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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, multi-layer 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.

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.

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

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).