

THERMAL PROPERTIES OF DOUBLE-ALUMINIZED KAPTON AT LOW TEMPERATURES

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ABSTRACT

Double-aluminized kapton (DAK) is commonly used in multi-layer insulation blankets in cryogenic systems. NASA plans to use individual DAK sheets in lightweight deployable shields for satellites carrying instruments. A set of these shields will reflect away thermal radiation from the sun, the earth, and the instrument's warm side and allow the instrument's cold side to radiate its own heat to deep space. In order to optimally design such a shield system, it is important to understand the thermal characteristics of DAK down to low temperatures. We describe experiments which measured the thermal conductivity and electrical resistivity down to 4 Kelvin and the emissivity down to 10 Kelvin.

KEYWORDS: Double-aluminized kapton, emissivity, resistivity, thermal conductivity.

INTRODUCTION

Double-aluminized kapton (DAK) is commonly used in multi-layer insulation blankets in cryogenic systems. In such blankets the parallel DAK layers are typically closely spaced, with only a thin mesh or fabric between them. Except for the outer layers, each DAK sheet in a blanket exchanges thermal radiation only with its two nearest neighbor sheets. NASA plans to use individual DAK sheets in lightweight deployable shields for future satellites carrying scientific instruments. In these shields the DAK layers will be spaced farther apart and angled relative to each other, so they will also have a view to deep space. When properly designed, these shields will reflect away thermal radiation from the sun, the earth, and the instrument's warm side, while allowing its cold side to radiate heat to deep space. The James Webb Space Telescope (JWST) is an example of such a mission. Its optics and most of its instruments will be cooled passively by radiating

to space, and they will be protected from incoming thermal radiation by a large, deployable 5-layer DAK shield.

Most NASA missions using these deployable shields will be extremely costly, so their thermal performance will need to be well understood before launch in order to reduce the risk of failure. Modeling these systems thermally is currently viewed as challenging, so the models will need to be verified via ground testing. Unfortunately, few if any facilities exist which are large enough to contain a full-sized large satellite with its shield and provide the proper thermal environment for testing. Such testing will require expensive modifications to existing large chambers which are already costly to operate.

A challenge of modeling realistic future radiator systems results from the fact that they will contain DAK layers at temperatures as low as 20 Kelvin or below. Little to no published data exist for the relevant thermal characteristics of individual DAK layers in this temperature range. We performed coupon tests on small samples of DAK, measuring its electrical and thermal conductivity down to 4 Kelvin and studying its emissivity down to 10 Kelvin. The samples all included a 25 μm thick kapton layer coated on both sides with equal aluminum thicknesses of either 100 nm or 500 nm. Because of anticipated shield creasing in stowing and deployment, we tested both smooth and intentionally creased samples. The latter had been smooth samples which were manually "crumpled" to produce visible creases. Here we refer to creases as permanent deformations which may affect the aluminum layer to the point of discontinuities. We report the current status of these tests, which are ongoing.

ELECTRICAL RESISTIVITY STUDIES

The manufacturer of the DAK, Sheldahl, measures the thickness during the coating process through the use of eddy current sensors. However, the specifications provided with purchased DAK commonly provide only their room temperature resistances in ohms/square, measured on one side of the sample. Since fairly pure aluminum samples should all have about the same electrical resistivity at room temperature, the ohms per square should allow a good estimate of the actual thickness. Interestingly, Sheldahl's specification sheet for a number of different rolls of the nominal 100 nm-thick DAK listed resistances that varied by a factor of two from lowest to highest.

We measured the residual resistance ratio, $\text{RRR} = R(300\text{K})/R(4\text{K})$, for both a smooth and a creased sample of DAK with each aluminum thickness. The RRR values were all fairly close to each other, between 4.22 and 5.46. This indicates that there was no significant difference in purity or in crystal structure between the samples with different aluminum thicknesses, and that any damage done by creasing did not involve a measurable resistivity change in the aluminum.

The manufacturer of the DAK with 100 nm thick aluminum coatings had noted that one side of this material had a "bad" coating which failed a tape pull test by peeling from the kapton. Creasing this sample resulted in some cracks through the coating on one side of the kapton. This damage was visible under a microscope, and these cracks had to be avoided in creating the RRR samples. Interestingly, it was noticed that a small area of bright light impinging on one side of the creased thick sample shone through in a larger pattern on the opposite side. This was a clear indication total internal reflection in the visible spectrum.

We cooled a smooth sample of DAK with 100 nm thick aluminum coatings in a cryostat and measured its electrical resistance as a function of temperature. The results are shown in FIGURE 1.

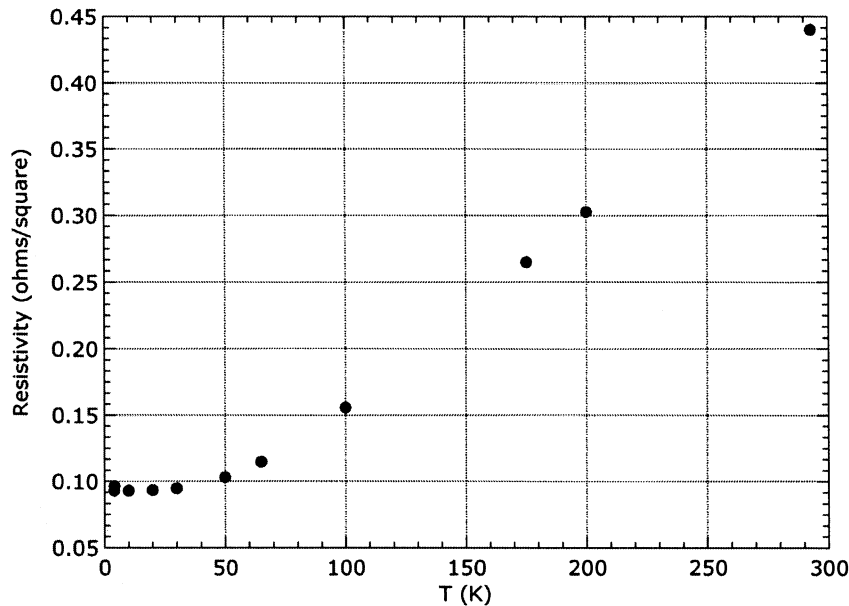


FIGURE 1. The electrical resistance of one side of a smooth, 100 nm thick DAK sample as a function of Temperature.

THERMAL CONDUCTIVITY MEASUREMENT

Knowing the thermal conductivity of DAK is obviously important in designing radiative shields. Calculations indicated that with either thickness the aluminum coatings, rather than the kapton, would dominate the thermal conductance over most of the temperature range below room temperature, particularly at the low temperature end. Still, we measured the thermal conductivity of the creased thin-aluminum DAK to determine the effect of damage to the aluminum coatings. It seemed possible that microscopic cracks could result in a tortuous path for conduction electrons in the 100 nm aluminum, but that they might be thermally shorted out by a parallel path through the 25 micron thick kapton.

Measuring the thermal conductance of a single DAK strip, which is quite low, is challenging at higher temperatures where radiative heat transfer dominates. Thus we tested twenty parallel DAK strips at once, restricted our measurements to fairly low temperatures, and used a special test rig built in our lab. FIGURE 2 shows a schematic of this rig, which has been described in detail elsewhere [1]. The DAK strips, each about 80 mm long and 13 mm wide, were epoxied into individual slots in four copper combs. These combs, cut with a wire EDM machine, provided thermal contacts to the parallel strips at appropriate locations along their lengths. The comb at one end was bolted to the base plate, the comb at the opposite end held a heater and the “sample” thermometer, and the two intermediate combs held “near” and “far” thermometers.

Surrounding the samples was a stainless steel guard cylinder with inner diameter just large enough to contain the samples and combs without touching them. The “sample” comb was carefully suspended from the guard can's far end by tiny kevlar strings, and the space between the samples and guard was filled with a ceramic fiber (Fiberfrax). The fiber was packed in to a density at which its thermal conductivity has been measured [2]. The guard's far end was closed out by a copper cap, which overlapped the guard down to the exact height of the sample comb. A guard thermometer and heater were mounted on this cap.

The measurements were performed by individually temperature-controlling both the “sample” comb and the guard's far end at a fixed temperature above that of the base, and carefully measuring the “near” and “far” temperatures and the controlling heat applied to

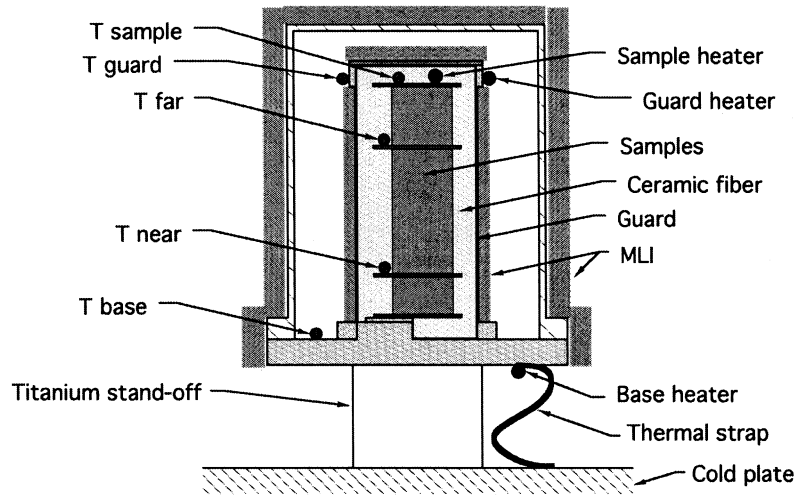


FIGURE 2. Schematic of the DAK thermal conductivity measurement apparatus, showing multiple levels of thermal shielding.

the sample comb. When all temperatures and heats reached steady-state, the sample and guard temperature profiles were very well matched, which nearly eliminated any radiative heat transfer between them in the radial direction. The ceramic fiber minimized the effect of axial radiation, and its thermal conductance was always trivial compared to that of the sample. For each average sample temperature we performed measurements with four different ΔT values, and the slope of the power vs. ΔT was used along with the sample geometry to compute the conductance.

FIGURE 3 shows the thermal conductance of creased DAK with 100 nm aluminum coatings converted geometrically to the equivalent values for a single square sheet. The plot shows that it is proportional to T below about 25 Kelvin. This is consistent with the aluminum dominating the thermal conductance, with no noticeable participation from the kapton. The creased 100 nm DAK thermal conductance value of 2.64×10^{-6} W/K/square at 4.0 Kelvin can also be compared to the electrical resistance value of 0.0778 ohms/square taken at 4.2 Kelvin for one side of the same material. The Wiedemann-Franz law, which predicts the behavior of metals at low temperatures remarkably well, states that $K = (2.44 \times 10^{-8}) T/R$, where K is the thermal conductance in Watts/Kelvin, and R is the resistance in ohms. Reducing the resistance by a factor of two to take into account both sides of the sample participating in the conduction, we get a predicted $K = 2.51 \times 10^{-6}$ W/K/square. This is within 5 percent of the measured value, so again there is no indication of kapton participating in the thermal conduction of creased 100 nm DAK.

EMISSIVITY STUDIES

Experimental Technique

The total normal emissivity of a bulk metal surface is predicted by an expression commonly referred to as the Hagen-Rubens equation:

$$\varepsilon = 0.576\sqrt{\rho T} - 0.124\rho T + \dots [3], \quad (1)$$

where ρ is the electrical resistivity in ohm-centimeters. Thin metal coatings allow some

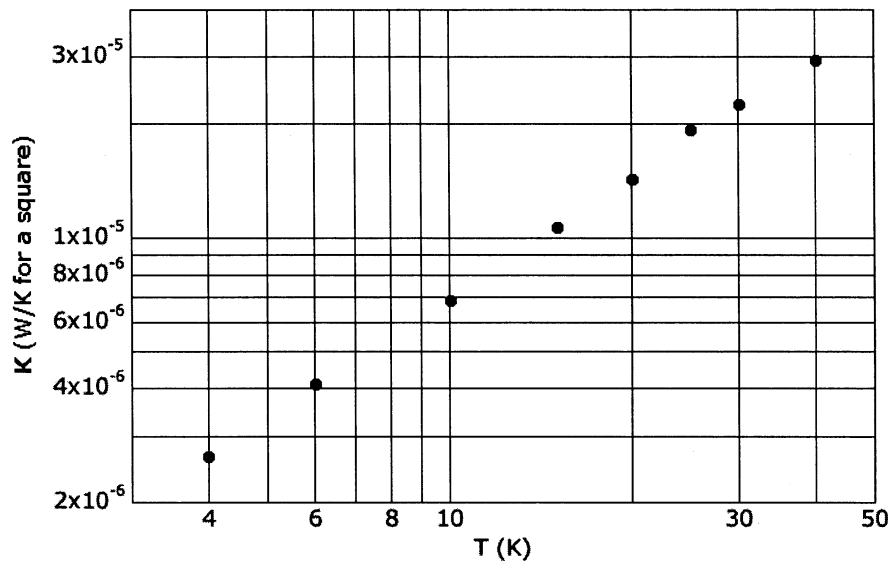


FIGURE 3. The thermal conductance of a single square sample of creased DAK with 100 nm thick aluminum coatings.

degree of penetration by longer wavelengths. The penetration falls off exponentially and is characterized by a skin depth:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}, \quad (2)$$

where ω is the angular frequency, and μ is the magnetic permeability. It was difficult to predict how our DAK samples would behave at low temperatures. The kapton most likely is quite black, but its 25 μm thickness is much less than the wavelengths which can penetrate the 100 nm aluminum coatings. Nonetheless, there is a lack of emissivity data for individual DAK sheets below about 35 Kelvin, the temperature range in which significant skin depth penetration might be seen. We attempted to measure the DAK emissivity at temperatures well below 20 Kelvin to look for this phenomenon.

In principle, the emissivity of a sample could be measured by suspending it from thermally isolating strings so that it only views deep space, temperature-controlling it at a desired temperature, measuring the controlling power, and using the Stefan-Boltzmann law to back out the emissivity. Typically one would probably suspend it in a large, cold chamber with black inner walls and try to correct for the heat conduction of the strings.

FIGURE 4 is a schematic of our attempt to adapt this concept to arrive at a more convenient and less expensive technique for measuring the emissivity. We replaced the large black chamber, which provided multiple bounces for emitted photons, with a small box lined with black-painted honeycomb. The box was a 200 mm inside dimension cube made from sheet copper, which was cut, bent and bolted together. The inner walls were lined with 25.4 mm thick aluminum honeycomb with 6 mm wide cells. The honeycomb was first painted with multiple coats of NAPA Auto Parts matte black spray paint and then bonded to the inner walls using Stycast 2850. We pried open approximately 6 mm diameter holes through the box and honeycomb in four corners located in a vertical plane crossing through the box center. The box was supported on G-10 standoffs coming up from a roughly C-shaped bent copper bar, which was in turn similarly stood off from a cryostat's cold plate. The bar ran diagonally across under the box and rose up vertically

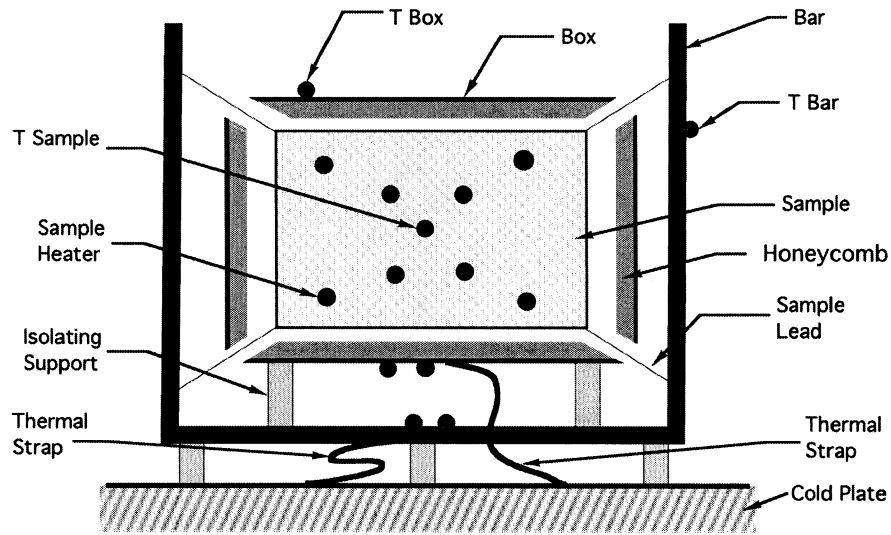


FIGURE 4. Schematic of the DAK emissivity apparatus. Note that the thermometer and heaters shown on the sample are actually inside the sample assembly and are not visible.

just outside the corner holes. The box and the bar were both thermally strapped to the cold plate, and on each was a heater and two thermometers.

The sample consisted of a 127×178 mm rectangular sandwich with layers of DAK on the outside and two sheets of aluminum foil on the inside. Between the foil layers were a tiny Cernox thermometer and a heater made with 8 strain gauges wired in series and distributed roughly evenly across the area. The thermometer and gauges were epoxied to one of the foil sheets, and foil and DAK sheets were all bonded together with as little epoxy as possible. The sample's edges were sealed with a tiny strip of aluminized kapton tape which comprised $< 7\%$ of the total area. The sample was suspended from the four twisted wire pairs of the thermometer and heater. These wire pairs ran out tiny holes in the sample corners, through the corner holes in the box, and through holes in the bar. The wires were attached to the bar mechanically and thermally by tape.

During the experiment the bar, box and sample could be simultaneously controlled at three different temperatures. The bar was always controlled at the same temperature as the sample, eliminating all heat flow in the wires except for the tiny amount which they radiated to their surroundings. We thus provided a "guarded" measurement. Usually the box was allowed to cool to a "low" temperature close to that of the cold plate. The steady state sample temperature controlling power, the area of the sample, and its temperature were used with the Stefan-Boltzmann law to derive the sample's effective emissivity.

Data Analysis

FIGURE 5 shows the raw data measured for a sample of DAK with 100 nm thick aluminum in a "low" temperature box. The box was not temperature controlled, but was allowed to cool to a steady-state temperature determined by the thermal conductances between the box and bar and between the bar and cold plate. When the sample temperature was above 50 Kelvin, it was 5 – 6 times the box temperature. This ratio dropped gradually to 2.5 times the box temperature when the sample was at 10 Kelvin.

The measured data were taken by controlling the sample at a temperature and measuring the controlling power, Q . From this the emissivity can be calculated using:

$$\epsilon = \frac{Q}{\sigma A(T_{\text{SAMPLE}}^4 - T_{\text{BOX}}^4)}, \quad (3)$$

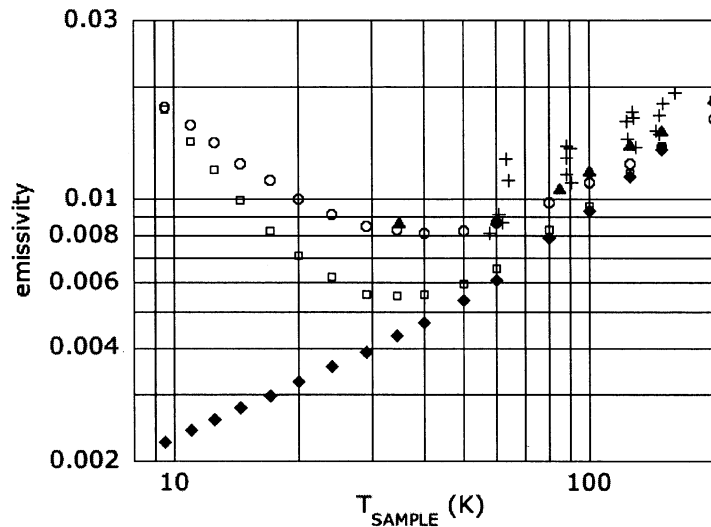


FIGURE 5. Effective emissivity of DAK with 100 nm aluminum coatings in a “low” temperature box. The symbols are as follows: open circles, measured data from this work; filled diamonds, predictions from Hagen-Rubens equation; open squares, predictions from Hagen-Rubens + calculated penetration depth effect; crosses, Cunnington data [4]; filled triangles, Lysek data [5].

where σ is the Stefan-Boltzmann constant and A is the sample area. The uncertainty in our data due to that of the power measurements is less than 1%. Our data’s temperature dependence matches those of other experimenters above about 35 Kelvin, although the absolute values are not a perfect match. This could be explained by differences in the quality of the aluminum coatings.

Most notable is the rise in our data as temperatures fall below about 40 Kelvin, a trend which contrasts with the behavior predicted by the Hagen-Rubens equation. We attribute this trend to the penetration of long-wavelength radiation through the aluminum coatings. This results in an additional emissivity contribution which depends on temperature and frequency and is “non-grey.” To predict the interaction of this term with the box, one must integrate over all wavelengths the product of the box spectrum and the skin-depth effect spectrum. We did this with no adjustable parameters, assuming that the inner box walls and the sample kapton were entirely black. The emissivity of aluminum honeycomb has been calculated by Yan et. al. [6] This “skin depth” contribution is then added to the Hagen-Rubens contribution. The results are shown in FIGURE 5, and they qualitatively match the shape of our measured data.

We tested this assumption by holding the sample at one particular temperature, 12.5 Kelvin, and varying the box temperature. FIGURE 6 shows the controlling power compared with the Hagen-Rubens prediction. There is an obvious difference, which increases for lower box temperatures. Here the Hagen-Rubens prediction seems intuitively correct; as the box temperature (and its T^4) get small relative to the sample temperature, the power should be less dependent on the box temperature. However, this ignores the non-grey nature of the sample’s emissivity. We again calculated the effect of the aluminum skin depth, and the resulting power prediction matches the measured data qualitatively.

CONCLUSION

We characterized electrical and thermal properties of DAK down to 10 Kelvin. Based on this work, the RRR value of DAK aluminum coatings is fairly independent of thickness and of creasing. It is possible to measure the aluminum electrical resistivity of a

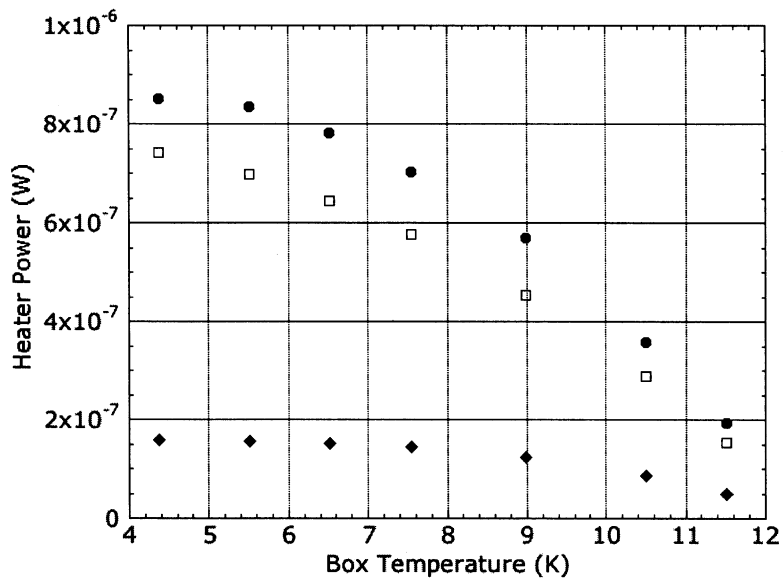


FIGURE 6. Controlling power for a 12.5 Kelvin DAK sample with the box temperature controlled. Symbols are: filled circles, measured in this work; filled diamonds, predictions from Hagen-Rubens equation; open squares, predictions from Hagen-Rubens + calculated penetration depth effect.

DAK sample at room temperature and low temperature and calculate the thermal conductivity via the Wiedemann-Franz equation. The emissivity of an undamaged sample can also be calculated given the additional knowledge of the coating thickness. We are in the process of performing a similar emissivity study of a DAK sample with 500 nm thick aluminum coatings.

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REFERENCES

1. Canavan, E.R. and Tuttle, J.G. , "Thermal Conductivity and Specific Heat Measurements of Candidate Structural Materials for the JWST Optical Bench," in *Advances in Cryogenic Engineering 52A*, edited by U. B. Balachandran et al., AIP, New York, 2006, pp. 233-240
2. Moore, J.P., Williams, R.K., and Graves, R.S., *Review of Scientific Instruments*, 45(1), pp. 87-95 (1973).
3. See, for example, Eckert, E.R.G, and Drake, R.M., *Analysis of Heat and Mass Transfer*, McGraw-Hill, New York, 1972, p. 608.
4. G.R. Cunnington, G.A. Bell, B.F. Armaly, C.L. Tien, "Total emittance measurements of metallic films at cryogenic temperatures," *J. Spacecraft 7* (1971) pp. 1496-1499.
5. Lysek, private communication, 2006.
6. Lu Yan, Han Jun, and Gong Tiequan, "Theory analysis and test study of cold black target for space radiative cooling environmental simulator", *Adv. Cry. Eng.* 41, pp.1181-1188 (1996).