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ANALYSIS OF MULTILAYER INSULATION SYSTEM ON THE TEMPERATURE FIELD AND HEAT FLUX USING ALUMINUM/CARBON NANOTUBE COMPOSITE

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Abstract. *Insulation in some space projects is requisite. A good solution presented by years is a system composed of several layers with high reflectivity separated by low conductivity material, forming a Multilayer Insulation blanket (MLI). This paper made an analysis using the material Aluminum/Carbon Nanotube Composite (CNT/AL) applied in MLI blanket in the space environment, space temperature as 4K and the surface of the spacecraft as 300K. Using numerical simulations in Python for solving the complex equations of the problem was possible to evaluate the variations of temperature field of the MLI, for stationary and transient cases. This work presents the analysis of the varying emissivity in the layer inside an MLI blanket. Increasing the emissivity only in the last layer optimizes the results. Therefore, better performance of an MLI blanket occurs when the last layer is composed of CNT/Al, with the conditions set in this work. The results show a good agreement of the material CNT/Al as the last layer of an MLI. Reducing by half the temperature when compared with a blanket without this material.*

Keywords: *Multilayer Insulation, Aerospace Engineering,Carbon Nanotube, Numerical Heat Transfer.*

1. INTRODUCTION

Thermal insulation is a critical factor in real applications in engineering projects, especially aerospace engineering, where uses thermal control technologies to isolate satellites and spacecraft. Meseguer *et al.* (2012) shows how works the thermal control in aerospace engineering. Multilayer Insulation (MLI) is usually a method to guarantee safety and reliable developments in this area. Based on multiple layers built with different materials and parameters, it is mandatory to ensure a correct study of them, generating safe projects, avoiding any miss calculation that could result in complete damage and total failure of a system.

An MLI blanket consists of a material, alternating high reflective layer, and a low conductive layer. For each purpose, the requirements of an MLI are different, and then the design usually is not the same. Many materials form an MLI blanket, each of them provides varied performances. Studies in the literature are, predominantly, experimental tests about variations in its compositions. However, numerical analysis progressively becomes a growing field in the last years and minimizing the costs of an experiment.

Li and Cheng (2006) has presented a study in MLI perforated, using most of the method presented by Zhitomirskij *et al.* (1979). This work used both studies as a guide in the methodology used. This paper focused on providing the temperature field and heat flux across the layers by numerical simulation for transient and stationary MLI performances using parameters of a recent and promising material presented in Cui and Wardle (2019), aluminum/carbon nanotube composite (CNT/Al), with properties close to a black body.

The differential equations used to model the physical phenomenon are based on transient radiation-conduction theory, consisting of a fourth-order coupled non-linear ordinary differential equations system. The numerical simulation will be fed with experimental data of CNT/Al, providing results on a subject where few contributions in the numerical field, with this material, are available.

The environment temperature was 4K for space temperature and 300K for the insulated surface. Also, the number of layers, outgassing rate, perforation coefficient, conductivity, and contact pressure were variable in the simulation. The best combination of these previous parameters, in a preliminary analysis, was the MLI with the lower values for each one, respecting the initial input. The last layer always losses for space in this case, so reaching a lower temperature in this layer is required due to its direct contact with the outside environmental. The number of layers used in simulations were based on literature data (Li and Cheng (2006)). Lacerda and Curi (2020) focused only on variations in distance between the layers; The emissivity of layer materials, and the perforation coefficient.

2. SOLUTION METHODOLOGY

Figure 1 exhibits the diagram of both algorithms, stationary and transient case. The methodology used was the same presented in Lacerda and Curi (2020). The calculation of thermal conductivity based on Bapat *et al.* (1990). The thermal conductivity is updated with the initial conditions, and the radiation incident flux could be calculated. Then, using Python's library Numpy and Scipy (Bressert (2012)), that uses Levenberg-Marquardt method for root finding, is possible to solve the equations to find the temperature field in each case, Equation 1 for transient and Equation 2 for stationary. The entire process resumes in an iteration starting with the initial conditions that gives the initial thermal conductivity and heat flux, with both given the temperature field, than the recalculation of thermal conductivity and heat flux, and consequently the temperature field. The simulation stops when the variation of temperatures are less than 0.001, for this paper purposes this stopping criteria was based on the available literature (Cui and Wardle (2019)), that established this value as good enough for practical applications. The thermal conductivity in the equation depends on the MLI blanket spacer, which in this simulation were used the glass fiber as a spacer.

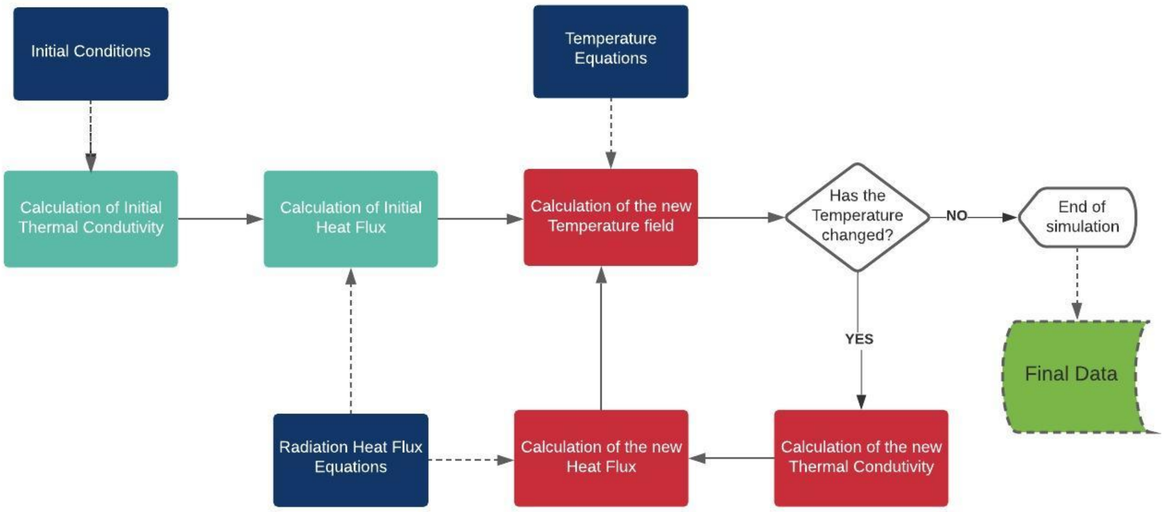

Figure 1. Diagram of the solution methodology.

$$-\rho_i c_i t_{c,i}\frac{dT_i}{dt} + \xi_i'\varepsilon_i(F_{1,i} + F_{2,i} - 2\sigma T_i^4) + \frac{k_i}{\delta_i}(T_{i-1} - T_i) - \frac{k_{i+1}}{\delta_{i+1}}(T_i - T_{i+1}) = 0 \tag{1}$$

$$\xi_i'\varepsilon_i(F_{1,i} + F_{2,i} - 2\sigma T_i^4) + \frac{k_i}{\delta_i}(T_{i-1} - T_i) - \frac{k_{i+1}}{\delta_{i+1}}(T_i - T_{i+1}) = 0 \tag{2}$$

Being i the index of the layer, c is heat capacity, ρ is density of reflective screen, t_c is the thickness of the screen, δ is the distance between the screens, ξ is the perforation coefficient, ξ' is $(1-\xi)$, F_1 and F_2 the incident radiant flux in a node, ε is the emissivity of the material and ε' is $(1-\varepsilon)$. Figure 2 shows the flux of radiation between layers.

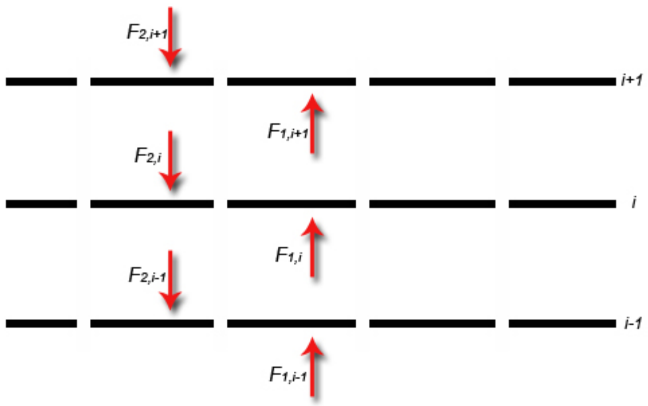

Figure 2. Diagram of the incident radiant flux.

$$F_{1,i} = \xi'_{i-1}\varepsilon_{i-1}\sigma T^4_{i-1} + \xi_{i-1}F_{1,i-1} + \xi'_{i-1}\varepsilon'_{i-1}F_{2,i-1} \tag{3}$$

$$F_{2,i-1} = \xi'_i\varepsilon_i\sigma T^4_i + \xi_i F_{2,i} + \xi'_i\varepsilon_i F_{1,i} \tag{4}$$

3. RESULTS AND DISCUSSIONS

Figure 3 shows the impact of varying the emissivity of the materials inside a unique MLI blanket with 20 layers. The green line shows the first 10 layers with emissivity value as 0.08. From layer 11 to the last one, the emissivity changes to 0.1. The black line has the opposite variation. The figure shows that increasing the emissivity (green line), the temperature reaches low values in the last layer.

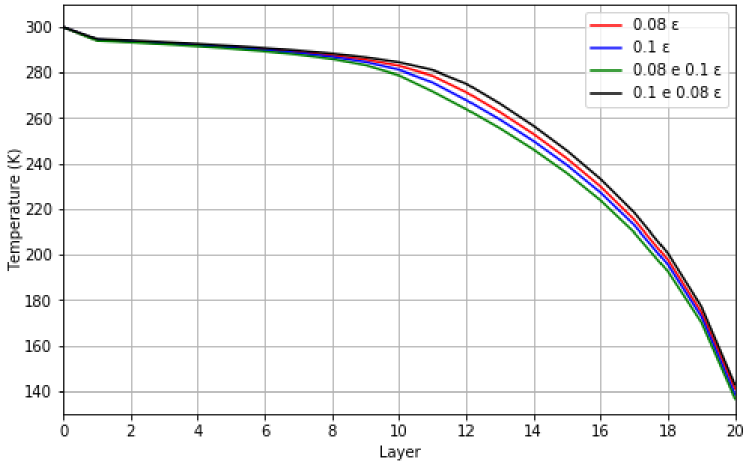

Figure 3. Variation on emissivity and its impact.

Figure 4 and Table 1 present the results, with this variation of the layer's emissivity. For reach the better form to vary the emissitivity inside the MLI, were set with the increasing of the emissivity, iniciating in the 5^{th}, 10^{th}, 15^{th} and in the last layer. It is noted a lower temperature value only in the last layer, with high emissivity. It is also possible to notice that the temperature variation is around 2K between the 5^{th} and the last layer, not a significantly change, in that specific analysis.

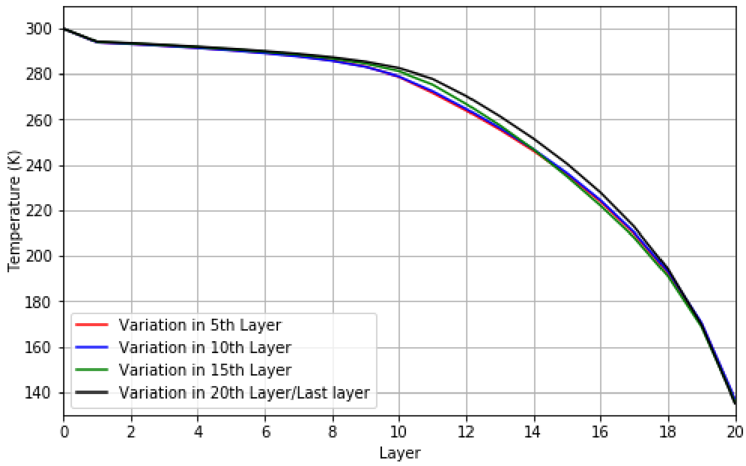

Figure 4. Optimization on varying emissivity.

Therefore, applying the material CNT/Al, which has a high emissivity, in the last layer was simulated, Figure 5 and Figure 6 being the steady-state and transient case, respectively. The difference in the last layer's temperature using the CNT/Al is notorious, different from the last analyses showed in Figure 4 (approximately 2K). This time, the high difference of emissivities impact on that difference. In Figure 6 the blue line is overlaped by the orange one.

Simulations aim to reach a better combination of parameters for designing an MLI. Combinations of the construction parameters of an MLI blanket, as the number of layers, perforation coefficient, outgassing rate, the thermal conductivity of the material used as a layer, and contact pressure. Thus, Figure 7, Figure 8, Figure 9 and Figure 10 are simulations with different number of layers. Figure 7 varying the perforation coefficient and Figure 8 varying the outgassing rate, both in the stationary case. Also, Figure 9 diversifying the perforation coefficient, and Figure 10 diversifying the outgassing rate, both in transient case.

Table 1. The temperature of last layer varying emissivity of layers in a MLI.

Layer where change ϵ from 0.08 to 0.1	**Temperature, K**
5^{th} until 20^{th}	136.9750
10^{th} until 20^{th}	136.6112
15^{th} until 20^{th}	135.6405
Only 20^{th}/Last	134.9844

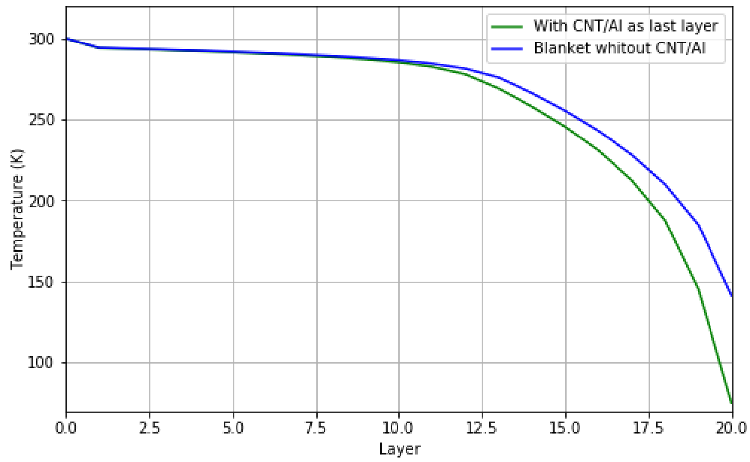

Figure 5. Comparison between MLI with and without CNT/Al, stationary case.

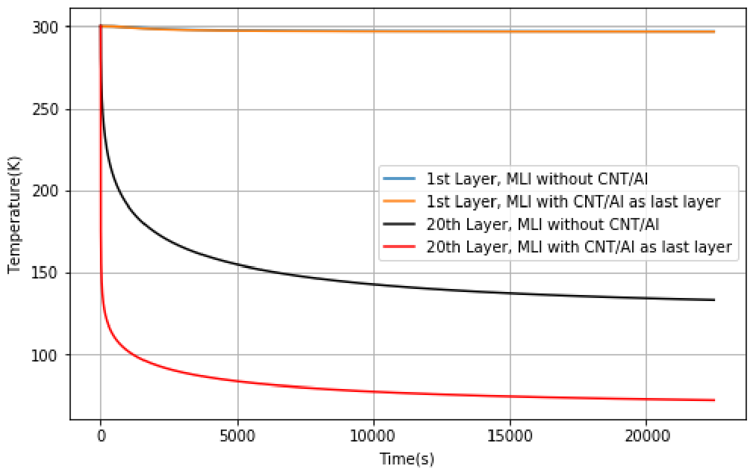

Figure 6. Comparison between MLI with and without CNT/Al, transient case.

Table 2 present the results of simulations using CNT/Al as the last layer only in the stationary case, varying the number of layers, perforation coefficient, and outgassing. The better condition, in this case, was applying a material with low outgassing and low perforation coefficient. The MLI with fewer layers and the MLI with most layers presented the lower temperature in the last layer.

Table 3 presents the results of simulations varying the perforation coefficient, outgassing, and the time of the temperature convergence. Different than the data given by the stationary simulation the comparison were between 3% and 6%. This show that the simulations with more layers have more difference between the temperatures in the last layer in both cases.

It is possible to see in Tab. 2 and Tab. 3, the best combination of parameters for a MLI blanket design according to the simulations, being the 10 layers MLI blanket the better one. With lower perforation coefficiente and lower outgassing using CNT/Al in the last layer. Table 2 also shows for a perforation coefficient 1,4% and the outgassing $1.1{\cdot}10^{-12}$

the 40 layers blanket reach a lower temperature than a 10 layers one. Although, analysing the cost, time to produce and the uncertainty that grows with more layers, it is possible to ensure that the best combinations is the 10 layers MLI blanket.

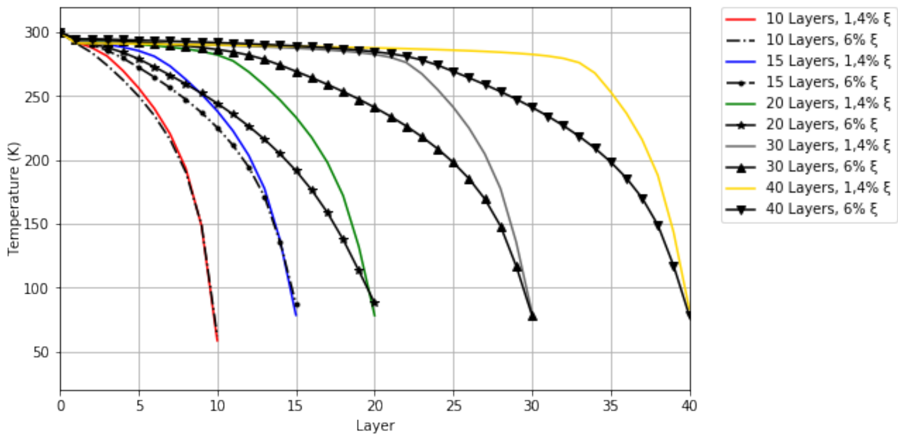

Figure 7. Varying number of layers and perforation coefficient using CNT/Al as last layer, stationary case.

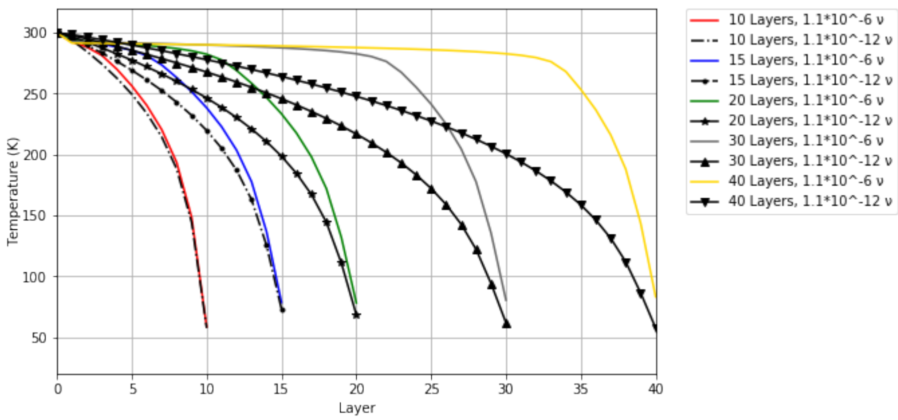

Figure 8. Varying number of layers and outgassing of the material screen and using CNT/Al as last layer, stationary case.

Table 2. The temperature of last layer varying parameters in a MLI, of steady state case.

Number of layers	Perforation coefficient	Outgassing	Temperature,K
10	1.4%	$1.1{\cdot}10^{-6}$	58.5387
10	1.4%	$1.1{\cdot}10^{-12}$	57.5169
10	6%	$1.1{\cdot}10^{-6}$	62.0938
15	1.4%	$1.1{\cdot}10^{-6}$	78.4810
15	1.4%	$1.1{\cdot}10^{-12}$	73.0849
15	6%	$1.1{\cdot}10^{-6}$	87.3611
20	1.4%	$1.1{\cdot}10^{-6}$	78.1510
20	1.4%	$1.1{\cdot}10^{-12}$	68.4925
20	6%	$1.1{\cdot}10^{-6}$	87.9095
30	1.4%	$1.1{\cdot}10^{-6}$	80.3976
30	1.4%	$1.1{\cdot}10^{-12}$	61.8090
30	6%	$1.1{\cdot}10^{-6}$	78.4556
40	1.4%	$1.1{\cdot}10^{-6}$	83.1105
40	1.4%	$1.1{\cdot}10^{-12}$	57.4793
40	6%	$1.1{\cdot}10^{-6}$	78.0952

The simulation time depends on the number of layers and if it is a steady state or transient analysis. The stationary cases were faster than transient. The stationary simulation time with 10 layers, was about 60 seconds, and with 40 layers less then 120 seconds. The transient simulation time with 10 layers, was about 240 seconds, and with 40 layers less then 500 seconds.

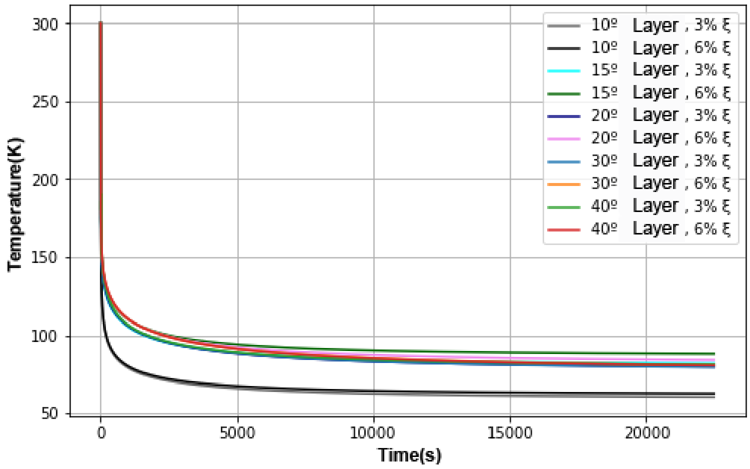

Figure 9. Varying number os layers and perforation coefficient using CNT/Al as last layer, transient case.

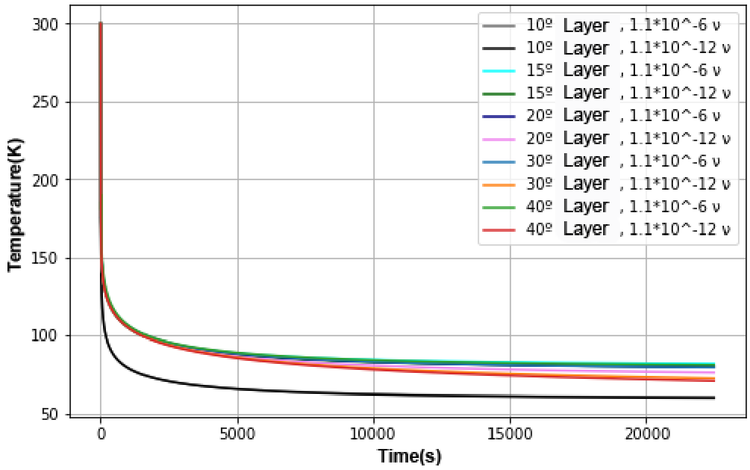

Figure 10. Varying number os layers and outgassing rate of the material screen and using CNT/Al as last layer, transient case.

Table 3. The temperature of last layer varying parameters in a MLI, of transient case.

Number of layers	Perforation coefficient	Outgassing	Time, s	Temperature,K
10	3%	$1.1 \cdot 10^{-6}$	35024	59.9311
10	3%	$1.1 \cdot 10^{-12}$	36327	59.5363
10	6%	$1.1 \cdot 10^{-6}$	31416	62.3162
15	3%	$1.1 \cdot 10^{-6}$	39541	81.2530
15	3%	$1.1 \cdot 10^{-12}$	45412	78.9015
15	6%	$1.1 \cdot 10^{-6}$	36156	87.6090
20	3%	$1.1 \cdot 10^{-6}$	48203	78.6158
20	3%	$1.1 \cdot 10^{-12}$	65079	73.8679
20	6%	$1.1 \cdot 10^{-6}$	47416	82.9717
30	3%	$1.1 \cdot 10^{-6}$	51077	78.1615
30	3%	$1.1 \cdot 10^{-12}$	110367	66.8285
30	6%	$1.1 \cdot 10^{-6}$	47416	82.9717
40	3%	$1.1 \cdot 10^{-6}$	44838	80.1587
40	3%	$1.1 \cdot 10^{-12}$	159300	62.0220
40	6%	$1.1 \cdot 10^{-6}$	63709	78.4182

4. CONCLUSIONS

This work presents results using CNT/Al in MLI blanket. Also presents the optimization of varying emissivity in an MLI blanket. Then the application for a different composition, CNT/Al is analyzed as the last layer in an MLI. The results presented are in ideal conditions of simulations. The paper verified the best combination of MLI's design parameters using this material in the last layer. It was noted that for a perforation coefficient 1,4% and the outgassing $1.1{\cdot}10^{-12}$ the 40 layers blanket reach a lower temperature than a 10 layers one. Although, analysing the cost, time to produce and the uncertainty that grows with more layers, it is possible to ensure that the best combinations is the 10 layers MLI blanket. The use of this material is encouraging based on the results. On the other hand, it has to be tested in experimental conditions to guarantee as a material for applications in space for a long duration.

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6. RESPONSIBILITY NOTICE