The Evolution of the MSL Heatshield

by

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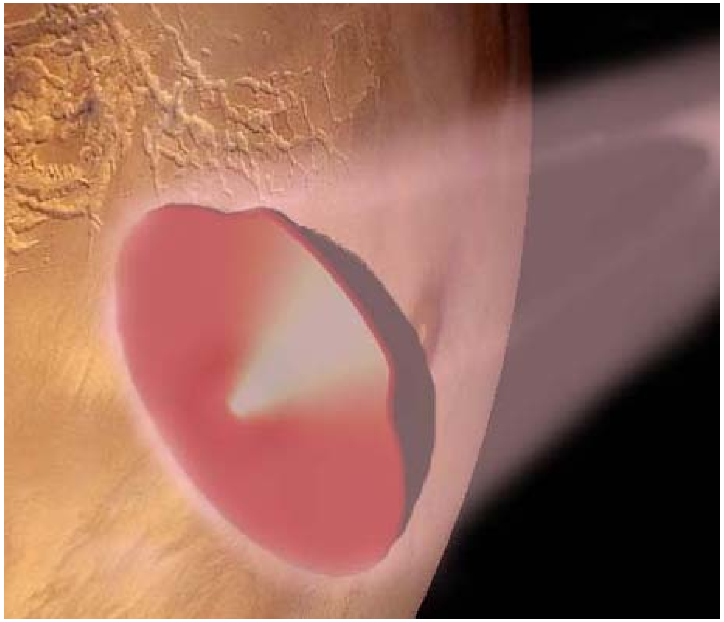
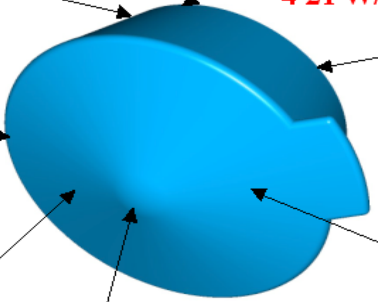
Original MSL Concept (2001)

- MSL stood for: Mars Smart Lander (circa 2001)

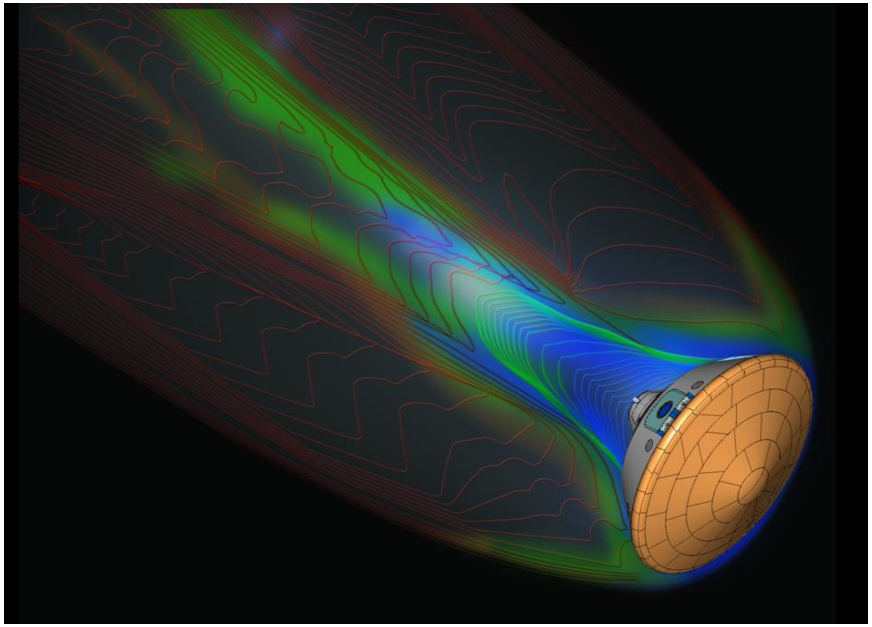




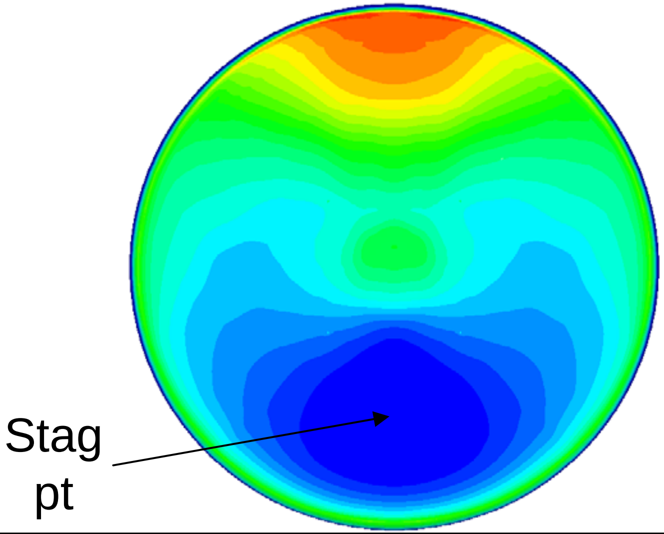
- Conditions were laminar and ~1.5x higher than previous Mars missions
  - Previous maximum heat flux for Mars mission achieved on Pathfinder ~105 W/cm^2
- Requirements creep abounded
  - Increase in rover size resulted in geometry and mass increases

MSL Concept Today

- Mars Science Laboratory (launch date Sept '09)



- Mass "grew", geometry changed, velocities increased
- Flow on the leeward side became turbulent
- Conditions were no longer moderate (~2.5x previous Mars missions)

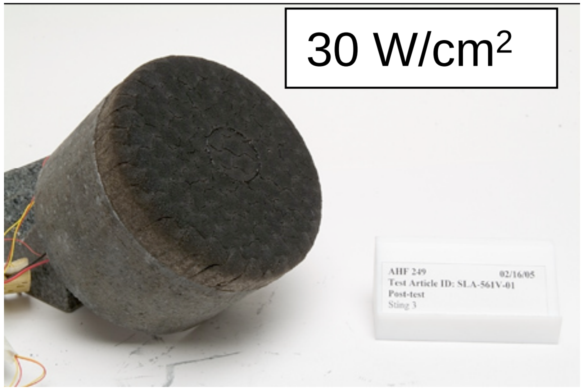


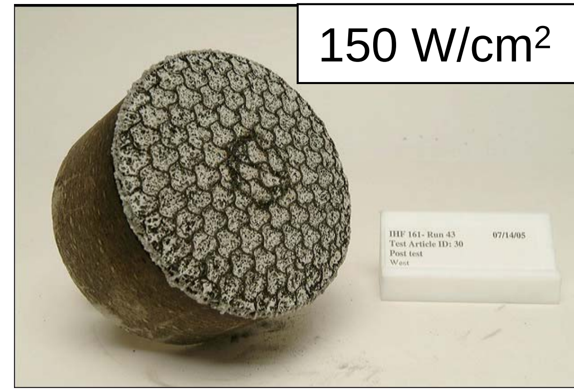
Heatshield Aerothermodynamics Requirements in 2007 at Max. Heat Flux Location	
Requirement	Value
Max. q_w (W/cm^2)	272
Max. τ_w (Pa)	639
Max. p_w (atm)	0.280
Max. Q_w (J/cm^2)	7588

Initial Approach

- Assume that what has always flown to Mars, SLA-561V, can fly this mission
- Perform stagnation arc jet tests
  - Tested from 30 W/cm^2 to 300 W/cm^2 (hot wall)
  - Instrumented with in-depth thermocouples
  - Specimens were well behaved
  - Some melted glass on the surface
  - Higher heat flux specimens were placed in collars to avoid removal of material from “open” honeycomb
  - Low shear over specimens, so no indication of melt flow
- Develop high fidelity response model (HFRM)
  - Good match of in-depth thermocouples and recession achieved assuming glass vaporizes (no melt flow)

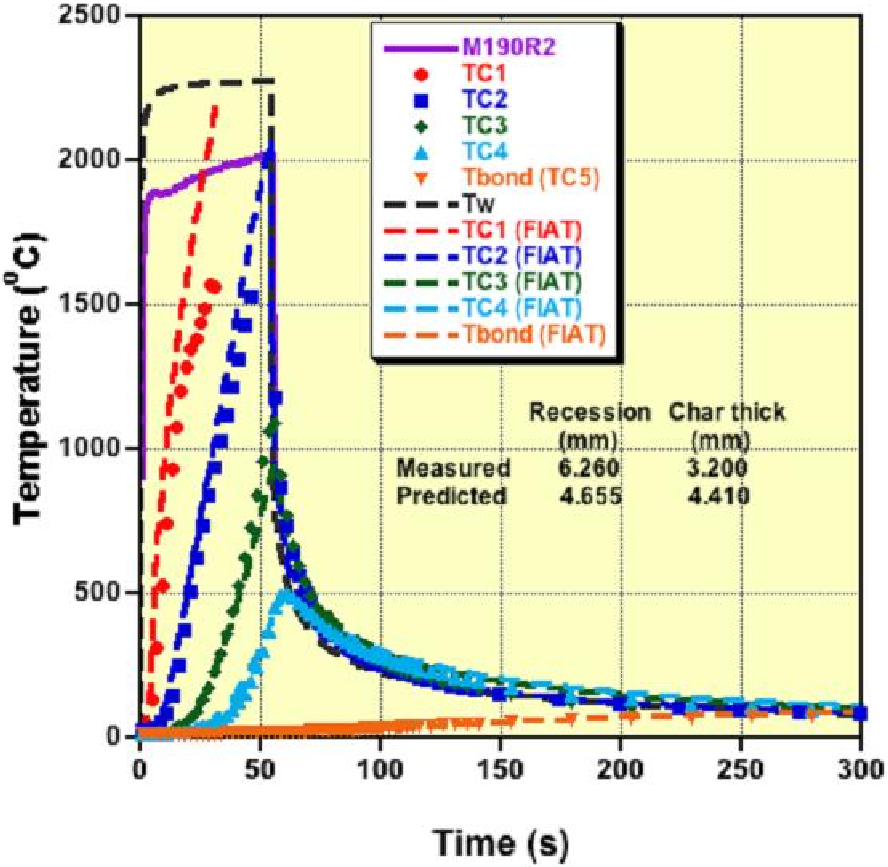
Post-test photos: SLA-561V longest exposure time at each heat flux

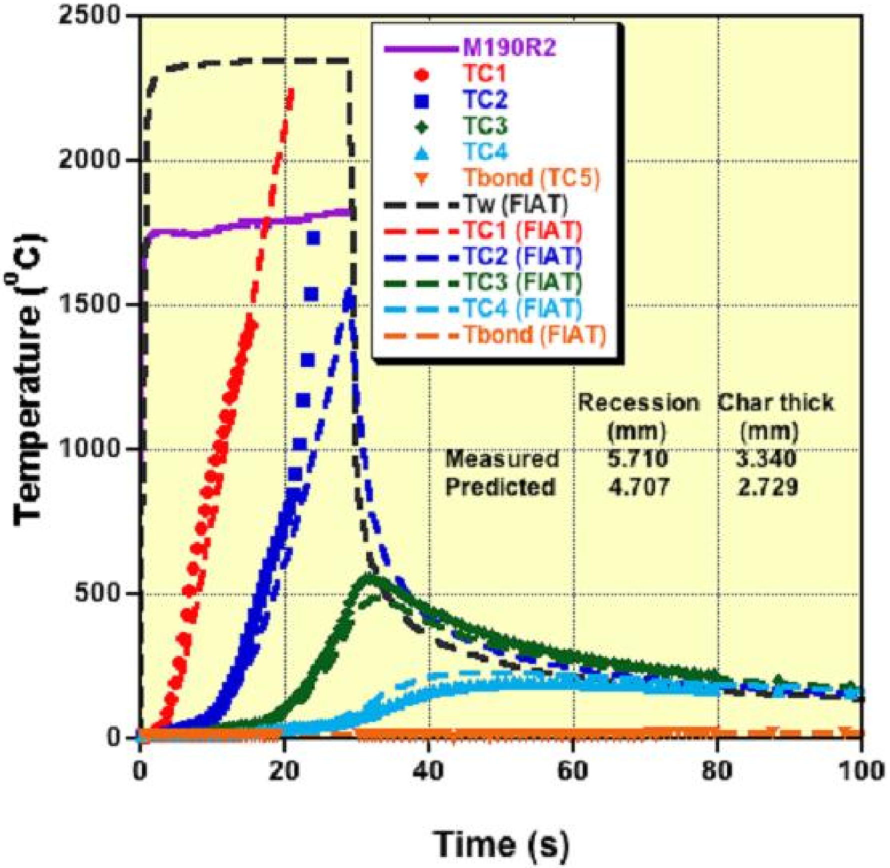




Hot wall heat fluxes are shown

HFRM results





Prediction vs data at 150 W/cm²

Prediction vs data at 210 W/cm²

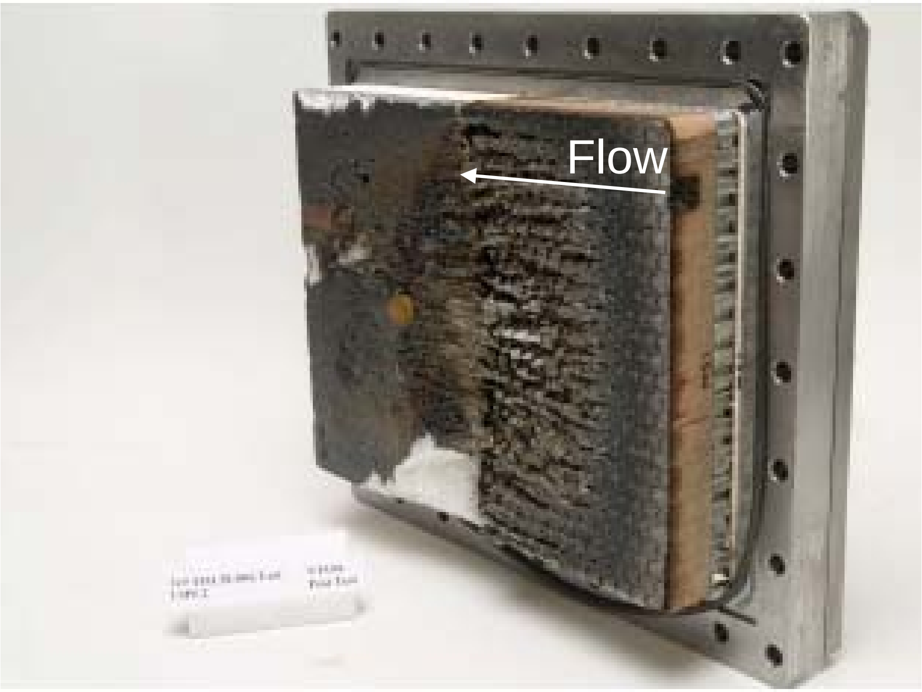
Next: Determine What Happens in Shear

- Ames Turbulent Flow Duct (TFD) was used to get a first look at SLA-561V response in shear
- Relatively high shear environment ~300 Pa
- Augmented heating with radiation plate opposite sample
  - Attempted to achieve maximum heat flux (~150 W/cm^2)
  - View factor effects may have resulted in non-uniform recession
  - In-depth deposition of the incident radiation may have resulted in thicker melt layer
- Grooves in samples (may be due to Goertler Vortices)
- Evidence of glass melt and shear-induced flow

TFD Samples

Test 1

Test 2

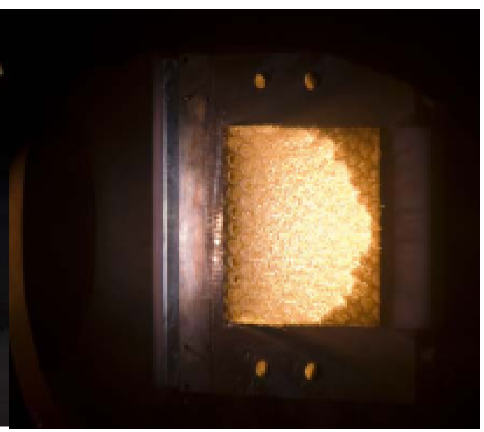


Additional Tests in Shear to Verify Behavior

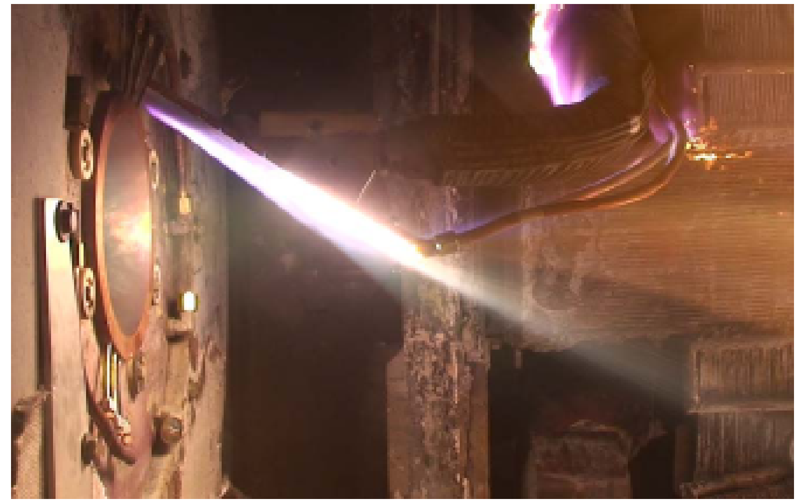
- Test in wedge and swept cylinder configurations in IHF and AEDC arc jet facilities
- Attempt to match flight heat flux, shear, enthalpy, pressure……can't be done simultaneously
- Material was somewhat well behaved (~2-4X HFRM recession) in high heating, high enthalpy conditions (albeit surface melted and flowed)
  - Could be modeled with HFRM with a "failing" surface at a melt temperature
- As enthalpy was reduced and heating became more moderate
  - *Catastrophic failure* occurred (~20X HFRM)
  - Filler material seemed to "turn to sand" and evacuate the cells
  - Honeycomb cells remained standing, but with little filler remaining
  - **Not a melt-fail condition**
  - **Could not understand the phenomenon, so it could not be predicted**
- The question became: How can we predict what will happen in flight if we can't predict what will happen in testing? Answer: *We can't*

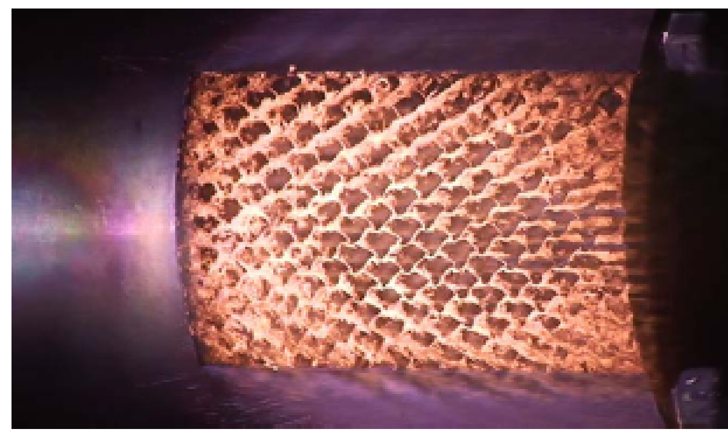
IHF Configurations

Wedges (20° and 30°)



Swept Cylinder at 30° and 40°

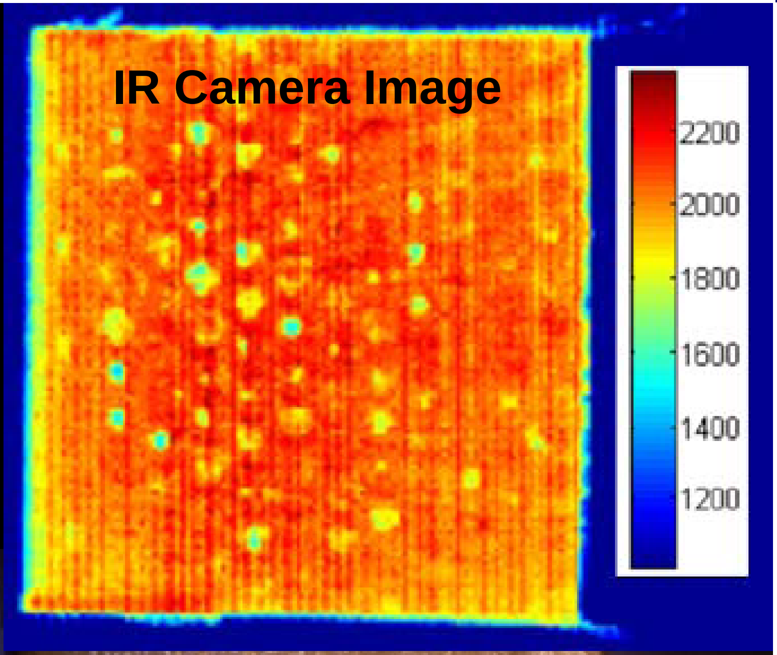


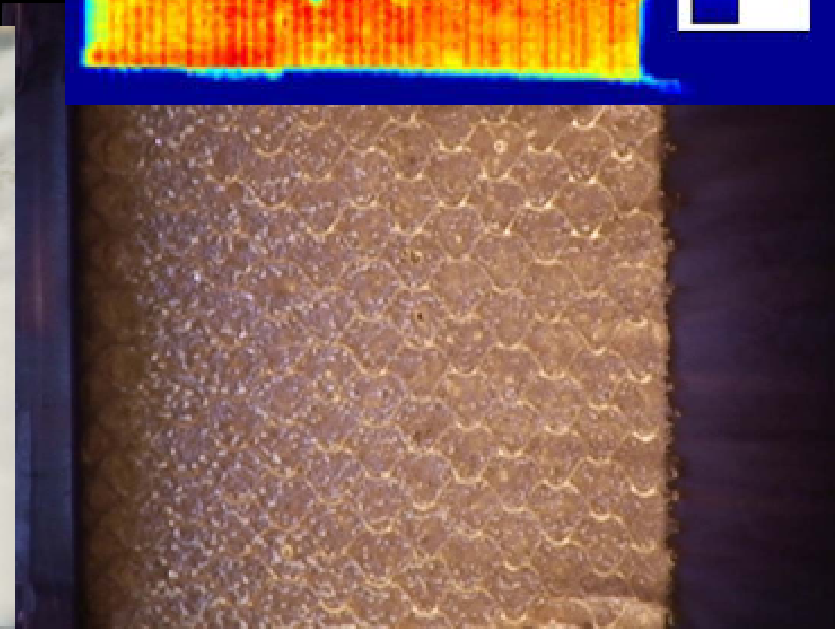


High Heating, High Enthalpy IHF Wedge

Condition 7b W-20°

Condition 7b run 09
q_cw=280 w/cm^2,
P= 0.25 Atm, τ=390 Pa
Hbulk = 19
20 sec Exposure, 0.25" recession
Rate=0.32 mm/s



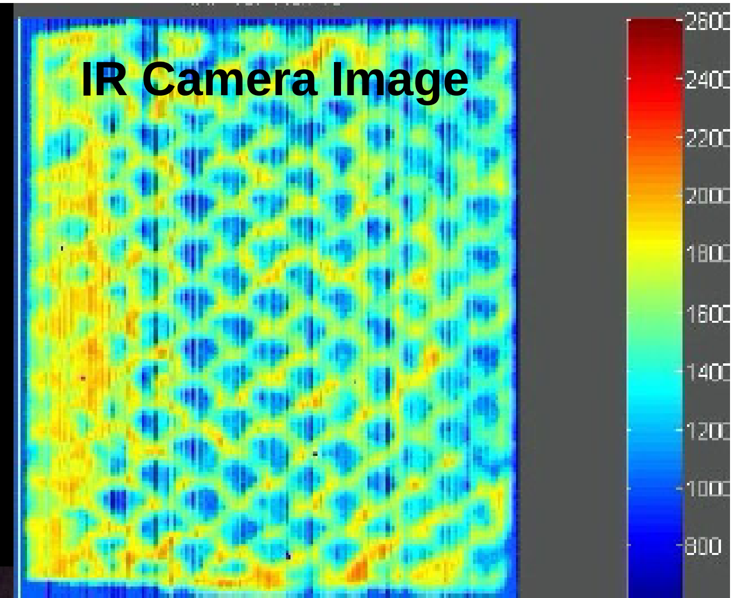


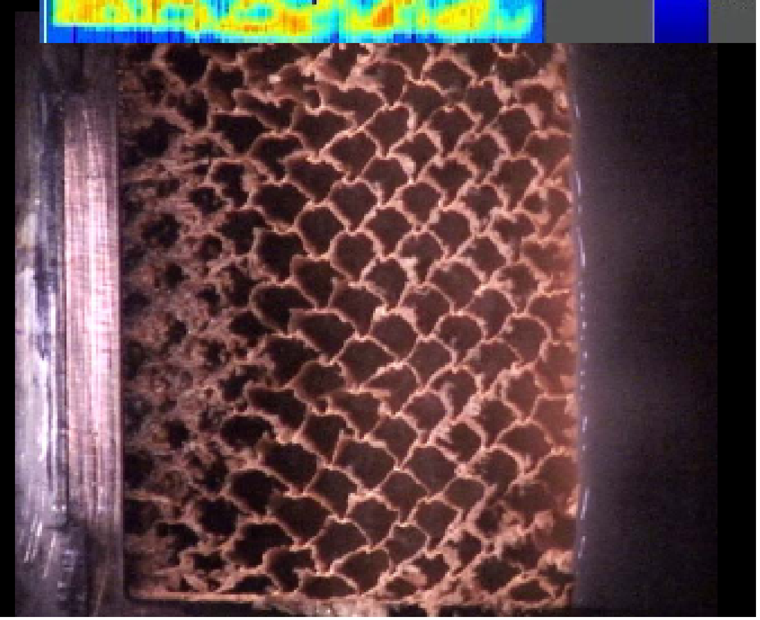
Low Enthalpy, Moderate Heating IHF Wedge

Condition A1 W-30°

Condition A1 run 16
q_cw=165 w/cm^2,
P= 0.39 Atm, τ=280 Pa
Hbulk = 8
4 sec Exposure, 0.5" recession
Rate=3.2 mm/s

Video IHF187_16dvd.mpg



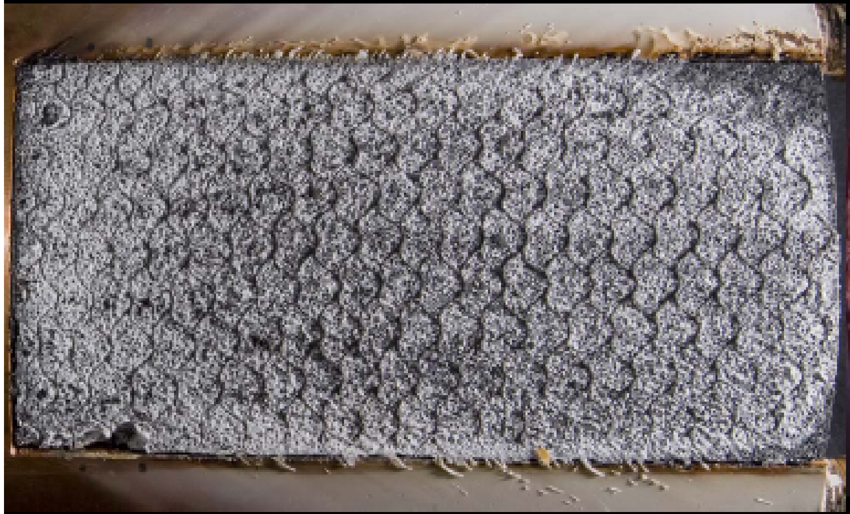


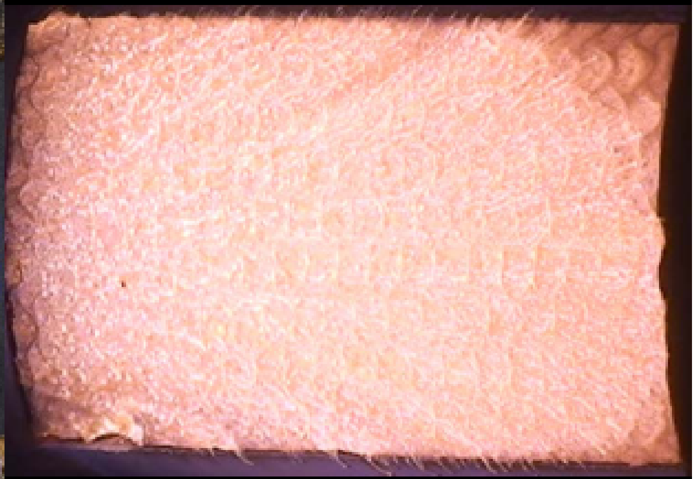
All cells emptied!

High Enthalpy, Moderate Heating IHF Swept Cylinder

Condition 3 SC-30°

Condition 3 run 23
q_cw=214 w/cm^2,
P= 0.19Atm,
Hbulk = 16
15 sec Exposure, 0.15" recession
Rate=0.26 mm/s



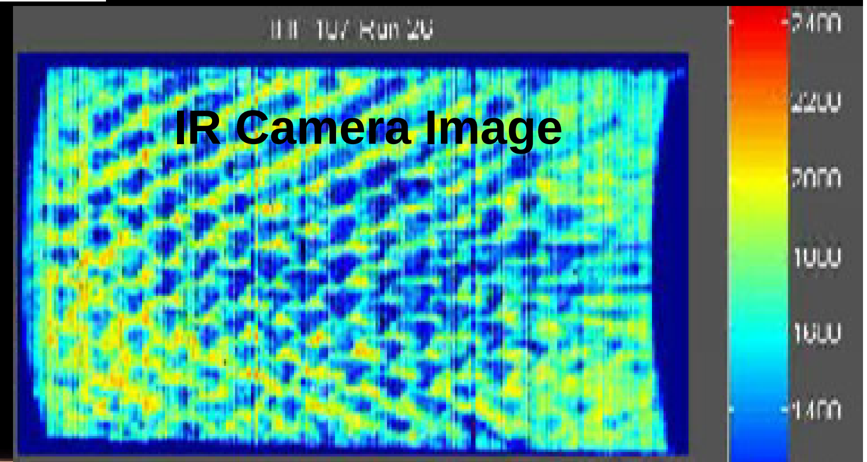


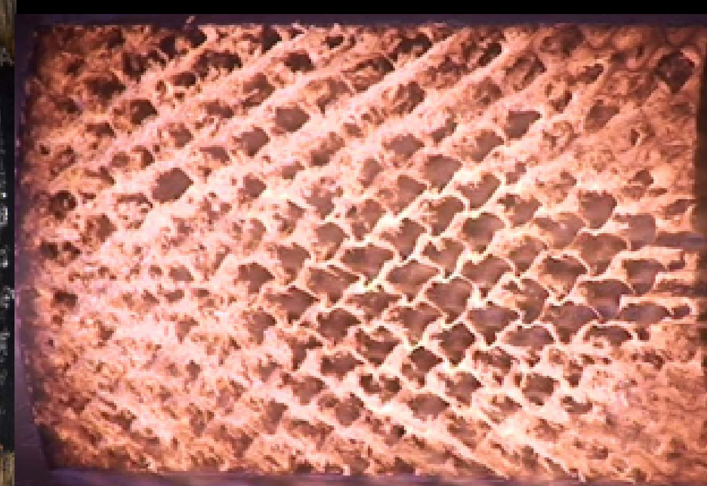
Low Enthalpy, Moderate-Low Heating IHF Swept Cylinder

Condition A1   SC-30°

Condition A1   run 26
q_cw=128 w/cm^2,
P= 0.26 Atm, τ=230 Pa
Hbulk = 9
3.4 sec Exposure, 0.31" recession
Rate=2.31 mm/s

Video   IHF187_26dvd.mpg





All cells emptied!

Additional Investigations

- Considered the possibility of the creation of a melt layer (in the high enthalpy flow) might protect the material as the enthalpy comes down during the flight…..
  - Ramped enthalpy during the exposure
- The cells still emptied, pushing away the protective melt layer, cascading down the specimen

Initial Condition

Cold wall heat flux = 175 W/cm2

Pressure = 0.30 atm

Bulk Enthalpy = 14 MJ/kg

3 second dwell

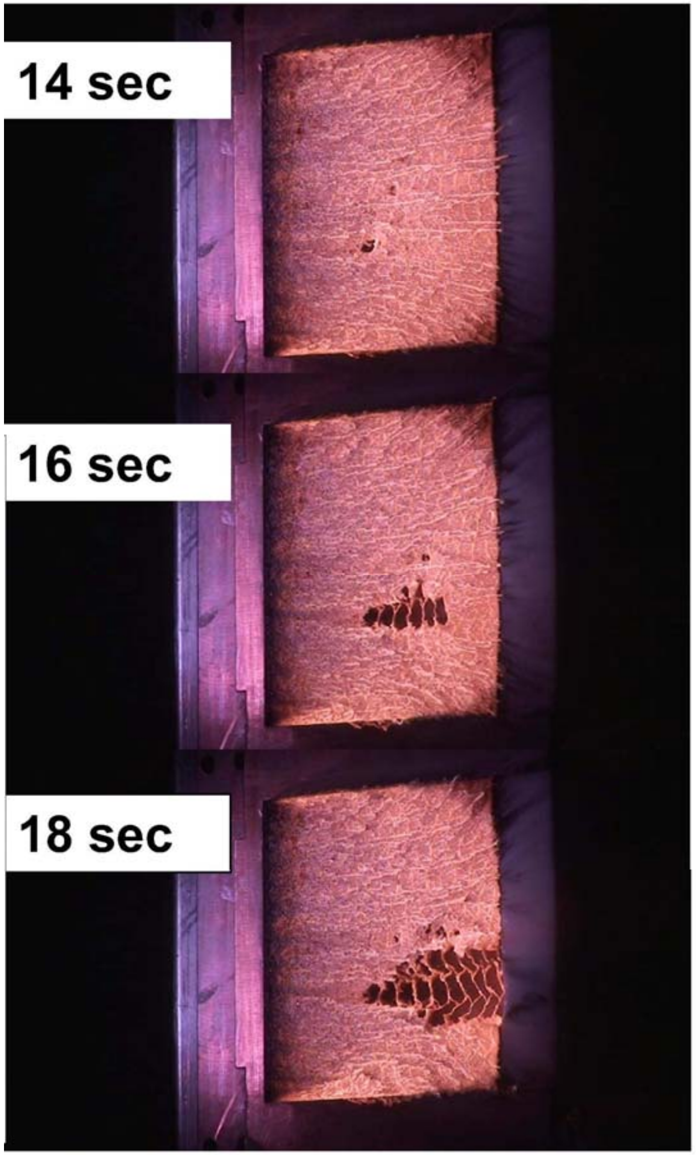
9 second ramp to final condition

Cold wall heat flux 165 W/cm2

Pressure = 0.39 atm

Bulk Enthalpy = 8 MJ/kg

12 second dwell



Decision Required

- At this point, the decision was made to recommend that the project determine if they could achieve the mission with a substantially reduced trajectory (peak heating < 100 W/cm2)
  - Heating low enough to preclude SLA-561V melt

The project determined that trajectory *could not* be reduced enough

- A new thermal protection system needed to be designed (~23 months before launch)

New Direction – Define a New TPS for MSL

- Leverage off work that the CEV Advanced Development Program (ADP) has performed on Phenolic Impregnated Carbon Ablator (PICA) tiled heatshield design
  - PICA had flight heritage – flew as a single piece as Stardust TPS
  - The ADP had already built a full sized Manufacturing Demonstration Unit (MDU) with large PICA tiles and filled gaps
  - The ADP had performed arc jet studies on gap sizes, fillers
  - CEV environments were higher than MSL (heat flux, shear, and pressure)
- Understand the differences between the CEV and MSL heatshields
  - MSL aeroshell has composite face sheets over aluminum honeycomb
    - Coefficient of Thermal Expansion (CTE) of face sheets comparable to PICA
    - Very little deflection
  - CEV aeroshell has metallic (Titanium) face sheets over titanium honeycomb
    - CTE of face sheets >> PICA
    - Much larger deflection than MSL design
- Develop MSL PICA TPS design, analyze and test
  - PICA tiles direct-bonded to structure
  - Filled gaps

This will be the first time NASA has flown a tiled ablator on a reentry heatshield

Where Are We Now?

- MSL has just completed the Heatshield CDR
  - MSL PICA specification has been defined
  - Tile layout has been designed
    - MDU's built to develop bonding and gap-filling processes
    - Engineering Demonstration Units (EDU's) in process
  - Mass allocation analysis has determined the maximum allowable PICA thickness
  - Aerothermal analyses for +3σ TPS thickness sizing are showing that the heatshield will have ~25% additional margin
  - Thermal structural tests show that the design has positive structural margin
- Performed over 80 developmental arc jet tests on MSL PICA concept at MSL conditions
  - Stagnation test (instrumented to validate PICA HFRM)
  - Swept cylinder and wedge tests to observe response in shear
  - Turbulent Flow Duct and AEDC wedge test to observe response in turbulent flow and shear
- We are currently planning qualification tests

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