

Effective Solar Absorptance of Multilayer Insulation

Pradeep Bhandari

Jet Propulsion Laboratory, California Institute of Technology

Copyright © 2009 SAE International

ABSTRACT

Multi Layer Insulation (MLI) is very commonly used in all spacecraft for heat conservation. In most instances one has to deal with MLI facing space or other cold surfaces while protecting the thermally controlled surface at more moderate temperatures than the heat sink. But in some instances, either in steady state or transient modes, one has to deal with the MLI facing the sun. Examples of such situations are during spacecraft turns, deliberate or inadvertent, when the MLI is exposed to solar insolation for short or extended periods.

The effective emittance of MLI is commonly used to describe its heat loss behavior in the absence of solar incidence and is well documented in widespread literature based on measurements and rules of thumb from practice. However, when MLI faces the sun, its effective solar absorptance comes into play to determine its effectiveness in controlling the temperature of the object that it was designed to protect thermally. The heat loss from the controlled object is different when it is absorbing solar energy on the MLI's external surface versus when it is not. The effective absorptance of MLI then simply is this difference in the heat loss flux of the MLI as a fraction of the incident solar flux.

This is where it is analogous to the effective emittance of MLI and provides a simple metric of the MLI's performance when exposed to the sun. Knowledge of the effective solar absorptance, just like the effective emissivity of MLI, allows for a simple accounting for the effect of solar incidence on the MLI's performance for thermal design and analysis.

Since MLI is not simply a series of radiation shields with only radiation between them but also has heat transfer by conduction due to thermal contact between them, the

effective absorptance cannot be easily characterized due to the non-linear complicated thermal coupling between the innermost and outermost layers. In this paper the effective solar absorptance of MLI is estimated analytically by utilizing the following three known properties of the MLI: effective emittance of the MLI blanket and the emissivity/absorptivity of the outermost surface of the blanket.

Two ways of making these estimates are presented in this paper and discussed in detail. The first way is bounding in nature by using two extreme assumptions to bracket the estimates: pure radiation or pure conduction between the innermost and outermost layers. A generalized relationship between the two extreme estimates as a function of the MLI's intrinsic properties (effective emittance, external layer emissivity and absorptivity) is presented, along with range of applicability, general trends and rules of thumb.

The second method is more rigorous which uses standard equations that break down the radiative and conductive components of heat flow through MLI which are based on measurements of MLI heat losses and effective emissivity as a function of temperature, layer density, number of layers and layer properties.

The two approaches are compared and traded off in terms of simplicity vs. rigor, accuracy vs. expediency.

INTRODUCTION

Multi Layer Insulation (MLI) is very commonly used in all spacecraft for heat conservation. In most instances one has to deal with MLI facing space or other cold surfaces while protecting the thermally controlled surface at more moderate temperatures than the heat sink. But in some instances, either in steady state or transient modes, one

has to deal with the MLI facing the sun. Examples of such situations are during spacecraft turns, deliberate or inadvertent, when the MLI is exposed to solar insulation for short or extended periods.

The effective emittance of MLI is commonly used to describe its heat loss behavior in the absence of solar incidence and is well documented in widespread literature based on measurements and rules of thumb from practice. However, when MLI faces the sun, its effective solar absorptance comes into play to determine its effectiveness in controlling the temperature of the object that it was designed to protect thermally. The heat loss from the controlled object is different when it is absorbing solar energy on the MLI's external surface versus when it is not. The effective absorptance of MLI then simply is this difference in the heat loss flux of the MLI as a fraction of the incident solar flux.

This is where it is analogous to the effective emittance of MLI and provides a simple metric of the MLI's performance when exposed to the sun. Knowledge of the effective solar absorptance, just like the effective emissivity of MLI, allows for a simple accounting for the effect of solar incidence on the MLI's performance for thermal design and analysis.

Since MLI is not simply a series of radiation shields with only radiation between them but also has heat transfer by conduction due to thermal contact between them, the effective absorptance cannot be easily crystallized due to the non-linear complicated thermal coupling between the innermost and outermost layers. In this paper the effective solar absorptance of MLI is estimated analytically by utilizing the following three known properties of the MLI: effective emittance of the MLI blanket and the emissivity/absorptivity of the outermost surface of the blanket.

Two ways of making these estimates are presented in this paper and discussed in detail. The first way is bounding in nature by using two extreme assumptions to bracket the estimates: pure radiation or pure conduction between the innermost and outermost layers. A generalized relationship between the two extreme estimates as a function of the MLI's intrinsic properties (effective emittance, external layer emissivity and absorptivity) is presented, along with range of applicability, general trends and rules of thumb.

The second method is more rigorous which uses standard equations that break down the radiative and conductive components of heat flow through MLI which are based on measurements of MLI heat losses and effective emissivity as a function of temperature, layer density, number of layers and layer properties.

The two approaches are compared and traded off in terms of simplicity vs. rigor, accuracy vs. expediency.

GENERAL THERMAL BEHAVIOR OF MLI

Consider an object that is covered with MLI and facing cold space (Figure 1). A heat load Q_1 is applied to it to maintain its temperature at T_1 to overcome its heat loss to space via the MLI. Equation 1 shows the heat balance for this object. ϵ^* represents the effective emittance of the MLI at the source temperature of T_1 and the sink temperature of space. ϵ_s is the emissivity of the outer surface of the MLI, whereas α_s is the corresponding solar absorptivity of the external surface. T_o is the temperature of the external sink, which for this initial estimation is assumed to be space (0 K). The object covered by MLI has an external area of A . The object's external area is assumed to be the external area of the MLI covering it. This is a reasonable assumption for most situations when the MLI is not very thick compared to the object dimensions. For situations where this is not true, the methodology discussed in this paper can be easily modified to account for that. T_{sa} is the resultant temperature of the external surface of the MLI due to the heat balance delineated in equation 1.

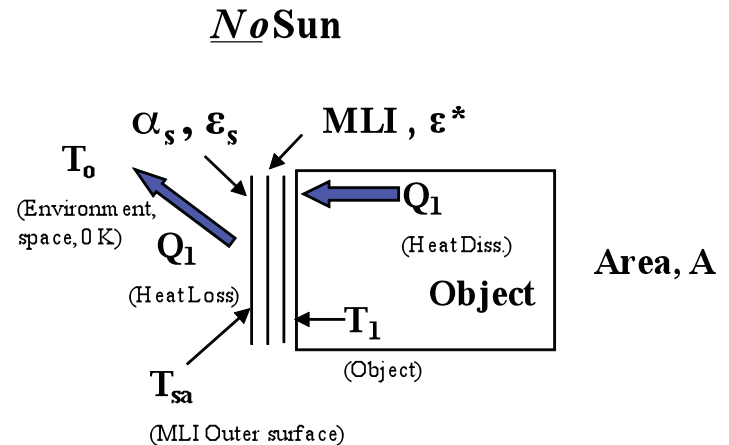


Figure 1: Heat balance of MLI with no solar input

$$Q_1 = A\sigma\epsilon^*T_1^4 = A\sigma\epsilon_sT_{sa}^4 \dots (1)$$

It is well known from experimental data that ϵ^* is a function of many parameters: size, layer density, number of layers, seams, layer emissivity and temperature. Even though MLI consists of several low emissivity radiation shields in series, its actual thermal behavior is far from the idealization of N radiation shields in series.

The reason for this deviation from the above ideal is due to the inevitable thermal contact between adjacent shields (layers). The above contact leads to a conductive link between adjacent layers. Hence the combination of the conductive and the radiative coupling between the layers' surfaces creates a series-parallel network of these links for the overall MLI. Therefore to delineate the overall MLI coupling from the hot source to the cold sink cannot be simply linearized in either the

radiative domain (by a constant value of emittance) or in the conductive domain (a constant conductance). This then leads to a non-linear thermal coupling of the MLI when represented in either domain. In other words, the thermal coupling through the MLI depends on temperature of the two boundaries of the MLI.

At room temperatures or at warmer conditions, the thermal coupling of the MLI is dominated by radiation couplings between the layers (T^4 effect between layers), hence an effective emissivity ϵ^* is a reasonable approximation to represent its internal thermal coupling. At lower temperatures the conduction becomes more dominant (because of T^4 being small). At very low temperatures (cryogenic) an effective conductance is a more accurate representation of its behavior.

In normal spacecraft thermal control practice, ϵ^* is commonly used to describe MLI behavior. Even though this is a good approximation, thermal engineers can sometimes forget that ϵ^* is a function of temperature and when large temperature changes occur in MLI in its application, this can lead to large errors in estimating the behavior of MLI and its consequence on the thermal control of the object protected by MLI. A key trend to note is that the ϵ^* decreases when either the hot or cold side temperature is increased. This is consistent with the relative significance of conductive and radiative links via the MLI layers. The corollary to this is that heat loss through MLI will be over-predicted at warmer temperatures if a constant ϵ^* is used in making these estimates.

DEFINITION OF EFFECTIVE SOLAR ABSORPTANCE OF MLI

Now consider again the same object that was covered with MLI to be now exposed to the sun. Equation 2 shows the heat balance of the object in this situation. Q_s is the solar heat input absorbed on the outside of the MLI, which is simply $A\alpha_o S$. Its external temperature increases when compared to not being exposed to the sun. Its external temperature will of course be a strong function of the external surface properties α_s (solar absorptivity) and ϵ_s (IR emissivity) and also heat transfer from the external surface to the MLI covered object via the MLI interior. This external heating leads to a smaller temperature difference across the inner and outer layers of the MLI, which then leads to a smaller heat loss from the object via the MLI. Q_2 and Q_1 are the heat inserted in the object to maintain its temperature to be at the same constant value of T_1 for the two cases. The difference in the heat loss via the MLI between the sunlit (Q_2) and without sun (Q_1) cases represents the measure of the effective solar absorptance of the MLI. The definition of the effective absorptance α^* is shown in equation 3 below and is simply the ratio of the difference in the heat loss flux between the sunlit and no sun cases and the solar constant:

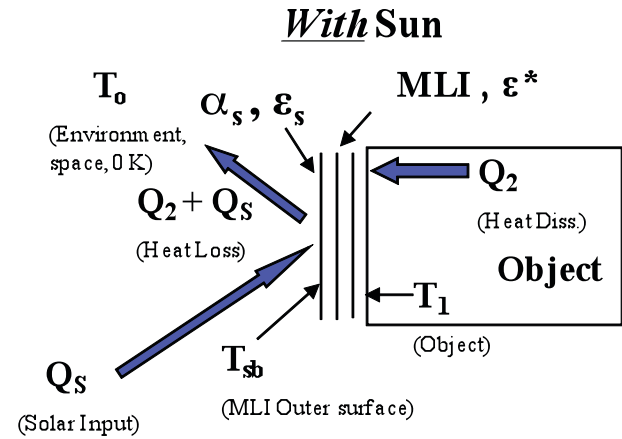


Figure 2: Heat balance of MLI with solar input

$$Q_2 + A\alpha_s S = A\sigma\epsilon_s T_{sb}^4 \quad (2)$$

$$\alpha^* = (Q_1 - Q_2)/AS \quad (3)$$

METHODS FOR ESTIMATING α^*

Since as noted before the thermal coupling within the MLI is both radiative and conductive one can make estimates of α^* by three methods. The first two are bounding in nature by assuming that the internal behavior of MLI is purely radiative or purely conductive. These are simplified and quick ways to bound the range of α^* . They are by their nature not as accurate as the more rigorous method of accounting for simultaneous radiation and conduction.

BASED ON PURE RADIATION ASSUMPTION WITHIN MLI

NO SUN - If we assume that MLI internal coupling represented by a radiative coupling (linear in the T^4 difference domain) is constant with temperature then the following equations describe the heat balance across it. ϵ^* represents the overall thermal coupling from the object to cold space heat sink, which can be represented by total conductance of two resistances in series: an internal radiative coupling within the interior layers of the MLI, ζ_{1s} and the external radiative coupling ϵ_s which is simply the IR emissivity of the exterior layer of the MLI. The thermal balance denoted by equations 4 is used to derive ζ_{1s} , which is obtained by subtracting the resistance due to the external surface emissivity ϵ_s from the overall resistance of the coupling (two resistances in series) to space via the MLI (ϵ^*). Solution of these equations yields ζ_{1s} , described in equation 5.