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Thermal Degradation of Multilayer Insulation Due to the Presence of Penetrations

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Abstract. Invented in the 1950s, cryogenic multilayer insulation (MLI) continues to be studied, tested, and analyzed as it represents a complex system that is integral with the total system to be insulated. Numerous tank and calorimeter tests have been performed using many different insulation approaches. Many different variables have been tested and documented, mainly within the insulation system itself. There are several factors in insulation application that can drive up the heat load on the entire system. These include the treatment of insulation seams, instrumentation wires running through the insulation, and the integration of the insulation with the structures and fluids. Several attempts have been made to identify the performance losses due to structural integration with a real system. Due to the nature of MLI, these were tied to specific programs and configuration dependent. In an effort to understand the complex heat transfer mechanisms surrounding such systems, a series of calorimeter testing coupled with thermal modeling of the calorimeter tests was put into place. Testing showed that a buffer of micro-fiberglass material such as Cryolite is a robust method of closing out MLI penetrations. Additionally, a validated thermal model was used to develop parametric analysis far beyond the limitations of the calorimeter testing. This paper presents the methodology and approach, with experimental data providing the basis for developing the thermal model and its results for applicability to future design cases.

KEYWORDS: Multilayer Insulation, Structural Integration, Boil-off Calorimetry

INTRODUCTION

Multilayer insulation (MLI) has been widely discussed and tested for over 50 years as a high performance solution to many insulation applications. However, the main draw back to MLI is that its practical application requires the understanding and practice of the art form of designing and building it as an integrated sub-system within the system it is insulating.

One of the issues with MLI is the integration of it into the full system that includes structural supports and fluid lines into and out of the storage tank. Previous efforts have focused on such issues in either an experimental or analytical modeling manner; however, none have combined the two approaches. As part of a larger study in multilayer insulation systems for large NASA launch vehicles in the late 1960s, Lockheed performed some calorimetry work with both liquid hydrogen and liquid nitrogen using aluminum foil based blankets (shown in Figure 1). [1] The main work focused on isolating the penetration from the main MLI using tissue paper. They determined that several inches of tissue paper were needed to minimize the impact of the penetration. At nearly the same time, Johnson and Sprague were investigating the same issue using nodal thermal models. [2] Their parametric analysis enabled them to develop several relationships for calculating the heat load penalties within the MLI due to the presence of a penetration. Again, the reflective layer of choice appears to be aluminum foil based on the analysis presented.

As thermal insulation blankets matured, little more was done on penetrations through the MLI. While testing candidate insulation systems for a cryogenic storage test vehicle, Sumner did testing on a specific candidate insulation system seam design and strut design. [3] Under contract to the Air Force in the late 1980s, a team lead by Mohling analyzed top level thermal considerations, but were not able to substantiate their analysis because the test program was cancelled. [4] Since that time, while much work has been focused on insulation systems, no other attempts have been made to understand the complex integration between multilayer insulation and various penetrations that caused by relatively large in-plane (or along a layer) thermal conductivity of an MLI blanket when compared to the thermal conductivity through the blanket which has several orders of magnitude lower thermal conductivity.

In preparation for large scale cryogenic upper stages, NASA had a need for more accurately predicting the thermal loads that are transmitted to the large tanks through the insulation. As these issues are usually accounted for by increasing the thermal margin on a blanket, getting a full grasp on the heat loads due to integration will allow for predicting those heat loads with less uncertainty. It was set out to more fully understand the integration issues between various penetrations and multilayer insulation blankets, both through experimentation and thermal modeling.

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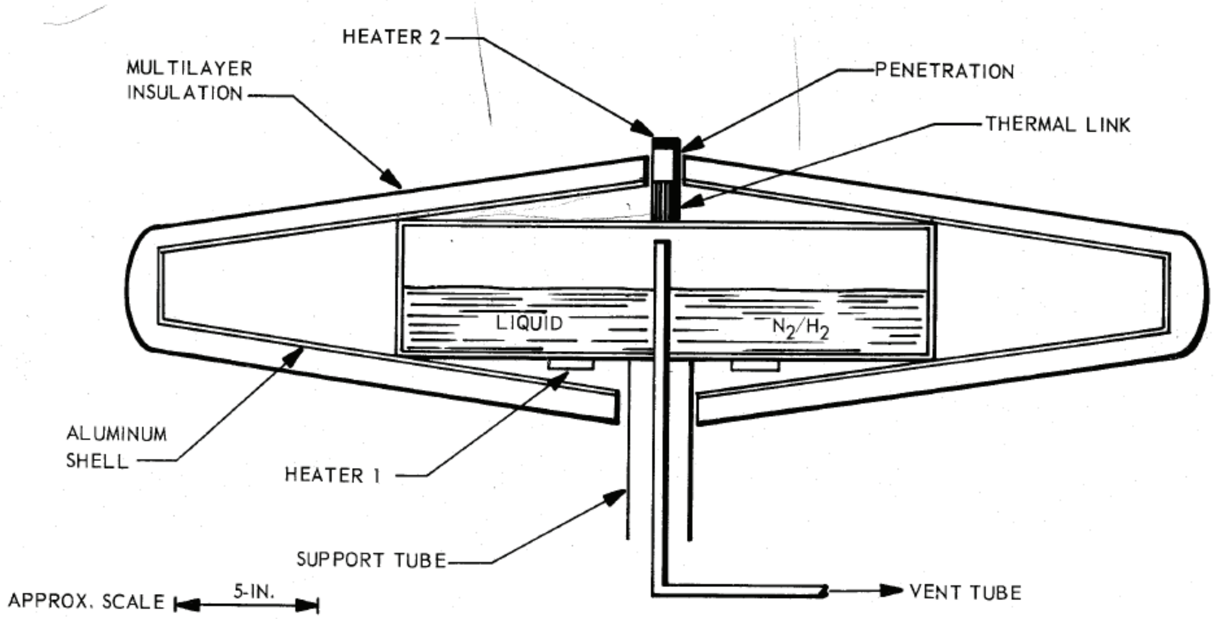


FIGURE 1: Sketch of insulation penetration cryostat from work performed by Lockheed.

EXPERIMENTATION

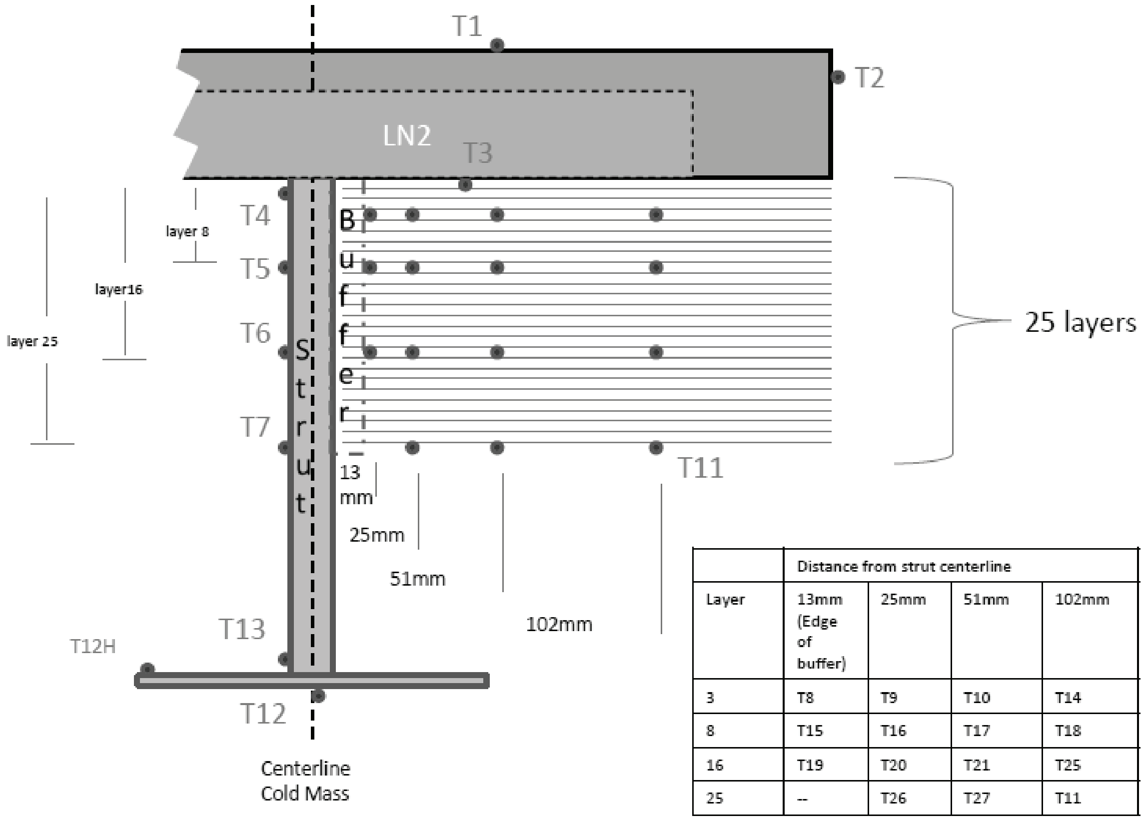
In order to perform testing on various penetration methods, a new type of calorimeter was needed. This calorimeter needed to be sensitive enough to measure very small changes in thermal performance of insulation blankets, yet have enough capacity to take the much higher heat loads associated with placing a penetration through the blanket. Based off the work of Fesmire and Augustynowicz [5], a guarded liquid nitrogen boil-off calorimeter (known as Cryostat-600) was designed and fabricated with built-in mounts for the penetrations. The built-in mounts were below the calorimeter to give a much more uniform cold boundary temperature for the insulation. A vacuum chamber was built for the calorimeter, and all tests were run at vacuum pressures in the $1x10^{-6}$ torr range.

To determine the actual degradation around the penetration, the applied MLI and penetration loads must be known. Each of the six MLI blankets used was tested without a penetration (in accordance with Test 1 in Table 1) prior to being damaged for testing with a penetration. This allowed for subtracting out the baseline heat load. To calculate the strut thermal loads, temperature sensors were placed at known locations along the penetration (which was made of a known material and geometry) as shown in Figure 2 to allow for the calculation of the heat load down the penetration. These known heat loads were then subtracted from the measured load for each of the penetration tests.

To understand if there were any in-layer temperature gradients, a two dimensional grid of type-E thermocouples were placed within the blanket as shown in Figure 2. The sensor placement assumed that the blanket was axis-symmetric around the penetration or strut.

The test matrix (shown in Table 1) was comprised of six different types of test, with subsets of each test being performed. Several different integration mechanisms were tested: no integration (both with the hole in the blanket cut to the size of the penetration and cut slightly bigger), with the penetration isolated (or with a buffer material), and temperature matching (this is further explained in Reference 6). Once the best method and materials were determined from these initial tests, the penetration size and material was varied to anchor the thermal models that were developed to allow for further parameterization.

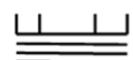
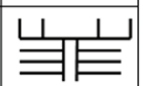
As a result of the testing, penetration isolation with a buffer material was determined to be the best method and cryolite was determined to be the best material to be used in this method. The results of the calorimeter data are much more fully presented and discussed by Johnson, Kelly, et. al. [7]



	Distance from strut centerline			
Layer	13mm (Edge of buffer)	25mm	51mm	102mm
3	T8	T9	T10	T14
8	T15	T16	T17	T18
16	T19	T20	T21	T25
25	--	T26	T27	T11

FIGURE 2: Temperature sensor location with strut present (assumes a 0.5" thick buffer).

Table 1: Penetrations Calorimetery Test Matrix

Test	Test Description	Reason	Figure
1	No Penetration	Baseline	
2	No Integration a) Without gap b) With gap (a no buffer case)	Worst Case	
3	Isolated Penetration a) 1/2" Aerogel Blanket b) ½" Bead Pack c) 1" Aerogel Blanket d) ½" CryoLite e) 1" CryoLite	Isolate bulk insulation from penetration insulation	
4	Temperature Matched a) Lockheed b) Test #1	Best Case (assumes single warm temperature)	
5	Variable Size a) 0.25" strut with best from above b) 5a. disturbed MLI c) 1" strut with best from above	Change size of strut	
6	Composite Strut a) Isolated b) No Adaption	Change penetrations conductivity	

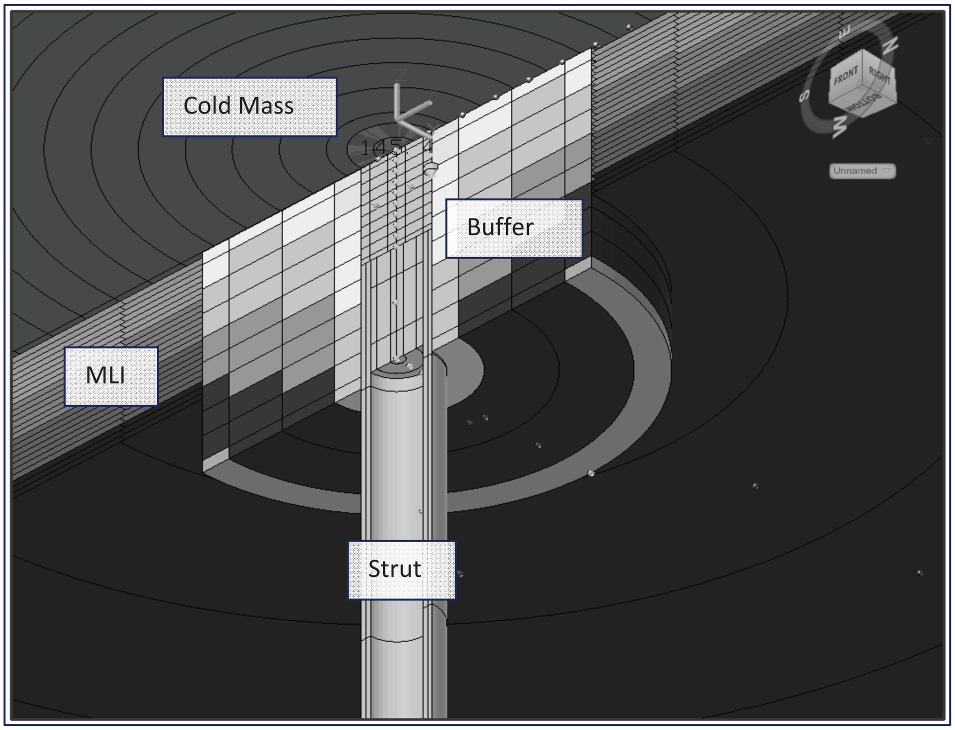


FIGURE 3: Section view of detailed thermal model.

ANALYTICAL MODELS

Thermal models were developed in Thermal Desktop and run on Sinda/Fluint to allow for scaling of the test results to larger struts and different boundary conditions. The models were anchored to the testing performed.

Two models were created, a detailed model of the Cryostat-600 cold mass that was used for validation of approach and a model that was used to scale those results to flight applications. Both models allowed for radiation and conduction heat transfer.

The detailed model (shown in Figure 3) included both the guard and test chambers, the penetration or strut, MLI test sections (each layer modeled individually as a radiating surface), the buffer, and other detailed components of the testing. For modeling purposes, the heat loads were assumed to be axis-symmetric; however, there were multiple radial nodes within both the buffer and each MLI layer to refine temperature gradients. The detailed model's purpose was to develop and validate a method for modeling the penetration issue. The model was verified to be within the uncertainty of the experiment (within 5%). The model validation is shown in Table 2.

The flight scaling model was a much more basic model within Thermal Desktop that used the validated methods developed in the detailed model but didn't include the details of the calorimeter such as the guard chamber and edge guards, instead looked at a much more basic and open configuration where edge effects were basically ignored. This model was used to extrapolate the test data to create parametric curve fits for a better understanding of how such integration would work on systems parameters much wider than what was directly tested.

Both models are more fully explained by Johnson, Kelly, and Jumper. [8]

Table 2: Verification of model to test results

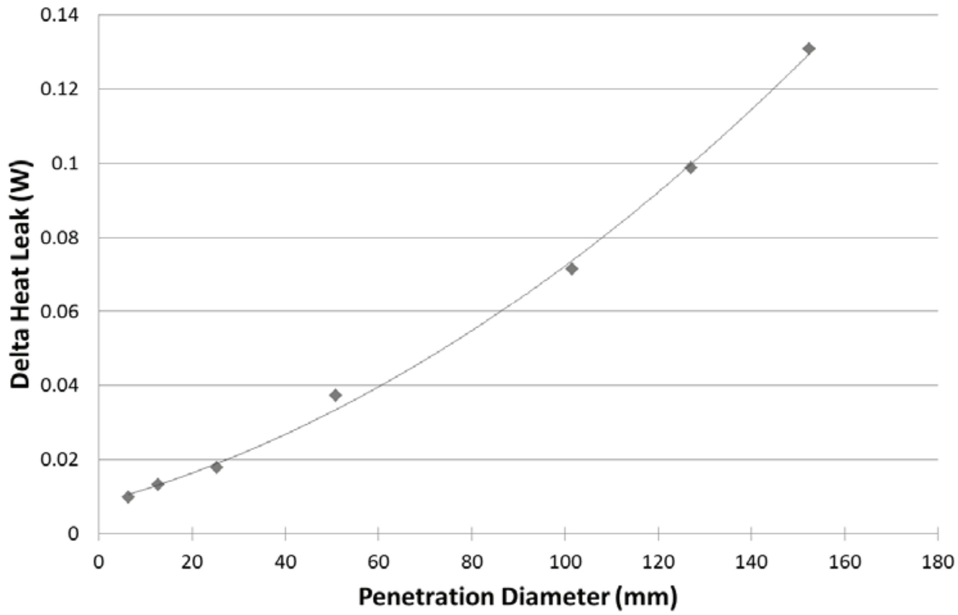
Test	Average Percent Error In Temperature Match Between Test Results And Model		Change In Heat Load Due To Penetration	
	Strut	MLI	Delta Q – Test (W)	Model difference (W)
12.7mm AL Strut, 25.4mm buffer	1.03%	1.87%	0.262	0.0199
6.35mm AL Strut, 25.4mm buffer	1.03%	0.71%	0.288	0.0175
25.4mm AL Strut, 12.7mm buffer	0.25%	2.96%	0.656	0.0806
25.4mm AL Strut, 25.4mm buffer	0.23%	2.61%	1.135	0.0785
25.4mm Composite Strut, 25.4mm buffer	2.13%	1.12%	0.252	0.002

RESULTS

After verification of the detailed thermal model to the test data, the flight scaling model was used to perform parametric analysis on a wide variety of conditions. The results of those parametric runs are shown in Figures 4 – 6. The main variables that were expanded upon were the penetration diameter, the buffer thickness, the number of MLI layers, and both boundary temperatures. The best fit lines are drawn through the data points from the flight scaling model and best fit lines give a method of turning the data into useful parametric scaling. The exponent on the warm boundary temperature was derived from the experimental test data when several tests were run at different warm boundary temperatures to assess the sensitivity of the integration method to environment (or warm boundary temperature).

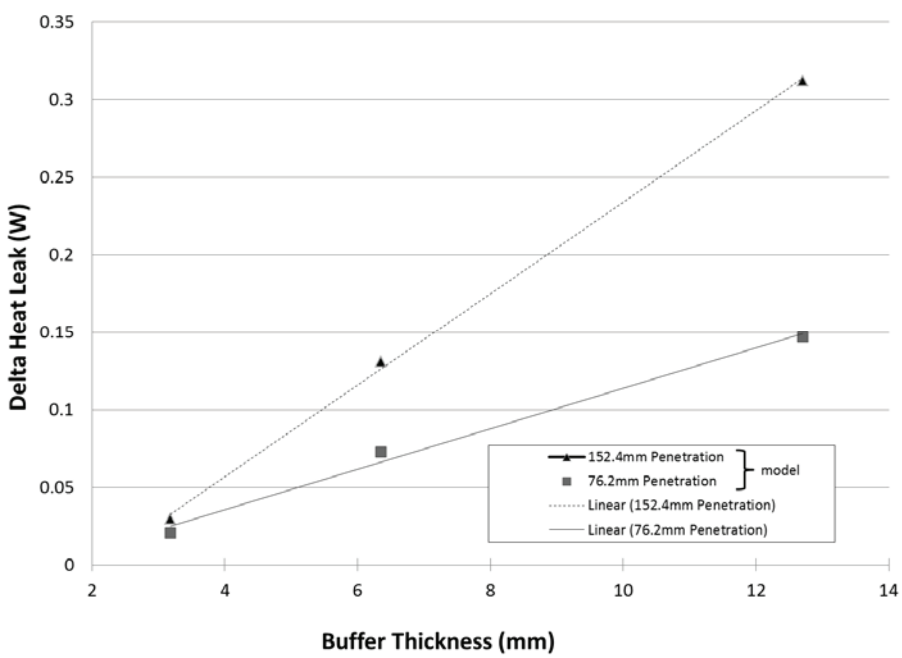
Equation 1 shows the implementation method associated with the parametric model. In order to use the equation, two different reference states are required. The first is recommended to be either a 0.0762 m diameter or 0.1524 m diameter penetration (whichever is closest to the actual penetration) through 25 layers of MLI with a 6.4 mm buffer. The second reference point should be the same diameter penetration and number of MLI layers with a 12.7 mm buffer. The first parenthetical term is from Figure 6, and represents the ratio of the actual application parameters to the second reference state. The equation from Figure 6 should be used to calculate the dQ for both parameter sets and then applied in the ratio. The second parenthetical calculated from Figure 5 using the two reference state. The fourth term also uses Figure 5, but compared the actual application state to the first reference state. The third term uses the equation in Figure 4 and compares the effect of the diameter of the penetration in the actual state to the references state.

$$dq = q_{ref}\left(\frac{q_{actual}}{q'_{ref}}\right)_{\#layers}\left(\frac{q'_{ref}}{q_{ref}}\right)_{buffer\ thick}\left(\frac{q_{actual}}{q_{ref}}\right)_{diameter}\left(\frac{q_{actual}}{q_{ref}}\right)_{buffer\ thick}\left(\frac{T_h}{297}\right)^{1.56} \quad (1)$$



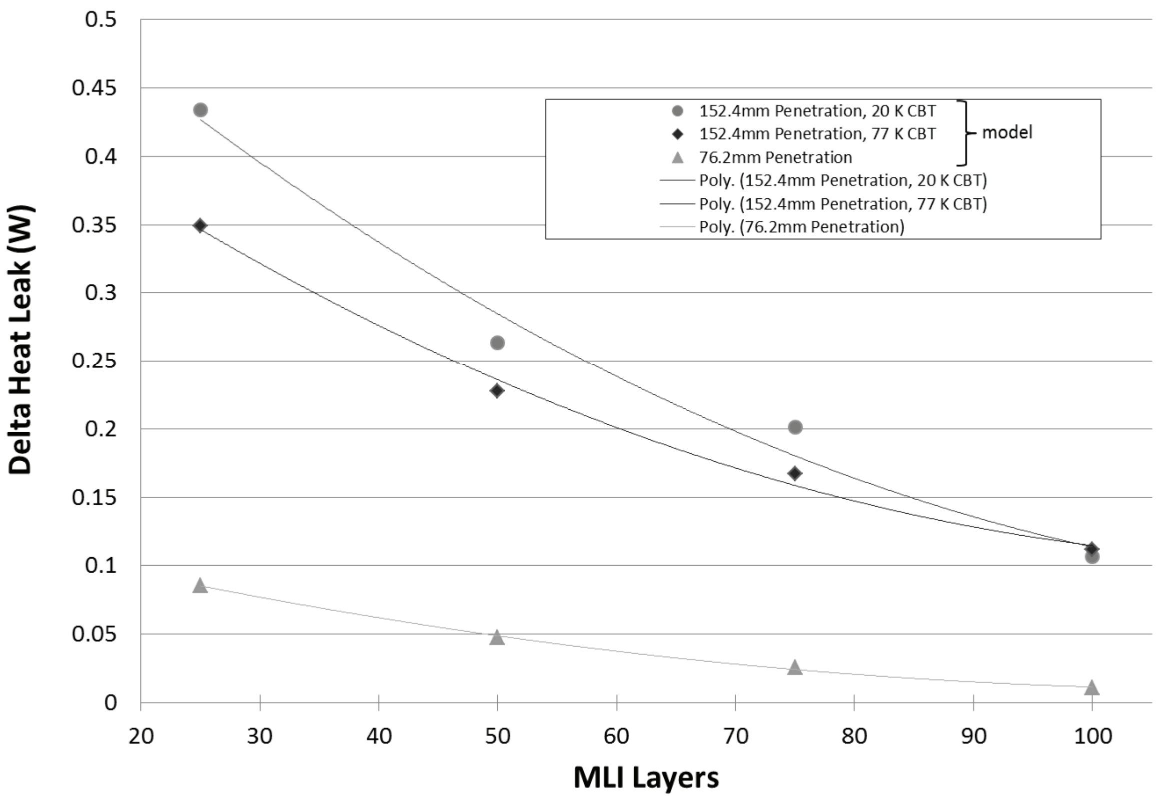
Penetration Details	Change in Heat Leak (W) with Strut Diameter (x in meters)
25 Layers, 6.4mm Cryolite Buffer	$2.95x^2 + 0.346x + 0.00826$

FIGURE 4: Model results for variation of integration heat load with penetration diameter for 25 layers of MLI and a 6.4 mm buffer.



Penetration and Environment	Change in Heat Leak (W) With Buffer Thickness (x in meters)
152.4 mm Strut, 25 Layers MLI	Y = 29. 5x – 0.0608
76.2 mm Strut, 25 Layers MLI	Y = 13.1x – 0.0168

FIGURE 5: Variation of integration heat load with buffer thickness for a 25 layer blanket.



Penetration Details	Change in Heat Leak (W) With MLI Layers (x)
152.4mm Penetration, 25.4mm Buffer, 20 K Cold Boundary	$3.03E\text{-}5x^2 - 7.97E\text{-}3x + 0.607$
152.4mm Penetration, 25.4mm Buffer, 77 K Cold Boundary	$2.68E\text{-}5x^2 - 6.44E\text{-}3x + 0.491$
76.2mm Penetration, 12.7mm Buffer	$9.51E\text{-}6x^2 - 2.17E\text{-}3x + 0.134$

FIGURE 6: Model results for variation of integration heat load with number of MLI layers.

CONCLUSIONS

Testing of various styles of integration of structural and fluid components into MLI blankets was completed at the Kennedy Space Center over the course of an eight month test matrix spanning 22 different tests. Both temperature and heat load data was gathered during the dedicated penetrations calorimetery testing. The data from these tests were then used to verify a detailed thermal model which was used to perform parametric analysis even beyond the testing. From that analysis, a simplified equation was generated to allow for the calculation of the integration heat loads from various penetrations into cryogenic tanks.

The results from this experimental and modeling study will allow for the quantification of integration losses for penetrations through MLI. This will decrease the uncertainty of the thermal performance of insulation systems applied to cryogenic tanks and vessels.

ACKNOWLEDGEMENTS

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