Vapor Cooling Methods for IMLI and Foam Insulations

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Abstract

Improvements in cryogenic propellant storage are a critical need for future NASA missions, with zero boil-off an important goal. A current emphasis is on use of effective passive or active vapor cooling. Discrete spacer IMLI systems can support embedded Broad Area Cooled shields, and systems have been designed that use both passive and active cryocooler coupled vapor cooling tube-on-shield methods.

Broad Area Cooled thermal shields have also been built into foam insulation systems and the thermal performance and effect of vapor cooling measured. While the thermal conductivity of foams is much higher than for IMLI, it offers benefits for in-air performance such as liquid hydrogen fueled aircraft. Vapor cooling can improve the apparent thermal conductivity of such foam insulation systems.

Broad Area Cooled shields were designed, fabricated and installed into IMLI and foam insulation on test tanks. We describe the thermal modeling, analysis and experimental heat flux results for several systems. Heat flux reduction using Broad Area Cooled shields is compared to heat removal using direct vapor cooling from an IMLI vapor layer.

Vapor cooling is an important process to intercept heat flux to a cryotank and contents. Heat loads can be reduced by 50 – 70%, depending on cooling configuration and cryocooler integration, helping actively cooled systems reach Zero Boil-Off.

Highlights

- Vapor cooling provides thermal performance benefit for a wide range of current and next-generation insulation solutions for cryogenic propellent storage.
- Vapor-cooled foam can provide a low-cost, moderate-performance solution by reducing tank system heat leak by 13.6%.
- Vapor cooling, particularly when used in conjunction with Quest Discrete Spacer Technology™ insulation, can significantly reduce heat leak.
- An 80K neon gas cryocooler and integrated tube-on-shield network can reduce tank that active cooling can reduce heat leak through an 18-layer LBMLI blanket by 62%.
- Variations of Quest Discrete Spacer Technology™ can carry structural loads to support embedded BAC shields and lightweight vacuum shells.
- VCSMLI can reduce heat leak through structural elements into a cryogenic tank system by 93% for LH2/GH2 and 77% for LN2/GN2.

Keywords

Multilayer insulation, Integrated multilayer insulation, Load bearing multilayer insulation; cryogenic propellant storage; active cooling, cryocooler

Abbreviations

Load Bearing Multilayer insulation	LBMLI
Integrated Multilayer Insulation	IMLI
Multilayer Insulation	MLI
Traditional MLI	tMLI
Technology Readiness Level	TRL
Dual-Aluminized Mylar	DAM
Dual-Aluminized Kapton	DAK
Reduced Boil-Off	RBO
Zero Boil-Off	ZBO
Spray-On Foam Insulation	SOFI
State-of-the-art	SOA

1. Introduction

(include relevant information from 11043 LBMLI Phase III kick-off charts

Human exploration requires advances in storage of cryogenic propellants for missions to Earth orbit, the moon, Mars and beyond. NASA is interested in improving thermal control systems for low Earth orbit spacecraft, future lunar and Mars landers, lunar and Mars surface ISRU cryogenic fuel production and storage. Cryogenic propellants have the highest energy density of any chemical rocket fuel and propel most NASA and commercial launch vehicles. Cryogenic propellants must be kept cold to preserve them and prevent loss via boil-off, therefore cryogenic spacecraft and storage tanks must have thermal insulation protecting the cryopropellant. Improvements in cryogenic propellant storage and transfer are a critical need for future NASA missions, with zero boil-off of cryogenic propellant an important goal [Ref 1, 2]. High performance insulation is also needed for future Mars missions to protect cryogenic fuels, such as LCH_4 and LOX, obtained from the Mars regolith (ISRU) or Earth supplied, and stored on Mars surface [Ref 3, 4]. Quest Thermal Group has designed and is developing an innovative, lightweight thermal insulation system, which insulates cryogenic propellants in multiple environments, such as in-air on Earth prelaunch and launch ascent, in-space cruise phase, during Mars EDL and ascent, and on-Mars surface. *Multi-Environment MLI* (MEMLI) is a novel multi-functional thermal insulation system that uses a ventable/sealable, lightweight Vacuum Shell, integrated and supported by Load Bearing MLI layers specifically tuned for Mars atmospheric pressure, and could offer excellent thermal performance in all mission phases and environments.

Quest insulation products utilize Discrete Spacer Technology™ to form high-performance insulation systems that are tunable to specific requirements for a wide range of applications with highly predictable thermal and structural characteristics. Integrated Multilayer Insulation (IMLI) achieves approximately half the heat leak per layer with similar mass compared to conventional netting-based MLI. Load Bearing Multilayer Insulation (LBMLI) is able to carry external loads to support lightweight vacuum shells and Broad Area Cooled (BAC) shields.

Discrete space multilayer insulation systems with load supporting spacers can be engineered to support external loads, such as lightweight vacuum shells and external atmospheric pressure. We report here efforts to design, build and test a multi-environment system that could provide exceptionally good thermal performance for all mission phases for Evolvable Mars Campaign, Mars Lander technology and Mars surface ISRU cryogen storage.

In 2011, NASA conducted a reduced boil-off (RBO) test using LH2 that employed an actively-cooled thermal radiation shield embedded within an MLI system. This MLI system utilized Quest's LBMLI to structurally support the actively-cooled foil shield. Design, analysis, installation, and testing were performed part of an R&D contract through the Cryogenic Propellant Storage and Transfer (CPST) project to demonstrate that the heat leak to a tank can be transferred to a thermal shield and rejected in order to reduce boil-off by 80% [1].

In 2015, Quest was awarded an SBIR contract to further develop novel Vapor Cooled Structure MLI using a hermetically-sealed vapor transport layer beneath the insulation stack. This technology is particularly relevant for tank structural elements such as skirts and struts, which can represent as much as 40% of the total heat leak into a cryogenic tank system.

Quest Thermal has developed several advanced thermal insulation systems for NASA that use discrete spacers to provide robust, structural insulation. *Integrated MLI* (IMLI) is a next generation MLI, with 37 to 50% lower heat leak per layer than traditional MLI, is currently at TRL 6, and will be flown on two NASA missions expected in 2018 (and reach TRL 9)[Ref 5, 6]. *Load Responsive MLI* is designed to operate both in-air and on-orbit, providing good performance in-air and high performance in-space [Ref 7]. *Load Bearing MLI* (LBMLI) completed testing in a Phase III NASA multicenter program (Glenn, Marshall, Ames and Kennedy) for Reduced Boil Off on Large Liquid Hydrogen Tanks, with 37% lower heat leak than traditional MLI with tank standoffs supporting a Broad Area Cooled thermal shield [Ref 8, 9]. *Launch Vehicle MLI* variants supply a ruggedized IMLI structure designed to survive launch loads, provide much better insulation than Spray On Foam Insulation (SOFI), and are in consideration by Prime Contractors [Ref 10]. Cellular Load Responsive MLI (CLRMLI) and Vacuum Cellular MLI (VCMLI) are other novel insulations designed for launch vehicles. CLRMLI uses a compartmentalized, cellular structure containing a selected gas species that cryopumps at cryogenic temperature to provide high internal vacuum for high thermal performance, with Load Responsive MLI structures within the cells to provide thermal insulation and support face sheets allowing operation both in-air and in-space. CLRMLI offers high thermal performance for operation in-air (28 W/m^2) and in-space (8 W/m^2), compared to 0.75" SOFI with 230 W/m^2, the ability to insulate cryopropellant tanks pre-launch without purge gas or air frost buildup, and excellent structural strength [Ref 11, 12]. VCMLI provides better thermal performance in-space but lower in-air (approx. 4.7 W/m^2 in-space and 47 W/m^2 in-air). In summary, Quest Thermal Group has developed several innovative, advanced thermal insulation systems, offering high performance for specific applications such as in-space, in-air, or for launch vehicles.

NASA in 2017 asked for proposals for cryogenic fluid management for in-space transportation, specifically looking for lightweight, multifunctional cryogenic insulation systems that can provide high thermal performance on-Mars surface for Mars ISRU cryogen storage, and help meet needs for cryogen preservative on long duration missions, Mars EDL and ascent for Mars Lander and Evolvable Mars Campaign missions.

The Quest team believes a novel system integrating a ventable/sealable lightweight Vacuum Shell, supported by Load Bearing MLI inner layers, can be engineered for high performance in-air, in-space and on-Mars, and could provide <0.3 W/m^2 in-space and on Mars surface with a robust, lightweight system.

Multi-Environment MLI could provide different benefits to various NASA future needs. This new insulation structure might be able to provide excellent thermal performance for LCH_4 storage tanks, insulating those tanks during the cruise in-space portion and while on Mars surface, and insulating LOX derived from Mars ISRU generation and storage. MEMLI could be developed robust enough to survive Mars EDL and ascent, and insulate LCH_4 for Mars Lander use.

2. Materials and Structures

The various works discussed in this report were performed across a wide range of R&D programs since 2011 with a wide range of materials, structures, and related equipment. Further development is currently proceeding under a new NASA R&D contract to increase understanding of multi-stage cryocooler performance in conjunction with Quest IMLI.

Quest's Discrete Spacer Technology™ concept is composed of a number of core materials, including the polymer discrete spacer, the radiant barrier films, bottom face sheet, a hermetically sealed vacuum shell/outer layer and some valves.

Discrete spacers are engineered to support various external loads, including external atmospheric pressures (such as 1 atm air pre-launch, high vacuum in space or 4.7torr CO_2 on Mars), provide precise support for the vacuum shell while minimizing vacuum shell material requirements and mass, providing layer separation under all operating conditions, and of course minimize solid heat conduction through the spacers from layer to layer.

As discussed below, materials and variables under Quest Thermal control include the type of spacer (for example, using our lightweight IMLI load with a low spring tension, or the stronger LRMLI spacer with much higher spring tension and load capability, or a custom engineered spacer with the precise loading force needed for Mars surface). Other variables include lateral grid spacing of the spacers; number of radiant barrier layers; thickness, mass and structural rigidity of the dual metallized polymer films used as layers. The vacuum shell design could be laminate films designed for low permeability, or thin metal sheets or foils, in flexible or semi-rigid geometries with various stiffening elements.

Fine-tuning a load bearing MLI structure for on-Mars surface high performance, as well as providing in-space high performance, has never been done. Quest Thermal, with discrete spacers, has worked on balancing heat flux versus structural loads for a number of prior insulation systems. Quest scientists and engineers were confident a high performing multi-functional, multi-environment system could be developed.

3. Vapor-Cooled Foam

The advantages and decades of heritage make foam insulations a natural starting point for insulating cryogenic tanks. Quest Thermal Group is constantly striving to be experts in the realm of insulation and thermal management. Test data and analysis of vapor cooled foam insulation in the literature is limited. To that end, Quest began a program to design, model, build, and test a prototype to quantify potential vapor cooling benefits for a foam insulated tank. A 40L tank was tested using liquid nitrogen boil-off calorimetry to evaluate the efficacy of vapor cooling using a BAC shield embedded in foam insulation.

3.1. Design & Modeling

Following a trade study of available materials, Evonik Rohacell 31 IG, a widely-used aerospace-grade polymethacrylimide (PMI) foam, was selected due to low thermal conductivity and rigid closed cell structure that could be machined to fit the test article. Foam-iT, a commercial pourable two-part polyurethane foam, was later substituted due to time and budget constraints.

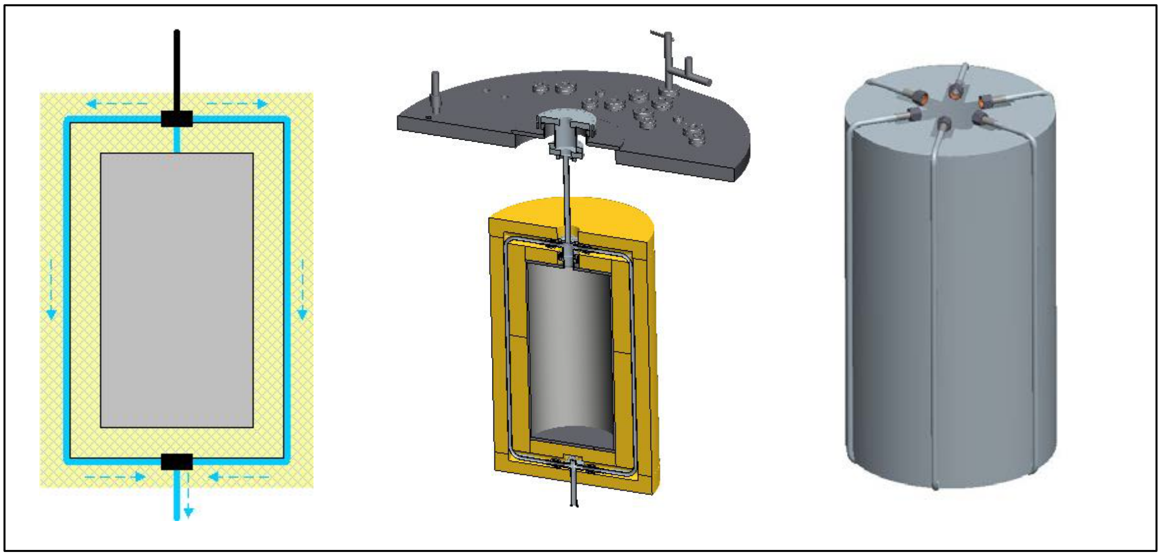

Figure 1: Boil-off path diagram, test article CAD images

The as-built prototype, shown in Figure 1 and Figure 2, consists of a cylindrical tank, inner and outer foam insulation, BAC shield, and associated vapor cooling components. Tank OD is 12” by 24” in height for an approximate capacity of 40L. Thicknesses of the inner and outer foam insulation sections were 2.5” and 3.5”, respectively, separated by the BAC shield. During passive vapor cooling, boil-off gas flows through the tank neck tube and is collected in an upper manifold to be distributed to six 60°-spaced ½” OD copper cooling tubes bonded to a 0.020” thick BAC shield made of 6061-Al. Boil-off gas is recollected in a lower manifold before being exhausted through inline flow measurement equipment.

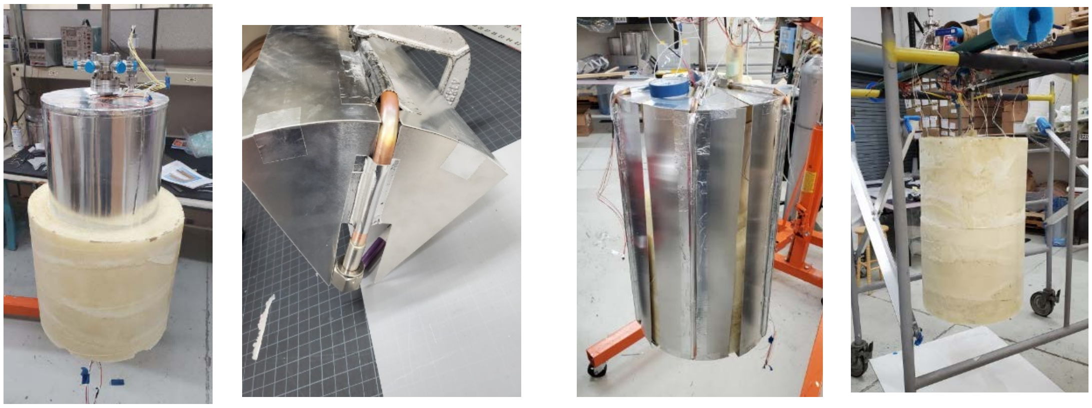

Figure 2: As-built vapor cooled test article

The BAC shield is also separated into six 60° sections with one cooling tube per section, each comprised of top, bottom, and barrel panels (Figure 2) due to assembly constraints. An array of temperature sensors was integrated into the foam insulation, which was poured in stages during fabrication. A sensor schematic is shown in Figure 3. The test article was divided into three cross sections (A-A, B-B, C-C) to characterize foam properties based on data at known locations.

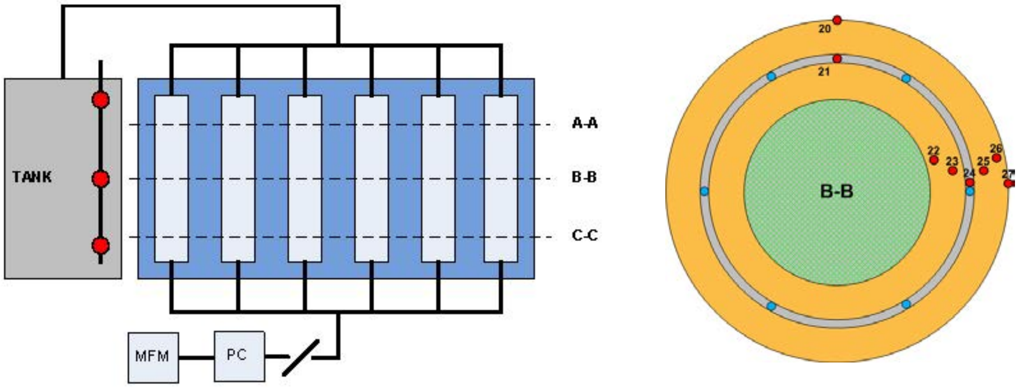

Figure 3: Sensor schematic showing cooled shield (blue box), six cooling loops (gray rectangles), and tank temperature probe; sample B-B cross section.

Models of the test article were developed to predict thermal performance using Thermal Analysis Kit (TAK), a SINDA-like energy network solver, and SolidWorks Simulation. Quest has extensive experience using TAK, with reported model accuracies within 10%. TAK is text-based software and does not easily replicate real geometry and flow properties. As a true FEA solver, SolidWorks Simulation fully integrates CAD functionality and can dynamically analyze gas flow through a vapor cooling network. Initial model predictions in Table 1 were based on Rohacell 31 IG and a four-loop cooling network; the TAK model was revisited post-testing to update foam properties and six cooling loops. Predicted heat leak reductions were consistent with Quest's previous modeling experience. Hydrogen is much more effective than nitrogen for vapor-cooling due to a nearly 12x higher heat capacity, 12.0 compared to 1.12 near the respective saturation points in units of J/g·K.

Table 1: Initial thermal modeling predictions

Cryogen	**Mode**	**Heat leak, TAK [W]**	**Heat leak, SW [W]**
Nitrogen	Non-cooled	*37.0*	*69.0*
300 – 77K	Cooled	*32.0*	*43.9*
	Reduction	*13.6 %*	*36.4%*
Hydrogen	Non-cooled	*53.0*	*85.1*
300 – 20K	Cooled	*32.2*	*15.5*
	Reduction	*39.4 %*	*81.8%*

3.2. Foam Test Results

Two operation modes were tested: (1) non-cooled and (2) cooled. The two configurations were accomplished by either removing or replacing a cap on the exhaust port of the lower manifold. This prevented gas flow through the cooling network, but did not prevent boil-off from collecting in the manifolds and tubes. Ideally, all boil-off gas would have been vented directly through neck tube without forming a “dead gas” zone in the cooling network. This would have been difficult to accomplish given that the shield, cooling tubes, manifolds, and fittings were all completely encased in the foam disallowing access. Also, the Quest team determined that the presence of this “dead gas” would not adversely affect the test. Results are summarized in Table 2 along with updated modeling predictions.

Table 2: Vapor cooled foam test results and comparison

NITROGEN 295 – 77K	**HEAT LEAK [W] MEASURED**	**HEAT LEAK [W] MODELED**	**REDUCTION MEASURED**	**REDUCTION MODELED**
Non-cooled	*49.8*	*45.8*	-	-
Cooled	*43.0*	*31.6*	*13.6%*	*31.0%*

By averaging data from temperature sensors strategically placed throughout the test article, a bulk thermal conductivity of 0.021 W/m·K was calculated for Foam-iT, compared to the published value of 0.031 W/m·K for Rohacell 31 IG. This calculation applies for this particular test article design and set of boundary temperatures.

The initial TAK model recognized the BAC shield as a single aluminum layer inside the foam, with no connection to the tank. In reality, the VCS is physically connected to the tank top cap via the inlet manifold. Also, since the cooling outlet is exposed to the warm ambient, heat leak may be transferred via solid conduction to the tank. This is captured in the updated TAK model, along with change in foam material and six cooling loops to generate the predictions in Table 2. Measured non-cooled heat leak matched the new prediction within 7%, but the cooled heat leak is still more than 10 W higher than the prediction and the 31% reduction is still twice the measurement.

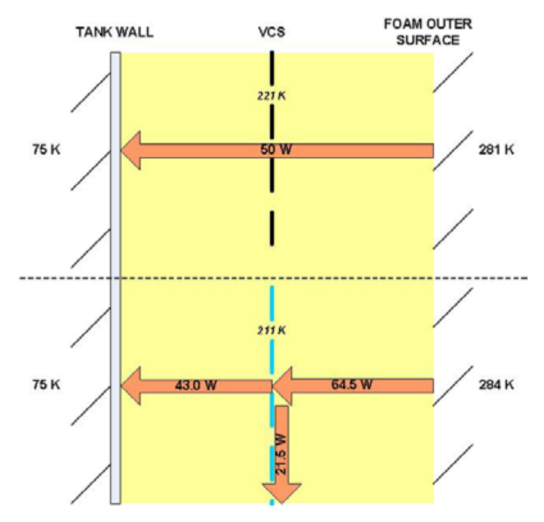

Figure 4: Heat flow diagram for (upper) non-cooled and (lower) cooled operation

Change in enthalpy of the gas was also examined. Using temperature measurements at relevant locations from Figure 3, the theoretical energy removed by the cooling gas can be calculated, illustrated by the energy balance diagram in Figure 4. Energy balance indicates that the passive vapor cooling flow absorbed 21.5 W of energy of the 64.5 W of total heat leak into the system from the warm boundary. An interesting result is that the TAK model results show 68.4 W is supplied from the warm boundary, within approximately 5% of this post-test enthalpy analysis.

4. Vapor-Cooled LBMLI

In 2013, Quest participated in the Reduced Boil-Off II (RBO-II) cryogenic propellant storage test series through NASA's Exploration Technology Development program with the goal of demonstrating significant reduction in LH2 storage tank boil-off using an actively-cooled BAC shield. Quest designed, fabricated, and installed a flight-like high-performance thermal insulation system using proprietary Load Bearing MLI (LBMLI). A primary test objective was to replace the inner tMLI blanket and related shield supports with Quest's self-supporting LBMLI. For RBO-II, a full-sized test article was evaluated using liquid hydrogen boil-off calorimetry at the Small Multi-Purpose Research Facility (SMiRF) located at NASA Glenn Research Center (GRC) in Cleveland, OH. Further testing of small coupons was performed at NASA Kennedy Space Center (KSC) in Florida, NASA Marshall Space Flight Center (MSFC) in Huntsville, AL, and Florida State University (FSU).

4.1. Design & Modeling

An LBMLI blanket was designed to fit around the NASA-provided test tank. The test tank was constructed of 304SS with 48" cylindrical diameter and 55" total height with elliptical dome ends. Stepanfoam S-180 polyurethane foam was applied to the tank with a nominal thickness of 0.7" at the cylindrical section and variable thickness up to approximately 4" at the domes, resulting in the cylinder and truncated cone net shapes shown in Figure 5. The LBMLI inner blanket design was fabricated in separate cylindrical, dome, and cap sections to match the foam surface profile.

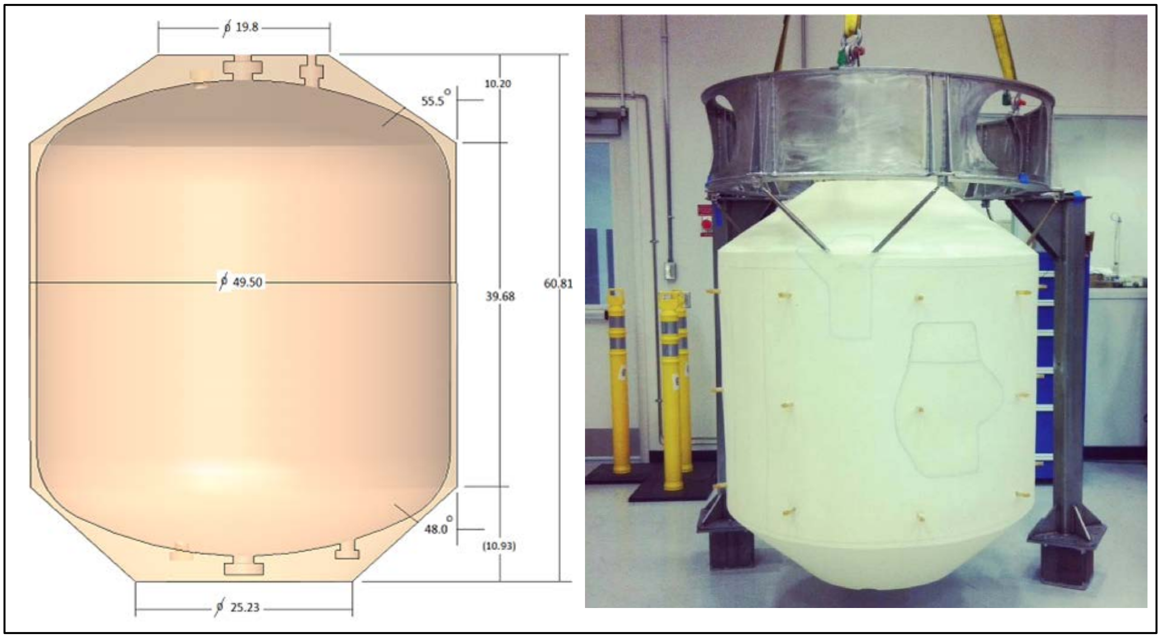

Figure 5: (left) drawing of CBRS/VATA test tank; (right) with SOFI applied

Figure 6 illustrates the insulation structure. In all configurations, 30 layers of tMLI was used as the outer blanket on top of the BAC shield. The LBMLI inner blanket provided structural support for the shield and was constructed of 19 dual-aluminized Mylar radiant film layers with 18 layers of Quest's load-bearing spacers. Inner and outermost film layers were attached with strips of Velcro, Layer 1 to the foam and Layer 19 to the BAC foil shield. The LBMLI blanket weighed 9.19 kg, or 1.14 kg/m², a 13% reduction over a thermally-equivalent 30-layer blanket using tMLI.

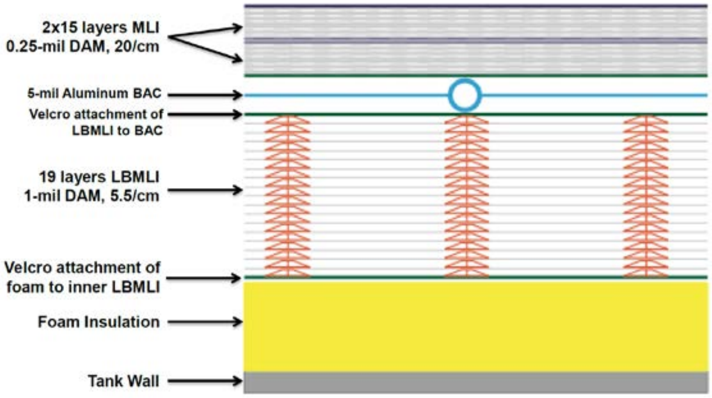

Figure 6: Insulation stack design with 18 layers of LBMLI and 30 layers of tMLI.

The BAC shield was constructed in three 120° panels of 5mil thick 1235-Al foil. Cooling loops were made from ¼" OD tubes, with two loops per panel. Similarly, the LBMLI blanket was also fabricated as three 120° panels. LBMLI spacers were arranged in a nominal 2" grid pattern throughout. A key advantage of Discrete Spacer Technology™ is the ability to thermally-match film layers, eliminating seaming penalties between panels. Another unique advantage of LBMLI is the ability to support the BAC shield and eliminate the need for support standoffs, which can represent a significant heat leak path from the shield directly to the tank surface. Penetrations were accommodated in the blanket structure using clearance holes with 0.5" gaps to the MLI film layer edges, which were then filled in with Cryolite. Additional flight blanket requirements related to launch loading were satisfied with ascent vibe test coupons and rapid depressurization analysis.

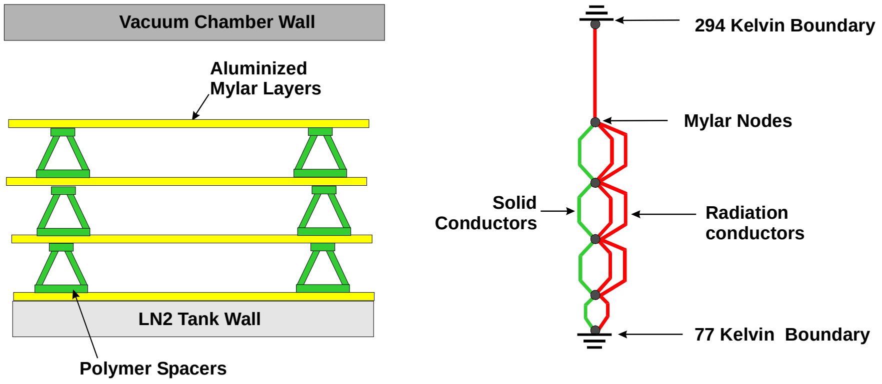

Figure 7: Layer-to-layer node energy network TAK modeling technique for Quest MLI.

Modeling was performed using SINDA-compatible Thermal Analysis Kit (TAK2000) software to predict thermal performance of the LBMLI blanket using two different warm boundary conditions. TAK models are reasonably accurate; Discrete Spacer Technology™ has well-defined geometries and component interfaces, illustrated by the sample schematic in Figure 7. TAK models have been validated via coupon and tank system measurements on a number of calorimeters and tanks [Ref 4, 5], with attainable accuracies within 5-10%. TAK Discrete Spacer Technology™ models include variables such as layer count, internal vacuum level, external pressure, material properties, and boundary temperatures.

Table 3: Initial LBMLI thermal analysis

Warm boundary [K]	**Heat flux [W/m²] No vent holes**	**Heat flux [W/m²] With vent holes**	**Total heat leak [W] With vent holes**
300	*0.599*	*0.601*	*4.20*
80	*0.014*	*0.014*	*0.099*

A warm boundary of 300K represents an insulation system using only the LBMLI blanket, with Layer 19 exposed to the ambient. A warm boundary of 80K represents the BAC foil shield being actively-cooled to a temperature of 80K. Initial predictions are provided in Table 3, showing a 2.5x margin on the 0.25 W requirement. The as-built test article utilized a flight-representative cooler circulating chilled neon gas, providing 11 W of lift at 80K and 15 W of lift at 90K.

4.2. RBO-II Test Results

RBO-II testing simulated several operating modes; this discussion will focus on steady state tank boil-off calorimetry with active cryocooling and ~90% LH2 tank fill. Heat leak results are summarized in Table 4.

Table 4: RBO-II LH2 boil-off calorimetry results

	COOLER OFF		**COOLER ON, 80K**		**COOLER ON, 90K**	
	TEST	MODEL	TEST	MODEL	TEST	MODEL
HEAT LEAK, TANK [W]	*3.32*	*3.22*	*1.67*	*1.16*	*1.83*	*1.27*
HEAT FLUX, TANK [W/m²]	*3.95*	*3.83*	*1.99*	*1.38*	*2.18*	*1.51*
TANK REDUCTION	-	-	*50%*	*64%*	*45%*	*61%*
HEAT LEAK, LBMLI [W]	*1.46*	*1.63*	*0.56*	*0.25*	*0.65*	*0.30*
HEAT FLUX, LBMLI [W/m²]	*1.74*	*1.94*	*0.67*	*0.30*	*0.77*	*0.36*
LBMLI REDUCTION	-	-	*62%*	*85%*	*55%*	*82%*

Overall, RBO-II testing of LBMLI was successful and highlighted the advantages of vapor cooling LBMLI. During 90K active cooling, the total heat leak through the 19-layer LBMLI blanket was 0.65 W, an 18% reduction compared to the 30-layer tMLI blanket used in RBO-I and a 56% reduction in heat leak per insulation layer. Tank heat leak is similarly reduced, with a 45% measured reduction during 90K active cooling. Such improvements are accentuated during 80K cooling.

An important takeaway from the Table 4 is that the models under-predicted heat leak values for 80K and 90K warm boundary temperatures. Low warm boundary temperatures apply to tube-on-shield actively-cooled LH2 systems that commonly use nitrogen and neon as process gas. Several cryogenic test programs have found that current thermal modeling tools are not accurate for such systems by as much as 2x margin. The reason for this is not clear; further investigation is needed to acquire additional data. These modeling discrepancies have been observed for both Discrete Spacer Technology™ insulations and conventional MLI blankets, using both energy network solvers like TAK and CAD-based tools such as Thermal Desktop.

5. Vapor-Cooled Structures

Significant benefit can also be realized by applying vapor cooling concepts to structural components such as tank skirts and struts. Quest's Vapor Cooled Structure MLI (VCSMLI) technology was selected for development under a NASA SBIR Phase I contract and continuation in a Phase II. The primary goal of this R&D work was to design, model, build, and test prototypes to demonstrate reduced heat leak by vapor cooling realistic tank support elements. Specifically, VCSMLI prototypes would reduce tank skirt heat leak by 50% in a flight-like design with low mass to further NASA's efforts to achieve reduced or even zero boil-off of cryogenic propellants. A Phase I test article successfully proved concept feasibility and established a design path for tank skirts. Two Phase II prototypes built upon the successes of Phase I to further reduce tank system heat leak, improve fabrication processes, and lower VCSMLI mass at relevant scale.

5.1. Design & Modeling

A 2nd generation 20L small-scale test article validated a unique skirt design containing integrated flow channels, shown in Figure 8, that passes gas through an S-shaped "serpentine" pattern fed by passive boil-off collected from the neck tube and directed along the tank surface to inlet manifolds. The skirt plate was constructed of 0.13" thick 304SS with flow channels machined to a depth of 0.06" by 2" wide before being rolled to the proper curvature. Hermetic sealing of the vapor flow channels was accomplished by a thin 5mil composite outer face sheet made of G10 fiberglass. PPG PR-1564 two-part polyurethane adhesive was used to bond the face sheet to the skirt plate. Bonding surfaces were first primed with PPG PR-420 two-part primer (orange visible in Figure 9) designed to enhance coupling of PPG PR-1500 series potting compounds.

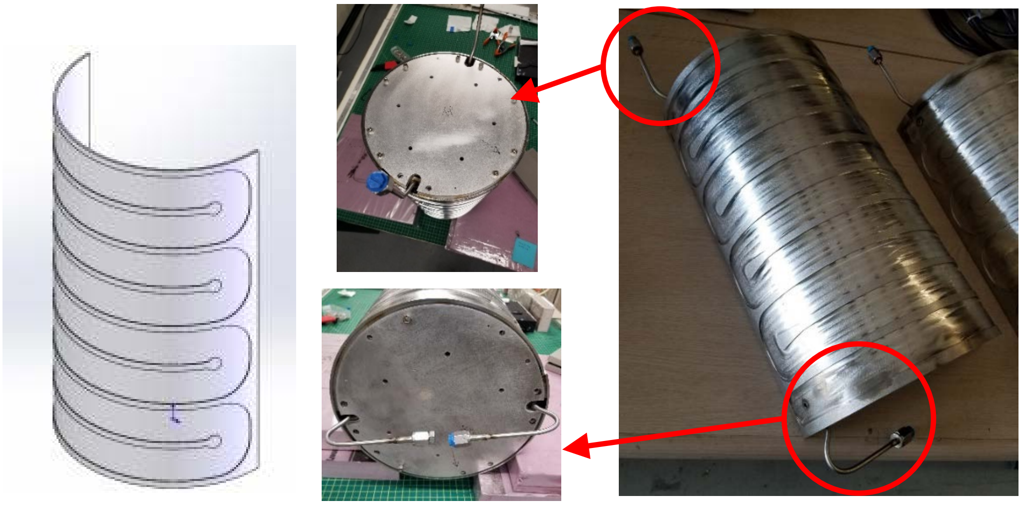

Figure 8: 20L tank skirt design with integrated vapor flow channels and manifolding

Figure 9: 20L vapor cooled skirt test article; orange primer applied to skirt surfaces to promote bond strength for composite face sheet

Preliminary analyses confirmed that such a design would meet all structural requirements as a lightweight high-strength solution. The design was analyzed for an internal flow pressure of approximately 1 atmosphere, with test coupons successfully pressure tested beyond 30 psi. Two half-shell skirt panels were fastened to the 20L tank (Figure 9) to form a skirt. Five layers of IMLI were used to insulate overtop of the skirt vapor transport layer. Additionally, the 20L tank was also insulated with 10 layers of IMLI. Lastly, a single layer of DAM was added to the inner surface of the skirt to lower emissivity.

Figure 10: (left) 400L tank with girth ring; (right) test article assembled prior to IMLI install

A larger 400L mid-scale test article was also built. Using the same design concepts, this larger skirt assembly consisted of five panels fastened to a girth ring (Figure 10) to replicate real tank structural integration. Skirt panels used the same serpentine flow channel pattern with additional plumbing and manifolding as needed.

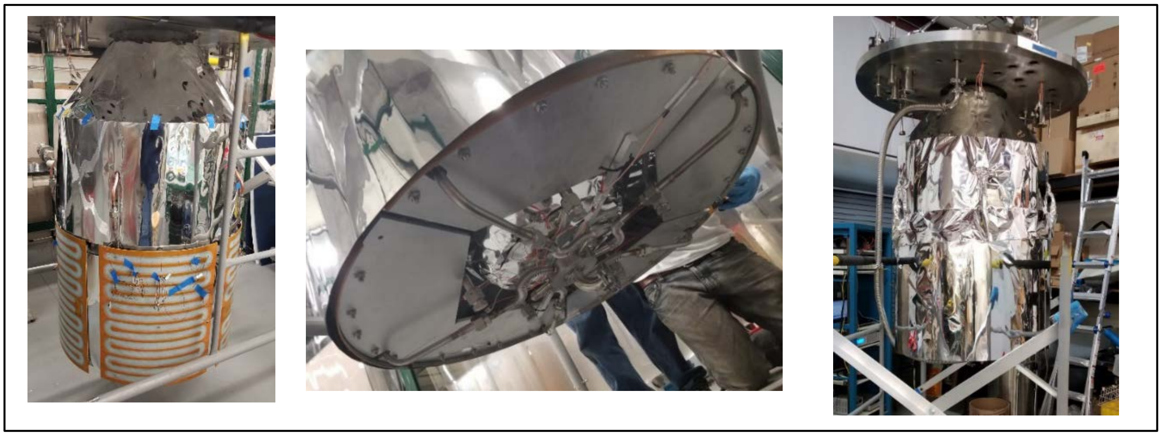

Figure 11: (left) 400L tank skirt with serpentine cooling flow; (middle) lower manifolding for cooling flow channels; (right) fully-assembled 400L test article with IMLI

The 5-layer IMLI blanket for the 400L tank was designed as two conical sections covering the hemispherical ends and barrel sections above and below the girth ring on the cylindrical section. Lightweight sheet metal blanket supports were constructed to raise the blanket mating surface and change the shape from a dome to cone, which is easier to design, fabricate, and install. Five layers of IMLI insulated overtop of the skirt vapor transport layer.

5.2. VCSMLI Test Results

Baseline tank-only testing allowed analysis to quantify the net effect of each component and function in the VCSMLI system. The 20L test article was evaluated in five LN2 operation modes:

1) Baseline, tank-only without the skirt installed
2) High-ε skirt surface, no cooling or IMLI insulation
3) Low-ε skirt surface, no cooling or IMLI insulation
4) Low-ε skirt surface with IMLI insulation, no cooling
5) Low-ε skirt surface with IMLI insulation and cooling

Liquid nitrogen boil-off calorimetry at Quest's facility in Arvada, CO. Results with LN2 for the 20L test article are presented in Table 5 and Table 6; System refers to Tank plus Skirt heat load. Reduction percentages are calculated in relation to operating mode (2).

Table 5: 20L LN2 testing, heat leak results

OPERATING MODE, HEAT LEAK [W] 20L TEST ARTICLE		**MODELED**	**MEASURED**	**DIFFERENCE**
(1) baseline, tank-only	-	*1.93*	*1.05*	*46%*
(2) non-cooled, non-insulated High-ε inner skirt surface	Skirt	*26.1*	*24.3*	*-7%*
	System	*28.0*	*26.3*	*-6%*
(3) non-cooled, non-insulated Low-ε inner skirt surface	Skirt	*10.9*	*8.24*	*-24%*
	System	*12.8*	*10.2*	*-21%*
(4) non-cooled, insulated	Skirt	*8.74*	*8.86*	*1%*

Low-ε inner skirt surface	System	*10.7*	*10.8*	*1%*
(5) cooled, insulated Low-ε inner skirt surface	Skirt	*5.14*	*5.53*	*8%*
	System	*7.07*	*7.74*	*6%*

Table 6: 20L LN2 testing, heat flux reduction

OPERATING MODE, HEAT LEAK REDUCTION 20L TEST ARTICLE		**MODELED**	**MEASURED**
(3) non-cooled, non-insulated Low-ε inner skirt surface	Skirt	*58%*	*66%*
	System	*54%*	*61%*
(4) non-cooled, insulated Low-ε inner skirt surface	Skirt	*67%*	*64%*
	System	*62%*	*59%*
(5) cooled, insulated Low-ε inner skirt surface	Skirt	*80%*	*77%*
	System	*75%*	*72%*

Results with LN2 for the 400L test article are presented in Table 7 and Table 8. Reduction percentages are calculated in relation to operating mode (2). The 400L test article was evaluated in four LN2 operation modes:

1) Baseline, tank-only without the skirt installed
2) Low-ε skirt surface, no IMLI insulation or cooling
3) Low-ε skirt surface with IMLI insulation, 50% cooling
4) Low-ε skirt surface with IMLI insulation, 100% cooling

Table 7: 400L LN2 testing, heat flux results

OPERATING MODE, HEAT LEAK [W] 400L TEST ARTICLE		**MODELED**	**MEASURED**	**DIFFERENCE**
(1) baseline, tank-only	-	*5.63*	*5.97*	*6%*
(2) non-cooled, non-insulated	Skirt	*5.80*	*4.68*	*-19%*
	System	*11.8*	*10.7*	*-10%*
(3) 50% cooled, insulated	Skirt	*3.20*	*1.43*	*-55%*
	System	*9.20*	*7.43*	*-19%*
(4) 100% cooled, insulated	Skirt	*3.00*	*2.99*	*~0%*
	System	*9.00*	*8.99*	*~0%*

Table 8: 400L LN2 testing, heat flux reduction

OPERATING MODE, HEAT LEAK REDUCTION 400L TEST ARTICLE		**MODELED**	**MEASURED**
(3) 50% cooled, insulated	Skirt	*45%*	*69%*
	System	*22%*	*30%*
(4) 100% cooled, insulated	Skirt	*48%*	*36%*
	System	*24%*	*16%*

Liquid hydrogen boil-off testing performed for the 20L prototype at Integrated Engineering Systems (now Agilitech) in Bakersfield, CA. Results with LH2 for the 20L test article are presented in Table 9. The 20L test article was evaluated in three LN2 operation modes:

1) Baseline, tank-only without the skirt installed
2) Low-ε skirt surface, no IMLI insulation or cooling
3) Low-ε skirt surface with IMLI insulation and cooling

Table 9: 20L LH2 testing, heat flux results & reduction

Heat load [W] 20K to 295K	**Baseline Tank-only**	**Non-cooled Non-insulated**		**Cooled Insulated w/ IMLI**			**Heat leak reduction**	
		<u>Skirt</u>	<u>System</u>	<u>Skirt</u>	<u>System</u>		<u>Skirt</u>	<u>System</u>
MODELED	*2.00*	*28.6*	*30.6*	*1.04*	*3.04*		*96%*	*90%*
MEASURED	*2.10*	*30.9*	*33.0*	*2.25*	*4.35*		*93%*	*87%*
DIFFERENCE	*5%*	*8%*	*8%*	*116%*	*43%*		*-3%*	*-3%*

Compared to the non-cooled non-insulated high-emissivity skirt (mode (2)), measured 20L LN2 heat flux was reduced by 77% and 72% for the skirt and system, respectively. Thermal predictions from TAK models for LN2 testing agreed within 10% of measured values, with minor exceptions for operating modes (1) and (3). Model predictions for 100% LN2 cooling on the 400L matched the measured heat leak almost exactly. The 400L skirt was also tested at 50% LN2 cooling to identify the effect of partial cooling. At 50% cooling, the heat leak measured through the 400L tank skirt was reduced by 69%. As previously discussed, hydrogen is much more effective for vapor cooling due to 12x higher heat capacity. Therefore, LH2 cooling on the 20L tank was significant with over 90% reduction in skirt leak. Model correlation for LH2 cooled and insulated skirt was not as good as with LN2. However, heat leak reduction fell within 3% of predictions.

Overall, vapor cooling of structural elements was effective. As expected, temperatures strategically measured along the skirt surface of both prototypes decreased with vapor cooling. Heat leak reduction percentages using nitrogen were higher for the 20L test article than the 400L. One possible explanation is the conductance between the skirt to the tank. The 20L skirt was attached using an aluminum plate bolted directly to bottom of the tank whereas the 400L skirt was attached with a stainless-steel ring clamped and metal-taped to the tank.

Table 10: Comparison of vapor cooling performance metrics

	Structural heat reduction	**Efficiency [W/kg/m²]**	**DCSS 2-skirt heat removed [W]**
TUBE-ON-SHIELD [1]	*36 – 50%*	*700*	*1540 – 2140*
TUBE-ON-SKIRT [2]	*50 – 67%* [4]	*1300*	*2140 – 2870*
VCSMLI [3]	*93%*	*11700*	*3967*

[1] Based on use of Broad Area Cooled (BAC) shield, RBO-I study preliminary results, GRC. Note this is for a BAC shield on a tank using active vapor cooling, %HR was 36%, could be up to 50%.

[2] From [2], and data from the 2016 eCryo Workshop, GRC. Uses vapor cooling boil-off, based on theoretical models from EUS tank with spiral tubing. Mass converted from 136 kg for EUS size to 43.1 kg for DCSS skirts. %HR taken from [2], applied to estimated DCSS skirt Q of 4283 W.

[3] Measured test data from final VCSMLI design with flow channels machined into skirt with 5mil G10 vapor layer.

[4] This reflects a ~55% heat flux reduction, from a model, with cooling tubes separate by 3.3 m.

Results show that VCSMLI compares favorably with current state-of-the-art tube-based cooling methods, as described in Table 11. Cooling efficiency can be compared using an Efficiency figure of merit with units of $W/kg/m^2$, which quantifies the heat removed per areal mass. The comparisons in Table 11 illustrate the clear advantages of VCSMLI for tank structural elements compared to traditional tube-based methods. VCSMLI provides approximately 2x higher heat leak reduction with much lower mass for a Vapor Cooling Efficiency that is a full of magnitude greater. Similar conclusions are apparent in the comparison for the Dream Chase Space System LH2 propellant tanks as an example of a real-world application.

6. Conclusions

Zero boil-off storage of cryogenic propellants for long-duration missions was previously ranked as the #2 technical challenge in NASA's Technology Roadmap. New technologies are necessary to effectively store and transfer cryogenic fluids in space to support NASA's future exploration goals. Advancements in active cooling technology may help unlock reduced or zero boil-off systems. Vapor cooling is a critical component of such advancements and is becoming a preferred method for reducing boil-off for cryogenic propellant tanks and extending hold times.

This paper reports on test results for three different vapor-cooled insulation systems: (1) foam-based materials for broad acreage storage tanks, (2) next-generation MLI based on Quest Discrete Spacer Technology™ for broad acreage storage tanks, and (3) next-generation MLI for tank support structures. The results of all three insulation systems clearly show the benefits of vapor cooling with varying levels of performance, and also highlight the need for continued investigation into refining modeling techniques to accurately predict performance, particularly at low warm boundary temperatures that apply to vapor-cooled hydrogen systems.

Foam has been a common aerospace insulation material choice for decades, and represents a familiar low-cost solution for cryogenic storage. Passive vapor cooling with nitrogen of a commercial polyurethane foam reduced system heat leak by 13.6%. Limited testing of vapor cooled foam for cryogenic storage is discussed in the literature. Additional testing and modeling refinement, particularly with hydrogen, will help characterize foam materials at cryogenic temperatures.

Discrete Spacer Technology™ represents the first MLI advancement in over 50 years, and possesses several advantages over conventional netting-based MLI. NASA evaluated LBMLI paired with an 80K neon gas cryocooler and integrated tube-on-shield network, and showed that active cooling reduced the heat leak into a tank system by 50%. LBMLI also retains key structural capabilities that make it a potentially attractive insulation solution when designing future long-duration cryogenic storage.

Vapor cooling can also provide thermal benefit for tank structural elements. Quest designed and tested a mid-scale 400L test article that reduced tank support skirt heat leak by 69% with passive LN2 cooling using a novel skirt design that combined an integrated vapor transport layer and IMLI blankets. Quest also directly compared the enhanced cooling capacity for hydrogen versus nitrogen using a small-scale prototype, showing a 93% reduction in tank support skirt heat leak.

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