INTEGRATED AND LOAD RESPONSIVE MULTILAYER INSULATION

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ABSTRACT

Multilayer insulation (MLI) is used to reduce heat leak into cryogenic systems such as tanks, dewars and instruments, and used to control spacecraft heat leak. MLI is typically used in a high vacuum ($<10^{-3}$ Pa) where its performance usually exceeds other insulations by 10-fold. Conventional MLI consists of layers of low thermal emissivity metalized polymer sheets separated by low conductance netting spacers.

We report on an improved MLI in which the spacer netting is replaced by micro-molded polymer parts with low thermal conductance that provide controlled layer spacing. Integrated MLI (IMLI) is a precisely engineered insulation system with advantages over conventional MLI, including higher performance, more predictable performance, more robust, lower particulate contamination, optional electrical conduction and lower cost.

A second novel insulation, Load Responsive MLI (LRMLI) is described which uses polymer spacers that dynamically respond to load, compressing to support a thin, light-weight vacuum shell under one atmosphere external pressure, and decompressing under reduced atmospheric pressure or vacuum for lower heat leak. Structural and thermal analysis and testing results are presented. IMLI and LRMLI performance are compared to conventional MLI and polymer Spray On Foam Insulation.

KEYWORDS: Multilayer insulation, cryogenic, thermal insulation

INTRODUCTION

Lightweight, high performance thermal insulation is critical to NASA’s next generation Exploration spacecraft. Zero or low cryogenic propellant boil off is required during extended missions and lengthy on-orbit times. Multilayer insulation (MLI) is currently the insulation of choice for cryotank insulation. MLI is typically used in a high vacuum ($<10^{-3}$ Pa) where its performance exceeds alternative insulations by a factor of ten. However, the heat flow through the MLI is usually by far the largest heat leak in cryogenic systems, so improvements in thermal performance are desirable, especially for new Exploration mission vehicles. Also, MLI by itself does not provide cryotank insulation during in-atmosphere pre-launch and launch.

Integrated Multi-Layer Insulation (IMLI) and Load Responsive Multi-Layer Insulation (LRMLI) are innovative new technologies, where polymer substructures are integrated with radiation barriers to provide improved ultra-high performance thermal insulation systems. Quest Product Development, teaming with Ball Aerospace, is developing these high performance insulations. Patent applications have been filed for IMLI and LRMLI.

IMLI consists of layers of metalized polymer film separated by a polymer substructure enabling precise control over layer spacing, with polymer spacers designed for ultra-low heat conduction, thereby providing higher thermal insulation performance. Integrated MLI uses micro-molded structures to support radiation barrier layers, offer inherent construction benefits, and have very low heat leak via conduction through the spacer. The polymer spacer uses unique fabrication in order to have a low cross-section area to length ratio (0.00002m) to reduce heat leak. Integrated MLI has been designed, modeled, prototyped and tested showing a heat leak lower than conventional MLI. IMLI is a conventional MLI replacement, and requires a vacuum to provide good thermal insulation.

A second innovative thermal insulation, Load Responsive MLI, has been thermally and structurally modeled and is in prototype fabrication and test. LRMLI is a dynamic system that compresses a dynamic beam under atmospheric pressure to support an integrated, thin vacuum shell, and disconnects under vacuum to reduce heat leak through the spacer. FIGURE 1 below conceptually shows IMLI and LRMLI.

IMLI Advantages Compared to Conventional MLI

IMLI offers an engineered thermal insulation system that can be optimized for desired characteristics such as lower thermal conductance, lower number of layers, less thickness or lower mass than conventional MLI. IMLI layers are precisely spaced and do not vary in density with gravity or fabrication technique, are attached to each other for a robust blanket, and are fabricated using semi- or automated processes. IMLI properties include:

Higher performance: Thermal modeling (see below) of IMLI predicts that a 40-layer blanket with a hot side temperature of 293K, cold side temperature of 77K and a thickness of 7.1cm would have a conductance of 0.16 W/m^2, 60% that of conventional MLI. Ten layer blankets of IMLI have been installed on a rectangular test fixture and have demonstrated a measured 37% lower heat leak than 10 layer blankets of conventional MLI.

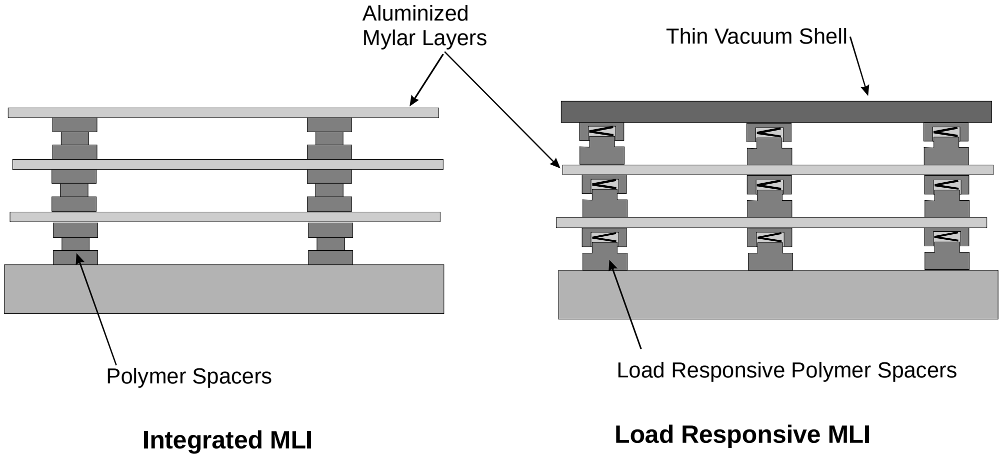

FIGURE 1. Conceptual Drawings of Integrated MLI and Load Responsive MLI.

More predictable performance: Unlike conventional MLI, the polymer spacers of IMLI do not allow the density and performance to vary due to gravity, number of layers or fabrication technique. The polymer spacers allow the density to be precisely controlled.

Lower particulate contamination: IMLI has no netting spacers, only polymer spacers that provide no particulate release and low out-gassing. This is an advantage for contamination sensitive insulation, such as those containing optics and focal planes.

Optional electrical conductivity: MLI used on spacecraft exteriors often must be electrically grounded. Current MLI grounding techniques require additional through-holes and grounding plugs, which are labor intensive and create heat leaks. IMLI blankets permanently contact each other through the spacers. Metalized spacers that are electrically conductive have been tested.

Robustness: Conventional MLI blanket layers are loosely held together with polymer ties or threads, which are structurally weak. IMLI/LRMLI spacers are bonded to each layer, holding layers in precise spacing and resulting in a much more structurally robust blanket that can withstand greater loading due to handling, acceleration or vibration.

Lower installed cost, automated production, less touch labor, fewer layers: Semi-automated fabrication processes have been designed and used for IMLI/LRMLI assembly. A clear path exists to fully automated blanket assembly techniques. Since IMLI has higher performance per layer, fewer layers are required for a given heat leak requirement, further lowering costs.

IMLI Estimated Performance and Testing

The thermal performance of IMLI was calculated using a heat transfer model which models the radiative and conductive heat transfer through the layers. The radiation heat transfer uses the parallel layer equation [1]. The conductive transfer is calculated from the area/length of each conductive element and the temperature dependant conductivity of the polymer used. The performance of conventional MLI was estimated using published equations based on empirical data [2]. The results are shown in FIGURE 2, for IMLI, conventional MLI and parallel layers with no solid conduction for 295K hot side and 77K (liquid nitrogen) cold side. The modeled conductance of IMLI is 65% of the conventional MLI conductance and is closer to the radiation limit of parallel layers.

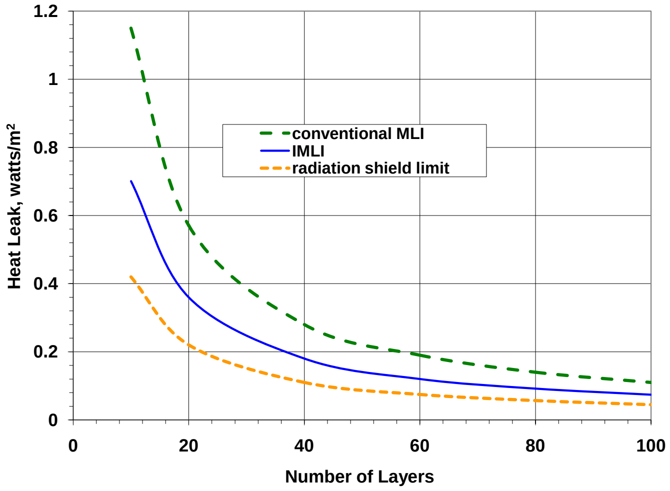

FIGURE 2. Calculated performance of IMLI, conventional MLI and theoretical radiation shields for 77K cold side and 295K hot side.

FIGURE 3. Calorimeter test tank insulated with IMLI.

IMLI thermal performance was measured using a liquid nitrogen calorimeter. A flat sided calorimeter tank was insulated with a 10 layer IMLI sample blanket (FIGURE 3). The tank was then put in a vacuum chamber, pumped to high vacuum (less than 10^{-4} Pa) and filled with liquid nitrogen. The nitrogen boil-off was measured with a wet test meter, with the vacuum chamber environment at 295K. The heat leak was calculated from the steady state boil-off and the heat of vaporization of liquid nitrogen. Data was also taken with the same fixture insulated with 10 layers of conventional MLI.

The heat leak measured with the IMLI insulation was 1.22 watts/m^2 and with the conventional MLI was 1.45 watt/m^2. Both heat leaks were higher than shown in FIGURE 2 because of effects of seams and corners that could not be accounted for in the modeled heat leak. IMLI blankets using 0.25 mil Mylar were created and tested. The performance was slightly better than the blankets fabricated with 1 mil Mylar, proving the IMLI concept and layer spacers work with very lightweight blankets. IMLI blankets made with 0.25 mil Mylar have approximately the same mass per area as conventional MLI and will have superior performance on a mass or layer basis (fewer layers required for same heat leak).

Ten layer IMLI was installed on a cylindrical calorimeter tank with the same area as the rectangular fixture, and a boil-off test was performed with liquid nitrogen. The measured heat leak was 1.06 watts/m^2 and 37% less than the conventional MLI.

Load testing was performed on the polymer spacers by bonding an array of spacers to a Mylar sheet. The sheet was then placed between the flat, parallel platens of a compression testing machine. The upper platen was lowered until it contacted the top of the spacers. The platen was continued to be lowered while a load cell measured the force on the spacer array. The displacement and load were measured and recorded until the load-displacement curve became significantly non-linear, indicating the posts had buckled or yielded. The result was that the posts buckled with a load of 1.1 kilograms/spacer. This is calculated to be sufficient to support over 100 layers of IMLI when subjected to space flight loads.

Adhesive tests were performed by bonding a spacer to a layer of aluminized Mylar. The post and Mylar were lowered into liquid nitrogen, where they cooled to the nitrogen temperature. The posts and Mylar were removed from the nitrogen and were immediately pull tested. The spacers withstood a pull test of 2.0 kilograms force without debonding.

Load Responsive MLI

Load Responsive MLI is a precisely engineered insulation system comprised of thin Mylar layers uniformly separated by polymer spacers. The polymer spacers are designed to be strong enough to support a thin wall vacuum shell under in-atmosphere operation and loading, and still provide low heat leak for a high performance thermal insulation.

Performance goals were higher performance than Spray On Foam Insulation (SOFI) or MLI in-atmosphere, lower mass and thickness than SOFI or conventional MLI with vacuum shell, and equivalent or better in-vacuum performance as conventional MLI. LRMLI is designed to dynamically adapt to loading conditions to provide both in-atmosphere and on-orbit high performance.

With tightly controlled layer spacing and consistency of materials LRMLI will have a much more predictable performance than SOFI. SOFI is very density and application dependent and the density can vary as much as 25%. Having dynamic load responsive capabilities, LRMLI offers much higher performance than either purged MLI or SOFI.

Estimated Performance of LRMLI

The performance of the LRMLI was modeled in the same way as the IMLI (above), with the change of the conductive area/length from the loaded to unloaded condition simulated. The thickness and mass of polyurethane SOFI with the same heat leak was calculated. SOFI is currently one of the highest performing insulation materials for use in one atmosphere. The thickness and mass of conventional MLI was calculated for comparisons. It was assumed that the conventional MLI would be purged with Helium in the one atmosphere case and this conductivity is based on Ball test data [3]. The results for one atmosphere and low pressure conditions for a liquid hydrogen tank at 20K are shown below. On a mass basis, three layers of LRMLI with thin vacuum shell offers 3.4 times better performance than SOFI in one atmosphere, and 14 times better performance on orbit. On a thickness basis, LRMLI with a thin vacuum shell should provide 30 times better performance than SOFI in atmosphere, and nearly 130 times better performance on orbit. Four layers of LRMLI, with a thickness of 0.82cm (0.32"), have the same heat leak as 25.9cm (10.2") of SOFI for pre-launch ground hold use. On orbit equal performance to four layers 0.82cm (0.32") of LRMLI (2.31 kg/m^2) would require 107.2cm (42.2") SOFI with mass of 39.5 kg/m^2.

TABLE 1. Insulation Performance for 20K cold side and 295K hot side with one atmosphere pressure (launch environment)

LRMLI layers	LRMLI Heat Leak watts/m^2	LRMLI thickness cm	He purged cMLI Same Heat Leak Thickness, cm	SOFI Same Heat Leak Thickness, cm	LRMLI Mass, kg/m^2	He purged cMLI Same Heat Leak Mass, kg/m^2	SOFI Same Heat Leak Mass, kg/m^2
1	76	0.25	9.83	6.58	1.75	3.00	2.42
2	38	0.44	19.48	13.02	1.94	5.92	4.80
3	26	0.63	29.08	19.44	2.12	8.84	7.16
4	19	0.82	38.68	25.85	2.31	11.755	9.52

TABLE 2. Insulation Performance for 20K cold side and 295K hot side with low atmospheric pressure (on-orbit environment)

LRMLI layers	LRMLI Heat Leak watts/m^2	LRMLI thickness cm	No Vacuum Shell cMLI Same Heat Leak Thickness, cm	SOFI Same Heat Leak Thickness, cm	LRMLI Mass, kg/m^2	No Vacuum Shell cMLI Same Heat Leak Mass, kg/m^2	SOFI Same Heat Leak Mass, kg/m^2
1	10.3	0.25	0.14	29.97	1.75	0.043	11.06
2	5.5	0.44	0.27	56.29	1.94	0.081	20.70
3	3.8	0.63	0.39	81.79	2.12	0.117	30.15
4	2.9	0.82	0.51	107.16	2.31	0.153	39.48

In the one atmosphere case, both SOFI and purged MLI are significantly thicker and heavier than LRMLI for the same heat leak, with the LRMLI advantage increasing with additional layers. In the low pressure case, SOFI is approximately 100 times thicker and 10 times heavier than LRMLI. MLI without a vacuum shell is lighter and thinner by the mass and thickness of the LMRLI vacuum shell (but only insulates in a vacuum).

Applications of LRMLI

LRMLI will have significant advantages for space applications in which the system is required to be cold at the time of launch. Space borne cryogenic instrumentation such as infrared cameras and spectrometers are frequently cooled by cryostats using expendable cryogens. These systems are typically enclosed in vacuum shell weighing 10 to 15 kg/m^2. If LRMLI is used to support a thin vacuum shell, such as 0.05cm (0.02") thick aluminum, the vacuum shell mass can be reduced to 1.7 kg/m^2.

Cryogenic propulsion tanks typically have not used vacuum shells because the mass is prohibitively high and the propellants are consumed within a few hours of launch. However, future missions require cryogenic propellants be efficiently stored for many days or months. This will require the tanks be insulated with blankets of multilayer insulation 40 to 120 layers thick. Without a vacuum shell, such blankets will require helium or nitrogen gas purges to prevent water or air condensing on the tank surface. It has been shown [3] that purged MLI has high heat leak and continues to add heat after launch. In the case of liquid hydrogen tanks, the purge gas would have to be helium, which has high cost and issues with future availability. An alternative approach for liquid hydrogen tanks [4] is to insulate the tanks with a layer of SOFI between the tank and the thick MLI blanket. The SOFI would have to be thick enough that the temperature on the outside of the SOFI would be greater than 77K so nitrogen could be used as a purge gas. FIGURE 4 shows this arrangement where LRMLI would be substituted for the SOFI.

TABLE 3 shows the thickness of SOFI and LRMLI required to keep the outside of the SOFI or MLI above 77K, with 8K margin for a given thickness of nitrogen purged MLI. A single layer of LRMLI is sufficient to prevent nitrogen condensation. A single layer of LRMLI is thinner and somewhat heavier than the required SOFI. An overall system analysis may show that the system mass with LRMLI is lower due to reduced system size such as launch fairing.

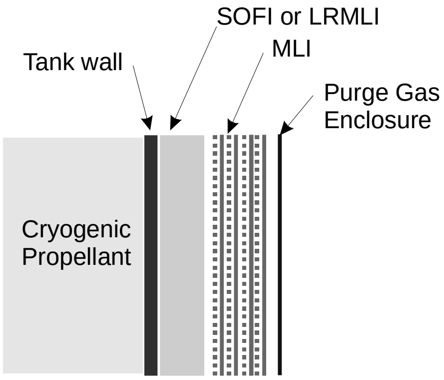

FIGURE 4. Propulsion tank insulation arrangement, soft vacuum shell concept

TABLE 3. Thickness and mass needed to keep purged surface temperature above 85K with 295K air temperature (nitrogen purge case).

Purged MLI layers	MLI thickness cm	SOFI thickness cm	LRMLI # layers	LRMLI thickness cm	MLI mass kg/m^2	SOFI mass kg/m^2	LRMLI mass kg/m^2	SOFI-MLI mass kg/m^2	LRMLI-MLI mass kg/m^2
40	4	1.2	1	0.21	1.2	0.5	0.8	1.7	2.0
60	6	1.8	1	0.21	1.8	0.8	0.8	2.6	2.6
80	8	2.4	1	0.21	2.4	1.0	0.8	3.4	3.2
120	12	3.4	2	0.39	3.6	1.4	0.9	5.0	4.5

The one atmosphere performance of LRMLI is sufficient that dry air with a dew point of -35C (1% humidity) could be used instead of nitrogen as a purge gas. This could result in considerable savings in ground support equipment and would eliminate the need for nitrogen. As shown in TABLE 4, this approach requires unfeasibly thick, heavy layers of SOFI, but feasible thicknesses and masses of LRMLI. On orbit, the SOFI contributes very little to the system thermal performance while LRMLI contributes significantly to the on-orbit performance of the overall insulation system. As shown in TABLE 1, LRMLI on-orbit has approximately the same heat leak per thickness as conventional MLI.

TABLE 4. Thickness and mass needed to keep purged surface temperature above 255K with 295K air temperature (dry air case with 17K margin).

Purged MLI layers	MLI thickness cm	SOFI thickness cm	LRMLI # layers	LRMLI thickness cm	MLI mass kg/m^2	SOFI mass kg/m^2	LRMLI mass kg/m^2	SOFI-MLI Mass kg/m^2	LRMLI-MLI Mass kg/m^2
40	4	51	6	1.2	1.2	51	2.19	52.2	3.2
60	6	76	10	1.9	1.8	78	2.48	79.8	4.0
80	8	102	13	2.4	2.4	102	2.66	104.4	4.7
120	12	130	19	3.5	3.6	154	3.05	157.6	6.1

Another application for LRMLI would be to insulate the fuel tanks for liquid hydrogen fueled aircraft. Two to three layers of LRMLI would provide an equivalent thermal performance to 0.08 - 0.18 meter (3 - 7 inches) thick SOFI at a weight savings about 3 times for low altitude operation. At high altitude and low atmospheric pressure, a single layer of LRMLI will be the equivalent of 0.030m (11.8”) of SOFI, at a mass savings of over six times.

LRMLI Testing

Structural testing has been performed and demonstrated that the small, lightweight (30milligram) spacer fabricated for LRMLI is capable of supporting in excess of 93.4 Newton (21 pounds) force. The spacer has also been tested to demonstrate elastic yield under the controlled displacement design to allow it to rebound when absent of atmospheric pressures as on orbit. Dynamic spacers fabricated into multiple layer columns supported over 80.0 Newton (18 pounds) per column, more than the 65.4 Newton (14.7 pounds) required to fully support a thin, flexible vacuum shell at one atmosphere external load with a 0.025m (1”) spacing.

CONCLUSIONS

We have developed Integrated Multilayer Insulation which is a significant advancement over conventional MLI. IMLI has considerable advantages over conventional MLI in thermal performance, number of layers/thickness/mass required for a given heat leak, robustness, predictability of performance, low contamination and electrical grounding. IMLI requires 30% fewer layers than MLI, will allow thinner and lighter insulation blankets, and with automated assembly will have substantially lower assembly costs in insulating cryogenic systems and spacecraft.

We have also developed a Load Responsive Multilayer Insulation, which has a novel dynamic response to external atmospheric pressure loading that allows it to provide high thermal performance in-atmosphere and ultra-high performance on-orbit (in a vacuum). LRMLI is a significant advancement over SOFI for cryogenic insulation in one atmosphere and on-orbit, providing much thinner and lighter insulation.

FUTURE WORK

In the near future, IMLI will be used to insulate a 500 liter cylindrical test tank which will then be placed in a vacuum chamber and pumped to high vacuum. The tank will be filled with liquid nitrogen, and the boil off rate under steady state conditions will be measured. The results will be compared to boil-off measurements made with the tank insulated with conventional MLI.

LRMLI will be applied to a 25 liter cylindrical test tank and enclosed in a thin vacuum shell. The vacuum shell will be evacuated and liquid nitrogen boil-off tests performed, with both in-atmosphere and on-orbit thermal conductances measured.

IMLI and LRMLI development will continue to mature these new technologies into commercially available insulation systems for NASA and non-NASA applications.

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