Simplified Plume and Aerothermal Heating Analysis for LDSD

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8/13/12

LDSD Project Overview

TFAWS-2012

- Low Density Supersonic Decelerator (LDSD).
- Enables landing payloads heavier than MSL on Mars using new atmospheric drag devices:
  - 6-m and 9-m diameter Supersonic Inflatable Aerodynamic Decelerators (SIAD).
  - 33-m diameter Super Sonic Ring-Sail (SSRS) parachute.

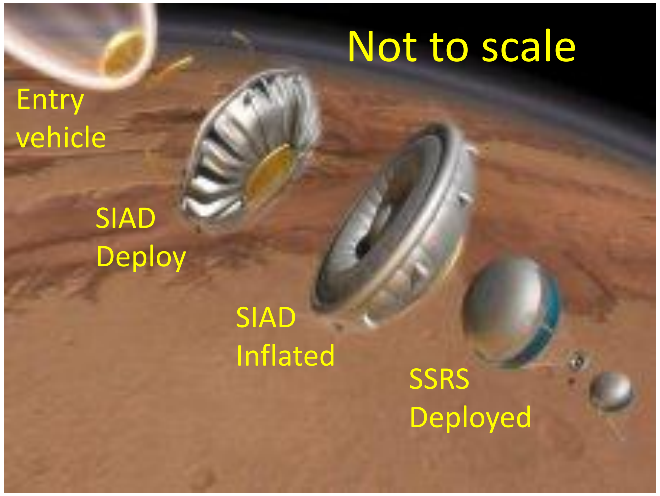
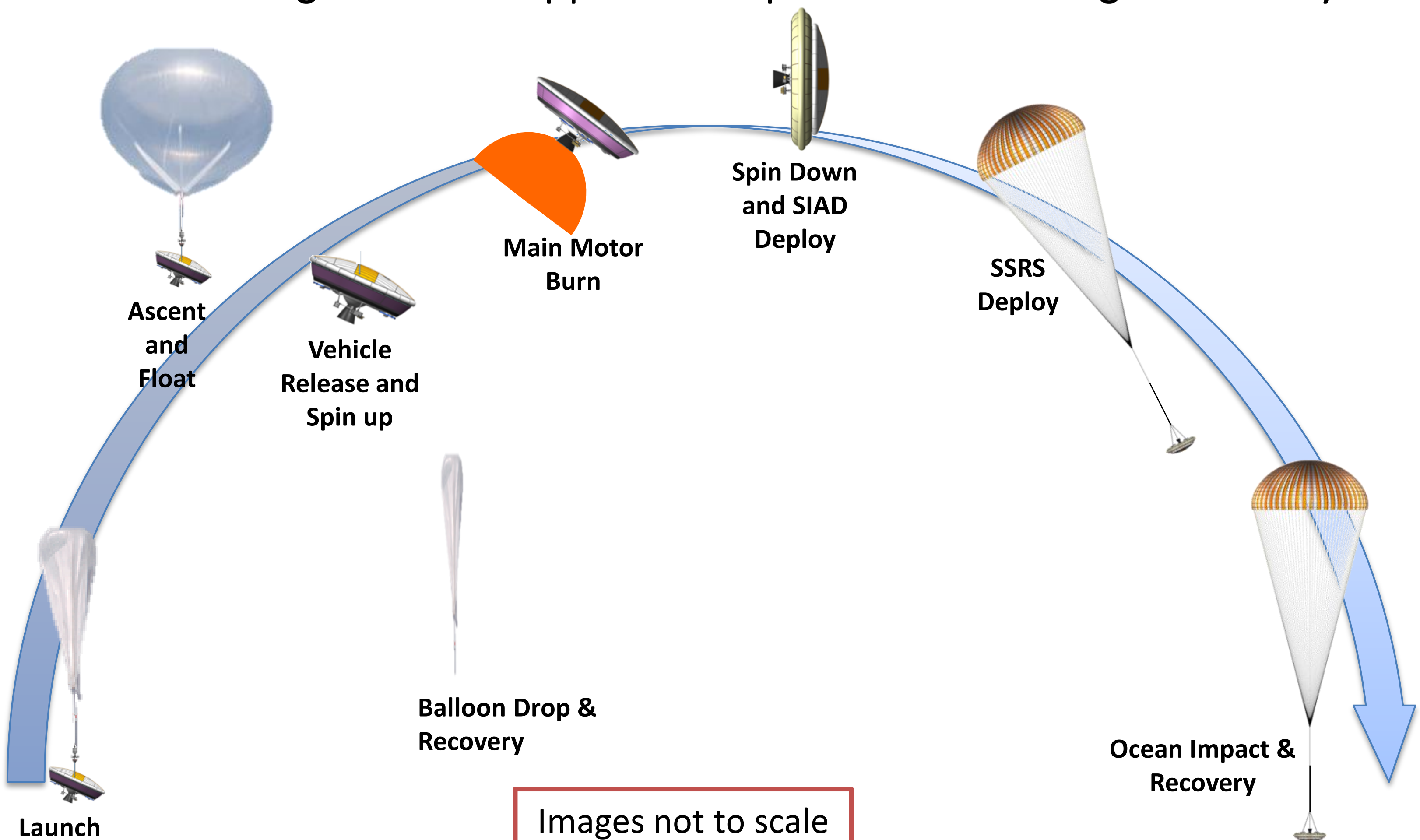


Image source:
http://www.nasa.gov/mission_pages/tdm/ldsd/ldsd_overview.html
Accessed 7/16/12

LDSD Super Sonic Flight Dynamics Test Overview

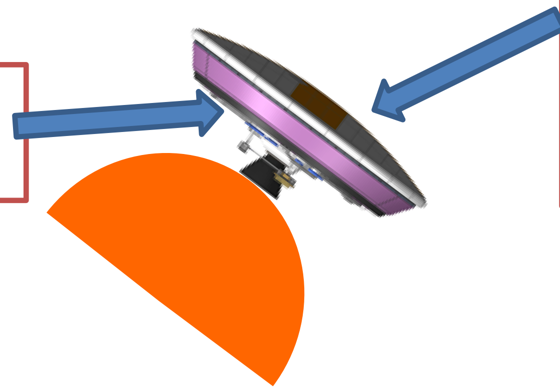
Full Scale Testing in Earth's Upper Atmosphere – Simulating Mars Entry



Images not to scale

Focus of Presentation

Base heating on backshell during motor burn.



Aerothermal heating on heatshield as vehicle accelerates to Mach 4 during motor burn.

Objective of Analysis:
Determine insulation thickness requirements to protect the vehicle core structure and other components exposed to high heat flux environments.

Viking's Balloon Launch Decelerator Test as Heritage Analysis

- Relied on ground fired motor plume test data.
- Used cylinder plume geometry as "best" representative of actual plume.
- Determined an effective emittance of the plume and doubled it as a conservative measure. **(Did not report what value they used but it has to be less than 0.5).**
- Calculated heat flux on the base cover from the plume data and emittance as shown in figure. Maximum heat flux was 2.9 W/cm^2.

Heat flux in W/cm^2 are ~15% higher than the numbers shown here.

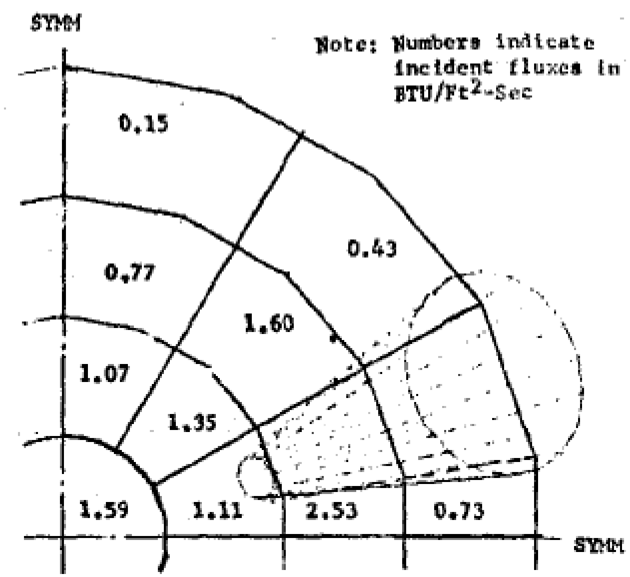


Fig. 9 Radiant Plume Heating Predictions-Base Cover - Supersonic Configurations

From (AIAA-1974-760-687)

Replicating Analysis from BLDT Plume Heating

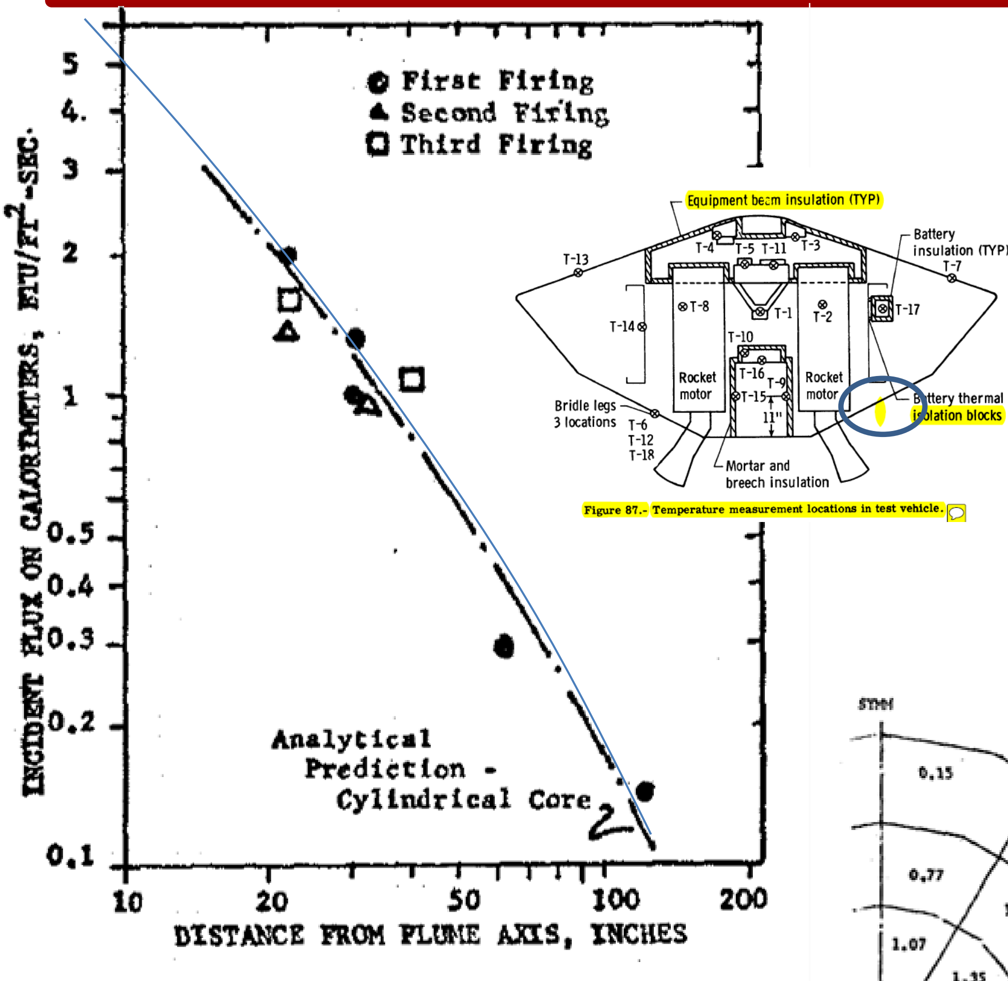
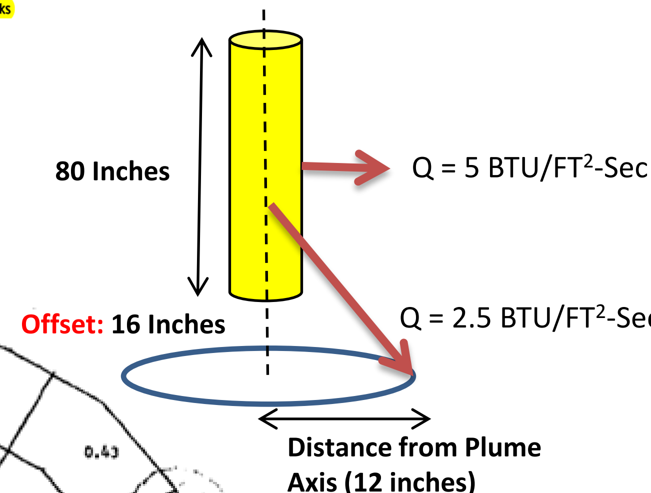


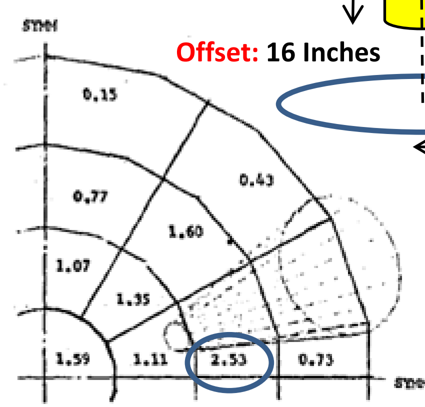
Figure 87.- Temperature measurement locations in test vehicle.

Fig. 8 Ground Firing Data Correlation

From (AIAA-1974-760-687)

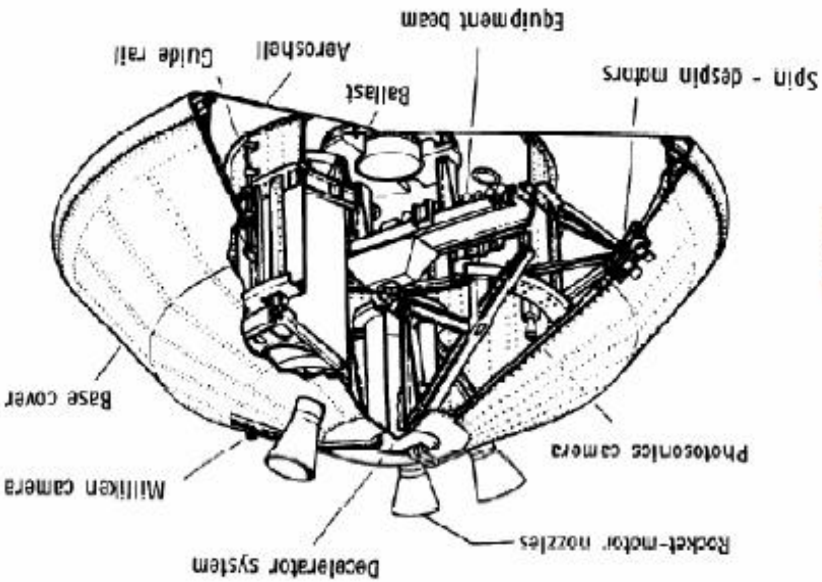
- •BLDT Plume Heat Flux is 5 BTU/FT^2-Sec at nozzle exit. Blackbody plume temp is 1000 K.
- •Built cylinder plume model with BLDT input parameters (estimated dimensions) to replicate their results.



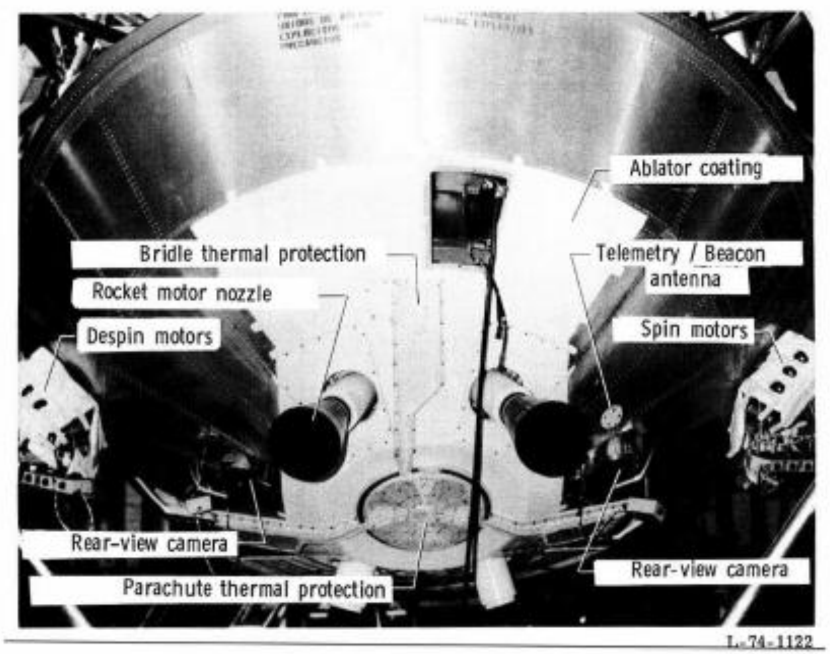


Viking Balloon Launched Decelerator Test

From NASA TN D-7692



Partially covered with ablative material
No signs of overheating on recovered back shell



Rational for Plume Analysis

- Thermal radiation modeling using a cylindrical plume assumption is believed to be conservative based on literature research.
- Model is based off a cylindrical plume and data taken at sea level conditions. This is conservative.
  - From AIAA-1974-760-687, "*particle temperatures during the ground firings are kept at higher levels by a cellular shock pattern within the inviscid core; and this is expected to more than offset the effects of the larger view factors at altitude. This conclusion is supported by data from other programs as well.*"
- A conical plume results in a **more uniform** heat flux at the back shell (Baek 1996)

Plume Heating Analysis Method

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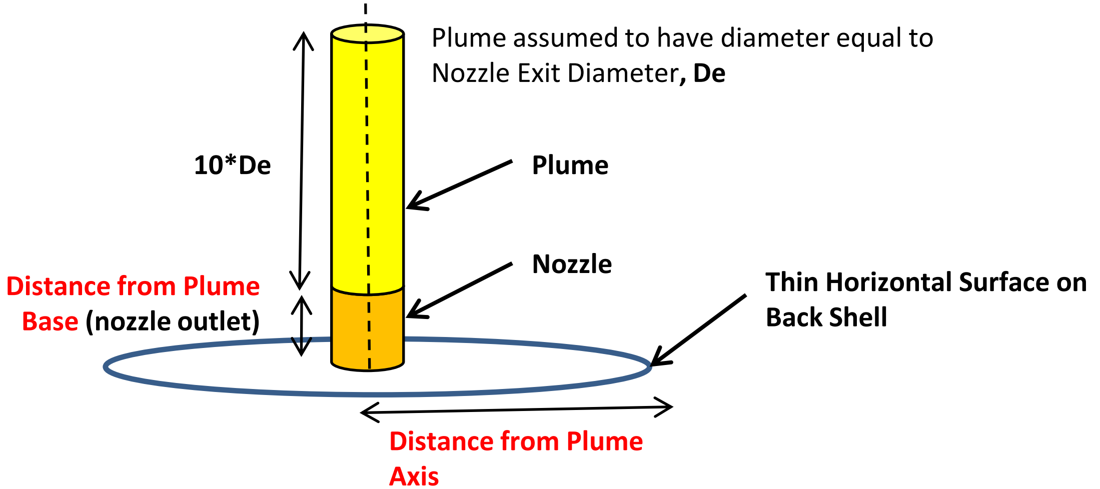
- Heating of Back Shell from Rocket Plume is ~ 100x more significant than from Nozzle and Motor Case
  - Nozzle / Case heating is only relevant at small radial distances or where a surface cannot "see" the rocket plume



- Incident Heat Flux is dependent on both the **Distance from Plume Base** and the **Distance from Plume Axis**.

Cylindrical Model Details

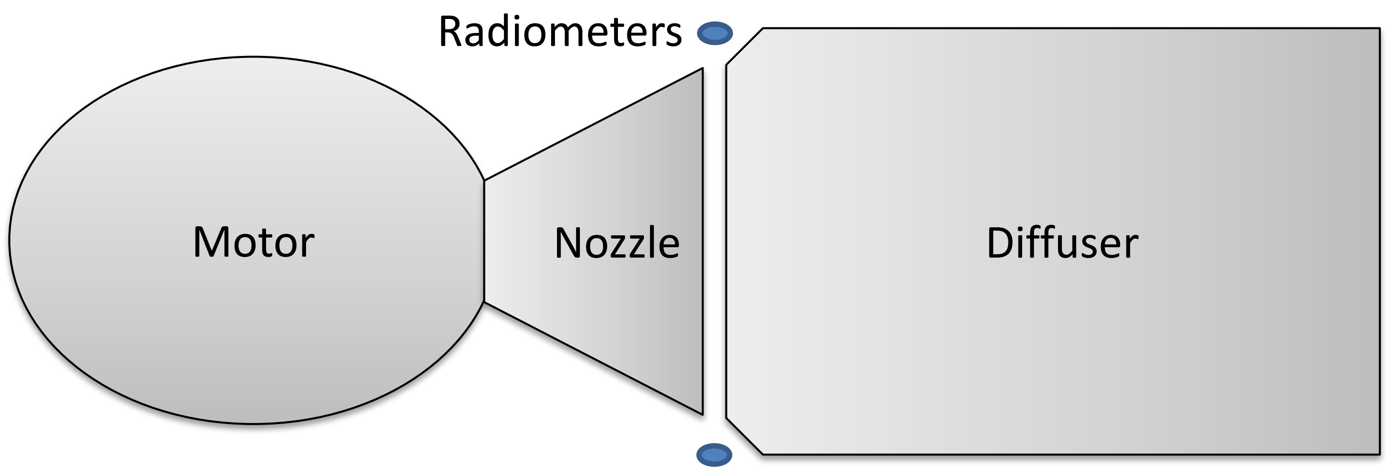
- The chosen plume length of 10*De is a rough estimate based on the continuum portion of rocket plumes. Some other models have used 3 or 5 times nozzle outlet diameter instead. It has been investigated:
  - Choosing a shorter or longer plume has little effect on heating rates. A plume length of 10 times nozzle outlet diameter is reasonable and somewhat conservative. It is expected to be conservative by about 5%, but not more than 15%.
- Effects of scattering (i.e. the "spotlight" or "searchlight" effect) is ignored. Using test data taken at the base is assumed to be adequate.
  - Baek and Kim determine that plume emission, rather than the spotlight effect, is the primary mode of radiant heating on a rocket base.

Baek, S. W. and M. Y. Kim (1997). "Analysis of Radiative Heating of a Rocket Plume Base with the Finite-Volume Method." International Journal of Heat and Mass Transfer **40**(7): 8.

Buna, T. and H. H. Battley (1974). "Thermal Design and Performance of the Viking Balloon-Launched Decelerator Test Vehicles." AIAA **74**(760): 9.

Plume Heating Data

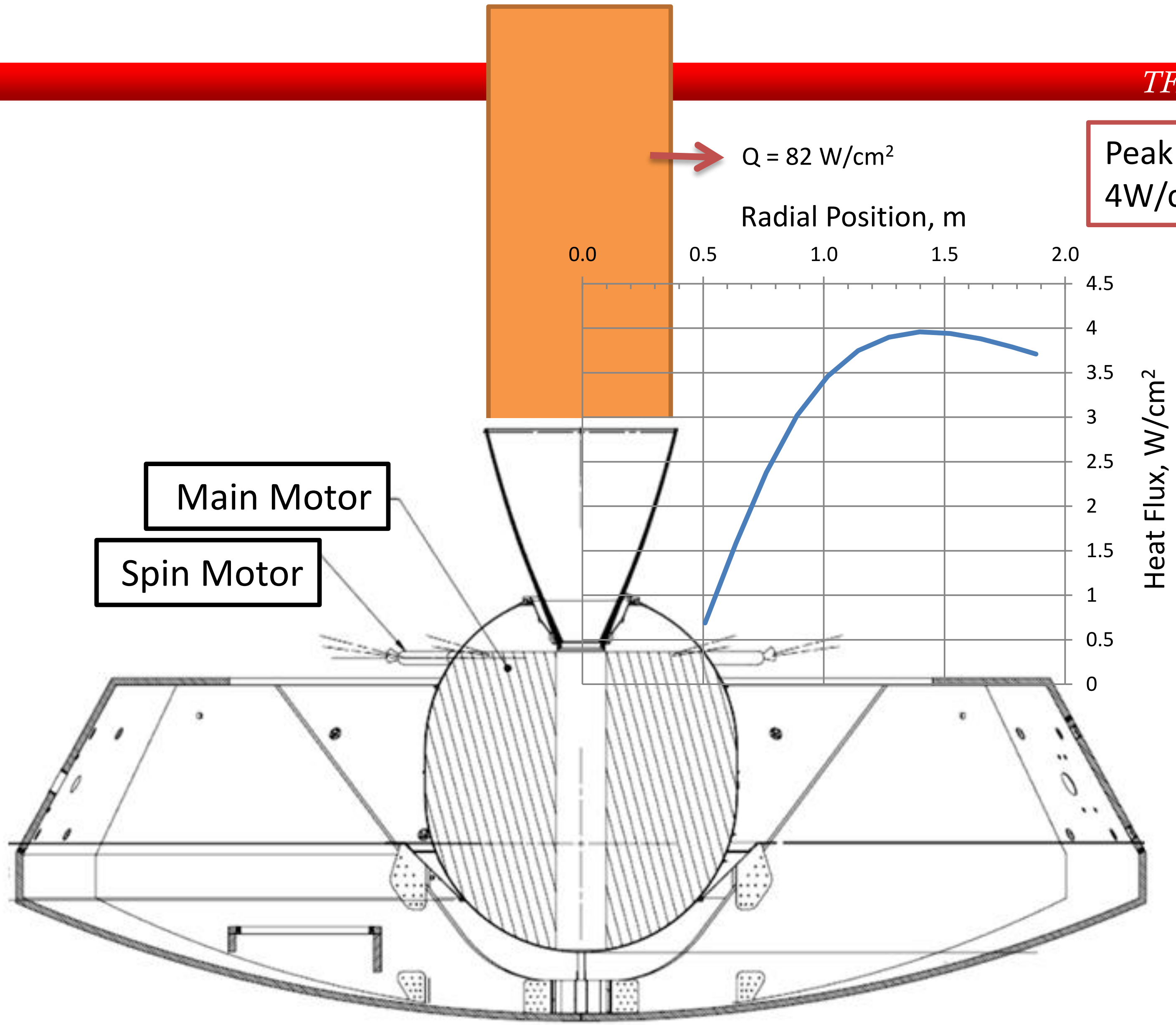
Measured Heat Flux Data of 50 W/cm^2 at radiometer location, yields 82 W/cm^2 at nozzle exit or an equivalent black body temperature of 1950K at nozzle exit.



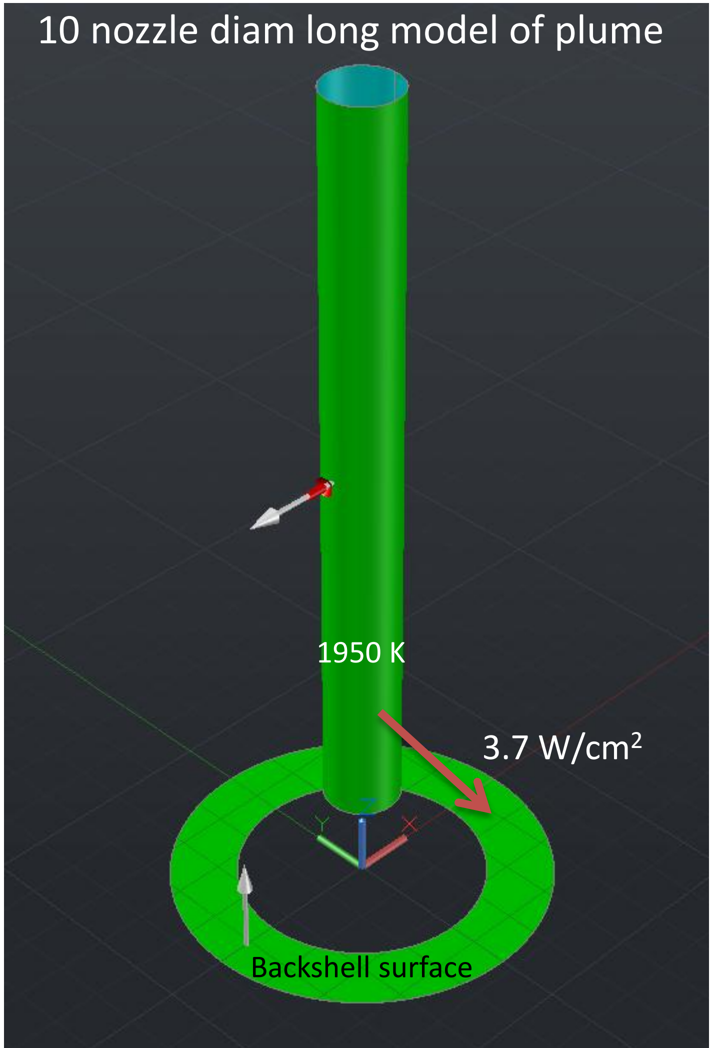
Typical Ground Firing Test Set up for Solid Rocket Motor

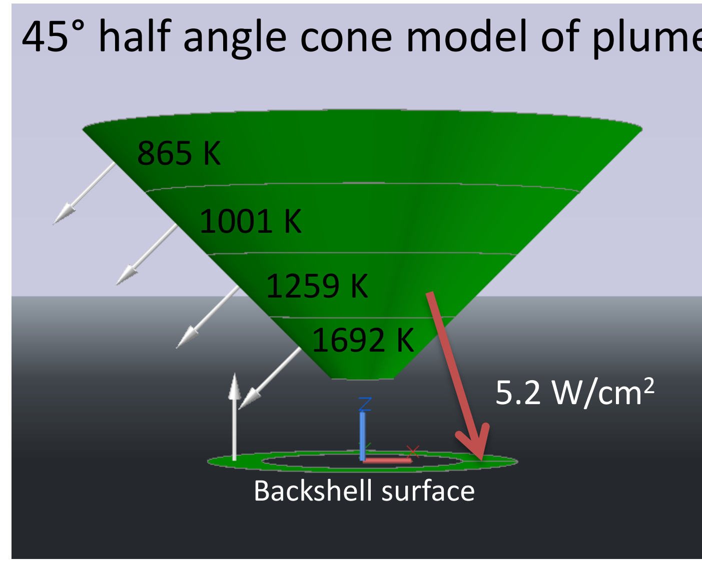
Heat Flux on Backshell

Peak heat flux is 4W/cm²



Thermal Desktop 3-D Plume Model



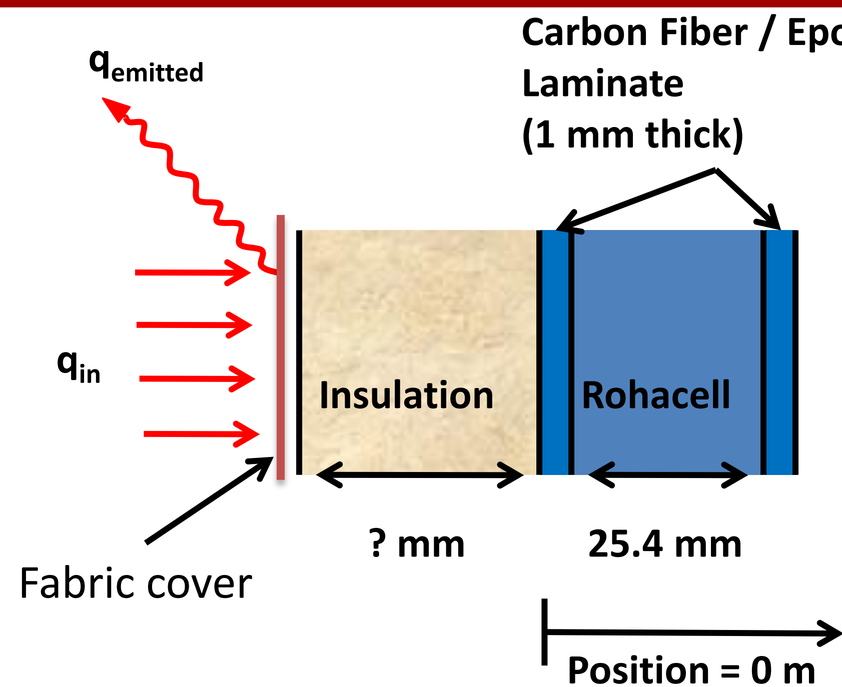


- Plumes are treated as black body emitters.
- Cylinder plume temperature derived from ground fire test data.
- Conical plume temperature derived from isentropic expansion of cylinder plume with $\gamma = 1.21$.
- View factors determined by 3-D model geometry from Thermal Desktop.
- These values are significantly conservative.

Composite Model Overview

- A 1D transient conduction model has been developed using MATLAB to model the insulation, fabric covering and composite structure to be used in the LDSD test vehicles.

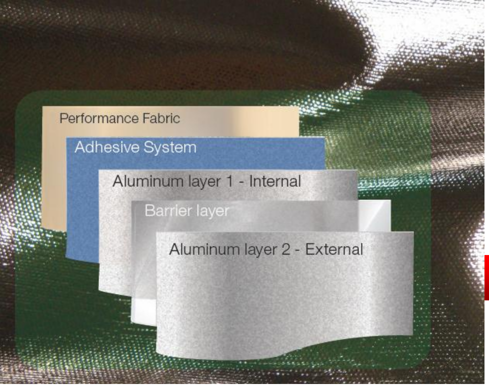
- An initial temperature distribution with a heat flux boundary condition is imposed over a certain amount of time and radiation is emitted from the surface.



* Thermal resistance model for 39% resin and 61% fiber by volume

** The specific heat of Rohacell is assumed to be similar to the specific heat of urethane foam.

Material	Conductivity (W/m-K)	Specific Heat (J/Kg-K)	Density (Kg/m^3)
Carbon-Epoxy Laminate	0.3832*	886	1596
Rohacell	0.029	1045**	51.3



TPS Materials

- Heat Reflective Fabric Covering

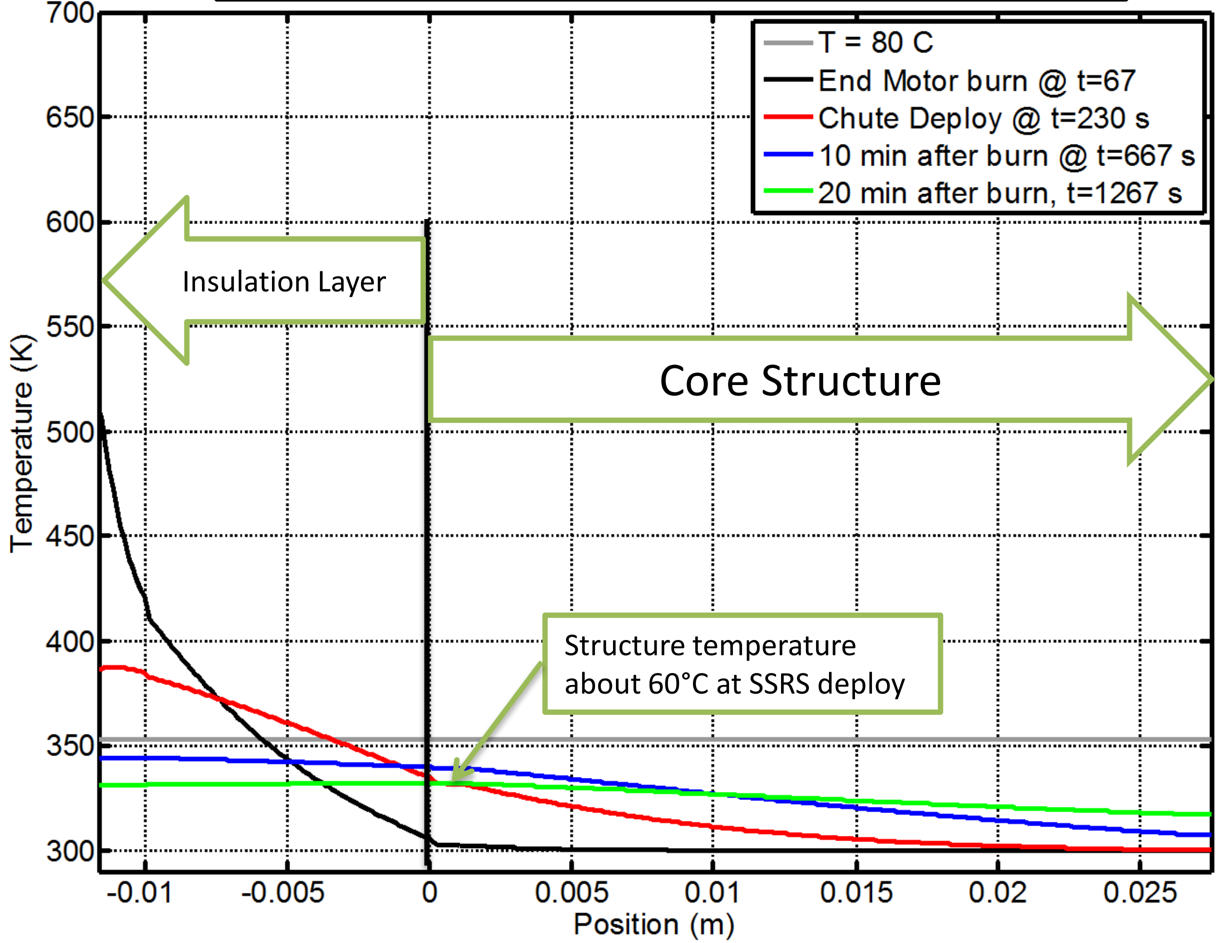
- Manufactured by Newtex Ind.
- Applications: Heat shielding for Automotive, Foundries, Glass/Casting Operations.
- Material: Texturized Fiberglass with Aluminized coating.
- Thickness & areal weight:
  - 1.0 mm, 0.42 kg/m^2
- Thermal properties of fiberglass.
- Temperature limit: 540°C

- Insulation: Q-fiber felt

- Manufactured by Johns Manville
- Applications in: Aircraft, missiles, spacecraft, industrial.
- Material: 99% silica fibers (SiO_2)
- Density: 48 kg/m^3
- Thicknesses & areal weight:
  - 10 mm, 0.46 kg/m^2
- Temperature Limit: 982°C (steady state)
- Thermal Conductivity: 0.08 W/m·K at 300°C.

Insulation and Backshell Transient Temperature Profile

Q-fiber felt, 10 mm thick, 5 W/cm^2 heat flux



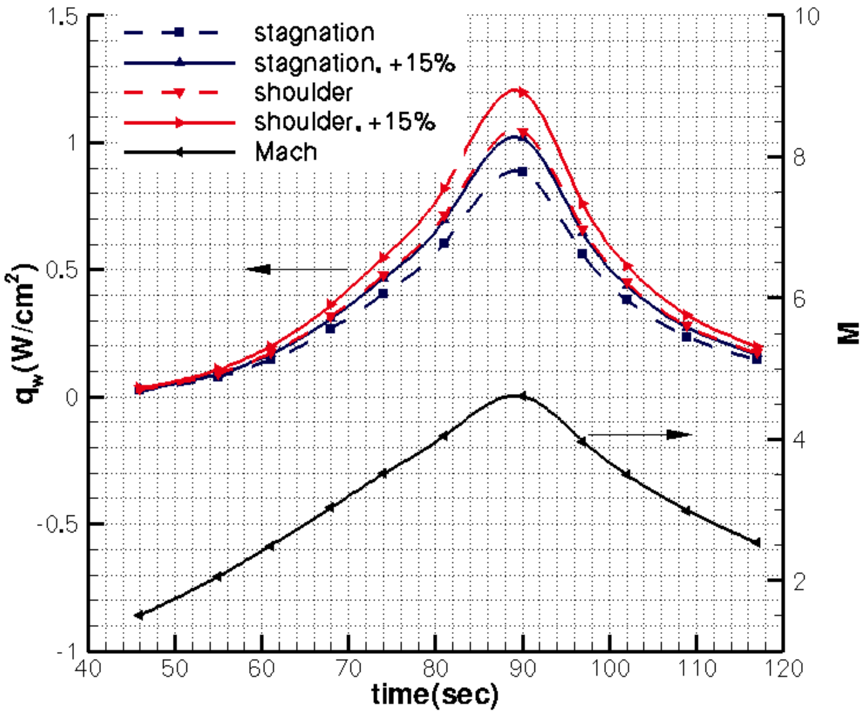
Core structure temp good at all times

Backshell Insulation Summary

- Heat flux on backshell from motor plume heating is conservatively estimated to be less than 5 W/cm^2.
- A 3-layer blanket design is adequate to keep core structure temperature within AFT limits.
- The outer layer of the blanket is a 1.0 mm thick fabric made from fiberglass and an aluminized coating.
- The fabric outer layer has good heat capacity and heat reflectivity to reduce heat flow into the insulation.
- The middle layer is a 10-mm thick Q-fiber felt blanket made from silica fibers.
- The inner layer closes out the blanket and is a thin fiberglass fabric without an aluminum coating.

Aeroshell Heating Analysis

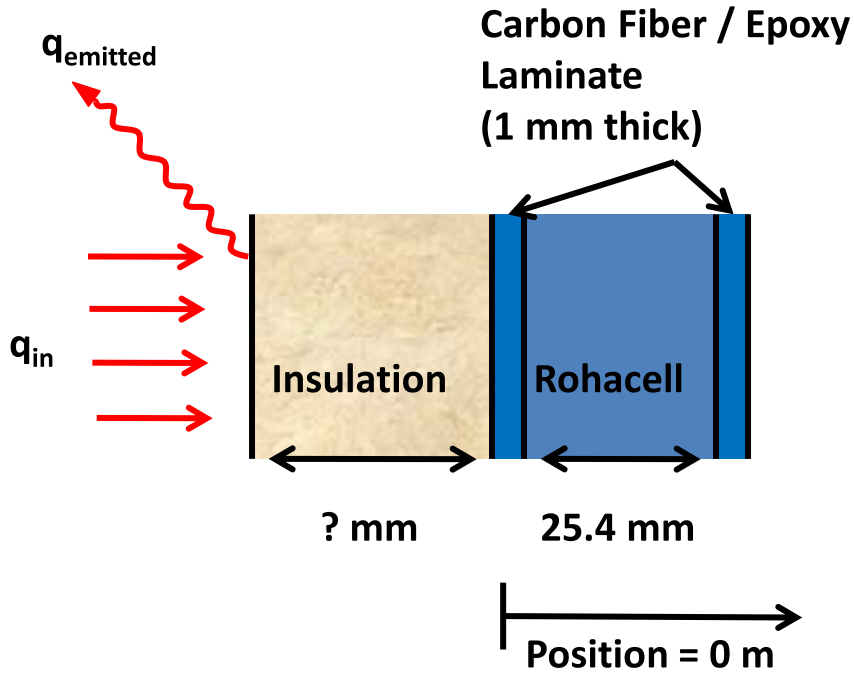
- The aeroshell heat flux during the Supersonic Flight Dynamics Test was provided by analysis from Ames.
- A 1-D conduction model of the insulation layer and the core structure was made to determine the thickness required for insulation.



1-D Model Overview

- A 1D transient conduction model has been developed using MATLAB to model the insulation and composite structure to be used in the LDSD test vehicles.

- The basic formulation for the back shell and the aero shell is identical. An initial temperature distribution with a heat flux boundary condition is imposed over a certain amount of time and radiation is emitted from the surface.



Material	Conductivity (W/m-K)	Specific Heat (J/Kg-K)	Density (Kg/m³)
Carbon-Epoxy Laminate	0.3832*	879	1577.7
Rohacell	0.029	1045**	51.3

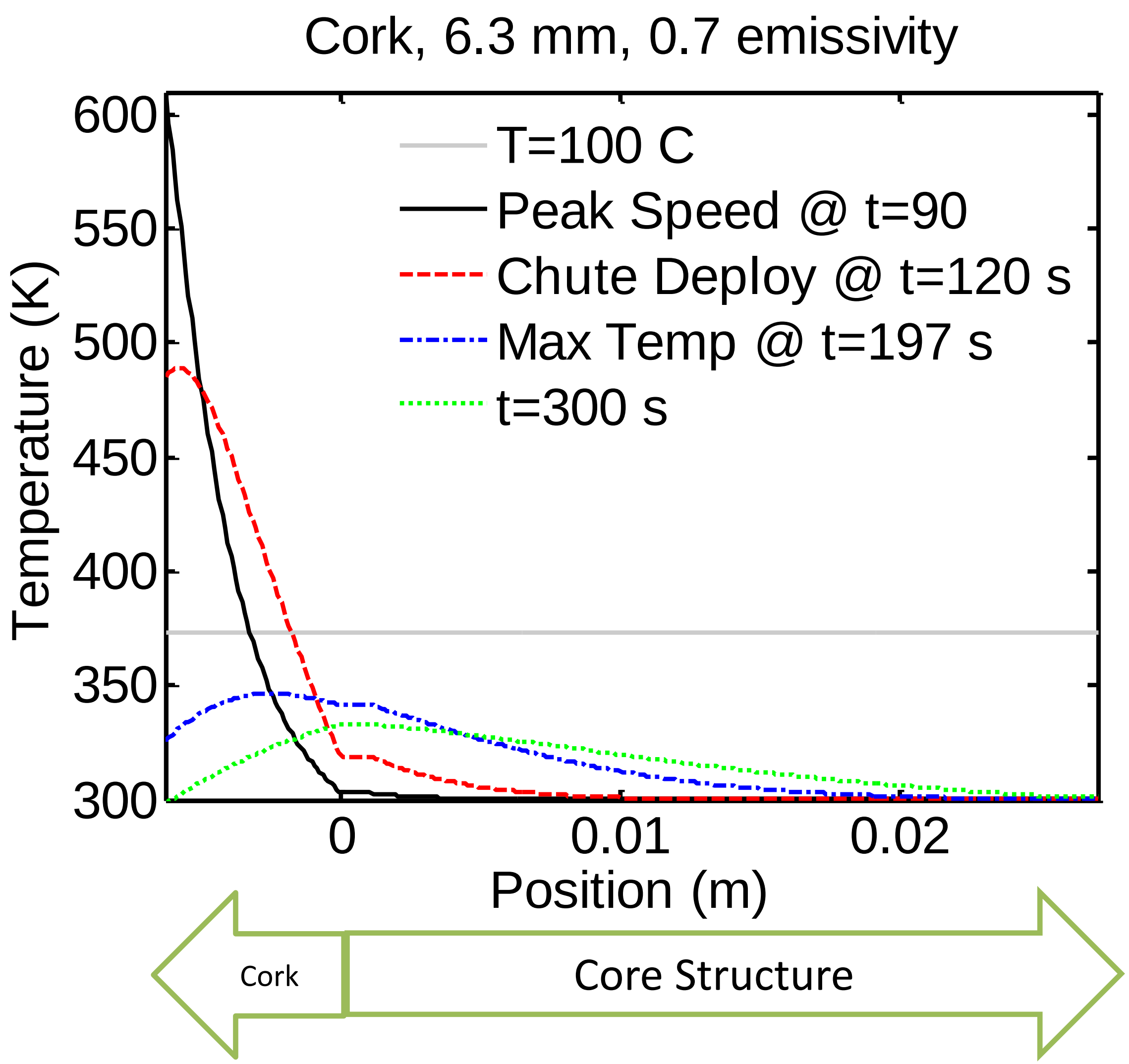
* 39% resin and 61% fiber by volume

** The specific heat of Rohacell is assumed to be similar to the specific heat of urethane foam.

Assumptions

- Primary conduction path is 1D, normal to aero shell surface
- Material properties and aero heating profile defined previously
- Contact Resistances Negligible (conservative)
- Aero shell is facing space, T = 0 K (aggressive)
- Initial temperature = 300 K
- Properties don’t change with temperature
  - Cork properties @ 300 K (aggressive)
  - Alumina silica properties @ 1300 K (conservative)
- Material does not undergo charring or thermal expansion

Transient Temperature Profile for Cork and Core Structure



Conclusions

- A cork layer 6.3 mm thick is adequate to protect the core structure during aerothermal heating.
- Can bond to core structure using silicon adhesive. Also RF transparent.
- Testing by Ames shows no charring expected for this heat flux.