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Self-Supporting, Cryogenic Propellant Insulation for Launch Vehicles

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Abstract

Cryogenic propellant storage is a critical component of cislunar transportation and long duration space travel. Launch loads from Earth complicate the challenge, as thermal insulation is often not structurally stable by itself. Ball Aerospace and Quest Thermal are providing an update on Integrated Multi-Layer Insulation (IMLI) and its variants that form structural insulation. Discrete Spacer Technology™ can reduce heat flux while providing load supporting benefits for a number of applications, including new technology for launch vehicle insulation. Updates on launch vehicle insulation systems, including the latest Phase II SBIR test results, will be provided in this session.

Discrete spacer systems can provide robust, structural MLI for launch vehicle applications. Ruggedized IMLI can withstand aerodynamic loads. Load bearing and cryopumping systems on launch vehicles can replace SOFI with lower heat flux both in-air and in-space. Vapor cooling systems (Vapor Cooled Structure MLI) can reduce heat leak through tank supports. Building on initial testing done in 2018, VCSMLI continues to progress. Heat flux reductions have been proven and VCSMLI was tested on larger tanks/skirts and at colder temperatures. The construct of the MLI inherently bears loads and it is the unique combination of load bearing characteristics plus heat flux reduction that makes this technology applicable in a variety of situations. Potential applications are launch vehicles, in space transportation, propellant storage facilities in space and on other bodies such as the moon, and long duration space flight.

Quest Thermal Group & Ball Aerospace have partnered to develop a vapor cooled thermal insulation to reduce heat leak through tank supports. Vapor Cooled Structure MLI (VCSMLI) is a novel system that uses a sealed vapor transport layer within IMLI for lightweight, efficient vapor cooling of tank skirts and struts. We discuss the results of recent testing performed on a more advanced vapor cooled structure prototype on a 400 litre liquid nitrogen tank skirt and its applications for exploration missions and in-space transportation.

1. Introduction

Improvements in cryogenic propellant storage are a critical need for future NASA missions, with zero boil off cryogenic propellant an important goal. Specifically, NASA has a high priority for simple mass efficient techniques for vapor cooling of structural skirts on large upper stages.

Integrated Multilayer Insulation (IMLI) is an advanced MLI that has been in development by Ball Aerospace and Quest Thermal Group since 2007. It uses bonded polymer spacer posts instead of netting, as shown in figure 1. IMLI has high performance with 50% lower heat leak per layer then conventional netting MLI as measured by the NASA KSC Cryogenic Test Lab. IMLI is robust; the bonded polymer spacers create a rugged structure which can self-support a large number of layers during launch loads and enables effective insulation of large structures such large spacecraft and fuel depot tanks. Conductance and overall heat leak can be accurately modeled using standard thermal network methods (such as SINDA).

Ball Aerospace and Quest Thermal Group have developed several advanced thermal insulation systems for NASA that use discrete spacers to provide robust, structural insulation, as shown in Table 1. IMLI flew on the NASA RRM3 mission in 2018 and the NASA GPIM mission in 2019, and is now at TRL 9 [1,2].

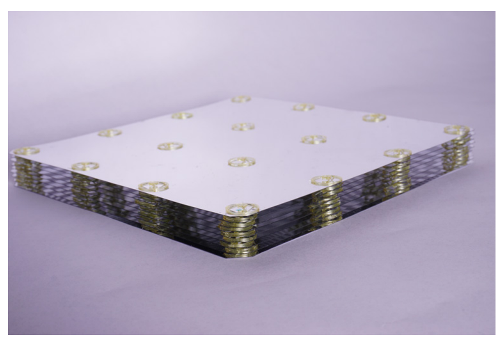

Fig 1. IMLI polymer spacers bonded to aluminized Mylar

Load Responsive MLI uses spacers to self-support a thin vacuum shell, allowing operation both in-air and on-orbit, providing good performance in-air and high performance in-space [3]. Launch Vehicle MLI, a ruggedized IMLI, can insulate the exterior walls of launch vehicle cryotanks, be exposed to the launch slipstream, and provide substantially reduced heat flux than Spray On Foam Insulation (SOFI) [5].

Load Bearing MLI completed testing in a Phase III NASA multicenter program (Glenn, Marshall, Ames and Kennedy) for Reduced Boil Off on Large Liquid Hydrogen Tanks, gave 37% lower heat leak than traditional MLI with tank standoffs supporting a Broad Area Cooled thermal shield [4].

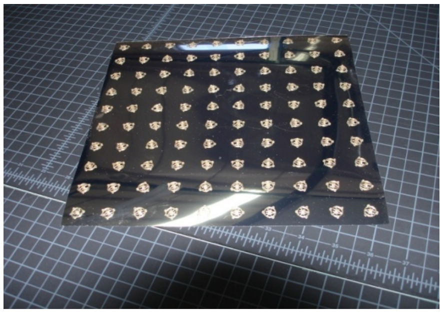

Fig 2. Launch Vehicle MLI uses discrete spacers to support bonded layer structure.

Vacuum Cell MLI (VCMLI) is another novel insulation designed for launch vehicle application. VCMLI uses a compartmentalized, cellular structure containing a selected gas species that is cryopumped at cryogenic temperature to provide high internal vacuum for high thermal performance. VCMLI offers some unique properties, such as high thermal performance and the ability to insulate cryopropellant tanks pre-launch without purge gas or air frost buildup, and excellent structural strength [6].

2. VSCMLI overview

Vapor Cooled Structure MLI (VCSMLI) is a novel system that uses discrete spacers to create a sealed vapor layer within IMLI for lightweight, efficient vapor cooling of tanks skirts. In this program, VCSMLI was modeled, designed, fabricated, installed on tank skirts and its thermal performance measured. VCSMLI uses discrete spacers and the controlled internal layer space to create and support a sealed vapor transport inner layer. The sealed vapor layer is in thermal contact with the tank support (skirts or struts), and cold vapor boiloff from the cryogenic tank (or cooling fluid from a cryocooler) is distributed through the vapor layer to vapor cool the tank skirt, reducing heat flux to the cryotank.

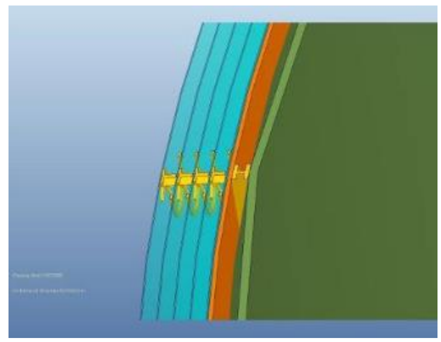

Fig 3. Inner vapor transport layer (orange) is created and supported by new custom discrete spacers

Table 1. A family of insulation systems have evolved based on the discrete spacer technology

	Application	Development Status	TRL
Integrated Multilayer Insulation (IMLI)	In space and high vacuum	Phase 3 SBIR completed, 1st spaceflight 2018	9
Load Bearing Multilayer Insultation (LBMLI)	Supports thermal shields for active cooled systems	Phase 3 SBIR completed	5
Vapor Cooled Structure MLI (VCSMLI)	Vapor cools tank support elements	Phase II SBIR complete	5
Cellular Load Responsive MLI (CLRMLI)	Replaces SOFI on launch vehicle cryotanks	Phase II SBIR complete	4
Vacuum Cell Multilayer Insulation (VCMLI)	Replaces SOFI on launch vehicle cryotanks	Phase I CRAD complete	4
Multi-Environment MLI (MEMLI)	Operation in environments from space to on-Mars	Phase II SBIR in progress	4
Micrometeorite and Orbital Debris MLI (MMOD MLI)	Thermal insulation and MMOD protection	Phase I SBIR complete	3
Variable Conductance Radiator Variable Gas Radiator	Spacecraft thermal control	Phase II SBIR in progress	4

3. VCSMLI Thermal Modeling

A preliminary thermal model of a Vapor Cooled Structure consisting of an inner vapor layer and 5 outer IMLI layers, cooling a stainless-steel skirt (0.040" thick), on a 400L LN_2 tank with 20 IMLI layers of insulation was created (0.5W/m^2 through IMLI). The warm boundary is 295 K. Heat flux through tank IMLI is 1.27W. Stainless steel skirt is 32" ID, wall thickness 0.040", 25" length.

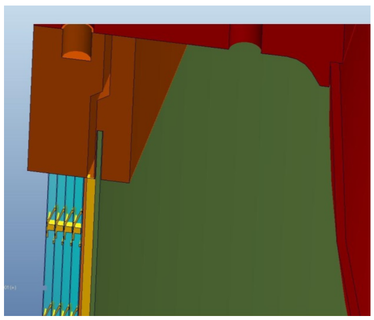

Fig 4. VCSMLI attached to outside of skirt. Vapor manifold is built into mounting for VCS, vapor transport layer shown in orange.

Predictions show five IMLI layers on the tank and a non-insulated, non-cooled skirt have a predicted total heat leak of 4.61 W. Adding a cooled VCS system over the skirt gives an estimated heat leak of 3.04 W, a 34% reduction in baseline total tank and skirt heat leak. If the skirt is cooled via the VCS system and insulated with five external IMLI layers (the full VCSMLI system includes integrated insulation), the heat leak would be 2.54 W, for a 45% reduction in total tank plus skirt heat leak. Heat leak through the skirt was predicted to be reduced from 3.56W to 1.50W, a 57% reduction. Thermal modeling calculated gas flow rates of 0.013 to 0.023 g/s, for expected vapor volume flow rates between 0.0029 L/sec and 0.054 L/s (depending on vapor exit temperature and test pressure). The 20L tank has adequate LN_2 capacity for thermal testing with these vapor flow rates. An 11.5" diameter Stainless Steel skirt with five layers IMLI insulation was selected as the baseline Phase I prototype after modeling various configurations. Phase I testing used LN_2 boiloff calorimetry, and therefore the cold boundary temperature is approximately 77K, and a heater was incorporated into the test setup to heat the bottom surface of the skirt to 295K for warm boundary temperature control.

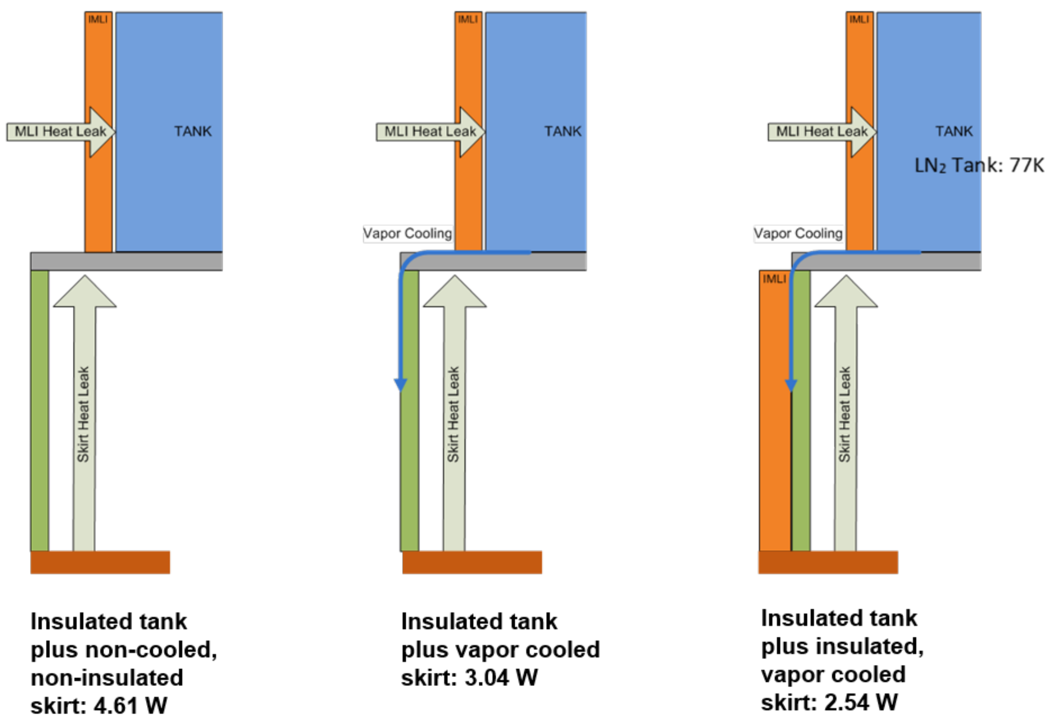

Fig 5. Modeled configurations

From the flow rate data predicted, analysis of the flow path helped define flow requirements for the VCS. Test protocols for both a high pressure (760 torr) and low pressure (155 torr) test condition were developed, with flow rates of 0.065 L/s (77K @ 155 torr) or 0.003 L/s (77K @ 760 torr). The thermal test was run at a reduced pressure of approximately 100 - 150 torr (above the triple point of LN_2), where the VCS would only have a 3 psi pressure differential across its surface. In Phase I, the VCSMLI prototype could only operate at 3 PSI differential. Testing at a reduced pressure was implemented by actively pumping the vent line with a pressure controller in line set to 103 torr.

In Phase II, VCSMLI test articles achieved up to 60 psi operating pressure. Several new spacer concepts were developed, including Ultem spacers, embossed spacers, and finally spacers formed integrally from the skirt wall (machined-in-wall flow channels). New vapor manifolds and sealing techniques were developed. Multiple prototypes were built and tested, several failures occurred and underwent root cause analysis. A new spacer was developed using spacers formed integral to skirt wall, these machined-in-wall flow channels were sealed with 5mil FR4/G10 facesheets, vapor flow and pressure drop were modeled, analyzed and measured for several flow channel concepts, and a single "S-flow" channel design selected.

TAK and Thermal Desktop models were refined as experimental data was obtained throughout the program and used to compare to measured heat flows, with good agreement between model and test data - model heat flows were typically within 4 – 8% of measured heat flows

4. Design trades

A vapor layer spacer was designed and used to control the vapor layer thickness and allow vapor flow. During the conceptual design phase, geometry and manufacturing methods for the spacer were studied. Custom spacer geometries were considered. After considering the thermal and structural requirements for heat transport within the vapor layer, a simple rectangular polymer spacer was selected for the Phase I prototype. Attachment methods and spacing were evaluated to assure adequate structural strength. The bond strength of the spacers with adhesive was evaluated and appeared strong enough to withstand calculated peel strength requirements, and there is extensive experience with adhesive at cryogenic temperatures.

The VCSMLI ground test article thermal performance testing was done in a vacuum chamber and depending on the boil off rate and the vacuum pump speed (ability to remove the boiloff from the vacuum chamber and maintain high vacuum), the VCS may be able to operate as low as 2.5 psi pressure differential or high as 14.7 psi. Note testing at a low differential pressure is mainly an artifact of the testing methodology, not an operational requirement. Nonetheless, the intent was to create as strong a VCS system as possible keeping mass as a critical design factor.

Use of discrete spacers is a major component of VCSMLI. Design factors for the spacer include the ability to control and maintain a determined vapor transport layer thickness, ability to allow free movement of gas species through the vapor layer, strength of the outer vapor layer "skin" when bonded or attached to the spacers (in order to allow the highest possible internal operating pressure within the VCS), and low cost.

The dimension of the vapor transport layer was analyzed and considered. The narrower the vapor layer, the better heat conduction and removal. A narrow 0.03" vapor channel, for example, would provide good gas flow rates for typical calculated vapor mass flows. Higher flow rates are desirable up to the point of causing a large pressure drop across the VCS. Mechanical constraints limited the Phase I prototype vapor channel to 0.06" thickness.

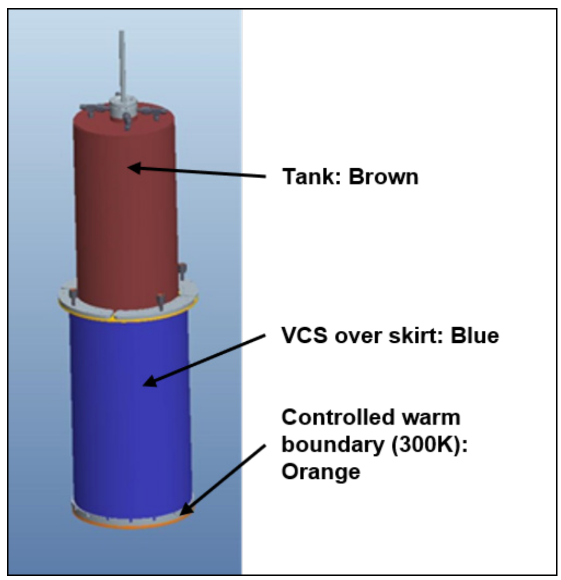

Fig 6. Conceptual Design: Skirt was suspended from tank due to vacuum chamber constraints. Warm boundary was controlled via a heater plate at bottom of skirt.

Outer vapor layer skin has various characteristics including strength, ability to be hermetically sealed, low emissivity (on the outer surface), low thermal conductivity along the longitudinal axis of the skirt, low mass and low cost. Due to limited mounting features in the vacuum chamber it was decided that the skirt would be suspended from the tank and the bottom of the skirt heated and temperature controlled as the warm boundary.

Vapor flow was carried from the neck tube vent line at the top of the tank via four copper lines that were in thermal contact with the tank going down the tank, that fed cold vapor into an upper manifold at the top of the skirt. Gas was distributed in quadrants in the upper manifold, then via orifices and slots into the VCSMLI vapor transport layer. A lower manifold collected the vapor to vent (to space normally; for ground testing to a line that ran outside the vacuum chamber to a flow meter and pump intake).

5. VCSMLI Small Tank Prototype Fabrication, Installation and Testing

With the Phase II flat panel coupon testing and thermal modeling complete, the S-flow vapor channel was selected for the next skirt prototype design. The Quest and Ball Aerospace team decided that the S-flow was preferable, and provided higher pressure drop resulting in greater heat transfer into the gas flowing along the channel. Thermal analysis of the S-flow was performed and compared the Quest integrated VCSMLI method with current state of the art tube-on-skirt vapor cooling. The vapor transport layer was created by machined-in-wall channels in 1/8" thick 304 stainless steel hermetically sealed with a lightweight composite face sheet. The vapor distribution manifold was simplified from previous designs as a result of lessons learned. The manifold consisted of a small machined 304 stainless steel block with cross drilled holes to accept 1/4" SS tubing. The tubes had a gland (with nut) welded at the ends to mate up to pre-existing flow lines on the tank. The block was designed to reduce the contact area to the roll formed panel to two edge features with thickness similar to the roll formed panel. After successfully dry-fitting the VCS panels and mounting hardware, the panels were surface prepped and the face sheet bonded. The panels were allowed to fully cure for 7 days at room temperature. The panels are shown in figure 7 below.

After the panels were installed and covered with IMLI the 20L VCS prototype could be mounted inside the vacuum chamber and pumped down. After being allowed to pump overnight, the chamber achieved good vacuum at approximately 1.2E-5 mbar. An LN_2 dewar was connected to the stinger port to start filling the 20L tank. The heater plate was switched on to maintain 295K. A vent port was added to the stinger port to allow excess pressure build-up during the tank fill process to vent out rather than being collected in the vapor manifold and passing through the VCS panels. This was a precautionary step taken to ensure the VCS panels experienced minimal pressure differential beyond ~1 atm from high vacuum. The 20L was filled in approximately 2 hours, at which point both the stinger and vent ports were sealed with compression fittings to direct all boil off gas through the VCS panel inlets, then out through the chamber lid pass-through, and finally through the flow meter in the DAQ system. After initial tank fill, the chamber pressure had dropped to 8.6E-7 mbar.

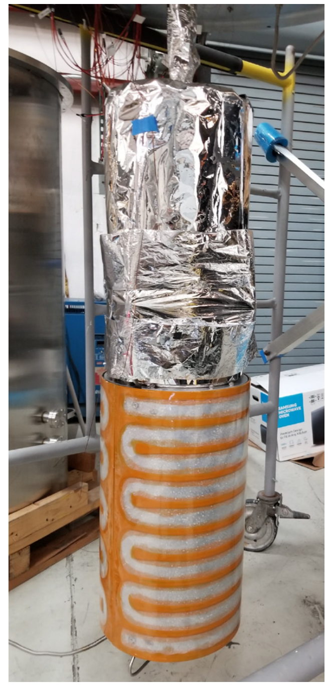

Fig 7. Panels installed on Phase II 20L tank/skirt prototype.

Tests were performed with four different configurations summarized in the table below. The results from all four VCS configurations are summarized in the table below. From the calculations, there is an interesting result from the low-emissivity non-cooled & non-insulated test compared to the non-cooled & insulated test. A likely explanation is that the emissivity is the primary factor in determining the heat leak of the VCS skirt. The 5 layer IMLI blanket accomplishes the same goal with the added insulating benefit. In this particular application, 5 layers of IMLI are likely unnecessary – the same performance could be attained with fewer than 5 layers. This indicates that the majority of the insulating benefit from the IMLI is taken up in the first layers of blanket. Adjusting the emissivity of the skirt surface in the TAK model to 0.028 for aluminized Mylar predicts a heat leak of 12.81 W, measured results were 20.6% lower. It is interesting to note that the heat leak for three of the four VCS configurations tested, the low-emissivity non-cooled & non-insulated case being the exception, are within 10% of the predictions made by the respective thermal models.

Overall, the measured results were in good agreement with the values of heat leak predicted by the thermal model, which validates the thermal models. The skirt and system (tank + skirt) measured heat leak was reduced by 58% and 54%, respectively, simply by reducing the skirt surface emissivity from 0.30 to 0.028. Adding the 5-layer IMLI skirt blanket and passing LN_2 boil off through the VCS channels reduced heat leak by another ~20%. The cooled & insulated VCS skirt was measured to have 75% less total heat leak compared to the high-emissivity non-cooled & non-insulated system.

Table 2. Summary of heat leak results for LN_2 boiloff from all four VCS configuration on 20 litre tank

Heat leak @ 295-77K	Non-Cooled Non-Insulated Skirt (e=0.3 SS)		Non-Cooled Non-Insulated Skirt (e=0.028 VDA mylar)		Insulated Non-Cooled skirt		VCSMLI Insulated Cooled skirt	
20L SS 5Lyr on tank	Skirt only (W)	Tank + skirt (W)	Skirt only (W)	Tank + skirt (W)	Skirt only (W)	Tank + skirt (W)	Skirt only (W)	Tank + skirt (W)
Modeled	26.11	28.04	10.88	12.81	8.74	10.67	5.14	7.07
Measured	24.33	26.26	8.24	10.17	8.86	10.79	5.53	7.46
Modeling Difference	-7%	-6%	-24.3%	-20.6%	1%	1%	8%	6%

6. Liquid Hydrogen Testing

Liquid Hydrogen testing was performed on the 20L VCS prototype at Innovative Engineering Solutions (IES) in Murrieta CA. Three tests were performed, tank baseline heat flux, tank and skirt heat flux with a non-insulated non-cooled skirt, and heat flux with VCSMLI insulated, vapor cooled skirt.

Data was collected to evaluate the effectiveness of the VCS system with LH_2/GH_2 cooling. Total system heat leak reduced from 33.0W to 4.35W with the VCS in operation. This is an 87% reduction in heat leak between the non-cooled and vapor cooled configurations. With the exception of the cooled test measured data corresponds well with the thermal model. The non-cooled test was only 8% higher than the model predicted, while the tank only was 5% higher. The 43% difference between modeled and measured of the cooled system is mostly due to the limited time of the test and would be much improved if the test had been run longer and a true steady state condition reached. The skirt heat leak was calculated by subtracting the tank only heat leak from the total heat leak of the system. Skirt heat leak was reduced from 30.93 W to 2.25 W, a substantial 93% reduction.

As a comparison the Nitrogen testing also showed vary good agreement with the thermal model. The non-cooled non-insulated test was within about 6% of the model similar to the Hydrogen test being within 8%. The nitrogen test was within 6% of modeled for the cooled test as well, this leads to the theory that given a longer test duration the hydrogen cooled test may have achieved similar performance to the thermal model predictions.

Table 3. Summary of heat leak results from the LH2 testing on the 20 litre tank

LH_2 Testing	Non-cooled Skirt		VCSMLI Vapor Cooled skirt		Tank Baseline
VCSMLI on SS skirt	Skirt only (W)	Tank + skirt (W)	Skirt only (W)	Tank + skirt (W)	Tank Only (W)
Measured	30.93	33.03	2.25	4.35	2.1
Modeled	28.6	30.6	1.04	3.04	2.0
Difference	8%	8%	116%	43%	5%
Modeled heat flux reduction			96% (skirt)	90% (total)	
Measured heat flux reduction			93% (skirt)	87% (total)	

7. VCSMLI Large Tank Fabrication, Installation and Testing

Lessons learned and techniques developed for the small scale 20 L test article were used for a larger 400 L tank/skirt prototype. A girth ring weldment was designed and fabricated that would allow a temporary assembly suitable to support the tank skirt without welding the assembly to the tank. The girth ring included a clamping mechanism to accommodate tank contraction due to temperature changes. It is expected that the girth ring should support in excess of 100 lbs, capable of supporting the skirt panels. The mass estimate of each of the VCS panels is approximately 11 lbs., for a total mass of 55 lbs. The skirt was suspended from the tank similarly to the small test tank to avoid having to design a true structural tank support capable of holding both the tank and liquid cryogen. This was deemed a simpler, safer method and allows a suitable simulation of a flight-type structural support. The tank is rigidly supported via the SS neck tube and suspended in the high vacuum chamber. The bottom plate was temperature controlled and held at 295.0K as the warm boundary.

Vapor channel design choice for the 400L build was to machine the spacers directly into the panel. This would alleviate the need to bond individual spacers as was done with the small scale build and would align well with early structural testing performed. Once the panels are machined, they are rolled to a finish diameter matching up to the girth ring support. The final design has five panels making up the circumference of the 34" diameter girth rings for a panel width of 21.5" and a length of approximately 20". This makes the panel size manageable for machining on standard CNC equipment. Once the panels are machined, they can readily be rolled to the 34" diameter.

Thermal analysis was conducted on the 400L VCS panels using two separate methods. One of the goals was to evaluate and determine the material needed for the skirt and consider the estimated heat leak prior to detailed design of the system. Using the S-flow channel thermal models, preliminary estimates of the solid conducted heat leak were calculated. Generating a 10x10 node array and using TAK to evaluate the conducted heat flow guided skirt material selection to balance tank and skirt heat leaks for the test article.

In looking at the solid conduction through the skirt from the warm bottom plate (295K) to the tank (77K) there is a significant difference in heat leak between aluminum and stainless steel. This stands to reason in comparing the thermal conductivity of aluminum at 205 W/m K and that of 304 SS at 16.2W/m K. What was important in this consideration is the amount of heat leak attributed to the skirt and how it compared to the tank heat leak. In this particular analysis the tank heat leak is estimated at 5.6W so the heat leak of an aluminum skirt would over 20 times higher than the tank heat leak. This would pose challenges in measuring and isolating the contribution of the skirt heat leak and the percentage of benefit from the effects of cooling.

The stainless steel skirt provides a material that can be readily fabricated and have similar heat leak as the tank such that testing a cooled and non-cooled system would show the benefits of the VCS system. Though stainless steel is not likely to be a material used for flight hardware structural supports, it allows demonstration of feasibility of the VCS technology.

400L test sequence evaluated VCSMLI performance on a mid-scale build. The complex curvature and larger geometry required innovative build techniques for successful fabrication, with a smooth installation of finished panels and insulation. Techniques developed would also work for larger scale, more flight-like tanks. The 400L VCSMLI test apparatus allowed four test configurations: tank baseline, 100% vapor cooled skirt, 50% vapor cooled skirt, and non-insulated non-cooled skirt.

Baseline testing was performed first. The test apparatus, shown in Figure 8, consisted of the 400L stainless steel tank with skirt connections capped off, stainless steel girth ring, and 5 layers of IMLI. A new IMLI staggered seam technique was developed for layer thermal matching reduced installation time by more than 75%. A 400L IMLI installation, which normally takes 8 hours, was reduced to 1 hour.

During filling cryopumping occurred with 4.0E-6 torr for the remainder of testing. After filling, boil off and temperature data for the baseline test was collected over three days. Ample testing time achieved multiple steady state periods lasting up to six hours at a time. Four sensors recorded temperatures on the chamber lid representing ambient temperature, upper vapor manifold where liquid nitrogen enters the tank, vapor inlet where the skirt connection was capped, and on the girth ring where the VCS will hang. Four steady state periods were analyzed; once the girth ring cooled, 24 hours later, 48 hours later, and when the girth ring was at its coldest. For the purposes of data comparison within all 400L tests, a steady state period following the initial 24 hour fill period was selected.

The fully insulated 100% skirt area vapor cooled test was performed next. Figure 9 shows the insulated 100% cooled test configuration. The VCS panels were attached to the top of the girth ring and hung to create the tank skirt with VCSMLI. The panels were plumbed to allow vapor cooling throughout the entire VCS skirt's "S" channel, testing 100% cooling capacity.

Fig 8. 400L VCS tank baseline test configuration

Fig 9. VCS 400L test fixture in 100% cooled & insulated configuration; skirt panels installed with heater plates and 100% surface cooling

The insulated 50% cooled 400L VCS test directly followed the fully cooled and insulated test since all test apparatus components remained, with the only difference being where the VCS skirt panels vapor cooling was capped off. Figure 10 shows the test configuration difference from the 100% cooled test. For this test the VCS panels were re-plumbed to vapor cool only 50% of the skirt surface. This evaluates the difference in measured heat leak between a fully cooling and partially cooling skirt and tank. The potential benefit being if the first half of the skirt performs the most cooling then VCS size can decrease to reduce system mass and foot print, simplifying fabrication and installation.

The non-insulated and non-cooled test evaluated the heat leak of the insulated tank and skirt without vapor cooling. The two-layer IMLI blanket was removed from the VCS panels, and the panels were capped off to isolate the tank and skirt; Figure 10 shows the non-insulated non-cooled test configuration.

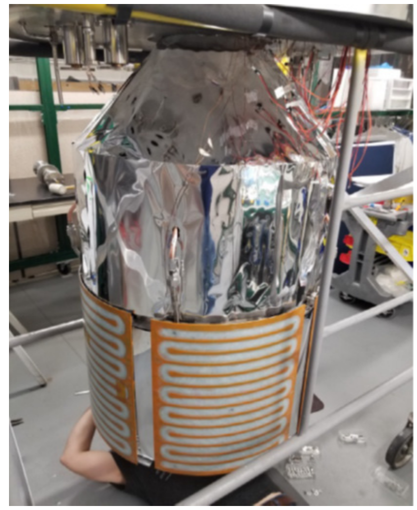

Fig 10. VCS 400L non-insulated non-cooled skirt test configuration

The results are of the 400 L testing are shown in Table 4. With 400L VCS measured data as it stands, the 100% cooled and insulated VCS system offers a 36% reduction in skirt heat leak and a 16% reduction in tank and skirt heat leak. This is slightly less than modeled for the 400L, and much lower than was measured and modeled for the 20L VCS system. The 50% cooled and insulated skirt provided a 69% reduction in skirt heat leak and a 30% reduction in skirt and tank heat leak. This is higher than modeled for the 400L and on par for what was measured in the 20L VCS system. Looking at the insulated cooled skirt from the 20L build, the reduced heat leak for the skirt alone was 77%. Going from an entirely cooled skirt removing 77% of heat leak to a partially cooled skirt removing 69% of heat leak could be realistic.

Table 4. Modeled and measured heat leak of the 400 L VCS.

Heat leak @ 295-77K	Non-Insulated Noncooled Skirt		Insulated Cooled 50%		Insulated Cooled 100%	
400L SS-2 5Lyr on tank	Skirt only (W)	Tank + skirt (W)	Skirt only (W)	Tank + skirt (W)	Skirt only (W)	Tank + skirt (W)
Modeled e=.3	5.80	11.80	3.20	9.20	3.00	9.00
Measured	4.68	10.68	1.43	7.43	2.99	8.99
Modeling Difference	19.3%	-9.5%	-55.2%	-19.2%	-0.3%	-0.1%
			Insulated Cooled 50%		Insulated Cooled 100%	
			% reduction of Non Cooled Skirt		% reduction of Non Cooled Skirt	
			Skirt	System	Skirt	System
Modeled			45%	22%	48%	24%
Measured			69%	30%	36%	16%

8. Conclusions

Discrete spacers allow IMLI and variants to have ruggedized structures, support thin vacuum shells, provide load bearing capabilities or advanced vapor cooling methods, and is an enabling technology for high performance launch vehicle insulation systems.

Vapor Cooled Structure MLI is a high-performance insulation system, with a vapor cooling layer with IMLI layers, that uses an IMLI-like vapor transport layer with high thermal contact to tank support elements. During this Phase II effort, VCS was thermally modeled, and flow analysis used to design a vapor transport layer. Vapor layer shell, discrete spacers, and manifolding were designed, machined channels and composite face sheets were used to create the vapor layer and shell. R&D was conducted in VCSMLI materials, bonding and fabrication processes led to improved vapor layer strength. New vapor layer designs were developed and tested.

- VCSMLI installed on tank skirt provided a 77% reduction in skirt heat leak with LN_2/GN_2, and a 93% reduction in skirt heat leak with LH_2/GH_2 vapor cooling.
- A larger scale 400L tank and skirt had VCSIMLI installed and tested, skirt heat flux was reduced from 4.68W to 1.43W (69% reduction) with LN_2/GN_2 vapor cooling.
- The final VCSMLI prototype was very lightweight, with an areal mass of 0.34 kg/m^2 (compared to 1.9 kg/m^2 for a current tube-on-skirt design)
- VCSMLI is a highly efficient vapor cooling method, with a measured efficiency of 11,700 W/kg/m^2 (heat removed per areal mass), compared to expected efficiency of 1300 W/kg/m^2 for tube-on-skirt
- VCSMLI technology has been successfully demonstrated to be highly effective at removing heat from strut and skirt tank structural elements.
- VCSMLI appears to offer significant advantages in performance and mass over current state-of-the-art tube-on-skirt cooling methods, and should be capable of helping
- NASA and Prime Contractors achieve Reduced Boil Off of passive vapor cooled LH_2 launch vehicle tanks or Zero Boil Off of actively cryocooled cryogenic propellant storage.
- VCSMLI technology might be a good candidate as the baseline vapor cooling method for further NASA testing and development of high performance insulation active systems for Zero Boil Off.
- VCSMLI is now at TRL 5 with breadboard validation in a relevant environment

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