Flame Deflector Ablation Analysis Based on Artemis 1 Launch Environment

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Introduction

The flame trench under Pad 39B contains a flame deflector to safely divert the exhaust plume from the SLS rocket during launch.

- During launch of Artemis I, the flame deflector experienced peak temperatures of over 2,000 degrees Fahrenheit (over 1,000 degrees Celsius) for several seconds.
- These extreme conditions caused ablation (material removal) from the steel plates of the flame deflector.

“Pre vs Post” Flame Deflector scan image measuring the post flight deviations are shown.

This analysis will be used to help determine how to reduce the material loss on the flame deflector plates for future launches

Artemis I Launch
November 16, 2022 at
1:47 AM EST

https://www.youtube.com/watch?v=jrDv0OdMt5s

Flame Deflector

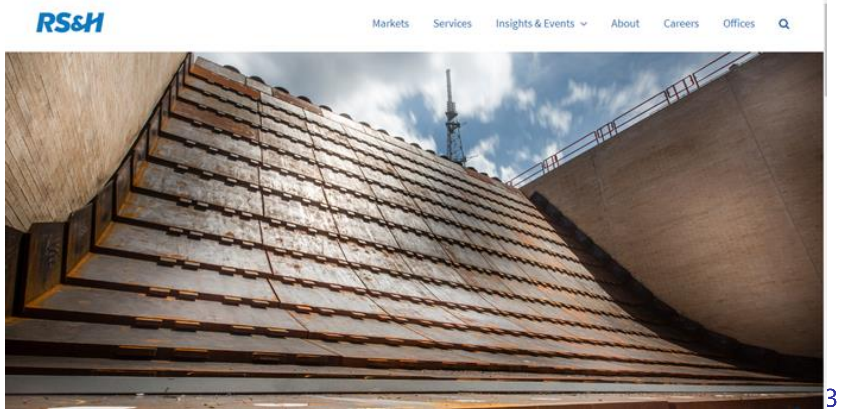
For Artemis I, Exploration Ground Systems at NASA's Kennedy Space Center in Florida designed a main flame deflector deflecting the plume exhaust from the SLS rocket during launch.

- Measuring approximately 57 feet wide, 43 feet high and 70 feet long, the deflector's north side is slanted at about a 58-degree angle and will divert the rocket's exhaust, pressure, and intense heat to the north at liftoff.
- The flame deflector’s purpose will contain and protect the vehicle and surrounding pad structures from the solid rocket boosters during liftoff.

The flame deflector incorporates several design approaches, including steel cladding plates, an open structure on the south side.

- Three-inch thick steel plates are installed on the flame deflector designed to withstand the exhaust and heat.
- A one-inch gap separates the plates on each side to allow for thermal expansion when heated.
- The steel plates closest to the exhaust plume are designed to be replaced if erosion occurs.

Artemis 1 Flame Deflector



Flame Deflector Ablative Damage After Launch

The Artemis I launch exhibited heat rates high enough to ablate steel on the Flame Deflector plates as shown in the figures below. Most of the damage occurred on the Flame Deflector steel plates under the Solid Rocket Boosters.

- The ablative damage occurred in three main areas:
  1. On the downstream edges of the Flame Deflector Plate.
  2. Downstream of the 1.0-inch gaps between the Flame Deflector Plates.
  3. Center of the plates in the gap regions between the teeth.

The image above shows where some of the ablation occurred.

- The left image shows an ablative region which appears to be caused by the plume of hot gas flowing through the 1-inch gap, carving a channel in the lower downstream plate.
- The center image shows the ablation occurring on the outer corner of the steel plate.
- The image on the right shows the same ablative region as the center image measuring a material loss of 1.25 inches of steel.
  - This was the largest loss of material measured.

Flame Deflector Ablative Damage After Launch

The image below shows the ablation scarring on half of the Flame Deflector plates occurring under one of the Solid Rocket Boosters.

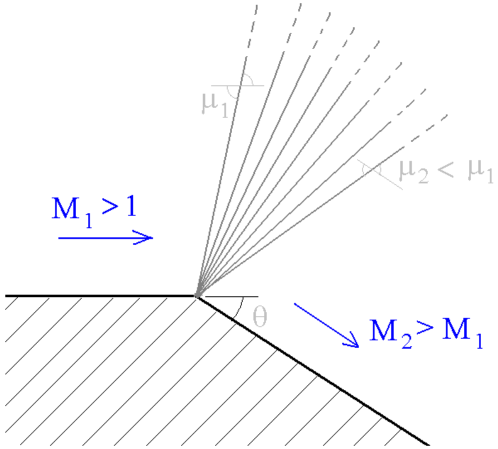
Flame Deflector Ablative Damage After Launch

The current theory regarding ablation on the gap corners of the flame deflector plates may be caused by a compression shock effect (Prandtl-Meyer expansion) increasing the heat flux on the flame deflector plate gap corners in certain local regions.

- Further mitigation of this effect is the focus of the design team to help reduce the material loss at the plate corners.

Michael Barad NASA Ames Research Center
NAS Division's Launch Ascent and Vehicle Analysis (LAVA) team
https://www.nas.nasa.gov/SC18/demos/demo7.html

When a supersonic flow encounters a convex corner, it forms an expansion fan, which consists of an infinite number of expansion waves centered at the corner. The figure on the right shows one such ideal expansion fan.



https://en.wikipedia.org/wiki/Prandtl%E2%80%93Meyer_expansion_fan

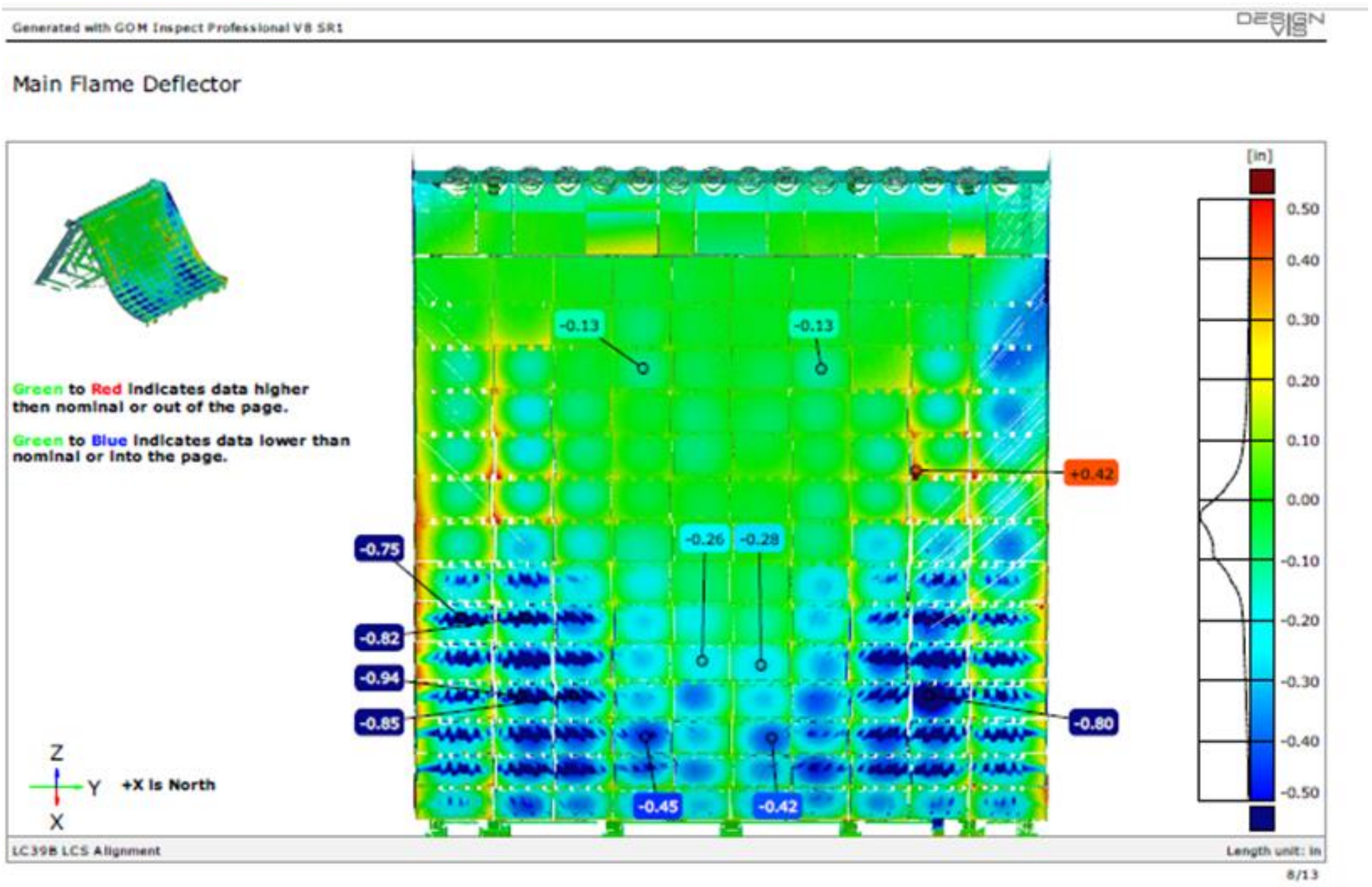
- The intent of this paper is to determine a relatively efficient and quick way to calculate how much heat flux would cause the material loss observed during the Artemis I launch.

Flame Deflector Scanned Deviations

Devin Swanson (Boeing, Design Visualization) performed a “Pre vs Post” Flame Deflector scan to measure the deviations on the Flame Deflector.

Inspector: Devin Swanson
Company: Boeing
Department: Design Visualization
Location: KSC
Date: 12/13/2022
Project: Pre vs. Post Flame Trench Deviations
Pre Launch Scans (Nominal): Scanned 8/24/2021
Post Launch Scans (Actual): Scanned 11/17/2022
Version: A
Software: GOM Inspect V8
Scanning System: Leica P30

- The color bar legend on the right shows the numerical deviations measured.
- The green regions indicate zero deviation,
- The shades of blue indicate negative deviations compared to the scan performed before launch.
    - The darker blue areas are the highest deviation on the plate surface indicating areas of high erosion/ablation.
- The yellow and red areas indicate positive deviation or potential expansion of the plate due to heating.



Generated with GOM Inspect Professional V8 SR1

Main Flame Deflector

Green to Red indicates data higher then nominal or out of the page.

Green to Blue indicates data lower than nominal or into the page.

LC39B LCS Alignment

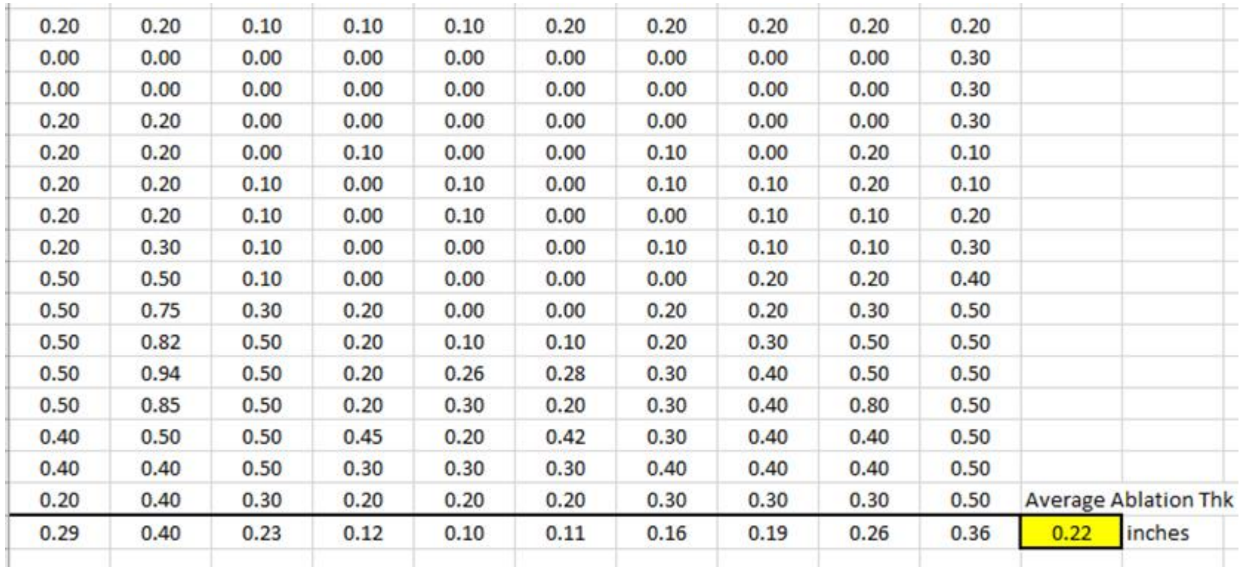
Length unit: in

8/13

Flame Deflector Scanned Deviations

An average deviation was determined by visualizing the scan contours and applying a value for each plate as shown in the figure below.

- An overall average deviation was calculated to be 0.22 inches. The average deviation will be used to determine the heat flux across the plates.



0.20	0.20	0.10	0.10	0.10	0.20	0.20	0.20	0.20	0.20		
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30		
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30		
0.20	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30		
0.20	0.20	0.00	0.10	0.00	0.00	0.10	0.00	0.20	0.10		
0.20	0.20	0.10	0.00	0.10	0.00	0.10	0.10	0.20	0.10		
0.20	0.20	0.10	0.00	0.10	0.00	0.00	0.10	0.10	0.20		
0.20	0.30	0.10	0.00	0.00	0.00	0.10	0.10	0.10	0.30		
0.50	0.50	0.10	0.00	0.00	0.00	0.00	0.20	0.20	0.40		
0.50	0.75	0.30	0.20	0.00	0.00	0.20	0.20	0.30	0.50		
0.50	0.82	0.50	0.20	0.10	0.10	0.20	0.30	0.50	0.50		
0.50	0.94	0.50	0.20	0.26	0.28	0.30	0.40	0.50	0.50		
0.50	0.85	0.50	0.20	0.30	0.20	0.30	0.40	0.80	0.50		
0.40	0.50	0.50	0.45	0.20	0.42	0.30	0.40	0.40	0.50		
0.40	0.40	0.50	0.30	0.30	0.30	0.40	0.40	0.40	0.50		
0.20	0.40	0.30	0.20	0.20	0.20	0.30	0.30	0.30	0.50	Average Ablation Thk	
0.29	0.40	0.23	0.12	0.10	0.11	0.16	0.19	0.26	0.36	0.22	inches

Analysis Methodology

The flame deflector plates under the solid rocket boosters are exposed to extreme temperatures causing a thin section on the top surface of the plate to increase rapidly in temperature and undergo a phase transition.

- This transition either goes to a liquid phase and then to the gas phase or directly to the gas phase (sublimation).
- This analysis assumes the thin section of material will go directly to the gas phase.

It is also assumed that once the material transitions to the gas phase, it is no longer thermally significant.

- The exhaust plume carries the vaporized material away.
- The hottest part of the plume on the deflector plates occurs for about 5 seconds as the vehicle lifts off from the pad.

This analysis does not account for the effects of the SRB aluminum particle impacts on the flame deflector plates and is assumed to be dominated by high heat flux causing the plate surface to vaporize and removed by the exhaust flow.

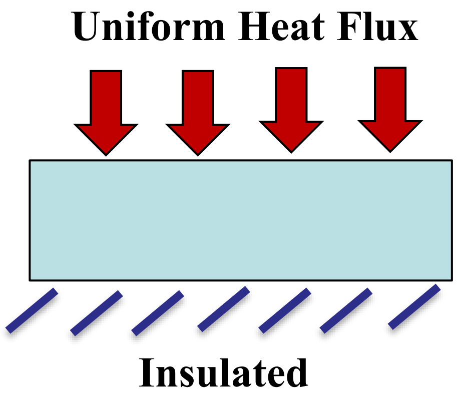
Analysis Methodology

The analysis methodology involves solving the temperature variation in a solid material over time, which includes the heat of sublimation and the material loss due to ablation.

- This method is based on the analysis shown in "Walter Frei, March 30th, 2016, COMSOL Blog".

A highly simplified model of the flame deflector plate assumes that the heat flux across the plate is uniform in time and space.

- An additional assumption is that the material properties of the plate are constant and that there are negligible temperature gradients in the plane of the plate as compared to through the thickness.
- Using these assumptions, the analysis is reduced to a one-dimensional domain.



As the plate material reaches the ablation temperature, the plate changes its state from a solid to a gas and is then removed from the domain.

- Therefore, the solid material cannot become hotter than the ablation temperature, and when the material is at its ablation temperature, there is a loss of mass from the surface that is governed by the material density and the heat of sublimation.

1D Thermal Ablation Model Analysis

Heat transfer in solid equation:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q$$

$$q = -k \nabla T$$

Where

- ρ - the solid density.
- C_p - the solid heat capacity at constant pressure.
- k - the solid thermal conductivity
- u - the velocity field defined by the Moving Mesh node when parts of the model are moving in the material frame.
- Q - the heat source
- q – heat rate equation

A COMSOL Deforming geometry domain node is added to specify the shape of the selected domains governed by the domain boundaries.

- This node is controlled by an explicit deformed mesh boundary condition node and by the shape of adjacent domains (or the node remains fixed if there is no adjacent domain).
- Explicit boundary conditions take precedence over implicit constraints.
- In the interior of the domains, the mesh is controlled by a smoothing equation.
  - The Yeoh mesh smoothing equation is used with a Stiffening factor of 10.

1D Thermal Ablation Model Analysis

Prescribed Normal Mesh Velocity

- The Prescribed Normal Mesh Velocity node specifies the velocity of the boundary in the current normal direction.
- The node can be used on the boundaries of deforming domains.
- No constraints are set on the tangential velocity.
- The moving boundary smoothing option smooths the normal mesh velocity of the Prescribed Normal Mesh Velocity node according to the following equation:

$$v_{mbs} = \delta_{mbs}|v_o|hH$$

Where

- δ_{mbs} is a moving boundary smoothing tuning parameter (unitless),
- h is the mesh element size (SI unit: m), and
- H is the mean surface curvature (SI unit: 1/m), defined as:

$$H = -\frac{1}{2}\nabla_T \cdot n$$

Where

- $\nabla_T \cdot$ is the surface gradient operator, and
- n is the unit vector.

1D Thermal Ablation Model Analysis

Boundary Conditions for 1D Domain Model

- The 1D domain COMSOL model assumes there is no removal of heat through back side of the plate.
- On the heated side of the plate, there is a uniform constant heat flux that approximates the effect of the plume heating (assuming no water).
  - As the material reaches its ablation temperature, it changes its state to a gas and is removed from the modeling domain.
    - Therefore, the solid material cannot become hotter than the ablation temperature.
  - When the material is at its ablation temperature, there is a loss of mass from the surface that is governed by the material density and the heat of sublimation.

1D Thermal Ablation Model Analysis

The thermal boundary condition to model ablation is an ablative heat flux condition of the form:

$$q_a = h_a(T - T_a) \qquad \text{Eq (1)}$$

Where:

- q_a is the heat flux due to material ablation,
- T_a is the ablation temperature,
- h_a is a temperature-dependent heat transfer coefficient
  - that is zero for $T < T_a$ and
  - increases linearly as $T > T_a$

The slope of this curve is very steep, enforcing that the temperature of the solid cannot markedly exceed the ablation temperature.

1D Thermal Ablation Model Analysis

In addition to the thermal boundary condition, there is also the material removal.

- The rate at which the solid boundary is eroded as:
  - $v_a = \frac{q_a}{\rho H_a}$ Eq (2)
- Where
  - v_a is the material ablation velocity,
  - q_a is the heat flux,
  - H_a is the heat of sublimation

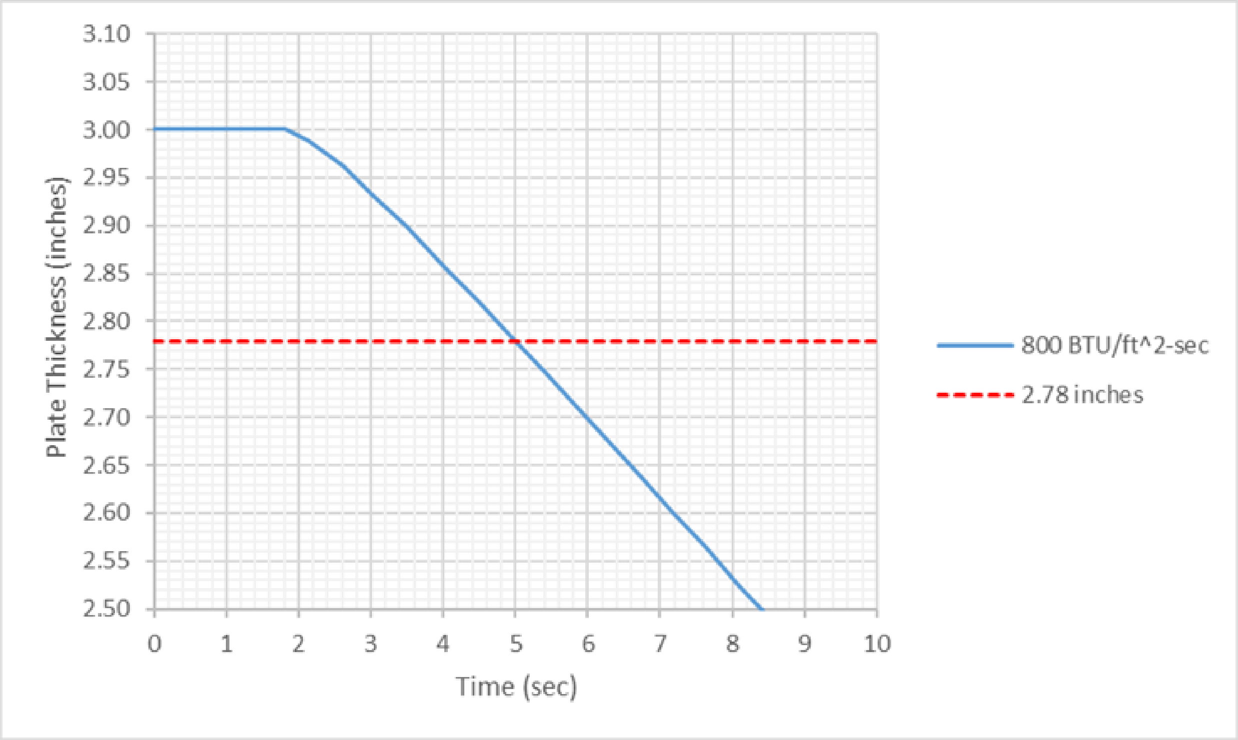
To model the material removal, the COMSOL Deformed Geometry interface is used.

- The Free Deformation feature allows the domain to change in size, as prescribed by the boundary conditions.
- On one side (the insulated side), a prescribed deformation enforces no displacement of the boundary.
- On the other end of the domain, the Prescribed Normal Mesh Velocity condition enforces Equation (2).

Results

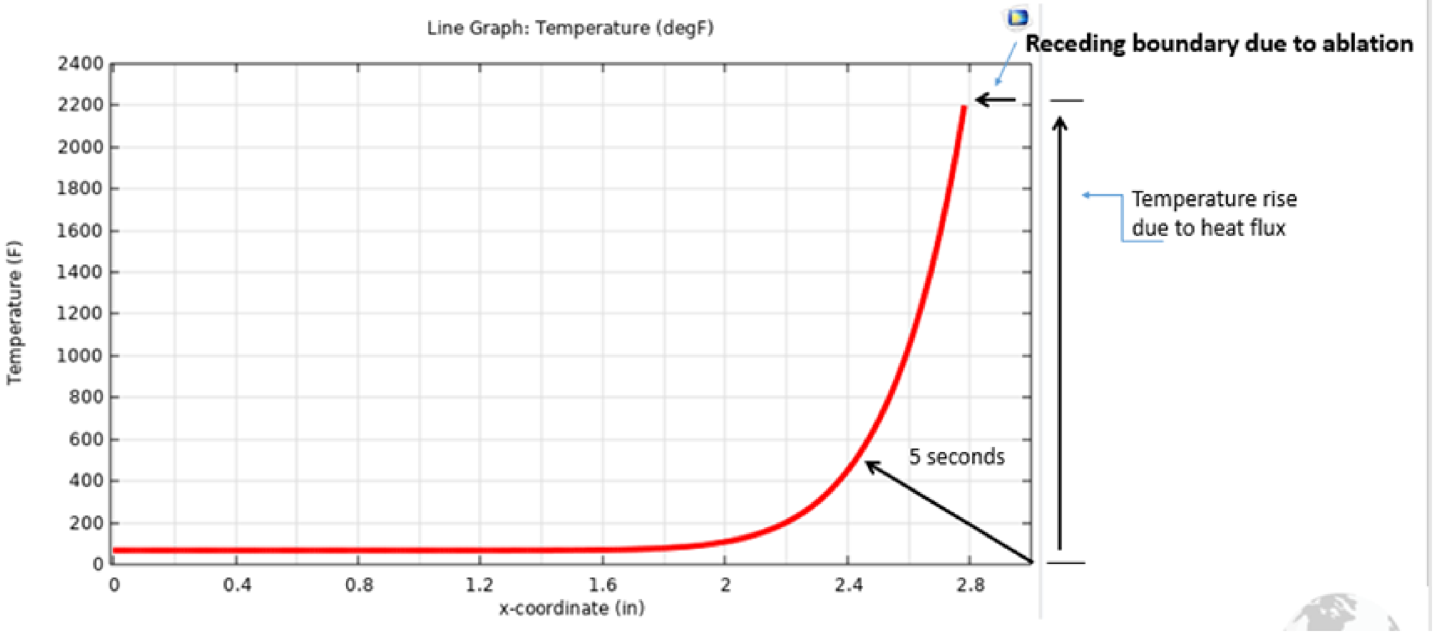
A series of runs were solved varying the heat flux until an average 0.22-inch ablation was achieved at 5 seconds.

- It was determined that an average 0.22-inch ablation corresponds to a heat flux of 800 BTU/ft^2-sec when applied for 5 seconds as shown in the graph below.



Results

The through thickness temperature profile for the 0.22-inch ablation corresponds to a heat flux of 800 BTU/ft^2-sec when applied for 5 seconds shown in the graph below.

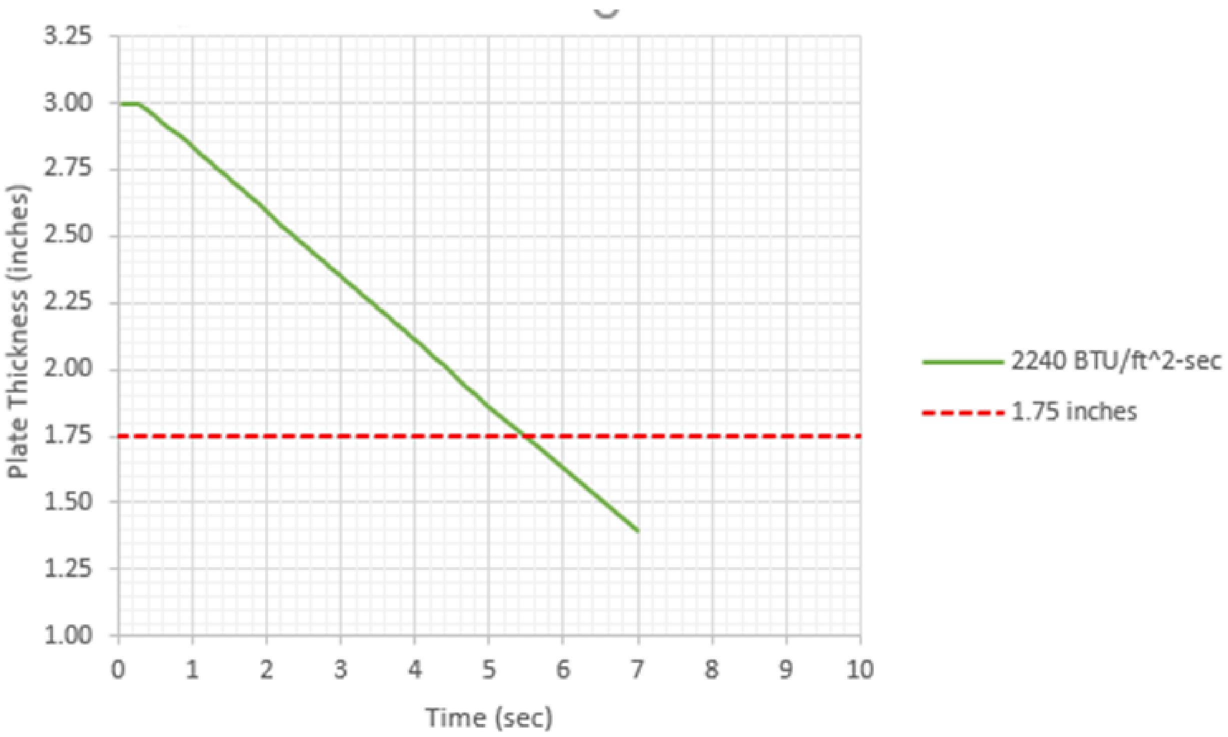


The temperature profile shown above was used to perform a Simcenter NX analysis (Don Myers, KSC) to determine the thermal expansion within the plate.

- This analysis showed that a thin section of the plate on the heated side expanded by about 0.125 inches.
- The one-inch gap between the plates can be reduced to about 0.25 inches.

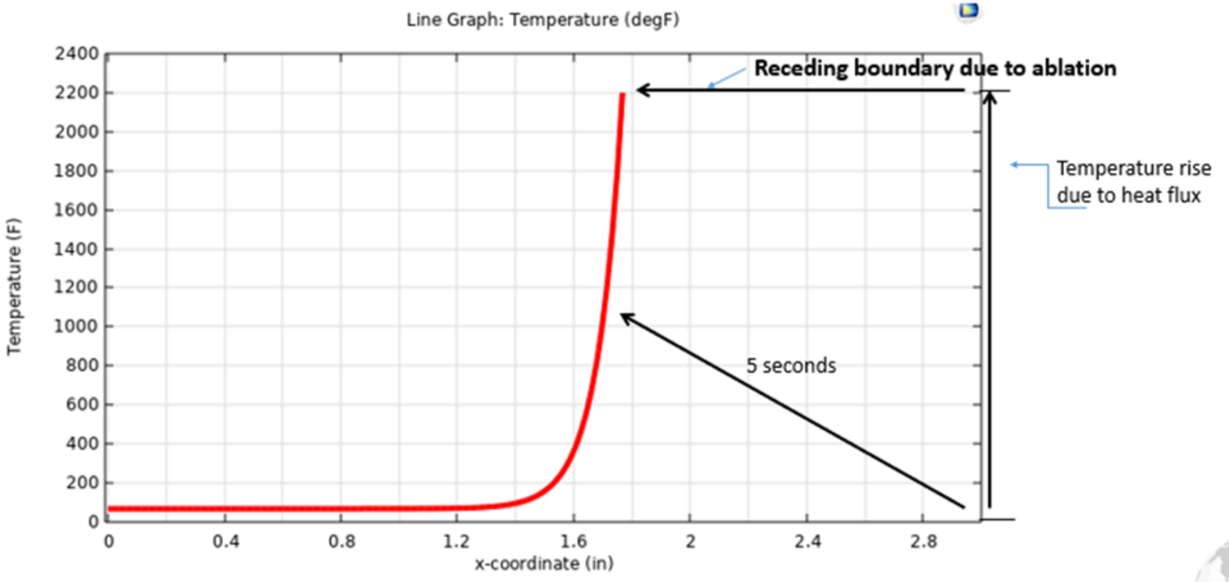
Results

The maximum measured 1.25-inch ablation in localized areas corresponds to a heat flux of 2240 BTU/ft^2-sec applied a little over 5 secs as shown in the graph below.



Results

Through thickness temperature profile for the 1.25-inch ablation corresponding to a heat flux of 2240 BTU/ft^2-sec when applied for just over 5 seconds is shown in the graph below.



Summary and Recommendations

Summary

- The average ablation across the entire deflector plate was calculated to be 0.22 inches based on the scanned Post Launch Deviations.
- The 0.22-inch ablation corresponds to a heat flux of 800 BTU/ft^2-sec when applied for 5 seconds.
- Localized higher heat fluxes causing greater ablation occur at gaps (channel flow) and below sharp corners.
  - The measured 1.25-inch ablation in localized areas corresponds to a heat flux of 2240 BTU/ft^2-sec applied for just over 5 secs.

Recommendations

- Based on this analysis, it was recommended to minimize channel flow by reducing the gap thickness between plates from one inch to 0.25 inches.
- Eliminate sharp corners on the deflector plates to reduce the compression shock effects of the Prandtl-Meyer expansion fan.

Acknowledgements

ACKNOWLEDGEMENTS

- The author would like to thank Kennedy Space Center Exploration Ground Systems and Boeing for their support of this work.