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Novel load responsive multilayer insulation with high in-atmosphere and on-orbit thermal performance

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ABSTRACT

Aerospace cryogenic systems require lightweight, high performance thermal insulation to preserve cryopropellants both pre-launch and on-orbit. Current technologies have difficulty meeting all requirements, and advances in insulation would benefit cryogenic upper stage launch vehicles, LH_2 fueled aircraft and ground vehicles, and provide capabilities for sub-cooled cryogens for space-borne instruments and orbital fuel depots. This paper reports the further development of load responsive multilayer insulation (LRMLI) that has a lightweight integrated vacuum shell and provides high thermal performance both in-air and on-orbit.

LRMLI is being developed by Quest Product Development and Ball Aerospace under NASA contract, with prototypes designed, built, installed and successfully tested. A 3-layer LRMLI blanket (0.63 cm thick, 77 K cold, 295 K hot) had a measured heat leak of 6.6 W/m^2 in vacuum and 40.6 W/m^2 in air at one atmosphere. In-air LRMLI has an 18× advantage over Spray On Foam Insulation (SOFI) in heat leak per thickness and a 16× advantage over aerogel. On-orbit LRMLI has a 78× lower heat leak than SOFI per thickness and 6× lower heat leak than aerogel.

The Phase II development of LRMLI is reported with a modular, flexible, thin vacuum shell and improved on-orbit performance. Structural and thermal analysis and testing results are presented. LRMLI mass and thermal performance is compared to SOFI, aerogel and MLI over SOFI.

1. Introduction

Lightweight, high performance thermal insulation is critical to NASA's next generation spacecraft and missions – which will increasingly use cryogenic propellants. Zero or low cryogenic propellant boiloff is required during extended missions and lengthy on-orbit times. Heat flow through multilayer insulation is usually the largest heat leak in cryogenic systems, so improved insulation is desirable. Insulation meeting requirements for low heat leak, low mass, no cryopumping and robustness is especially challenging when the system must operate both within the atmosphere and on orbit.

Multilayer insulation (MLI) in a vacuum can usually provide the thermal performance required but requires a prohibitively heavy vacuum shell for use in air. 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 higher thermal conductivity than MLI and has a lack of robustness.

Quest Product Development Corp., working with Ball Aerospace, has developed a next generation MLI product called "Integrated MLI" (IMLI) [1]. IMLI uses discrete ultra-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. IMLI prototypes produced for NASA and independently tested by NASA's Cryogenics Test Laboratory show a measured heat leak of 0.41 W/m^2 (20 layers, 3.7 cm, 78–292 K, 1.2×10^{-6} torr) [2], about 37% lower heat leak per layer than typical conventional netting-based MLI. Load Responsive Multi-Layer Insulation (LRMLI) is based on IMLI discrete spacer technology.

LRMLI is an innovative new technology 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.

Abbreviations: MLI, multilayer insulation; LRMLI, load responsive multilayer insulation; IMLI, integrated multilayer insulation; SOFI, Spray On Foam Insulation; atm, atmosphere (pressure).

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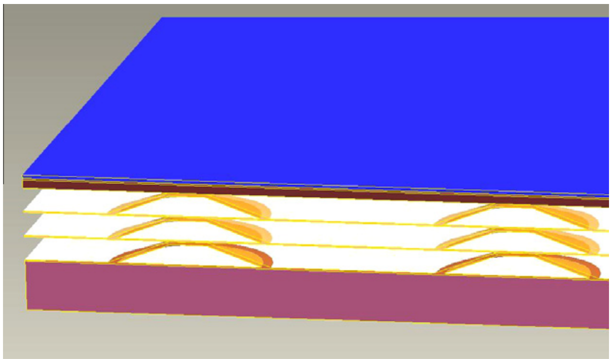

Fig. 1. LRMLI and integrated vacuum shell concept.

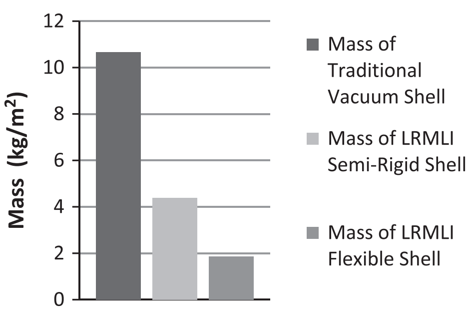

Fig. 2. Vacuum shell mass comparisons.

LRMLI consists of layers of metalized polymer thermal radiation shields that are separated and supported by proprietary micro-molded 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, 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 NASA applications include:

- Cryopropellant thermal insulation for launch vehicles, commercial crew vehicles and orbital fuel depots.
- Replacement for SOFI insulation.
- Space cryogenic instrument thermal insulation.

Possible Non-NASA applications include:

- Liquid hydrogen fueled aircraft fuel tank insulation.
- Terrestrial applications requiring high performance thermal insulation.

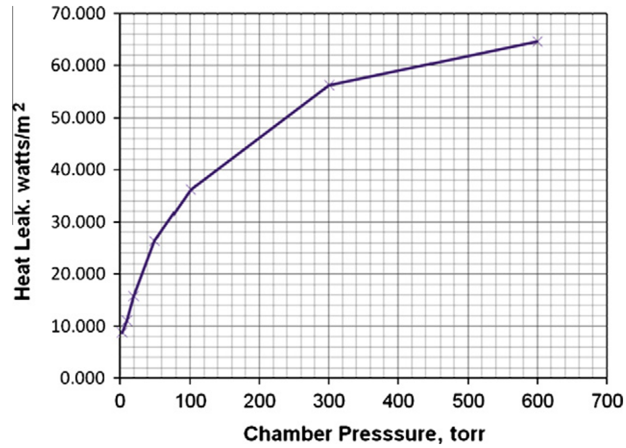

Fig. 3. LRMLI heat leak from 295 °K to 77 °K as a function of external atmospheric pressures.

- Cryogenic dewar insulation for research, medical and industrial uses.
- Appliances including refrigerators, freezers and water heaters.
- Liquid hydrogen fueled ground vehicles.
- Insulating superconducting devices such as MRI and superconducting power systems.
- Insulated and refrigerated shipping and storage containers.
- Thin insulation panels for high efficiency buildings.

2. Results and discussion

2.1. Phase I work

LRMLI development was performed under a NASA Phase I 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 20 L test tank. The vacuum shell was a thin semi-rigid shell supported by the LRMLI blanket. The mass of the shell was approximately 4.4 kg/m^2. Thermal performance was measured via LN_2 boil-off calorimetry. LRMLI exhibited good performance with a 3-layer, 0.63 cm thick blanket having a measured heat leak of 7.1 W/m^2 (0.19 mW/m K) for in vacuum operation and 14.3 W/m^2 (0.34 mW/m K) for one atmosphere operation. Predicted performance for a three layer LRMLI system was 6.9 W/m^2 for in vacuum operation and 31 W/m^2 at one atmosphere, using a thermal model created by Quest and Ball that calculates solid conducted heat and radiated heat in a layer by layer model. Modeling allows heat leak prediction, and comparison to actual measured values then allows determination of the accuracy of the model and its usefulness in designing new insulation systems. The Phase I prototype in-vacuum heat leak matched predictions reasonably well, but the in-air "loaded condition" heat leak measured was less than predicted. The Phase I vacuum shell supporting flanges were very stiff and may have kept the LRMLI dynamic posts from fully compressing (see Phase II work below). LRMLI was successfully proven feasible in Phase I work, thereby reaching Technology Readiness Level (TRL) 4, component validation in the laboratory.

2.2. Phase II work

A NASA Phase II contract is in progress to advance system design, build and test larger scale prototypes, and progress the technology to TRL5 (component validation in a relevant environment). The LRMLI Phase II program has already identified primary applications,

Table 1
Insulation performance in-air with one atmosphere pressure (pre-launch environment) (77 °K cold, 295 °K hot).

In-atmosphere thermal performance							
LRMLI Layers	LRMLI Heat Leak (W/m^2)	LRMLI Thickness (cm)	SOFI Same Heat Leak Thickness (cm)	Aerogel Same Heat Leak Thickness (cm)	LRMLI Mass (kg/m^2)	SOFI Same Heat Leak Mass (kg/m^2)	Aerogel Same Heat Leak Mass (kg/m^2)
3	41 (measured)	0.63	11.3	10.1	2.44	4.7	12.6
4	31 (estimated)	0.82	14.8	13.4	2.63	6.2	16.7
5	25 (estimated)	1	18.4	16.6	2.82	7.7	20.7

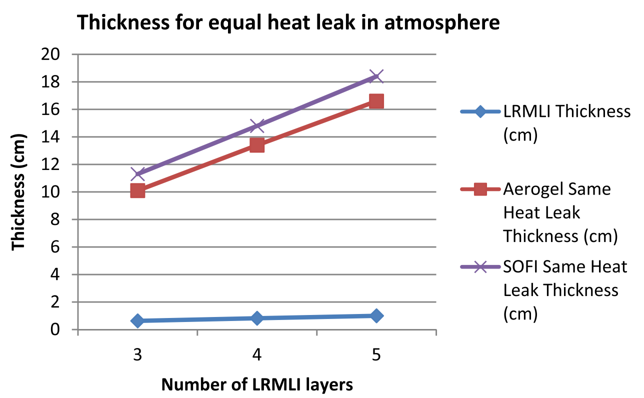

Fig. 4. Insulation thickness required for equal heat leak to 3, 4 and 5-layer LRMLI.

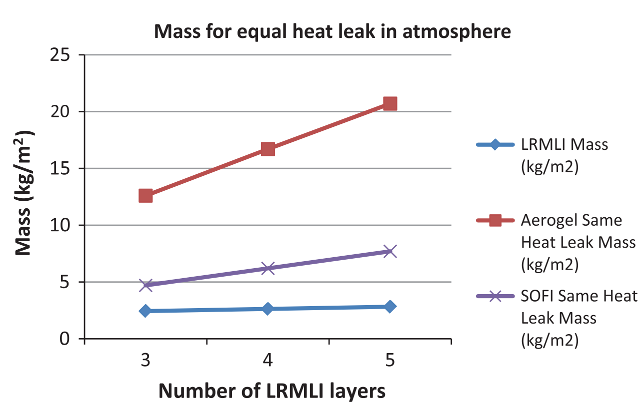

Fig. 5. Insulation mass required for equal heat leak to 3, 4 and 5-layer LRMLI.

optimized dynamic post design, designed modular vacuum shells for ease of application, built and tested small scale LRMLI prototypes. Tasks underway are to evaluate mixed LRMLI/Integrated MLI insulation systems, and insulate and measure LRMLI performance in the relevant environment of mid-scale cryotanks.

The dynamic beam post spacer is a key component of LRMLI and has been redesigned to provide higher structural strength and a higher safety margin, and more easily micromolded in the preferred low conductivity, low outgassing polymer material. A trade study of strength, moldability and heat leak through the part was completed, and indicates that larger cross-sections and center beam supports would be acceptable with a change in polymer (to a lower conductivity material).

A 2nd generation Tripod Post was designed, heat flow through the part analyzed, structural strength analyzed via FEA, and should achieve the desired safety margin under external atmospheric loading with lower conducted heat leak. The latest design dynamic post (with a mass of 32 mg) can support over 29 lb for a safety margin of 2 with external 1 atm loading. Posts can support this force, and still dynamically rebound in the absence of compressive loading to reduce thermal conduction. Thermal solid conductance through the spacer decreases six fold after disconnect and rebound.

A second major focus of Phase II work is 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 would allow less expensive application to varying tank geometries. Design of a thin, flexible vacuum shell has been 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.

An image of the LRMLI concept as applied to a cryogenic tank is shown in Fig. 1. The spacers are bonded to each Mylar layer and are aligned to transmit the load from the vacuum shell to the tank wall.

The LRMLI thin wall self-supported vacuum shell offers significant mass advantages over vacuum shells required for conventional MLI (see Fig. 2). 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 1.9 kg/m^2 (17% the mass of a traditional shell). This mass savings is due to the strength of the LRMLI dynamic spacer. The new design is modular for application across a broader range of tank sizes and geometries, based on a thin vacuum shell supported by the LRMLI spacers which support a hermetic outer layer.

Phase II testing has shown results of 6.6 W/m^2 in vacuum and 41 W/m^2 at one atmosphere (0.63 cm, 77 K, 295 K). The on-orbit performance of the LRMLI system has a slightly lower heat leak than predicted from our thermal model, while the one atm heat leak is substantially higher than modeled. The high one atm heat leak has been determined to be due to collapse of the first generation LRMLI post after repeated cycles with extended duration under atmospheric loading. It is believed the in-atmosphere performance will be improved with the stronger, 2nd generation spacer posts that can withstand 1 atm loading and provide reduced heat leak via solid conduction through the dynamic beam. Phase II LRMLI in-air performance was improved from 65 W/m^2 to 41 W/m^2 with better sealing of the outer hermetic layer.

LRMLI thermal performance 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 and rebound causes a decrease. See in Fig. 3 the steep slope of heat

Table 2
Insulation performance in vacuum (77 K cold, 295 K hot).

In vacuum thermal performance							
LRMLI Layers	LRMLI Heat Leak (W/m^2)	LRMLI Thickness (cm)	SOFI Same Heat Leak Thickness (cm)	Aerogel Same Heat Leak Thickness (cm)	LRMLI Mass (kg/m^2)	SOFI Same Heat Leak Mass (kg/m^2)	Aerogel Same Heat Leak Mass (kg/m^2)
3	6.6 (measured)	0.63	49.2	4	2.44	20.7	5
4	5.0 (estimated)	0.82	65.6	5.3	2.63	27.5	6.6
5	4.0 (estimated)	1	82	6.6	2.82	34.4	8.3

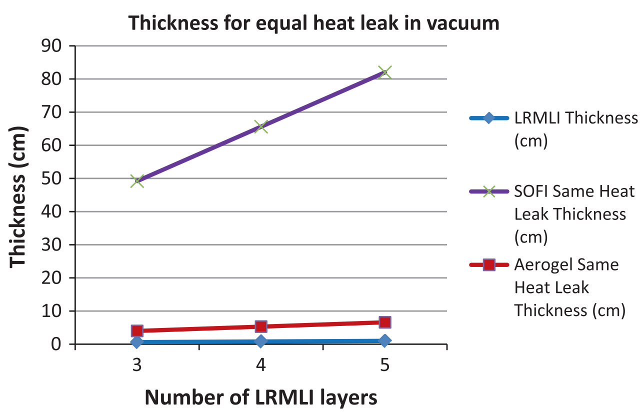

Fig. 6. Insulation thickness required for equal heat leak to 3, 4 and 5-layer LRMLI.

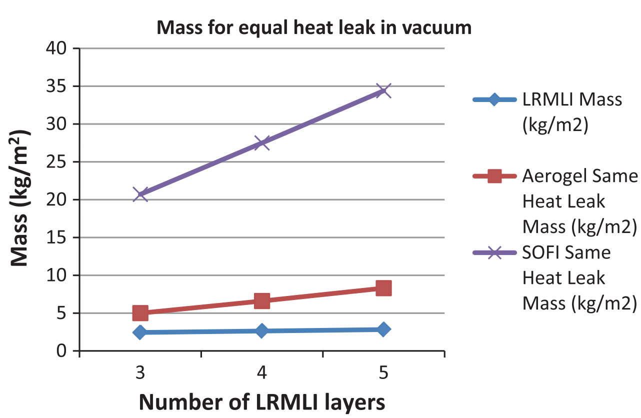

Fig. 7. Insulation mass required for equal heat leak to 3, 4 and 5-layer LRMLI.

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 corresponds to an external load of 52 torr. Note that IMLI (and conventional MLI) has an approximately 470-fold increase in heat leak between high vacuum and one atmosphere, but LRMLI shows only a sixfold increase in heat leak.

3. LRMLI performance comparisons

3.1. Thermal performance, mass and thickness comparisons between LRMLI, SOFI and aerogel

In a comparison of LRMLI to SOFI and aerogel, LRMLI shows significant advantages [3,4]. The three types of insulation were compared on a thickness and mass basis. Table 1 compares the in-atmosphere thermal performance of LRMLI, SOFI and aerogel, Fig. 4 compares the insulation thickness required for equal heat leak through LRMLI, SOFI and aerogel, and Fig. 5 compares the mass for equal heat leak through each insulation.

Table 2 compares the in-vacuum (on-orbit) thermal performance of LRMLI, SOFI and aerogel, Fig. 6 compares the insulation thickness required for equal heat leak through LRMLI, SOFI and aerogel, and Fig. 7 compares the mass for equal heat leak through each insulation.

3.2. LRMLI compared to SOFI

LRMLI Advantages over SOFI

- To achieve equal heat leak in vacuum of a 3-layer LRMLI blanket (0.63 cm thick, 2.44 kg/m^2) would require 49.2 cm of SOFI at 20.7 kg/m^2.
- LRMLI has 78× lower heat leak per thickness than SOFI and a 8× mass advantage for on-orbit operation.
- To achieve equal heat leak in-air of a 3-layer LRMLI blanket (0.63 cm thick, 2.44 kg/m^2) would require 11.3 cm of SOFI at 4.7 kg/m^2.
- LRMLI has 18× lower heat leak per thickness than SOFI and a 2× mass advantage for one atm operation.
- LRMLI has inherent construction benefits with controlled layer spacing, can provide reliability and robustness, and provides excellent thermal performance both in-atmosphere and on-orbit.
- Robust LRMLI can replace SOFI, which has significant problems and a lack of robustness with cracking and cryopumping.

3.3. LRMLI compared to aerogel

Aerogels have an apparent thermal conductivity of 1.2 mW/m K at high vacuum, and 19 mW/m K at 1 atm, 77–295 °K (Ref. [3]). Phase II LRMLI prototypes currently have thermal conductivities of 0.19 mW/m K in vacuum and 1.17 mW/m K at one atm.

A 3-layer LRMLI blanket has sixfold better in high vacuum (on-orbit) and 16-fold better thermal performance at one atmosphere than aerogel of equal thickness.

- To achieve equal heat leak on-orbit of a 3-layer LRMLI blanket (0.63 cm thick, 2.44 kg/m^2) would require 4.0 cm of aerogel blanket at 5.0 kg/m^2.
- On-orbit LRMLI has 6× lower heat leak per thickness than aerogel, and 2× lower mass than equal heat leak aerogel blanket.
- To achieve equal heat leak in-air of a 3-layer LRMLI blanket (0.63 cm thick, 2.44 kg/m^2) would require 10.1 cm of aerogel at 12.6 kg/m^2.
- In-air (one atm) LRMLI has 16× lower heat leak per thickness than aerogel and a 5× mass advantage.
- LRMLI provides substantially better thermal performance in-air than aerogel blankets on both a thickness and mass basis.

3.4. LRMLI and IMLI compared to conventional MLI and MLI/SOFI

LRMLI with integrated vacuum shell for performance in-air is difficult to compare to conventional MLI without the mass penalty of a vacuum shell. IMLI can be more directly compared to conventional MLI and MLI over SOFI.

A comparison data point is Variable Density MLI over SOFI (Martin and Hastings), in which a 45-layer netting-based MLI blanket covered a 3.5 cm SOFI layer. This insulation weighed 2.16 kg/m^2 and had an in-air heat leak of 62 W/m^2 and in-vacuum heat leak of 0.31 W/m^2. A 45-layer IMLI blanket would weigh 0.69 kg/m^2 and has a predicted heat leak in-vacuum of 0.18 W/m^2 (based on 10- and 20-layer blanket data). A three-layer LRMLI blanket, designed to give sufficient insulation to prevent cryopumping in air, and ideally covered with an IMLI blanket for on-orbit use, has a mass of 2.44 kg/m^2 and an in-air heat leak of 41 W/m^2. An LRMLI/IMLI system is currently being built, and would be a good comparison to MLI/SOFI.

Comparisons between IMLI and state of the art low density netting MLI indicate IMLI has 28% less heat leak per layer (based on measurements made on the KSC Cryostat-100 and on a 500 L cryotank at Ball Aerospace).

One figure of merit for insulation systems, suggested by Martin and Hastings, is $Q_{heatleak} * mass$. The Variable Density MLI system's actual $Q * m$ is 0.67 W kg/m^4. Conventional netting MLI has a $Q * m$ of 0.36, and IMLI has a $Q * m$ of 0.13 W kg/m^4. This figure of merit for LRMLI/IMLI will be measured in upcoming Phase II work.

4. 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.

Continuing R&D includes building and testing mixed LRMLI/IMLI insulation systems, and designing, fabricating, installing and testing an LRMLI system on a larger 400 L cylindrical with spherical ends cryotank. Goals are to continue to reduce overall system mass, increase structural integrity, reduce manufacturing and installation cost, and provide a versatile insulation system suitable for various tank geometries.

LRMLI is proving to be a new innovative product for both aerospace and commercial applications.

An excellent non-NASA aerospace application has already been selected, that of cryotanks for LH_2 powered aircraft, as operational requirements cannot be met by SOFI and can be readily met by LRMLI. First prototypes of such aircraft are currently being built. The best application for NASA application is under study, including launch vehicle cryogenic upper stages and cryogenic fueled landers, and requires consideration of NASA's mission and direction. LRMLI may provide extremely high performance thermal insulation for a variety of terrestrial applications, such as cryogenic dewars, refrigerator-freezers and water heaters.

Note added in proof

New spacers corrected the structural failure noted in this paper, LRMLI with new spacers has a measured heat flux of 5.75W/m^2 in-vacuum and 30.4W/m^2 in-air (0.63cm, 77K, 295K).

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