Next Generation Multilayer Insulation with Discrete Spacer Technology

Part 1: Use of Discrete Spacers for Advanced Thermal Insulation

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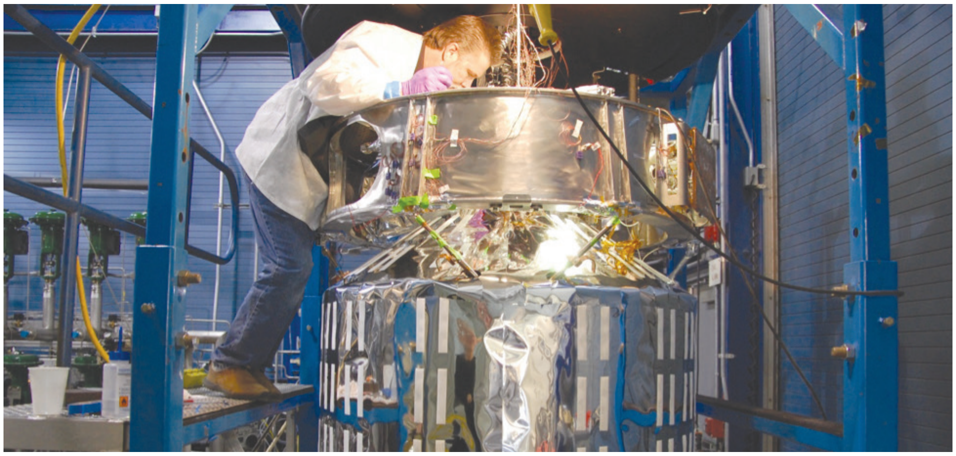
Cryogenic thermal engineers are familiar with multilayer insulation (MLI), developed in the late 1950s as lightweight insulation for cryogenic propellants. MLI is used as high performance thermal insulation for launch vehicles, spacecraft, cryogenic tanks, dewars and spaceborne instruments. MLI operates in high vacuum, where its performance exceeds other insulations by a factor of ten. However, the heat leak through acreage MLI is still a major one for cryotanks, making it difficult to achieve the NASA goal of zero boiloff needed for long duration missions, and real world application of MLI has some well-known challenges.



Load Bearing MLI installation complete on the NASA Glenn SMiRF tank. Image CH

Conventional MLI technology is over 60 years old and is currently based on gold or aluminized metalized polymer films separated by polyester or silk netting. The metalized films act as radiation barriers and reduce radiated heat flux, while the netting separates the barrier layers and reduces solid heat conduction. MLI soft blankets involve a lot of touch labor, are difficult to control density and compression, have seams that cause additional heat leak and can be difficult to support and control on large cryogenic tanks. In the 1970s, a study by Lockheed Corporation on MLI resulted in the Lockheed Equation, which was formulated as a semi-empirical fit to data on thermal performance (see Figure 2). Heat leak through conventional MLI is dependent on layer density to the 3.56 power and is therefore sensitive to compression, which is not well controlled. MLI thermal performance is also dependent on design, workmanship and installation. MLI is neither robust nor structural, i.e., it can't support itself well on large tanks, nor any external loads such as lightweight vacuum shells or broad area cooled thermal shields. Due to layer compression and other factors, MLI performance is difficult to predict, leading to "degradation factors" from the Lockheed Equation that can range from 1.5 into the 20s (heat leak 1.5 to 20 times larger than predicted).

These factors led to the creation and development of a next generation MLI technology, called integrated MLI (IMLI), by Gary Mills of Ball Aerospace and Scott Dye and Alan Kopelove at Quest Thermal Group. IMLI replaces the netting separator with discrete, low thermal conductance, micromolded polymer spacers. Discrete spacers offer numerous advantages over netting MLI, including precise control over layer spacing and density, a robust bonded structural MLI system and an engineered geometry that can be thermally modeled accurately and performs close to predicted behavior with repeatable thermal performance.

Discrete spacers offer elegant engineered solutions that can be designed for specific properties, such as low heat flux or structural strength. This is accomplished by careful control over the geometry of the spacer, including the cross sectional area to length ratio (which controls solid heat conduction from layer to layer) and static or dynamic response properties. The IMLI spacer is a micromolded polymer which provides about 1/1000 the contact area that netting spacing has, is fabricated from a low thermal conductance engineering polymer, and has an Area/Length ratio of about 0.0001 m. IMLI performance has been measured via boiloff calorimetry on test tanks ranging from 10L to 500L at Quest, Ball Aerospace and the NASA KSC Cryogenics Test Lab (with help from Wesley Johnson and James Fesmire), and had a measured heat flux of 0.41 W/m^2 for a 20 layer IMLI structure (78K, 292K, 3.7 cm). IMLI typically has 30-50 percent less heat flux per layer than conventional MLI, so fewer layers are needed for a specific heat flux. IMLI will reach TRL (Technology Readiness Level) 9 with its first spaceflight in 2016 on the NASA/Ball Aerospace Green Propellant Infusion Mission. Ball and Quest began work on IMLI in 2007, so you can see how long the technology development and infusion cycle is for aerospace! This work was made possible because cryogenic fluid management groups at multiple NASA centers saw the possibilities to improve on traditional MLI, and supported this work via NASA Small Business Innovation Research (SBIR) contracts.

With the success of Discrete Spacer Technology in IMLI, the team began looking at other applications in need of advanced thermal insulation. Load responsive MLI (LRMLI) was designed to provide both ultrahigh performance in-space and high performance in-air, as a possible Spray On Foam Insulation (SOFI) replacement. LRMLI uses a unique dynamic spacer with a central support rib, which in the unloaded condition (in-space) has a 0.005" gap between the support rib and the underlying

$$Q_{leak} := \frac{2.11\ 10^{9}\ \overset{\text{MLI layer density}\ \swarrow}{MLI^{3.56}}\ T_{med}\ \left(T_h\ \ T_c\right)}{N_{layers}+1} + \frac{5.39\ 10^{10}\ .031}{N_{layers}}\ T_h^{\ 4.67}\ \ \ T_c^{\ 4.67}$$

Semi-empirical equation for MLI performance developed by Lockheed under NASA contract.

layer and no heat leak through the rib. When loaded, for example with external air pressure, the LRMLI spacer dynamically responds and supports the load (but with additional heat leak).

The 30 mg load responsive dynamic spacer blends both low thermal conductivity and structural strength, and has supported 90 lbf. A 0.25" three-layer LRMLI system has a measured heat flux of 4.8 W/m^2 in vacuum and 29.1 W/m^2 in air (77K, 295K, 0.63 cm), which is a 24x advantage in air over SOFI per thickness and a 144x lower heat leak per thickness than SOFI on-orbit. LRMLI self-supports loads; for example, operation in air requires only a thin, lightweight metal vacuum shell. First generation LRMLI had a mass of 2.5 kg/m^2, equal heat leak through SOFI would require 91 cm and 33.7 kg/m^2. Later work developed a lower mass polymer laminate vacuum shell LRMLI with an Areal mass of 1.35 kg/m^2.

Another application considered is MLI for cryogenic propellant feedlines. Heat leak through spiral wrapped MLI on pipes is 3 to 10 times higher than tank MLI. The poor performance of traditional MLI wrapped on feed lines is due in part to compression of the MLI layers, with increased interlayer contact and heat conduction. Quest Wrapped MLI uses a novel discrete spacer to maintain layer spacing and reduce heat leak. A Triple Orthogonal Disk spacer was engineered to minimize contact area/length for use in concentric MLI configurations. Wrapped MLI prototypes were fabricated and tested, and offered superior performance, 2.2 W/m^2 heat flux compared to 26.6 W/m^2 for traditional spiral-wrapped MLI (five layers, 77K to 295K). Wrapped MLI as inner insulation in vacuum jacketed pipe had a heat flux as low as 0.09 W/m, compared to industry standard products with 0.3 W/m, and could enable improved spacecraft cryogenic feedlines and industrial hot/cold transfer lines.

The structural strength of discrete spacers can be used to support a variety of loads, including vacuum shells or thermal shields. An interesting project that Quest Thermal worked on with NASA focused on large tank MLI for reduced boiloff. Load bearing MLI was engineered so that the insulation itself supported the external load of a broad area cooled thermal shield as part of an actively cooled system on the large NASA Glenn SMiRF LH$_2$ tank. Tank standoffs were not needed since the discrete spacers in LBMLI easily supported the thermal shield and external MLI. LBMLI provided a 51 percent reduction in heat leak per layer over traditional MLI and thermal shield supports, with a 38 percent reduction in mass. These advances in MLI may help achieve the zero boiloff goals required for long duration space exploration missions.

Part 2 of this series will describe recent work developing new advanced insulation systems for launch vehicles and large cryotank support structures.

Finally, I want to give credit for this R&D work to Dye and Phillip Tyler of Quest and Mills of Ball Aerospace. Quest has received great support from our NASA technical monitors, including Johnson and Dave Plachta at Glenn, Shuvo Mustafi at Goddard and Brian Banker at Johnson Space Center, among many others interested in advancing passive thermal insulation. This work was initially supported by the NASA SBIR program, which took the concepts from the back of a napkin to TRL 4, then by NASA Game Changing Development, and finally by a NASA Technology Demonstration Mission that will fly IMLI next year and reach TRL 9. This is a great success story of NASA investing in and helping new technologies (and small businesses) mature. ■