Integrated and Load Responsive Multilayer Insulation

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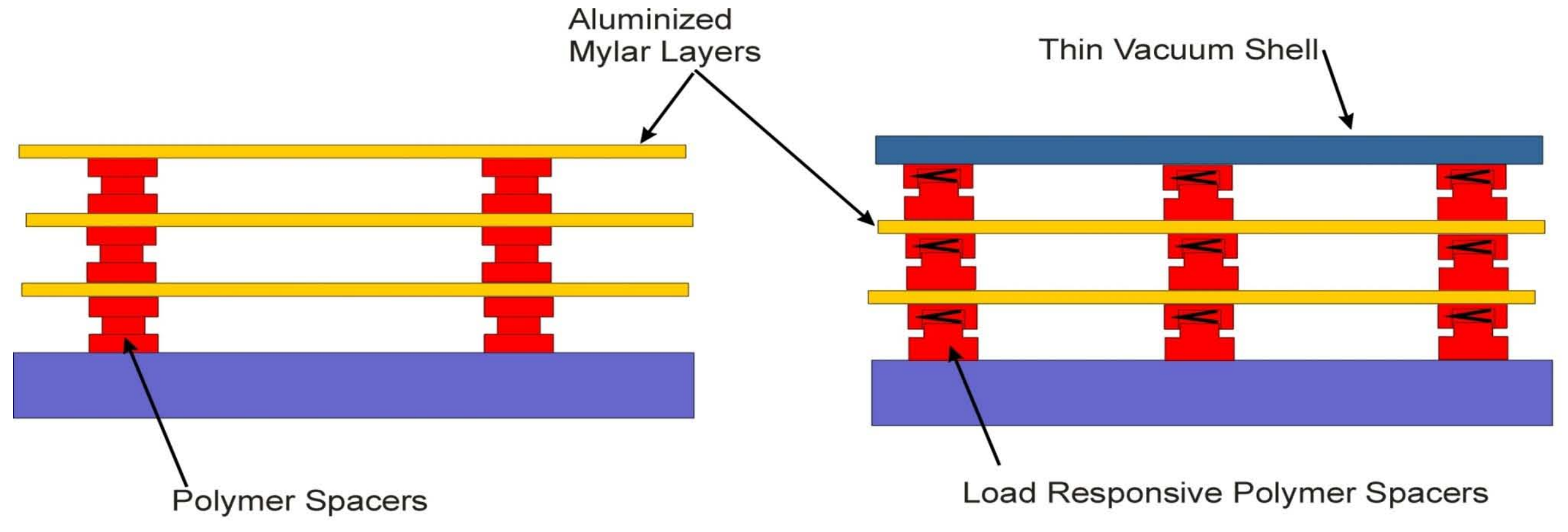
Introduction

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.

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. 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 new technologies with support from NASA via SBIR contracts. Patent applications have been filed for various aspects of IMLI and LRMLI

Integrated Multi-Layer Insulation 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 for high thermal insulation performance. The polymer spacer uses unique fabrication in order to have an low cross-section area to length ratio to reduce heat leak. Integrated MLI has been designed, modeled, prototyped and tested showing a heat leak lower than conventional MLI. IMLI is designed as a conventional MLI replacement, and requires a vacuum to provide good thermal insulation.

A second innovative thermal insulation, Load Responsive MLI, 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. LRMLI has been thermally and structurally modeled and is in prototype fabrication and test.

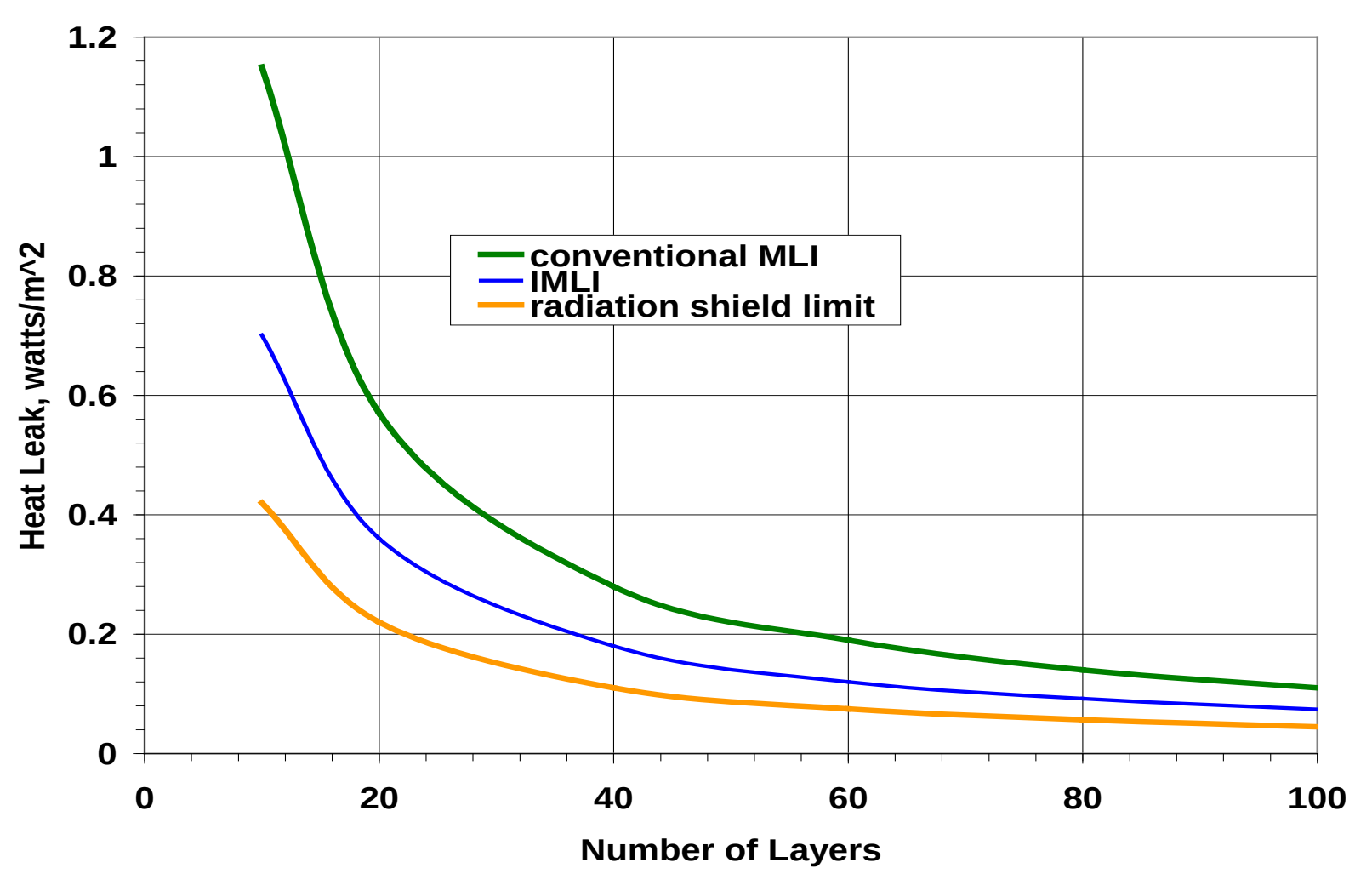


Integrated MLI **Load Responsive MLI**

IMLI Estimated & Tested Performance

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. 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. The results are shown in the figure (below) for IMLI, conventional MLI and parallel layers with no solid conduction for 295K hot side and 77K (liquid nitrogen) cold side. The calculated conductance of IMLI is 65% that of conventional MLI and is closer to the radiation limit.

IMLI thermal performance was measured using LN_2 calorimetry (images above right and below of rectangular and cylindrical test installations). Design, build and test prototype cycles have improved the performance to a current 1.06 W/m^2 (e* = 0.0025) for a 10-layer blanket (1.8cm thick, 294K hot, 77K cold, 0.5m^2 area). See the table to the right. IMLI 10-layer blankets on the rectangular fixture have demonstrated 37% higher performance than 10-layer blankets of conventional MLI.



IMLI Advantages over MLI

IMLI is an engineered thermal insulation system that can be optimized for desired characteristics such as:

- Higher performance; modeled 40-layer blanket would have conductance of 0.16 W/m^2, 60% that of MLI per layer
- More predictable performance; layer density is precisely controlled
- More robust; IMLI spacers and layers are bonded together in a structually robust blanket
- Lower particulate contamination; IMLI has no netting, polymer spacers have no particulates and are low out-gassing
- Optional electrical conductivity; metalized spacers have been tested and could provide a blanket completely electrically conductive
- Lower installed cost; semi-automated assembly procedures have been developed, with a path to automated assembly, and fewer IMLI layers are required for a given heat leak
- In-atmosphere high performance; available from LRMLI with thin vacuum shell, no purge gas may be needed and lower overall heat gain from pre-launch

Rectangular LN_2 tank insulated with IMLI blanket, used for boil-off calorimetry to measure thermal conductance of IMLI.

IMLI Thermal Conductance Test Results		
Conventional MLI (corrected for layer overlap)	1.74 W/m^2	0.00412 e*
Test0 (Phase I design)	**1.93 W/m^2**	**0.00458 e***
Test1 (Phase II spacer)	1.65	0.00391
Test2 (improved seams)	1.38	0.00327
Test2B (retest)	1.36	0.00322
Test3 (0.25mil mylar)	1.35	0.00320
Test4 (increased spacing)	1.24	0.00295
Test5 (metalized spacers)	1.22	0.00290
Test 6 (cylindrical blanket)	0.95	0.00225

Note: e* for a 10-layer blanket, T_{hot} = 294K, T_{cold} = 77K, area 0.54m^2.

Table 1: Insulation Performance for 20 K hot side and 295 K cold 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	0.23	9.83	6.58	1.75	3.00	2.42
2	38	0.42	19.48	13.02	1.94	5.92	4.80
3	26	0.61	29.08	19.44	2.12	8.84	7.16
4	19	0.81	38.68	25.85	2.31	11.755	9.52

Table 2: Insulation Performance for 20 K hot side and 295 K cold 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

Table 3: Thickness and mass needed to keep purged surface temp. above 85 K with 295 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 System Mass kg/m^2	LRMLI-MLI System 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

Table 4: Thickness and mass needed to keep purged surface temp. above 255 K with 295 air temperature (dry air 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 System Mass kg/m^2	LRMLI-MLI System 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

Cylindrical LN_2 tank insulated with cylindrical IMLI blanket.

NASA applications

- Cryopropellant thermal insulation for NASA Exploration vehicles
- Launch vehicle structural/thermal system
- Satellite bus thermal insulation
- Space cryo instrument thermal insulation
- Micrometeorite & Orbital Debris protection for spacecraft

Non-NASA applications

- Insulate liquid H_2 fuel tanks for aircraft
- Cryogenic dewars for research, medical & industrial uses
- Insulated and refrigerated shipping & storage containers
- Refrigerator-freezers & water heaters
- Applications requiring high performance thermal insulation
- Insulating superconducting devices such as MRI
- Building insulation panels

Load Responsive MLI

Load Responsive MLI (LRMLI) 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 SOFI or MLI in-atmosphere, reduced 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.

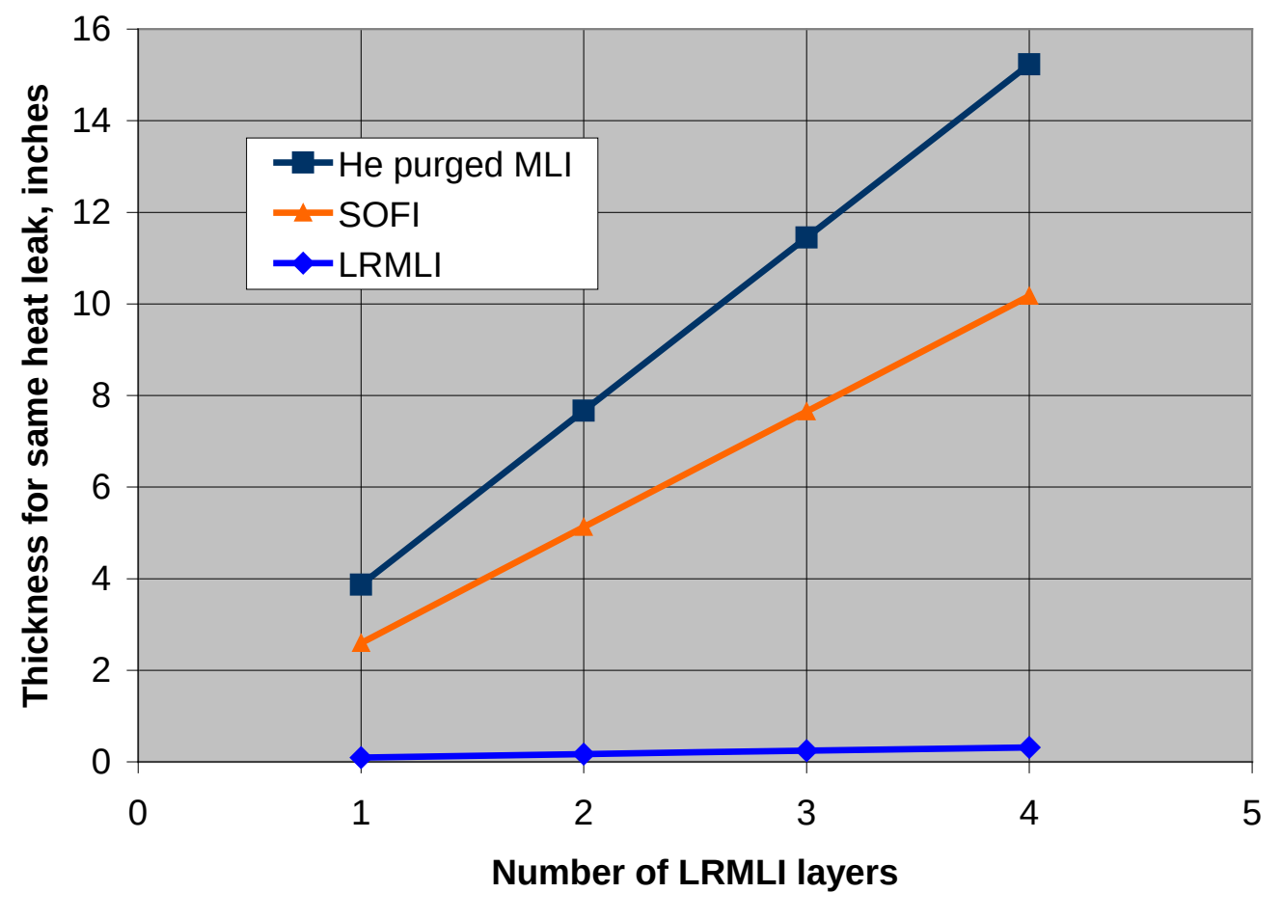
With tightly controlled layer spacing and consistency of materials LRMLI will have a much more predictable performance than SOFI. SOFI is very density and application dependent and the density can vary as much as 25%. Having dynamic load responsive capabilities, LRMLI offers a much higher performance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

LRMLI Estimated Performance & Comparison to SOFI

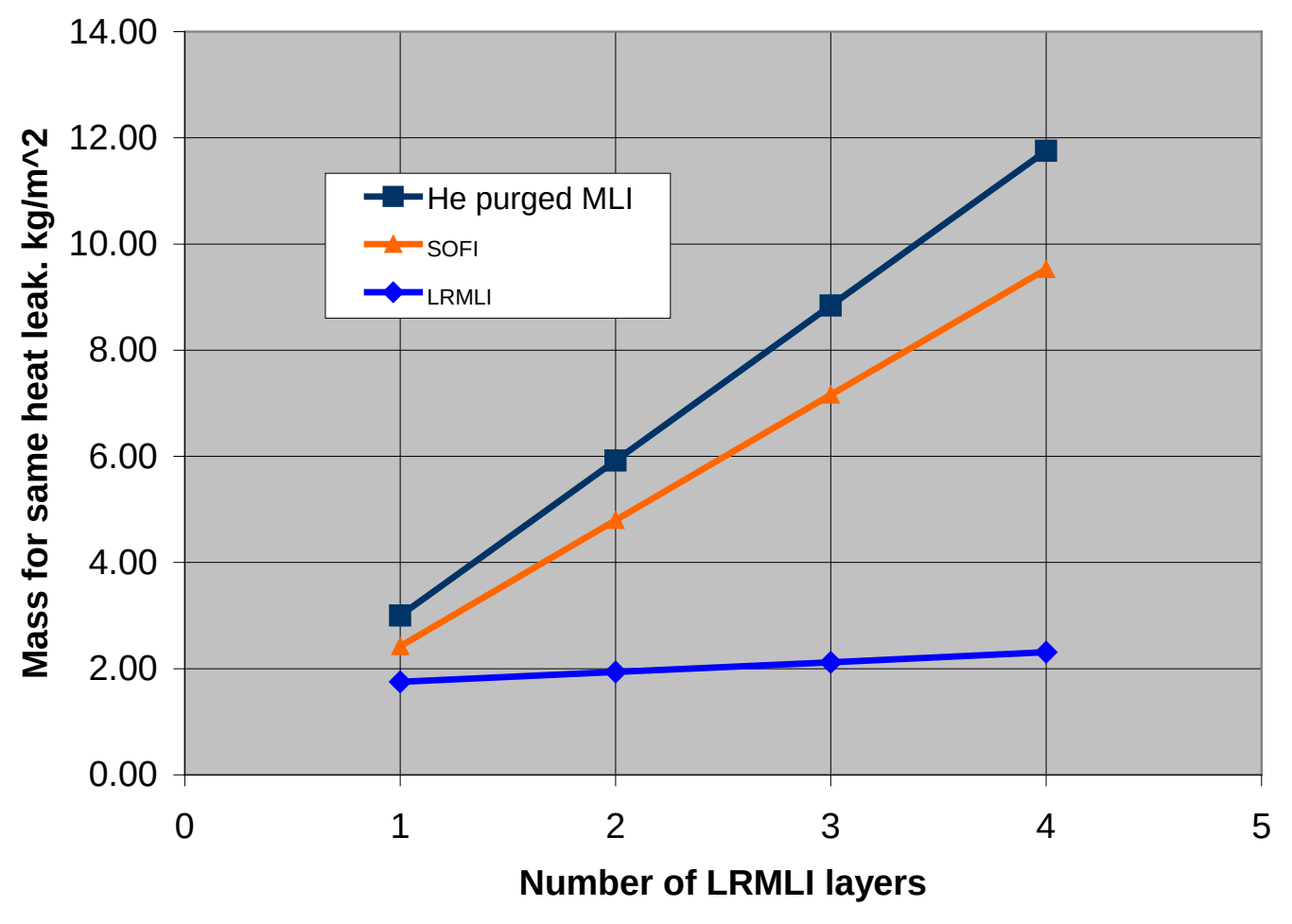
LRMLI performance has been modeled, and the change of the conductive area/length from the loaded condition (external loading of atmospheric pressure) to the unloaded condition (in vacuum) simulated. The thickness and mass of SOFI and conventional MLI (with He purge) with the same heat leak was calculated.

On a thickness basis, LRMLI with thin vacuum shell is 30X better performance than SOFI in atmosphere, and nearly 130X better on orbit. On a mass basis, LRMLI is 3.4X better performance than SOFI in atmosphere and 14X better on orbit. See the graphs below and tables (left) for more comparisons. Four layers of LRMLI, with a thickness of 0.32" (0.82cm), has the same heat leak as 10.2" (25.9cm) of SOFI for pre-launch ground hold use. On orbit equal performance to four layers (0.32") of LRMLI (2.31 kg/m^2) would require 42.2" SOFI (39.5 kg/m^2). See Tables 1 & 2.

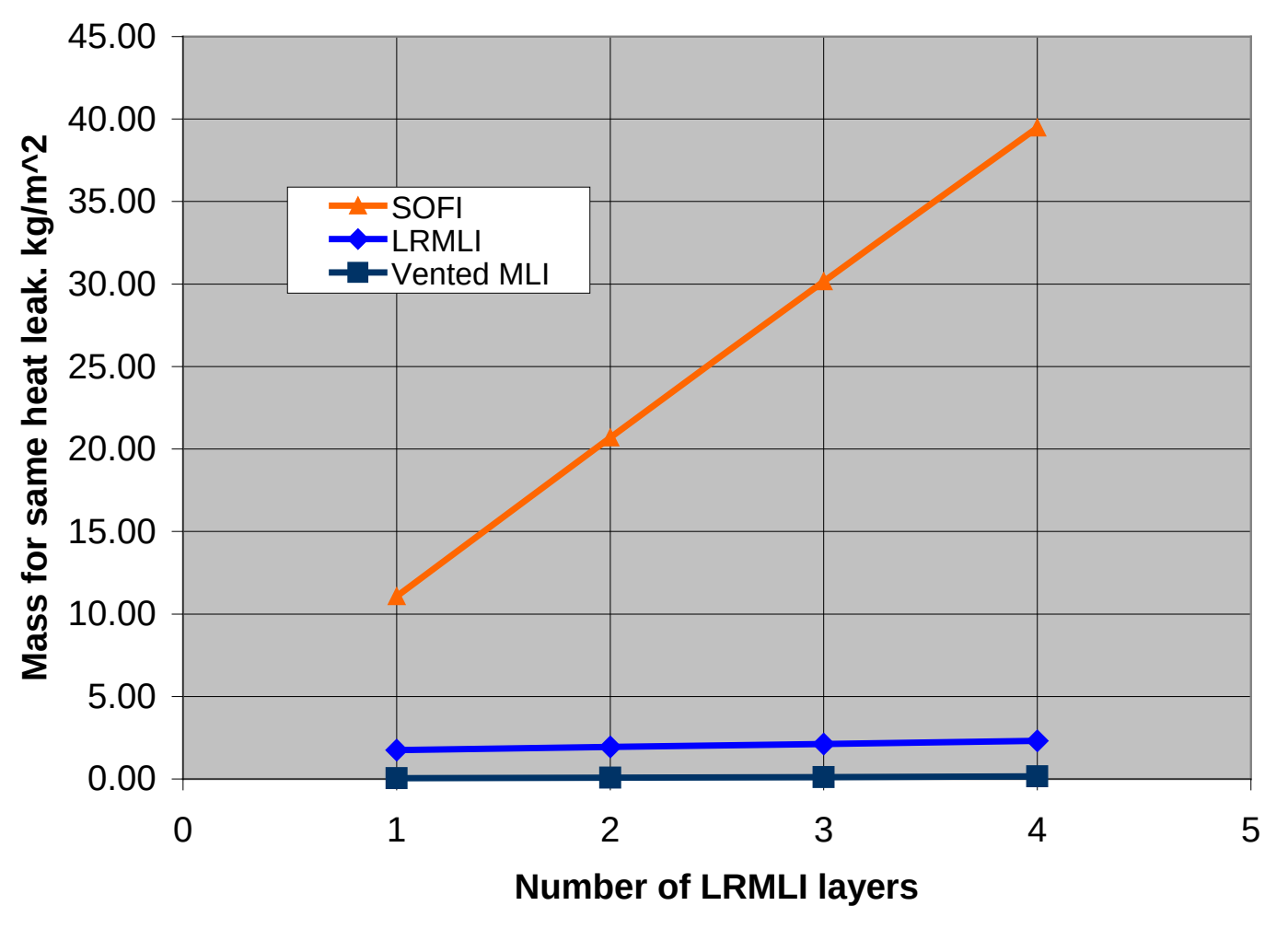
Comparison of LRMLI to Other Insulations 1 atm, LH2 Tank Application



Comparison of LRMLI to Other Insulations at 1 atm, LH2 tank Application



Comparison of LRMLI to other Insulations on-orbit, LH2 Tank Application



LRMLI Applications

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, 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. 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 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 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. Tables 3 & 4 show thicknesses of LRMLI & SOFI needed to keep the outer surface above 77K.

Another application for LRMLI would be to insulate the fuel tanks for liquid hydrogen fueled aircraft. A thickness of 2 to 3 layers of LRMLI would provide an equivalent thermal performance to SOFI 0.08 to 0.18 meter (3 to 7 inches) thick at a weight savings of 2.5 to 3.5 times for low altitude operation. At high altitude and low atmospheric pressure, a single layer of LRMLI will be the equivalent of 0.030 meter (11.8 inches) of SOFI, at a mass savings of over 6 times.

Conclusions

Quest and Ball have developed a new Integrated MultiLayer Insulation technology, which is a significant advancement over conventional MLI. IMLI has significant advantages over conventional MLI in thermal performance, number of layers/thickness/mass required for a given heat leak, robustness, predictability of performance, low contamination, electrical grounding and assembly cost in insulating cryogenic systems and spacecraft.

We have also developed a Load Responsive MultiLayer Insulation, which has a novel dynamic response to loading that allows it to provide high thermal performance in-atmosphere and ultra-high performance on-orbit. LRMLI is a significant advancement over SOFI for cryogenic insulation in one atmosphere and on-orbit.

Insulation System Comparisons

SOFI: Spray on Foam Insulation
LRMLI: Load Responsive Multilayer Insulation
IMLI: Integrated Multilayer Insulation
LDMLI: Ball Low Density MLI