FLAME DEFLECTOR ABLATION ANALYSIS BASED ON ARTEMIS I LAUNCH ENVIRONMENT

William M. Dziedzic
Kennedy Space Center

ABSTRACT

This paper presents the ablative analysis methods used to determine Artemis I launch load environment on the flame deflector for the design based on Artemis I Assessments. The flame trench under Pad 39B at Kennedy Space Center contains a flame deflector to safely divert the exhaust plume from the Space Launch System (SLS) rocket during launch. During launch of Artemis I, the refurbished flame trench and the new 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. This paper contains flame deflector heat flux values for design based on Artemis I assessment. Post flight images of the flame deflector are shown along with “Pre vs Post” Flame Deflector scan image to measure the post flight deviations. Using COMSOL, a method to calculate heat flux values due to measured deviations in the Flame Deflector plates caused by ablation is shown. This analysis will be used to help determine how to reduce the material loss on the flame deflector plates for future launches.

INTRODUCTION

The millions of pounds of thrust during lift-off for the Artemis I Space Launch System (SLS) rocket can cause quite a bit of damage on the surrounding ground system. Exploration Ground Systems at NASA's Kennedy Space Center in Florida designed a new 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. This will help contain and protect the vehicle and surrounding pad structures from the solid rocket boosters during liftoff.

The deflector incorporates several design approaches, including steel cladding plates, and an open structure on the south side. Thick steel plates installed on the flame deflector are designed to withstand the exhaust and heat. The steel plates closest to the exhaust plume are designed to be replaced if erosion occurs. A one inch gap separates the plates on each side to allow for thermal expansion when heated. Artemis I post flight inspection has shown significant material loss near the gap regions. Images of the material loss is shown later in this paper. The design team is focused on possibly reducing the gap thickness using analysis.

There have been several CFD studies on the numerical simulation of gap effects in supersonic and hypersonic flows. Some studies were carried out with comparison to wind tunnel experiments. For some additional details on gap effects in supersonic and hypersonic flows please see references 5, 6, and 7 at the end of this paper for further details. As written in Reference 6 "…peak values of the heating ratio at the corner of the windward surface goes up with the increase of the Mach number." With the increase of Mach number, the boundary layer becomes thinner, thus the mass flow rate of outflow into gaps decreases, which causes a decrease of heating ratio on the windward surface of gaps. Owing to the compression effect of the subsequent shock wave, the heating ratio at the corner of the windward surface goes up as Mach number increases."

The current hypothesis on the gap corners of the flame deflector plates is 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.

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.

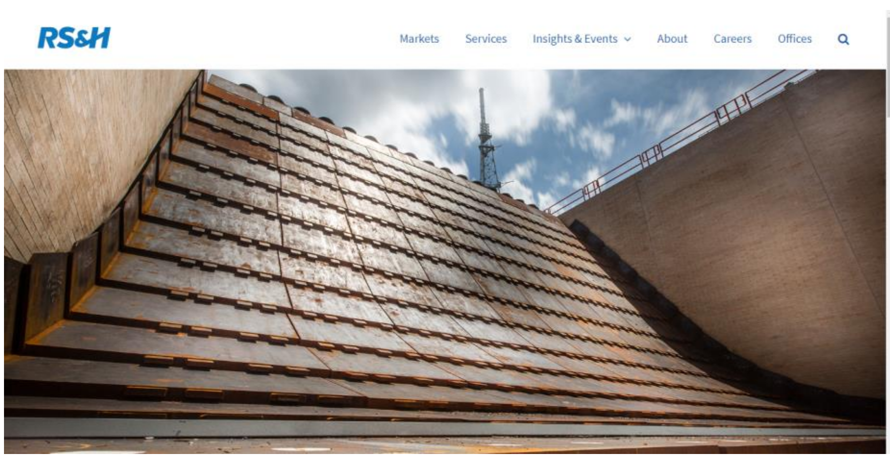

Figure 1 Artemis I Flame Deflector Design

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 plates in the gap regions between the teeth.

The image below 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” of steel. This was the largest loss of material measured.

Figure 2. Artemis I Post Flight image of Ablation in Local Areas of Flame Deflector Plates

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

Figure 3 Artemis I Post Flight image of Ablation on Right Side of the Flame Deflector

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

Figure 4 Boeing, Design Visualization Pre vs Post Flame Deflector Scan Information

The image below is a color contour plot showing the numerical deviations from the “Pre vs Post” Flame Deflector scan. 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 expansion of the plate due to heating.

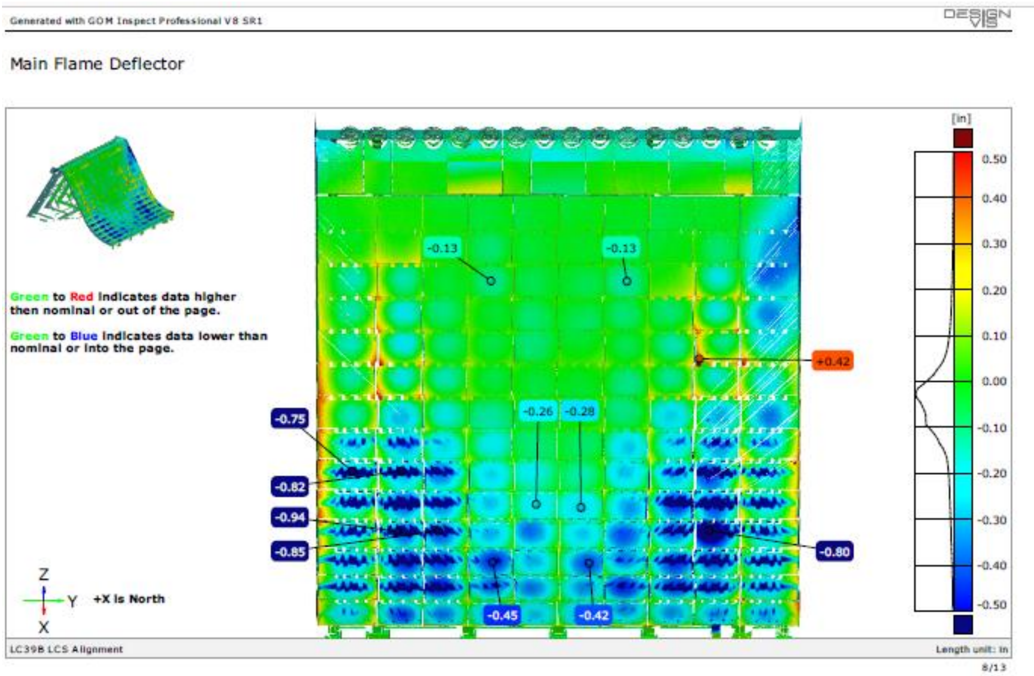

Figure 5 Boeing, Design Visualization Scanned Post Launch Artemis I Material Thickness Loss on Flame Deflector Plates

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.

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

Figure 6 Average Material Thickness Loss on Each Deflector Plate

ANALYSIS METHODOLOGY

The flame deflector plates under the solid rocket boosters (SRB) are exposed to extreme temperatures causing a thin section 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. This is a reasonable assumption since the exhaust plume carries the vaporized material away (ablation). The hottest part of the plume exhaust on the deflector plates occurs for about 5 seconds.

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.

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 Reference 1, “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 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.

A thermal boundary condition is applied for the solid material that doesn't exceed the sublimation temperature.

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.

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:

$$\frac{\partial X}{\partial t} \cdot n = v_o + v_{mbs}$$

where v_o is the desired normal mesh velocity, and v_{mbs} is a smoothing velocity according to:

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

Here 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.

<u>1D Modeling Thermal Ablation Analysis for Material Removal</u>

- Assumptions
  - Sublimation occurs at the surface.
  - No erosion due to solid particles from the plume.
  - As the material reaches its ablation temperature, it changes its state to a gas and is removed from our modeling domain.
    - Once the material transitions to the gas phase, it is no longer thermally significant.
    - The surrounding gas flow carries the vaporized material away.
  - The heat flux across the flame deflector plate is uniform in time and space.
  - The material properties of the flame deflector plate are constant
  - There are negligible temperature gradients in the plane of the plate as compared through the thickness.

Under these assumptions, the model can be reduced to a one-dimensional domain.

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 our 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. This requires both a thermal boundary condition and a model for the material removal.

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
  - zero for $T < T_a$ and
  - increases linearly as $T > T_a$.

In addition to the thermal boundary condition, there is also the material removal. The rate at which the solid boundary is eroded is given by the following equation:

$$\nu_a = \frac{q_a}{\rho H_a} \qquad \text{Eq (2)}$$

Where

- ν_a is the material ablation velocity,
- q_a is the heat flux,
- H_a is the heat of sublimation
- ρ is the material density,

The flame deflector plate model consists of a 1D domain that represents the 3.0-inch-thick plate. The Heat Transfer in Solids interface is used to model the temperature over time. The incident heat flux is applied at one side and the thermal insulation condition is applied at the other side.

Material Removal

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), the material removal rate.

The mesh for this model contained 100 1-D elements. The fully coupled solver uses the damped version of Newton's method. The linear system used the multifrontal massively parallel sparse direct solver. The solver type was set to the implicit time stepping method using the backward differentiation formula.

FLAME DEFLECTOR ANALYSIS RESULTS

To determine the heat flux necessary to ablate an average 0.22 inches, a COMSOL model was created. The model consists of a 1D domain that represents the 3.0-inch-thick Flame Deflector plate. The Heat Transfer in Solids interface is used to model the temperature evolution over time. The incident heat flux is applied at one side of the plate and the thermal insulation condition is applied at the other side.

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

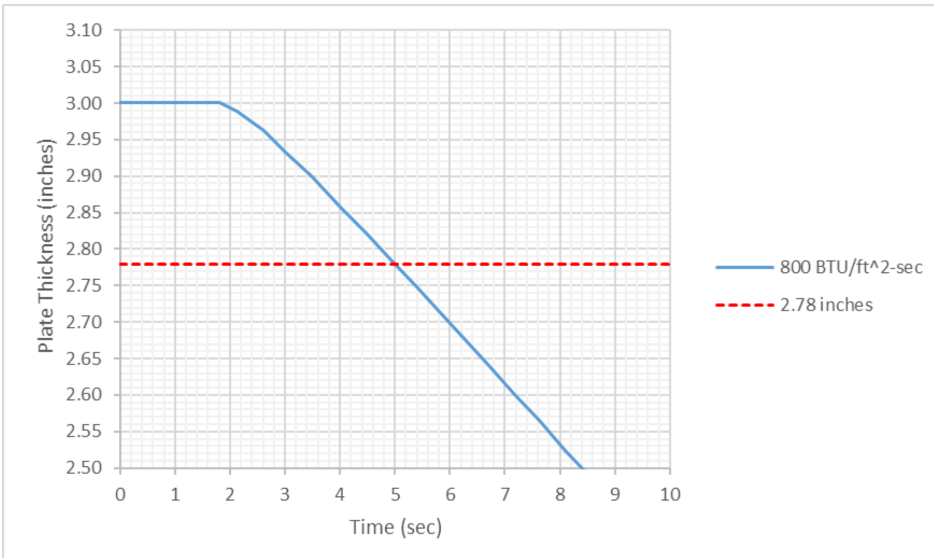

Figure 7 Deflector Plate Thickness, 800 BTU/ft^2-s

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.

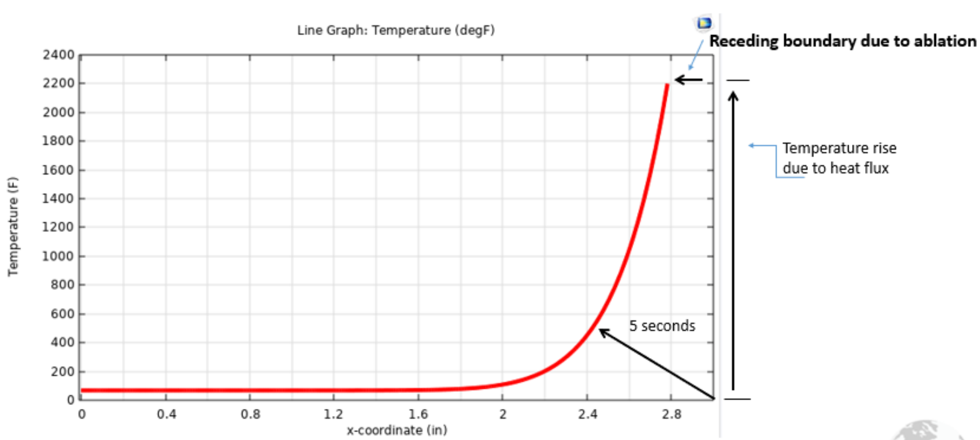

Figure 8 Temperature Profile Through Deflector Plate After 5 Seconds, 800 BTU/ft^2-s

The temperature profile shown above was used to perform a Simcenter NX analysis (by Don Meyers, 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.

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

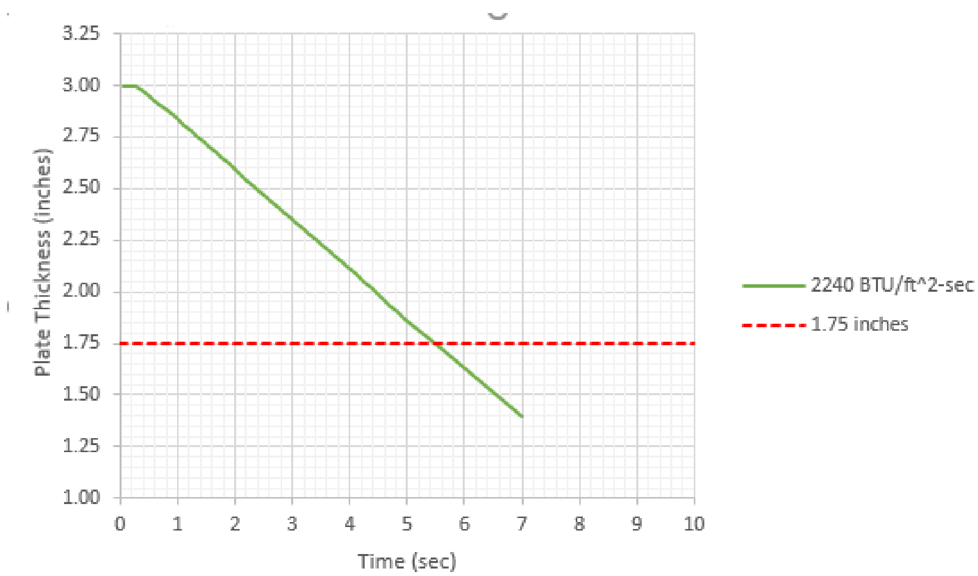

Figure 9 Deflector Plate Thickness, 2240 BTU/ft^2-s

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

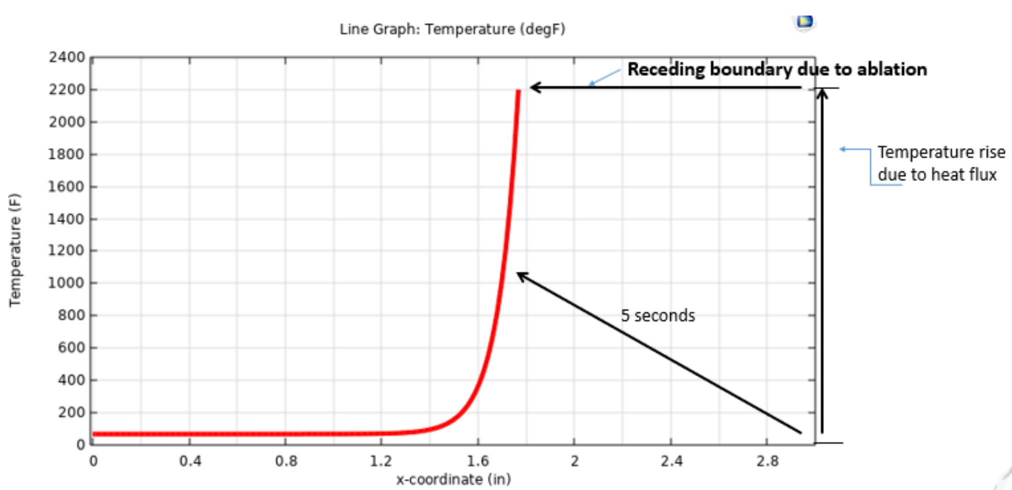

Figure 10 Temperature Profile Through Deflector Plate After 5 Seconds, 2240 BTU/ft^2-s

SUMMARY AND RECOMMENDATIONS

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 to 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 5 secs.

Based on this analysis, it is 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

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