Design of Multilayer Insulation for the Multipurpose Hydrogen Test Bed

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Multilayer insulation (MLI) is a critical component for future, long term space missions. These missions will require the storage of cryogenic fuels for extended periods of time with little to no boil-off and MLI is vital due to its exceptional radiation shielding properties. Several MLI test articles were designed and fabricated which explored methods of assembling and connecting blankets, yielding results for evaluation. Insight gained, along with previous design experience, will be used in the design of the replacement blanket for the Multipurpose Hydrogen Test Bed (MHTB), which is slated for upcoming tests. Future design considerations are discussed which include mechanical testing to determine robustness of such a system, as well as cryostat testing of samples to give insight to the loss of thermal performance of sewn panels in comparison to the highly efficient, albeit laborious application of the original MHTB blanket.

Nomenclature

MLI = Multilayer Insulation
MHTB = Multipurpose Hydrogen Test Bed
PET = Polyethylene Terephthalate
SOFI = Spray On Foam Insulation
UV = Ultraviolet
AO = Atomic Oxygen

I. Introduction

USING current thermal expansion propulsion or electronic propulsion techniques, future space missions will require the storage and efficient delivery of cryogenic fuels for extended periods of time with little to no boil-off. Cryogenic fluid management teams study advanced technologies for propellant management and require the use of multilayer insulation as an enabling technology. MLI has been investigated for several decades because of its exceptional radiation insulating properties in vacuum.

The Multipurpose Hydrogen Test Bed housed at Marshall Space Flight Center is a test bed designed to mimic, in relative size, a fully integrated space vehicle fuel tank[1]. Due to the extremely limited availability of orbital testing, and the pending retirement of the Space Shuttle system, terrestrial testing of the MHTB is imperative to test and verify cryogenic fluid management (CFM) concepts. MHTB was outfitted with a 45 layer MLI blanket in 1993 which remains installed as of August 2010. Due to handling and various problems encountered during testing, the blanket has fallen into disrepair. When reviewing the installation procedures for the blanket, it is evident that repairing the current blanket would incur substantial materials, labor and equipment costs. Due to the roll wrap installation technique, reaching underlying layers or repairing portions of the tank would be quite difficult. For the purposes of the MHTB as a ground system scheduled for upcoming testing, a new method of outfitting the tank with an MLI blanket with the ability to be repaired easily and quickly is desired.

II. Background

Multilayer insulation was originally developed in 1951 by P. Peterson[2], opening the door for future improvements and research. Originally designed for metallic films and rather dense fiberglass paper substrate to minimize metal to metal contact, the insulation had shown extreme promise with the materials available at the time. With the invention of new, more reliable and less expensive materials, MLI has become a staple for many in-space systems and is promising for long-term cryogenic in-space fuel storage.

Since its invention, methods of improving the system have been investigated. Though it remains a simple insulation system, often comprised of only one or two unique materials alternating layers, MLI is an excellent thermal barrier for vacuum applications. Apparent thermal conductivities have been recorded to as little as 0.3 μW/cm·K (between 300K and 20K)[3]. MLI systems work effectively in vacuum below 7.5×10^{-5} torr[3]; in fact, their success is highly dependent on maintaining a state of vacuum, where little or no gaseous particles are trapped between the layers. Residual gas pressures due to material outgassing can have substantial effect on the apparent thermal conductivity of typical multilayer insulations, which illustrates the critical nature of minimizing these effects for systems designed and built for flight. The scope of this paper is not to focus on flight-ready hardware, but typical outgassing effects can be seen to negate the radiation properties by several hundred percent[2]. Methods of minimizing material outgassing are presented in the Results and Discussion section.

The original MHTB roll-wrapped MLI blanket yielded heat leak results (excluding penetration heat leak) on the order of 0.22 – 0.27 W/m^2 at the warm boundary condition (305 K) for multiple tests, including tests performed while the blanket was slightly damaged. The results showed a performance surpassing any previously recorded MLI system by a heat leak reduction of over 40%[4]. While this system performed extremely well, photos of the current installation, seen in Fig. 1 show an obvious deterioration of the blanket, which presents a problem for reparation. Concepts for material handling and design of a new, modular blanket are presented, along with the benefits and drawbacks of such an installation.

Figure 1. MHTB and MLI system as of July 2010

III. Methodology

Design of a new MLI blanket for the MHTB began with reviewing previous designs and installations. Detailed evaluations are presented in the appendix. After evaluations, it was concluded that several methods provided higher viability and ease of fabrication with available equipment. Several 48 in × 48 in blanket panels were produced for test samples, mock-up blanket raw materials and for general purpose handling study.

A. Blanket Panels

Blanket lay-up was a process of layering the raw materials and trimming to a manageable size. Materials used for fabrication were ¼ mil double aluminized Mylar and Dacron B2A and B4A netting. The materials were in 54" rolls mounted on a roll stand for ease of installation, pictured below in Fig. 2.

Figure 2. Material rolls on fabrication stand

The insulation blankets were produced by using a swiveling, double sided cutting table with routed notches used as the 48 in × 48 in cutting guides. The cutting table was positioned parallel to the material stand with enough clearance for rotation and roughly 36 inches of clearance between the outermost edge of the table and the material roll. Enough Mylar and Dacron netting was pulled to attach to the far edge of the cutting table while in a horizontal position, and was attached using clear tape along the edge. The Mylar was laid beneath the Dacron netting to begin, as handling the netting presents difficulties.

Forming the layered blankets followed by swiveling the table, giving special consideration to the Dacron netting. The mesh snags easily on rough surfaces and does not drape well when under tension. Therefore, approximately two widths of the cutting table were unrolled and left to hang prior to rolling the table and stretching over the Mylar layer by hand. A layer was assembled and smoothed out, ensuring no wrinkles before proceeding to turn over the cutting board to continue onto the opposite face. While turning over, tension was thoroughly maintained by hand to avoid sagging. This process was repeated for the desired number of layers; in the case of the blankets used, 15 layer blankets were prepared in this manner.

After the blanket raw materials were laid out, the blankets were prepared for cutting. The thin Mylar material and netting shift easily, and must be maintained in some fashion; to do so, a cloth tagging gun was used. An initial cut along a side of the blanket was made using a sharp hobby knife and applying pressure with a long straight edge. The layers of material were lifted, and a 1 in^2 piece of Polyimide (Kapton) tape was applied to both outer layers of the blanket in the same area, followed by a nylon cloth tag through the blanket and Kapton. These nylon tag and Kapton connectors were positioned along the first cut edge, approximately 10 inches apart and 2 inches from each end and the edge. After tagging one edge, each subsequent edge was cut and prepared in the same fashion.

The handling lessons learned from the blanket fabricating are presented below:

Process	Tool Used	Comments
Cutting layered blanket materials	Hobby knife	Generous pressure must be applied along the entire edge of the cut to avoid material shifting. Metal clamps and long straight edges are beneficial. Knife blades must be replaced often to avoid snagging of the netting and tearing the thin Mylar layers.
Tagging blanket for handling	Fabric tagging gun	A Kapton "sandwich" must be created by placing tabs on the outermost Mylar layers to give the material extra robustness, as the tag perforation will easily propagate into much larger tears, possibly compromising a large area of the blanket. The fabric tagging needle will need to be replaced periodically, it will dull or bend over time, causing larger perforations through the blanket

Table 1 – Handling lessons learned

B. Bumper Strips

A crucial component for replicating the variable density MLI concept seen on the MHTB is the addition of Dacron bumper strips of various thicknesses to layers within the MLI blanket. This provides variable radiation shielding from warm boundary conditions on the outside of the tank to the cold conditions at the SOFI boundary. Bumper strips in the original MHTB application were fabricated in three different thicknesses to give the blanket a 50% increase in density through the three distinct regions[1].

To reproduce this type of variable density, the concept of creating separate blankets was explored. For this concept, rather than one blanket housing all three density regions, three distinct blankets would be created to house a specific density. Blankets would have a distinctive design, each growing larger to accommodate the underlying blanket(s). For such a design, blanket seams would be designed to stagger around the tank, negating any direct radiation leak pathways into the tank. This allows future tests to have the flexibility to monitor heat flux throughout the separate regions of the MLI blanket installation, rather than only at the boundaries; it also allows for the removal of damaged panels and easier access to any portion of the tank (assuming a non-permanent installation around tank hardware and support fixtures).

To examine the characteristics of the bumper strips, several samples were created as well as testing to gauge the robustness of the strip installation within a blanket. The tighter-mesh Dacron netting was used to fabricate the test articles. Netting was cut into various widths along the roll to produce strips of approximately 30 feet in length. The various widths were folded accordingly to produce 2, 4 and 6 layer bumper strips of approximately 3 to 3.5 inches in width; the following table presents information about bumper strip widths.

Bumper strip density	Material width	Comments
2 Layer	6-6.5"	For each fold, a 0.5" buffer of material is added, due to the loose handling of the netting
4 Layer	12-13"	
6 Layer	18-19.5"	

Table 2 – Bumper strip width details

Bumper strip samples were used to test methods of holding strips within a blanket. During blanket fabrication and installation, there will be a high amount of material handling, which can lead to the installed bumper strips sagging, twisting or becoming torn from their positions. During blanket build up strips will be secured at the blanket seams, but can remain loosely hanging within. To mitigate this, a simple test was applied to two bumper strips installed on a test blanket. One strip was allowed to hang freely; the other was tacked to the underlying Dacron netting every ten inches using nylon thread knots, see Fig. 3. The blanket was taken down, folded, moved about and reinstalled on the cutting table to remain installed vertically for several weeks to simulate fabrication and installation movements. After this time period the blanket and strips were reexamined. The unsupported strip showed over two inches of displacement from the ends. With the supported bumper strip the top portion of the strip was slightly draped over the supporting knots, see Fig. 4.

Figure 3. Set up of Bumper Strip testing

Figure 4. Strips after one week of vertical installation

The following table presents handling lessons learned for bumper strips:

Process	**Tool Used**	**Comments**
General handling	N/A	Material snags easily on many surfaces including tools, and rough skin. This leads to the bumper strips losing shape. While rolling out strips, ends must be secured to keep folds taut, see Fig. 5. Recommend PVC "self-healing" cutting mat material to provide smooth cutting surface.
Cutting strips	Hobby knife, scissors	Quite difficult to trim material to exact sizes due to snagging and shifting of material. Ends of material must be secured prior to cutting to minimize movement. Ample pressure and sharp blades are highly recommended. An alternate method would be cutting the entire roll into appropriate widths using industrial methods.
Folding	Sewing pins	Material resists folding and cannot be pressed by hand to encourage maintenance of folds. Must be folded, pinned and rolled immediately to keep folded shape. Folds can possibly be better managed by ironing with low heat to crease the fabric.

Sewing	Sewing pins, standard domestic scale Kenmore sewing machine, zigzag foot, nylon thread	Attempts to sew strips proved unsuccessful; the fabric gathers together and density control is not possible. Using sewing techniques such as a tissue paper backing as with shear cloths works to stop the gathering and allows for density control. However, when the tissue is removed, all of the foreign material cannot be recovered, leaving bits of paper on the strips along the seams.

Table 3 – Bumper strip lessons learned

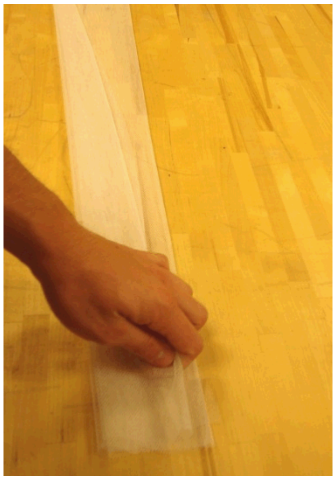


Figure 5. Folding bumper strips

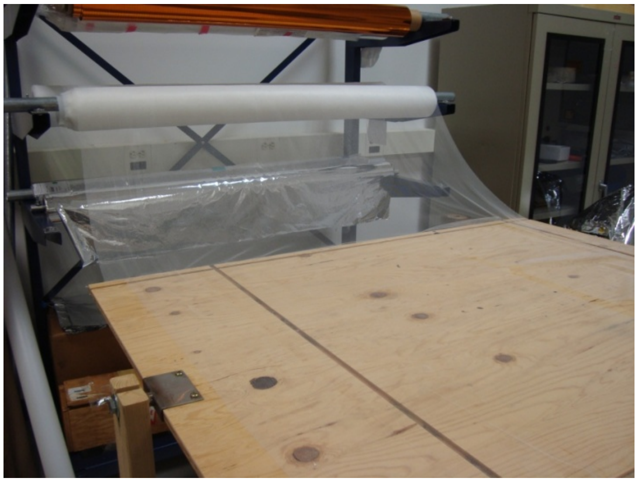


Figure 6. Rolling out Dacron B4A for cutting

C. Sample Swatches

Several small scale samples (less than 12 inches square) were created to explore sewing and connection methods. Processes tested were standard sewing and the use of hook and pile connections. Various methods of connecting panels and alternatives to sewing are presented in the Appendix.

1. Sewing

Panels were sewn using a standard domestic-sized sewing machine. To test the limits of the machine, thicker blankets of 35 layers were sewn. The machine would not properly handle blankets of this proportion, stalls were common, forcing backups and excess punctures to the fabric. An optimal thickness was 15 layers with a nylon hook or pile connector. Several seam types were examined including tight straight seams, standard straight and zigzag seams. An optimal stitch length for the sewing machine was approximately 6 stitches per inch, yielding mainly uniform results, see Fig. 7. For termination treatments, seams were backed up 0.5 inches over the existing stitch holes to reinforce seams from unraveling. During build up, as recommended, the lengths of seams were minimized, and continuous stitch lines were whenever possible to minimize direct heat leaks through the blanket[5].

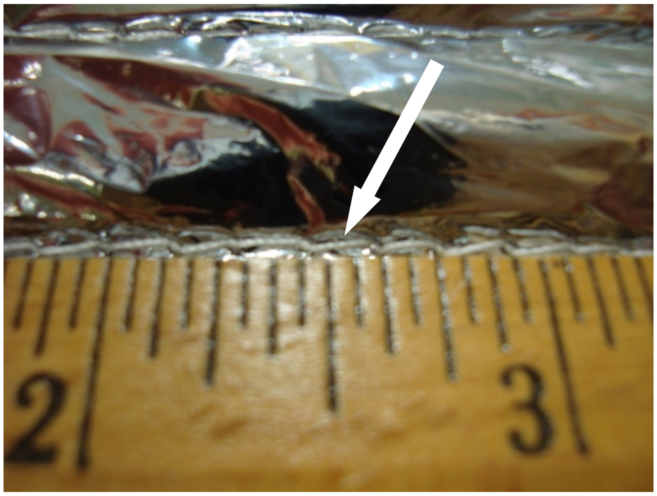


Figure 7. Stitch length set at approximately six stitches per inch

2. Variable Density samples

Samples of each density layer were created to gauge the effectiveness of the standard sewing machine on the extra material. These swatches were created by introducing a layer of an appropriate bumper strip to each intermediate MLI layer. These samples were held together using the standard clips and passed through the sewing machine. They proved more challenging for the standard sewing machine; the increases in material density caused the feeding foot to damage, and in some cases, tear the bottom Mylar layer as it passed through. The added material did not have adverse effects on the performance of the machine perforating the MLI swatch.

Lessons learned are shown in the table below.

Process	Tool Used	Comments
Handling	Bag clips	The added material between layers gives rise to extra shifting. Fasteners of some sort must be used for larger blankets during build up.
Sewing	Standard domestic scale Kenmore sewing machine, zigzag foot, nylon thread	Recommended stitch lengths are 4-8 stitches per inch[5]. Seam terminations are overlapped 0.5 inches to negate unraveling during handling. Fabrics must be secured during sewing, shifting is a much greater concern while feeding into the machine due to the increase in thickness; this will lead to gathering and tearing of the material as it passes beneath the foot. The use of an industrial machine will would be ideal for the thicker material.

Table 4 – Handling lessons learned

3. "Layer by Layer" sample

In an attempt to minimize radiation leak from the lateral direction, a sample was created to judge the ability to join panels together using a layer by layer approach. This sample proved to have very little density control; the use of aluminized tapes to join the sheets leads to the overlap growing several times the original density. Significant difficulty arises when attempting to control the movement of the Dacron netting within the substrate layers. Overlapping is difficult with larger samples, proving that up scaling the process would give rise to areas where the netting can falter, leaving areas open for direct conductive heat leak through the Mylar layers. This layer by layer approach is extremely time intensive, and sensitive to the effects of gravity. In perspective of the goal of the modular blanket design, this approach will not work well; it leads to a labor intensive, permanent approach.

4. Hook and Pile connection

Availability of materials and feasibility of installing this type of connection led to the fabrication of several test patches using the hook and pile connection. One inch wide strips of standard hook and loop connectors were used during build up. Strips were mounted to the MLI substrate using sewing pins placed inline of the future seam; this minimizes extraneous pin holes. Seams are made approximately 1/8 inch from all edges of the connector strip to ensure a strong bond to the MLI blanket. Samples showed consistent strength to resist tearing or loosening under normal connection/disconnection cycles.

Lessons learned from the previously described samples are presented in the table below.

Process	**Tool Used**	**Comments**
Sewing	Sewing pins, standard domestic scale Kenmore sewing machine, zigzag foot, nylon thread	Technician-recommended stitch lengths are 4-8 stitches per inch[5]. Seam terminations are overlapped 0.5 inches to negate unraveling during handling. Fabrics must be secured during sewing, shifting is a major concern while feeding into the machine; this can lead to gathering and tearing of the material as it passes beneath the foot; samples were secured using household bag clips. Adequate machine tension must be maintained to ensure proper seams.
Hook and Pile fastening	Sewing pins, standard domestic scale Kenmore sewing machine, nylon thread	With an MLI substrate of 15 layers, a typical household machine works properly. Once secured with pins, shifting of the MLI is rarely a concern. Care must be taken to ensure pins will align as closely as possible to the seam path to ensure a minimized presence of punctures. The buildup of the connector strips and the underlying layers yields a robust section of the MLI sample, capable of being used without extreme care.

Table 5 – Sample lessons learned

D. Small Scale Blanket

After working with the materials and compiling handling experiences, a small scale blanket was built up for a cryogenic test bed housed at MSFC. The purpose of the blanket was to demonstrate the feasibility of the modular blanket fabrication, paving the way for the design and build up of a full-scale blanket for the MHTB. The tank chosen is a spherical tank, approximately 24 inches in diameter. A tank of this size of radius presents opportunities to develop methods of designing and fabricating for a complex, domed feature. The domed portion of MHTB presents the most difficulty, aside from hardware and structural components, in installing a blanket.

Buildup began by creating paper templates for the first blanket layer. Panels were modeled with paper and transferred to a prepared MLI 15-layer blanket. As the patterns were being laid out on the blankets, excess material was added to the perimeters of the patterns to allow for Kapton tape and cloth tag binders to hold the pattern layers together during the first stages of fabrication. In designing the blanket patterns, care was taken to account for the overlap of the hook and pile connectors. The first layer was designed with 6 wedge shapes of equal size, with slight variations due to hand fabrication.

After pattern layout was complete, sewing was accomplished by using the methods previously described. Patterns were held together with cloth tags and standard clips. As the blanket sections were passed through the machine, clips were removed; tension was maintained by pulling the MLI layers evenly against the tension of the sewing machine feed area, see Fig. 8.

Figure 8. Sewing of MLI blanket sections

After the first blanket layer was fabricated and installed (see Fig. 9), a finishing element was constructed and portions of a secondary layer were started. The finishing element was designed to direct the lateral heat flow from the upper portions of the six first layer segments outward and back onto the blanket. This concept still needs further investigation and refinement. Patterns for the second layer blanket sections were fashioned from the original paper patterns, slightly altered to add length to accommodate the larger radius of the tank and MLI blanket system. Two blanket panels were created using methods described earlier with no added difficulty.

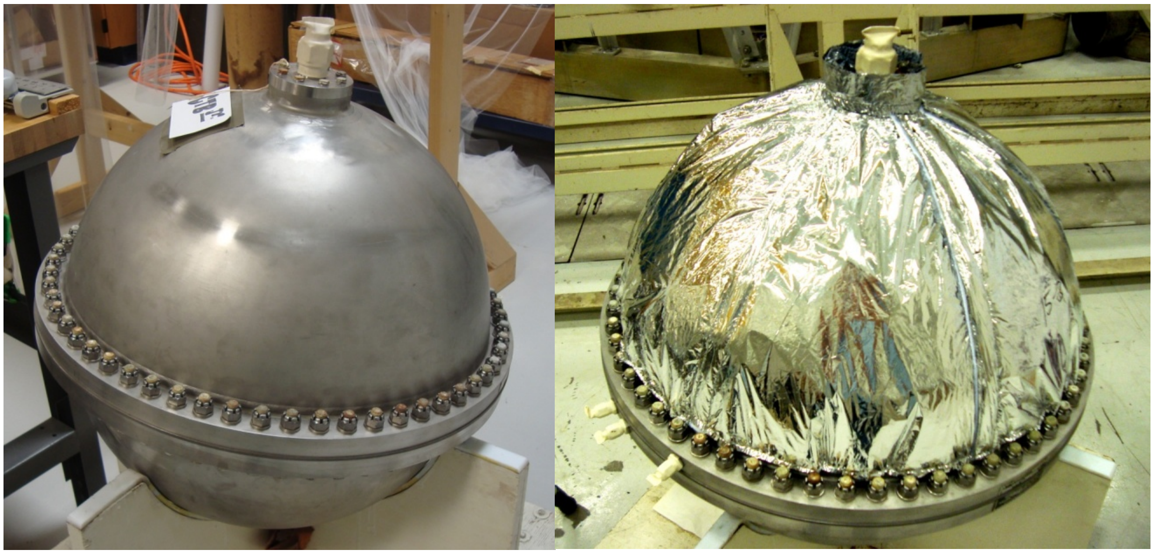


Figure 9. Cryogenic tank prior to (left) and after (right) fabrication and installation

IV. Results and Discussion

Material handling characteristics and sample construction yields a wealth of knowledge to a blanket designer and those technicians undertaking the fabrication. Through hands-on blanket design and fabrication, several methods of construction thought to be the most promising from a listing of possibilities have been attempted. Previously given lessons learned give insight to the difficulties encountered while working with this tedious material; further evaluations are outlined in the appendix section.

The properties of the system as a whole yield an entirely new set of engineering questions which have yet to be answered for the MHTB specifically. When scaling up to a blanket design for the full system, there are several factors that must be addressed further, and they are:

A. Venting

During vent down, the system must have the ability to reach simulated vacuum levels that follow a typical Saturn V or Shuttle ascent timeline[1]. The current MHTB MLI blanket relies on large (1.27 cm-diameter) perforations in the Mylar material to allow gas flow out of the blanket. The holes in the radiation shielding material allow heat leak, this may be negated by using Mylar substrate without holes. The blanket design proposed would have large seams through which the trapped gases may purge; this requires testing or further numerical analysis to verify the concept.

Billowing may be of concern for a blanket design as large as that for the MHTB. To prevent billowing and possible damage of the blanket, UV and AO resistant buttons may be employed to hold the blanket layers sturdy during pump down[5]. Appropriate space environment materials should be used to fasten the buttons, when required. For the installation of a new MLI blanket for the MHTB, such environmental considerations need not be addressed.

B. Advanced Construction Methods

For the construction of a large scale blanket for the MHTB, several concepts can be employed that may assist in the build up and later reparation (if needed) of the MLI system.

For the domed and cylindrical portions of the tank, separate wooden jigs representative of the geometries can be created to layout and trim the materials. Jigs may be constructed to the size of one of several equally sized panels to ensure equal size and handling of the separate panels. A clamp system can be employed on the jig to hold the MLI materials from moving while cutting. Ample, evenly distributed pressure over the length of the cut is required and can be achieved using such a method. This would provide an efficient technique of cutting large panels to size.

Due to the nature of the panel blanket, methods of minimizing heat transfer to combat the seam heat leak through the blanket are important. Heat treating the blankets after construction may help reduce outgassing by encouraging vapors to evacuate prior to installation. Dusting intermediate layers with activated carbon or using a carbon-filled substrate as a spacer material would allow the carbon to absorb any outgassing that may occur during testing or use.

C. Testing

To fully verify the feasibility of a large scale blanket for the MHTB or other possible vehicle uses, mechanical and thermal testing should be performed.

Mechanical testing should be performed on the blankets to analyze their robustness. Vibration and simulated acceleration load testing would verify the ability of the hook and pile seams to withstand the weight of the panel which they support. Although preliminary handling testing provided some insight to the rigidity of the fully-built seams, further testing would provide data for the failure of a typical sewn MLI/hook and pile system. Vent down testing on sample panels will allow designers to better understand the ability of a blanket to vent through seams rather than through a large number of blanket layer perorations.

Thermal testing should be performed on the blankets to conclude the amount of thermal performance gained or compromised with using this panel method. Studies on labor costs and time frames for creating such a blanket can give insight to the cost benefit of such a system; these studies can be weighed with data gathered from thermal testing and analysis. Several panels were created and given to test engineers at Kennedy Space Center to perform cryostat testing on different seam types to determine an optimal design with the given samples. Results will help future designers optimize seams and construction techniques.

V. Conclusion

The Multipurpose Hydrogen Test Bed housed at Marshall Space Flight Center is a versatile test bed which will be used to further the development of advanced cryogenic fluid management techniques and concepts, and is scheduled for upcoming testing. The refurbishment of the MLI blanket for the MHTB is a critical step for this testing. However, the nature of an MLI system presents significant handling and design challenges.

The samples and recommendations previously described give an understanding of the design and construction processes required for building a modular, variable density MLI blanket for the refurbishment of the MHTB cryogenic fuel tank. Benefits of a panel blanket include a decrease in labor costs associated with installation and repairing blankets and an added benefit of easier pump-down venting. A modular blanket design presents the possibility of more flexibility during experimentation, allowing for removal and reconfiguration of the MLI system. For the described benefits, there will also be marked tradeoffs in thermal performance due to radiation leaks through seams and connections. Future experiments on prepared samples will yield empirical evidence to give insight into these losses.

Appendix

Appendix A - Material Handling Evaluation

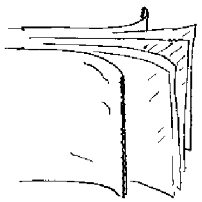
Tool or Method	**Comments**
Hobby razor knife	Blades must be changed frequently to avoid snagging. Must be used in conjunction with method of applying pressure to material and a cutting mat.
Scissors	Allow material to slide during cutting. Leave jagged edges, which if not treated can lead to tear propagation.
Manual paper cutter	Would allow slippage of material, and is highly constrained on cut geometries.
Rotary cutter	Blades must be changed often, cannot cut full blanket thickness.
Hydraulic paper cutter	Would produce straight cuts through heavy MLI blankets. Provides compression during cut. Limited cut geometry.
Vacuum table	Would allow for layer by layer cutting without slipping.
Layup jig	To be built for specific tank application. Would allow for exact dimensioning of all blanket panels
Ultrasonic welding	Versatile in connecting multiple layers. May have restrictions for MLI maximum thickness. Samples showed signs of fatigue through normal handling. Seams are rather rigid, which might add to the structural rigidity of a blanket.
Staples	Provide quick fabrication. Direct thermal leaks are present through the staple holes. Blankets are pinched at staple sites, and require reinforcement at staples to avoid tearing from regular handling.
Sewing	Versatile in connecting multiple layers. Machines will have varying maximum blanket thickness. Samples proved rather robust through rigorous handling. Thermal shorts are present through the entirety of seams.

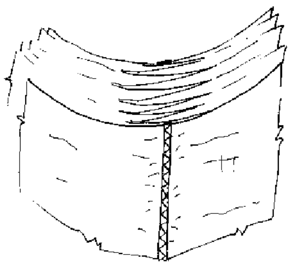
Appendix B – Tools and Materials Used

Tool or Material	Details
Sears Kenmore Sewing Machine	Model: 385.17622 Zigzag foot used
#11 Hobby Blade	Standard, stainless steel
3.5 inch Clip	Plastic food bag clip
6 inch Clip	Plastic food bag clip
Avery Fabric Tag Gun	Model: Mark III
Avery 2 inch Polypropylene Barbs	Model: Swiftach Fasteners P/N: 10417
Nylon Upholstery Thread	MFG: Coats P/N: ART AD64CO 256
Transparent Nylon Thread	MFG: Coats P/N: ART AD67CO .005/C
1 inch Hook Strip	MFG: Velcro P/N: 190528
1 inch Loop Strip	MFG: Velro P/N: 190388
Polyimide Tape (Kapton)	MFG: Furon 1 in wide roll
Dacron Netting	MFG: Apex Mills B2A Netting – 54 inch wide roll
Dacron Netting	MFG: Apex Mills B4A Scrim – 54 inch wide roll
Double Aluminized Mylar	Flat, non-perforated 0.00025 in × 56 in

Appendix C - Detachable Installation Method Evaluation

Layer by Layer





Description

Blankets can be built up with an outside structural layer using Kapton or several layer of the blanket. Outside layer would be shorter than inner layers, to provide the ability to layer the inner substrate to an attached panel. A connector would secure the outer layers for final installation. Panels would have to be quilt like, with buttons or thrlead tags holding layers together

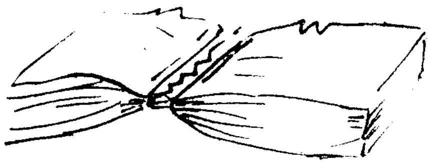
Pros

Higher protection against heat leak through panel connections.
More closely resembles the original roll wrapped installation, where connected intermediate layers would form unified panels.

Cons

Poor layer density control at connection.
Addition of buttons or tags would pinch blanket and allow direct thermal leaks.
Highly labor intensive.

Zipper



Description

Similar to fabrication of hook and pile connector; install at edges of blankets to allow for end to end connection of panels.

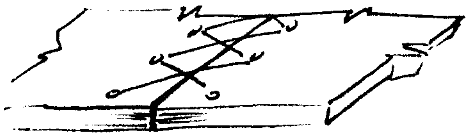
Pros

Quick installation of blankets. Zippers give structural rigidity along their length.

Cons

Direct thermal leak through zipper hardware. Pinching of MLI layers at sewing seam provides thermal short. During blanket installation zippers may snag underlying MLI panels.

Laces



Description

Blankets would be fabricated with eyelets or grommets to allow for a lacing material to join the segments. Instead of end to end connection, panels may be stacked with staggered lap joints to improve thermal performance.

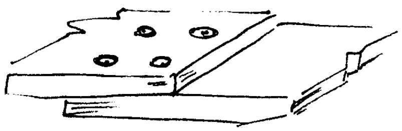
Pros

Quick installation of blankets. Possibility of setting eyelets inwards of edges, allows layering of MLI layers of separate panels together

Cons

Direct thermal leak through eyelet hardware. Provides no structural stability, blankets may easily shift positions

Buttons



Description

Utilize UV or AO resistant buttons for space applications. Standard button installation.

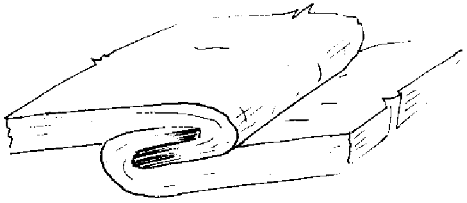
Pros

Quick installation of blankets and fast fabrication. Buttons may keep layers from shifting, much like the fabric tags.

Cons

Direct thermal leak through button installation. MLI would need reinforcement to keep perforations from propagating.

Folded Seam



Description

Panels would be sewn to secure layers and joined by folding into one another. Installation requires secondary method of securing to tank.

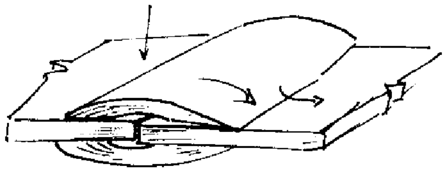
Pros

Quick installation of blankets and fast fabrication. Thermal shorts would not be directed to tank, instead re-routed to the blanket.

Cons

Lateral heat flow will be directed into the seam, increasing heat load at that area. Folded installation would compress material and compromise density control greatly.

Shielded Seam



Description

Using any method of joining two adjacent panels, seams would be covered with a separate MLI layer on the interior or exterior (or both) of the blanket.

Pros

Coupled with staggered seams, this installation would minimize heat transfer through seam perforations

Cons

Complicated installation and lack of density control at seams. Increases mass of blanket and labor costs.

References

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