RESEARCH ARTICLE | APRIL 09 2010

ANALYSIS AND TESTING OF MULTILAYER AND AEROGEL INSULATION CONFIGURATIONS FREE

W. L. Johnson; J. A. Demko; J. E. Fesmire

AIP Conf. Proc. 1218, 780–787 (2010)
https://doi.org/10.1063/1.3422431

ANALYSIS AND TESTING OF MULTILAYER AND AEROGEL INSULATION CONFIGURATIONS

W. L. Johnson[1], J. A. Demko[2], and J. E. Fesmire[1]

[1]NASA Kennedy Space Center, KT-E
Kennedy Space Center, FL 32780, USA

[2]Oak Ridge National Laboratory
Oak Ridge, TN 20775, USA

ABSTRACT

Multilayer insulation systems that have robust operational characteristics have long been a goal of many research projects. Such thermal insulation systems may need to offer some degree of structural support and/or mechanical integrity during loss of vacuum scenarios while continuing to provide insulative value to the vessel. Aerogel-based composite blankets can be the best insulation materials in ambient pressure environments; in high vacuum, the thermal performance of aerogel improves by about one order of magnitude. Standard multilayer insulation (MLI) is typically 50% worse at ambient pressure and at soft vacuum, but as much as two or three orders of magnitude better at high vacuum. Different combinations of aerogel blanket and multilayer insulation materials have been tested at the Cryogenics Test Laboratory of NASA Kennedy Space Center. Analysis performed at Oak Ridge National Laboratory showed an importance to the relative location of the MLI and aerogel blankets. Apparent thermal conductivity testing under cryogenic-vacuum conditions was performed to verify the analytical conclusion. Tests results are shown to be in agreement with the analysis which indicated that the best performance is obtained with aerogel layers located in the middle of the blanket insulation system.

KEYWORDS: Multilayer insulation, aerogel, composite insulation materials.

INTRODUCTION

Structural superinsulation, or multilayer insulation (MLI), has long been a goal of many research projects [1]. Since structural and thermal designs for many cryogenic applications are performed independently, the end result can be a total system design that is

CP1218, *Advances in Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference - CEC, Vol. 55,* edited by J. G. Weisend II
2010 American Institute of Physics 978-0-7354-0761-9/10/$30.00

far from optimum in regard to thermal performance. In fact, structures often account for 50% or more of the heat leaks into cryogenic vessels and piping [1]. Robust MLI systems with less need for structural supports could then reduce the overall heating rate and improve the overall thermal performance. Additionally, the insulation system should be capable of surviving loss-of-vacuum scenarios while continuing to provide an acceptable insulative value to the vessel in this contingency situation. In terms of apparent thermal conductivity (k-value), aerogels are the best insulation materials for ambient pressure. In high vacuum environments, the thermal performance of aerogels typically improves by one order of magnitude. Aerogels are from two to three times better than conventional foam insulations in ambient pressure and about five to ten times better in high vacuum [2]. Development and testing of combinations of aerogels and multilayer insulation have been ongoing at the Kennedy Space Center's Cryogenic Test Laboratory (CTL) for several

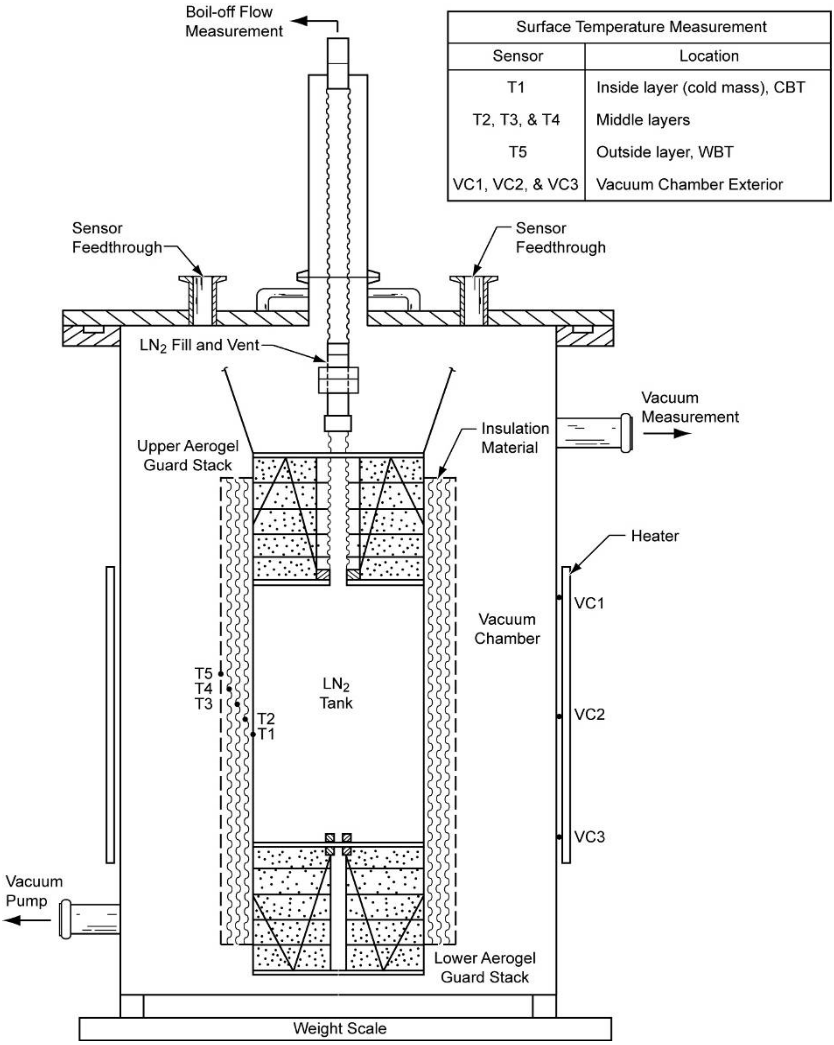

FIGURE 1. Simplified schematic for Cryostat 3

years. Most recently analysis performed at the Oak Ridge National Laboratory showed an importance to the order of the MLI and aerogel blankets. Apparent thermal conductivity testing using cryostat insulation test instruments was performed to investigate this analytical conclusion.

EXPERIMENTAL

The steady-state liquid nitrogen boil-off (evaporation rate) calorimeter methods established by the Cryogenics Test Laboratory were used to determine apparent thermal conductivity (k-value) of thermal insulation systems [3,4]. The cylindrical test apparatus, Cryostat-3, includes a cold mass of overall dimensions 132 mm diameter by 533 mm length and provides comparative k-values for insulation systems. The 254 mm tall liquid nitrogen tank has five aerogel disks and radiation shields on both top and bottom of it to minimize the parasitic heat leak into the tank. The insulation system is wrapped around the cold mass so that the total heating rate into the liquid nitrogen tank can be measured. A simplified schematic of the insulation test article is given in FIGURE 1. Comparison of results to results of the same material tested on Cryostat-100, an absolute calorimeter, can be used to calibrate the results from Cryostat-3. Cryostat-3 (a copy of Cryostat-2) has been shown to have up to 3.25% error. [3]

The liquid nitrogen cold mass maintained the cold boundary temperature (CBT) at approximately 78 K. The warm boundary temperature (WBT) was maintained at approximately 293 K using an external heater. The difference between the WBT and CBT (ΔT) was therefore 215 K. Vacuum environments, or cold vacuum pressures (CVP), included the following three basic cases: high vacuum (HV) [below 1×10^{-4} torr], soft vacuum (SV) [1 torr], and no vacuum (NV) [760 torr]. Additional tests were performed at CVP from 1×10^{-4} torr to 760 torr. Nitrogen was the residual gas within the vacuum chamber for all tests [3,4]. MKS Type 627b Baratrons are used to measure the vacuum pressure and are accurate to 0.15% of the full scale reading per the manufacturer's specifications.

INSULATION TEST MATERIALS

Five test series were run to test the comparative k-value of various combinations of aerogel and multilayer insulation. For the first test series (T207), aerogel blankets were placed underneath multilayer insulation comprised of double-aluminized mylar (DAM) radiation shields and micro-fiberglass paper spacers. The bottom layer of aerogel was butt-joint fitted to the cold mass. The other two layers of aerogel blanket were then continuously wrapped around the first layer. Six layers of DAM and paper were then applied using overlapping joints. These joints were rotated 120 degrees between layers. The total thickness of the first test specimen was 31.9 mm thick. The total thickness of the aerogel blankets was 27.4 mm with the remainder of the thickness coming from the six layers of DAM and paper. Thermocouples were included through the thickness to determine the temperature profile of the insulation.

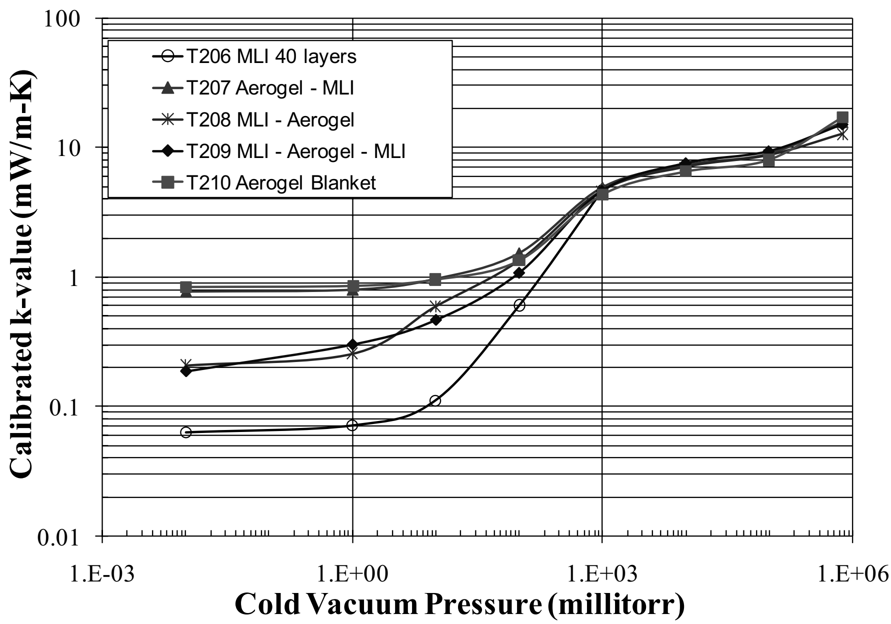

FIGURE 2. Variation of apparent thermal conductivity (k-value) with cold vacuum pressure, between the temperatures of 78 K and 293 K at a total thickness of approximately 1 inch. Pressure is measured in the vacuum can, not within the material itself.

The second test article (T208) was comprised of multilayer insulation underneath aerogel blankets. The first six layers of DAM and paper were continuously wrapped around the cold mass. The first layer of aerogel blanket was joined using a butt joint; the following two layers were continuously wrapped around the cold mass. The total thickness of the second test specimen was 27.4 mm thick. The six layers of MLI were 2.8 mm thick with the remainder of the thickness coming from the aerogel blankets.

The third test article (T209) included aerogel blankets between two sections of multilayer insulation. The same inner six layers of roll wrapped DAM and paper were left on the cryostat coldmass as were the first two layers of aerogel blanket. However, the third layer of blanket was removed so that the aerogel was only 15.8 mm thick. Outside of the aerogel blankets, 20 more layers of MLI (DAM and Paper) were roll wrapped onto the cryostat. These twenty layers had the same layer density as the first six and were 7.1 mm thick. The total test article thickness was 25.4 mm.

A fourth test series (T210) was run with only aerogel blankets. Three layers of blanket were applied for a total thickness of 24.4 mm. The same blanket material was used, which includes an aluminized plastic outer layer for weather protection.

The comparative approach of this experimental work requires a suitable baseline performance for MLI systems. In other related experiments, a number of different MLI systems, including DAM and micro-fiberglass paper, have been tested using Cryostat-3. These test specimens included roll wrapped, overlapped, and folded over MLI of 40 layers in approximately 13-mm thickness. The results from this parallel work provide a benchmark for heat flux comparisons and a standard reference for instrument calibration [5].

RESULTS

As can be seen in FIGURE 2, 40 layers of MLI outperformed the composite insulations below 1000 millitorr. Among the composites, when the MLI was on the cold side, it clearly outperformed the systems where MLI was on the hot side at high vacuum. In fact, when the aerogel was underneath the MLI, it performed only marginally better than the aerogel blanket. However, when the same number of MLI layers were placed underneath the aerogel blanket, the high vacuum performance increased by half of an order of magnitude. Again, the outer layer of aerogel blanket was removed for T209 and replaced with MLI, but only a slim margin of performance was gained.

As the pressure increases, the performance of all the material systems converges on each other. At approximately 1000 millitorr, the aerogel blanket becomes the highest performer and the MLI becomes the worst performer. The various systems remain close together until no vacuum. While the slope (degradation) of the thermal insulation systems was lower than MLI, the MLI blanket still outperformed the other systems below 100 torr.

At ambient pressure, the MLI-Aerogel is the best performer by a slim margin. The other two composites are grouped closely together just below the performance of the aerogel at no vacuum. If the MLI test had gone all the way to no vacuum, it would have been the worse than the composites, however, the cryostat cannot maintain the warm boundary for MLI testing above 1000 millitorr.

ANALYSIS

A cryogenic heat transfer program based on the extensive insulation materials test data from the Cryogenics Test Laboratory plus other well-documented thermal conductivity data from the literature has been previously developed.[6] This program uses previous test

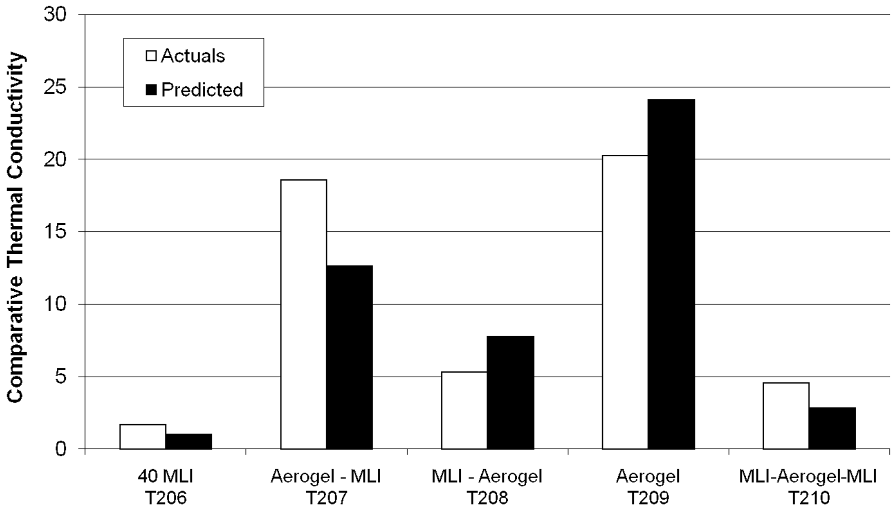

FIGURE 3: Measured and predicted high vacuum comparative k-values of aerogel and MLI combinations, normalized to the MLI fold-over predicted as a standard reference. Values are measured between 77K and 293 K.

data to estimate one dimensional heat transfer through insulation systems using a resistance model. Using this program, estimates were made for several insulation combinations at high vacuum: MLI, aerogel blankets, and combinations of the two including the three test cases. These results were normalized based on the heat leak of aerogel blankets alone.

As shown in FIGURE 3, the high vacuum comparative k-values for the actual and predicted thermal performance are quite similar. Overall, the aerogel blanket under MLI heat leak was under-predicted by 32 percent, and the MLI under the aerogel blanket was over-predicted by 45 percent. The aerogel in-between the two MLI blankets heat leak was under-predicted by 38 percent at high vacuum. Considering that the thermal conductivity of the aerogel was assumed constant (rather than varying with temperature), this is an excellent estimate. These tests confirm the theory that the MLI located nearest the cold mass is more effective at lowering the thermal conductivity of the system. Only a slight improvement was seen when the outermost layer of aerogel was removed and replaced with 20 layers of MLI.

As shown in FIGURE 3, MLI is a much better insulation at high vacuum than aerogel blankets. 40 layers of MLI are shown to be over 10 times better than aerogel at high vacuum. However, analysis shows that the aerogel performs better at the warmer temperatures when combined with MLI. Currently, the opposite approach is being considered as foam or other low-conduction substrates are placed underneath the MLI to prevent liquid air formation in non-vacuum situations [7]. Conversely, the heat leak through MLI is a function of T to the fourth power (T^4), so even though the aerogel might not be as efficient at higher temperatures, it allows the MLI to have a lower warm boundary temperature and therefore be more efficient (overall, less heat leak).

Considering that temperature was taken into account in the MLI portions, but not the aerogel blanket portions (a constant thermal conductivity from previous aerogel testing was used), there was some skepticism with these results. Generally, thermal conductivities increase with increasing temperature, thus if your temperature dependant insulation is in

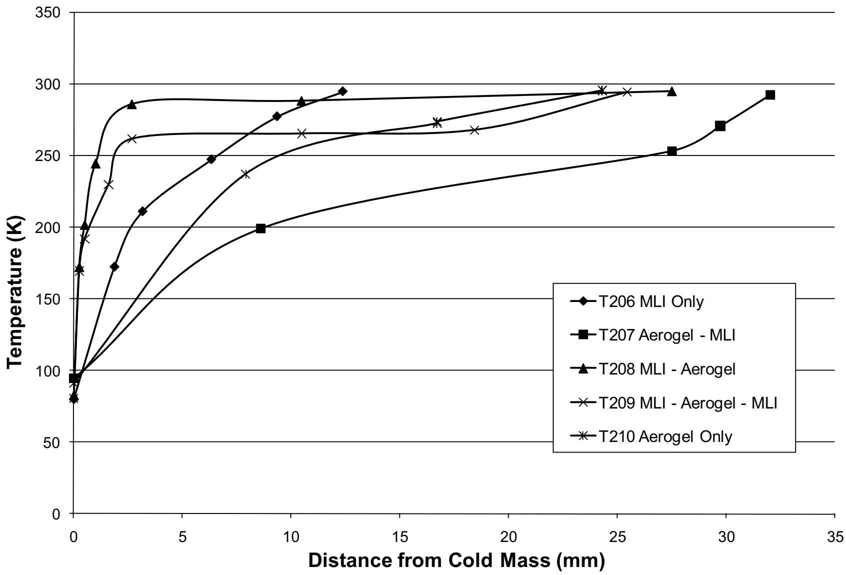

FIGURE 4: Temperature profiles for insulation systems at high vacuum

colder regions in one simulation than another, it is expected that the thermal conductivity will show an overly optimistic decrease in thermal conductivity.

This result indicates that at high vacuum, the MLI is highly effective in setting up the steep thermal gradients in the region of the insulation near the cold mass. However, since at soft vacuum and no vacuum, the temperature gradients are fairly linear throughout the insulation, the first few millimeters are not nearly as important in the scheme of the whole insulation blanket. FIGURE 4 shows the temperature profiles at high vacuum for all five tests. This result further confirms that the initial distances are the most important of the total system. This characteristic allows the aerogel blanket to set up its thermal resistance at the higher pressures even though it is away from the cold mass.

The heat leak for the aerogel underneath the MLI is approximately three times higher than with the MLI underneath the aerogel at high vacuum. At high vacuum, most of the thermal resistance is due to the MLI. This behavior is evident in FIGURE 4 from the temperature profiles. With the MLI under the aerogel, most of the temperature change occurs in the MLI (note the first few millimeters left of the dashed line). As pressure increases, the cold boundary temperature of the Aerogel slowly decreases, until at soft vacuum (test 5) the MLI absorbs very little of the temperature change. However, as the pressure transitions from free molecular flow to continuum flow, the aerogel is much better than the MLI and all of the thermal resistance is due to the aerogel blankets. Since the aerogel blankets were the same thickness and material, the apparent thermal conductivities converged (see FIGURE 5). As the materials transition to continuum flow regimes, the outer aerogel blanket would be expected to perform better since the MLI is dominated by the thermal conductivity of the nitrogen purge gas which fills the porous spacer.

CONCLUSION

Testing was performed on various combinations of aerogel blankets and multilayered insulation in actual use conditions. An analytical design tool for thermal insulation systems was established and utilized to predict the heat flow of the several composite insulation systems. The tool was able to predict the heat flow to within 50% and correctly determine the comparative ranking of each composite insulation system. The thermal performance was best with the aerogel blanket in the middle of the MLI at all vacuum levels, though the different schemes were fairly similar in performance in soft vacuum to ambient pressure environments. This result shows that MLI is most effective when located closest to the cold boundary of 80 K.

These data are especially interesting in the development of robust MLI systems. Robust MLI systems can be designed for a minimal drop in thermal performance in the soft vacuum range. This feature is afforded by the presence of aerogel blankets. These tests demonstrate a method of installing MLI underneath aerogel blankets without diminishing the thermal performance of the blanket; in fact, the thermal performance of the system was enhanced by this technique.

Additionally, it was shown that aerogel blankets could be used in between the layers of MLI to allow for better performance at soft and no vacuum. The high performance at high vacuum associated with MLI is still attained, but the aerogel improves the overall system performance at degraded vacuum levels. Since the aerogel layer is also structurally capable, it can help support the fragile, easy-to-disturb MLI layers.

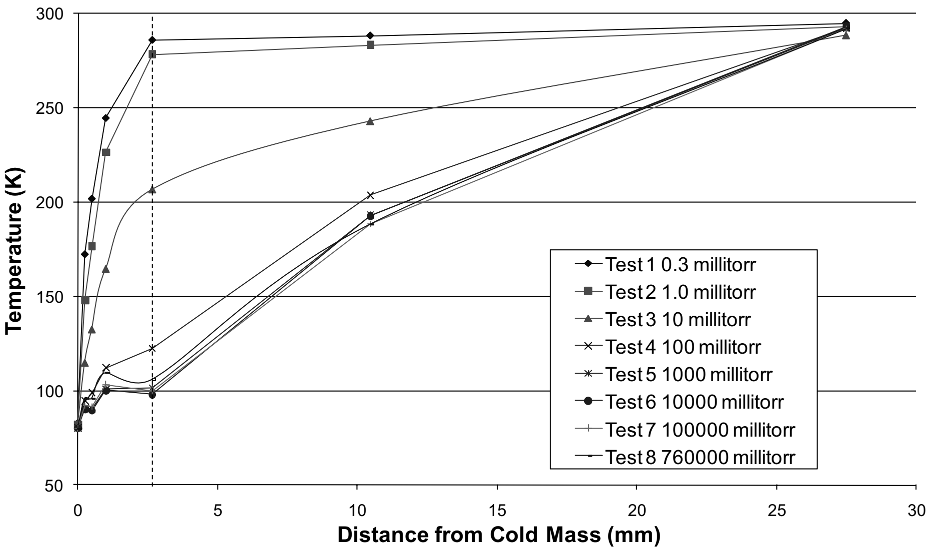

FIGURE 5: Temperature Profiles from T208 (MLI-Aergoel) . MLI is left of the dotted line, underneath the aerogel blanket

REFERENCES

1. Shu, Q.S., Cheng, G., Yu, K., Hull, J.R., Demko, J.A., Britcher, C.P., Fesmire, J.E., Augustynowicz, S.D., Low thermal loss cryogenic transfer line with magnetic suspension," *Advances in Cryogenic Engineering*, Vol. 49, American Institute of Physics, New York, 2004, pp. 1869-1876.
2. Fesmire, J.E., "Aerogel insulation systems for space launch applications," *Cryogenics* Vol. 46, issue 2-3, February 2006, pp. 111-117.
3. Fesmire, J.E., Augustynowicz, S.D., Heckle, K.W., and Scholtens, B.N., "Equipment and Methods for Cryogenic Thermal Insulation Testing," *Advances in Cryogenic Engineering*, Vol. 49, American Institute of Physics, New York, 2004, pp. 579-586.
4. Fesmire, J.E., Augustynowicz, S.D., Scholtens, B.E., and Heckle, K.W., "Thermal performance testing of cryogenic insulation systems," *Thermal Conductivity 29*, DEStech Publications, Lancaster, PA, 2008, pp. 387-396.
5. Johnson, W.L, and Fesmire, J.E., "Testing of Various Seams in MLI," presented at the 2009 Cryogenic Engineering Conference, Tuscon, AZ.
6. Demko, J.A., Fesmire, J.E., and Augustynowicz, S.D., "Design Tool for Cryogenic Thermal Insulation Systems" *Advances in Cryogenic Engineering*, Vol. 53, American Institute of Physics, New York, 2008, pp. 145-151.
7. Martin, J.J. and Hastings, L., *Large-Scale Liquid Hydrogen Testing of a Variable Density Multilayer Insulation With a Foam Substrate*. NASA TM-2001-211089, June 2001.