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EXPERIMENTAL DETERMINATION OF THE EFFECTIVE THERMAL PROPERTIES OF A MULTI-LAYER INSULATION BLANKET

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Abstract. *This work presents results of the experimental determination for the effective thermal properties of a Multi-Layer Insulation blanket (MLI) for space application. The main parameter of the test (vacuum chamber wall's temperature) was determined based on a possible orbital condition for a satellite with attitude control based on three axis stabilization. Also, the nominal temperature level was applied. A typical MLI blanket is composed of multiple layers of low emittance films (to reduce radiation heat transfer) with spacers, in order to reduce the conduction heat transfer. MLI blankets have been used for a long time in space applications, and actually its main function is not only based on thermal issues, but also in protection of micrometeorites, atomic oxygen, electron charge accumulation, etc. The results presented in this paper are regarding to a 25 layers blanket, focused on the determination of the effective emissivity, effective absorptivity and effective thermal conductance. It should be noted that all obtained results have shown a good agreement in comparison with literature, and are within expected range.*

Keywords: *MLI, Thermal Insulation, Satellite Thermal Control.*

1. INTRODUCTION

Multilayers insulations (MLI) are among the most common thermal-control elements on spacecraft. MLI blankets prevent both excessive heat loss from a component and excessive heating from environmental fluxes, rocket plumes, and other sources. Most spacecraft flown today are covered with MLI blankets, with cutouts provided for areas where radiators reject internally generated waste heat. MLI blankets are also typically used to protect internal propellant tanks, propellant lines, solid rocket motors, and cryogenic dewars (Gilmore, 2002). Just as example of some satellites with MLI are PETSAT (16 Sugawara *et al*., 2009), BIRD (Lura *et al.*, 2002), HAMSAT (Narayana and Reddy, 2007) and TUSAT (Sozbir *et al.*, 2008).

The basic configuration of MLI is a blanket composed of multiple layers of low-emittance films, from thin Mylar® (polyester) sheets (approximately 6 µm), with both sides vacuum-deposited aluminum finish (Gilmore, 2002). The number of layers varies between three and thirty metallized films. The low thickness minimizes weight and facilitates the packaging of the equipment with the MLI. The outer layer is usually made of Kapton® (polyamide) with about 25 µm thick, since it is more resistant than Mylar® (regarding to thermal and mechanical issues) providing protection during installation and handling. Mylar® cannot be used as outer layer, since it disintegrates on long exposure to ultraviolet rays, as well as a maximum operating temperature of 120 °C. The aluminized Kapton® provides a desirable ratio between solar absorptivity and infrared emissivity, justifying its use as outer layer. Also, Beta cloth can be used as outer layer, similar to the blanket employed at ATV program (Ferrero *et al*, 2010). The MLI blankets can also use separators, such as Nomex®, Tulle (both made of nylon), Dacron®, besides another materials. So, for 15 Mylar® layers (or Kapton®) there will be, also, 15 spacer layers (Gilmore, 2002). Nomex® is used when internal predicted temperatures are higher than 100 °C. Figure 1 presents the drafting of a blanket.

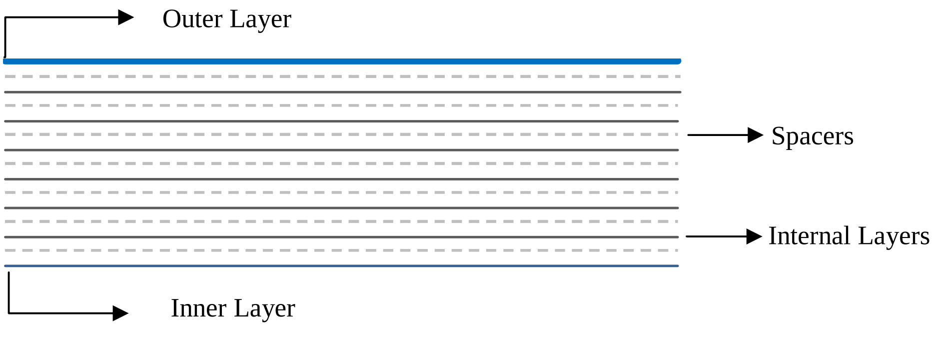

Figure 1 - Schematic representation of a MLI blanket

Blankets were originally used only for limiting the heat flow to and from a spacecraft. Today they may also protect against micrometeoroids, atomic oxygen (AO), electron charge accumulation, and rocket-engine plume impingement. In addition, blanket design must accommodate requirements for durability, flammability, contamination control, launch loads, pressure decay, spacecraft venting, glint minimization, and restrictions on magnetic materials. Because most launch sites are near beaches (or even in the middle of the ocean, as in the case of Sea-Launch), exposure to salt spray and other corrosive agents is possible, so blanket design must take that exposure into account. All of these functions and design requirements must be addressed by blanket developers, who are also striving to minimize mass, cost, risk, and development time. (Gilmore, 2002)

2. DETERMINATING MLI'S EFFECTIVE THERMAL PROPERTIES BY TEST

The effective thermal properties of MLI are determined experimentally by tests in a thermal-vacuum chamber. In this, a pressure level less than 0.0013 Pa is necessary to eliminate the convective heat transfer, caused by residual gases. Typically, during the test, power is applied to a plate while the chamber's walls (shroud) are kept in cryogenic temperatures, T_w, (Karam, 1998). Figure 2 illustrates the basic configuration of the test.

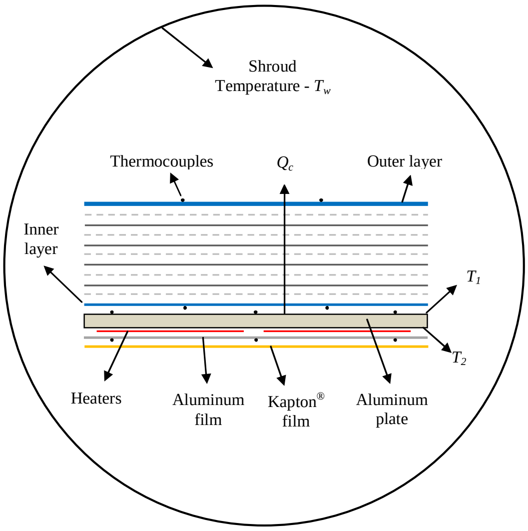

Figure 2 - Test setup scheme.

Specifically, in this test, the effective emissivity, ε_{ef}, is obtained by the relationship shown in Eq. 1: (Karam, 1998)

$$\varepsilon_{ef} = \frac{Q_c}{A\sigma(T_1^4 - T_w^4)} \tag{1}$$

Where:

ε_{ef}: effective emissivity;
Q_c: heat rate across MLI [W];
A: plate's area [m²];
σ: Stefan-Boltzmann constant [W/m².K^4];
T_1: temperature of the plate's surface in contact with MLI (surface 1) [K];
T_w: shroud's temperature [K].

The heat rate through the blanket, Q_c, can be obtained by calculating the heat exchange between the outer layer of the MLI and the shroud, and is achieved with the use of Eq. 2:

$$Q_c = \varepsilon A\sigma(T_e^4 - T_w^4) \tag{2}$$

Where:

ε: emissivity of blanket's outer layer;
T_e: blanket's outer layer temperature [K].

By replacing Eq. 2 in Eq. 1, an expression for the calculation of the effective emissivity is obtained, according to Eq. 3:

$$\varepsilon_{ef} = \varepsilon \frac{(T_e^4 - T_w^4)}{(T_1^4 - T_w^4)} \tag{3}$$

Thus, the effective emissivity is a function of measured temperatures and outer layer's emissivity, reducing the sources of uncertainty in the results.

3. EXPERIMENTAL ANALYSIS

To determine the values of the MLI effective thermal properties an experimental analysis was carried out in the Integration and Testing Laboratory (LIT) at National Institute for Space Research (INPE). The MLI submitted to test consisted of 25 layers of Mylar® (6 µm thick each layer) aluminized on both sides. Among the inner layers Dacron® spacers were used to minimize the heat conduction. A Kapton® layer, aluminized just on inferior face, was used as outer layer of the blanket. Figure 3 presents photographs of the blanket.

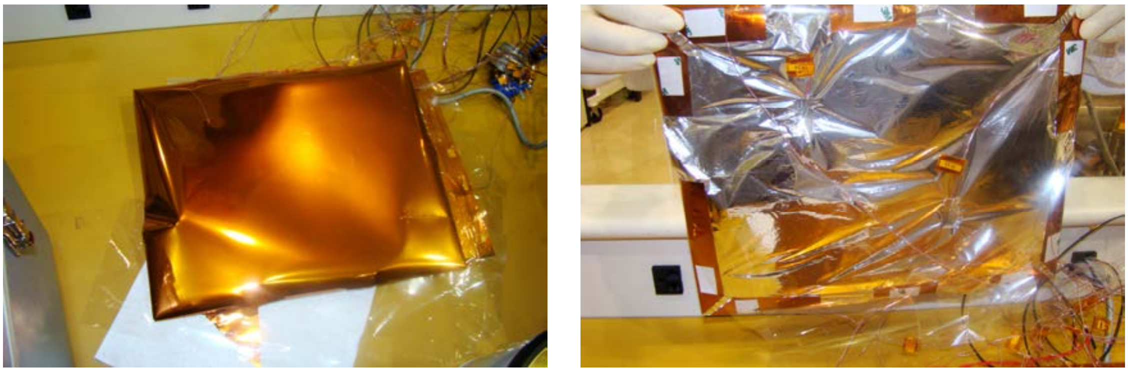

Figure 3 - MLI testing sample.

In an aluminum plate (317 mm length, 257 mm high and 2.45 mm thick) two skin heaters were bounded, covering almost completely one of the faces (surface 2). Figure 4 shows the approximate positioning of heaters and thermocouples.

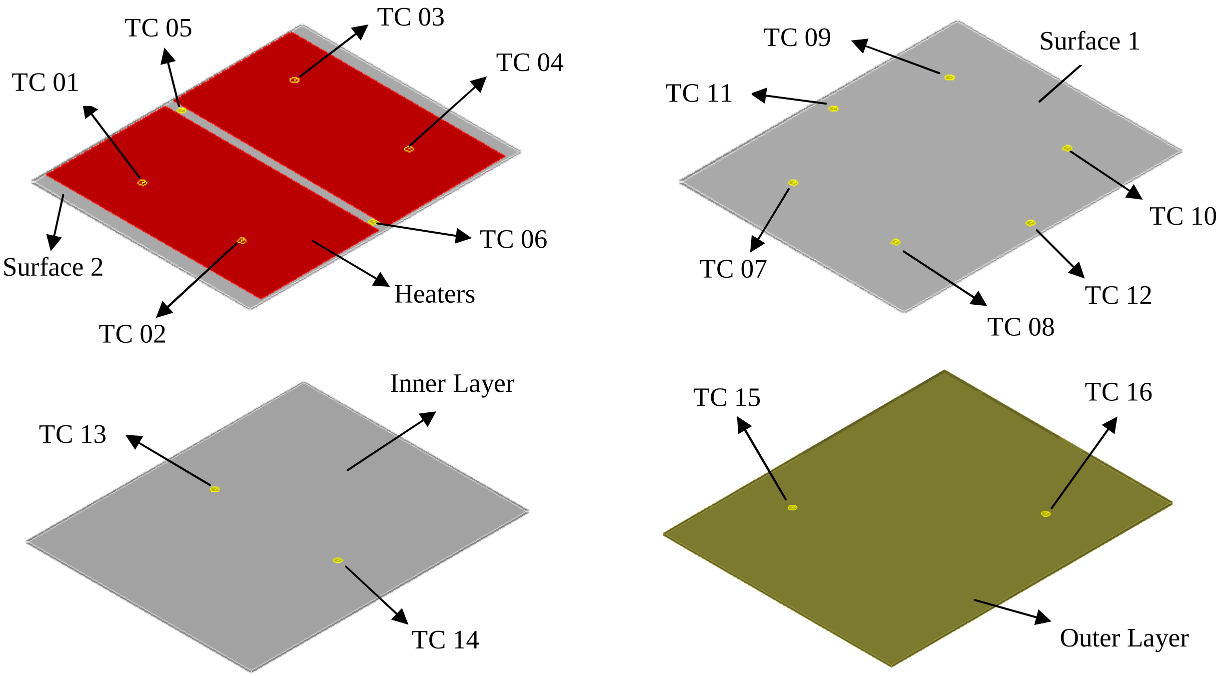

Figure 4 - Thermocouples approximated positioning.

On every plate's surfaces 6 T-Type thermocouples, in symmetrical positions, have been used. Also, 2 thermocouples in the inner layer and other 2 in the outer layer of the MLI have been employed, resulting on 16 thermocouples.

After mounting the testing sample, the reflectivity, in infrared spectrum, was measured in the surface with heaters and in the blanket's outer layer and, in this last one, the reflectivity in the solar spectrum was also measured. Finally, the test specimen was positioned inside the thermal-vacuum chamber, as presented in Fig. 5.

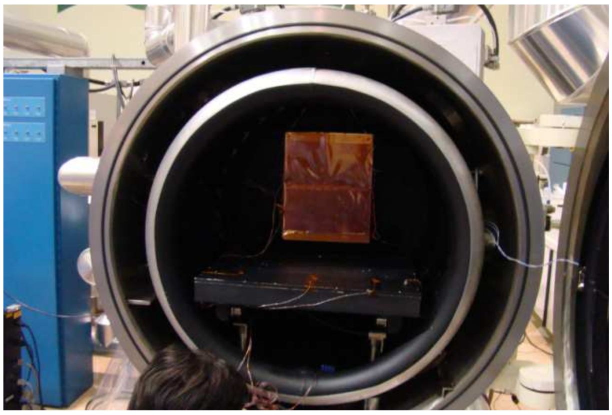

Figure 5 - Testing sample within vacuum chamber

In order to make environmental conditions similar to those during orbit, the shroud's temperature was determined based on orbital parameters. The sink temperature for an on orbit satellite, subjected to external heating fluxes, in steady state condition, is given by Eq. 4 (Gordon, 1981):

$$T_\infty = \sqrt[4]{\frac{\alpha\left(q^S + q^A\right)}{\sigma\varepsilon} + \frac{q^P}{\sigma}} \tag{4}$$

Where:

α: solar absorptivity of blanket's outer layer;
T_∞: sink's temperature [K];
q^S: solar heat flux [W/m²];
q^A: albedo heat flux [W/m²];
q^P: planetary (Earth) heat flux [W/m²].

The environmental heat loads were determined from an orbital condition, which could be achieved by the satellite during its life. This condition was considered to be the coldest possible, aiming achieve lower temperatures to the environment (sink) and, thus, decrease the intensity of the heat exchange by radiation between the camera and the specimen.

To obtain the values of the incident environmental fluxes, a simulation was performed, in a simplified way, with SINDA/FLUINT thermal analyzer. The orbital parameters considered in the simulation are shown in Tab. 1.

Table 1 - Orbital parameters considered in the sink's temperature determination.

Parameter	Value
Earth Radiation - q^P	198 W/m²
Solar Radiation - q^S	1300 W/m²
Albedo - q^A	38 % (494 W/m²)
Orbit Inclination - i	98.5°
Beta Angle - β	0°
Altitude - H	500 km
Outer Layer Emissivity - ε	0.761 ± 0.031
Outer Layer Absorptivity - α	0.139 ± 0.006

In this analysis the satellite attitude control is based in three axes stabilization, with appointment in relation to the Sun. An illustration of the positioning of the satellite in orbit is presented in Fig. 6.

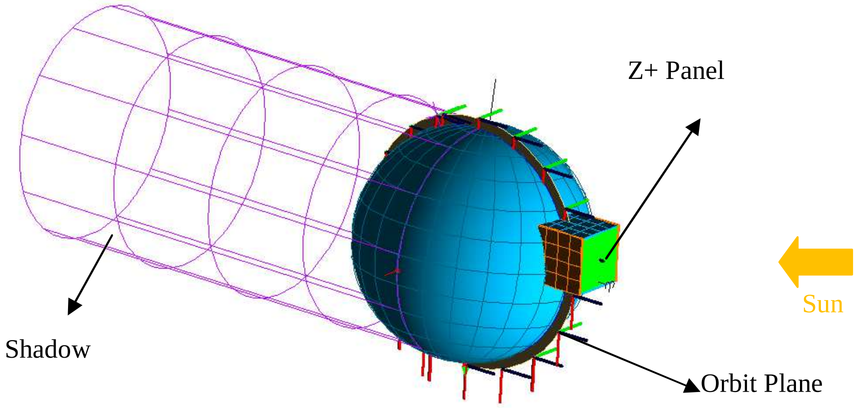

Figure 6 - Satellite pointing to determine sink temperature.

As shown in Fig. 6, the panel Z+ will always point to the sun while the opposite panel, Z-, will point to Earth. In the calculation of the equilibrium temperature, the external heat loads on Z- panel are considered, since it will never point to the Sun during operational mode. The variation of the incident environmental heat fluxes on Z- panel, to an orbital period, is presented in Fig. 7.

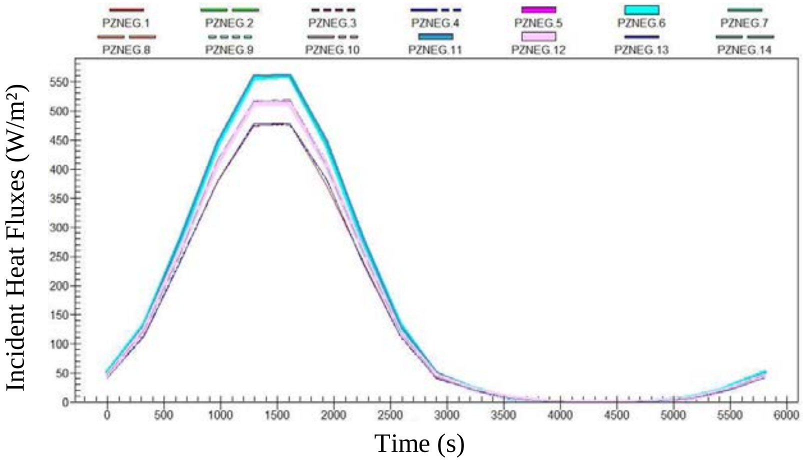

Figure 7 - Incident external heat fluxes variation.

The average value of the incident flux is 94.02 W/m² for albedo, 59.48 W/m² for terrestrial radiation and 0 W/m² for solar radiation. The reduction of these values, in comparison to those presented in Tab. 1, is due to the shape factor between the Z- panel and Earth. It reduces the albedo and terrestrial radiation, while the solar radiation is null, due to Z-panel never point to the Sun.

By replacing in Eq. 4 the values obtained in the simulation, in conjunction with the thermal optical properties values presented in Tab. 1, the equilibrium (sink) temperature is approximately -82 °C.

4. TESTING RESULTS

The temperatures measured during test are shown in Fig. 8.

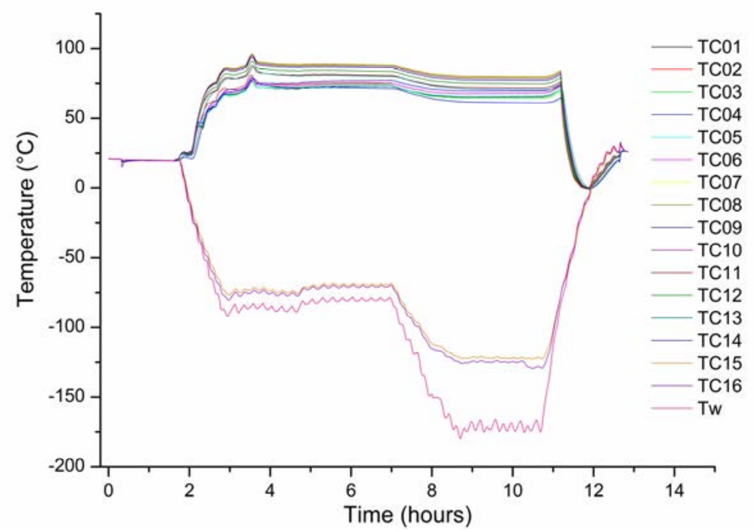

Figure 8 - Temperatures profiles.

By analyzing the results, only temperatures in steady state condition have been considered. It was considered initiated after 5 hours, remaining until, approximately, 6.8 hours. During this interval 211 measurement points were analyzed, with temperatures measured every 30 seconds.

The temperature of surface 2, T_2, is the arithmetic mean of thermocouples TC1, TC2, TC3, TC4, TC5 and TC6, while the temperature of surface 1, T_1, is the arithmetic mean of thermocouples from TC7 and TC12. Also, the temperature of the inner layer, T_i, is the arithmetic mean between TC13 and TC14, and the temperature of the outer layer, T_e, is the arithmetic mean between TC15 and TC16. Figure 9 presents these average temperatures during analysis period.

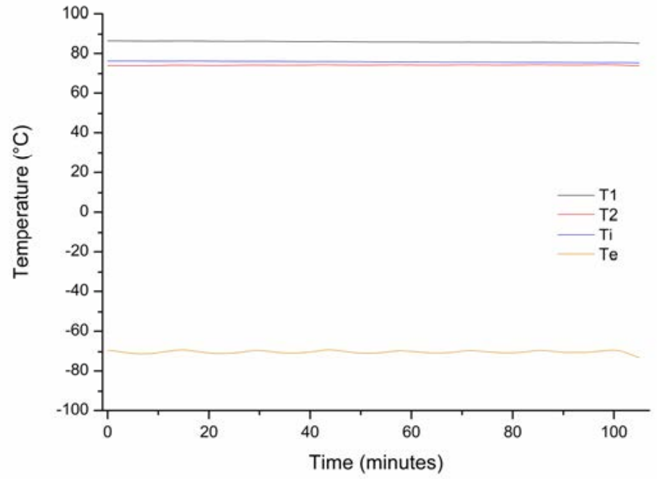

Figure 9 - Average temperatures.

It should be noted that for all temperature profiles presented in Figs. 8 and 9 the rejection point criterion of Chauvenet (Holman, 2001) was applied, and the results have shown to be valid. A summary of the parameters required for determination of blanket's effective thermal properties is presented in Tab. 2:

Table 2 - Parameters for determination of MLI's effective properties.

Parameter	Value
T_1	85.91 ± 1.94 °C
T_2	74.35 ± 0.95 °C
T_i	76.05 ± 4.35 °C
T_e	-70.11 ± 1.4 °C
T_w	-80.31 ± 1.21 °C
α	0.139 ± 0.006
ε	0.761 ± 0.031
Area - A	0.08147 ± 0.0002 m²

The effective solar absorptivity, α_{ef}, is related to other properties by the relation presented in Eq. 5 (Karam, 1998):

$$\alpha_{ef} = \varepsilon_{ef} \frac{\alpha}{\varepsilon} \tag{5}$$

Another way of measuring the MLI effectiveness can be defined by the specific effective thermal conductance, K_{ef}, determined according to Eq. 6 (Gilmore, 2002).

$$K_{ef} = \frac{Q_c}{A(T_i - T_e)} \tag{6}$$

Where:

K_{ef}: blanket's specific effective thermal conductance [W/m².K].

By replacing the results presented in Tab. 2, in Eqs. 3, 5, and 6, the values of blanket's effective thermal properties are achieved, as shown in Tab. 3.

Table 3 - MLI's effective thermal properties.

Effective Property	Value
Infrared emissivity - ε_{ef}	0.016 ± 0.003
Solar absorptivity - α_{ef}	0.0029 ± 0.0006
Conductance - K_{ef}	0.093 ± 0.018 W/m².K

As the shroud's temperature was determined based on an orbital condition, an analysis to remove possible uncertainties was accomplished. In this additional analysis, the shroud's temperature was reduced to usual levels (approximately -170 °C). The temperatures present in Fig. 8 were considered after 8.8 hours, remaining until, approximately, 10.8 hours, resulting in 241 measurement points. The required parameters for the MLI's effective properties, in this new condition, are arranged in Tab. 4. Still on the Tab. 4, the temperature difference between the conditions (ΔT is equal to the current temperature minus the previous temperature) is displayed.

Table 4 - Temperatures on testing second level.

Parameter	Value	ΔT
T_1	77.04 ± 2.10 °C	-8.87 °C
T_2	66.78 ± 1.14 °C	-7.57 °C
T_i	65.96 ± 4.82 °C	-10.09 °C
T_e	-123.64 ± 2.15 °C	-53.52 °C
T_w	-171.68 ± 1.25 °C	-91.37 °C

The parameters as area, emissivity and dissipated power remained constant. By replacing these values, in conjunction with the arranged in Tab. 4 in the equations already presented, in a process similar to that carried out earlier, the values of effective thermal properties for the new temperature T_w are obtained, as shown in Tab. 5.

Table 5 - Comparative results.

Effective Property	Value	Variation %
Infrared emissivity - ε_{ef}	0.020 ± 0.0018	25.0
Solar absorptivity - α_{ef}	0.0037 ± 0.0004	27.6
Conductance - K_{ef}	0.089 ± 0.008 W/m².K	-4.1

By analyzing the results presented in Tab. 5, the values of blanket's effective thermal properties have changed, compared to those presented in Tab. 3. However, these variations are within the ranges of uncertainty. This demonstrates that the option to determine the shroud's temperature depending on orbital parameters was valid, since the obtained results were similar to those in conventional temperature level. Another important factor to be considered is the reduced consumption of liquid nitrogen, necessary to achieve the shroud's specified temperature, since the calculated temperature is approximately 90 °C higher than usual temperature range.

5. DISCUSSION

The experimental results presented are within expectations and in line with those presented in the literature. Figure 10 (Gilmore, 2002 and Fortescue *et al.*, 2002) presents the variation of blanket's effective emissivity as a function of the number of layers and, in this figure, theoretical and experimental data are presented indicating that, in practice, an increase in the number of layers will not always result in an improvement in the blanket's thermal performance.

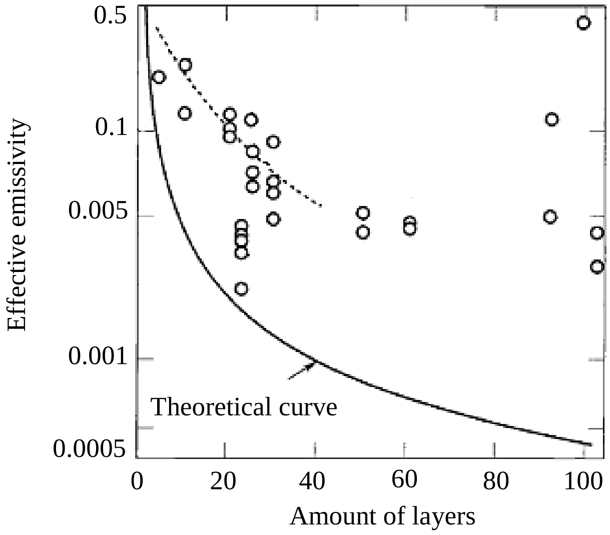

Figure 10 - Effect of the amount of layers on MLI performance. (Gilmore, 2002)

By analyzing Fig. 10 it can be noted that for a 25 layers blanket, as the one subjected to the test, a greater efficiency could be achieved. However, as shown in (Gilmore, 2002), there are several factors that influence the blanket's performance. Among these factors are the pressure level, the fastening points, provision for venting, area, sewing points, as well as issues related to preparation and handling of the blanket. Also, as presented by (Baturkin, 2005), the effective emissivity depends on discontinuity of MLI blankets, averaged temperature, pressure, and pressing of blankets and, for draft estimation, the value of effective emissivity is 0.03 with tolerance of ± 0.02. The effective emissivity presented in (Karam, 1998) is within this range, and a value ≤ 0.02 is proposed for manufacturing purposes.

In this work, since it is a blanket with reduced area, the results were acceptable and consistent with those recommended by literature. It should be noted that all results were obtained for a 95% confidence level.

6. ACKNOWLEDGEMENTS

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