THERMAL PERFORMANCE OF LOW LAYER DENSITY MULTILAYER INSULATION USING LIQUID NITROGEN

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ABSTRACT

In order to support long duration cryogenic propellant storage, the Cryogenic Fluid Management (CFM) Project of the Exploration Technology Development Program (ETDP) is investigating the long duration storage properties of liquid methane on the lunar surface. The Methane Lunar Surface Thermal Control (MLSTC) testing is using a tank of the approximate dimensions of the Altair ascent tanks inside of a vacuum chamber to simulate the environment in low earth orbit and on the lunar surface. The thermal performance testing of multilayer insulation (MLI) coupons that are fabricated identically to the tank applied insulation is necessary to understand the performance of the blankets and to be able to predict the performance of the insulation prior to testing. This coupon testing was completed in Cryostat-100 at the Cryogenics Test Laboratory. The results showed the properties of the insulation as a function of layer density, number of layers, and warm boundary temperature. These results aid in the understanding of the performance parameters of MLI and help to complete the body of literature on the topic.

KEYWORDS: Multilayer Insulation, Boil-off Calorimetry

INTRODUCTION

As people return to the moon for longer durations and proceed to Mars, more efficient and lighter weight propulsion systems are needed. Liquefied cryogenic propellants provide more efficient combustion, especially in the vacuum of space; however, high performance insulation systems are required to prevent large mass penalties due to the extremely cold temperatures. Much work has been done on understanding the properties of thermal insulation in high vacuum environments, leading to the development of multilayer insulation (MLI) systems. Multilayer insulation systems are fairly well understood from an engineering point of view during steady state, high vacuum operation. More recently, interest has grown in testing different MLI in ambient Earth pressure as well as intermediate vacuum pressures, in a steady state environment. Such testing also yields information on the performance of vacuum insulated systems here on Earth including vacuum jacketed piping and storage vessels.

Currently, the Altair Project is considering both cryogenic (liquid methane/liquid oxygen) and hypergolic propulsion methods for the Altair ascent stage. In order to support the decision between the two types of propulsion, the Cryogenic Fluid Management (CFM) Project of the Exploration Technology Development Program (ETDP) is investigating the long duration storage properties of liquid methane on the lunar surface. The Methane Lunar Surface Thermal Control (MLSTC) testing is using a tank of the approximate dimensions of the Altair ascent tanks inside of a vacuum chamber to simulate the environment in low earth orbit and on the lunar surface.

Basic understanding the performance of the MLSTC insulation system, prior to the actual large-scale testing, is essential. This initial test information will allow a better characterization of the total heat loads that are expected for the MLSTC testing. As a part of the MLI procurement, two insulation "coupons" were specified to fit the Cryostat-100 test apparatus of the Cryogenics Test Laboratory at Kennedy Space Center.

TEST COUPONS

Two MLI "coupon" test articles were procured from Ball Aerospace for testing on Cryostat-100. The first coupon is representative of the insulation installed on the MLSTC test tank at GRC by Ball Aerospace personnel and serves to give an approximate heat leak through the MLSTC insulation. The second coupon is a calorimetric test sample intended to test the heat transfer effects of changing the layer density of an MLI blanket.

The first coupon, Coupon A, consists of 60 layers of alternating double aluminized Mylar (DAM) and Dacron netting. Every 4 layers are joined to form a "sub-blanket" the sub-blankets were held together by pieces of Velcro sewn into outer layer; these seams were purposely staggered around the circumference of the cold mass to prevent bulges in the insulation blanket.

The second coupon, Coupon B, is identical to Coupon A with several notable exceptions. The sub-blankets are held in place by pieces of tape instead of Velcro; this attachment method brought up the possibility of thermal bridging (heat conduction) between layers. However, bridging was minimized by using pieces of Dacron netting on the tape to minimize conduction where the tape was applied across the layers (see FIGURE 1). Coupon B was made so that the layer density of the sample could be adjusted between 1.0, 1.5, and 2.5 layer/mm.

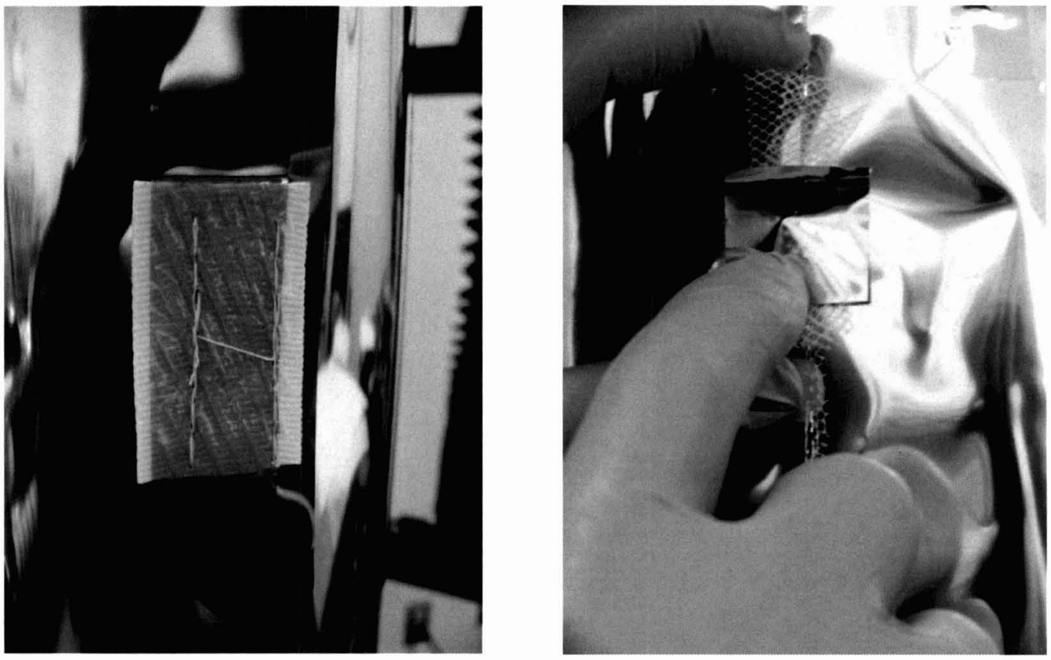

FIGURE 1: Typical tape attachment on MLI Coupon B using a small piece of Dacron netting to minimize thermal bridging.

EXPERIMENTAL SETUP

Testing was performed using the insulation test instrument Cryostat-100 (1). The principle of heat energy rate measurement is the liquid nitrogen boil-off method. The cylindrical cold mass is 40-in (1-meter) length by 6.6-in (167-mm) diameter. The insulation was wrapped around the cold mass, with each sub-blanket having its own overlap seam. Installation included placing temperature sensors between the blanket layers in accordance with TABLE 1. The temperature sensors were Type E thermocouples, 32 gage size, with vacuum-side lengths of approximately 6 feet. Evacuation and heating was performed in accordance with lab procedure. Cooldown, stabilization, and testing were performed in accordance with the standard lab procedure (2). For all tests, the cold boundary temperature (CBT) was approximately 78 K. The warm boundary temperature (WBT) was defined by the heater shroud assembly inside the vacuum can. The cold vacuum pressure (CVP) was maintained in the range of 10^{-6} torr by active vacuum pumping for high vacuum testing.

TABLE 1: Thermocouple placement for each test series.

Thermocouple	A138 Coupon A 60 layers	A139 Coupon A 40 layers	A140, A141, A144 Coupon B
T1,T2, T3	Cold Boundary	Cold Boundary	Cold Boundary
T4	DAK – layer 0	DAK – layer 0	DAK – layer 0
T5	Layer 4	Layer 4	Layer 4
T9	N/A	N/A	Layer 8
T6	Layer 12	Layer 12	Layer 12
T7	Layer 20	Layer 20	Layer 20
T10	N/A	N/A	Layer 28
T8	Layer 36	Layer 36	Layer 36
T11,T12,T13	Layer 60	Layer 40	Layer 60

RESULTS

Testing of Coupon A was completed between October 26, 2009 and November 23, 2009. Testing of Coupon B was completed between December 3, 2009 and March 24, 2010. The key geometric parameters for each test series are shown in TABLE 2. Heat flux values were generally in the range of ¼ to ½ W/m^2 for the high vacuum test condition. The corresponding effective thermal conductivities (k-values) were in the range below 0.1 mW/m-K or generally from 0.07 to 0.09 mW/m-K.

FIGURE 2 shows the effective thermal conductivity (k-value) of both coupons as a function of cold vacuum pressure (CVP). It is interesting to note that for Coupon A, at either warm boundary temperature, the thermal conductivity was nearly identical for the 40 and 60 layer tests (A138 and A139). Even though the heat flux increases by around 50% (see FIGURE 3) the change is offset by the area-to-thickness ratio used to calculate the k-value. For Coupon B, and **Error! Reference source not found.**show that by increasing the layer density from 0.94 to 2.6 layer/mm the k-value decreased while the heat flux is varies in combination with the changes in k-value and mean area. This effect is also a function of the thickness variation of the blankets being tested. For the two Coupon B tests, FIGURE 3 and FIGURE 4 show the changes in heat flux and k-value with cold vacuum pressure; as expected, the heat flux is higher when the layer density is higher. However, the k-value curves are much more interesting in that the higher layer density has a lower k-value at the lowest pressure and then increases quicker than the lower density blanket, crossing over the lower layer density curve. FIGURE 5 indicates that the thermal conductivity at atmospheric pressure (No Vacuum) is a function of thickness.

TABLE 2: Key Geometrical Parameters for MLSTC Cryostat-100 Testing

Test Series	Coupon	Number of Layers	Layer Density (layer/cm)	Thickness (mm)	Mean Area (m^2)	Density (kg/m^3)
A138	A	60	9.5	63.3	0.409	45
A139	A	40	9.4	42.7	0.377	45
A140	B	60	9.4	63.6	0.409	37
A141	B	60	14.5	41.4	0.375	57
A144	B	60	26.5	23.0	0.344	95

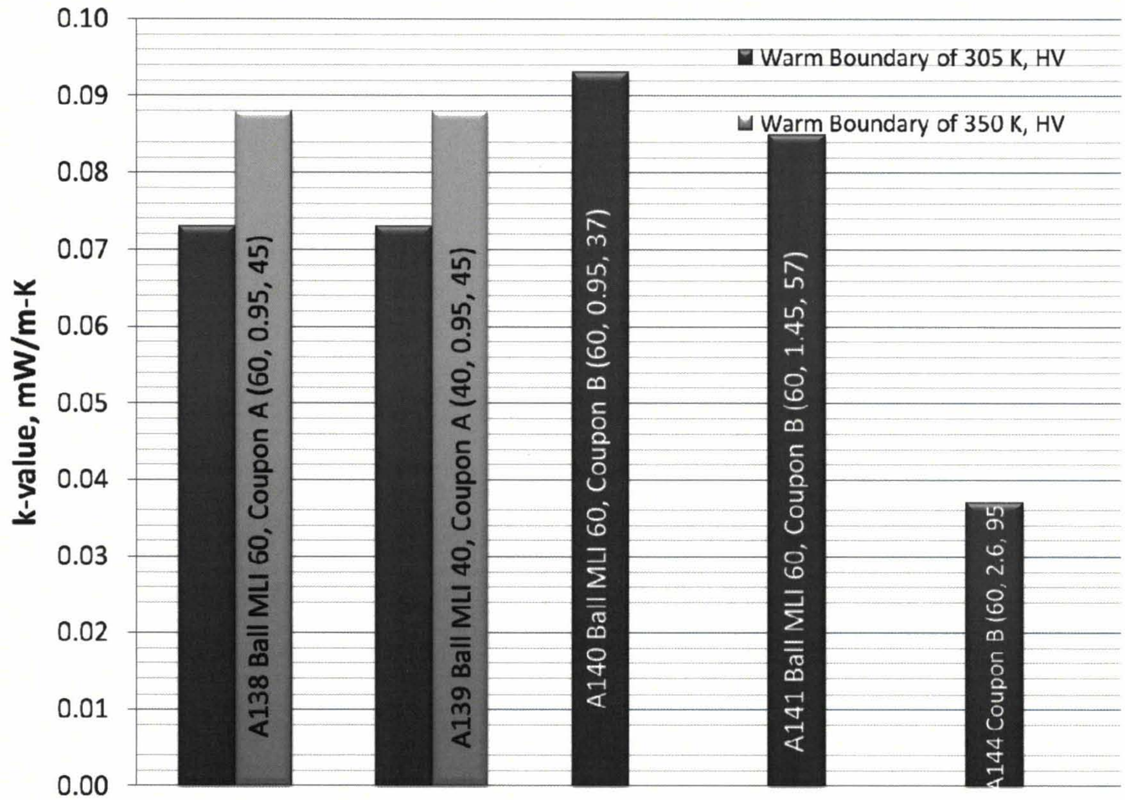

FIGURE 2: High Vacuum Thermal Conductivity of MLI Systems

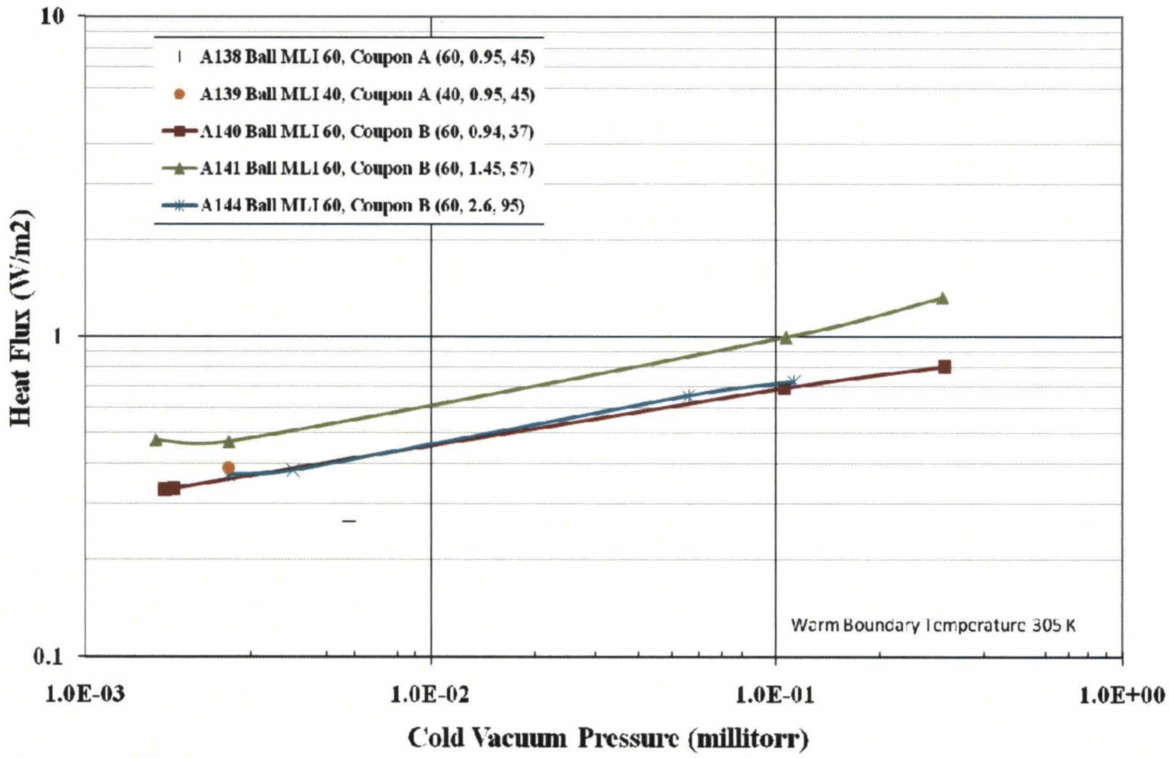

FIGURE 3: Heat Flux as a function of Cold Vacuum Pressure (CVP).

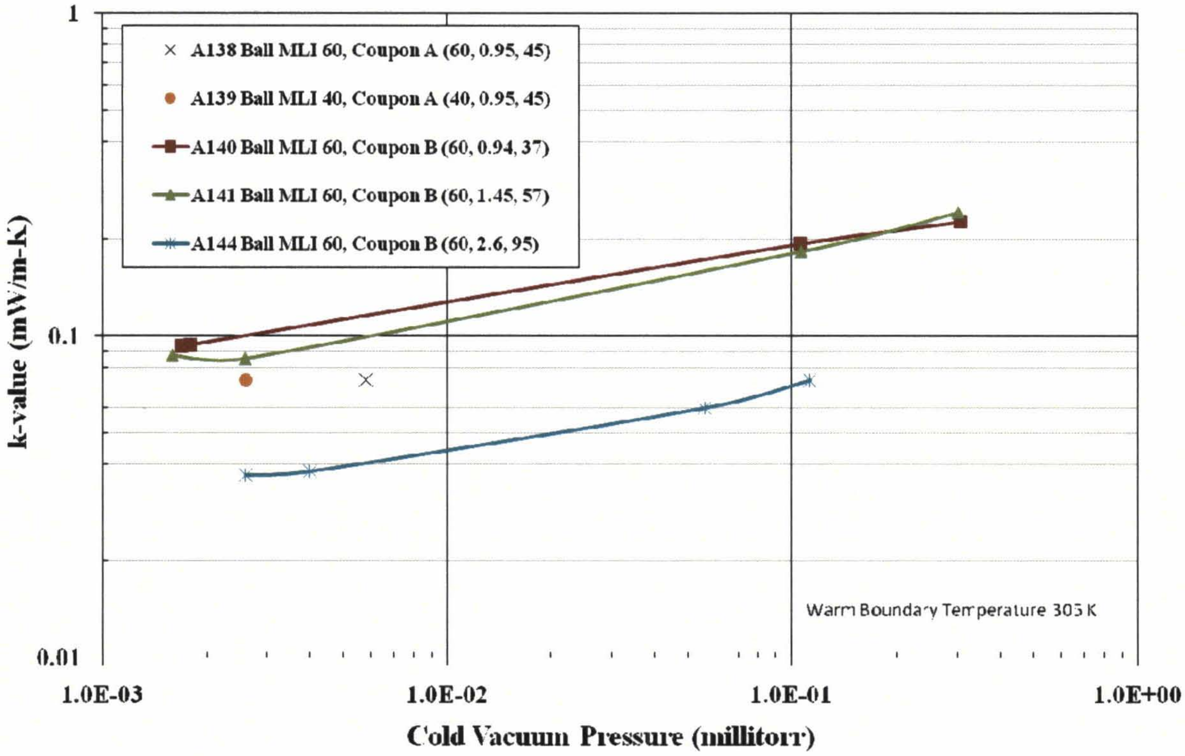

FIGURE 4: Effective thermal conductivity (k-value) as a function of Cold Vacuum Pressure.

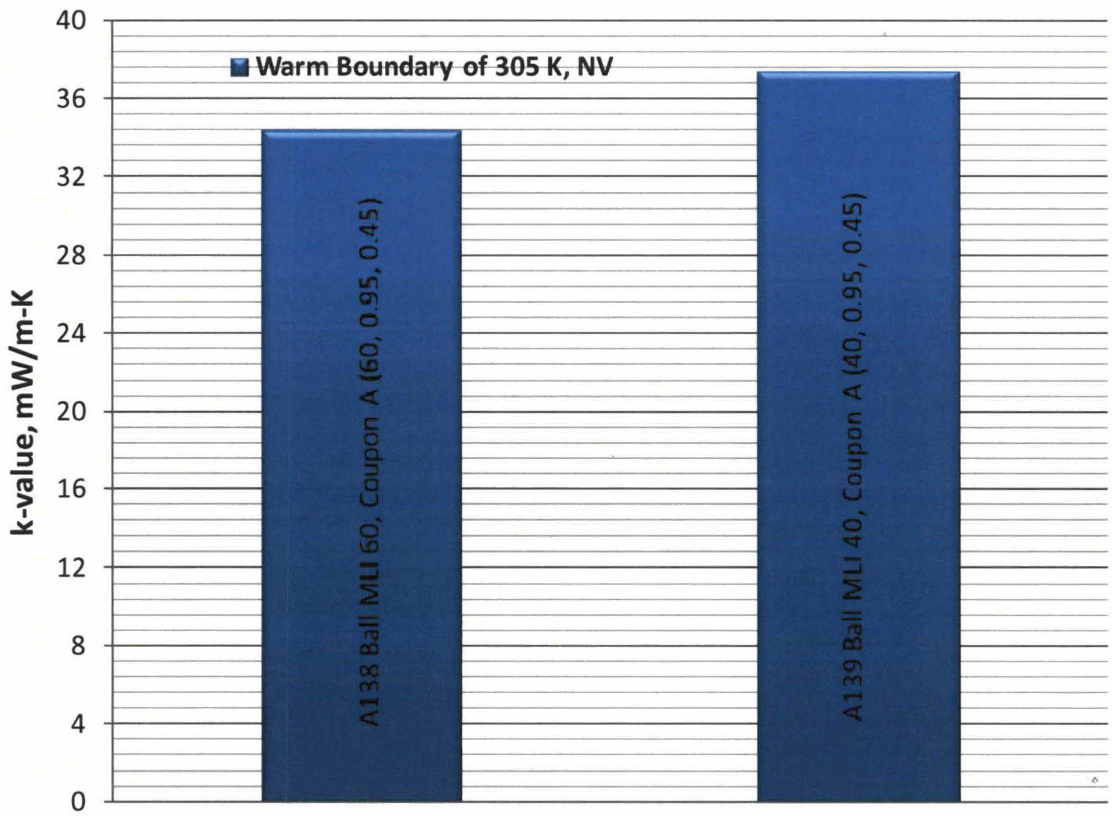

FIGURE 5: Effective thermal conductivity (k-value) of all No Vacuum Tests with 78 K CBT.

The thermal performance of the actual MLSTC blanket was determined to be 0.50 W/m^2 at a WBT of 305 K and 0.774 W/m^2 at a WBT of 350 K (3). This shows that the ratio between calorimeter and tank is 1.9 at 305 K and 2.05 at 350 K. The 1.9 value at 305 K is very similar to the value of 1.68 published by Jacob (4). The fact that the MLSTC tank applied insulation was not ideal further validates the relationship between calorimeter and tank applied insulation.

DISCUSSION

In order to make proper analysis and application of the Cryostat-100 test results, some historical reference and investigation is first presented. In 1973, Keller and Cunnington delivered a report at the conclusion of several years of testing many different variations of MLI, this report became known as the Lockheed report (5). The equations they developed to predict the performance of MLI have become industry standards, at least within the aerospace community.

The tricky part of using the Lockheed Equations (LE) involved picking the correct equation to use. Even though many different spacer materials and perforation combinations were tested, the exact combinations were often times not actually used. In November, 2009, Ball Aerospace provided predictions using the "As-received Silk Net" equation that was originally developed in a different report, but adapted by Keller and Cunnington (5) (6). Additionally, Hedayat and Hastings developed a "modified Lockheed equation" (MLE) for Dacron netting spacers and a specific perforation pattern that was tested at Marshall Space Flight Center (7). A third equation (New) can be derived from a combination of the two, using the Dacron netting portion of the MLE and the radiation and gas conduction portions of the Lockheed Equation (see below). The LE and MLE equations are compared to the actual test results at high vacuum in TABLE 3. The scale factors (SF) for the 350 K warm boundary test are much lower than the scale factors for the 305 K warm boundary tests, indicating that the temperature dependence of the equations is not entirely correct.

$$\left(\frac{Q}{A}\right)_{NEW} = \frac{5.39E-10 * \epsilon * \left(T_h^{4.67} - T_c^{4.67}\right)}{Ns} + \frac{1.46E4 * P * \left(T_h^{0.52} - T_c^{0.52}\right)}{Ns} + \frac{\left(2.4E-4 * \left(0.017 + 7E-6 * \left(800 - T_{avg}\right) + 0.0228 * \ln\left(T_{avg}\right)\right)\right) \bar{N}^{2.63}\left(T_h - T_c\right)}{Ns + 1}$$

TABLE 3: Correlation Comparisons to Test Results

Test (WBT)	Test Q (W/m^2)	LE Q (W/m^2)	LE SF	MLE Q (W/m^2)	MLE SF	New Q (W/m^2)	New Q SF
A138/305	0.262	0.118	2.22	0.147	1.79	0.160	1.63
A138/350	0.377	0.220	1.71	0.245	1.54	0.271	1.39
A139/305	0.388	0.177	2.19	0.218	1.78	0.240	1.62
A139/350	0.557	0.330	1.69	0.364	1.53	0.406	1.37
A140/305	0.332	0.118	2.81	0.147	2.27	0.160	2.07
A141/305	0.472	0.134	3.52	0.242	1.95	0.256	1.84

CONCLUSIONS

Cryogenic-vacuum thermal performance testing of several multilayer insulation blankets was performed on Cryostat-100 by the Cryogenics Test Laboratory at Kennedy Space Center. Ball Aerospace Low Density MLI was tested in simulation of the Methane Lunar Surface Thermal Control (MLSTC) tests to be performed at Glenn Research Center. A total of 14 liquid nitrogen absolute boil-off tests were performed on four different MLI configurations. Heat flux values were generally in the range of ¼ to ½ W/m^2 for the high vacuum test condition. The corresponding effective thermal conductivities (k-values) were in the range below 0.1 mW/m-K or generally from 0.07 to 0.09 mW/m-K. Ambient environment tests (No Vacuum) tests were also performed: heat flux ranged from 122 to 147 W/m^2 and k-value ranged from 34 to 37 mW/m-K.

Initially, for Coupon A, 60 layers were installed. Later, the outer 20 layers were removed and the sample was retested under the same conditions. This testing revealed that the thermal conductivity was identical for both 40 and 60 layers of MLI at the same boundary temperatures. Testing was conducted at both 305 and 350 K warm boundary temperatures. A second blanket, Coupon B, with changeable density, was tested at 9.5 and 14.5 layer/cm.

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