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Cryogenic Vacuum Insulation for Vessels and Piping

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Kogan A., Fesmire J.*, Johnson W.*, Minnick J.

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Lydall Performance Materials, 68 George Str., Green Island, NY 12183 USA

*NASA Kennedy Space Center, NE-F6, Kennedy Space Center, FL 32899 USA

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Cryogenic vacuum insulation systems, with proper materials selection and execution, can offer the highest levels of thermal performance. Three areas of consideration are vital to achieve the optimum result: materials, representative test conditions, and engineering approach for the particular application. Deficiency in one of these three areas can prevent optimum performance and lead to severe inefficiency. Materials of interest include micro-fiberglass, multilayer insulation, and composite arrangements. Cylindrical liquid nitrogen boil-off calorimetery methods were used. The need for standard thermal conductivity data is addressed through baseline testing. Engineering analysis and design factors such as layer thickness, density, and practicality are also considered.

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INTRODUCTION

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Cryogenic thermal insulation systems that incorporate a vacuum environment can provide the lowest possible heat transfer from the local environment to the stored cryogen. Thermal conductivities in the range of 0.01 to 1 mW/m-K are achievable with the right combination of materials in a high vacuum environment less than 1 millitorr. While multilayer insulation (MLI) systems can provide the ultimate thermal insulating capability, overall system design and operational factors prevent complete utilization of their effectiveness. Fiberglass insulation composed of low outgassing micro-fibers can provide effective high-performance capability in vacuum as well. Vacuum level requirements are considerably less strict for fiberglass, providing cost advantages both in manufacturing and life cycle for cryogenic vessels and piping. Installation around piping, structural supports, and other complex geometries can be readily accomplished using fiberglass. Compression, seams, penetrations and edge effects are known to increase heat leak through MLI systems by 100 percent or more if the system is improperly designed.

Combining MLI and fiberglass in the vacuum annulus of vessels and piping can be done in a number of ways. The materials can work together to meet different thermal performance, cost, or mechanical objectives such as space and weight. Materials, representative conditions, and engineering approach must be considered for a particular application. Deficiency in one of these three areas can prevent optimum performance and lead to costly inefficiencies. Materials of interest include micro-fiberglass, MLI, and composite arrangements. Thermal performance data under representative cryogenic-vacuum conditions are needed for calculating the overall efficiency of a given design and assessing the long-term economics of the operational system.

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TEST EQUIPMENT AND METHOD

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Cryostats using steady-state liquid nitrogen boil-off calorimetery methods are used to determine apparent thermal conductivity (k-value) and heat flux. The Cryogenics Test Laboratory at NASA Kennedy Space Center has developed several cryogenic insulation test instruments for testing of materials and systems under large temperature differential and full-range vacuum conditions [1, 2]. Cryostat testing is performed using laboratory standard practices. A comparative cylindrical unit, Cryostat-2, was recently reactivated at the Lydall cryogenics laboratory in Green Island, NY for use in this study (see Figure 1).

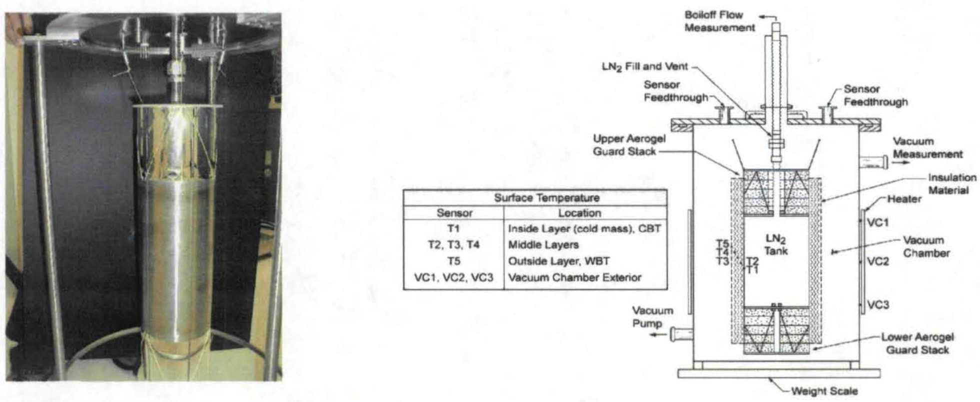

Figure 1. Insulation test instrument, Cryostat-2, installed at the Lydall cryogenics laboratory (left) and simplified schematic showing locations of temperature sensors and equipment connections (right).

Cryostat-2 includes a 132-mm-diameter by 500-mm-long cold mass and can accept specimens up to 50 mm thick. The cold-mass assembly is easily removed and mounted on a wrapping machine. Each test measures the steady-state heat leak (watts) through the specimen at a prescribed set of environmental conditions, including a stable warm-boundary temperature (WBT), a stable cold-boundary temperature (CBT), and a stable cold vacuum pressure (CVP). The liquid nitrogen maintains the cold mass CBT at approximately 78 K and the WBT is maintained at approximately 293 K using an external heater with an electronic controller. Vacuum levels cover the full range from high vacuum (HV) (below 10^{-4} torr) to soft vacuum (SV) (~1 torr) to no vacuum (NV) (760 torr).

The rate of the heat transfer, Q, through the insulation system into the cold-mass tank is directly proportional to the flow rate of liquid nitrogen boiloff. The k-value is determined from Fourier's law for heat conduction through a cylindrical wall. The mean heat flux is calculated by dividing the total heat transfer rate by the effective area of heat transfer. Further details on the heat transfer calculations as well as uncertainty analyses for each apparatus have been previously reported [1,2].

Each test requires a number of temperature, pressure, gas flow, and weight measurements and controls. All signals are processed and recorded through National Instruments (NI) compact Field Point (cFP) hardware using Labview 8.6 Software. Temperatures are measured using Type K thermocouples through NI cFP TC-120 modules. Warm boundary temperature is controlled through a JKEM Model 250-HP-RC616 using Omega heater blankets. Pressure is measured using two MKS Baratron 627B capacitance manometers (0.1 and 100 torr), and a Granville-Phillips 356 Micro Ion Plus transducer (full range). Pressure is controlled through an MKS model 250 pressure controller using an MKS model 0248 proportional control valve. Gas flow from liquid nitrogen boil off is measured with four MKS M10MB analog, elastomer-sealed mass flow meters. To cross check the flow meter, weight change due to liquid nitrogen boiloff is measured with a Mettler Toledo PBA430x weight scale.

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MATERIALS

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The MLI materials used in this study consist of layers of aluminum foil (7.2 micron thick, having emissivity of 0.03) separated by a micro-fiberglass paper spacer (Cryotherm™243, 12 g/m^2). The materials can be applied separately but are preferably collated and applied from a single roll (CRS Wrap). The blanket material is a 25 mm thick micro-fiberglass blanket of density 16 kg/m^3 (Cryolite™). Photographs of the materials are shown in Figure 3. The removable cold mass assembly of Cryostat-2 is placed on a wrapping machine for precise control during installation of all materials and temperature sensors.

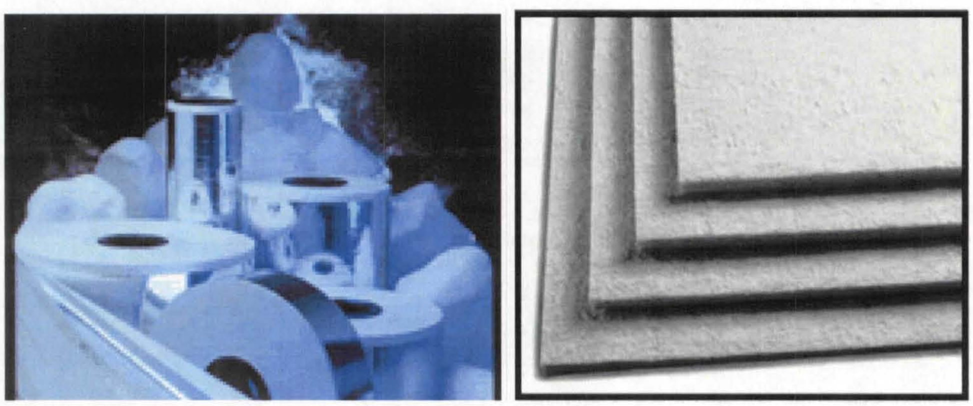

Figure 2. Photographs of micro-fiberglass spacer for MLI (Cryotherm) and micro-fiberglass blanket material (Cryolite)

The micro-fiberglass material Cryolite™ was developed as an alternative to the commonly used perlite powder insulation for cryogenic tankers, such as for liquid oxygen or liquid nitrogen, that are not otherwise insulated with MLI. Cryolite™ offers low density to minimize tanker weight and maximize capacity of the vessel; ease of installation with no settling or compaction issues; oxygen compatibility; and fast vacuum pumpdown rates with minimal outgassing. While many stationary storage cryogenic vessels are still insulated by perlite (as perlite settling is not as severe an issue as in the transport vessels), Cryolite still offers the advantages of fast vacuum pumpdown, better vacuum integrity, and therefore improved insulation properties.

The Cryolite blanket material has been used in combination with MLI in the past, with different orders of installation arrangements. The goal of this study is to determine the best possible combination for the composite arrangement. The following two arrangements have been tested: 1) 40 layers of MLI on the inner vessel (cold mass) followed by one layer of Cryolite blanket and 2) Cryolite blanket on the inner vessel followed by 40 layers of MLI.

Because Cryolite blanket has very limited protection from radiation heat transfer due to its low opacity, the evaluation of the effect of adding several layers of aluminum foil to the blanket is also of interest. Several such arrangements were also tested.

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RESULTS

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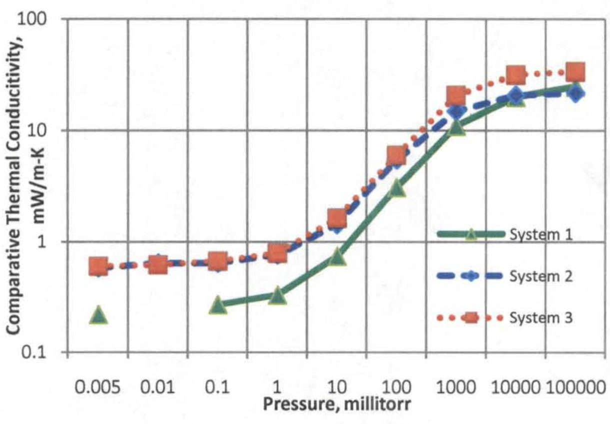
The following are the results of the experiments carried out in this study. All the experiments were conducted over the wide pressure spectrum from high vacuum ($<10^{-5}$ torr) to soft vacuum (1 torr) to near atmospheric pressure (100 torr). The residual gas was nitrogen. Results are reported in terms of the *comparative* effective thermal conductivity (comparative k-value) in mW/m-K and the total heat leakage rate (Q) in W.

MLI and MLI/Cryolite composite

The thermal performance data for the following three insulation systems were obtained:

- System 1 - 40 layers of MLI
- System 2 - 1 layer of Cryolite plus 40 layers of MLI
- System 3 - 40 layers of MLI plus 1 layer of Cryolite

As shown in Figure 3a, the comparative k-values were lowest for the system 1, which consisted of only MLI. However, taking advantage of available space by adding a layer of Cryolite like with System 2 or System 3 shows overall heat leak improvement of as shown in Figure 3b (heat leak chart). This result is expected as the overall insulation thickness is increased due to the additional layer of Cryolite.



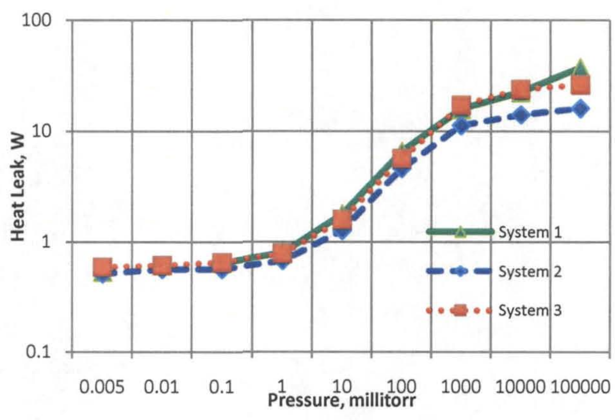


Figure 3 (a & b). Variations of comparative k-value and heat leak rate with cold vacuum pressure for fiberglass/MLI composites and MLI.

Of a particular interest is the question of where to position theCryolite: Is it more efficient to have the Cryolite closer to the cold side or the warm side? Considering that MLI performance is governed by a T^4 relationship, one may assume that the MLI should be preferably located on the warm side. However, as the work of the MLI is to impose the steepest possible temperature gradient and as emissivity values are reduced at lower temperatures, this assumption may not be valid in all cases. But to accept the warm side placement assumption, System 2 (Cryolite/MLI) would be expected to perform somewhat better than System 3 (MLI/Cryolite).

Cryolite and Cryolite/foil.

Cryolite blanket (just as perlite) gives minimal protection against radiation heat transfer due to its relatively low opacity. And while it is not practical to use reflective shields with Perlite, it is a quite easy application process when used with Cryolite. While the improvement from the adding reflective layers seems obvious, an objective of this study is to quantify the effect of the reflective layers. Two layers of Cryolite were compared to two layers of Cryolite with Aluminum foil (7.2 micron thickness) on each layer having the following configuration starting from the cold inner vessel Cryolite /Foil/Cryolite/Foil: (Figures 4a and 4b show the curves of k-value and heat leak respectively).

Figure 5 Photograph of Cryolite/Foil configurations.

- System 4 - Cryolite (1 layer)
- System 5 - Cryolite (2 layers)
- System 6 - Cryolite/foil (2 layer-pairs)

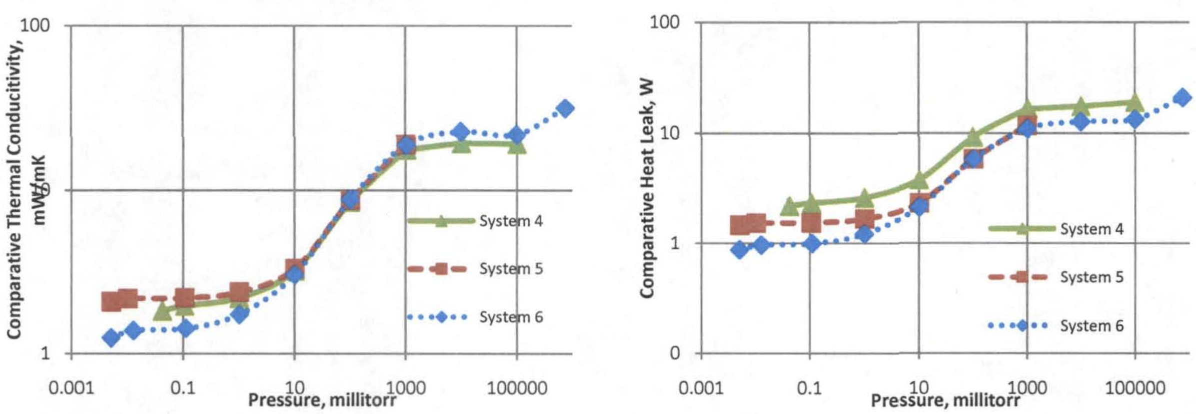


Figure 4 (a & b). Variation of comparative k-value and heat leak rates with cold vacuum pressure for Cryolite/Foil combinations.

At high vacuum levels, the one layer of Cryolite (System 4) gives a slightly lower k-value than the two layers of Crylolite (System 5). While in the idealized world the thermal conductivity should stay approximately the same with the increased thickness, the increase of k-value for two layers is explained by the slight compression that takes place during the installation of the second layer. The compression results in a density increase, which causes the higher solid conduction heat transfer. At the higher pressures this difference is negligible, as gas conduction starts to dominate in the soft to no vacuum regime. The heat leak is obviously reduced due to the second layer of Cryolite insulation. As seen in both charts, addition of the reflective layers does indeed improve the thermal performancein the pressure range of interest, below 10 millitorr.

DISCUSSION AND ANALYSIS

MLI and MLI/Cryolite composite

Results show that indeed the heat flux is lower with the Cryolite/MLI (System 2) combination. While the difference in heat leak between the two systems is evident over the whole range of pressures from high vacuum ($<10^{-5}$ torr) to very soft vacuum (100 torr), it is more pronounced with increased pressures. This result is expected as with increased pressure the radiation heat transfer becomes less significant, while gas conduction becomes more prevalent. The Cryolite being next to the cold mass is providing more protection in this case. Figure 5 summarizes the percent of improvement of heat flux from positioning Cryolite blanket next to the inner vessel.

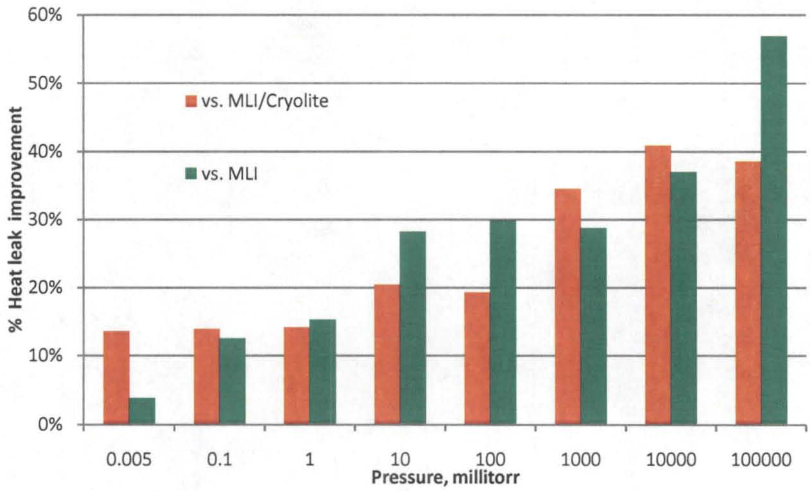


Figure 5. Percent improvement in heat leakage rate for the Cryolite/MLI composite.

It is interesting to compare these findings with those for a similar study involving MLI and aerogel blanket combinations [3]. As reported from this work, aerogel blanket performed better when positioned on the outside of the MLI than when positioned on the cold mass. One of the possibilities is that the aerogel blanket density is several times that of the Cryolite, allowing for more solid conduction when put next to the inner vessel (colder temperatures). Also, Cryolite is highly permeable to gas, where aerogel blankets are designed to minimize heat transfer by gas conduction or convection. Thus due to different material properties of different materials, it can easily be seen why the optimal location changes. These results underscore the importance of fully understanding the operating environment and requirements for a specific thermal insulation system.

Cryolite and Cryolite/foil

Figure 6 summarizes the percent of improvement in heat flux over above mentioned pressure range. The pressure most commonly used in the Perlite insulated vessels is in range from 1 to 10 millitorr, and as shown, addition of the reflective layers does offer a quite significant reduction of the heat leak. Also, the ease of evacuation of the annular space insulated with Cryolite could offer opportunities for even better vacuum, approaching 0.1 millitorr.

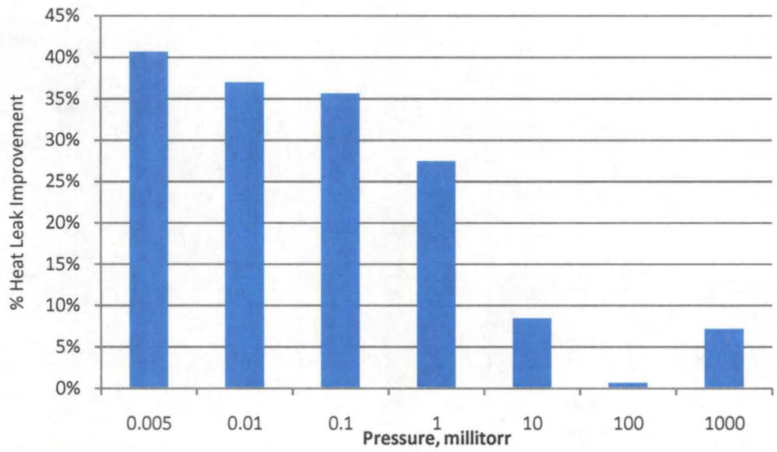


Figure 6. Percent improvement in heat leakage rate for the Cryolite/foil compared to Cryolite only

CONCLUSIONS

Thermal performance tests were conducted to determine optimal placement and use of MLI (foil and paper type) and Cryolite fiberglass blanket within cryogenic storage systems. These tests indicated that it is preferential to use Cryolite on the cold side of the MLI, and that placing radiation shields within several blankets of Cryolite drastically improves thermal performance of the insulation system at higher vacuum levels. These results can be used to define or optimize future systems design and construction techniques.

Evaluation of additional variations in MLI and Cryolite combinations is planned. A practical benefit of incorporating the Cryolite as part of a MLI-based high-vacuum system is two-fold. First, the Cryolite layers can allow for better evacuation between layers. Second, the mechanical elasticity (spring effect) offers protection to the MLI layers to minimize compression and edge effects. The total thermal performance of the insulation system must be considered along with the mechanical performance advantages to determine the most effective system for a given vessel or piping application.

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