USING THERMAL DESKTOP TO MODEL THE EFFECTS OF PLUME HEATING ON MLI

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ABSTRACT

Gateway draws on experience from International Space Station (ISS) and geostationary satellites for many aspects of design, including Multilayer Insulation (MLI) material selection. MLI is used on many external surfaces, some of which can be exposed to high plume heating from visiting vehicle during docking and undocking. Due to Gateway's smaller size and closer proximity of sensitive hardware to plumes from visiting vehicles, the expected and contingency plume heating loads are higher than those experienced by the ISS. Because of MLI's low mass and thermal conductivity between layers, high plume heating loads can potentially heat MLI past its thermal limits. MLI is typically modeled as a single node of insulation with a given effective emissivity. This method is not adequate for modeling plume heating impacts because the temperature of each individual layer cannot be determined. Modeling MLI is complicated because there are several layers and the conduction between each layer is undefined. It is further complicated by the variety of material options for MLI and their respective mass, optics, transmissivity, and temperature limits.

This paper shows modeling of a MLI blanket exposed to solar and plume heating loads using Thermal Desktop. Several sensitivity studies were run including examining distance between layers, varying effective emissivity, effects of different MLI materials, and plume heating loads and durations.

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

α	Solar absorptivity
A	Area of MLI surface
c_p	Specific heat
ε	IR emissivity
ε^*	Effective emissivity
$\varepsilon_{theoretical}$	Theoretical Emissivity

$G_{interface}$	Thermal conduction between layers
k	Thermal conductivity
N	Number of internal MLI layers
$\dot{q}_{blanket}$	Total heat transferred through blanket
$\dot{q}_{radiation}$	Heat transferred through the blanket by radiation
$\dot{q}_{conduction}$	Heat transferred through the blanket by conduction
ρ	Density
$R_{interface}$	Thermal Resistance between layers
R_{total}	Total thermal resistance throughout the entire MLI blanket
σ	Stefan-Boltzmann's constant
T_{surf}	Steady state temperature of MLI surface with no conduction
T_{sink}	Temperature of internal structure boundary node
τ	Solar transmissivity

INTRODUCTION

MLI is a thin, lightweight blanket consisting of multiple layers of reflecting material and is an effective insulator in vacuum due to the low thermally conductive path and the low radiative heat transfer between layers. MLI blankets used on the Gateway program draw heritage from those used in Geostationary Orbit (GEO) and Low Earth Orbit (LEO), from small satellites to the ISS. Because of this, some blankets are better equipped to meet certain requirements for Gateway. GEO blankets are better at handling the harsh radiation environment Gateway will experience, but ISS blankets are more equipped to handle plume heating due to dealing with multiple vehicles docking and firing thrusters nearby. It is expected that Gateway surfaces will need to withstand even higher plume heating than ISS surfaces due to Gateway being more compact than ISS while still having large visiting vehicles docking. Because of the low conduction and low mass of MLI blankets, high plume heating loads may heat some MLI past its thermal limits. Temperature limits of MLI layers vary significantly as can be seen in **Error! Reference source not found.**.

Thermal modeling is the easiest way to get a first look at what temperature individual layers could be within a specified environment. Typically, when modeling MLI, it is represented as a single node of insulation with a given effective emissivity. This method is not adequate for modeling with plume heating because individual MLI layers are not modeled and thus layer temperature cannot be measured. Modeling MLI is complicated because conduction between each layer is undefined and the many design options for MLI and their respective mass, layer optics, layer thickness, transmissivity, and temperature limits must be considered. This paper thermally models a multi-layer blanket subjected to high plume heating loads in Thermal Desktop. A 21-layer blanket with a beta cloth exterior layer, Kapton with vapor deposited aluminum on top side second layer, double aluminized Mylar internal layers, and double aluminized Kapton scrim innermost layer is used in this example, as seen in Figure 1. This model assumes no separators between layers. The assumed optical and thermophysical properties for this stack up can be seen below in **Error! Reference source not found.**. Sensitivity analyses were performed examining, distance between each layer, effective emissivity, and plume heating profile.

Table 1. Material Temperature Limits

Material	**Intermittent (°C)**	**Continuous (°C)**
Beta Cloth	315	260
Kapton	400	290
Aluminized Mylar	150	121

Table 2. Optical and thermophysical properties of example blanket layers [1] [2] [3].

Material	**α**	**ε**	**Solar τ**	**ρ (kg/m³)**	**Cp (J/kg·°C)**	**k (W/m·°C)**
Beta Cloth	0.15	0.88	0.28	1270	750	1.38
Aluminized Kapton	0.14	0.05	0	1400	1090	0.12
Non-Aluminized Kapton	0.44	0.71	0	1390	1170	0.14
Aluminized Mylar	0.14	0.04	0	1390	1170	0.14

THERMAL MODEL

The thermal model is a 1 m^2 blanket with each layer modeled individually. The thickness of each layer is taken from blanket specifications. Between each blanket layer is a face-to-face contactor and between the innermost layer and the boundary node there is an additional conductor. The boundary node in this model represents the vehicle surface that is under the blanket. Surrounding the stack-up is a closeout that prevents radks from escaping.

The distance between each layer is initially assumed to be 0.01 inches. A sensitivity analysis was run using this parameter and will be discussed later in this report. The initial ε* was set to 0.03 and a sensitivity analysis was also run on this value.

The solar heating is provided by a solar source in Thermal Desktop. This is a 1 m^2 layer that sits above the MLI stack-up. This solar source emits radks with a radiant flux of 1400 W/m^2. The plume heat is modeled as a heat load that is applied across the outermost layer of the 1 m^2 blanket. A sensitivity analysis was run to determine which combination of plume exposure duration and intensity would result in the largest temperature spike.

The internal temperature for the boundary node was set to 20 °C, this was based on nominal internal volume shell temperature. The inner Scrim layer of the MLI is connected to this boundary node by a 10 $W/m^2/°C$ conductor. This conductor value was chosen because it is large enough to not act as a bottleneck to heat transfer.

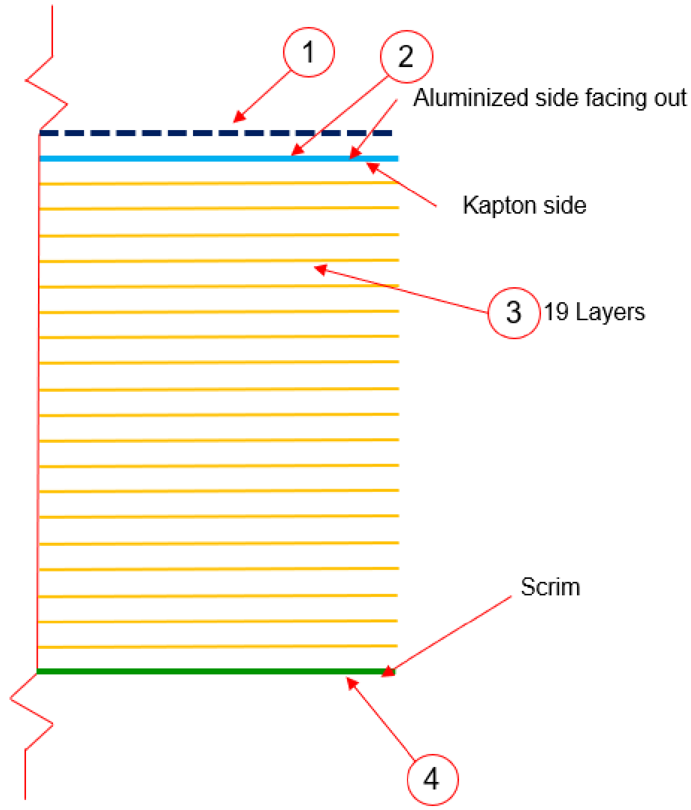

Figure 1. MLI Stack Up Diagram

Thermal Desktop performs radiation calculations by putting surfaces into radiation analysis groups. These groups determine which surfaces see radks from various sources. In this model, the top side of the beta cloth layer radiates to space and absorbs the solar source, while the inner side of the beta cloth radiates to the Kapton layer. Due to the transmissivity of beta cloth, the top layer of Kapton radiates out to both space and the beta cloth layer. Additionally, the bottom side of the Kapton layer radiates internally to the next layer down. Each internal Mylar layer radiates to the layer above and below it. The innermost layer of Scrim only radiates out from the top to the nearest internal layer, while the bottom side has no radiation. Below in Figure 2 is the model as it appears in Thermal Desktop.

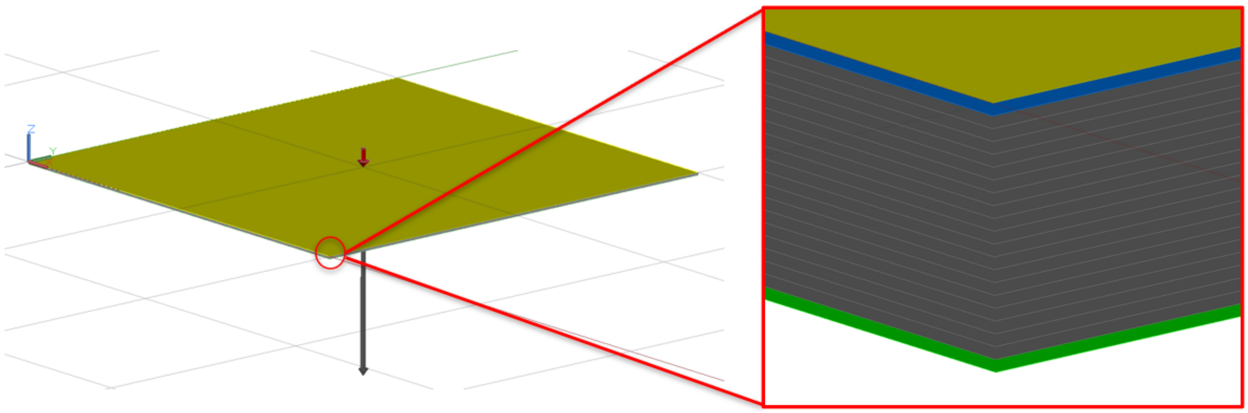

Figure 2. Thermal Desktop Model

To determine initialization temperatures, the model is first run in a steady state with the solar source as the only active heat load. The model is then run in a 300 second transient case that initializes with the previously determined steady state temperatures. During the transient case, the plume heat load is applied at the start of the run and the solar source is active the entire run.

CONDUCTION CALCULATION

The method for calculating conduction between layers requires an expected effective emissivity, either from testing or assumption, and a theoretical effective emissivity through the blanket assuming no contact between layers. The difference in heat transfer between this theoretical emissivity and effective emissivity can then be attributed to linear conduction through the blanket. This calculation methodology was derived in previous work by Laurie Carrillo [4]. An example of this calculation can be seen below:

Given:

$\sigma = 5.67\text{x}10^{-8}\frac{W}{m^2K^4}$ $\varepsilon^* = 0.03,$ $\varepsilon_{layer} = 0.04,$ N = 20

Where σ is the Stefan-Boltzmann constant, ε^* is the assumed emissivity, ε_{layer} is the emissivity of the internal layers (in this case, aluminized Mylar), and N is the number of layers not including the outer and inner layers.

$$\varepsilon_{theoretical} = \frac{1}{\frac{1}{\varepsilon_{layer}} + \frac{1}{\varepsilon_{layer}} - 1}\left(\frac{1}{N+1}\right) = 0.00097 \tag{1}$$

Using Equation **Error! Reference source not found.** above, $\varepsilon_{theoretical}$ can be calculated [5]. This value is the theoretical emissivity of the blanket not including conduction.

$$\dot{q}_{blanket} = \dot{q}_{radiation} + \dot{q}_{conduction} \tag{2}$$

$$\dot{q}_{blanket} = \sigma\varepsilon^* A\left(T_{surf}^4 - T_{sink}^4\right) = \sigma(0.03)(29.1^4 - 20^4) = 1.64\ W/m^2 \tag{3}$$

Here $\dot{q}_{blanket}$ represents the total heat transfer through the entire blanket. To calculate this, the assumed effective emissivity of the blanket, determined either by testing or requirements, is used as the ε^*. The surface temperature, T_{surf}, refers to the temperature of the blanket surface in steady state, and is obtained by removing all linear conductors from the model and running it in steady state with only solar heating. The sink temperature, T_{sink}, refers to the module surface the MLI is attached to, determined from requirements.

$$\dot{q}_{radiation} = \sigma \varepsilon_{theoretical} A\left(T_{surf}^4 - T_{sink}^4\right) = 0.05\, W/m^2 \tag{4}$$

$$\dot{q}_{conduction} = \dot{q}_{blanket} - \dot{q}_{radiation} = 1.64 - 0.05 = 1.58\, W/m^2 \tag{5}$$

The heat transferred via radiation ($\dot{q}_{radiation}$) is calculated using the same temperature values seen in Equation 3, but now multiplied by the theoretical emissivity calculated in Equation **Error! Reference source not found.**. The difference between $\dot{q}_{blanket}$ and $\dot{q}_{radiation}$ can then be used to determine $\dot{q}_{conduction}$, as seen in Equation 5.

$$\dot{q}_{conduction} = AG\Delta T \rightarrow G = \frac{\dot{q}_{conduction}}{A\left(T_{surf} - T_{sink}\right)} = \frac{1.58}{(1)(29.1 - 20)} = 0.174\, W/K \tag{6}$$

$$R_{total} = \frac{1}{G_{total}} \tag{7}$$

$$R_{interface} = \frac{R_{total}}{N} = \frac{1}{G_{total}} * \frac{1}{N} = \frac{1}{0.174\, W/K} * \frac{1}{20} \tag{8}$$

$$G_{interface} = \frac{1}{R_{interface}} = 3.47\, W/K \tag{9}$$

With $\dot{q}_{conduction}$ calculated, the total conduction between the layers can be determined as seen in Equation (6). This conductor is then converted into a total resistor, R_{total}, to model the system as a thermal circuit in Equation (7). To determine the resistance between each layer, $R_{interface}$, R_{total} is divided by the number of layers, N, in Equation (8). Finally, the conductor between each layer, $G_{interface}$, can be determined by taking the reciprocal of $R_{interface}$ as seen in Equation (9).

ANALYSIS RESULTS

Distance Between Layers

The first set of cases run were sensitivity studies examining the effects of varying distance between each layer. MLI blankets are often crumpled and some space between each layer is needed to minimize conduction. A range of distances between 0.01 and 0.5 inches were examined. The steady state results can be seen below in Table 3.

Table 3. Steady State Temperatures Varying Distance Between Layers

Layer	Material	Max Continuous Temp Limit (°C)	0.01 in (°C)	0.05 in (°C)	0.1 in (°C)	0.5 in (°C)
Outer	Beta Cloth	260	28.1	28.2	28.1	28.2
1	Kapton	290	52.6	52.5	52.6	52.8
2	Mylar	121	51.1	51	51.2	51.2
3	Mylar	121	49.5	49.4	49.4	49.6
…						
Inner	Kapton	290	20.6	20.6	20.6	20.6

These steady state results were then used to initialize the next set of plume heating cases, each with varying layer distances. The plume heat load used was 64 kW/m^2 applied for 0.5 seconds. The maximum temperatures experienced by each layer can be seen below in Table 4.

Table 4. Max Temperatures Varying Distance Between Layers Plume Heating Cases

Layer	Material	Max Intermittent Temp Limit (°C)	0.01 in (°C)	0.05 in (°C)	0.1 in (°C)	0.5 in (°C)
Outer	Beta Cloth	315	190.7	190.8	190.8	190.9
1	Kapton	400	101.4	101.3	101.4	101.4
2	Mylar	150	89.4	89.2	89.3	89.3
3	Mylar	150	79.9	79.8	79.9	79.9
…						
Inner	Kapton	400	20.8	20.8	20.8	20.8

Varying Effective Emissivity Assumptions

The next set of cases examined effective emissivity assumptions. To ensure the analysis was comprehensive, cases were run covering a range of assumed emissivities. Additionally, the conduction calculation demonstrated above was repeated for each individual emissivity value. Below in Table 5 are the results of the steady state cases for each assumed effective emissivity.

Table 5. Varying Effective Emissivity Steady State Temperatures

Layer	**Material**	**Max Continuous Temp Limit (°C)**	**e* = 0.011 (1.2 W/K) (°C)**	**e* = 0.019 (2.16 W/K) (°C)**	**e* = 0.03 (3.47 W/K) (°C)**	**e* = 0.05 (5.86 W/K) (°C)**
Outer	Beta Cloth	260	28.5	28.3	28.07	28
1	Kapton	290	80.5	63.9	52.5	43.5
2	Mylar	121	77.9	61.9	51	42.4
3	Mylar	121	74.9	59.7	49.4	41.2
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Inner	Kapton	290	20.4	20.5	20.6	20.7

A plot comparing the temperatures seen by each layer for all effective emissivity values can be seen below in Figure 3.

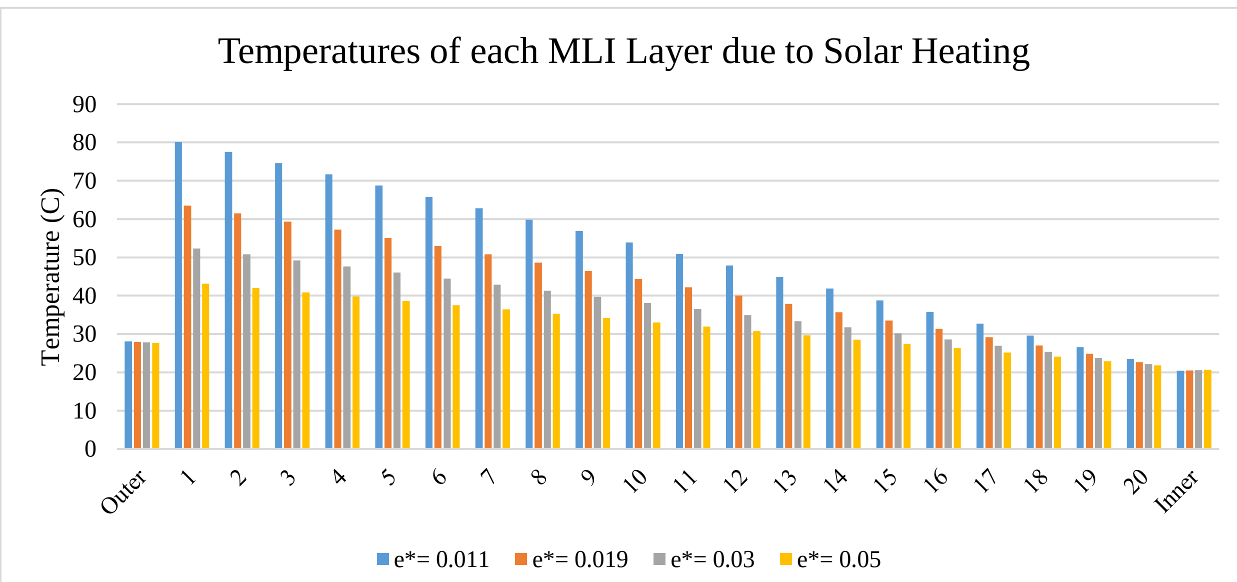

Figure 3. Temperatures of each MLI Layer due to Solar Heating

The above steady state temperature values were then used to initialize the plume heating cases. The plume used in these cases was 64 kW/m^2 applied for 0.5 seconds. The peak temperatures experienced by each layer can be seen below in Table 6.

Table 6. Varying Layer Conduction Plume Heating Results

Layer	Material	Max Intermittent Temp Limit (°C)	e* = 0.011 (1.2 W/K) (°C)	e* = 0.019 (2.16 W/K) (°C)	e* = 0.03 (3.47 W/K) (°C)	e* = 0.05 (5.86 W/K) (°C)
Outer	Beta Cloth	315	191.6	191.2	190.7	190.2
1	Kapton	400	115.6	106.1	101.3	100.1
2	Mylar	150	104	94.2	89.2	87.9
3	Mylar	150	94.3	84.6	79.7	78.4
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Inner	Kapton	400	20.5	20.6	20.8	21.3

A plot comparing the maximum temperatures seen by each layer from plume heating can be seen below in **Error! Reference source not found.**.

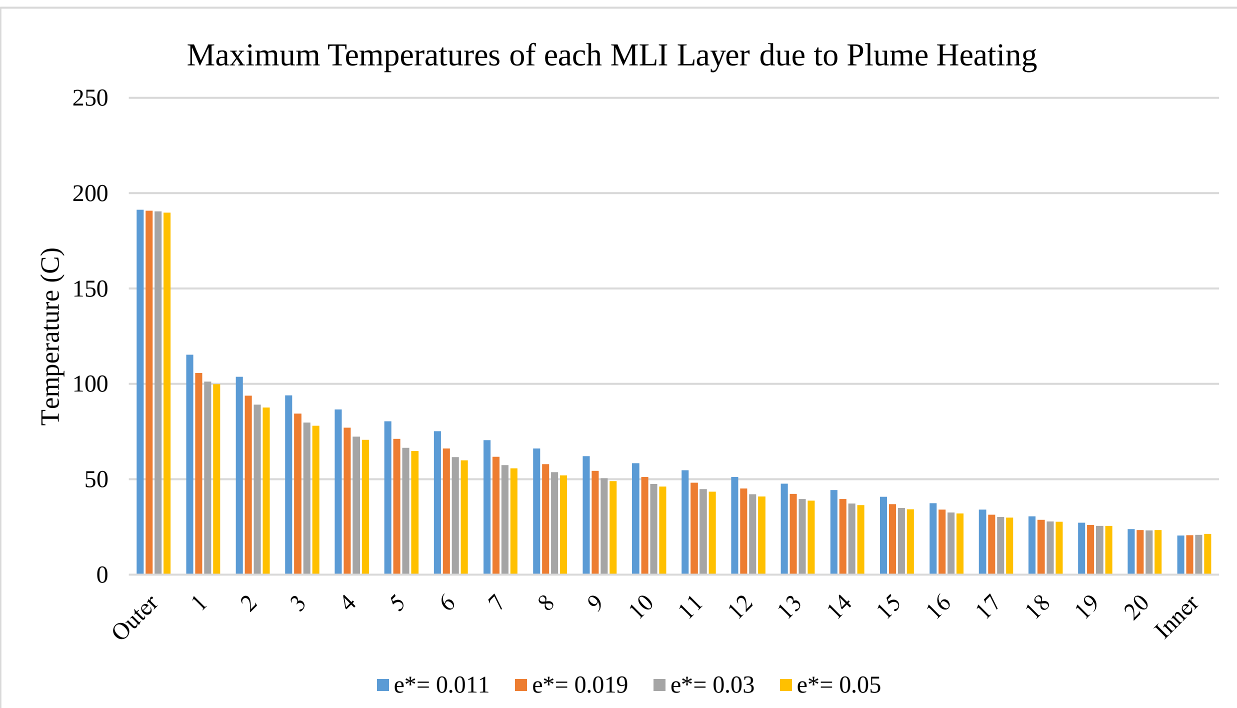

Figure 4. Maximum Temperatures of each MLI Layer due to Plume Heating

Varying Heat Flux and Duration

The final sensitivity analysis varied heat flux intensity and duration combinations to see which pairing resulted in the highest temperatures. Heat fluxes and durations for Gateway can be obtained from requirements. To account for a range of heat fluxes, five cases were run, with the results for key layers show in Table 7 below.

Table 7. Varying Plume Load Peak Temperatures Results

Layer	**Material**	**Max Intermittent Temp Limit (°C)**	**64 kW/m^2 for 0.5 sec (°C)**	**48 kW/m2 for 0.66 sec (°C)**	**32 kW/m^2 for 1 sec (°C)**	**16 kW/m^2 for 2 sec (°C)**	**0.5 kW/m^2 for 64 sec (°C)**
Outer	Beta Cloth	315	190.7	181.4	187.9	182.6	83.6
1	Kapton	400	101.3	100.3	101.4	101.6	93.5
2	Mylar	150	89.2	88.5	89.3	89.5	85.6
3	Mylar	150	79.7	79.2	79.8	80	78.4
…							
Inner	Kapton	400	20.8	20.8	20.8	20.8	20.9

DISCUSSION

Varying distance between MLI layers did not have any significant effect on layer temperatures. The space between layers was still small enough that the view factor between each layer stayed nearly the same. Also, the use of a closeout around each layer meant increased layer distance did not result in increased view to space. Due to the insignificant effect of layer spacing on temperatures, it is not necessary to rerun this sensitivity analysis for future work.

For steady state cases, seen in Figure 3, the model showed the second layer of the MLI was the hottest, despite the top layer having the most direct exposure to solar radiation. These high temperature values are largely due to the transmissivity of beta cloth. The transmissivity of beta cloth means solar radiation will penetrate the top layer and directly affect the aluminized Kapton layer below. Aluminized Kapton has a high α/ε ratio, meaning the heat that passes through beta cloth will be absorbed and not emitted as easily from the Kapton. Additionally, the top beta cloth layer blocks the aluminized Kapton layer’s view to space, lowering its ability to radiate heat out. Finally, beta cloth’s lower α/ε ratio means it is better able to reject heat than the Kapton layer. All these factors combine to create a model where the Kapton layer is the hottest layer in steady state.

In all cases, as conduction and effective emissivity increase, temperatures throughout the blanket decrease. This is due to improved conduction of heat throughout all layers and greater heat rejection due to higher effective emissivity. In future work, lower effective emissivity values can be treated as the conservative case.

In the sensitivity analysis comparing varying heat loads, the maximum temperature of most of the layers, especially the outside layers, were seen in the 64 kW/m^2 case. This high intensity short duration plume load does not allow enough time for significant heat diffusion into the interior layers, concentrating the heat into the top layers. Additionally, the high surface temperature results in increased heat dissipation to space, due to higher temperature differential, causing less heat to penetrate to the interior layers. The highest internal layer temperatures can be seen in the 0.5 kW/m^2 case. Due to lower surface temperature peaks, more heat can penetrate the inner layers across the extended exposure time. For this MLI stack, the top layers approach their temperature limits in the 64 kW/m^2 case, although there still a large margin before the limit is reached. While it is likely the higher flux, shorter duration case will create worst-case temperatures for most stack ups, it is still recommended to analyze the other plume combinations due to difference in thermal blanket design and materials.

CONCLUSION

For the blanket analyzed in this paper no layers exceeded their material temperature limits. Blankets made of other materials with higher α/ε ratios on outer layers may still exceed temperature limits. This modeling methodology can be applied to different blanket layups with and without transmissive outer layers. For future work, sensitivity analysis varying distance between MLI layers is unnecessary. Sensitivity analysis examining a range of effective emissivities and plume heat loads is beneficial.

For future work, this modeling methodology can be used to model blankets exposed to plume on Gateway. Additionally, this methodology can be used to model future plume impingement testing on MLI blankets.

ACKNOWLEDGEMENTS

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