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Wrapped multilayer insulation design and testing

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ABSTRACT

New vehicles need improved cryogenic propellant storage and transfer capabilities for long duration missions. Multilayer insulation (MLI) for cryogenic propellant feedlines is much less effective than MLI tank insulation, with heat leak into spiral wrapped MLI on pipes 3–10 times higher than conventional tank MLI. Better insulation for cryogenic feed lines is an important enabling technology that could help NASA reach cryogenic propellant storage and transfer requirements. Improved insulation for Ground Support Equipment could reduce cryogen losses during launch vehicle loading. Wrapped-MLI (WMLI) is a high performance multilayer insulation using innovative discrete spacer technology specifically designed for cryogenic transfer lines and Vacuum Jacketed Pipe (VJP) to reduce heat flux.

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. WMLI uses discrete spacers that maintain precise layer spacing, with a unique design to reduce heat leak. A Triple Orthogonal Disk spacer was engineered to minimize contact area/length ratio and reduce solid heat conduction for use in concentric MLI configurations.

A new insulation, WMLI, was developed and tested. Novel polymer spacers were designed, analyzed and fabricated; different installation techniques were examined; and rapid prototype nested shell components to speed installation on real world piping were designed and tested. Prototypes were installed on tubing set test fixtures and heat flux measured via calorimetry. WMLI offered superior performance to traditional MLI installed on cryogenic pipe, with 2.2 W/m^2 heat flux compared to 26.6 W/m^2 for traditional spiral wrapped MLI (5 layers, 77–295 K). WMLI as inner insulation in VJP can offer heat leaks as low as 0.09 W/m, compared to industry standard products with 0.31 W/m. WMLI could enable improved spacecraft cryogenic feedlines and industrial hot/cold transfer lines.

1. Introduction

New NASA vehicles and long duration missions using cryogenic propellants need improved cryogen storage, preservation and transfer Ref. [1]. Insulation on cryogenic transfer feedlines is problematic, with current feedline Multi-Layer Insulation (MLI) performance about 10X worse per area than tank MLI insulation Ref. [2]. Heat leak through cryogenic piping can be as much as 80% of the total system heat leak, limiting use of cryogenic spacecraft propulsion systems. Cryogenic propellant transfer lines used as Ground Support Equipment lost about 50% of LH_2 during transfer, chill down and ground hold during an STS launch. Quest Thermal Group LLC, teaming with Ball Aerospace, has developed an advanced insulation system for cryogenic transfer lines called Wrapped MLI (WMLI). Wrapped MLI (WMLI) uses discrete spacers to control layer spacing and reduce heat leak to provide high performance insulation for cryogenic piping and industrial Vacuum Jacketed Pipe.

New developments in cryogenic insulation, such as Integrated MLI (IMLI) with discrete spacers, are leading to higher performing systems, playing a role in providing Reduced or Zero Boil Off of cryogenic propellants. Better insulated piping could provide more efficient cryogenic fluid transfers, improved spacecraft cryogenic propulsion, cryogenic propellant storage and transfer in orbiting fuel depots, and higher performing Ground Support Equipment for loading cryogenic launch vehicles or liquid hydrogen fueled

Abbreviations: WMLI, wrapped multilayer insulation; MLI, multilayer insulation; IMLI, integrated Multilayer insulation; SOFI, spray on foam insulation; VJP, Vacuum Jacketed Pipe.

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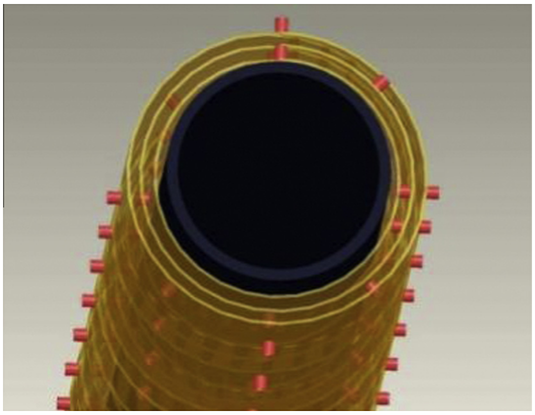

Fig. 1. WMLI conceptual design shows discrete spacers separating radiation barriers.

aircraft. Wrapped MLI uses a new spacer engineered to reduce heat leak for insulation installed on small diameter piping. WMLI development included designing several new spacers, modeling them for thermal performance, fabricating rapid prototypes, developing new installation methods, installing on cryogenic piping test fixtures and measuring thermal performance.

Discrete spacer technology provides precise, controlled layer spacing and insulation density, reduces the thermal conductance from layer to layer, and can form a bonded up, robust and repeatable structure. Next generation insulation IMLI uses low thermal conductance polymer micromolded spacers between radiation shield layers Ref. [3]. IMLI systems show a measured heat leak of 0.41 W/m^2 (20 layers, 3.7 cm, 77–293°K) Ref. [4], 37–50% lower heat leak per layer than traditional netting-based MLI, and perform close to their modeled behavior.

Other unique insulation systems have been designed and tested using discrete spacers for Load Responsive MLI that dynamically respond to external pressure and operate both in-air and on-orbit Ref. [5], Load Bearing MLI in which the spacers self-support a Broad Area Cooled shield without the heat leak of tank supports Ref. [6], and MMOD-MLI where the spacers support high strength ballistic layers to provide micrometeoroid/orbital debris shielding.

WMLI has different requirements than large acreage tank MLI, and so a unique, specialized spacer for wrapped insulation with limited space and concentric layers on cryogenic feedlines or industrial hot/cold transfer piping was a focus of this work.

2. Results and discussion

2.1. Wrapped MLI design

The WMLI concept uses discrete spacers to separate radiation barrier layers (Fig. 1). An early WMLI design used a simple glass spherical spacer and had a heat flux nearly four times lower than spiral wrapped traditional MLI insulation. It was thought

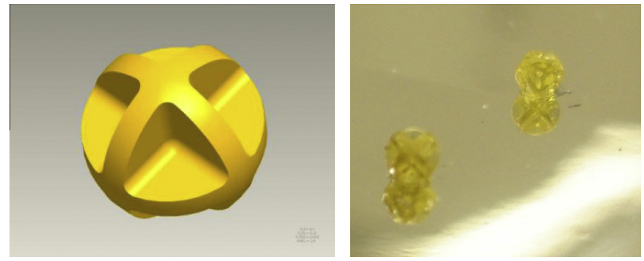

Fig. 3. Triple Orthogonal Disk spacer CAD image (left), and actual TOD spacers showing alignment bonded to a radiation barrier (right).

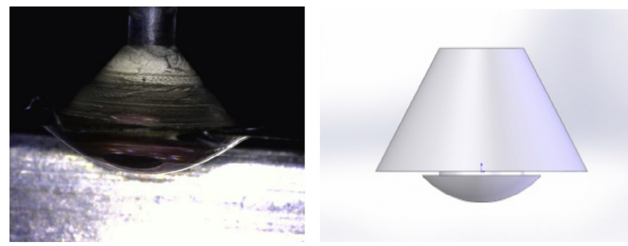

Fig. 4. Post-on-demand fabrication of a spacer; right is conceptual design of microslurry spacer with pass through layer holder; image left is actual formed spacer sitting above and below a radiation layer.

performance could be further improved with spacers designed to minimize contact area and offer lower thermal conductivity.

The WMLI system performance is obviously dependent on design and development of a discrete spacer for use on tightly wrapped insulation on piping. Some 15 different micromolded polymer spacers were designed, thermally modeled and considered. The design process included variables such as thermal contact area between spacer and radiation barrier, length of spacer between layers, spacer material thermal conductivity, and optimal height and strength of the spacer. From these initial concepts, several were selected to prototype using stereolithography. See Fig. 2.

The spacer was designed around principles that reduce the effective area/length, minimizing solid heat conductance. The final selected design was a Triple Orthogonal Disk (TOD) spherical polymer spacer that touches adjacent dual aluminized mylar layers on the edges of thin disks, providing for very small contact area and a low effective area/length ratio Ref. [7]. See Fig. 3. The TOD spherical spacer was thoroughly modeled and analyzed, and selected as the spacer design of choice. The TOD spacer was tooled, micromolded, and used to build WMLI prototypes.

During WMLI spacer design, a second novel approach was studied in which "post-on-demand" spacers were formed on-the-fly with a microslurry rapid curing manufacturing process. A slurry allows different materials with different thermal properties to be combined such as microspheres in a polymer curable matrix. This process allows various shapes to be fabricated, and may be a good approach for high volume manufacturing of WMLI. See Fig. 4.

Fig. 2. Spacer designs fabricated using rapid prototyping processes.

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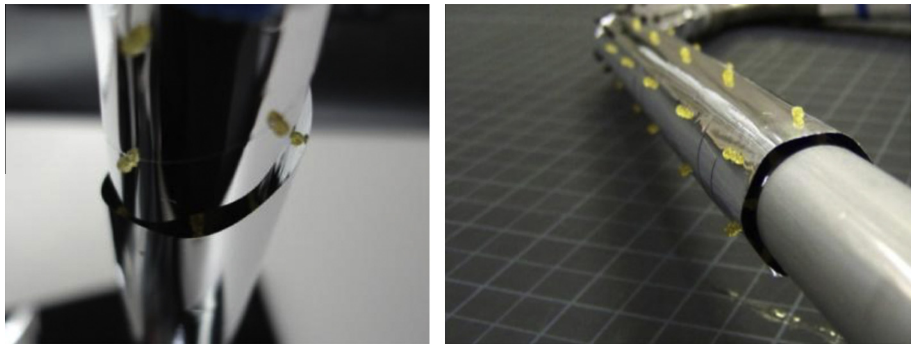

Fig. 5. Wrapping methods studied include (left) helical pitch and (right) clamshell wrap.

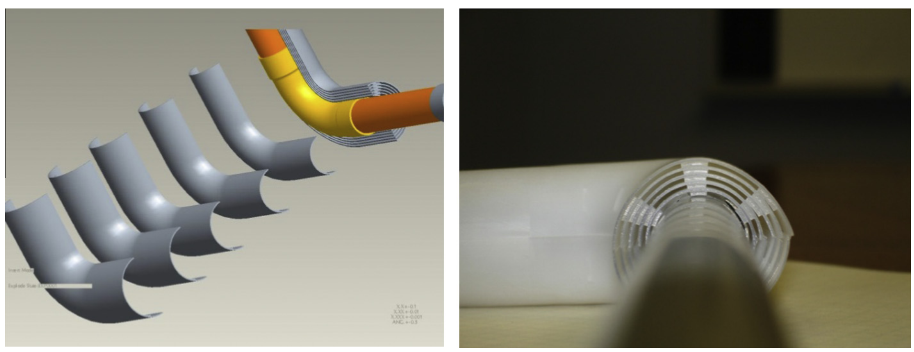

Fig. 6. WMLI rapid prototype nested shells provide fast installation on piping features such as bends, T's, crosses.

In addition to the spacer development, several methods were studied for fabrication and installation of WMLI onto piping. A new WMLI fabrication/installation process was designed and implemented using a "clamshell" installation approach as opposed to the previous helical wrap, which provided faster installation as well as superior thermal performance. Novel methods were for wrapping discrete spacer insulation around corners, T's, valves and flanges and was another aspect in achieving a low heat flux. See Fig. 5.

Another invention, novel nested shell components made with rapid prototyping techniques, was developed to enable easy installation on complex geometries and minimized A/L. These stereolithographic (SLA) pre-formed corner shells were shown to be a practical approach for rapid installation on complex cryogenic tubing such as T's, 4-way valves or flanges, and offered reasonable thermal performance. See Fig. 6.

2.2. WMLI modeling

Thermal modeling of the TOD spacer was done in Thermal Desktop and exported into Thermal Analysis Kit for further analysis. The ability to model and predict thermal performance is useful in designing insulation systems such as WMLI. These thermal models allowed design of a WMLI system for specific requirements, and also provided useful insight into what factors affect total system heat leak, guiding system improvements.

The Thermal Desktop model for the TOD, Fig. 7, estimated the heat leak through the part, and was modeled with the TOD sitting on a "pocket" (the edges of three adjacent orthogonal disks) and on an edge, and both bonded (with adhesive) and unbonded to the radiation barriers.

Modeled thermal results match measured results reasonably well, and predictability of WMLI performance is greater than for conventional MLI insulation. Traditional MLI on cryo piping shows "installation" factors of 6–20 over heat leak predicted by the Lockheed equation; WMLI TD/TAK model results from all tested configurations had an average correction factor of 0.77 to match measured heat fluxes, and as the model is improved predictive ability should improve. See Table 1 for Thermal Analysis Kit predicted heat flux vs. measured heat flux. Test configurations of "Wrapped Corners" indicate wrapped layers with TOD spacers were folded around each corner or bend in the test tubing, "SLA Nested Shell Corners" indicate the stereolithographic nested shells

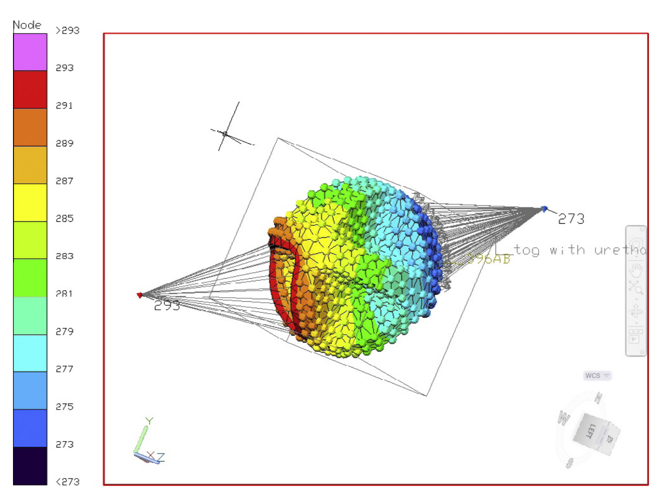

Fig. 7. Thermal Desktop model of heat conducted through TOD spacer sitting on a pocket and bonded to radiation barrier layers.

Table 1
WMLI modeled vs. measured heat flux.

Spacer	Piping diameter	Test configuration	Predicted heat leak (W/m^2)	Measured heat leak (W/m^2)	Correction factor
TOD	0.5″	Wrapped corners	4.71	2.22	0.47
TOD	0.75″	Wrapped corners	4.92	3.14	0.64
TOD	0.5″	SLA nested shell corners	5.49	5.81	1.06
TOD	0.75″	SLA nested shell corners	5.53	5.03	0.91

Fig. 8. WMLI installed on complex geometry tubing set – containing 45°, 90° bends, T's, flanges and sweeping corners – for LN_2 boil-off calorimetry.

components were used to insulate all bends and corners. The thermal model included heat leak from each component (straight pipe insulation, bends, etc.).

2.3. WMLI prototype builds and testing

WMLI systems were fabricated, installed on different diameter piping and different complexity tubing test fixtures, and WMLI thermal performance measured via LN_2 boiloff calorimetry. See Fig. 8. Fourteen different build and test prototype cycles were conducted testing different WMLI parameters.

2.4. WMLI prototype Ground Support Equipment testing

A Ground Support Equipment testbed was designed and built to test WMLI as the inner insulation in Vacuum Insulated/Vacuum Jacketed Pipe, Fig. 9, and WMLI was installed on this 10′ long 1.5″ diameter VJP.

2.5. WMLI performance

WMLI prototypes with the TOD spacer provided thermal performance as low as 2.22 W/m^2 for 5-layer pipe insulation (77 K, 295 K). WMLI offered superior performance to traditional MLI installed on cryogenic pipe; traditional spiral wrapped MLI had 26.6 W/m^2, and an advanced clamshell netting MLI had 5.5 W/m^2 (5 layers, 77–295 K). See Table 2.

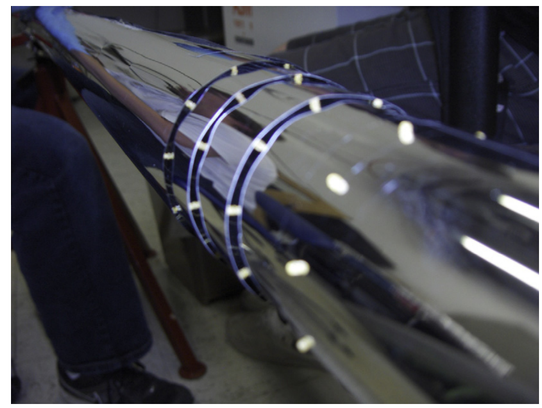

Fig. 9. WMLI inner insulation for Vacuum Jacketed Pipe prototype showing spacers and good layer separation.

Table 2
Wrapped MLI measured performance versus spiral wrapped & clamshell wrapped conventional netting MLI.

Insulation system	Layers	Heat leak (W/m^2)	Effective emissivity	Conductivity (mW/m K)
WMLI	5	2.22	0.005	0.063
Clamshell MLI	5	5.5	0.013	0.13
Spiral MLI	5	26.6	0.062	0.62

Table 3
Comparison of WMLI/VJP and typical commercial Vacuum Jacketed Pipe.

Insulation system	WMLI/VJP heat leak (W/m)	Standard VJP heat flux (W/m)	Advantage WMLI/VJP over standard VJP (%)
0.5″ Diameter pipe	0.09	0.31	71
0.75″ Diameter pipe	0.19	0.37	49
1.5″ Diameter pipe	0.30	0.54	44

WMLI as inner insulation in Vacuum Jacketed Pipe provided a heat flux of 2.52 W/m^2, or 0.09 W/m, compared to typical commercial VJP with 0.31 W/m. See Table 3.

3. Conclusions

WMLI is a new insulation system designed for use on cryogenic piping. WMLI offered superior performance to traditional MLI installed on cryogenic pipe, with 2.2 W/m^2 heat flux compared to 26.6 W/m^2 for traditional spiral wrapped MLI (5 layers, 77–295 K). WMLI as inner insulation in Vacuum Jacketed Pipe provided heat leaks as low as 0.09 W/m, compared to typical commercial VJP with 0.31 W/m.

WMLI development included design of a new discrete spacer to control the spacing of tightly wrapped radiation barriers on piping, along with new fabrication and installation processes for fast installation on complex geometries.

Specific results for WMLI include:

- A unique discrete spacer was designed for concentric feedline insulation with low Area/Length to control insulation layer spacing and reduce heat conduction.
- New feedline insulation techniques were developed leading to high performance thermal systems with rapid installation.
- WMLI thermal models were developed that provide fair accuracy in predicting heat fluxes of installed insulation.
- WMLI provided substantially lower heat leak than traditional MLI on feedlines, and better performance than MLI in Vacuum Jacketed Pipe.

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