Efficiency of aluminized mylar insulation at cryogenic temperatures

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ABSTRACT

An estimate of the transparency of aluminized mylar 'superinsulation' was obtained by measuring the far-infrared/submillimeter wave transmittances of 3 pieces randomly selected from a 25.4μm-thick (nom. 0.001 in.) sheet of mylar that was aluminized on one side. Measured transmittance values were less than 1×10^{-4} in the 100μm - 1000μm wavelength region. The emissivities of mylar and aluminum were computed from published optical constants to be, respectively, about 5×10^{-2} and 2×10^{-4} for temperatures near 20K and an effective wavelength of 150μm. Due to the strong attenuation of the aluminum layer, the radiant power from an elemental area on the outer surface of the superinsulation is about 10^4 times more significant than radiance originating within the insulating mylar layer, for temperatures near 20K. Radiant power passing through doubly aluminized mylar (the usual configuration) would be attenuated by a factor of about 10^{-10}.

Keywords: 'superinsulation', aluminized mylar, skin depth

1. INTRODUCTION

Aluminized mylar insulation material consists of thin sheets of mylar, about ¼ mil to several mils thick, that have thin films of evaporated aluminum deposited onto one or both sides, as sketched in Figure 1. Often referred to as 'multilayer insulation' (MLI) or 'superinsulation', it is frequently used in multiple layers separated by non-conducting spacers to prevent heat transport between volumes at significantly different and relatively cold temperatures. In some configurations, the mylar sheets are aluminized on one side only, with the mylar sheets acting as thermal insulators between layers. In this configuration, the sheets are often embossed to further minimize thermal transport by limiting physical contact to the embossed portions that are only a small fraction of the total sheet area. In an alternate configuration, the mylar sheets are aluminized on both surfaces and each sheet is separated from its neighbor by a non-thermally conducting netting , usually of Dacron. A typical spacecraft thermal blanket made of this material may be composed of as many as eighteen layers of ¼ mil (6.4μm) mylar, aluminized on both sides, separated by Dacron mesh, with a 3 mil (76μm) aluminized Kapton outermost sheet, and a 1 mil (25.4μm) aluminized Kapton innermost sheet. The aluminized (low emittance) side of both Kapton sheets face the inner MLI stack. The high emittance Kapton side on the outer layer promotes heat dissipation away from the insulated structure. Other variations on this basic theme are possible, as dictated by the component that one is trying to insulate thermally, or to shield from some exterior heat source.

Heat transport through the MLI is a combination of radiation, conduction, and convection. Operation in a vacuum, given sufficient time, will eliminate convection as a heat transport mechanism. Individual sheets are usually perforated with numerous holes about 1 mm in diameter to facilitate the rapid removal of trapped gas in a vacuum environment.Heat transport by conduction is usually much more difficult to eliminate for structural reasons. The MLI has to be held in place by some physical means. Good construction practices, proper embossing, and careful arrangement of non-conducting spacers between sheets of the MLI are necessary to minimize conduction. Heat transport by radiation among the inner MLI layers is predominantly a function of the transmittance and emittance of the evaporated Al layers. It is the

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radiation issue that will be the focus of this report.

The investigation proceeded by generating an estimate of both the effective opacity to thermal radiation of a single aluminized mylar sheet and its ability to re-radiate absorbed radiant power. In order to estimate the magnitude of radiant throughput of 'superinsulation' operating at a temperature near 20K, the transmittances of three randomly selected pieces of 25.4μm-thick mylar, coated with evaporated aluminum on one side only, were measured over the 100μm - 1000μm wavelength region. Although the aluminized mylar 'superinsulation' is typically coated with evaporated aluminum on both sides of the mylar sheet, the doubly coated material is too strongly attenuating to allow accurate transmittance measurements.

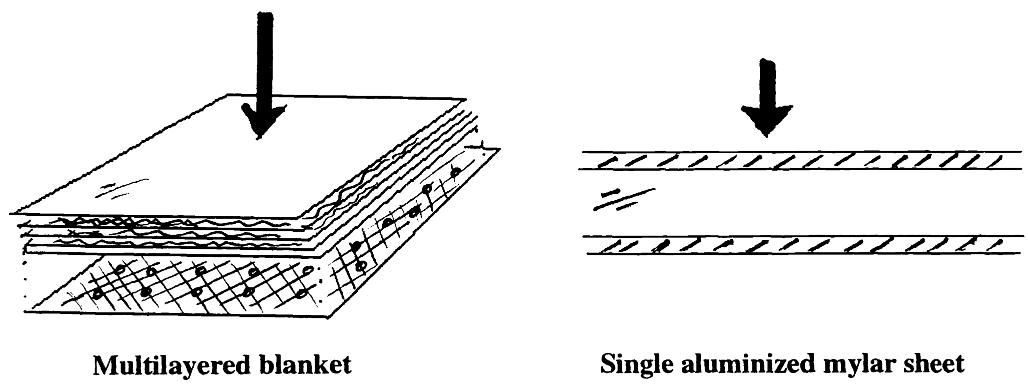

FIGURE 1. A sketch of a multilayerd blanket composed of n sheets and an individual aluminized mylar sheet.

2. SAMPLE DESCRIPTION

Samples of mylar, approximately 25.4μm (0.001in.) thick, coated with evaporated aluminum on one side, were cut from the corner, middle, and edge of a larger piece that was cut from a roll of the material. The thickness of the aluminum layer was not known, but all three pieces were slightly transparent to the unaided eye. This indicated an upper limit of about 60nm for the aluminum film thickness.

3. EXPERIMENTAL PROCEDURE

Transmittance was measured, at room temperature and normal incidence, over the 100μm - 1000μm wavelength region, using a Nicolet 8000HV Michelson Fourier transform spectrometer with a liquid helium cooled bolometer detector. With this device, the lower limit of transmittance measurement was about 10^{-4}. Because the samples had a slight visible transparency, their transmittances were measured at λ = 550nm with a Perkin-Elmer Lambda 9 spectrophotometer to provide data from which aluminum film thickness could be determined. The measured transmittance data were used with published values of the refractive indices of mylar and aluminum[1], to compute the thickness of the aluminum film. The computations were performed using a thin film multilayer analysis program based on a recurrent solution of Maxwell's equations for the electric and magnetic field intensities for a series of boundary layers. [2,3] A thorough discussion of this computation procedure is beyond the scope of this paper and may be found in the indicated references.

In general, for metals at visible and infrared wavelengths, $(n^2 + k^2) >> 1$, where n is the refractive index and k is the extinction coefficient related to the attenuation of an electromagnetic wave in an absorbing medium, such as a metal. The magnitude of reflected intensity for an electromagnetic wave that strikes an absorbing surface, such as a metal, at normal incidence is expressed in terms of the optical constants as:

$$\rho = \{(n_o - n)^2 + k^2\} / \{(n_o + n)^2 + k^2\}$$

where n_o is the refractive incidence of the nonabsorbing incident medium, either air or mylar for the aluminized mylar insulation, depending on which direction an electromagnetic wave is incident on the aluminum surface, and k is the extinction coefficient of the aluminum. When the relation $(n^2 + k^2) >>1$ holds, most of the incident power is reflected, provided that the film is sufficiently thick.

Once the thickness of the aluminum layer was determined, it was then compared with the skin depth, δ, defined as the thickness at which transmitted intensity declines to 1/e of its initial value. This comparison was necessary in order to determine if the evaporated Al film was sufficiently thick to prevent radiant transmittance at far-infrared wavelengths. In general, the magnitude of transmitted electromagnetic energy within a metal film as a function of film thickness can be expressed as:

$$\tau = \tau_o e^{-4\pi k d/\lambda} = 1/e \text{ when } d = \lambda/4\pi k = \delta ,$$

where d is the film thickness, λ is the wavelength of the electromagnetic wave, k is its extinction coefficient in the metal, and τ_o is the transmittance for zero metal film thickness. For the insulation material discussed here, the Al film is deposited onto a mylar substrate that has a finite, but small, reflectance when the Al film thickness is zero. The Al film is much more reflecting and absorbing than its mylar supporting film and the contribution of the mylar film may be ignored, to a good approximation, when estimating reflectance and transmittance for the aluminized material. I.e., $\tau_o = 1$. In the computerized computational methods described above (refs. 2 & 3), the mylar film was easily included for the sake of completeness.

An estimate of the skin depth was obtained by two methods. First, a published value for the extinction coefficient of aluminum[4] at λ = 150μm and a temperature of 300K was used to compute $\delta_{300K,150\mu m}$. A second estimate of δ was obtained using published bulk resistivity data for Al at a temperature of 300K[5] and 20K[6]. The two methods produced results at 300K that differed by about 5%. Data for the extinction coefficient of Al at temperatures below 300K were not available. The skin depth is smaller in value at cryogenic temperatures because the conductivity of aluminum increases. The result computed for a temperature of 300K is useful as a simple check on the accuracy of the method. At a temperature of 20K, the resistivity of Al was obtained from Ref. 6 and used to calculate $\delta_{20K,150\mu m}$ and then used to obtain a computed estimate of the extinction coefficient, k, of Al at 20K. The two computation methods used to generate values for the skin depth at temperatures of 300K and 20K, and at a wavelength of 150μm, are described in references 7 and 8.

The emissivity of mylar for a temperature of 20K was then computed using published values of the absorption coefficient[9] at 300K. Data at 20K were not available. Since the absorption of mylar may decrease slightly at lower temperatures, the computed emissivity may be slightly high. Similarly, 300K temperature values of the optical constants of aluminum and resistivity values at 300K and 20K were used to compute the emissivity of the outer aluminum thin film layer.[4,5,6] Again, these computed values, valid for a computational consistency check, may also be slightly high.

4. RESULTS

4.1 MEASURED AND COMPUTED ESTIMATES OF TRANSMITTANCE AND REFLECTANCE

The measured and computed transmittances of aluminized mylar 'superinsulation', for $\lambda = 550$nm and 150μm, and the computed Al film thickness, are presented in Table 1 for a temperature of 300K. The refractive index values of mylar that were used in the calculations are n = 1.6, k = 0.

TABLE 1

COMPUTED AND MEASURED VALUES FOR THE TRANSMITTANCE AND REFLECTANCE OF ALUMINIZED MYLAR INSULATION AT A TEMPERATURE OF 300K

λ	n	k	Computed Al Film Thickness	Measured Transmittance	Computed Transmittance	Computed Reflectance
550nm	0.89[a]	5.99[a]	48nm ± 3nm	$7.2(\pm 2.0)\times10^{-4}$	N/A	N/A
150μm	375[b]	431[b]	N/A	$<1\times10^{-4}$	1.3×10^{-5}	0.9938

[a])Ref. 1
[b])Ref. 4

4.2 SKIN DEPTH

The skin depth, δ, at 300K and a wavelength of 150μm, was computed using the two methods described above and the data from Table 1.

Method (1) (Ref. 7): $\delta = \lambda/4\pi k = 28.0\text{nm}$

where:

k - the extinction coefficient for aluminum at $\lambda = 150\mu m$
= 431 (Ref. 4)

Method (2) (Ref. 7): $\delta = (1/4\pi)(c\lambda/\mu\sigma)^{1/2} = (1/4\pi)(cr\lambda)^{1/2} = 29.0\text{nm}$

where:

μ - magnetic permeability = 1 for aluminum
c - the velocity of light
r - the resistivity of aluminum at 300K = $2.7\mu\omega$-cm = 3.0×10^{-18} sec
λ = 150μm (wavelength in vacuum)

The relatively good agreement between the two results obtained from methods (1) and (2) simply indicates that the published value for the extinction coefficient of aluminum is in good agreement with the published resistivity at 300K in the context of the Drude theory of metals. More importantly, it verifies the comparability of the computation methods. The computed skin depth of 29nm is less than the estimated thickness of the Al film on the measured insulation samples, 48nm (Table 1).

At a temperature of 20K, only method (2) can be used because data for the extinction coefficient of Al are not available in this temperature range. From Ref. 6, the resistivity of Al at 20K is:

$$r_{20K} = 3.6 \times 10^{-11}\ \omega\text{-m} = 3.6 \times 10^{-3}\mu\omega\text{-cm} = 4 \times 10^{-21}\ \text{sec}.$$

Using method (2) yields for the computed skin depth at 20K:

$$\delta_{20K,150\mu m} = 1.1\text{nm}.$$

This is then inserted back into method (1) to compute an extinction coefficient of Al at 20K:

$$k_{20K} = \lambda/4\pi\delta_{20K} = 1.2 \times 10^{4}$$

4.3 EMITTANCE

4.3.1 MYLAR

The emissivity of mylar, weighted for a blackbody temperature of 20K, but using published absorption data taken at 300K[9], was computed from:

$$\varepsilon_\lambda = \{(1 - \rho_{s,\lambda})(1 - \tau_{o,\lambda})\}/(1 - \rho_{s\lambda}\tau_{o\lambda})$$

and

$$\varepsilon_{20K} = \int_{50\mu m}^{1000\mu m} \varepsilon_\lambda E_\lambda(20K)d\lambda \Big/ \int_0^\infty E_\lambda(20K)d\lambda = 0.05$$

where:

ε_{20K} - weighted (total) emissivity
ε_λ - spectral emissivity
$\rho_{s,\lambda}$ - single surface reflectance of mylar, $\cong 0.05$ for $50\mu m < \lambda < 1000\mu m$
$\tau_{o,\lambda}$ - $e^{-\alpha d}$, α_λ = published absorption coefficient of mylar[9]
d - mylar thickness (25.4μm)
$E_\lambda(20K)$ - Planckian spectral irradiance function for a blackbody at 20K.

Note that the mylar absorption data published in reference 9 do not extend to wavelengths longer than 200μm. Consequently, in order to satisfy the limits in the above integral in the region 200μm - 1000μm, a reasonable extrapolation of the absorptance data was made at the longer wavelengths. The absorptance of mylar is very low in this region and the consequential error is small.

4.3.2 ALUMINUM

The emissivity (300K) of aluminum at $\lambda = 150\mu m$ can be computed using the optical constants of aluminum (Method 1) or the static resistivity (Method 2), similar to what was done above for the skin depth.

Method (1): The n and k values of Table 1 are used to compute reflectivity, ρ, and transmittance, τ. Then emissivity, ε, is obtained directly from:

$$\varepsilon_{300K} = 1 - (\rho + \tau) = 6 \times 10^{-3}.$$

Method (2) uses the Hagen and Rubens relation (Ref. 7) with the static resistivity of aluminum, as follows.

$$\varepsilon_{300K} = 1 - \rho, \quad (\rho >> \tau)$$

$$\varepsilon_{300K} = 2(\nu r)^{1/2} = 2(rc/\lambda)^{1/2} = 5 \times 10^{-3}.$$

where:

$r = 3 \times 10^{-18}$ sec (at 300K)
$c = 3 \times 10^{10}$ cm/sec
$\lambda = 150\mu m = 1.5 \times 10^{-2}$ cm

These two results are consistent with the calculated emissivity (for $\rho >> \tau$) of aluminum published by J.J. Bock et al. (Ref. 10) for a film thickness to skin depth ratio (t/δ = 48nm/29nm) of about 1.7 and a wavelength of 150μm, although it lies just outside their calculated range. The results of their experimental measurements indicated that the emissivity of metals decreases to a minimum at t/δ equal to about 3 and remains more or less constant for $t/\delta > 3$.

Repeating the above calculation for a temperature of 20K yields:

$$\varepsilon = 2(rc/\lambda)^{1/2} = 1.8 \times 10^{-4}$$

where

$$r_{20K} = 3.6 \times 10^{-3} \mu\omega\text{-cm} = 4 \times 10^{-21} \text{ sec.}$$

A summary of computed aluminum film transmittances, skin depths, and emissivities, at a wavelength of 150μm and temperatures of 20K and 300K, is presented in Table 2.

TABLE 2

	20K	**300K**
$\tau_{150\lambda}$	n.a.	$< 1 \times 10^{-4}$ [(a)] $< 1.3 \times 10^{-5}$
$\delta_{150\lambda}$	1.1nm	28nm
$\varepsilon_{150\lambda}$	1.8×10^{-4}	$5 - 6 \times 10^{-3}$

[(a)] Measured value.

For a single piece of mylar superinsulation, aluminized on both sides, at a constant temperature, T, the radiant contribution to surrounding objects, such as other insulation layers, is much greater from the thin aluminum film 'skin' than from the insulating mylar layer. The ratio of radiant power leaving an individual superinsulation sheet from the outer Al layer, as compared to the sandwiched mylar sheet, is given by:

$$\Phi_{Al}/\Phi_{mylar} = \varepsilon_{Al}\sigma T^4 / \tau_{Al}\varepsilon_{mylar}\sigma T^4 \quad > 10^4 \quad \text{at 300K;}$$

$$> 10^5 \quad \text{at 20K}.$$

5. SUMMARY OF RESULTS

* The measured transmittance of 25μm-thick mylar, aluminized on one side, was less than 1×10^{-4} (measurement noise limit) in the 100μm - 1000μm wavelength region.

* A transmittance of 1.3×10^{-5} at $\lambda = 150\mu m$ was computed from published values of the optical constants of aluminum and mylar.

* The skin depth in the aluminum layer was computed to be about 28nm at 300K and about 1.1nm at $\lambda = 150\mu m$ from published values of the extinction coefficient and the resistivity of aluminum.

* The emissivity of aluminum at $\lambda = 150\mu m$, computed from published values of the optical constants, n & k, and the static resistivity is about 6×10^{-3} at 300K and about 1.8×10^{-4} at 20K.

* The emissivity of mylar, weighted for a blackbody temperature of 20K, but derived from published absorption data at 300K, was estimated to be about 0.05.

* The computed emissivities of mylar and aluminum, combined with the measured transmittance of aluminized mylar, indicate that radiant power originating in the external aluminum film is 10^5 times more significant than that from a unit volume of mylar within the insulating layer for temperatures in the 20K range. Radiant power arriving from outside the doubly aluminized mylar 'superinsulation' sheet (the usual configuration) would be attenuated by a factor of about 10^{-10}.

6. Conclusions

Radiant transfer through multilayers of 'superinsulation' is attenuated by a factor in the order of $(1.3 \times 10^{-5})^2$ per layer for surrounding temperatures near 20K. Thermal radiation arising in the mylar film that is sandwiched between layers of evaporated aluminum that are thicker than the skin depth is transferred to the surroundings with an efficiency of about 6.5×10^{-7} ($= \varepsilon_{mylar}\tau_{Al}$). The outermost, or final, aluminum layer in a multilayer stack of 'superinsulation' sheets radiates with an emittance less than 2×10^{-4} for temperatures near 20K. This is a larger coupling factor than either of the two preceding terms. Consequently, the surface temperature of the outermost aluminum layer is a dominating concern. The results indicate that a radiant path leakage for multilayers of 'superinsulation' is unlikely. Conductance coupling and convective transport remain as potential sources of heat leakage.

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