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Demonstration of Hybrid Multilayer Insulation for Fixed Thickness Applications

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Abstract. Cryogenic multilayer insulation (MLI) systems provide both conductive and radiative thermal insulation performance. The use of radiation shields with low conductivity spacers in between are required. By varying the distance and types of the spacers between the radiation shields, the relative radiation and conduction heat transfers can be manipulated. However, in most systems, there is a fixed thickness or volume allocated to the insulation. To understand how various combinations of different multilayer insulation (MLI) systems work together and to further validate thermal models of hybrid MLI systems, test data are needed. The MLI systems include combinations of Load-Bearing MLI (LB-MLI) and traditional MLI (tMLI). To further simulate the space launch vehicle case wherein both ambient pressure and vacuum environments are addressed, different cold-side thermal insulation substrates were included for select tests.

The basic hybrid construction consists of some number of layers of LB-MLI on the cold side of the insulation system followed by layers of tMLI on the warm side of the system. The advantages of LB-MLI on the cold side of the insulation blanket are that its low layer density (0.5 – 0.6 layer/mm) is better suited for lower temperature applications and is a structural component to support heat interception shields that may be placed within the blanket. The advantage of tMLI systems on the warm side is that radiation is more dominant than conduction at warmer temperatures, so that a higher layer density is desired (2 - 3 layer/mm) and less effort need be put into minimizing conduction heat transfer. Liquid nitrogen boiloff test data using a cylindrical calorimeter are presented along with analysis for spacecraft tank applications.

1. Introduction

While ideal radiation shielding has no conduction between reflectors, real systems have to deal with conduction between the reflectors. Within a high vacuum environment or for on-orbit spacecraft, high performance multilayer insulation (MLI) systems are a balance between minimizing solid conduction and radiation between reflective layers. This balance is generally accomplished by varying the “fluffiness” or layer density of the insulation system. Much effort has gone into demonstrating that, for traditional MLI (tMLI) systems, there is a optimal minimum in the trade between solid conduction and radiation to minimize the heat flux through a fixed thickness blanket [1-4].

Recent advances have generated new types of MLI systems that can be used to create composite systems called Load-Bearing MLI (LB-MLI) [5]. The advantage of using LB-MLI is its structural capability within a blanket and repeatability in the installation process. This structural capability, however modest, can be used to support thermal shields, whether cryocooler or boil-off vapor cooling driven. Recent thermal and acoustic testing at Glenn Research Center (GRC) and Marshall Space Flight Center (MSFC) demonstrated that such combinations can provide excellent thermal performance while at the same time providing some degree of structural capabilities within the blanket [6]. Due to the cost necessity to reuse test hardware, the LB-MLI system used in the testing at GRC and MSFC was required to fit within a volume defined by a previous design. Thus, a one-off test demonstrated the benefits, but did not demonstrate in any manner the potential for optimization of the system. To understand how various possible combinations of LB-MLI and tMLI systems could work together and to further validate thermal models of such hybrid MLI systems, experimental test data are needed.

The thermal performance coupled with structural capability of LB-MLI has made it a desirable candidate for flight MLI systems. During the design of the Cryogenic Propellant Storage and Transfer (CPST) Technology Demonstration Mission, a hybrid insulation system of LB-MLI and tMLI was conceptualized in order to minimize radiative heat loads through the insulation as well as for flight qualification of new insulation materials for use on cryogenic spacecraft tanks and piping [7].

2. Experimentation

To measure the thermal performance of various insulation systems, NASA Kennedy Space Center's Cryogenic Test Laboratory uses liquid nitrogen boiloff calorimetry for a variety of instruments. This test program used the Cryostat-100 cylindrical boiloff calorimeter, which is well documented elsewhere [8-9]. Cryostat-100 testing yields absolute thermal performance of the multilayer insulation systems in terms of heat load (Q). The heat load can then be normalized to the logarithmic mean surface area and converted to heat flux (q) in accordance with ASTM C1774, Annex A1 [10]. Standard ASTM C740 provides further details on cylindrical test specimen preparation and terminology for calculations [11]. The cold boundary temperature (CBT) was approximately 78 K in all cases. The warm boundary temperature (WBT) was approximately 293 K or 325 K.

The objectives of the testing are to measure and compare the thermal performance of different combinations of low density MLI (LB-MLI) and higher density or traditional MLI (tMLI). The test matrix was established to develop a relationship for heat load as a function of the number of layers and thickness of each layer type. Temperature sensors (type E thermocouples, 30 gage) were placed on the interfaces between materials to determine the interface temperatures. Thermocouples were also installed at select locations within the tMLI to provide data for the temperature profiles through the thickness.

The test specimens were installed in a layer-by-layer fashion. The layers were secured by numerous small tabs (about 25-mm squares) of high vacuum tape (3M #8333). In general, each tMLI layer of double-aluminized Mylar with Dacron netting was given an overlap of about 25-mm. For test specimens A187-A189, with 16 or 20 layers of LB-MLI, it was necessary to make a wider layers of some of the subsequent tMLI layers by splicing in vertical strips of similar material. This approach worked well for installation but made a challenge for removal and reuse of the tMLI materials for future test specimens.

In an effort to make the testing more like actual flight applications, rigid polyurethane foam was used as a substrate insulation material. At high vacuum the foam provides little to no thermal benefit and so it is assumed that the replacement of the foam would not change the data significantly. The spray on foam insulation (SOFI) selected was Stephan S-180, designed for NASA's next generation rocket family. The foam was sprayed onto two custom clamshell fixtures to a thickness of approximately 14.7-mm. The clamshells were then precision machined and sanded for a precise fit-up onto the Cryostat-100 cold mass assembly at a final thickness of 12.5-mm. The microfiberglass blanket CryoLite was also used as a substrate material for comparison. The CryoLite was used at two different installed densities, 16 kg/m^3 and 32 kg/m^3, as indicated in Table 1. The heat flux values for the SOFI and low density CryoLite were calculated to be about the same at approximately 1 W/m^2 while the high density CryoLite was approximately 0.6 W/m^2. Because the 10-layer LB-MLI blanket was reused from previous testing and not sized to allow for a substrate, no substrate was used in tests A174, A175, A181, or A182.

The vacuum pumping and heating process typically included the laboratory standard number of five gaseous nitrogen purge cycles at up to 330 K. The target cold vacuum pressure (CVP) for all tests was below 1x10^{-5} torr.

Because the Cryostat-100 cold mass (167-mm diameter by 1-m length) has a fairly tight radius of curvature, the outer insulation system has a larger normal surface area than the inner surface area. This geometry accounts for the increasing radius with increasing thickness. The ideal configuration would be tMLI layer densities close to 2.0 layers/mm for each test. However, as is common with MLI systems it is not a simple matter in actual practice to achieve an exact layer density. The complete test matrix and dimensional parameters of the 11 test specimens are shown in Table 1.

Table 1. Cryostat-100 Test Matrix and Dimensions for Hybrid MLI Systems.

Test Specimen	*Substrate*		*LB-MLI*				*tMLI*				*Totals*	
	$t_{substrate}$	$A_{substrate}$	n_{LB-MLI}	t_{LB-MLI}	z_{LB-MLI}	A_{LB-MLI}	n_{tMLI}	t_{tMLI}	z_{tMLI}	A_{tMLI}	t_{MLI}	t_{total}
	mm	*m²*	*layers*	*mm*	*/mm*	*m²*	*layers*	*mm*	*/mm*	*m²*	*mm*	*mm*
A174 (0+10+40)	0	0	*10*	14.3	0.70	0.330	*40*	18.9	2.1	0.390	33.2	33.2
A175 (0+10+50)	0	0	*10*	14.3	0.70	0.330	*50*	24.2	2.1	0.399	38.5	38.5
A181 (0+10+40)	0	0	*10*	14.3	0.70	0.330	*40*	19.3	2.1	0.391	33.6	33.6
A182 (0+10+30)	0	0	*10*	14.3	0.70	0.330	*30*	8.5	3.5	0.372	22.8	22.8
A183 (S+12+50)	14.7	0.331	*12*	18.6	0.65	0.391	*50*	8.9	5.6	0.442	27.4	42.1
A184 (C'+12+40)	12.6	0.327	*12*	19.1	0.63	0.384	*40*	13.1	3.1	0.443	32.2	44.8
A185 (C+14+40)	12.6	0.327	*14*	19.6	0.71	0.385	*40*	17.2	2.3	0.452	36.8	49.4
A187 (C+16+40)	12.6	0.327	*16*	25.1	0.64	0.394	*40*	13.2	3.0	0.466	38.3	50.9
A188 (C+16+30)	12.6	0.327	*16*	25.1	0.64	0.394	*30*	10.5	2.9	0.461	35.6	48.2
A189 (C+20+30)	12.6	0.327	*20*	32.4	0.62	0.407	*30*	13.6	2.2	0.493	46.0	58.6
A190 (S+14+40)	14.3	0.330	*14*	21.2	0.66	0.394	*40*	19.2	2.1	0.468	40.4	54.7

Code: (substrate + layers of LB-MLI + layers of tMLI); C = CryoLite (16 kg/m^3), C' = CryoLite compressed (32 kg/m^3), S = SOFI (38 kg/m^3).
WBT: 293 K for A174 & A175; 293 K and 325 K for all others.

3. PERFORMANCE MODELLING

With the development of LB-MLI, models have been developed to aid in understanding the performance of the insulation system [12]. Also, recent refinements to exiting traditional MLI models have led to further improvement in modeling these systems [13]. Combining the models to iterate to a constant heat load allows the use of both models to better understand a hybrid MLI set up. Because the steady-state heat energy flowing through the two blanket type MLI systems has to be identical, the only variables are the mean area of the two systems and their relative resistances. The free parameter for model convergence is therefore the interstitial temperature between the two blankets. The results of this combined model are shown in Figure 1-2. An optimum point for insulation performance is shown to be around 10 layers of LB-MLI in the configuration as defined in Table 2. The benefit shown by this result amount to an increase of approximately 20% in thermal performance compared to a pure LB-MLI system or a pure tMLI system. The results also show that the bottom of the "bucket" is rather shallow as suggested in Figure 1.

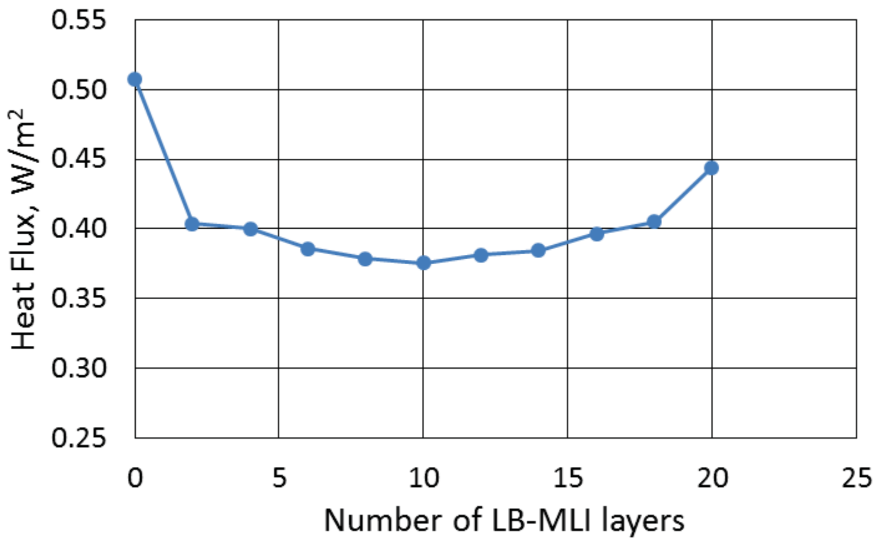

Figure 1. Sample heat load distribution for a constant thickness MLI blanket (38-mm) with varying number of LB-MLI and tMLI layers making up the rest of the constant total thickness.

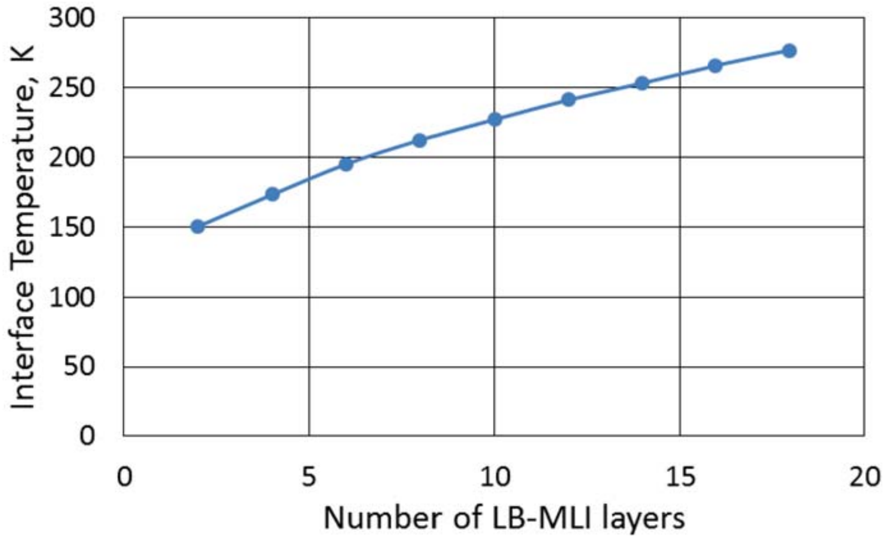

Figure 2. Interface temperature between LB-MLI and traditional MLI blankets on a constant thickness MLI blanket (38-mm) with varying number of LB-MLI and tMLI layers making up the rest of the constant total thickness.

4. Results And Discussion

The Cryostat-100 testing included tests at warm boundary temperatures (WBT) of 293 K and 325 K. The heat flux values for the different test specimens at WBT of 293 K and 325 K are given in tables 1 and 2, respectively. As indicated by the CVP values, the vacuum pressure in the chamber started to miss the target value with test series A182. The $1x10^{-6}$ torr range was achieved for all tests except A182-A185. Test series A183 and A184 were just slightly off the target of $1x10^{-5}$ torr. Additional heating and pumping cycles were applied and additional tests were performed but with no improvement of the CVP values. Eventutally test series A185 was not close to the target, so a complete trouble-shooting program was commenced on the entire test apparatus. Through extensive helium leak testing, two of the three liquid nitrogen feedthroughs were found to be damaged. After the repairs, operation returned to normal and the remainder of the test series were completed starting again with A187. To conclude the test program, test series A190 was performed as a repeat of A185. Vacuum levels were again in the $1x10^{-6}$ torr range and the resulting heat flux was lower.

Initial review of the data suggested that the substrate was causing significant issues either through outgassing or some other means of system performance degradation. When the data were fully analyzed, this conclusion was found not to be the case. Figure 3 shows the comparison of the tMLI to their respective theoretical predictions. The "scale factor" is the ratio of the test heat flux to a theoretical performance. A value of 1 would imply that the test and theory are well in agreement while a value greater than 1 suggests that the theory under-predicts performance and a value less than 1 that the theory over-predicts performance. The LB-MLI maintained a fairly constant scale factor of 2.0 for both the 293 K WBT and 325 K WBT cases (there are a few outlyers but not significantly different). In Figure 3, we see that the tMLI starts off at a scale factor of approximately 1, dips down well below 0.5 and then rises to values over 4. While both the heat flux values for 293 K and 325 K mirror each other, the heat flux values for 325 K are lower. This result is assumed to come from the reuse the tMLI blanket materials (Mylar and netting). Each time they were used, they became slightly more physically degraded. Because the fragile tMLI layers were installed layer-by-layer and reused from test series to test series, including the numerous tabs of tape securing the seams and the thermocouple wires taped between some layers, the individual pieces of material were slightly and cumulatively degraded over the test program. Degraded tMLI blankets perform much worse than fresh blankets. Masses are shown in Figure 5 and 6.

The optimization is reliant on the two systems performing similarly in line with theoretical predictions, however, as shown from the testing, there is some margin. The performance of each relative its respective model, will skew the combined model relatively towards or away from that type of MLI. Combining the data from this experimental testing with previous testing of MLI coupons [14] all tMLI or all LB-MLI (see Figure 7) shows that indeed, the hybrid MLI can improve on both.

Table 2. Heat fluxes for **293 K** Warm Boundary Temperature.

Test	Substrate q (W/m²)	LB-MLI q (W/m²)	tMLI q (W/m²)	Heat Load Q (W)	Interface Temperature (K)	CVP (mTorr)
A174		0.410	0.343	0.137	181	2.0E-03
A175		0.395	0.328	0.132	178	5.0E-03
A181		0.376	0.317	0.127	194	2.6E-03
A182		0.552	0.489	0.182	194	6.7E-02
A183	0.976	0.824	0.730	0.322	228	7.5E-02
A184	0.635	0.542	0.472	0.207	219	4.2E-02
A185[a]	*1.239*	*1.028*	*0.865*	*0.404*	*215*	*5.8E-01*
A187	1.046	0.868	0.735	0.341	261	4.8E-03
A188	1.046	0.868	0.742	0.342	268	3.5E-03
A189	1.031	0.828	0.684	0.336	265	2.8E-03
A190	0.970	0.814	0.685	0.320	254	3.4E-03

[a]Poor vacuum condition.

Table 3. Heat fluxes for 325 K Warm Boundary Temperature.

Test	Substrate *q* (W/m²)	LB-MLI *q* (W/m²)	tMLI *q* (W/m²)	Heat Load *Q* (W)	Interface Temperature (K)	CVP (mTorr)
A181		0.420	0.354	0.142	199	2.6E-03
A182		0.673	0.597	0.222	210	5.6E-02
A183	1.255	1.059	0.939	0.414	247	5.9E-02
A184	0.859	0.733	0.638	0.28	240	3.8E-02
A185	*Not Attempted due to Poor Vacuum Conditions*					
A187	1.331	1.104	0.935	0.434	280	5.9E-03
A188	1.355	1.124	0.961	0.443	290	6.4E-03
A189	1.340	1.076	0.890	0.437	289	4.5E-03
A190	1.330	1.117	0.940	0.439	275	1.0E-02

Figures 4-5 show the system mass densities for each test specimen. For the insulation systems with similar thicknesses, and with increasing number of widely spaced MLI layer and decreasing number of total layers (as the test number increased), the density of the system decreased by over 10%. The trade between mass and weight is a system dependent trade that can not be made independent of the mission requirements of the system, thus no attempt to trade them is made here.

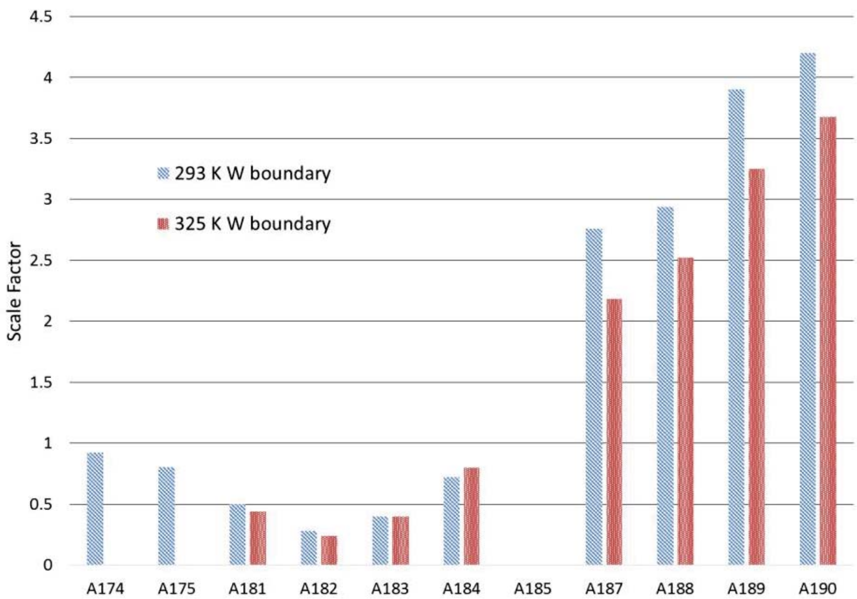

Figure 3. Comparison of tMLI test data to theoretical predictions.

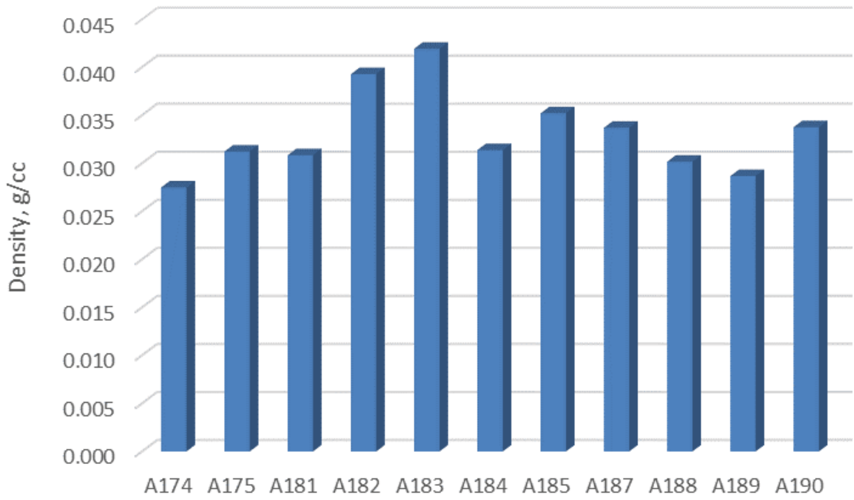

Figure 4. Insulation system densities for each test.

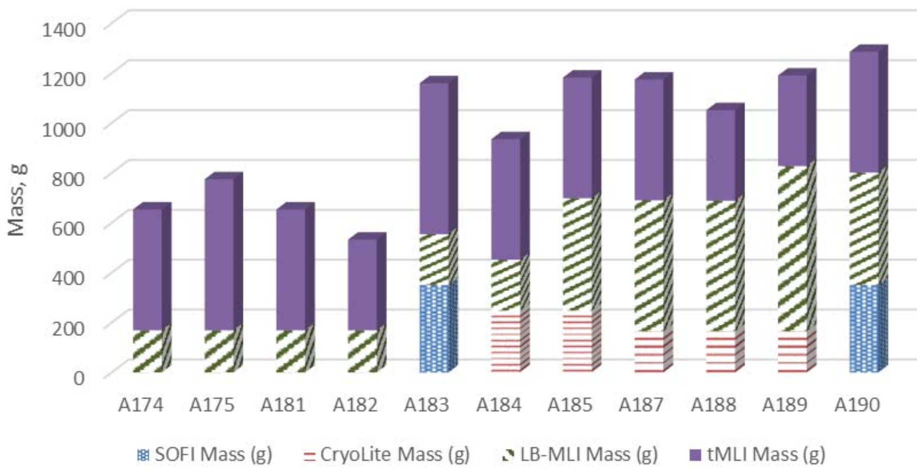

Figure 5. Insulation system masses broken out by component.

5. Conclusion

A series of tests were run at Kennedy Space Center to determine the effect of optimization of MLI systems between Load-Bearing MLI (LB-MLI) and traditional MLI (tMLI) systems. Eleven test specimens were prepared and tested using the Cryostat-100 cylindrical boiloff calorimeter. Each test specimen was a different combination of cold-side substrate material (foam or fiberglass or none), LB-MLI blanket, and tMLI blanket. The results of the test matrix revealed a heat flux slope that was much steeper than predicted due to the wildly varying performance of the tMLI portion of the blanket. The sensitivity of the insulation system to the design criteria was shown to be a driving factor in the optimization of the system.

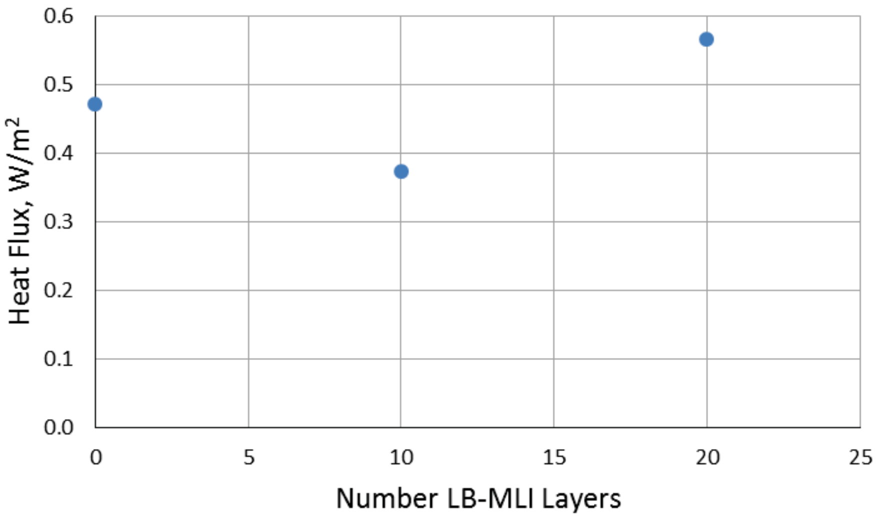

Figure 6. Test data from A141, A142, and A181

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