Load Responsive Multilayer Insulation Performance Testing

S. Dye[1], A. Kopelove[1], and G. L. Mills[2]

[1]Quest Thermal Group, 6452 Fig Street Suite A, Arvada, CO 80004 USA
[2]Ball Aerospace & Technologies Corp, 1600 Commerce Street, Boulder, CO 80301 USA

Cryogenic insulation designed to operate at various pressures from one atmosphere to vacuum, with high thermal performance and light weight, is needed for cryogenically fueled space launch vehicles and aircraft. Multilayer insulation (MLI) performs well in a high vacuum, but the required vacuum shell for use in the atmosphere is heavy. Spray-on foam insulation (SOFI) is often used in these systems because of its light weight, but can have a higher heat flux than desired. We report on the continued development of Load Responsive Multilayer Insulation (LRMLI), an advanced thermal insulation system that uses dynamic beam discrete spacers that provide high thermal performance both in atmosphere and vacuum.

LRMLI consists of layers of thermal radiation barriers separated and supported by micromolded polymer spacers. The spacers have low thermal conductance, and self-support a thin, lightweight vacuum shell that provides internal high vacuum in the insulation. The dynamic load responsive spacers compress to support the external load of a vacuum shell in one atmosphere, and decompress under reduced atmospheric pressure for lower heat leak.

Structural load testing was performed on the spacers with various configurations. LRMLI was installed on a 400 liter tank and boil off testing with liquid nitrogen performed at various chamber pressures from one atmosphere to high vacuum. Testing was also performed with an MLI blanket on the outside of the LRMLI.

Introduction

NASA’s next generation spacecraft and launch vehicles will increasingly use cryogenic propellants and will require a lightweight insulation with high performance in one atmosphere and on orbit vacuum, to minimize propellant boil-off. Liquid hydrogen has distinct advantages as a fuel for high altitude long endurance aircraft (HALE) but also requires a lightweight insulation with high thermal performance at sea level pressure and high altitude.

Multilayer insulation (MLI) in a vacuum provides the thermal performance required but requires a prohibitively heavy vacuum shell for use in the atmosphere. Spray On Foam Insulation (SOFI) is typically used to insulate cryogenic propellant tanks pre-launch because of its light weight and insulating ability in air, but it has much higher thermal conductivity than MLI and has a lack of mechanical robustness.

Quest Thermal Group, and Ball Aerospace, have developed a next generation MLI product called “Integrated MLI” (IMLI) [ref. 1], which uses discrete low thermal conductance polymer micromolded spacers between radiation shield layers. This proprietary discrete spacer technology provides precise, controlled layer spacing and blanket density, reduces the conductance from layer to layer, and forms a bonded up, very robust and repeatable structure.

Load Responsive Multi-Layer Insulation (LRMLI) is a derivative of IMLI and is designed to provide high performance insulation both in-atmosphere and on-orbit. LRMLI uses a dynamic beam polymer spacer that provides both low thermal conductance and support of a lightweight integrated vacuum shell.

LRMLI consists of layers of metalized polymer thermal radiation shields that are separated and supported by proprietary micromolded spacer posts with low thermal conductance. In-air, the posts support a thin, lightweight hermetic vacuum shell that allows high vacuum to be maintained within the insulation. The spacers dynamically respond to load, compressing to support the external load of atmosphere acting on the thin wall vacuum shell, and disconnecting under reduced atmospheric pressure for lower heat leak at high altitudes or on-orbit. The dynamic spacer supports a vacuum shell under external atmospheric pressure, allowing a very thin, lightweight, flexible vacuum shell to be used. As external pressure is reduced at high altitudes or on-orbit, the spacers dynamically disconnect to provide lower solid conduction resulting in lower heat leak.

IMLI is designed as a next generation MLI replacement with higher thermal performance, robust structures and a lower installed cost. LRMLI is designed as an insulation layer for use where both in-atmosphere and on-orbit performance is important. LRMLI could be a SOFI replacement for use in ground hold and pre-launch insulation to reduce ice formation and to enable use of sub-cooled cryogens. A mixed LRMLI/IMLI insulation system could provide ultra high thermal performance for cryopropellant tanks, spacecraft, space-borne instruments and orbital fuel depots.

Possible applications include:

- Cryopropellant thermal insulation for space launch vehicles, spacecraft and orbital fuel depots
- Liquid hydrogen fueled aircraft fuel tank insulation
- Cryogenic dewar insulation for research, medical & industrial uses
- Liquid hydrogen fueled ground vehicles
- Insulating superconducting devices such as MRI & superconducting power systems

LRMLI development

LRMLI development was begun under a NASA Phase I SBIR contract that was completed in 2009 demonstrating the feasibility of the LRMLI insulation system. A small scale LRMLI prototype was designed, fabricated and installed on a 20L test tank. [ref 1].

LRMLI development continued in a NASA Phase II SBIR contract that was completed in 2012. The dynamic beam post was redesigned to provide higher structural strength and a higher safety margin, and for easier fabrication in the preferred low conductivity, low outgassing polymer material. A 3rd generation Tripod Post was designed, heat flow through the part analyzed, structural strength analyzed via FEA, and should achieve the desired safety margin of 2 under external atmospheric loading of 14.7 psi, with lower conducted heat leak. Figure 1 shows a cross section view of a three layer version of LRMLI. The two stage feature of the posts can be seen.

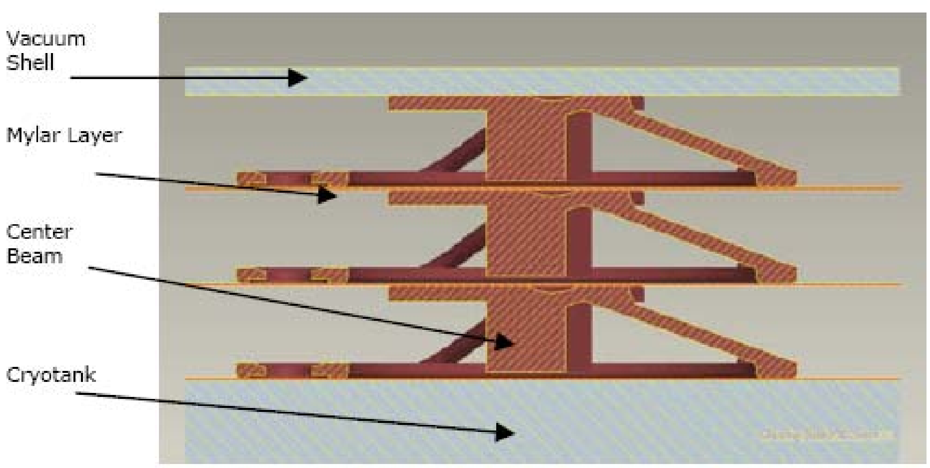

Figure 1, Cross section view of LRMLI on a cryogenic tank.

A second major focus of the Phase II work was to develop improved thin, lightweight vacuum shell designs to reduce mass, increase structural integrity, and ease design, manufacture and installation burdens. A modular vacuum shell design allows less expensive application to varying tank geometries. Design of a thin, flexible vacuum shell was a technical challenge. Analysis of the vacuum shell flexibility required with cryotank temperature changes and external pressure changes was completed. Shell FEA was performed analyzing vacuum shell stresses, thickness and mass. A trade study was performed for seven possible vacuum shell designs comparing their technical risks, performance and handling/manufacturing characteristics. The system was designed, prototyped and tested, showing good thermal performance.

Through careful design and innovative ideas the mass of the vacuum shell has been reduced by 57% to 1.87 kg/m^2. The new design is modular for application across a broader range of tank sizes and geometries, based on a flexible and thin vacuum shell, supported by the LRMLI spacers, and supporting a hermetic outer layer. The vacuum shell panels have shown good structural integrity through thermal cycling and repeated atmospheric pressure/high vacuum cycles.

The LRMLI thin wall self-supported vacuum shell offers significant mass advantages over vacuum shells required for conventional MLI. Traditional vacuum shells required to provide internal high vacuum for MLI weigh approximately 10 kg/m^2 for a 0.15" thick 5083 Al shell, whereas the LRMLI semi-rigid shell is approximately 1.9 kg/m^2 (17.5% the mass of a traditional shell). This mass savings is due to the strength of the LRMLI dynamic spacer.

Liquid nitrogen boil off testing.

LRMLI was installed on a 20 liter tank and a 400 liter tank. The LRMLI had 3 layers of support post and shields. The vacuum shell consisted of thin aluminum segments mounted to the outer layer of spacer posts, with small gaps between the segments. An aluminized polymer membrane was installed over the aluminum segments and was the hermetic layer. The 20 liter tank was a cylinder with flat ends. It was 10 inches in diameter and 24 inches long. The tank was tested with the LRMLI and then with 10 layers of integrated MLI applied over the LRMLI.

The 400 liter tank was a cylinder 30 inches in diameter with hemispherical heads and was 45 inches long. A photo of the LRMLI installation, under vacuum, on the 400 liter tank is shown in Figure 2.

Figure 2: LRMLI installation on a 400 liter tank

The boil off test was performed by installing LRMLI on the test tank suspended in a vacuum chamber. The tank was filled with liquid nitrogen and was allowed to come to steady state boil off and the flow rated was measured. Initially the chamber was at ambient pressure, and was pumped to the lower pressures during testing. The tank heat leak was calculated from the published heat of vaporization of liquid nitrogen. The tank was suspended by a low thermal conductance stainless steel fill/vent tube which is cooled by the nitrogen boil off gas. It can be shown analytically that the heat leak down the fill/vent tube is completely intercepted by the cold nitrogen gas boil off. Therefore, the LN2 boil off is only a result of the heat flux through the LRMLI test article. The heat flux is calculated by dividing measured heat leak by the tank area.

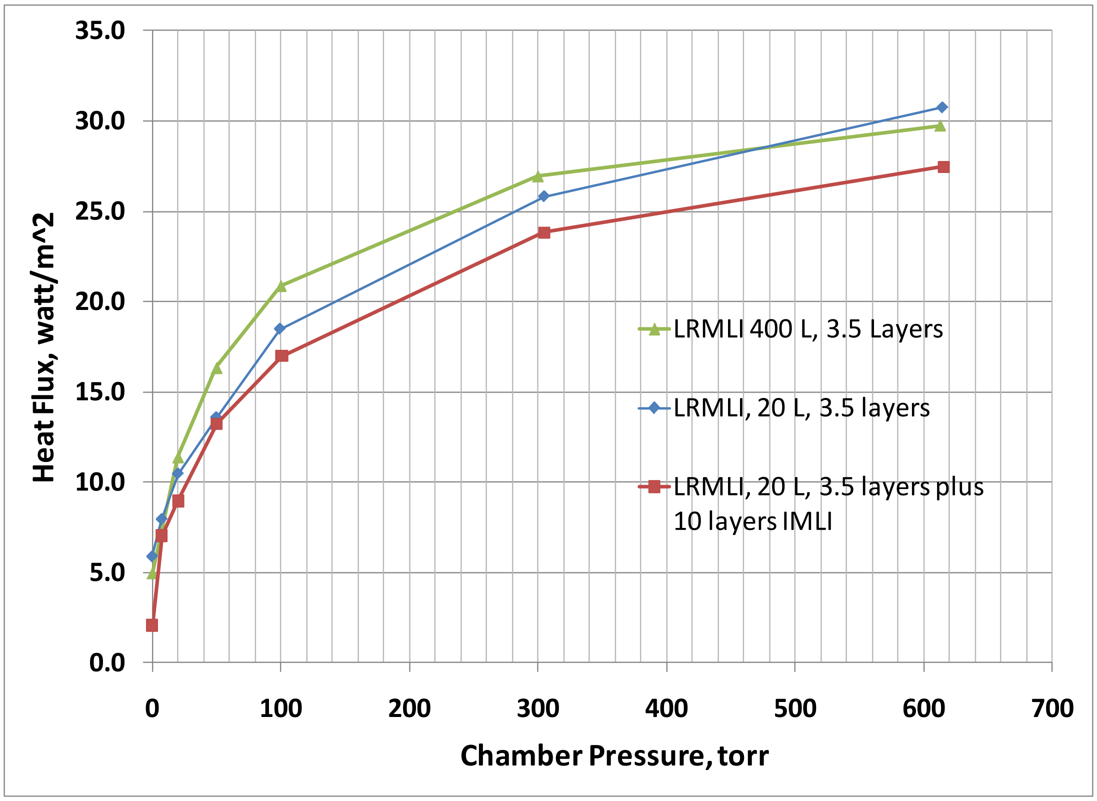

Figure 3. LRMLI heat leak from 295°K to 77°K as a function of external atmospheric pressure.

The LRMLI heat flux was measured at various external pressures, from high vacuum to one atmosphere, to evaluate the change in LRMLI heat leak and validate dynamic post performance with external load. Full compression of the dynamic beam results in a sharp increase in heat leak as the posts connect, disconnection with spacer rebound causes a sharp decrease. See in Figure 3 the steep slope of heat leak at chamber pressures around 50 torr. The LRMLI polymer spacer posts were tested for structural load capacity, and began to compress at one pound force per post, which in the LRMLI blanket corresponds to an external load of 52 torr, where compression should occur.

A mixed insulation system composed of 3 layers of LRMLI, with 10 layers of outer IMLI external to the vacuum shell, was installed on a test tank and tested. The effect of adding 10 layers of IMLI reduced the heat flux by only a small fraction except at high vacuum, where the heat leak was reduced by over 100%. This was not surprising, as the thermal performance of IMLI (or conventional MLI), is low until the pressure drops below 10^{-4} torr.

LRMLI Performance Comparisons

Based on the results of LRMLI testing , comparisons were made to other high performance insulation typically used in pressures ranging from one atmosphere to high vacuum [reference 3 and 4]. A 5 layer LRMLI system was assumed. The comparison at 5300 Pa, or the standard pressure of 65000 feet altitude, was done because of the possible application of LRMLI to high altitude long endurance aircraft liquid hydrogen fuel tanks. The results are shown in tables 1 and 2. LRMLI has much lower conductivity than the other insulations at all operating pressures by large factors. LRMLI has the highest apparent density, because of the mass of the vacuum shell, but still has the lowest density x conductivity because of the low conductivity.

Table 1: Conductivity comparison, average between 77°K and 294°K, mW/m-°K

Environment	LRMLI	SOFI (S-180)	Aerogel	Nanopore
One atmosphere	0.89	13.0	19.0	13.0
5300 Pa, (65,000 feet)	0.48	13.0	6.0	3.6
Vacuum	0.14	13.0	1.2	2.0

Table 2: Mass & conductivity comparison: density x conductivity, W*gram/m^4*°K

Density:	LRMLI, 279 kg/m^3	SOFI (S-180) , 41.6 kg/m^3	Aerogel, 51 kg/m^3	Nanopore, 200 kg/m^3
One atmosphere	248	541	969	2603
5300 Pa, (65,000 feet)	134	541	306	720
Vacuum	39	541	61	400

Conclusions

Load Responsive Multi-layer Insulation (LRMLI) offers a unique insulation product that is lightweight, high performing, and supports its own thin wall vacuum shell enabling both in-air and on-orbit operation. LRMLI prototypes have been built, installed on small tanks, and actual heat leak measured. LRMLI has demonstrated significant improvements over conventional insulations such as SOFI and aerogel. The LRMLI performs well for both in-atmosphere and in-vacuum (equivalent to on-orbit conditions).

LRMLI in-air thermal performance is achieved by an innovative approach using low thermally conductive micromolded polymer spacers that dynamically respond to external atmospheric pressure (load) to support a thin, lightweight vacuum shell, and disconnect in on-orbit condition to provide even higher thermal performance on orbit.

Acknowledgements

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