressure at launch, required post flight adjustments
 - Island (thermal mass, isolator) delayed ice formation



<https://kulite.com/products>

Flow Direction Probes

- Bi-Directional Pressure Probe
 - Medtherm model 50532
- Performance
 - Unable to get valuable data
 - Half the pressure data was erroneous



<https://raptor-scientific.com/about-us/medtherm-corporation/>



Validation of Aerothermal Design Models



Aerothermal environments consist of different heating and pressure sources, DFI were installed in support of six aerothermal flight test objectives (FTO) to measure:

1. Aerodynamic Heating
2. Base Plume-Induced Radiation
3. Base Plume-Induced Convection
4. Plume-Induced Flow Separation
5. Plume Impingement
6. CAPU Plume Heating

For each FTO DFI data was used to substantiate and revise models where necessary



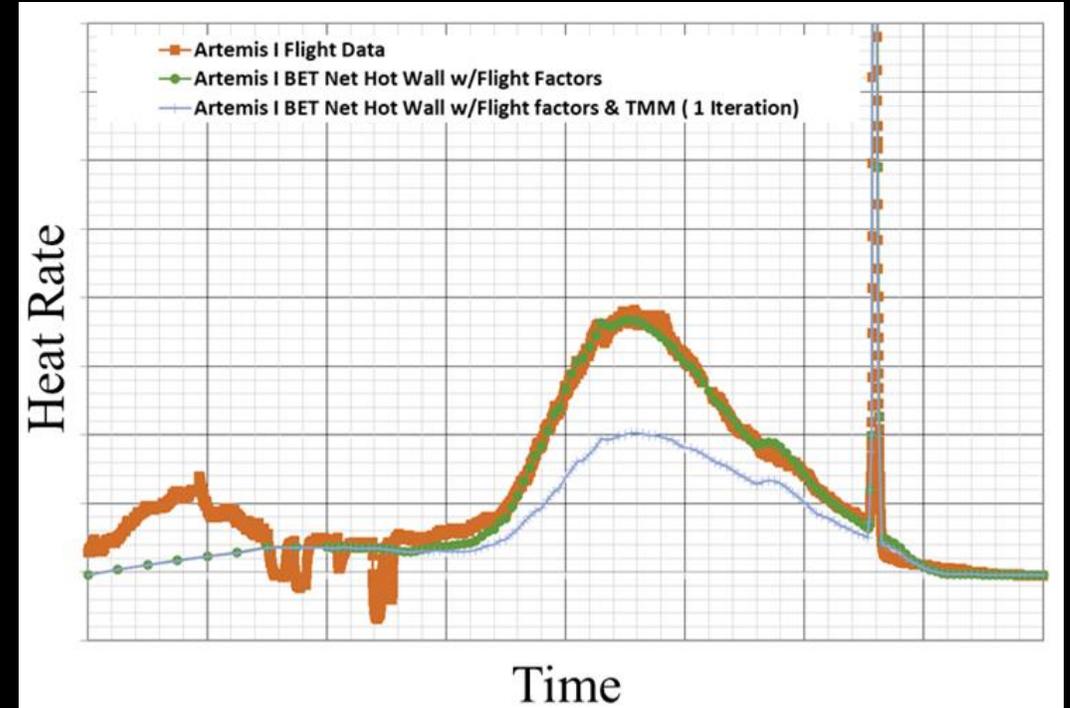
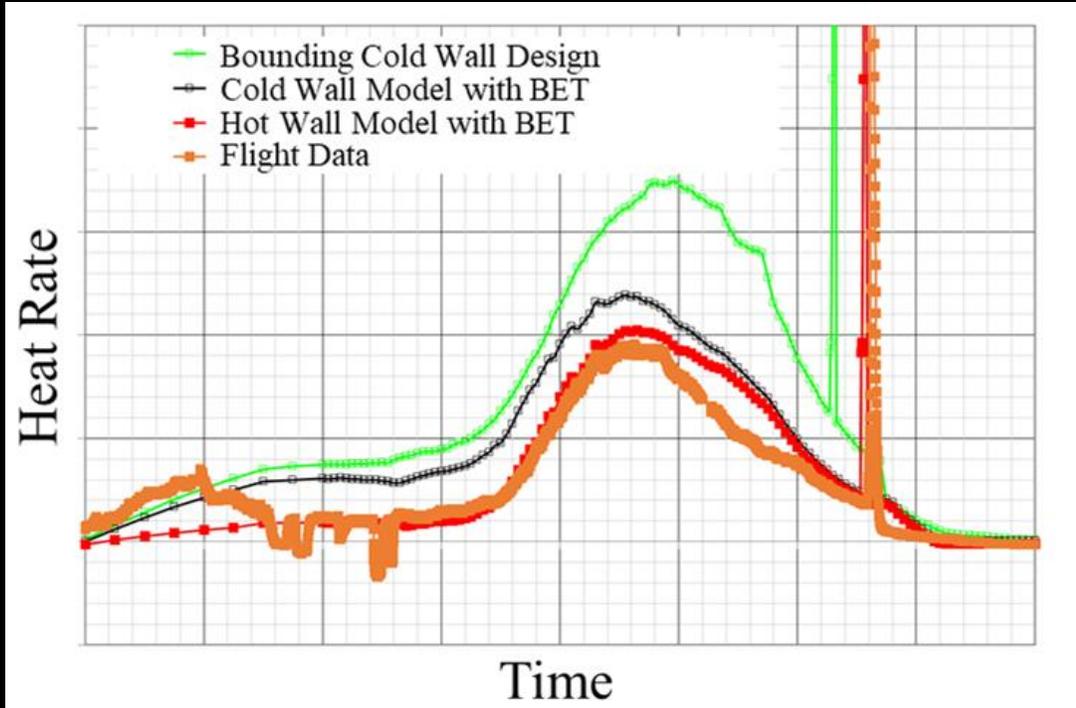
Flight Adjustments



Artemis I Reconstructed Flight Environments Accounted For:

1. Best Estimated Trajectory
2. Hot wall heating using Flight DFI temperatures
3. Flight derived Boundary Layer Transition criteria
4. Flight Factors
5. Thermal Mismatch Correction
6. Calorimeter Re-radiation
7. Updated Flight Radiation Files
8. New Flight derived plume models
9. Remove Model Uncertainty Factor
10. Cold wall env using above model corrections/factors

Example of Flight Adjustments:



Design models were adequately conservative, updates to the models were implemented to improve modeling accuracy and reduce conservatism



Aerodynamic Heating

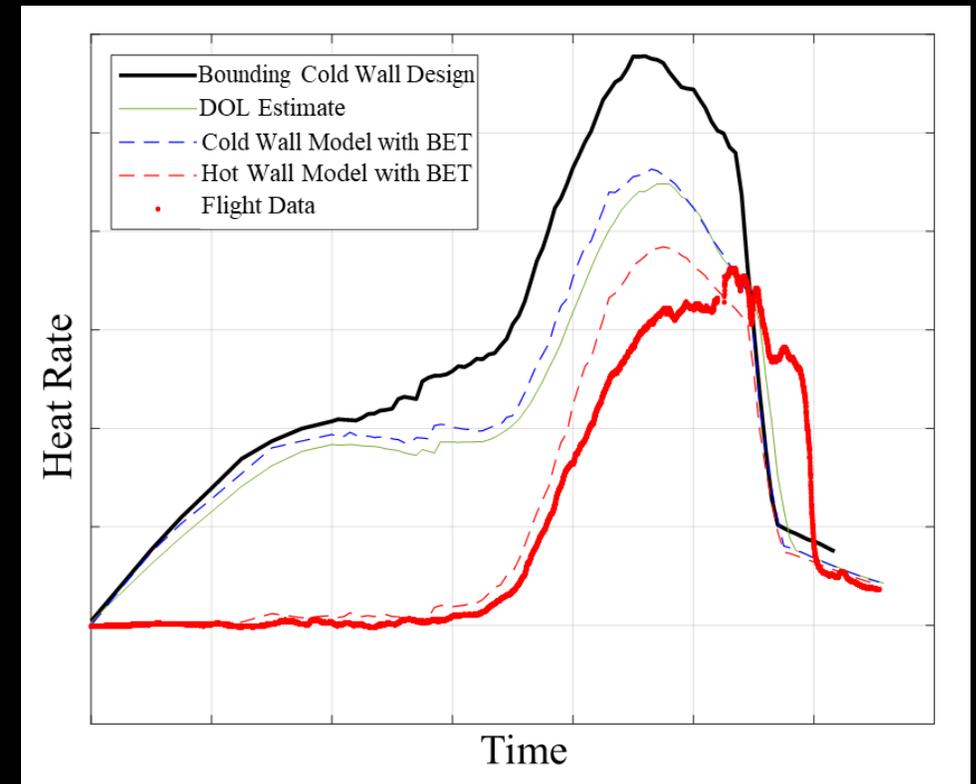


Boundary Layer Transition Criteria

- Design criteria based on Shuttle
- Flight data showed transition happens later

Implications

- Increase duration of turbulent heating
- Increase heat load



Flight-derived transition criteria has been implemented



Aerodynamic Heating

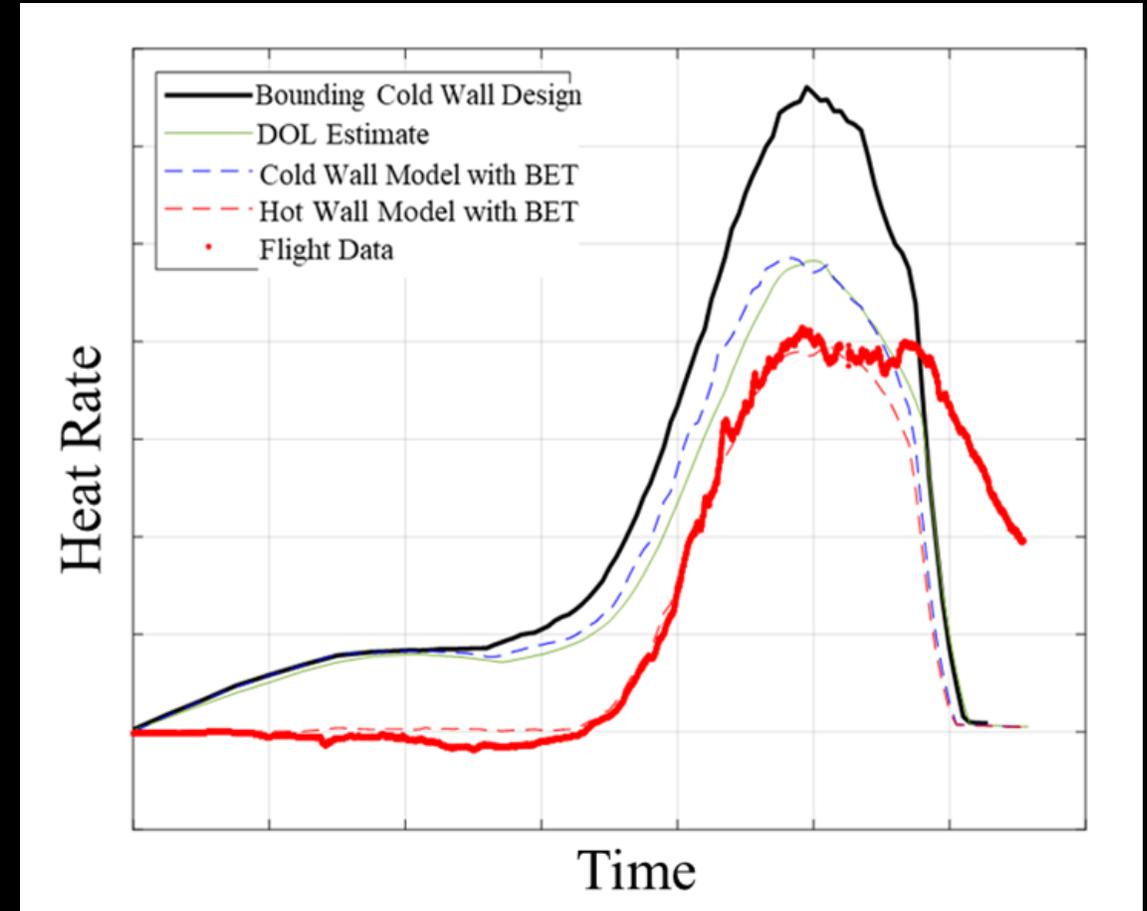


Boundary Layer Transition Criteria

- Design criteria based on Shuttle
- Region in between Core and SRB transition was not observed

Implications

- Flow remains turbulent
- Increased heat load



Design models, in-between CS and SRB, were updated to turbulent until SRB separation



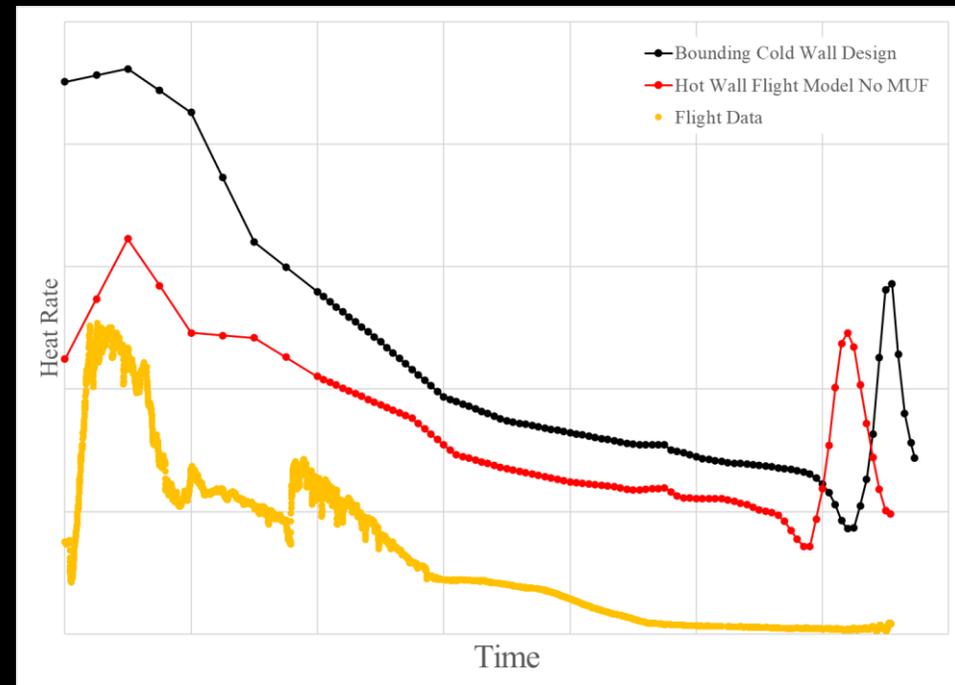
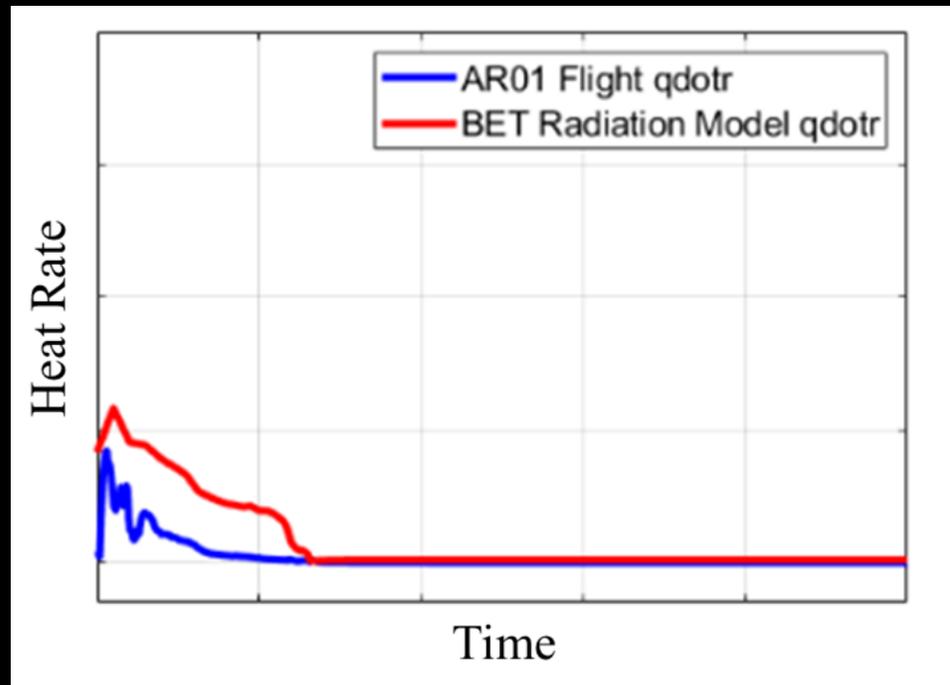
Base Plume-Induced Radiation



Minor radiation model changes were implemented to better agree with flight:

- Model Uncertainty Factor has been removed
- All aft facing areas received an additional radiation knock down factor

Further investigation of the effects of sensor contamination and attenuation from TPS offgas on incident radiation should be pursued





Base Plume-Induced Convective Heating



Plume Convective Heating models were updated after Green Run

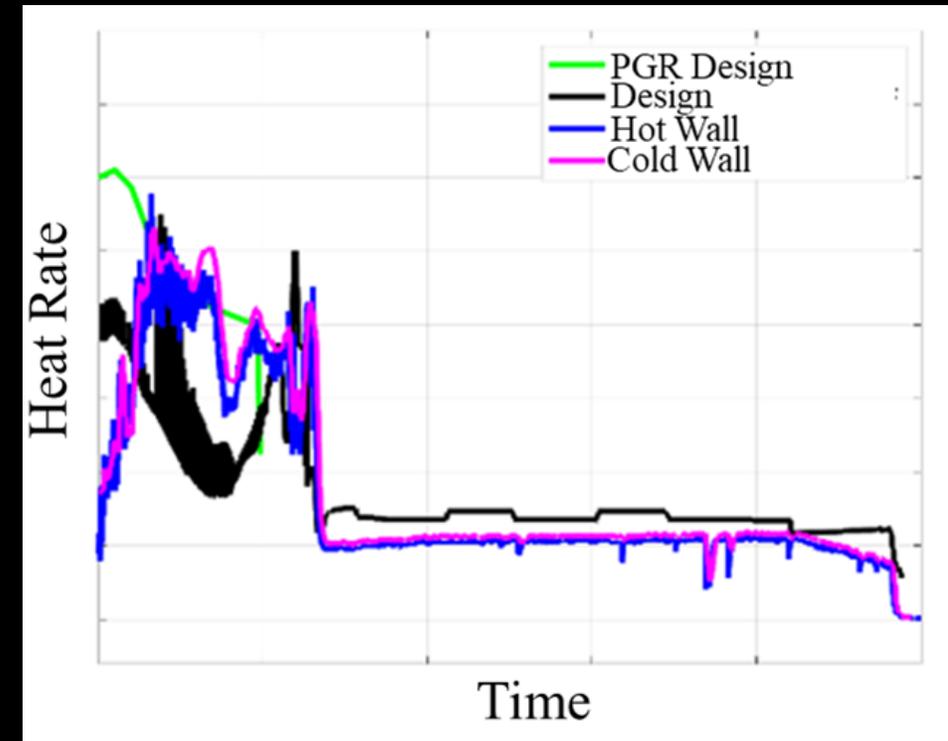
- Observed TPS burning on the base heat shield
- Used ground test data to model burning during flight

Flight Observations:

- May not have captured peak heat rate
- Overall heat load was bounding

Model Adjustments:

- Revised TPS burning-induced convection model
- Spatially expanded TPS burning environments to additional areas



New methodology to account for BHS TPS combustion increased the overall plume induced convection



Base Plume Convective Heating



SRB Nozzle and CS Engine Configuration is unique to SLS

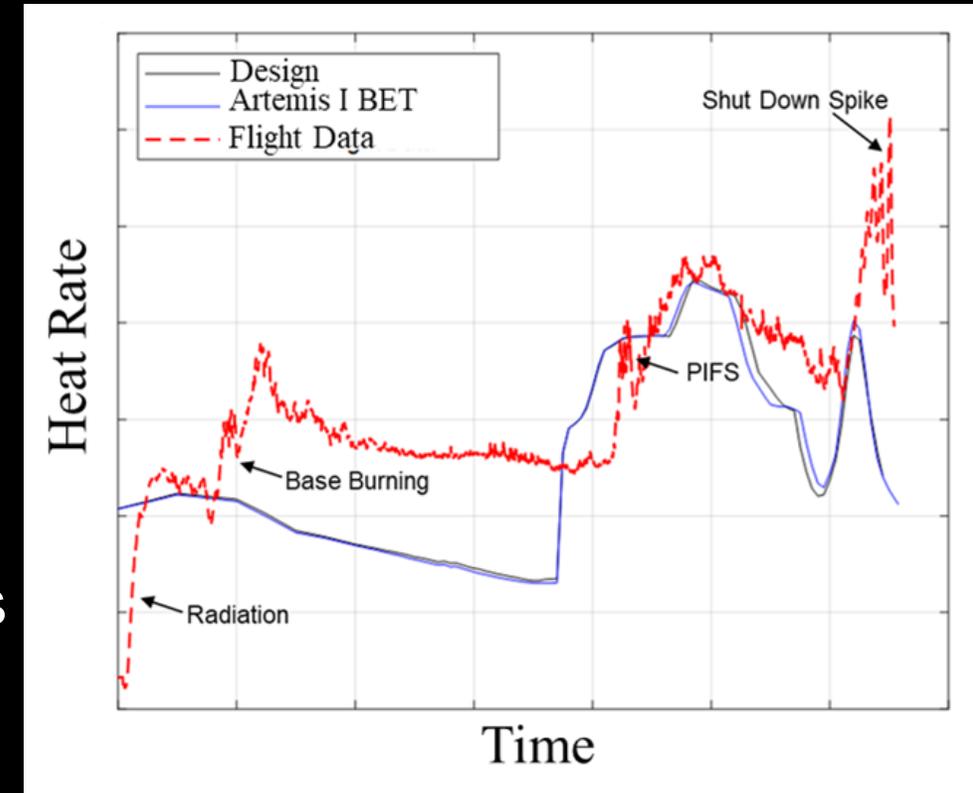
- Booster aft skirt is downstream of CS base heat shield and engines

Flight Observations:

- Models were not updated after Green Run
- Inboard regions experienced effects from CS base TPS burning

Model Adjustments:

- Created new methodology to include increases from upstream TPS burning



SRB experienced increased plume convective heating from CS TPS Burning



Plume Induced Flow Separation

Several instrumentation islands were mounted on the CS and SRB to observe PIFS environments

- Capture the time and spatial distribution of the forward freestream separation point induced by the plume
- Capture the pressure and heating characteristics of the recirculated gas in the separation zone

Flight Observations:

- Unable to get usable data from flow direction probe
- PIFS environments occurred later in flight than predicted, were less in magnitude, did not travel up the vehicle as far as expected
- PIFS environments were minimal after SRB separation (density of gases within PIFS region decreased, considerably reduced convection)

PIFS models were found to be conservative and MUFs were removed



Plume Impingement



Booster Separation Motor Plume Impingement

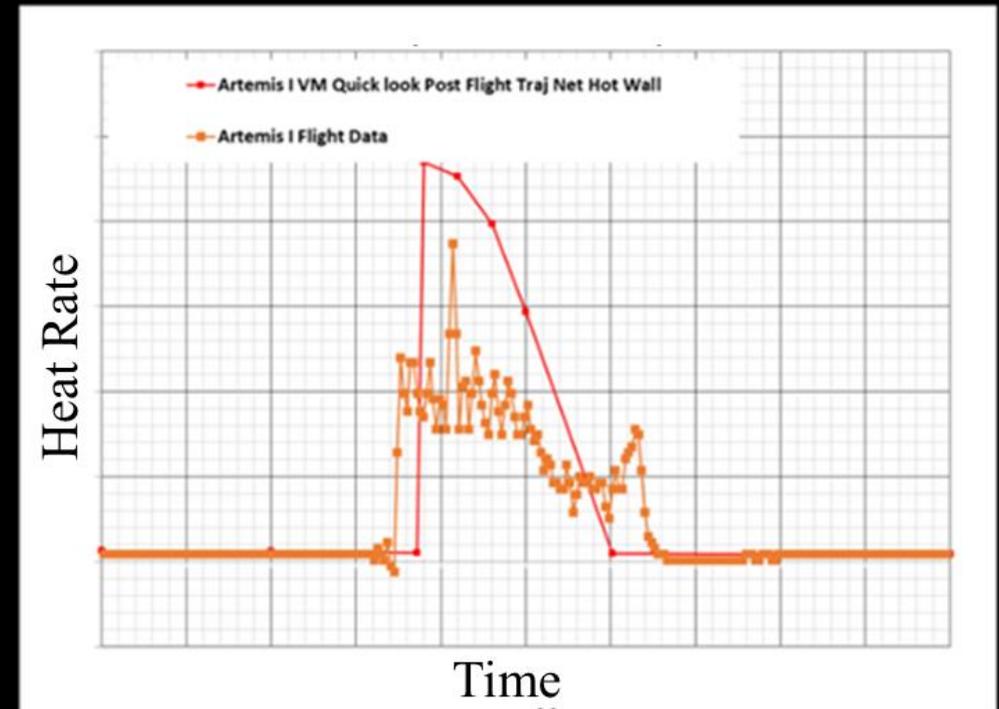
- Quick event (1-2 seconds)
- Plume sweeps across and engulfs entire vehicle

Impacts from data filtering:

- Timing of events
- Magnitudes may have been clipped

Post Flight Adjustments

- Design environments were conservative
- New models developed over a CFD database (multiple separation conditions)



BSM impingement location and magnitude was dependent on separation altitude and dynamic pressure (plume expansion, injection into freestream crossflow)



Plume Impingement

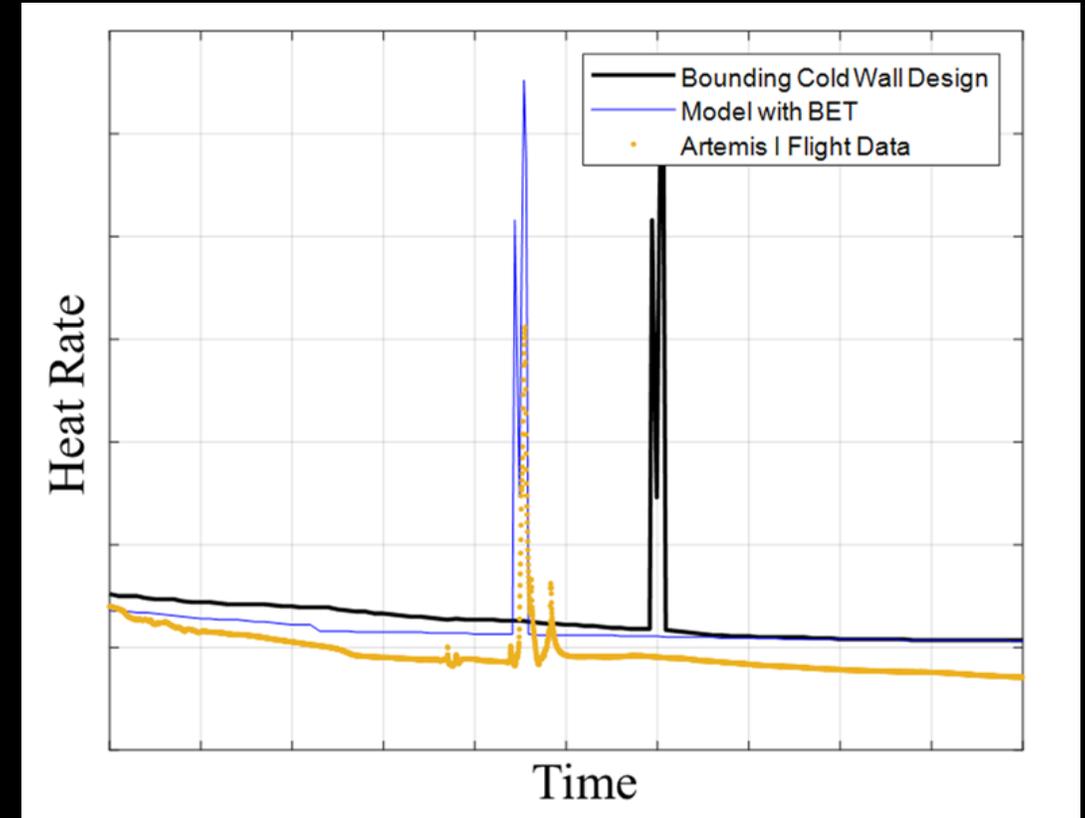


LAS Jettison Motor Plume Impingement

- Quick event (1-2 seconds)
- LAS jettisons off the vehicle and plumes impinge on Orion MPCV

Impacts from data filtering:

- Timing of events
- Magnitudes may have been clipped



Predicted LAS JM environments were found to be conservative and bounded all flight data



CAPU Plume Heating



Core Auxiliary Power Unit (CAPU) ports on the CS BHS

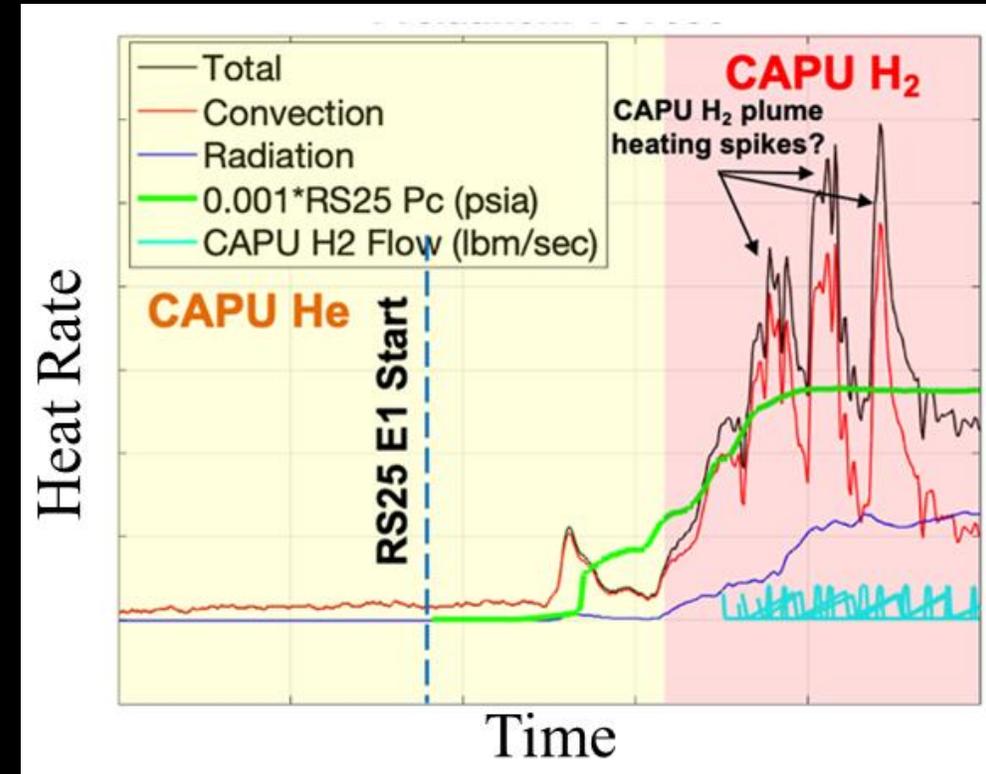
- Enables the gimbaling of the RS-25 engines for vehicle control authority

Prelaunch

- High/low flow rate oscillations were observed
- Dumps gaseous hydrogen exhaust into base region

Flight

- Free hydrogen ignites in close proximity to the BHS
- Increases plume induced convection



CAPU heating only observed in prelaunch, during flight became integrated with plume convection



Conclusion



- Artemis I SLS vehicle had a nominal flight
- Aerothermal design models largely aligned with the flight data
- No thermal exceedances or anomalies were observed due to excessive aerothermal environments

Several updates to the models were implemented to improve overall modeling accuracy:

1. Boundary Layer Transition Criteria
2. Flight Factors
3. Removed Model Uncertainty Factors
4. Flight derived Plume-Induced Flow Separation models
5. New Base Burning Methodology



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