General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

ROBUST MULTILAYER INSULATION
FOR CRYOGENIC SYSTEMS

J.E. Fesmire[1], S.D. Augustynowicz[2], B.E. Scholtens[1]

[1]NASA Kennedy Space Center, KT-E
Kennedy Space Center, FL, 32899, USA

[2]Sierra Lobo, Inc., SLI-2
Kennedy Space Center, FL, 32899, USA

ABSTRACT

New requirements for thermal insulation include robust Multilayer insulation (MLI) systems that work for a range of environments from high vacuum to no vacuum. Improved MLI systems must be simple to install and maintain while meeting the life-cycle cost and thermal performance objectives. Performance of actual MLI systems has been previously shown to be much worse than ideal MLI. Spacecraft that must contain cryogens for both lunar service (high vacuum) and ground launch operations (no vacuum) are planned. Future cryogenic spacecraft for the soft vacuum environment of Mars are also envisioned. Industry products using robust MLI can benefit from improved cost-efficiency and system safety. Novel materials have been developed to operate as excellent thermal insulators at vacuum levels that are much less stringent than the absolute high vacuum requirement of current MLI systems. One such robust system, Layered Composite Insulation (LCI), has been developed by the Cryogenics Test Laboratory at NASA Kennedy Space Center. The experimental testing and development of LCI is the focus of this paper. LCI thermal performance under cryogenic conditions is shown to be six times better than MLI at soft vacuum and similar to MLI at high vacuum. The experimental apparent thermal conductivity (k-value) and heat flux data for LCI systems are compared with other MLI systems.

INTRODUCTION

Because radiation heat transfer from the Sun is assumed to be constant factor, MLI systems operating at high vacuum levels are not likely to be replaced in this century. However, major improvements can be sought in two areas: support structures and vacuum levels. For high performance MLI systems (that is, heat fluxes below about 1 W/m2 or apparent thermal conductivity values below about 0.1 mW/m-K), the amount of energy coming through the supports can 50 percent or more of the total heat leak [1]. New thermal insulation requirements for high performance cryogenic systems cannot be reasonably met with current technology. Superconducting power cables, for example, require k-values below 1 mW/m-K [2]. Laboratory or idealized constructions of MLI can easily provide this level of performance. Some examples of ideal MLI systems with k-values in the range of 0.05 mW/m-K are given by Ohmori [3] and Kaganer [4]. However, the reality of design, fabrication, and operation can reduce the thermal effectiveness by one or two orders of magnitude. Refrigeration systems cannot be simply boosted for the additional heat load to compensate for the reduced insulation effectiveness.

Ideal MLI versus Practical MLI

Practical experimental comparisons between ideal MLI and rigid versus flexible piping have been previously reported. For similar 60-layer systems of foil and paper, the increased heat transfer was about 80 percent for the rigid piping installation and about 50 percent more from rigid to flexible [5]. Even ideal MLI performance can be degraded by weight of the MLI itself and the resulting contact heat transfer between layers. A non-dimensional contact pressure parameter has been proposed by Ohmori to account for this additional heat transfer [6]. In the case of flexible piping, the weight of the inner line pressing against the outer line combined with the bending that compresses the layers of materials increases solid conduction while decreasing the vacuum pumping. Localized damage due to spacer structures and bending of piping has been shown to increase heat transfer by approximately 40 percent [7]. The term k_{oafi} has also been defined as a practical measure of the overall efficiency of the total insulation system [8].

The first and foremost operational problem with MLI is the vacuum pumping. Many closely spaced layers make proper evacuation below 0.1 millitorr between all layers difficult to achieve. A degraded vacuum to 100 millitorr will cause an increased in heat flux by more than two orders of magnitude, from 1 to 100 W/m^2 [9]. The support structures require the MLI blankets to be truncated, terminated, and otherwise chopped up which will greatly hinder any vacuum pumping process. Studies of variable density MLI systems have shown that lower layer density nearer the cold mass will provide a significant performance benefit [10]. The lower density in the innermost layers should also provide a more complete evacuation of the system.

A loss of vacuum can mean a major loss of product or a facility shut-down. A sudden loss of vacuum in a system could have catastrophic consequences including personnel injury and major equipment damage. The possibility for these events in new high performance systems must of course be minimized by engineering and technical standards. The demand and the stakes continue to increase as cryogenics becomes standardized in areas such as electric power (LN2) and public transportation (LNG and LH2).

The Case for Robust MLI Systems

What is needed for future cryogenic systems is a robust MLI combined with load-supporting elements. The new layered systems can be tailored for a certain design requirements including three parameters: thermal performance (heat flux), range of operating pressure (cold vacuum pressure), and mechanical performance (compressive load and vibration damping). The support structures for MLI insulated tank or piping systems increase the solid conduction heat leak. These mechanical supports also have the effect of increasing both the radiation (due to gaps in the MLI) and the gas conduction (due to the restriction of the vacuum pumping process). Combining thermal, mechanical, and operational considerations, the insulation system design could include supports comprised by the insulation materials. Robust MLI systems therefore meet all of the following criteria to a reasonable extent:

- System design must allow for coverage of complex shapes
- System design must consider structural supports and other mechanical obstacles
- High vacuum environment is required
- Evacuation or release of vacuum must not damage the layers
- Evacuation must include reaching high vacuum between all layers
- Layers must stay put during installation, evacuation, operation, and maintenance
- Installation must not introduce any significant heat paths nor prevent proper evacuation

Requirements for Robust MLI systems are developing in two areas: 1) industry products for soft vacuum operation (cost-efficiency and safety) and 2) spacecraft for lunar (high vacuum) and ground-hold (no vacuum) operations. Moving in the direction of a robust MLI system, a new Layered Composite Insulation (LCI) system has been developed.

LAYERED COMPOSITE INSULATION

Like MLI, LCI is a thermal insulation system composed of alternating layers of reflectors and spacers [11,12]. The reflectors are radiation shields made of, for example, aluminum foil or aluminized plastic film. The LCI system is inherently flexible and conformable and not limited to any specific size or shape. LCI placed inside an annular space vacuum environment allows the structure to maintain its fully flexible, conformable property. This arrangement also allows the spacer layers to keep their loftiness which is a key part of the very low thermal conductivity.

LCI designs have larger interlayer spacing to reduce vulnerability to compression (and consequent heat leak) caused by installation and use. The overall density of the LCI is typically about 1 layer per mm. The density of the spacer layer is largely determined by the amount of compression of the powder which is self-regulating depending on the insulation wrapping process. The powder is typically compressed by 20-60 % from the bulk density during wrapping.

An LCI system includes radiation shield layers, powder layers (aerogel or fumed silica), and carrier layers (non-woven fabric or fiberglass paper). The layers are put together by a continuous roll-wrap process. The power layer can be deposited on the surface of the carrier layer or within the carrier layer itself. LCI products can be produced in forms such as multiple layer rolls, blankets, and cylindrical sleeve packages. The products can be tailored for a specific application. Optional edge strips can be used to set a gage of layer thickness. A single layer or many layers can be used. The optional outer wrapper material can be used if improved handling

ability or extra measure of powder containment is desired. A stack 5, 10, or 15 layers for installation within a tank or piping annular space is a typical installation. Various configurations of LCI, including radiation, powder, and carrier layers, were tested for cryogenic thermal performance.

EXPERIMENTAL

Liquid nitrogen boiloff calorimeter equipment and methods established by the Cryogenics Test Laboratory were used to determine the k-values of the cryogenic insulation systems [13]. Three cylindrical test apparatuses were used. Cryostat-2 (0.5-meter long) is a comparative test while Cryostat-1 (1-m long) and its replacement, Cryostat-100, are absolute methods.

A cryostat test series begins with specimen preparation, installation, and then vacuum pumping and heating to obtain the initial high-vacuum condition. A test is defined as the steady-state heat leak rate (watts) through the specimen at a prescribed set of environmental conditions, including a stable warm-boundary temperature (WBT), a stable cold-boundary temperature (CBT), and a stable vacuum level. Tests are conducted starting at high vacuum (less than 0.1 millitorr) and working up to no vacuum (760 torr). The residual gas is nitrogen in all tests. Eight or more different cold vacuum pressures (CVP) are produced for each test series. The liquid nitrogen cold mass maintained the CBT at approximately 78 K (from 85 to 90 K for Cryostat-1 testing with copper sleeve) while the WBT was maintained at approximately 293 K using external heaters with electronic controllers.

The insulation test materials were horizontally roll-wrapped onto the cylindrical cold mass for Cryostat-2 tests. The cold mass for Cryostat-2, before and after insulation wrapping, is shown in FIGURE 1. The materials were horizontally roll-wrapped onto a copper sleeve for Cryostat-1 tests. Cryostat-100 test article preparation was accomplished by hand lay-up of the materials onto the vertically positioned cold mass. Standard MLI or superinsulation (SI) constructions are composed of a reflective shield (aluminum foil 0.00724 mm thick) and spacer (fiberglass paper 0.061 mm thick), double-aluminized Mylar with paper spacer, or double-aluminized Mylar with bonded non-woven polyester spacer (Cryolam). The installed thickness for most test articles was from 20 to 25 mm.

FIGURE 1. Cryostat-2 cold mass shown before (left) and after (right) roll-wrapping with insulation materials.

THERMAL TEST RESULTS

Over 400 tests of 30 different MLI and LCI systems were performed. Preliminary results using Cryostat-1 have been previously reported [14]. Further testing was completed using Cryostat-2 and Cryostat-100. Cryostat-2 testing was conducted on different combinations of reflector, carrier, and powder layers. The comparative thermal performance results are presented in Figure 2. The thermal conductivity of LCI systems are also shown in comparison with three popular MLI systems. Performance is comparable at high vacuum even though the LCI systems have only half the layers compared to MLI systems. The LCI combinations utilizing Mylar were found to have an advantage for the full vacuum range. From this optimization study, Cryostat-1 testing resumed with test series C130.
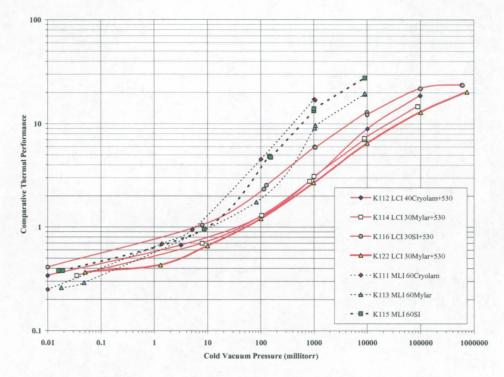

FIGURE 2. Comparative thermal performance test results from LCI optimization study. Boundary temperatures are approximately 78 K and 293 K; the residual gas is nitrogen.

A compilation of selected results from Cryostat-1 and Cryostat-100 testing is given in Figure 3. Table 1 presents the descriptions of these test articles including thickness and density as-installed. The LCI systems shown by the solid lines are clearly superior in the soft vacuum range. The optimized LCI system C130 is also shown to be comparable to the benchmark MLI system C123 in the high vacuum range. The Kaganer line, representing ideal MLI, is for the following system: aluminum foil and fiberglass spacer, 40 layers, 1.5 layers per mm, 293 and 90 K boundary temperatures. For comparison, layered systems of aerogel blankets and aerogel blankets plus MLI are also presented. As expected, the layered aerogel is best in the ambient pressure range while the aerogel and MLI combination system gives a dramatic advantage at higher vacuum levels. A prototype LCI system, the higher density A110, is not the best thermal performer but should offer a high degree of mechanical load-carrying capability.
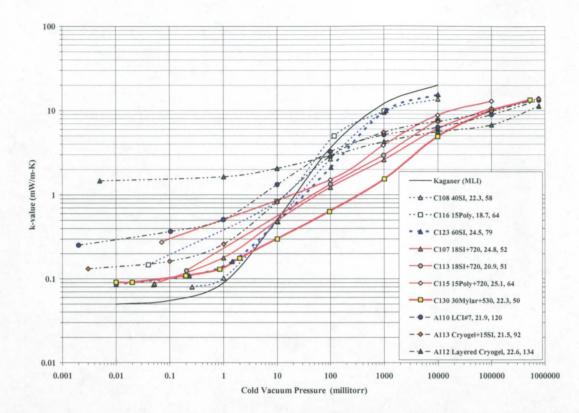
FIGURE 3. Apparent thermal conductivity test results of LCI, MLI, and other layered insulation systems. Boundary temperatures are approximately 78 K and 293 K; the residual gas is nitrogen.

Table 1. Description of cryostat insulation test articles from Cryostat-1 and Cryostat-100 testing.

Test Series No.	Insulation System Type	Description of Insulation System	Total Thickness (mm)	Installed Density (kg/m^3)
C107	LCI	18 layers foil + paper + fumed silica 720	24.8	52
C108	MLI	40 layers foil + paper at 1.8 layers/mm (40 SI)	22.3	58
C113	LCI	18 layers foil + paper + fumed silica 720	20.9	51
C115	LCI	15 layers foil + polyester fabric + fumed silica 720	25.1	64
C116	MLI	15 layers foil + polyester fabric	18.7	51
C123	MLI	60 layers foil + paper (60 SI)	24.5	79
C130	LCI	30 layers mylar + paper + fumed silica 530	22.3	50
A110	LCI	Prototype system using aerogel blankets	21.9	120
A112	Material	6 layers of Cryogel aerogel blanket	22.6	134
A113	Material	Cryogel with 15 layers foil + paper	21.5	92

DISCUSSION

Cryogenic thermal performance of LCI systems are approximately six times better than MLI systems at soft vacuum (1 torr) and comparable to MLI systems in high vacuum environments. For the benchmark MLI system C123 compared the optimized LCI system C130 the k-values are summarized as follows: 0.086 versus 0.091 mW/m-K at HV and 10.0 versus 1.6 mW/m-K at SV. The LCI thermal performance is excellent at ambient pressure but not as good as the aerogel blankets at this condition. LCI systems consisted of half the number of layers of corresponding MLI systems, but with overall thicknesses kept approximately the same. Presenting the results in terms of k-value rather than heat flux gives the best comparison between different systems as small variations in thickness and boundary temperatures are normalized.

LCI development work is continuing in three areas: soft vacuum designs, high vacuum designs, and combination high vacuum to no vacuum designs. Potential low-temperature applications include:

- Low-cost, high-efficiency pipelines
- Superconducting power cables
- Bulk storage tanks with safety back-up feature
- Mars surface storage of liquid oxygen
- Small, robust liquid hydrogen tanks
- Spacecraft for lunar, ascent, and ground-hold performance

The mechanical capability of these systems has not been quantified but is the subject of current work to develop mechanical load-carrying LCI systems.

CONCLUSION

Thermal insulation systems of robust MLI are needed for advancing the efficient storage and transfer of cryogens. A robust MLI design must consider the total system design including coverage of complex shapes, structural supports, and other mechanical obstacles. The high vacuum requirement is further defined to mean that evacuation or release of vacuum must not damage the layers and that evacuation must include reaching high vacuum between all layers. Finally, installation methods for robust MLI systems must be worked out to prevent additional heat leaks and to allow complete evacuation of the system.

A family LCI systems has been successfully developed and serve as one example of a robust MLI system. The thermal performance of LCI is shown to be comparable to MLI at high vacuum (0.9 mW/m-K), but is six times better at soft vacuum (1.6 mW/m-K). Several LCI systems typically composed of 15 layers of radiation, carrier, and powder materials have been described. These LCI systems are targeted for double-wall piping or tank constructions where degraded vacuum or loss of vacuum is a concern. Designed as HV systems, LCI would provide a back-up level of performance to prevent loss of product or to reduce system maintenance. With the expense required to produce and maintain high vacuum level, industry in many cases is looking for an efficient, low-cost system with high performance in the soft vacuum range [15].

New aerospace and space exploration initiatives are requiring cryogenic insulation systems that will perform well under the full range of vacuum levels: Earth (no vacuum), Mars (soft

vacuum), and Moon (high vacuum). Earth-to-Moon missions requiring cryogenic tanks will require launch pad hold times in the ambient pressure environment and then long-term storage in the high vacuum environment of space. Robust MLI, working in concert with load-supporting insulation technology and active thermal systems, will help enable truly mass-efficient spacecraft designs by replacing the complex and heavy and support structures with an insulation system that does its thermal job, and carries the mechanical loads, and also provides vibration damping in the operational environments. The potential benefits of the robust MLI approach are many: higher thermal performance for the total system, combined thermal and mechanical capability, and enhanced safety and reliability. Robust MLI technology such as LCI applied existing design problems can enable new technology in other energy-intensive areas such as hydrogen transportation and superconducting power transmission.

REFERENCES

1. Shu, Q.S., Cheng, G., Yu, K., Hull, J.R., Demko, J.A., Britcher, C.P., Fesmire, J.E., Augustynowicz, S.D., Low thermal loss cryogenic transfer line with magnetic suspension," in Advances in Cryogenic Engineering, Vol. 49, American Institute of Physics, New York, 2004, pp. 1869-1876.
2. Nuemann, H., "Concept for thermal insulation arrangement within a flexible cryostat for HTS power cables," *Cryogenics* 44 (2004) 93-99.
3. T. Ohmori, et al. June 1987. "Thermal Performance of Candidate SSC Magnet Thermal Insulation Systems," SSC-N-459, Superconducting Super Collider Laboratory.
4. Kaganer, M. G. *Thermal Insulation in Cryogenic Engineering*, Israel Program for Scientific Translations, Jerusalem, 1969.
5. Fesmire, J.E., Augustynowicz, S.D. and Demko, J.A., "Thermal insulation performance of flexible piping for use in HTS power cables", *Advances in Cryogenic Engineering*, Vol. 47, American Institute of Physics, New York, 2002, pp. 1525-1532.
6. Ohmori, T., "Thermal performance of multilayer insulation around a horizontal cylinder," *Cryogenics* 45 (2006) 725-732.
7. Fesmire, J.E., Augustynowicz, S.D., and Demko, J.A., "Overall thermal performance of flexible piping under simulated bending conditions," *Advances in Cryogenic Engineering*, Vol. 47, American Institute of Physics, New York, 2002, pp. 1533-1540.
8. Fesmire, J. E. and Augustynowicz, S.D., "Thermal performance of cryogenic piping multilayer insulation in actual field conditions," *Cryogenics 2002,* International Institute of Refrigeration, Refrigeration Science and Technology Proceedings, Praha Czech Republic, 2002, pp. 94-97.
9. Fesmire, J. E., Augustynowicz, S.D., and Darve, C., "Performance Characterization of Perforated MLI Blanket," Proceedings of the Nineteenth International Cryogenic Engineering Conference, ICEC 19, Narosa Publishing House, New Delhi, 2003, pp. 843-846.
10. Hastings, L.J., Hedayat, A., and Brown, T.M., "Analytical modeling and test correlation of variable density multilayer insulation for cryogenic storage," NASA/TM-2004-213175, May 2004.
11. Augustynowicz, S.D. and Fesmire, J.E., "Thermal Insulation Systems," US Patent 6,967,051 B1 November 22, 2005.
12. Fesmire, J. E. and Augustynowicz, S.D., "Improved thermal-insulation for low temperatures," *NASA Tech Briefs*, September 2003, pp. 54-55.
13. Fesmire, J.E., Augustynowicz, S.D., Heckle, K.W., and Scholtens, B.E., "Equipment and methods for cryogenic thermal insulation testing," *Advances in Cryogenic Engineering*, Vol. 49, American Institute of Physics, New York, 2004, pp. 579-586.
14. Augustynowicz, S. and Fesmire, J., Cryogenic insulation system for soft vacuum, *Advances in Cryogenic Engineering* (2000), 45 1691-1698.
15. Augustynowicz, S.D., Fesmire, J.E., and Wikstrom, J.P., Cryogenic insulation systems, *20th International Congress of Refrigeration Sydney,* no. 2000-1147, International Institute of Refrigeration, Paris, 2000.