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Design, fabrication and test of Load Bearing multilayer insulation to support a broad area cooled shield

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ABSTRACT

Improvements in cryogenic propellant storage are needed to achieve reduced or Zero Boil Off of cryopropellants, critical for long duration missions. Techniques for reducing heat leak into cryotanks include using passive multi-layer insulation (MLI) and vapor cooled or actively cooled thermal shields. Large scale shields cannot be supported by tank structural supports without heat leak through the supports. Traditional MLI also cannot support shield structural loads, and separate shield support mechanisms add significant heat leak. Quest Thermal Group and Ball Aerospace, with NASA SBIR support, have developed a novel Load Bearing multi-layer insulation (LBMLI) capable of self-supporting thermal shields and providing high thermal performance.

We report on the development of LBMLI, including design, modeling and analysis, structural testing via vibe and acoustic loading, calorimeter thermal testing, and Reduced Boil-Off (RBO) testing on NASA large scale cryotanks.

LBMLI uses the strength of discrete polymer spacers to control interlayer spacing and support the external load of an actively cooled shield and external MLI. Structural testing at NASA Marshall was performed to beyond maximum launch profiles without failure. LBMLI coupons were thermally tested on calorimeters, with superior performance to traditional MLI on a per layer basis. Thermal and structural tests were performed with LBMLI supporting an actively cooled shield, and comparisons are made to the performance of traditional MLI and thermal shield supports. LBMLI provided a 51% reduction in heat leak per layer over a previously tested traditional MLI with tank standoffs, a 38% reduction in mass, and was advanced to TRL5. Active thermal control using LBMLI and a broad area cooled shield offers significant advantages in total system heat flux, mass and structural robustness for future Reduced Boil-Off and Zero Boil-Off cryogenic missions with durations over a few weeks.

1. Introduction

Cryogenic propellants are important to NASA future architectures, and improvements in cryogenic propellant storage and transfer are critical to long duration NASA spacecraft and missions. High performance active and passive thermal insulation is needed for next generation spacecraft, where Reduced Boil-Off (RBO) or Zero Boil-Off (ZBO) will be required during extended missions and lengthy on-orbit times. The NASA Propulsion Systems Technology Roadmap calls “Zero Boil Off storage of cryogenic propellants for long duration missions” the #2 ranked technical challenge for NASA mission objectives and needs [1]. Improved active thermal control of cryogenic systems was also identified by the National Research Council as one of the highest priority technologies needed [2]. Innovations in low temperature cryocoolers, integration with propellant tanks, and low conductivity structures and supports will be required to minimize heat leaks and active cooling power and mass. A recent NASA program, funded by the Cryogenic Propellant Storage and Transfer program and the NASA Space

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Abbreviations: LBMLI, Load Bearing multilayer insulation; IMLI, integrated multilayer insulation; LRMLI, Load Responsive multilayer insulation; MLI, multilayer insulation; BAC, broad area cooled shield; TRL, technology readiness level; FEA, finite element analysis; DAM, dual aluminized mylar; RBO, Reduced Boil-Off; ZBO, Zero Boil-Off; MMOD, micrometeoroid/orbital debris; SOFI, spray on foam insulation; CBRS, cryogenic boil-off reduction system; VATA, Vibro Acoustic Test Article.

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Technology Mission Directorate's Game Changing Development program, has focused on technology maturation for RBO of liquid hydrogen, combining new technologies in advanced passive insulation to work efficiently with actively cooled thermal shields [3]. This development in insulation involved Load Bearing MLI (LBMLI), a structural MLI technology that uses robust discrete spacers between radiation barriers to provide high performance thermal insulation and self-support large Broad Area Cooling (BAC) shields.

Novel high performance discrete spacer MLI development by Quest Thermal Group and Ball Aerospace began with *Integrated MultiLayer Insulation* (*IMLI*), which has lower heat flux per layer than traditional MLI. IMLI uses proprietary discrete spacer technology to reduce heat leak through the insulation, with the spacers and radiation barriers bonded together into a strong, robust structure [4]. Quest's Load Responsive MLI (LRMLI) uses a dynamic spacer able to support up to 90 lb-force per square inch, and disconnects under no load for lower heat leak. LRMLI's unique structure is able to support a thin, lightweight vacuum shell for in-air operation, high strength ballistic layers for MMOD shielding, or an external Broad Area Cooling Shield. Load Bearing MLI uses the structural strength of the discrete spacer to self support the mass of a thermal shield with tube-on-shield cooling loop attached to a cryocooler.

Vapor cooled shields have been used in dewars for a long time, where boil off gas is routed through a thermal shield to intercept large portions of heat flow into the cryogenic tank. More recently, actively cooled systems use cryocoolers and circulate cooled gas through a broad area cooled shield. Supporting large thermal shields is problematic for traditional MLI, composed of loosely sewn or pinned blankets of radiant barriers and netting spacers. MLI compresses under a load, which significantly reduces thermal performance. To prevent MLI compression, standoffs can be used, which further degrade traditional MLI performance and directly conduct heat to the tank. Also, this becomes difficult with the large cylinder tank barrels envisioned for the large LH_2 tanks for future cryogenic propulsion vehicles. Load Bearing MLI was designed specifically to support a large thermal shield without requiring tank standoffs or any other direct supports. LBMLI is inherently a structural MLI, able to self support large BAC or vapor cooled shields.

The goals of the Reduced Boil-Off Liquid Hydrogen Storage test program were to design, build, install, test and demonstrate the LBMLI/BAC shield is structurally sound and can survive launch loads with no damage or degradation while providing high thermal performance insulation. Successful testing would mature LBMLI and increase its Technology Readiness Level.

This paper reports on progress on these goals, including the design, analysis, structural testing, and installation and testing on an LBMLI tank applied system.

2. LBMLI tank applied system design and development

This test program called for the design, fabrication, delivery, and installation of two flight-representative high performance tank-applied MLI systems, consisting of 19 layers of Double Aluminized Mylar (DAM) with 18 layers of discrete spacers, capable of structurally supporting the actively cooled aluminum BAC shield and overlying 30-layer traditional MLI blanket, and of surviving launch environments. This called for a novel design approach, as conventional MLI does not possess the required structural capabilities.

LBMLI uses discrete spacers bonded to radiation barrier layers to reduce conducted heat leak between layers and to provide structural support for an external load such as a thermal shield. Load Responsive MLI spacers have a dynamic load response in which a support beam connects to support loads, and disconnects under no load [5]. Integrated MLI spacers are light-weight spacers without the dynamic beam. Preliminary analysis indicated either spacer had adequate strength, but a conservative approach selected the stronger Load Responsive spacer for this application, and the lateral spacing was determined for optimal balance of structural strength and heat leak.

Table 1
LBMLI quasi-steady state load analysis.

Mass LBMLI + BAC shield + conventional MLI	2.58 kg/m^2
Load at 14 g	36.2 kg/m^2
LBMLI load carrying capacity	143.5 kg/m^2
Safety Factor	4X

A 19 layer LBMLI structure was designed to meet the heat flux goal and to support the 6 kg mass of the Broad Area Cooled shield (5mil Aluminum with 0.25" OD stainless steel cooling tubes) and the 6 kg mass of a 30 layer outer traditional MLI blanket.

2.1. LBMLI structural analysis and design

Load Responsive posts were designed to support >30 psi (for a 100% safety margin on atmospheric pressure load), and previous testing determined that each post could support 90 psi prior to a buckling failure of the post. LBMLI structural analysis was attempted using several approaches. A static, quasi steady state analysis of the forces from the BAC shield and outer MLI, with 14 g launch loads, shows a large margin on failure (see Table 1).

In an attempt to perform dynamic analysis of the LBMLI system, FEA analysis was performed on a simplified model for LBMLI in which the mylar was modeled as rigid sheets, there was no support beam on the spacer, and the post to mylar bonds were not modeled. This analysis suggested the LBMLI would fail in the mylar or at the post-mylar joint. With these mixed analytical results, more accurate and realistic structural testing was performed by fabricating prototype coupons matching the flight-like system areal mass and doing vibe testing.

2.2. Dynamic structural test results

LBMLI 19 layer coupons were fabricated and velcroed to SOFI, with the BAC shield and outer 30 layer MLI blanket equivalent areal mass attached. This sample was subjected to random and sine vibe at protoflight levels. Random vibe was done at +3 dB above Maximum Predicted Environment (MPE) with no effect, and sine vibe done at +25% above MPE with large displacements at resonances at 12 and 16 Hz. The LBMLI design successfully passed +25% MPE vibe testing, with minor damage to a couple of unsupported corner posts (an artifact of the free standing edges in the coupon test setup), indicating the LBMLI design has adequate structural strength to support a BAC shield and outer MLI at launch loads (see Fig. 1).

For light mass, large surface area structures such as MLI, acoustic loading experienced during the launch phase of a mission can be substantial, and LBMLI panels were subjected to ca. 130 dB Sound Pressure Level over 20 Hz to 10 kHz, which is equivalent to up to 5000g acceleration force. Two LBMLI panels were fabricated and shipped to Marshall Space Flight Center for acoustic shock load testing. LBMLI was exposed to a +12db level above Maximum Predicted Environment and showed very minor spacer debonding at unrestrained outer edges (again, an artifact of the test setup).

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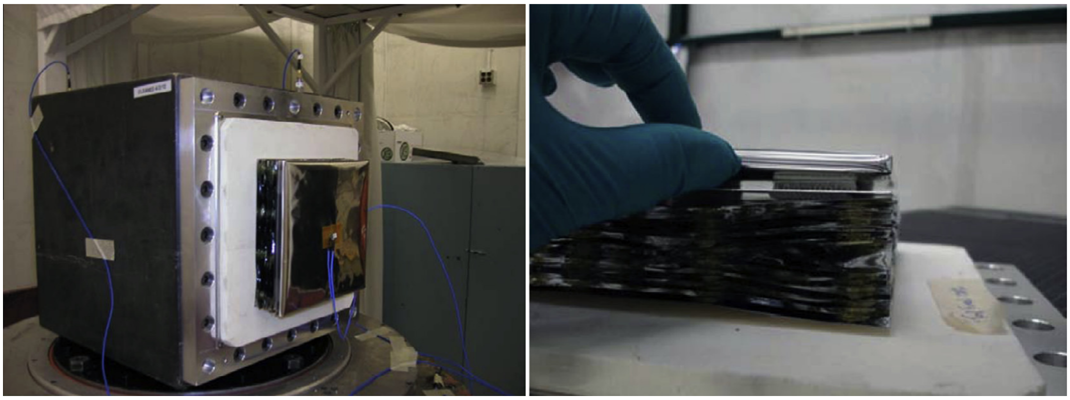

Fig. 1. Vibration coupon test set-up and post-test inspection of debonded spacers.

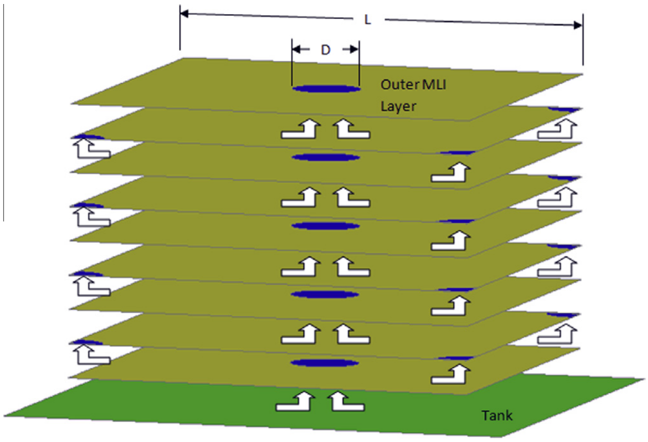

Fig. 2. Equivalent venting model description.

2.3. Depressurization analysis and testing

Rapid depressurization analysis was performed using Thermal Desktop as an interface for Fluint. The gas flow and resistance through the LBMLI structure was calculated using geometry of vent holes (perforations), distance between them and the launch depressurization profile [6,7]. While seams were included in the blanket design, due to their nature and uncertainty as how to model them, they were excluded from this analysis. The maximum allowable internal pressure was determined by the spacer tensile strength and lateral spacing. A trade study optimized vent hole diameter versus lateral spacing. A flow diagram of the model is shown in Fig. 2 and the results of the parametric analysis are shown in Table 2.

Table 2
Results of venting analysis.

Vent hole dia (in)	Vent hole spacing (in)	Open area (%)
0.125	14	0.0063
0.25	24	0.0085
0.375	26	0.0163

The 24” spacing was chosen for the combination of low open area (0.0085%) and the low number of holes that would have to be put into the mylar. The venting analysis was conservative as it did not include any venting through LBMLI seams.

2.4. LBMLI thermal analysis and coupon test results

LBMLI spacer solid thermal conductance has been modeled using various tools, including TAK, custom models and FEA. The general accuracy of these models has been validated via coupon and tank system measurements on a number of calorimeters and tanks [4,5]. Spacer structural characteristics have been modeled with FEA, and physical measurements made of compressive, tensile and shear strength of the spacers bonded to DAM.

LBMLI thermal performance was modeled via a SINDA compatible Thermal Analysis Kit (TAK) layer-by-layer thermal model, and estimates the 19 layer LBMLI structure should have a heat flux of 0.022 W/m^2, or 0.16 W for the entire tank, less than the design goal of 0.25 W (20–90 K). In order to build confidence understanding

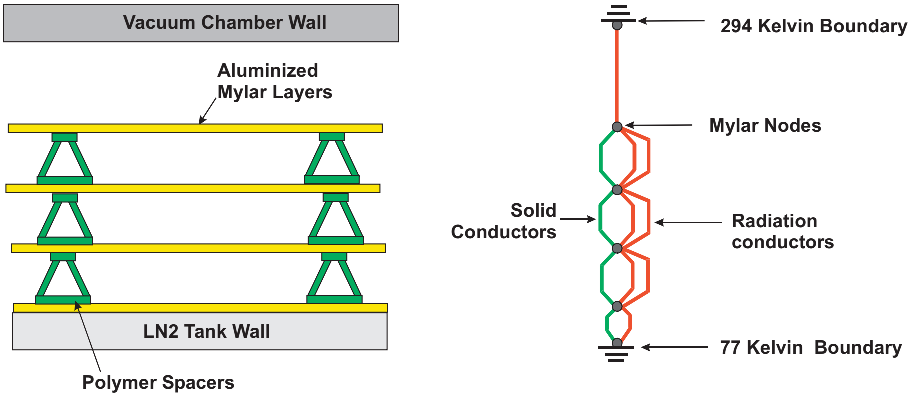

Fig. 3. Equivalent layer-by-layer thermal model.

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Table 3
LBMLI predicted and measured heat flux from 78 K to 295 K.

LBMLI coupon	Modeled heat flux (W/m^2)	Measured heat flux (W/m^2) [10]	% Model error
4 Layers	2.06 W/m^2	1.77 W/m^2	16
9 Layers	0.997	0.924	8
19 Layers	0.490	0.545	−10

Table 4
LBMLI estimated and measured heat flux from 20 K to 90 K.

LBMLI coupon	Modeled heat flux (W/m^2)	Measured heat flux (W/m^2) [13]	% Model error
4 Layers	0.0685 W/m^2	0.201 W/m^2	−66
9 Layers	0.0393	0.148	−73

the heat flow through the LBMLI system, several different thermal models were constructed for comparison to the test data (see Fig. 3 and Table 3).

In addition to the tank applied insulation systems, several LBMLI test coupons, representative of the tank-applied LBMLI systems, were fabricated for thermal characterization using calorimeters at Kennedy Space Center (KSC) and Florida State University (FSU). Measured heat flux was 0.924 W/m^2 for a 9-layer LBMLI coupon, and with typical [reported in the literature] heat leak through 10-layer conventional netting-based MLI in the range of 1.5–2.5 W/m^2 [8,9], LBMLI has about 40% less heat flux per layer than conventional MLI.

Note the good agreement between the estimated heat leak for LBMLI and the measured performance. Over the range from 78 K to 295 K, the model is within 16% of the measured heat flux. This is an excellent correlation between the LBMLI layer-by-layer model and actual performance, when compared to that of traditional MLI, which can have model errors much greater than 100% (typical Degradation Factors in the Lockheed Equation of 2–4) [11,12].

Note the larger difference in measured performance to that modeled for LBMLI at low temperatures. There clearly is some unknown issue effecting LBMLI (see Table 4).

2.5. Effect of number of layers and compressibility

In Fig. 4 the heat flux times number of layers shows an increasing heat flux (W/m^2) per layer for traditional MLI as the number of layers increases, likely due to compression of the layers with resultant increase in heat flux. For LBMLI this function is nearly flat indicating less degradation with thicker blankets. This is the expected behavior for IMLI and discrete spacer insulation systems, where the layer spacing and density is controlled by the bonded spacer structure. LB-MLI has a low density of 5.5 layers/cm, the traditional MLI in Fig. 4 have layer densities between 10 and 40 layers/cm.

2.6. LBMLI tank applied system design and installation

The LBMLI structure was fabricated and installed in pre-formed panels. The entire 7 m^2 tank was covered with three LBMLI panels, each of which is rigid enough to be lifted and installed on the tank. LBMLI was designed to use interleaved, overlapping seams between panels, that provide precise temperature matched layers at seams and prevent any line of sight radiation to reach the tank. The LBMLI panels were attached to the SOFI on the tank via Velcro, for ease of removal and reuse, with the external BAC shield also attached to the LBMLI via Velcro. The spacers in each layer were applied in a precise manner so that they were aligned with the spacers on adjacent layers to increase load bearing capability.

The LBMLI tank applied insulation panels were built up on forms at Quest Thermal Group and then the tri-sector panels were shipped to MSFC and GRC, and installed. Fit and installation were good. Installation at on the CBRS tank at Glenn was completed by 3 engineers in 2 days (see Figs. 5 and 6).

3. LBMLI tank applied system performance

3.1. Thermal performance of LBMLI compared to traditional MLI on tank applied system

Heat flux for LBMLI/BAC/outer MLI was 0.21 W/m^2 (1.46 W for 7 m^2 tank). The program goal was to be <0.25 W/m^2, so the LBMLI insulation allowed the goal to be met (traditional MLI tested previously did not meet the goal) (see Table 5).

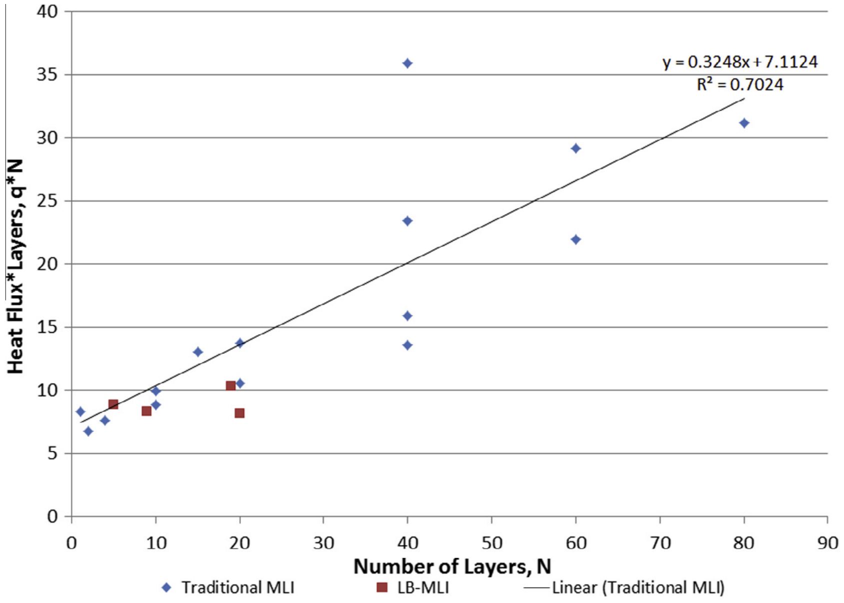

Fig. 4. Effect of layers and compressibility on MLI [14] and LBMLI.

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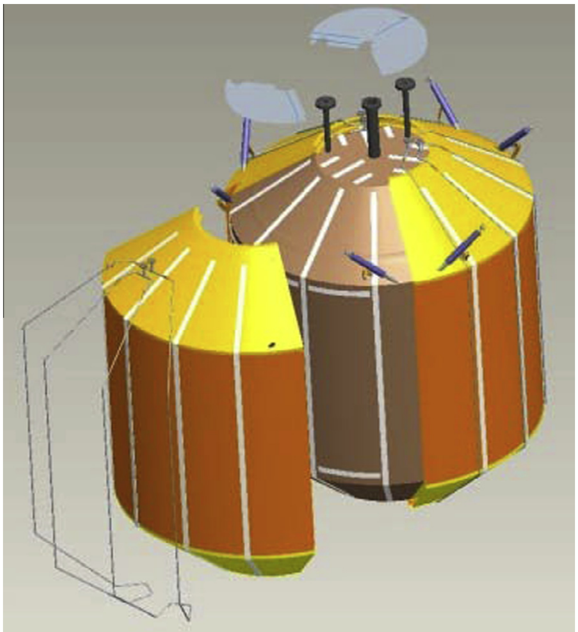

Fig. 5. LBMLI was installed on the tank in tri-sector panels. Also visible are the cooling tubes that attach to the thermal shield (not shown) and Velcro strips for anchoring to the SOFI.

The LBMLI showed significant lower heat flux compared to low density traditional netting MLI previously tested in the same configuration. Comparisons in the passive case are less than ideal (due to insulation being on the outside of the cryocooler system), but the LBMLI (19 layers) had 27% less heat flux than MLI (30 layers). In the actively cooled test, with the cryocooler maintaining a 90 K boundary on the thermal shield, the LBMLI (19 layers) had 18% lower heat flux than MLI (30 layers).

As found with the coupon testing, the tank applied system performance at 20–90 K was worse than modeled. Analysis of the data suggests the extra heat load is radiation related [15]. Several theories have been put forward as to why LBMLI is underperforming at these low temperatures. Further work is planned, with several prototypes and experiments to attempt to clarify this behavior (see Table 6).

3.2. LBMLI mass comparison

LBMLI system mass was 9.2 kg (10.5 kg with additional Velcro as installed), compared to 14.5–16.5 kg for traditional MLI with tank standoffs (two different tank systems); therefore LBMLI provided an average 38% reduction in system mass. The LBMLI mass was 0.060 kg/m^2 – layer (without embedded instrumentation and Velcro attachments), meeting the program goal. This LBMLI first prototype was fabricated conservatively using heavier DAM layers than believed necessary, so LBMLI could readily be reduced in mass in future implementations.

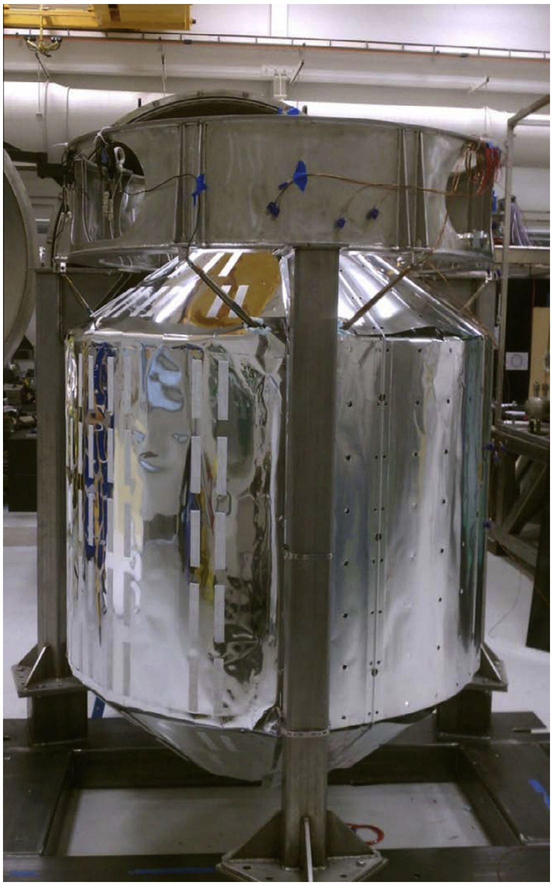

Fig. 6. LBMLI installed on VATA tank at NASA Marshall; left half is LBMLI, right half has BAC shield installed.

Table 6
LBMLI tank applied system modeled versus measured heat flux [15].

	LBMLI on tank modeled	LBMLI on tank measured	% Model error
CBRS, cooler off, 25–182 K	0.097 W/m^2	0.21 W/m^2	−53
CBRS, cooler on, 25–90 K	0.018 W/m^2	0.092 W/m^2	−80

3.3. LBMLI structural test results

LBMLI supported the BAC shield and outer MLI through vibe testing on the Vibro Acoustic Test Article (VATA) tank at NASA Marshall with no apparent motion of shield or degradation in thermal performance. LBMLI proved capable of supporting a flight-like Broad Area Cooled shield and outer insulation blanket on a 1400 L cryogenic tank.

4. Conclusions

Load Bearing MLI is a next generation MLI that uses discrete polymer spacers to maintain layer density, structurally support

Table 5
LBMLI heat flux compared to traditional MLI [15].

	LBMLI 19 Layers (W/m^2)	MLI 30 Layers (W/m^2)	LBMLI/MLI % Reduction	LBMLI/MLI % Reduction on a per layer basis
CBRS passive heat leak (25 K cold, 180 K warm)	0.21	0.29	27	56
CBRS active heat leak (25 K cold, 90 K warm)	0.092	0.112	18	51

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thermal shields and reduce heat leak through the insulation system. It has advantages over traditional netting MLI with improved thermal performance per layer, more predictable and repeatable performance, estimated lower fabrication and installation costs, and can be installed onto large cryotanks using modular panels.

Benefits of LBMLI over conventional MLI were successfully demonstrated for both passive and active thermal control. LBMLI (and traditional MLI) heat flux at low temperatures (20–90 K) was higher than modeled and requires additional study. LBMLI technology was recommended for infusion into future Cryogenic Propellant Storage and Transfer Technology Demonstration Missions.

Specific results from this NASA test program include:

- Quantitative data was obtained on the thermal and structural performance of LBMLI, an advanced insulation technology, with coupon and tank ground testing in simulated space thermal-vacuum environment and launch ascent environment.
- LBMLI successfully structurally supported a 8.6 kg BAC shield (1.23 kg/m^2) and 6 kg (0.86 kg/m^2) outer MLI through launch ascent loads (acoustic loading, vibe loading and rapid depressurization).
- LBMLI reduced heat load into the tank by 18% compared to traditional MLI on a thickness basis for operation between 20 K (LH_2 tank) and 90 K (BAC shield), and reduced heat flux by 51% on a per layer basis.
- LBMLI reduced mass over conventional MLI with tank supports by 38%.
- LBMLI was matured to TRL5.

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