Multilayer Insulation for In-Space Cryogenic Applications

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Logistics

- **Egress**
- **Restrooms**
- **Breaks**

Outline

- **Cryogenic MLI Introduction**
  - Heat Transfer basics
  - Terminology
  - Fundamental
  - History
- **Cryogenic MLI blanket variables**
  - Empirical Equations
  - Vacuum Pressure
  - Layer Count
  - Layer Density
  - Warm Temperature
  - Cold Temperature
  - Transient Performance
- **Cryogenic MLI materials**
  - Reflectors
  - Perforations
  - Spacers
- **Cryogenic MLI builds**
  - Seaming
  - Venting
  - Small Penetrations
  - Med Penetrations
  - Grounding
  - Repeatability
- **IMLI**

About the Instructor

- **Cryogenics Test Laboratory – KSC (10 yrs)**
- **Fluid and Cryogenics Group (LTF) – GRC (10 yrs)**
- **Over twenty years hands on experience with liquid nitrogen and other cryogenic fluids**
- **Past Experience:**
  - Multiple liquid hydrogen tests
  - Structural Heat Intercept, Insulation, and Vibration Evaluation Rig
  - Integrated Refrigeration and Storage Oxygen and Hydrogen Demonstrations
  - 9 years of insulation thermal performance testing & test design
  - Space Shuttle Return to Flight
  - Trouble shooting & improvement of operations at KSC launch pads
  - 4 patents (3 from insulation measurement devices)
  - Operation of nearly 10 different calorimeters varying in size
  - Much of the data you will see today originates from testing and analysis I was directly involved in

Course Objective

- A fundamental understanding of what multilayer insulation is.
- Understand the history and development of cryogenic multilayer insulation.
- A fundamental understanding of the different elements associated with cryogenic multilayer insulation design, fabrication, and installation.
- A list of places to go for more information.
- To touch the inquisitive nature of an engineer.

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Introduction to Multilayer Insulation

What is Multilayer Insulation?

- **Multilayer Insulation targets the reduction of all types of heat transfer:**
- **Gas Convection/Gas conduction:**
  - On the launch pad, closely spaced layers significantly impede gas convection to where a MLI blanket can loosely be modeled as a stagnant gas pocket.
  - In a vacuum: Either through a man-made vacuum or launching to space, the gas between the layers is removed, thereby, eliminating any convective heat transfer leaving only free molecular flow of gas particles between layers.
- **Radiation:**
  - The outer layers of a multilayer insulation blankets are devised to allow the minimal amount of heat into the system from a radiative source.
  - The inner layers of a multilayer insulation blanket are high reflectivity, low absorptivity materials that allow on the order of less than 5% of energy to be transferred radiatively between individual layers.
- **Solid Conduction:**
  - Ideal multilayer insulation systems have no materials / contact between layers (i.e. floating shields)
  - Low conductivity spacer materials (dacron/nylon, paper, other polymers) are usually [but not always] used in between layers to minimize what is needed to support blankets.
  - Low constrictive pressure (large spaces between layers; low layer density) forcing contact between spacer materials and reflector materials.

How was Multilayer Insulation developed?

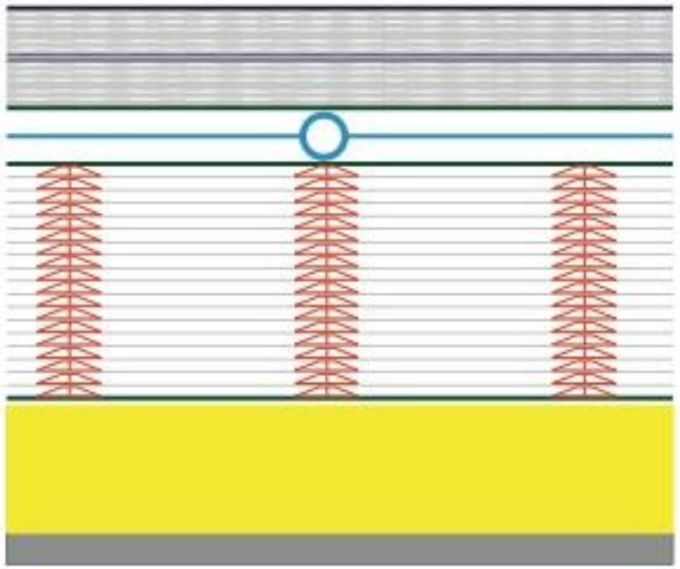
- **Sir James Dewar (c 1900)**
  - Double wall glass container with vacuum in between the two walls
  - Silvering of inner wall to lower radiation heat load and keep cryogens around longer
- **Peterson (c 1957)**
  - Multiple reflective layers stacked to improve the performance and reduce radiative heat loads
- **Era of AD Little Company (Black, Glaser, etc.; 1960s)**
  - Multiple test setups
  - Testing all different types of reflectors and spacers
  - Begin the area of more detailed characterization
- **Era of Primes (Lockheed, General Dynamics; 1970s)**
  - Characterization of specific MLI designs favored by principle aerospace primes
  - Ready for implementation on an array of applications
  - Development of basic spacecraft MLI design techniques
  - Industrial uses baselined for earth-based uses
- **Era of Government (NASA; 1980s – 2010s)**
  - Maintain testing capabilities and understanding of system performance
  - Development of new philosophies (variable density, spray foam / GN2 purging)
  - Implementation of prime specific designs on many [relatively] small orbital observatories/dewars
- **Era of Primes Part 2 (2020s?)**
  - Required implementation to meet ambitious architectural goals
  - Sharing of knowledge retained by government back to primes

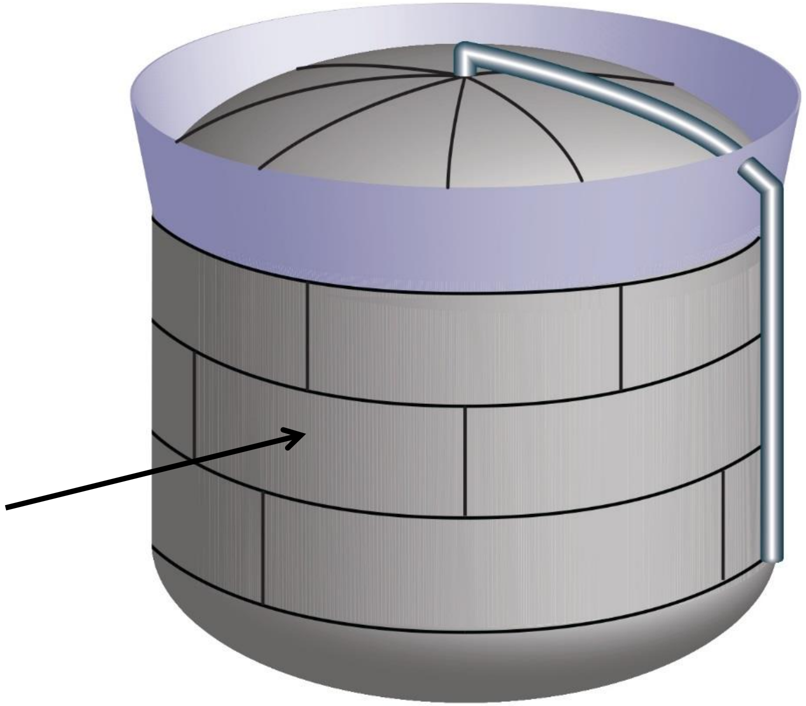
Multilayer Insulation Basics - Terminology

- **Multilayer Insulation and Super Insulation (what it was called prior to the mid-60s) are generally the same thing.**
- **Multilayer Insulation = MLI**

- **Warm Boundary Temperature (WBT)**
  - Can be either the outer layer temperature of the MLI blanket or the radiative source temperature of a test.
  - Typically the two are fairly close
- **Cold Boundary Temperature (CBT)**
  - Typically the temperature of the cryogenic fluid that the MLI is protecting
  - Generally referred to in a generic sense (i.e. LH_2 NBP = 20.4 K, often referred to at 20 K)
- **Cold Vacuum Pressure (CVP)**
  - The vacuum pressure achieved when a test article is full of cryogens or at appropriate cold boundary temperature.
- **Warm Vacuum Pressure (WVP)**
  - The vacuum pressure achieved via mechanical pumping only (system still warm)

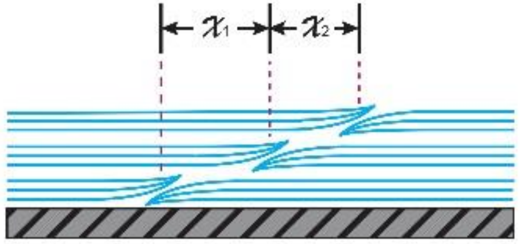
Improved Fundamental Understanding of Super Insulation (IFUSI)



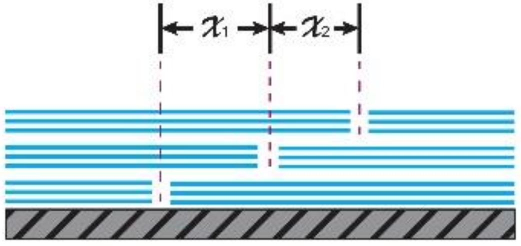


MLI Blankets
- Traditional
- IMLI
- Hybrid

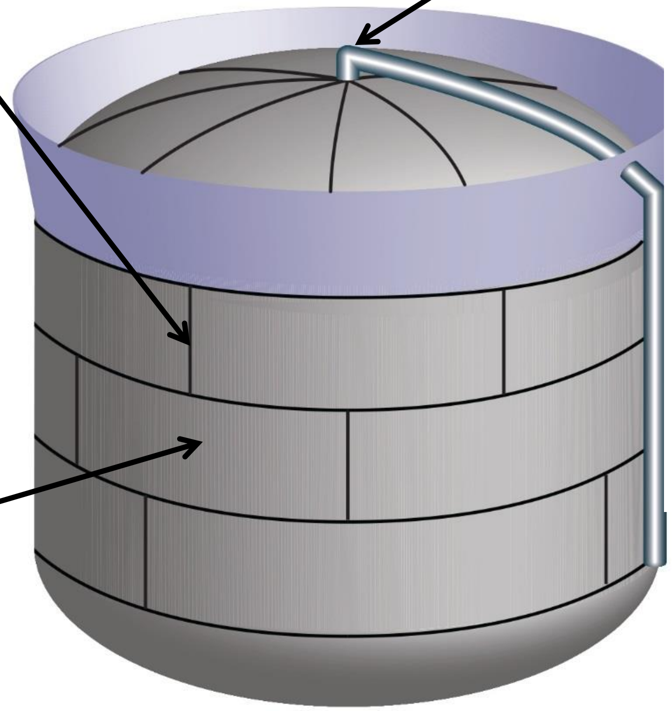
Improved Fundamental Understanding of Super Insulation (IFUSI)



3 Blanket Overlap Staggered



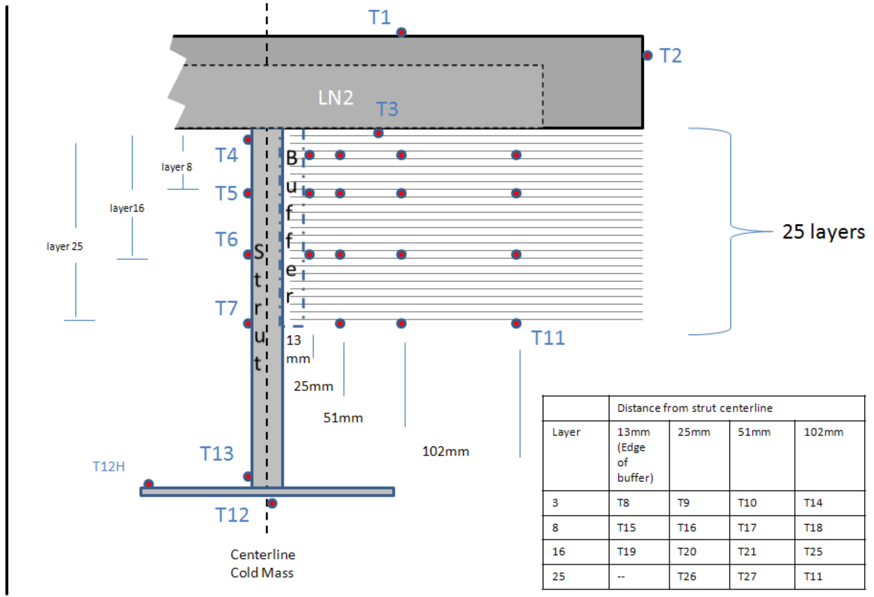
3 Blanket Staggered



Seams

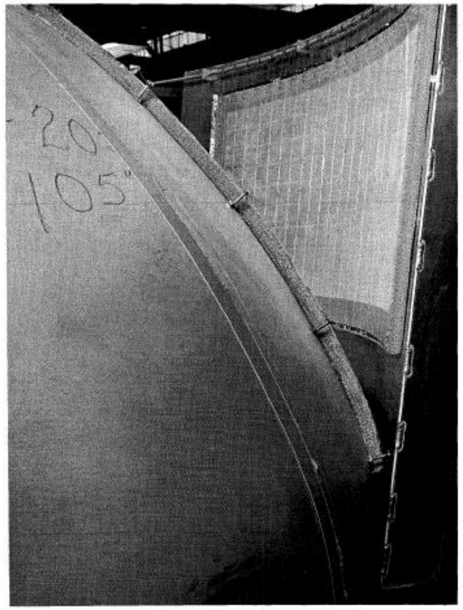
MLI Blankets
- Traditional
- SS-MLI
- IMLI
- Hybrid

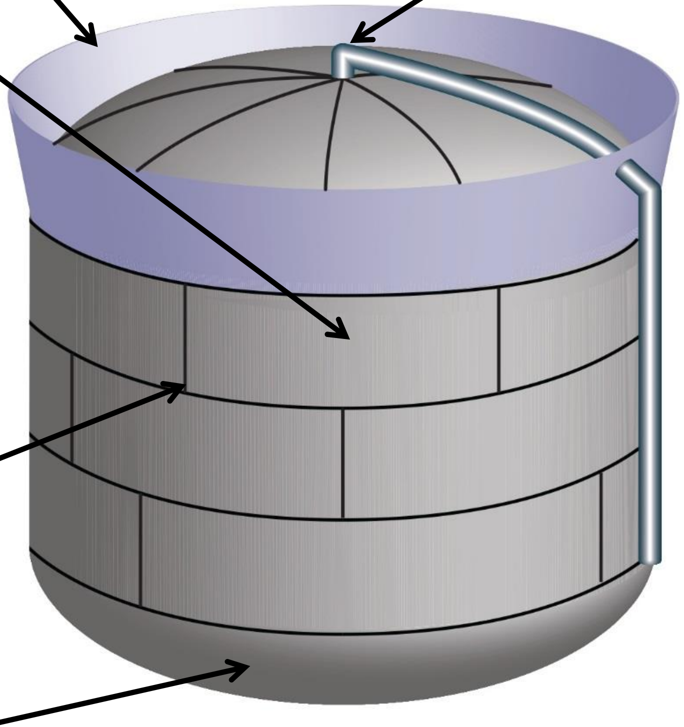
Penetration Integration:
- NASA-TP-2012-216315



	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

Improved Fundamental Understanding of Super Insulation (IFUSI)





Skirt Integration

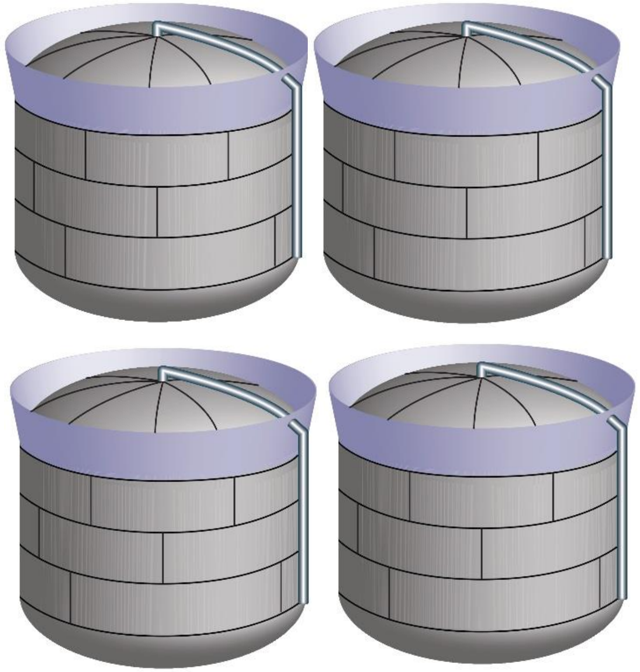
Penetration Integration:
- NASA-TP-2012-216315

Seams

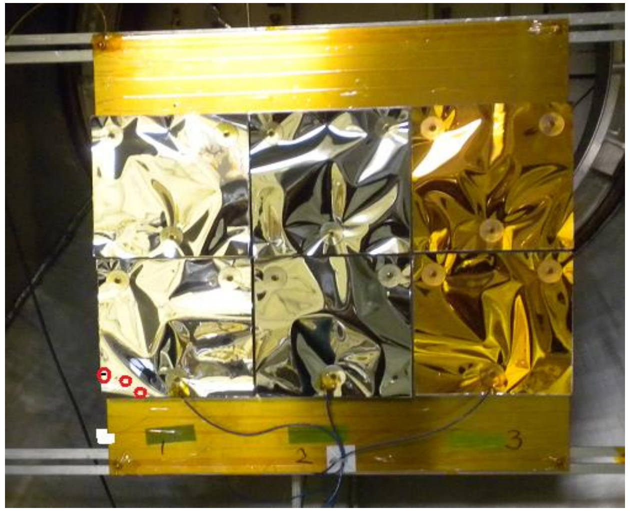
MLI Blankets
- Traditional
- SS-MLI
- Hybrid

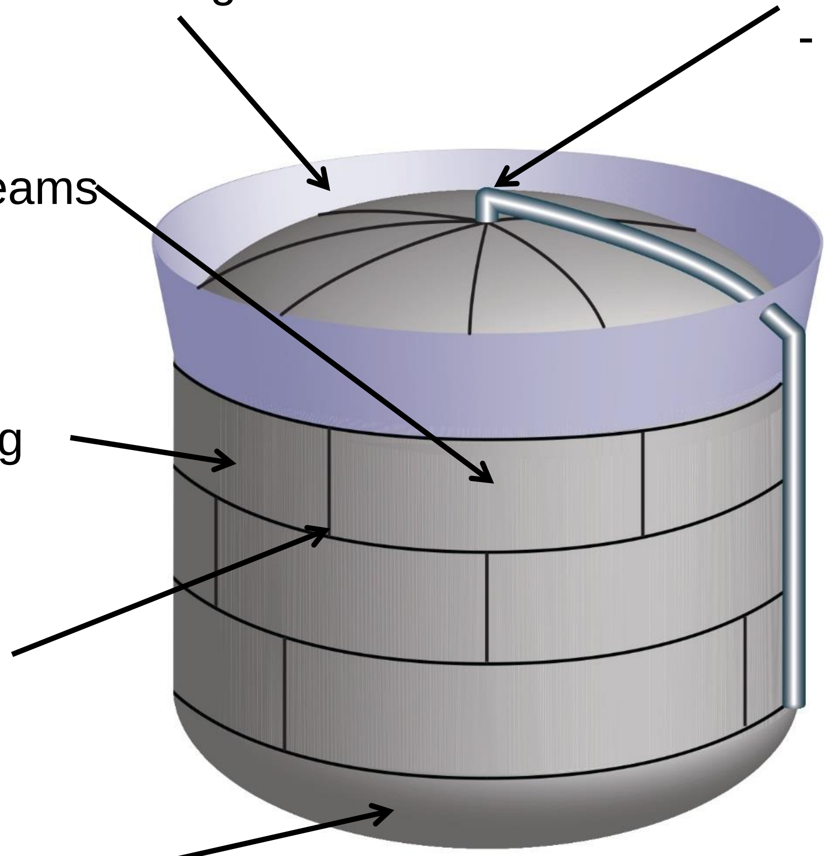
Tape, Pins & Attachments

Repeatability



Improved Fundamental Understanding of Super Insulation (IFUSI)





Skirt Integration

Penetration Integration:
- NASA-TP-2012-216315

Seams

Repeatability

Grounding

MLI Blankets
- Traditional
- SS-MLI
- Hybrid

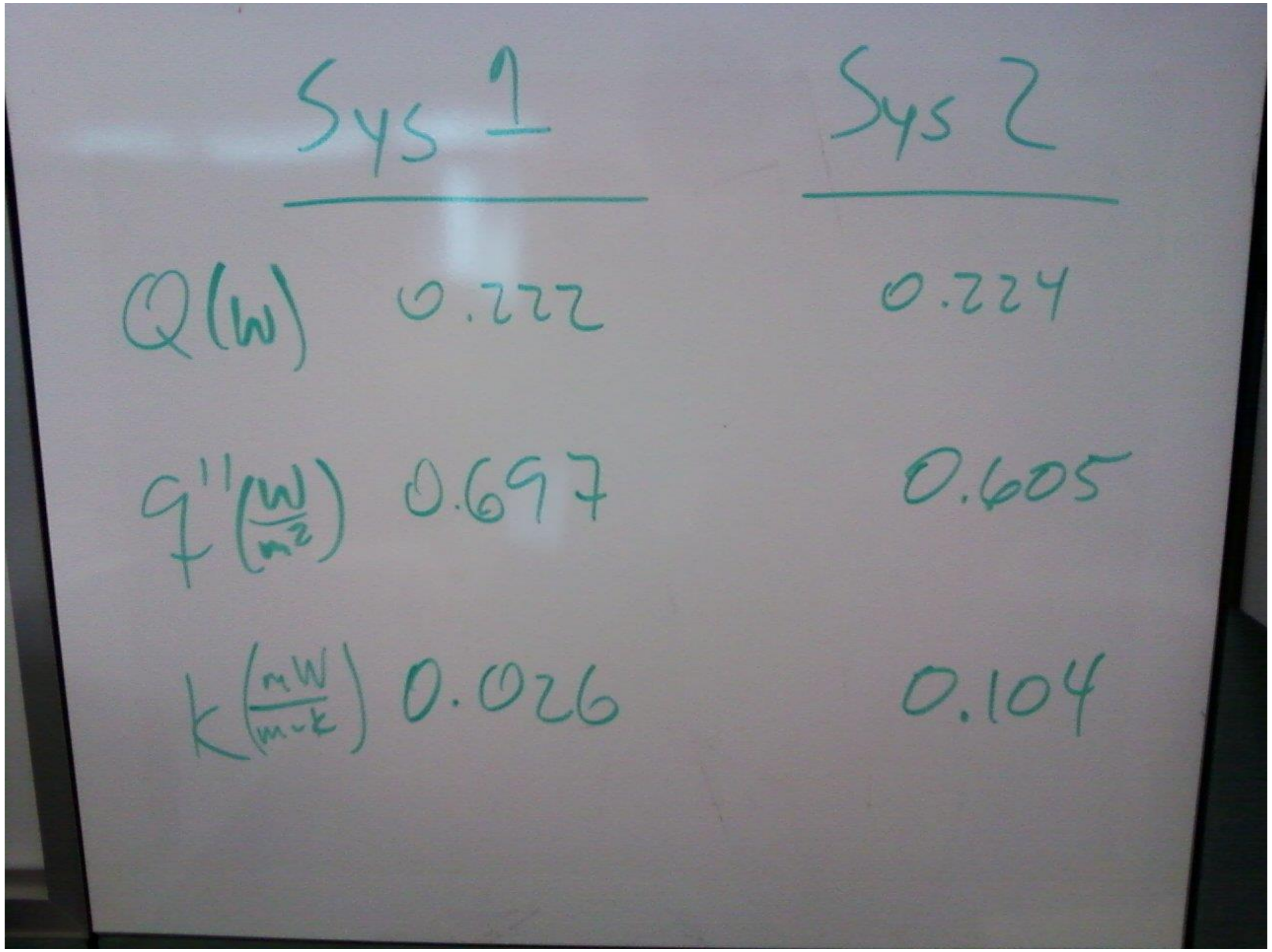
Tape, Pins & Attachments

By accounting for each item separately, we can more accurately predict total MLI performance.

Basic MLI Fundaments

- **System model must match the hardware design**
  - Include the different aspects of implementation discussed in previous slides
  - System-level analysis must be setup account for inefficiencies
    - A majority of current tools are not set up to do this well
  - Hardware implementation and components used must reflect what is in system-level analysis
- **Must understand environments**
  - Thermal
  - Vibration / Acoustic
  - Electrical
  - Launch Pad / Evacuation
  - Ultimate vacuum pressure
- **Cryogenic MLI and Spacecraft MLI are fundamentally different**
  - Cryogenic MLI requires at least one order of magnitude better system level performance.
  - Spacecraft MLI has a fairly constant “Warm Boundary Temperature” whereas Cryogenic MLI has fairly constant “Cold Boundary Temperatures”.
  - Cryogenic MLI requires more careful treatment in “off-nominal” environments (pad, etc).

Which MLI System is Better?



	Sys 1	Sys 2
Q (W)	0.222	0.224
$q''\left(\frac{W}{m^2}\right)$	0.697	0.605
$k\left(\frac{mW}{m\text{-}K}\right)$	0.026	0.104

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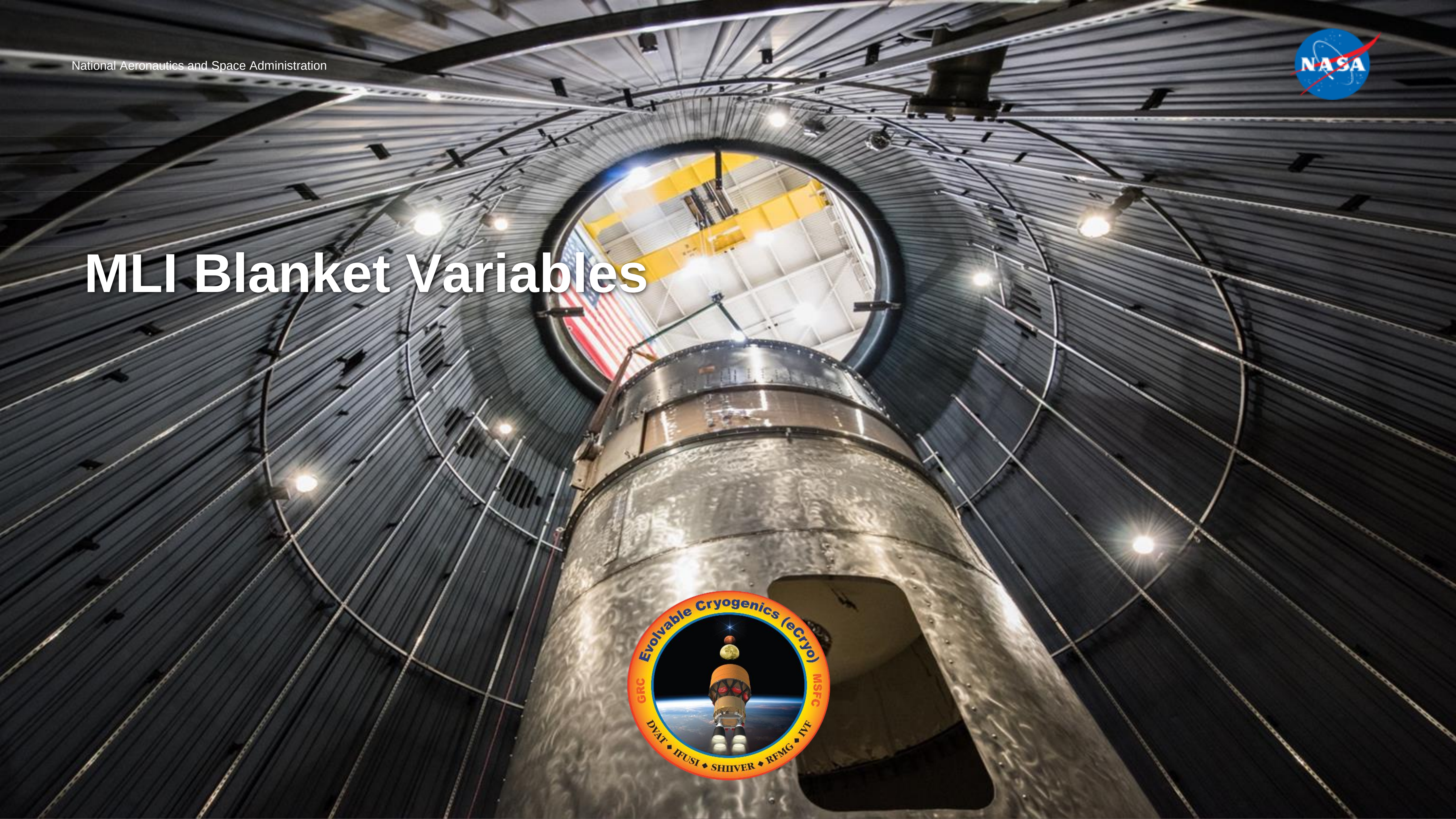
MLI Blanket Variables



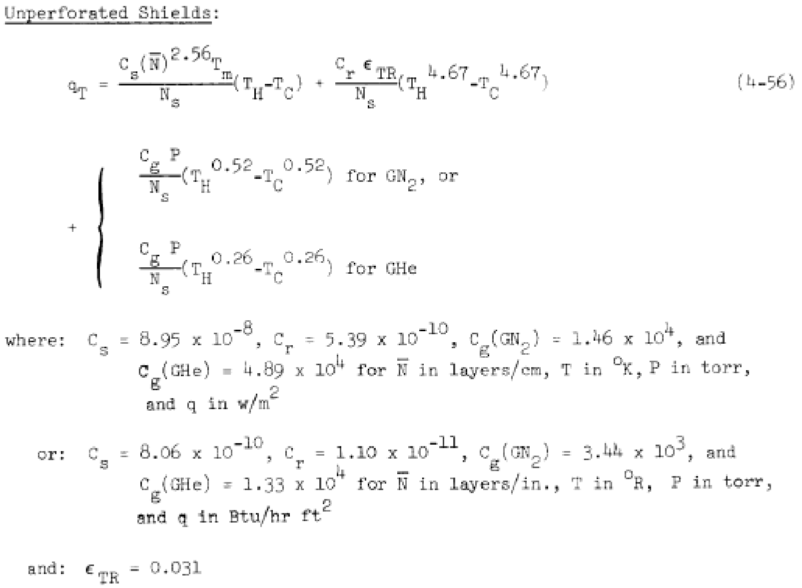
Empirical Equations – Lockheed & McDonnell Douglas

In the early 1970s, NASA awarded contracts to various companies to develop equations for MLI:

Th	293	K
Tc	78	K
N	30	layers
Nbar	14.1	layers/cm
P	2.00E-06	Torr

NASA Report #		Heat Flux	
TM-2004-213175	Modified Lockeed Equation - CDMLI	0.411	W/m2
NAS3-14377	Lockheed Unperforated Mylar & Silk Net	0.294	W/m2
NAS3-14377	Lockheed Perforated S-604	0.350	W/m2
NAS3-14377	Lockheed Perforated S-603	0.321	W/m2
NAS3-14377	Lockheed Perforated S-602	0.280	W/m2
NAS3-14377	Lockheed Perforated 937	0.346	W/m2
NAS3-14377	Lockheed Perforated 937S	0.321	W/m2
NAS3-14377	Lockheed As received Silk (non-perf)	0.227	W/m2
NAS8-20758	Lockheed DAM/Nylon	2.681	W/m2
NAS8-21400	Fredrickson	5.813	W/m2
TM-2004-213175	MHTB Style - VDMLI	0.298	W/m2

Examples from Lockheed/Keller:



Unperforated Shields:

$$q_T = \frac{C_s(\bar{N})^{2.56} T_m}{N_s}(T_H - T_C) + \frac{C_r \epsilon_{TR}}{N_s}(T_H^{4.67} - T_C^{4.67}) \qquad (4\text{-}56)$$

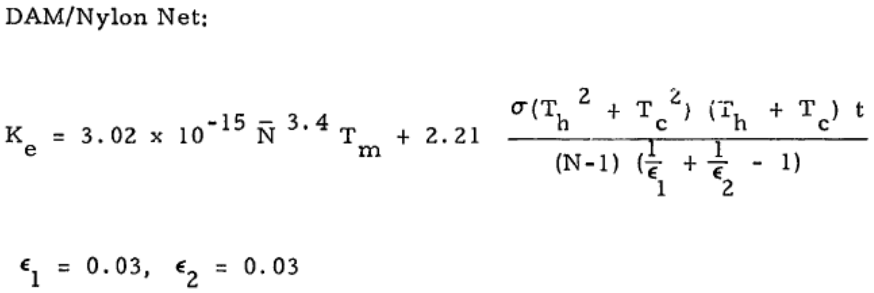
$$+ \begin{cases} \dfrac{C_g P}{N_s}(T_H^{0.52} - T_C^{0.52}) & \text{for } GN_2\text{, or} \\ \dfrac{C_g P}{N_s}(T_H^{0.26} - T_C^{0.26}) & \text{for GHe} \end{cases}$$

where: $C_s = 8.95 \times 10^{-8}$, $C_r = 5.39 \times 10^{-10}$, $C_g(GN_2) = 1.46 \times 10^4$, and $C_g(GHe) = 4.89 \times 10^4$ for $\bar{N}$ in layers/cm, T in °K, P in torr, and q in w/m^2

or: $C_s = 8.06 \times 10^{-10}$, $C_r = 1.10 \times 10^{-11}$, $C_g(GN_2) = 3.44 \times 10^3$, and $C_g(GHe) = 1.33 \times 10^4$ for $\bar{N}$ in layers/in., T in °R, P in torr, and q in Btu/hr ft^2

and: $\epsilon_{TR} = 0.031$

Examples from Douglas/Fredrickson:



DAM/Nylon Net:

$$K_e = 3.02 \times 10^{-15} \bar{N}^{3.4} T_m + 2.21 \frac{\sigma(T_h^2 + T_c^2)(T_h + T_c)\, t}{(N-1)\left(\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1\right)}$$

$\epsilon_1 = 0.03$, $\epsilon_2 = 0.03$

Modified Lockheed Forms

- **In concert with the development and testing of variable density multilayer insulation on the Multipurpose Hydrogen Test Bed (MHTB) at MSFC, Hastings and Hedayat developed what they called a “modified Lockheed equation”[1].**

$$q_{\text{total}} = \overbrace{2.4\times10^{-4} *(0.017 + 7\times10^{-6}(800 - T) + 0.0228\ln(T))* (N*)^{2.63}(T_H - T_C)/N_s}^{\text{Dacron conduction from McIntosh [2]}}$$

$$+ \underbrace{4.944\times10^{-10}\varepsilon\,(T_H{}^{4.67} - T_C{}^{4.67})/N_s}_{\text{Radiation with 2” dia perfs}} + \underbrace{1.46\times10^4\,P\,(T_H{}^{0.52} - T_C{}^{0.52})/N_s}_{\text{Normal Lockheed gas conduction}}\ . \qquad (13)$$

- **Johnson [3] developed a “New-Q” equation based on experimental data correlations using Dacron conduction term and unperforated Lockheed double aluminized mylar terms.**

$$\frac{\mathbf{Q}}{\mathbf{A}} = \frac{\left(2.4E-4*\left(0.017+7E-6*\left(800-T_{avg}\right)+2.28e-2*\ln\left(T_{avg}\right)\right)\right)\bar{N}^{2.63}(T_h-T_c)}{Ns+1}$$

$$+\frac{5.39E-10*\epsilon*\left(T_h^{4.67}-T_c^{4.67}\right)}{Ns}+\frac{1.46E4*P*\left(T_h^{0.52}-T_c^{0.52}\right)}{Ns}$$

1. L. Hastings, A. Hedayat, et al.,Analytical Modeling and Test Correlation of Variable Density Multilayer Insulation for Cryogenic Storage, NASA-TM-2004-213175, 2004.
2. G. E. McIntosh, Layer by Layer MLI Calculation using a Seperated Mode Equation, in: Advances in Cryogenic Engineering, Vol 39B, Plenum Press, NY, 1993, pp. 1683-1690.
3. Johnson, W.L. and Fesmire, J.E., “Thermal Performance of Low Layer Density Multilayer Insulation Using Liquid Nitrogen”, *Advances in Cryogenic Engineering*, Vol. 57A, American Institute of Physics, Melville, NY, 2012. Pg. 39-46.

Analytical Look at Cryogenic Modeling Approaches

Lockheed style:

Warm Boundary Temperature (T_h)
Cold Boundary Temperature (T_c)

Gas Pressure (P)
-note only good less than 10^{-4} Torr

Layer Density ($\bar{N}$)

Room Temp Emissivity (ε)

$$q'' = \frac{C_s * \bar{N}^{2.63}(T_h - T_c) * (T_h + T_c)}{2 * (N + 1)} + \frac{C_R * \varepsilon * (T_h^{4.67} - T_c^{4.67})}{N} + \frac{C_G * P * (T_h^{0.52} - T_c^{0.52})}{N}$$

Number of layers (N)

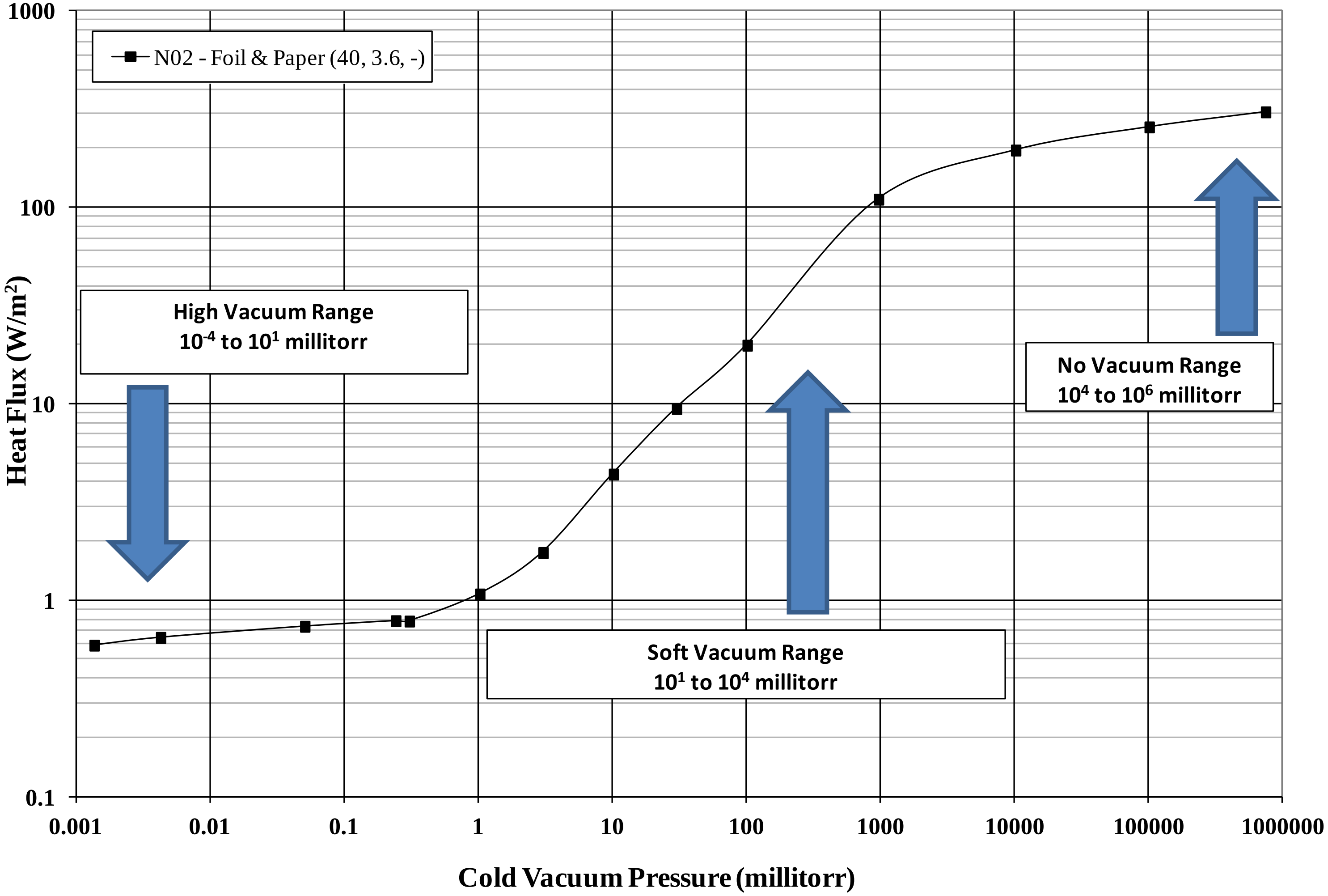
Empirical Coefficients

McIntosh / Layer by Layer style:

$$q'' = \frac{\sigma(T_h^4 - T_c^4)}{\left(\frac{1}{\varepsilon_h} + \frac{1}{\varepsilon_c} - 1\right)} + C_1 P \alpha (T_h - T_c) + C_2 f k \frac{(T_h - T_c)}{\Delta x}$$

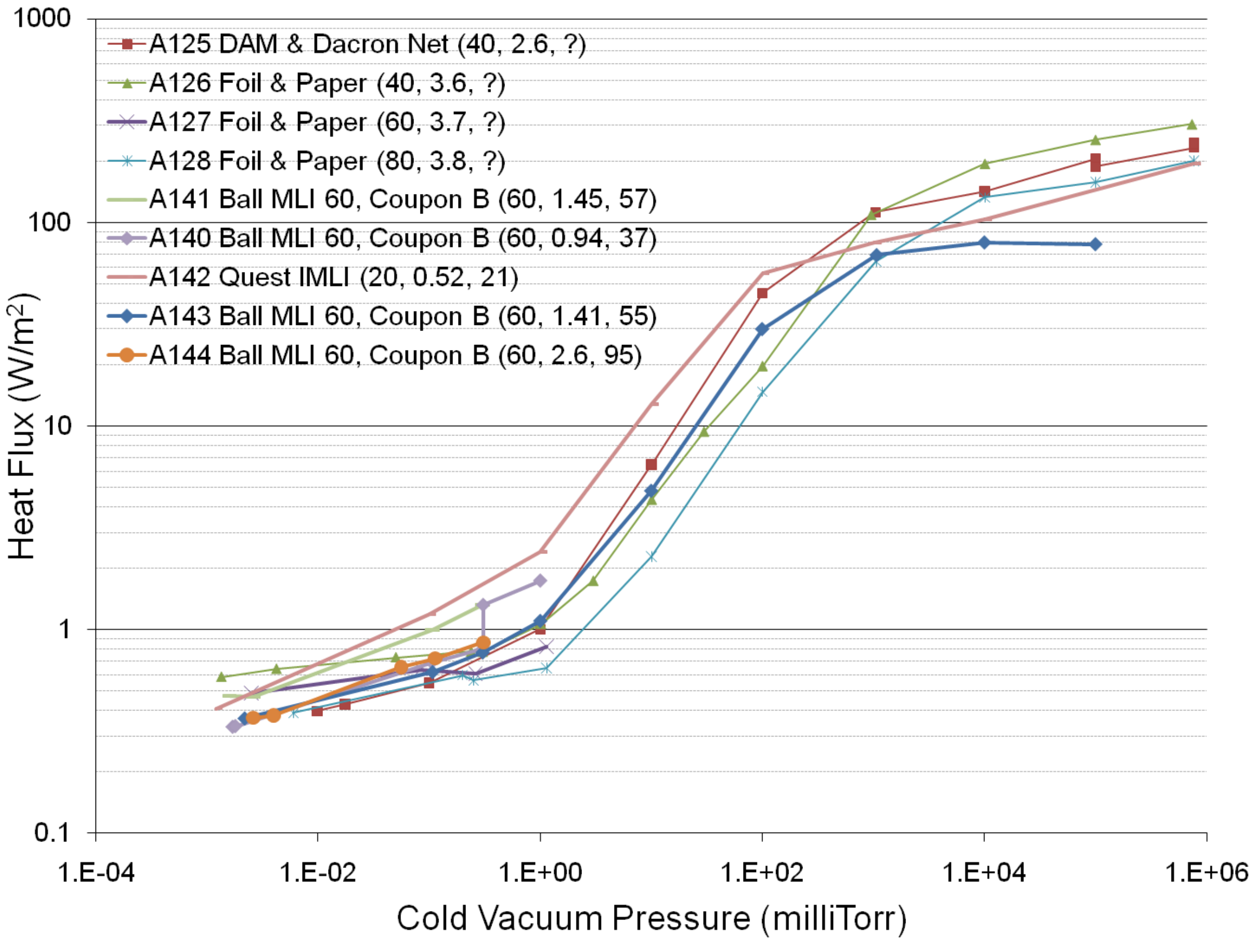
Measurable Values

The Effect of Vacuum Pressure on MLI



Degraded (Soft) Vacuum

Why is there so much data spread at High Vacuum and Soft Vacuum?



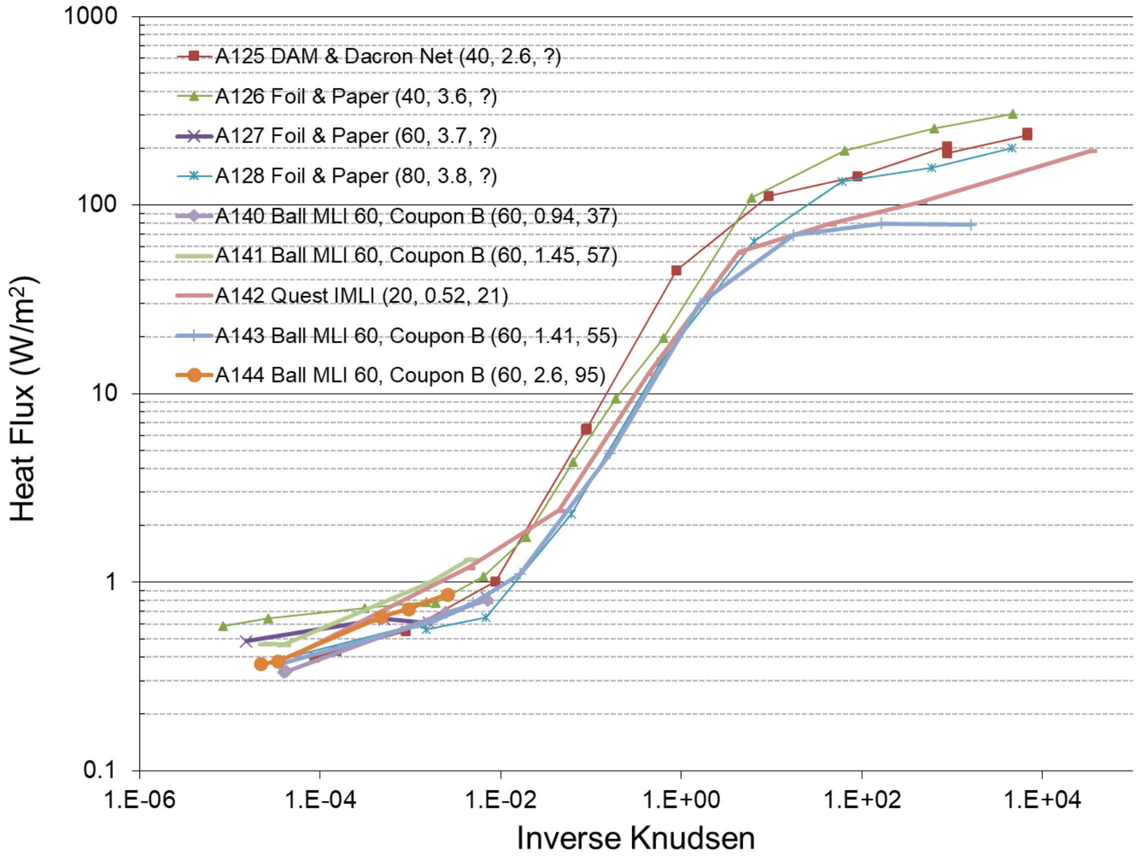
Legend:
(# layers, layer density (lay/mm), mass density (g/cc))

Knudsen Number

- Historical MLI performance predicted by vacuum pressure
- Here we plot against the mean inverse Knudsen number

$$\lambda = \frac{k_B T}{\xi^2 P} \qquad Kn = \frac{\lambda}{N/\overline{N}} \qquad iKn = \frac{N}{\overline{N}\lambda}$$

  - Assume same pressure through blanket as chamber
  - Mean temperature
  - ξ is the diameter of the gas molecule, nitrogen: 3.14E-10m



Boundary Temperatures

$$q'' = \frac{C_s * \overline{N}^{2.63}(T_h - T_c) * (T_h + T_c)}{2 * (N + 1)} + \frac{C_R * \varepsilon * (T_h^{4.67} - T_c^{4.67})}{N} + \frac{C_G * P * (T_h^{0.52} - T_c^{0.52})}{N}$$

Based on this equation format, which boundary temperature is more important?

		Warm Boundary Temperature (K)			
	Heat Flux (W/m^2)	345	290	240	200
Cold Boundary Temperature (K)	100	0.54	0.28	0.14	0.07
	77	0.55	0.28	0.15	0.08
	20	0.56	0.30	0.16	0.09
	4	0.56	0.30	0.16	0.09

Approximately factors of 2 in heat flux.

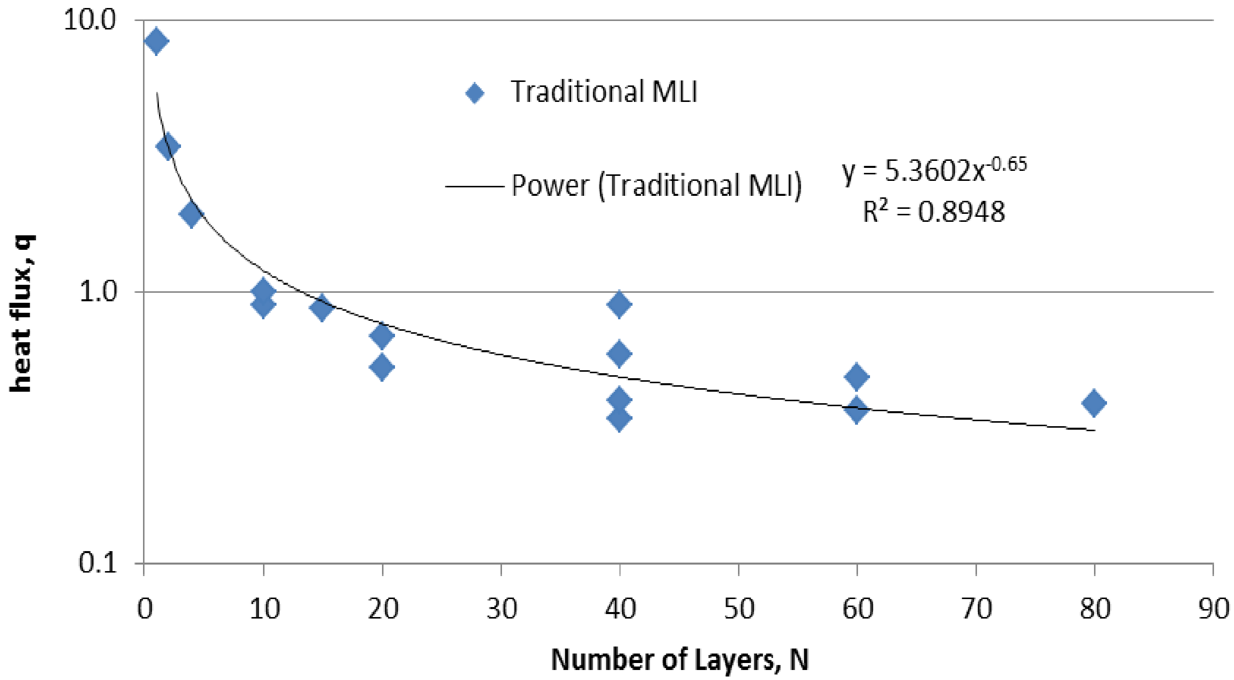
Next temp in sequence is 165 K.

4% --→ 24% change

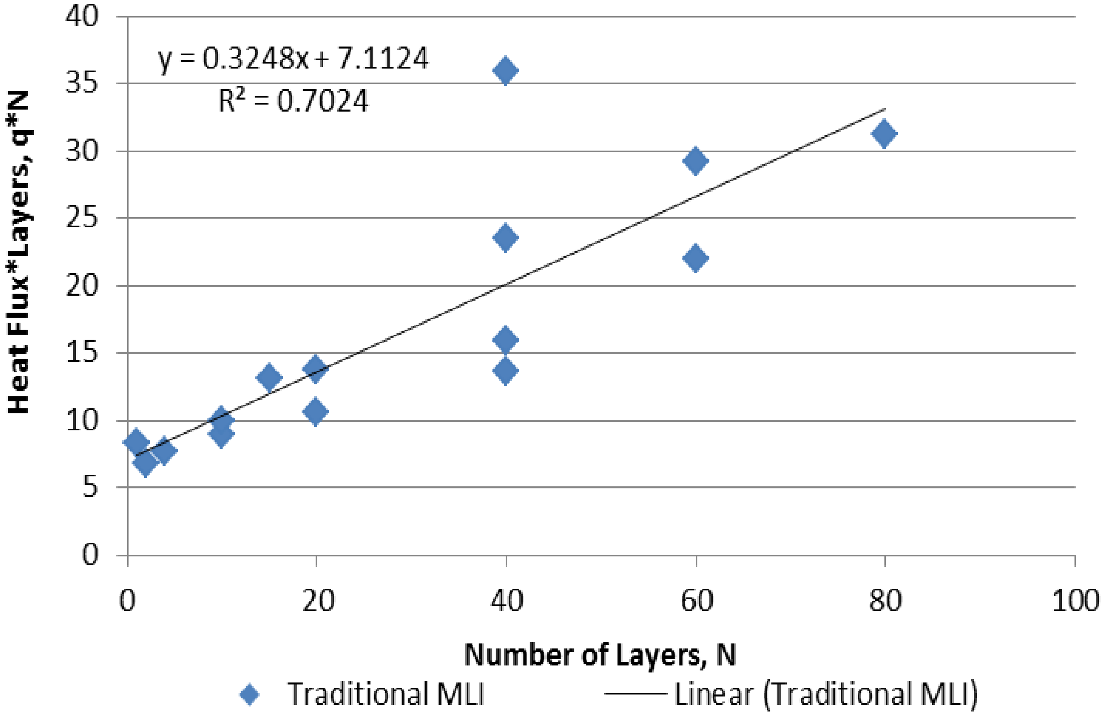
Data generated using the above equation for 30 layers at 14.1 layer/cm and high vacuum

Number of Layers

Variation of heat flux q with the number of layers

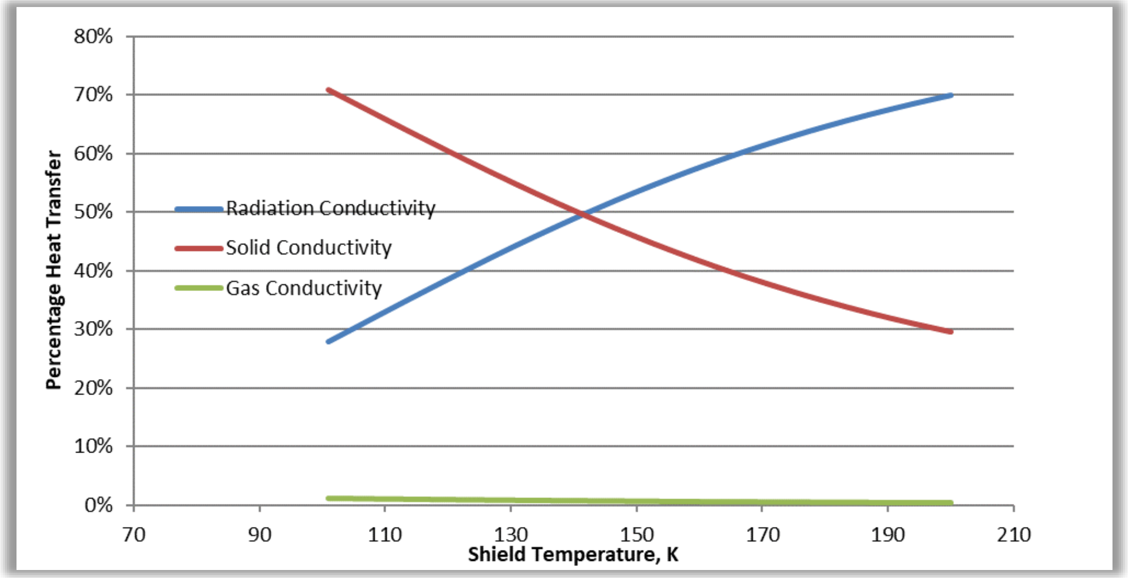


Variation of the quantity q*N with the number of layers

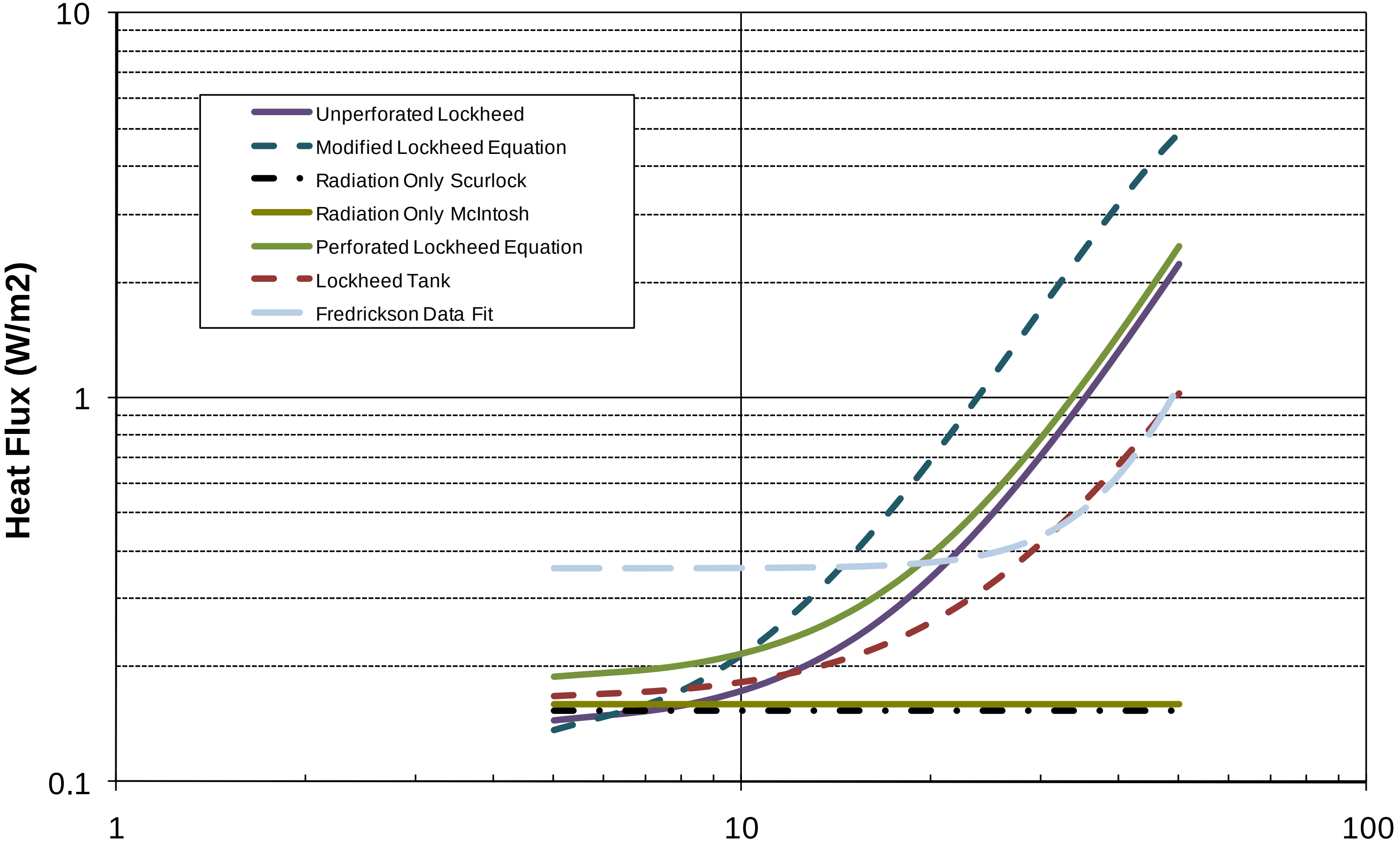


Conduction vs Radiation Heat Transfer

- **Given different situations, either solid conduction or radiation heat transfer could be the dominant form of heat transfer in an MLI system.**
- **The plot below is an example of what the relative heat transfer percentages might be through a blanket.**
  - In this example, the warm portion of the blanket is radiation dominant while the cold portion is solid conduction dominant.
  - Gas conduction plays a very small role in heat transfer at a high vacuum MLI system.



Effect of Layer Density at a Constant Number of Layers

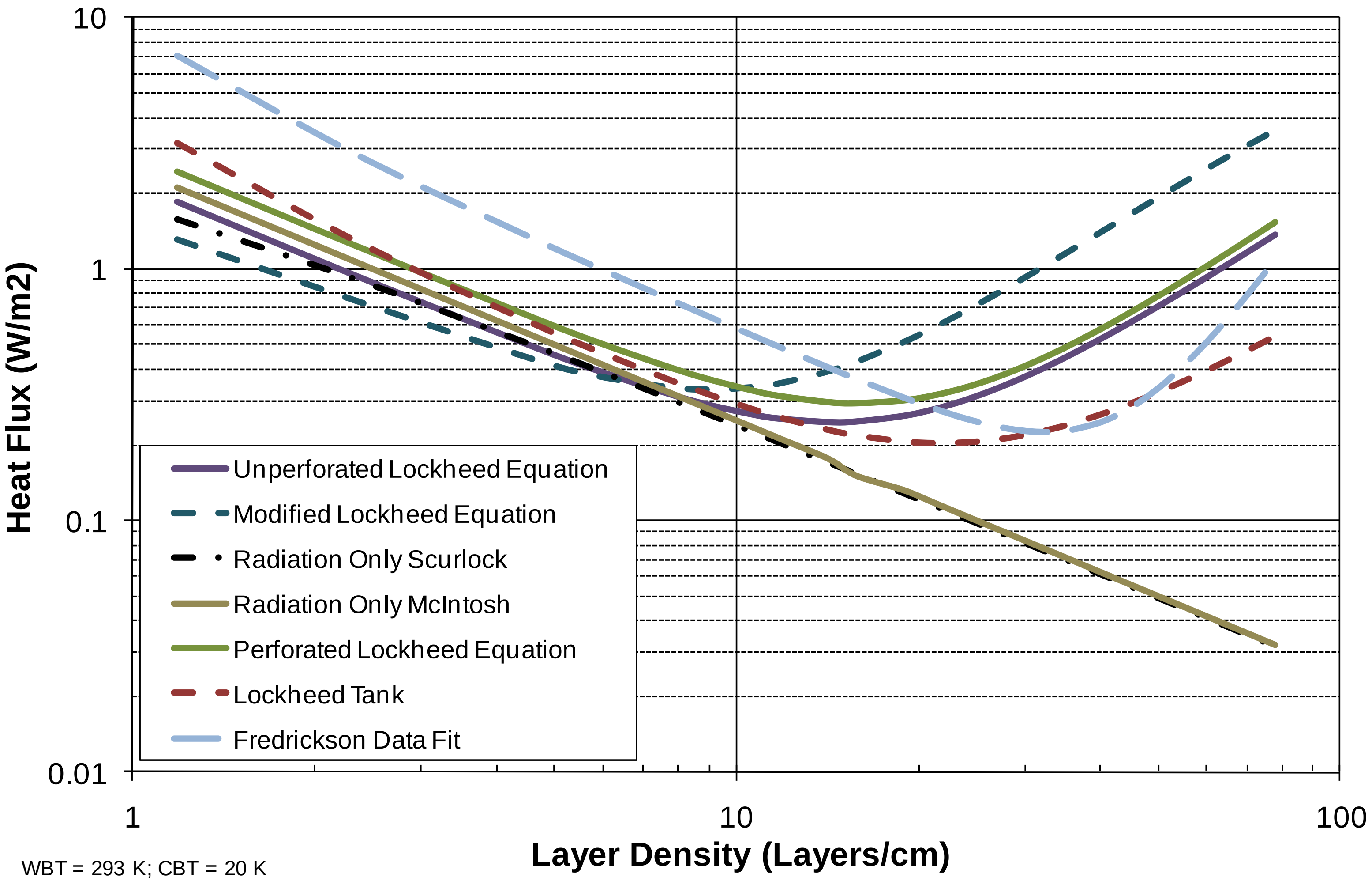


WBT = 293 K; CBT = 20 K

Constant number of layers: 40

Johnson, W.L, "Optimization of Layer Densities for Multilayered Insulation Systems," *Advances in Cryogenic Engineering*, Vol. 55A, American Institute of Physics, Melville, NY, 2010. Pg. 804-811.

Layer Density at a Constant Thickness

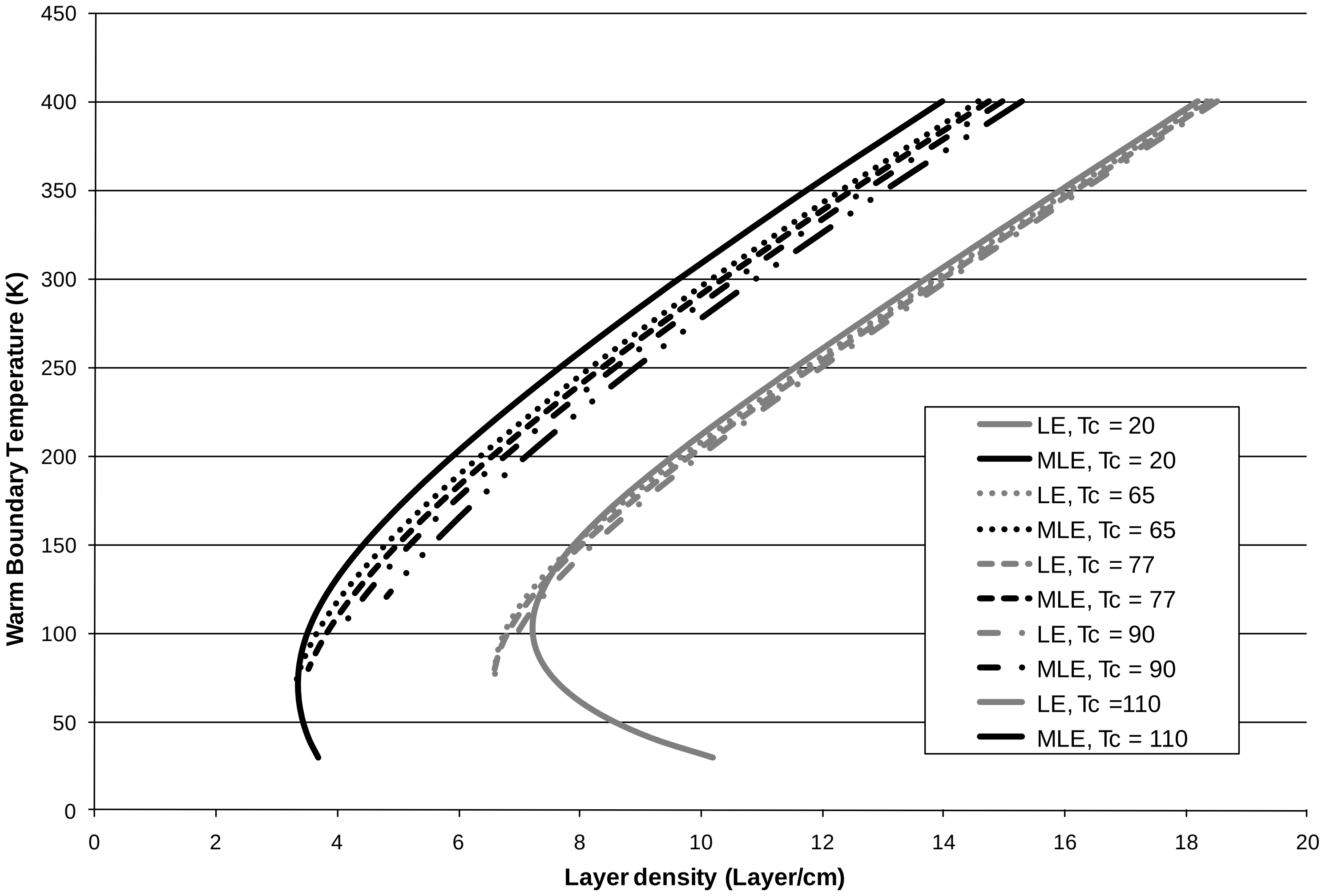


WBT = 293 K; CBT = 20 K

Constant thickness of 2.5 cm

Johnson, W.L, "Optimization of Layer Densities for Multilayered Insulation Systems," *Advances in Cryogenic Engineering*, Vol. 55A, American Institute of Physics, Melville, NY, 2010. Pg. 804-811.

Optimal Layer Densities



$$\overline{N}_{opt,MLE} = \left[\frac{C_R * \varepsilon * \left(T_h^{4.67} - T_c^{4.67}\right) + C_G * P * \left(T_h^{0.52} - T_c^{0.52}\right)}{1.63 C_s * \left(T_h - T_c\right)} \right]^{\frac{1}{2.63}}$$

$$\overline{N}_{opt} = \left[\frac{C_R * \varepsilon * \left(T_h^{4.67} - T_c^{4.67}\right) + C_G * P * \left(T_h^{0.52} - T_c^{0.52}\right)}{0.78 C_s * \left(T_h^2 - T_c^2\right)} \right]^{\frac{1}{2.56}}$$

LE is the Lockheed Unperforated equation [equation 4-14]
MLE is the Modified Lockheed Equation [equation 13]

Johnson, W.L, “Optimization of Layer Densities for Multilayered Insulation Systems,” *Advances in Cryogenic Engineering*, Vol. 55A, American Institute of Physics, Melville, NY, 2010. Pg. 804-811.

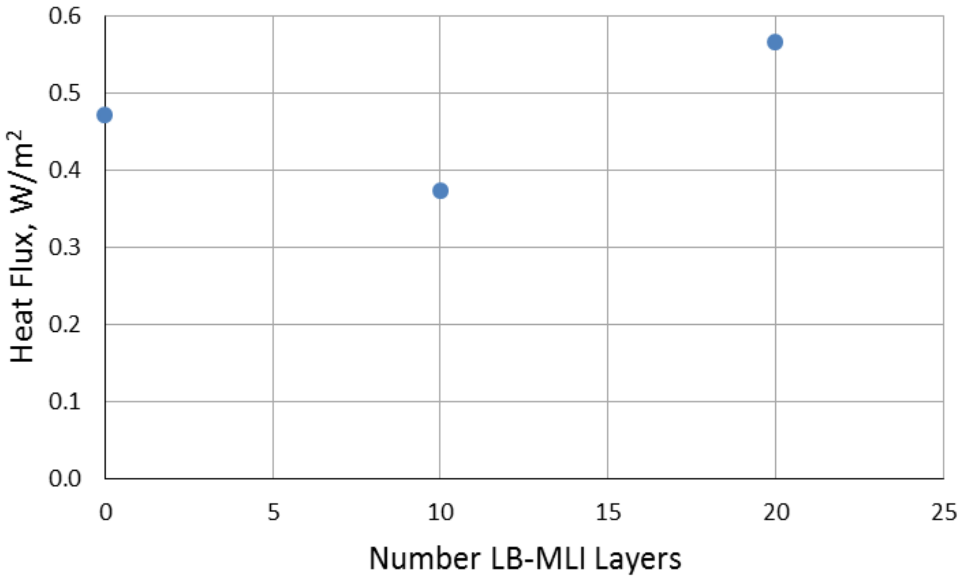
Non-Constant MLI Layer Densities

Variable Density MLI:

- Multipurpose Hydrogen Testbed Developed by MSFC
- MLI System designed by Glen McIntosh
  - Foam to prevent liquefaction of air
  - 10 layers at 8 layer/cm
  - 15 layers at 12 layer/cm
  - 16 layers at 16 layer/cm
  - Built using bumper layers to achieve nominal spacing.
- Modify MLI solver to include layer density
  - 10 layers at 7.1 layer/cm (CBT 77 K, WBT 209 K)
  - 15 layers at 11.8 layer/cm (CBT 209 K, WBT 261 K)
  - 20 layers at 14.8 layer/cm (CBT 261 K, WBT 298 K)
- Used Modified Lockheed Equation

Hybrid MLI:

- Developed to take advantage of simpler methods of low density MLI manufacturing
- IMLI and double layer dacron netting
- Testing at KSC



Constant thickness ~ 38 mm (1.5 inches)
Data from A139 (60 layers tMLI) and A142 (20 layers LB-MLI) for 0 and 20 layer LB-MLI

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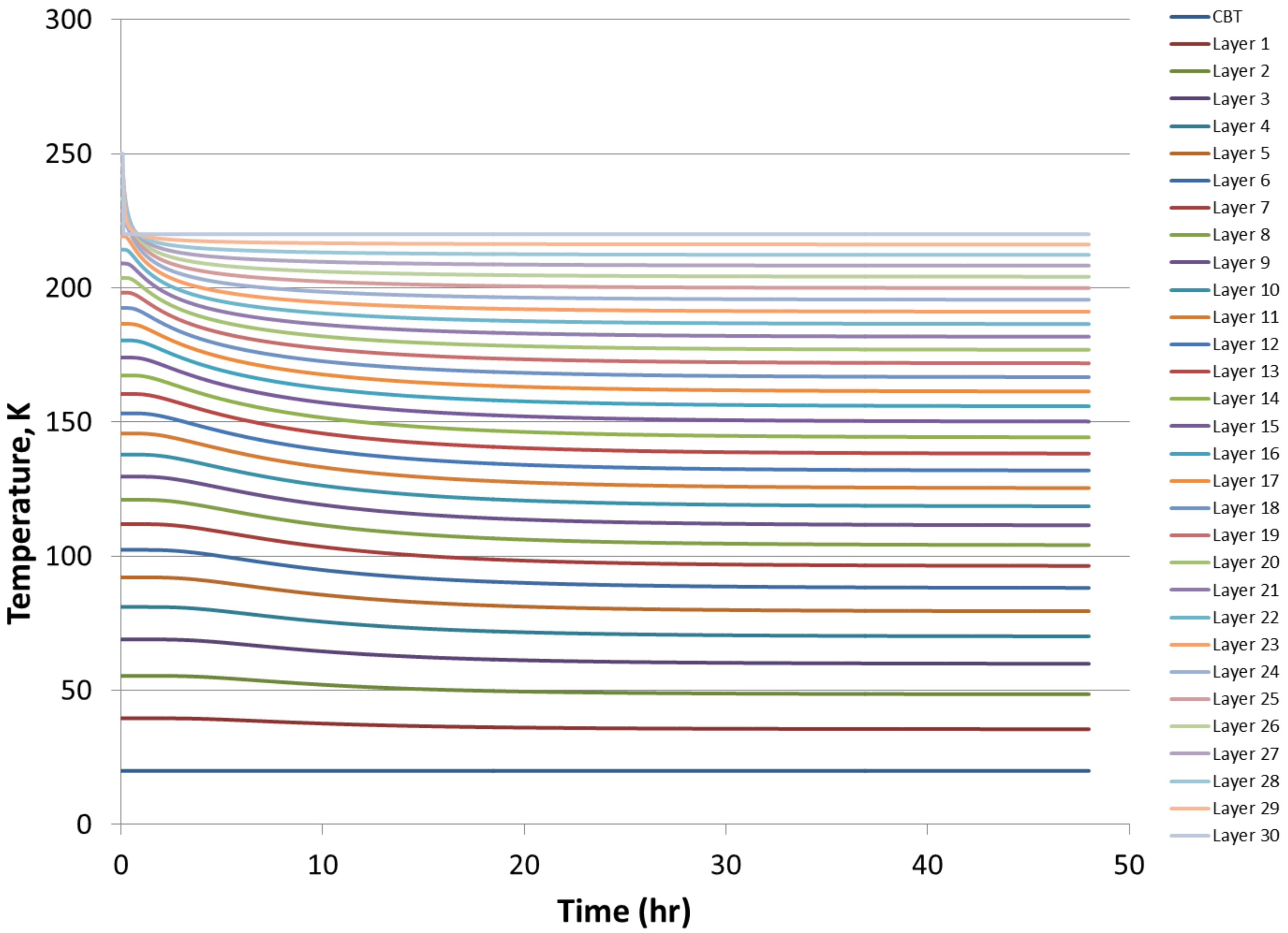
Transient MLI Performance

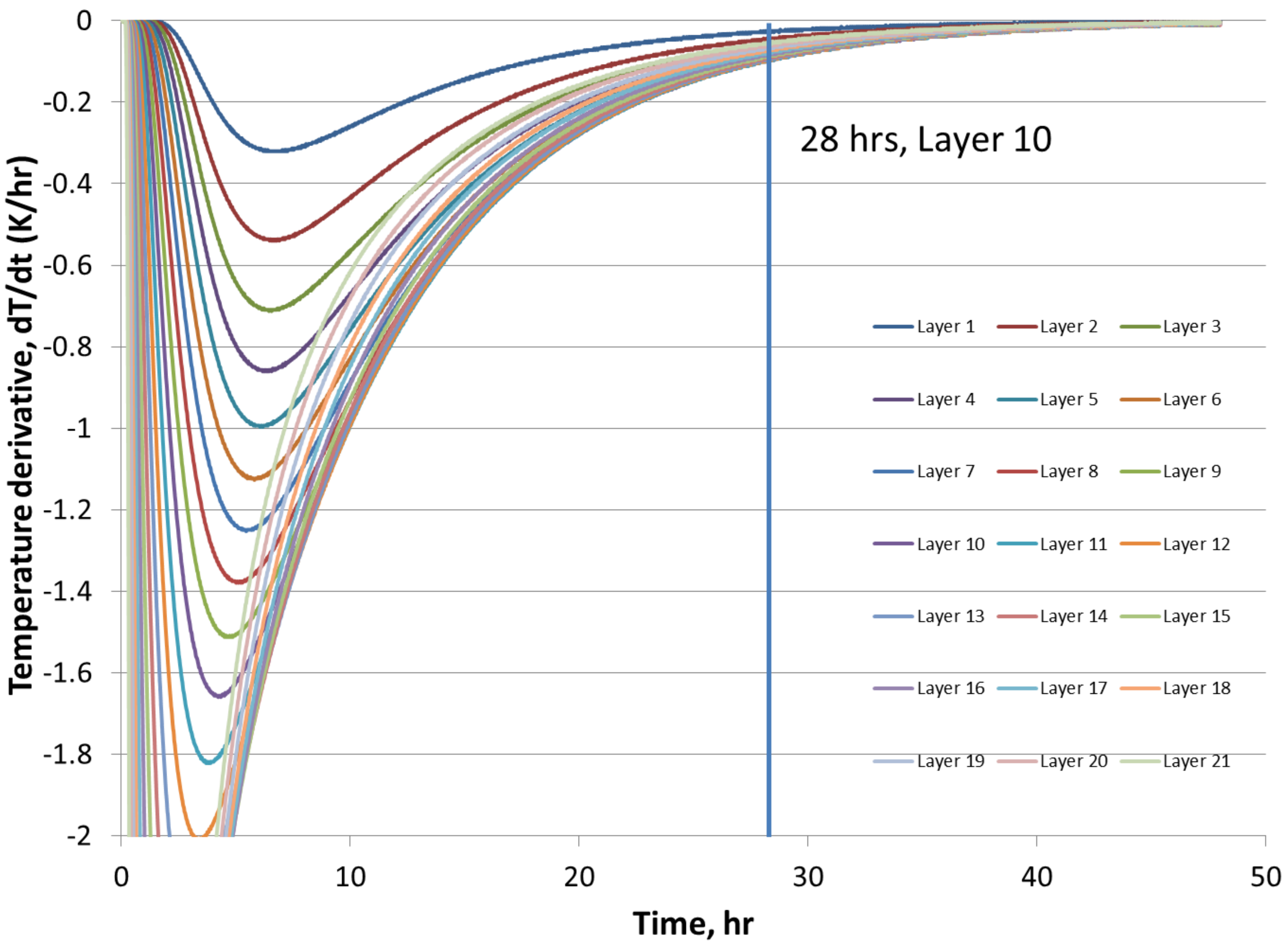
Analysis Method

- **Use Transient MLI code developed under ETDP/CFM**
  - 30 layer blanket at 20 layer/cm
  - Lockheed Report Equation 4-56
  - Calculates temperature of every layer at every time
  - Accounts for thermal mass of each layer & dacron
  - Background pressure of $1*10^{-6}$ Torr
- **Start with steady state WBT at T1**
- **After 0.1 hour, drop WBT to T2**
- **Monitor layer temperatures, determine the length of time to reach temp change rate**
- **Two different temperature sets:**
  - Start at 250 K end at 220 K
  - Start at 300 K end at 200 K

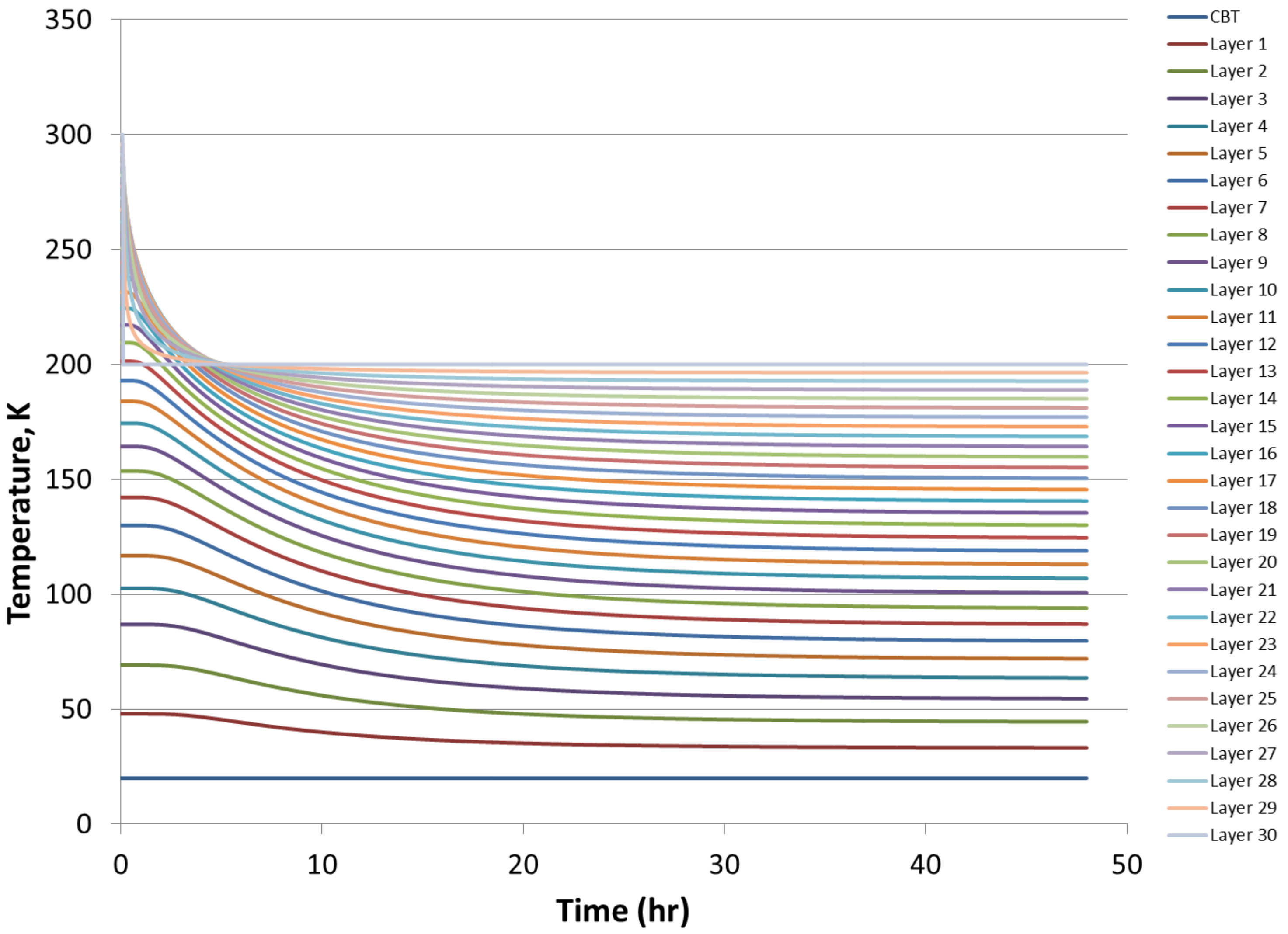
Small Perturbation - Temperatures



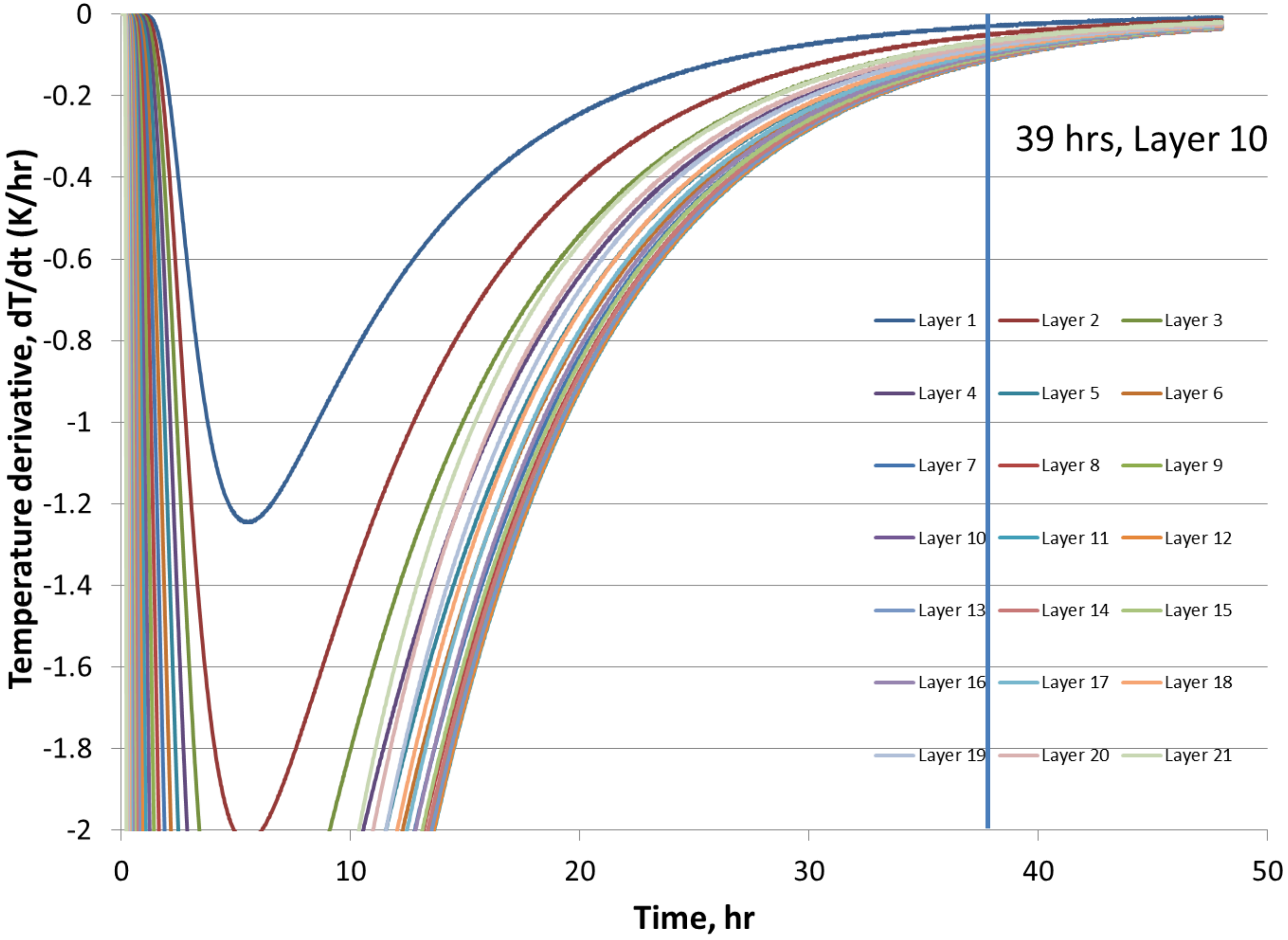
Small Perturbation – Time Derivative



Large Perturbation - Temperatures



Large Perturbation – Time Derivatives



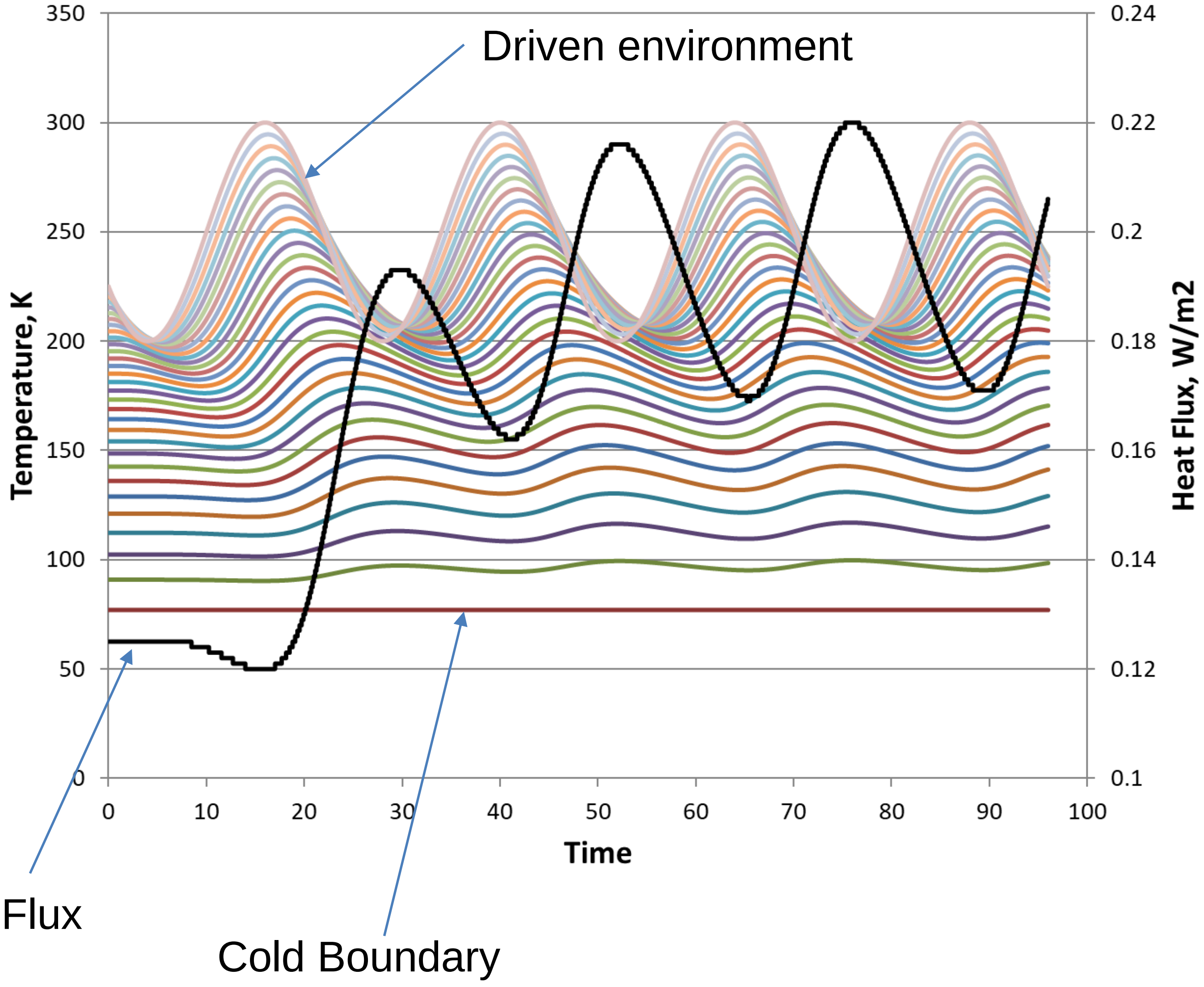
Typical MEO response for LOX tank

Inputs:
Sinusoidal boundary condition
- Mean Temp ~220 K
- Amplitude ~35 K

30 Reflectors (each on plotted)

3-hour period

Note – I ran all of these cases probably 10 years ago.



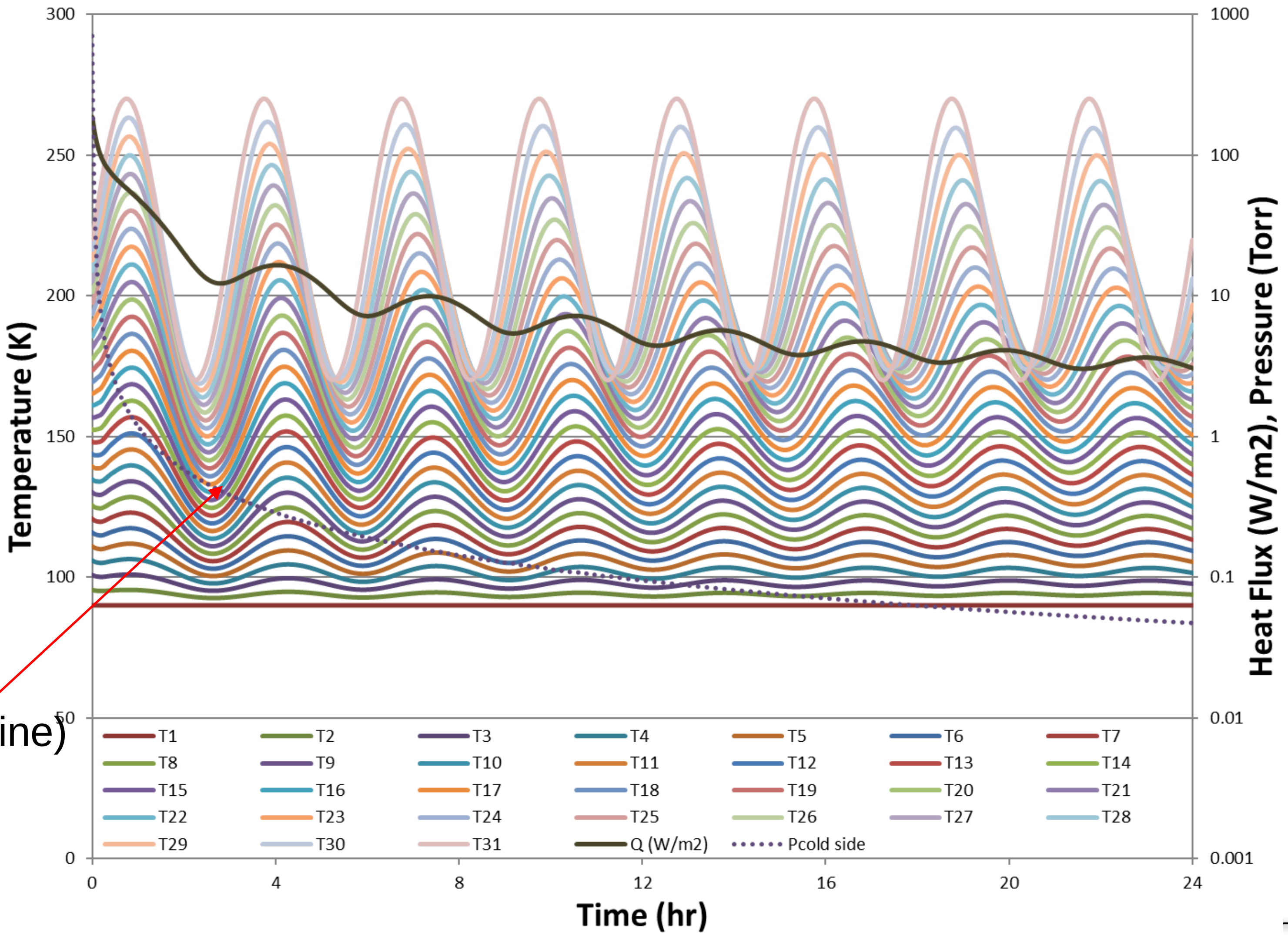
Evacuation and transients

First 24 hours

220 K +/- 50 K
Sinusoidal ~ 3 hour period

This run is a combination of evacuation and transient thermal.

I believe the evacuation assumes that all layers are in series. Again, ran it 10 years ago.



Pressure (dotted line)

Preliminary

MLI Materials

Evolvable Cryogenics (eCryo)

GRC MSFC

DVAT ◆ IFUSI ◆ SHIIVER ◆ RFMG ◆ IVF

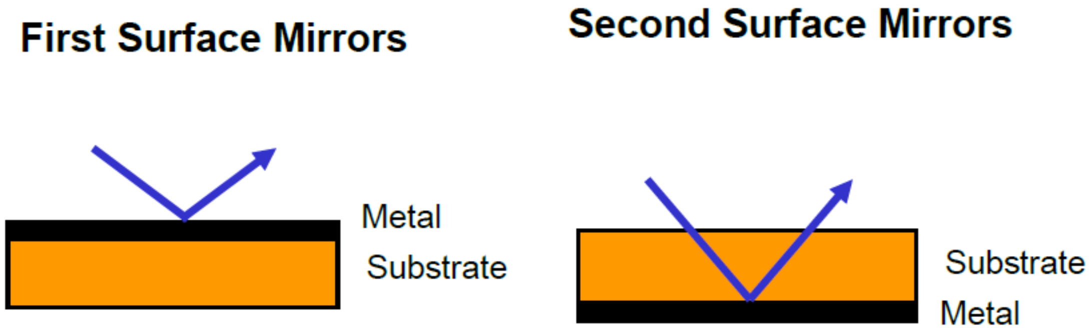
Reflectors

- **Aluminum**
  - Generally a foil, much thinner than what you cook with.
  - One side looks shiny, other side looks dull, not indicative of actual IR emissivity.
  - Interaction between aluminum and oxygen creates an oxidation layer on the surface which dramatically impacts the optical properties.
  - Still used in many industrial applications.
  - Not used for spacecraft anymore because the aluminum holds standing waves from various acoustic / vibrational modes within the geometry of the blanket.
- **Gold**
  - A more expensive, but higher performing (lower emissivity) reflector that has been used in lieu of aluminum on a few occasions.
  - There is a significant cause for use at higher temperatures as well.
  - Does not have issues with oxidation.
- **Vacuum Deposited Films**
  - Aluminum, gold, or other highly reflective material deposited via sputtering on to a polymeric film
    - Polyethylene Terephthlate (Mylar), polyimide (Kapton)
  - Can be deposited on a single side or both sides.
  - Typically have radiation transmissive coating to prevent oxidation

The Folly of Visually Observing Reflectors

- It is very hard to spot 2nd surface reflectors with the naked eye when the substrate is transparent.
- The easiest way to tell is that generally, 1st surface mirrors have a backing on the tape, 2nd surface mirrors don't.
- Substrate is either FEP or Polyimide
- The radiative heat load onto a surface is proportional to the emissivity of the surface.

$$\dot{Q}_{rad} = \varepsilon \sigma A_{surf} (T_H^4 - T_C^4)$$



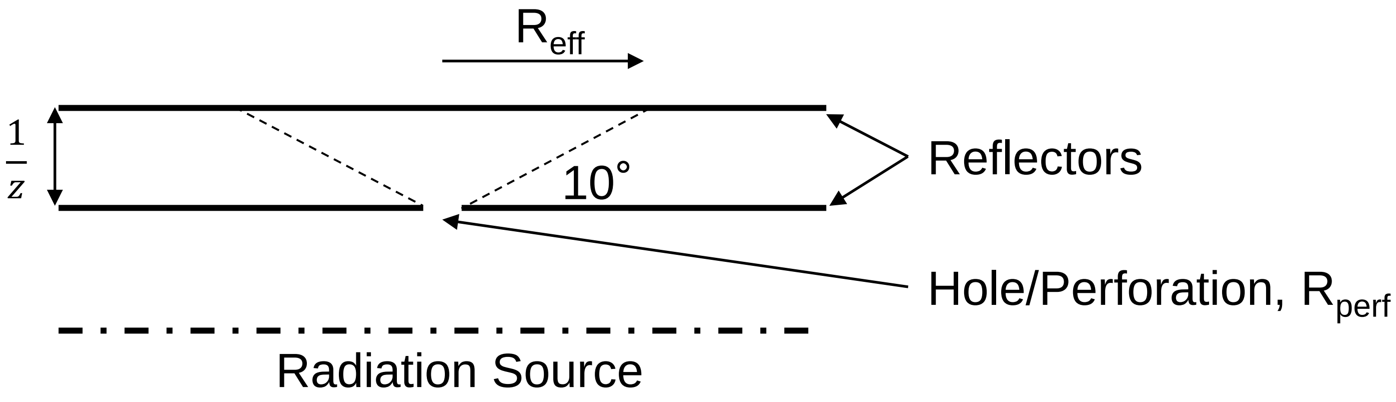
Metal	Typical Emittance (ε)
Gold	0.02
Silver	0.02
Aluminum	0.03

Film Thickness		Typical Emittance	
Mils	Microns	FEP	Polyimide
0.5	12.5	0.41	0.52
1	25	0.52	0.64
2	51	0.65	0.76
5	127	0.79	0.85
10	254	0.86	

Images and data from Sheldahl Red Book

Perforations

- **Perforations can be added to a reflector to improve the venting characteristics of a blanket during the launch and ascent sequences.**
- **Perforations allow transmission of radiative energy through the hole with a cone angle of 10 degrees, significantly degrading the blanket performance.**
  - In AIAA paper 73-718, Tien and Cunnington analytically demonstrate that perforation can easily increase the radiative heat transfer portion of the blanket between 30% - 70%.
  - For the same open area percentage, it is better to have larger, more spread-out perforations / holes.
  - Venting analyses can be performed to determine the open area required or if edge venting can be tolerated.



Note in this figure, z is the layer density (using the nomenclature from ASTM C-740

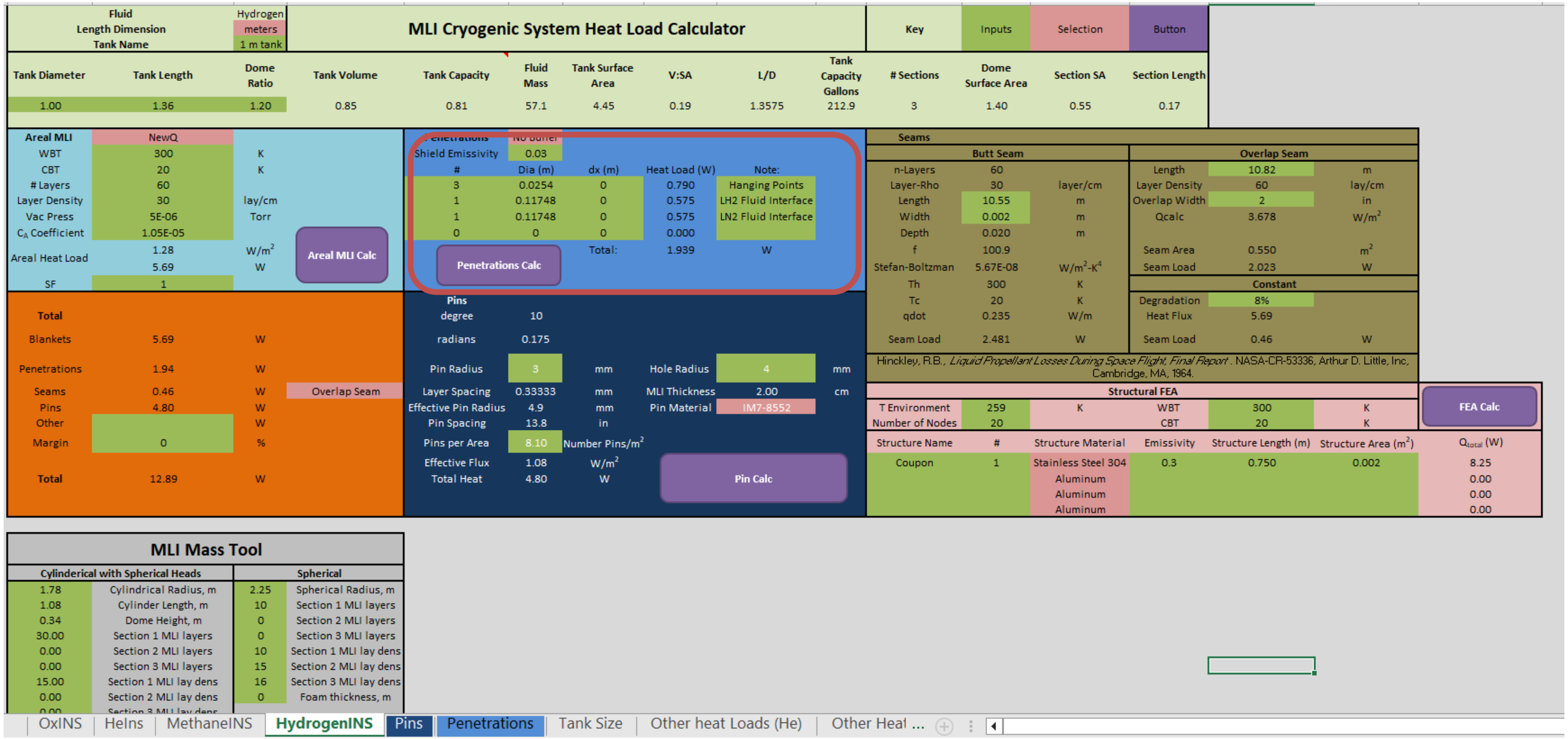
Spacer Materials

- **No-spacer / dimpling**
  - Dimpling / forming of reflector to minimize contact between layers
  - Other times, for less performing systems, can get away with simple contact resistance between layers
    - Comparative testing has been performed.
- **Tissue Paper**
  - First used material due to low cost and ease of handling.
  - Still used in many industrial applications.
- **Non-woven fiberglass**
  - Fairly cheap, easy to integrate, directly paired with foils or films.
  - Less performance than other spacers, but cheaper than netting and easier to handle.
- **Silk Netting**
  - Used on most early spacecraft due to superior thermal performance than other types of netting
  - High costs and lack of manufacturers in the US have nearly eliminated the use
  - We did do comparative testing at KSC in ~2012.
- **Dacron Netting**
  - Main spacer used on spacecraft for contemporary spacecraft
  - Two forms B2A (less coarse – 2x the mass), B4A (much harder to handle)
- **Other**
  - Superflok – Convair General Dynamics incorporation of specially formed dacron needle shaped spacer tufts
  - xMLI – Quest Thermal Group developed tripod spacers

All spacer types increase the heat load between otherwise not in contact reflective layers

Non-ideal Effects on Multilayer Insulation

MLI Cryogenic System Heat Load Calculator for Trad Cryo MLI



MLI Cryogenic System Heat Load Calculator

Fluid	Hydrogen
Length Dimension	meters
Tank Name	1 m tank

Key	Inputs	Selection	Button

Tank Diameter	Tank Length	Dome Ratio	Tank Volume	Tank Capacity	Fluid Mass	Tank Surface Area	V:SA	L/D	Tank Capacity Gallons	# Sections	Dome Surface Area	Section SA	Section Length
1.00	1.36	1.20	0.85	0.81	57.1	4.45	0.19	1.3575	212.9	3	1.40	0.55	0.17

Areal MLI	NewQ	
WBT	300	K
CBT	20	K
# Layers	60	
Layer Density	30	lay/cm
Vac Press	5E-06	Torr
C_A Coefficient	1.05E-05	
Areal Heat Load	1.28	W/m^2
	5.69	W
SF	1	

Areal MLI Calc

Penetrations	No Buffer			
Shield Emissivity	0.03			
#	Dia (m)	dx (m)	Heat Load (W)	Note:
3	0.0254	0	0.790	Hanging Points
1	0.11748	0	0.575	LH2 Fluid Interface
1	0.11748	0	0.575	LN2 Fluid Interface
0	0	0	0.000	
		Total:	1.939	W

Penetrations Calc

Seams					
Butt Seam			Overlap Seam		
n-Layers	60		Length	10.82	m
Layer-Rho	30	layer/cm	Layer Density	60	lay/cm
Length	10.55	m	Overlap Width	2	in
Width	0.002	m	Qcalc	3.678	W/m^2
Depth	0.020	m			
f	100.9		Seam Area	0.550	m^2
Stefan-Boltzman	5.67E-08	W/m^2-K^4	Seam Load	2.023	W
Th	300	K	Constant		
Tc	20	K	Degradation	8%	
qdot	0.235	W/m	Heat Flux	5.69	
Seam Load	2.481	W	Seam Load	0.46	W

Hinckley, R.B., *Liquid Propellant Losses During Space Flight, Final Report*. NASA-CR-53336, Arthur D. Little, Inc., Cambridge, MA, 1964.

Total			
Blankets	5.69	W	
Penetrations	1.94	W	
Seams	0.46	W	Overlap Seam
Pins	4.80	W	
Other		W	
Margin	0	%	
Total	12.89	W	

Pins					
degree	10				
radians	0.175				
Pin Radius	3	mm	Hole Radius	4	mm
Layer Spacing	0.33333	mm	MLI Thickness	2.00	cm
Effective Pin Radius	4.9	mm	Pin Material	IM7-8552	
Pin Spacing	13.8	in			
Pins per Area	8.10	Number Pins/m^2			
Effective Flux	1.08	W/m^2			
Total Heat	4.80	W			

Pin Calc

Structural FEA						
T Environment	259	K	WBT	300	K	
Number of Nodes	20		CBT	20	K	
Structure Name	#	Structure Material	Emissivity	Structure Length (m)	Structure Area (m^2)	Q_{total} (W)
Coupon	1	Stainless Steel 304	0.3	0.750	0.002	8.25
		Aluminum				0.00
		Aluminum				0.00
		Aluminum				0.00

FEA Calc

MLI Mass Tool

Cylinderical with Spherical Heads		Spherical	
1.78	Cylindrical Radius, m	2.25	Spherical Radius, m
1.08	Cylinder Length, m	10	Section 1 MLI layers
0.34	Dome Height, m	0	Section 2 MLI layers
30.00	Section 1 MLI layers	0	Section 3 MLI layers
0.00	Section 2 MLI layers	10	Section 1 MLI lay dens
0.00	Section 3 MLI layers	15	Section 2 MLI lay dens
15.00	Section 1 MLI lay dens	16	Section 3 MLI lay dens
0.00	Section 2 MLI lay dens	0	Foam thickness, m
0.00	Section 3 MLI lay dens		

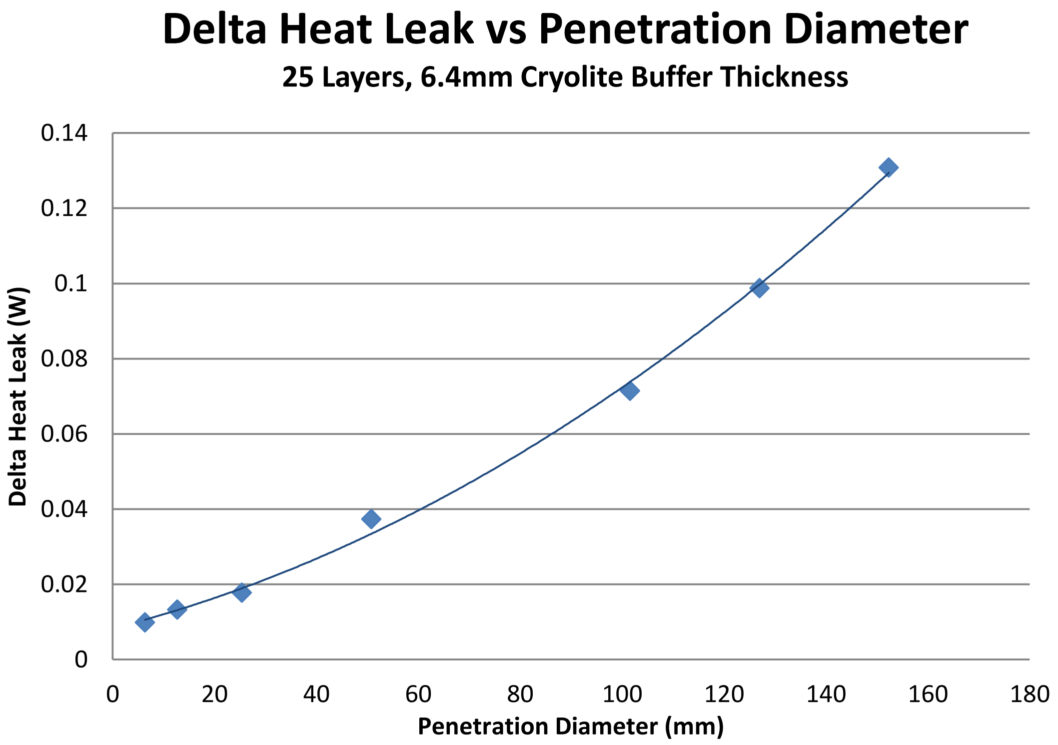
Penetrations Executive Summary

- **Testing was performed on a wide variety of penetration integration techniques**
- **Buffered integration using Cryolite was found to be the best performing integration technique**
- **A detailed Thermal Desktop-based model was built and validated to the testing data**
- **Using the same techniques from the detailed thermal model, a more general model was developed to allow for parameterization of the model and understanding how it reacted to the changing of different variables**
- **Based on the result of the general model, an equation was developed to predict the integration heat load for a given penetration**
- **Testing was also performed with IMLI, but not included in this analysis. For more information, contact the author.**
- **Conduction through the penetrations accounted for in addition to this format.**

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

NASA TP-2012-216315

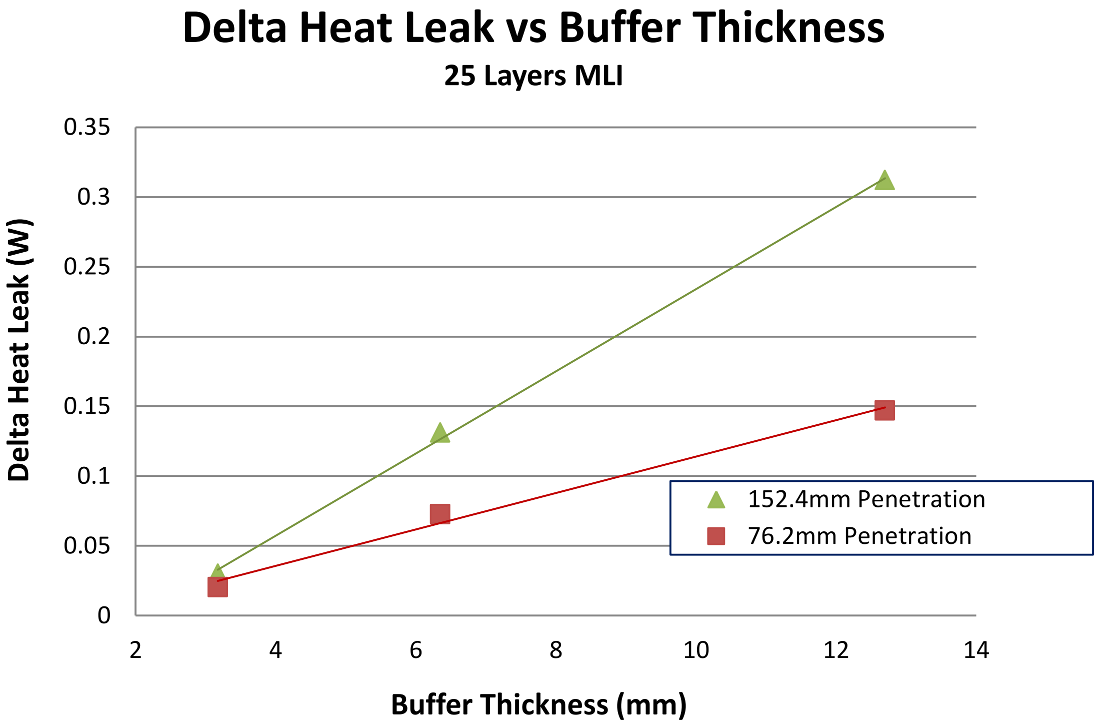
Model – Scaling - Diameter



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

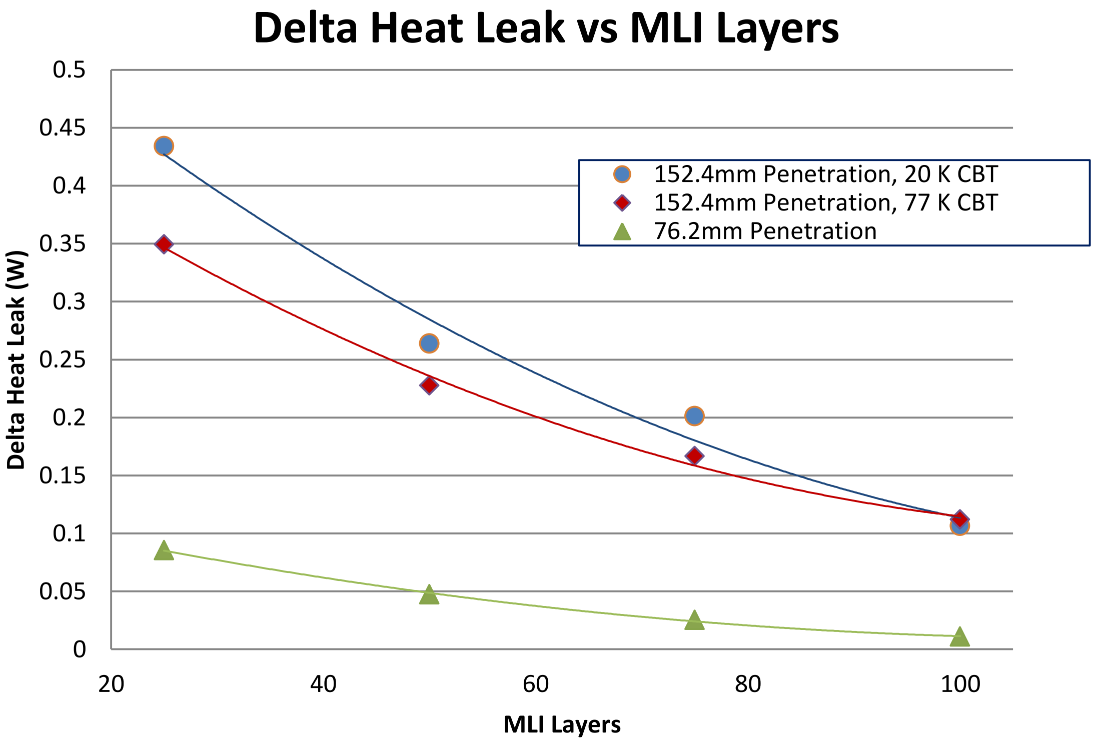
Note: data points shown are from the model and the curve is a curve fit

Model – Scaling – Buffer Thickness



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

Model – Scaling - # Layers



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	$9.51E\text{-}6x^2 – 2.17E\text{-}3x + 0.134$

Results – Model Summary

- **As a result of the model scaling, a multipart equation was developed**
- **Considers warm boundary temperature, MLI system # of layers, penetration diameter, and buffer thickness**

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

- **Requires the use of two reference states**
  - Recommend:
    Reference 1: 0.0762 m diameter penetration with 25 layers MLI, and 0.0064 m buffer
    Reference 2 (or prime): 0.0762 m diameter, 25 layers, 0.0127 m buffer
  - Alternate: use 0.1524 m diameter penetration for both with same other variables

Results – Model Sample Calculation

Calculate the degradation due to a 104 mm (4 inch) pipe going through 60 layers of MLI using an 8 mm (~0.75 inch) Cryolite buffer with a warm boundary temperature of 297 K.

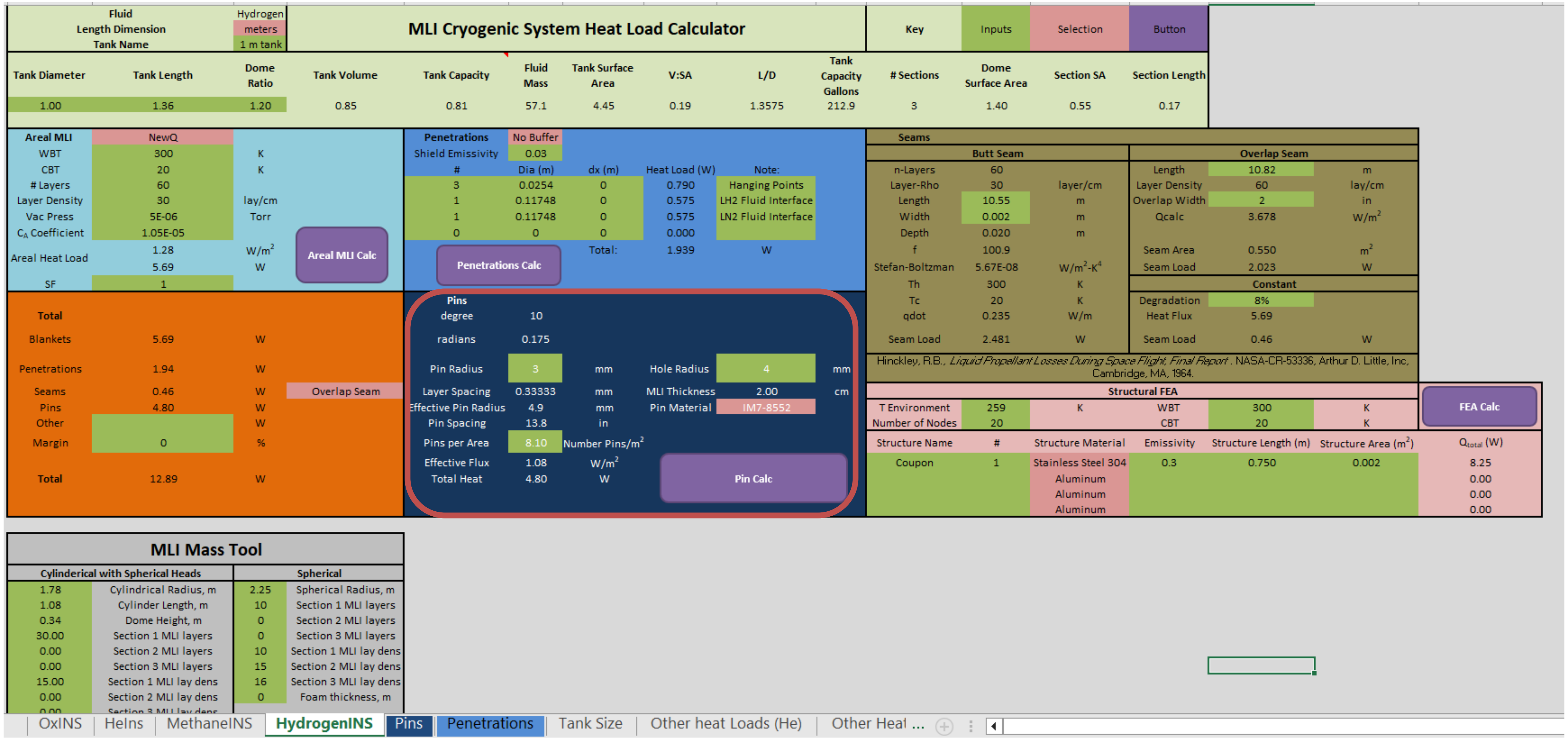
$$dq = q_{ref}\left(\frac{q_{actual}}{q'_{ref}}\right)_{\#layers}\left(\frac{q'_{ref}}{q_{ref}}\right)_{buffer\ thick}\left(\frac{q_{actual}}{q_{ref}}\right)_{diameter}\left(\frac{q_{actual}}{q_{ref}}\right)_{buffer\ thick}\left(\frac{T_h}{297}\right)^{1.56}$$

- **For reference case one use 25 layers of MLI with a 76.2 mm penetration and a 6.4 mm Cryolite buffer. Qref equals 0.052 W from Slide 46.**
- **For reference case two use 25 layers of MLI with a 76.2 mm penetration and a 12.7 mm Cryolite buffer. Qref' then equals 0.086 W from Slide 48.**
- **Q actual for the pipe diameter (using a 104 mm penetration with 25 layers of MLI & 6.4 mm Cryolite buffer) is 0.076 W from Slide 46.**
- **Q actual for the buffer thickness (using an 8 mm Cryolite buffer with 76.2 mm penetration and 25 layers) is 0.088 W from Slide 47.**
- **Q actual for the number of layers (using 60 layers with a 12.7 mm buffer and a 76.2 mm penetration) is 0.038 W from Slide 48.**
- **Since the WBT is 297 K, we can neglect the last term as 1**

$$dq = 0.052\left(\frac{0.038}{0.086}\right)_{\#layers}\left(\frac{0.086}{0.052}\right)_{buffer\ thickness}\left(\frac{0.076}{0.052}\right)_{diameter}\left(\frac{0.088}{0.052}\right)_{buffer\ thickness}$$

$$= 0.095W$$

MLI Cryogenic System Heat Load Calculator for Trad Cryo MLI



MLI Cryogenic System Heat Load Calculator

Fluid	Hydrogen
Length Dimension	meters
Tank Name	1 m tank

Key	Inputs	Selection	Button

Tank Diameter	Tank Length	Dome Ratio	Tank Volume	Tank Capacity	Fluid Mass	Tank Surface Area	V:SA	L/D	Tank Capacity Gallons	# Sections	Dome Surface Area	Section SA	Section Length
1.00	1.36	1.20	0.85	0.81	57.1	4.45	0.19	1.3575	212.9	3	1.40	0.55	0.17

Areal MLI	NewQ	
WBT	300	K
CBT	20	K
# Layers	60	
Layer Density	30	lay/cm
Vac Press	5E-06	Torr
C_A Coefficient	1.05E-05	
Areal Heat Load	1.28	W/m^2
	5.69	W
SF	1	

Penetrations	No Buffer			
Shield Emissivity	0.03			
#	Dia (m)	dx (m)	Heat Load (W)	Note:
3	0.0254	0	0.790	Hanging Points
1	0.11748	0	0.575	LH2 Fluid Interface
1	0.11748	0	0.575	LN2 Fluid Interface
0	0	0	0.000	
		Total:	1.939	W

Seams					
Butt Seam			Overlap Seam		
n-Layers	60		Length	10.82	m
Layer-Rho	30	layer/cm	Layer Density	60	lay/cm
Length	10.55	m	Overlap Width	2	in
Width	0.002	m	Qcalc	3.678	W/m^2
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f	100.9		Seam Area	0.550	m^2
Stefan-Boltzman	5.67E-08	W/m^2-K^4	Seam Load	2.023	W
Th	300	K	Constant		
Tc	20	K	Degradation	8%	
qdot	0.235	W/m	Heat Flux	5.69	
Seam Load	2.481	W	Seam Load	0.46	W

Hinckley, R.B., *Liquid Propellant Losses During Space Flight, Final Report*. NASA-CR-53336, Arthur D. Little, Inc, Cambridge, MA, 1964.

Total			
Blankets	5.69	W	
Penetrations	1.94	W	
Seams	0.46	W	Overlap Seam
Pins	4.80	W	
Other		W	
Margin	0	%	
Total	12.89	W	

Pins					
degree	10				
radians	0.175				
Pin Radius	3	mm	Hole Radius	4	mm
Layer Spacing	0.33333	mm	MLI Thickness	2.00	cm
Effective Pin Radius	4.9	mm	Pin Material	IM7-8552	
Pin Spacing	13.8	in			
Pins per Area	8.10	Number Pins/m^2			
Effective Flux	1.08	W/m^2			
Total Heat	4.80	W			

Structural FEA						
T Environment	259	K	WBT	300	K	
Number of Nodes	20		CBT	20	K	
Structure Name	#	Structure Material	Emissivity	Structure Length (m)	Structure Area (m^2)	Q_{total} (W)
Coupon	1	Stainless Steel 304	0.3	0.750	0.002	8.25
		Aluminum				0.00
		Aluminum				0.00
		Aluminum				0.00

MLI Mass Tool

Cylinderical with Spherical Heads		Spherical	
1.78	Cylindrical Radius, m	2.25	Spherical Radius, m
1.08	Cylinder Length, m	10	Section 1 MLI layers
0.34	Dome Height, m	0	Section 2 MLI layers
30.00	Section 1 MLI layers	0	Section 3 MLI layers
0.00	Section 2 MLI layers	10	Section 1 MLI lay dens
0.00	Section 3 MLI layers	15	Section 2 MLI lay dens
15.00	Section 1 MLI lay dens	16	Section 3 MLI lay dens
0.00	Section 2 MLI lay dens	0	Foam thickness, m
0.00	Section 3 MLI lay dens		

Attaching MLI Blankets: Is this really an issue?

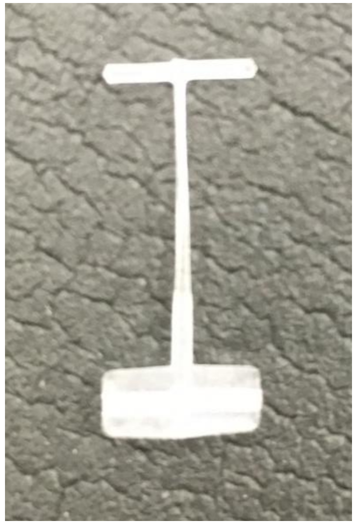
ATV 1 (Joules Verne) incident

- During launch, more power draw required than expected, was traced to blanket disengagement.
- Root causes came down to improper structural attachment
- AIAA-2010-6197

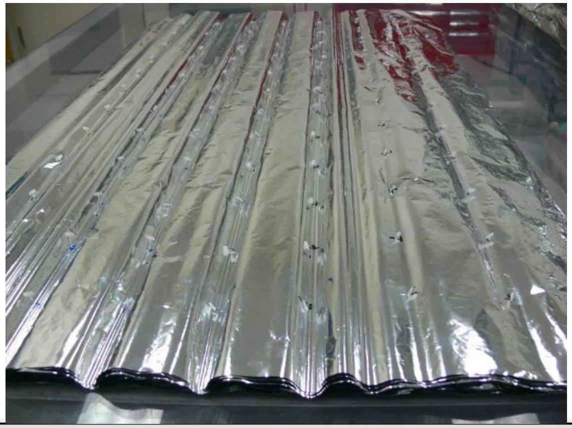
Nylon Tag Testing

- **Nylon tags have long been used to hold MLI together**
- **Installed 56 pins into an existing 10 layer LB-MLI blanket**
  - Individual pins have a really small heat load (~0.9 mW each)
  - Needed repeatable MLI coupon to do initial test and pinned test
  - Pin spacing ~ 3 inch
- **Blanket Heat flux (KSC – Cryostat 100):**
  - A164 July 2012[1]: 0.92 W/m^2
  - A191 March 2015: 1.04 W/m^2
  - Was also used in Hybrid MLI testing[2] (A174, A175, A181, A182)
- **Predicted disturbance:**
  - Variable tag geometry
  - 20 node conduction model (NIST nylon props): 0.5 mW/tag
  - Direct radiation through hole: 8 μW/tag

Cold side



Hot side



[1] Johnson, W.L., Heckle, K.W., and Hurd, J. **“Thermal coupon testing of Load-Bearing Multilayer Insulation”**, *AIP Conference Proceedings 1573*, pg. 725, 2014.

[2] Johnson, W.L., Fesmire, J.E., and Heckle, K.W., **Demonstration of Hybrid Multilayer Insulation of Fixed Thickness Applications**, *IOP Conf. Ser.: Mater. Sci. Eng.* **101** 012015, 2015.

Nylon Tag Test Results Analysis

- **Total heat to the blanket (with 56 tags): 0.51 W**
  - 0.35 W through blanket
  - 0.16 W (+/- 0.025) residual (i.e. through tags)
- **Predicted load: 45 mW**
- **Measured heat load is 3.5 x predicted heat load**

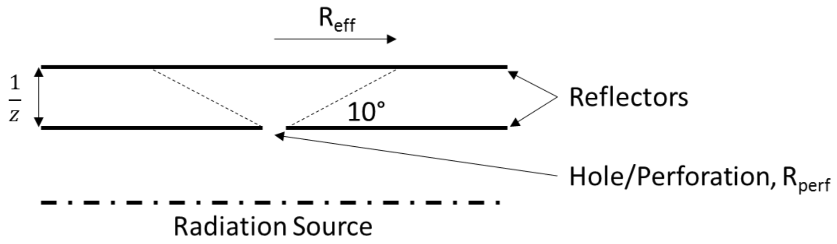
- **Similar to Arthur D. Little, Inc results from 1966[3]**
  - Single 0.8 mm nylon pin through 10 layers MLI (1.0 mm diameter hole)
  - Predicted heat load of 0.3 mW
  - Measured change in heat load of ~ 3 mW, which was the experimental error

- **Need revised model**

[3] Black, I.A, Glaser, P.E., Reid, R.C., "Heat Loss Through Evacuated Multilayer Insulation Penetrated By a Low-Conductivity Pin", Bull. IIR, Annex 1966-2, 233-243 (Meeting Of Commission 2, Trondheim, Norway, Jun 22-24, 1966)

Small Penetration Revised model

- **Based on perforations model developed for MHTB large perforations, the radiation through a perforation is not limited to direct radiation[4]**
- **Instead the effective radiation area is defined by a 10 deg angle**
- **Using layer density as the spacing for LB-MLI, this can be extrapolated to a tag hole.**



$$\theta = 10\,deg = 0.175\,rad$$

$$r_{eff} = \frac{1}{z\cos\theta} + r_{perf}$$

$$A_{eff} = \pi r_{eff}^2$$

$$\dot{Q} = A_{eff}\varepsilon_{layer}\sigma\left(T_h^4 - T_c^4\right) + \int \frac{A}{dx} \int kdT$$

- **Revised model estimates 3.6 mW per tag on recent testing (~30% more than actual)**
- **Revised model estimates 3.6 mW heat load for tag & hole in ADL test**

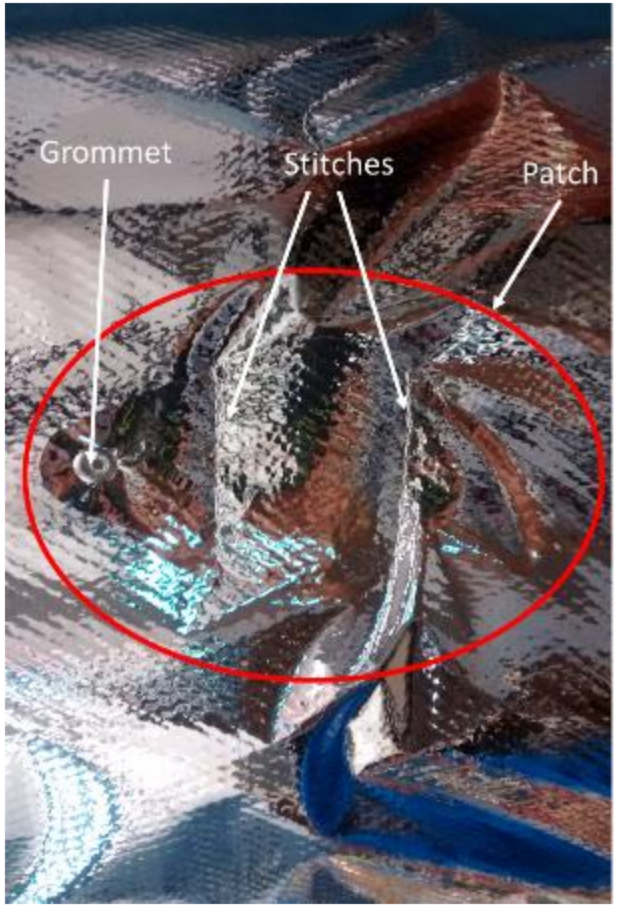
[4] Fox, E.C., Keifel, E.R., and McIntosh, G.L., et.al. “Multipurpose Hydrogen Test Bed System Definition and Insulated Tank Development”, Martin Marietta Astronautics, NASA CR-194355, July 1993.

SHIIVER Structural Attachments

Test article included 4 patches as shown in the pictures to the right.

Stitching only in outer sub-blanket

Thermocouples on the inside of the blanket as shown below.



SHIIVER Attachment Thermal Results

Thermal Testing:

Configuration	**Q_{total}, W**	**Q_{net}, W**	**Q_{attach}, W**	**WBT, K**	**T_{stitch}, K**	**$T_{blanket}$, K**
Baseline	0.928	0.923		261		
Attachments	0.979	0.974	0.052		235	207

Thermal Penalty of 52 mW for four patches

Thermal Modeling:

Heat Loads for one stitch or hole	**WBT = 260 K CBT = 230 K**	**WBT = 260 K CBT = 200 K**	**WBT = 260 K CBT = mixed***
Conduction (mW/thread)	0.10	0.21	0.10
Radiation (mW) all holes	3.4	5.7	5.7
Total (mW)	11.8	22.6	13.8

*Radiation cold boundary of 200 K, conduction cold boundary of 230 K

Thermal Penalty of 55 mW for four patches

Johnson, W.L., Heckle, K.W., and Fesmire, J.E., **Heat Loads Due to Small Penetrations in Multilayer Insulation Blankets**, *IOP Conf. Series: Materials Science and Engineering* **278** 012197, 2017.

Small Penetration Summary

- **Completed testing on an MLI blanket with multiple small penetrations.**
- **Results show that heat load much more than conduction only.**
- **Analytical approach with combined radiation and conduction shows uncertainty less than 30%.**
  - Change in vacuum level may account for difference
- **Verified model approach for SHIIVER test articles in predicting SHIIVER heat loads.**

Test Series	**Hole Radius (mm)**	**# layers**	**Layer Density (lay/mm)**	**Q_{hole} (mW)**	**Q_{pin} (mW)**	**Q_{total} (mW)**	**Q_{meas} (mW)**
A192	0.5	10	0.6	3.1	0.52	3.6	2.0-2.8
Black [9]	0.5	10	1.3	3.3	0.3	3.6	~3

From: Johnson, W.L., Heckle, K.W., and Fesmire, J.E., Heat Loads Due to Small Penetrations in Multilayer Insulation Blankets, IOP Conf. Series: Materials Science and Engineering 278 012197, 2017.

Johnson, W.L., Oberg, D., Frank, D., Mistry, V, and Koci, F.D., Testing of SHIIVER MLI Coupons for Heat Load Predictions, IOP Conf. Series: Materials Science and Engineering 755 012151, 2020.

9. I.A. Black, P.E. Glaser, and R.C. Reid, “Heat Loss Through Evacuated Multilayer Insulation Penetrated By a Low-Conductivity Pin”, Bull. IIR, Annex 1966-2, 233-243 (Meeting Of Commission 2, Trondheim, Norway, Jun 22-24, 1966).

MLI ATTACHMENTS

Small Penetration, MLI Standoff, Structural Testing

- In order to attach MLI blankets to spacecraft in a manner to survive a combination of acceleration, acoustic, and venting loads while minimize the parasitic heat load to the tank.
  - The attachments serve as direct heat loads to the tank and often are a significant portion of a tank applied heat load [1].
  - There have been instances where MLI was not appropriately attached to spacecraft and has been lost or damaged, compromising the mission. [2, 3].
  - Based on a review of typical attachment methods, most use plastic (nylon or ultem) holders to minimize conduction loss through a blanket. However, these plastics have a much larger coefficient of thermal contraction and often contract 1% or more than most base metals [4]. As such, an epoxy must be able to handle the differential contraction between the two materials and also handle the many other forces that it may encounter.
- A typical insulation system for a cryogenic upper stage would include spray-of foam insulation (SOFI) underneath the MLI blankets to prevent air liquefaction.
  - The polyetherimide standoffs would be attached to the tank and protrude through the SOFI to provide points of attachment for the MLI blankets. Previous attempts to attach the MLI directly to SOFI has induced cracking in the SOFI as shown in Figure 1.
- For reference, Figure 2 shows a possible configuration of a standoff with an MLI blanket.

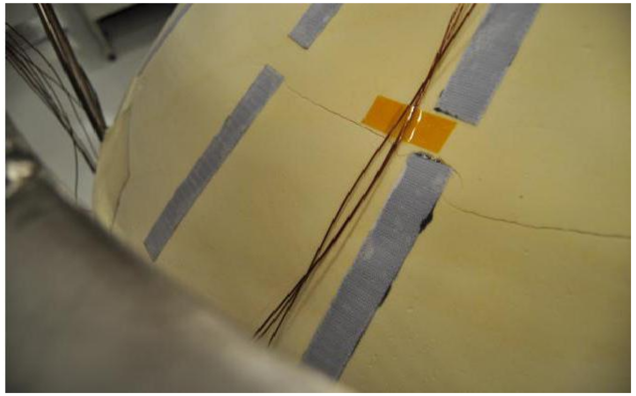


Figure 1. SOFI after MLI was directly attached to the surface.

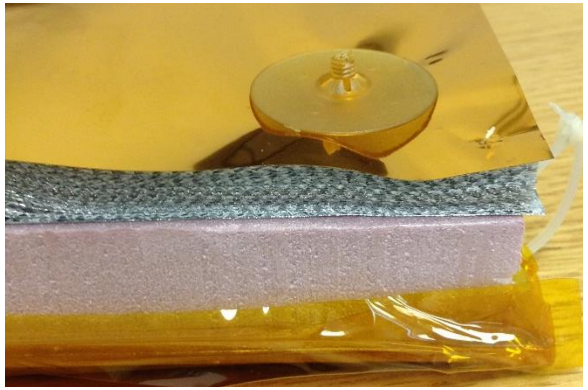
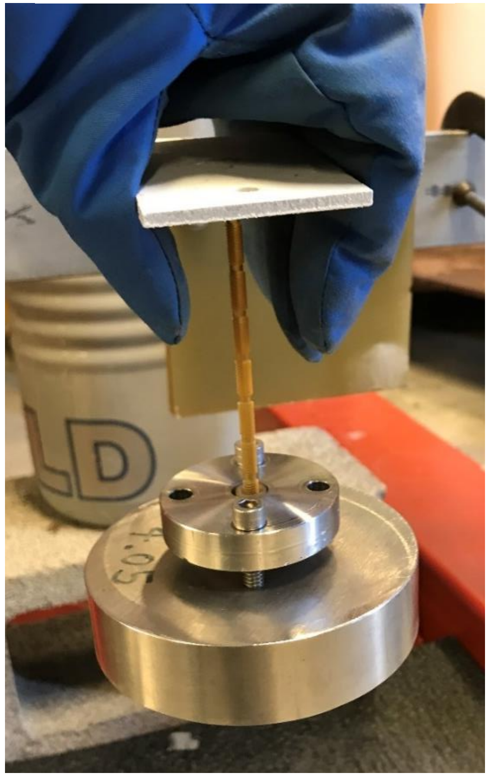


Figure 2. An MLI standoff holding the MLI blanket and foam insulation to the metal surface.

Coupon Tensile and Shear Testing Method

Pull Tests



Shear Tests

Epoxy Tensile and Shear Testing Results

✓ Epoxy success
X Epoxy failure (EF)
- Standoff Break (SB)
* Popping noises while cooling
** Sound observations not recorded

Epoxy Brand		Coupon Material	Trial	Popping	Cryogenic Tensile Epoxy Testing										Cryogenic Shear Epoxy Testing									
					Weight, lbs (Coupons maintained at approx. -187°C)																			
					2.9	4.5	8.0	11.6	15.2	17.6	23.1	26.1	35.4	40.8	2.5	4.1	7.6	11.2	14.8	17.2	22.7	25.7	35.0	40.4
Altheris	C1	AL - 2195	1	*	✓	✓	✓	✓	✓	✓	✓	✓	X Epoxy failure											
			2	*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X EF
		SST 304	1	*	✓	✓	X Epoxy failure																	
			2	*	X Epoxy failure																			
	EA-2A	AL - 2195	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			2		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		SST 304	1		X Epoxy failure																			
			2		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CTD	621	AL - 2195 primered	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			2		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		AL - 2195	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		SST 304	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			2		✓	✓	✓	✓	✓	✓	✓	- Standoff break												
GE	Varnish	AL - 2195	1	**	X Epoxy failure																			
		AL - 2195	1		X Epoxy failure																			
		SST 304	1		X Epoxy failure																			
Huntsman	EPIBond	AL - 2195 primered	1	*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			2	*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		AL - 2195	1	*	X Epoxy failure																			
		SST 304	1	*	X Epoxy failure																			
			2	*	✓	X Epoxy failure																		
HYSOL	EA 9430	AL - 2195	1	**	X Epoxy failure																			
		AL - 2195	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		SST 304	1		X Epoxy failure																			
	EA 9369	AL - 2195 primered	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			2		✓	✓	✓	✓	✓	✓	✓	✓	✓	- Standoff break										
		AL - 2195	1	*	X Epoxy failure																			
		SST 304	1	*	✓	X Epoxy failure																		
			2		X Epoxy failure																			

Additional Surface Preparation

Great Performance

Epoxy Tensile and Shear Testing Results (cont.)

✓ Epoxy success
X Epoxy failure (EF)
\- Standoff Break (SB)
* Popping noises while cooling
** Sound observations not recorded

Epoxy Brand	Coupon Material	Trial	Popping	Cryogenic Tensile Epoxy Testing										Cryogenic Shear Epoxy Testing									
				Weight, lbs (Coupons maintained at approx. -187°C)																			
				2.9	4.5	8.0	11.6	15.2	17.6	23.1	26.1	35.4	40.8	2.5	4.1	7.6	11.2	14.8	17.2	22.7	25.7	35.0	40.4
Masterbond AE-10	AL - 2195	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		2		✓	✓	✓	✓	✓	✓	✓	- Standoff break												
	SST 304	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	- SB
		2	*	X Epoxy failure																			
EP29LPSP	AL - 2195 primered	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		2		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	- SB
		3		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	AL - 2195	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	SST 304	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		2		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		3		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X Epoxy failure				
EP21TCHT-1	AL - 2195 primered	1	**	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		2		✓	✓	✓	✓	- Standoff break															
	SST 304	1		X Epoxy failure																			
		2		X Epoxy failure																			
EP30-2	AL - 2195 primered	1		✓	✓	✓	✓	X Epoxy failure															
		2		✓	✓	✓	X Epoxy failure																
	SST 304	1		X Epoxy failure																			
		2		X Epoxy failure																			
SUP12AOHT-LO	AL - 2195 primered	1		✓	✓	✓	X Epoxy failure																
		2		✓	X Epoxy failure																		
	SST 304	1		X Epoxy failure																			
		2		X Epoxy failure																			
Scotchweld 2216	AL - 2195 primered	1	**	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	AL - 2195	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	SST 304	1		✓	✓	✓	✓	✓	✓	✓	✓	Missing coupon											
STYCAST 2850FT	AL - 2195 primered	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		2		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	AL - 2195	1	*	✓	✓	X Epoxy failure																	
	SST 304	1	*	✓	✓	✓	X Epoxy failure																
		2		✓	✓	✓	X Epoxy failure																
1266	AL - 2195 primered	1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		2		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	AL - 2195	1		X Epoxy failure																			
	SST 304	1	*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X Epoxy failure									
		2		✓	✓	✓	✓	✓	✓	✓	✓	X Epoxy failure											

Additional Surface Preparation

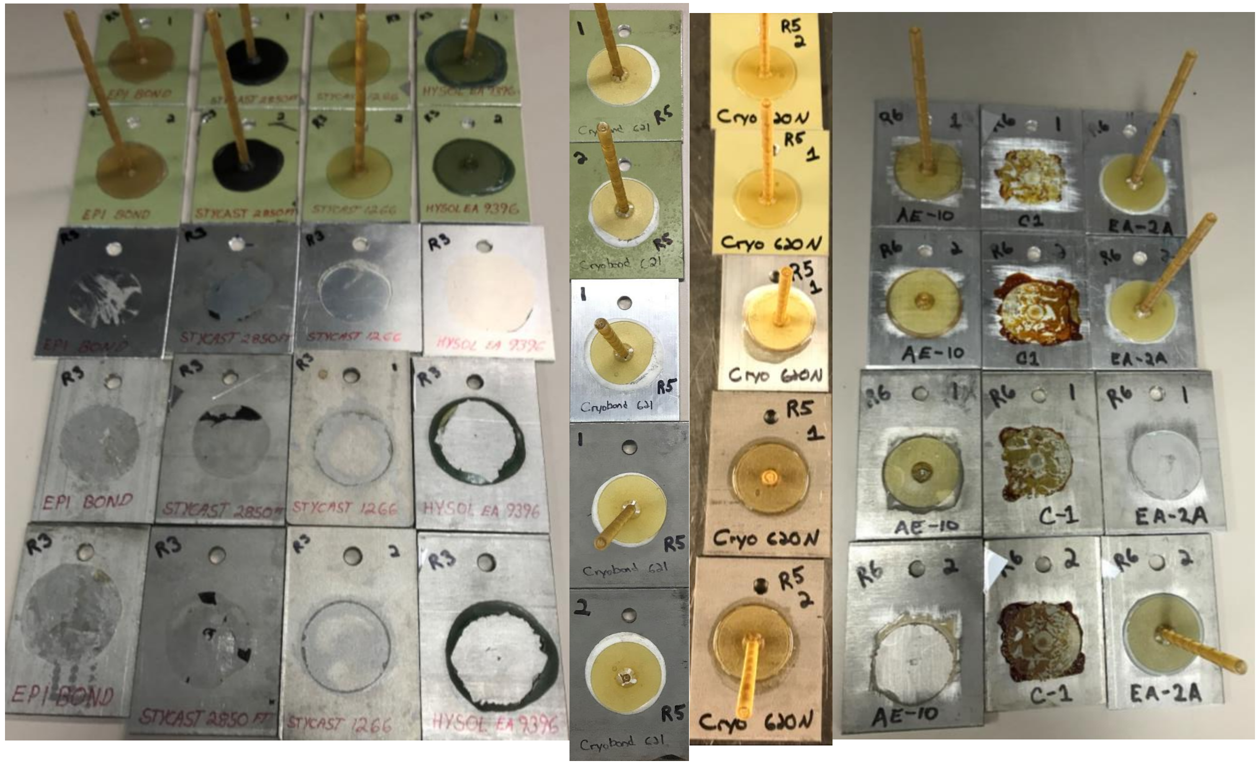
Great Performance

Great Performance

Conclusions/Results

- Best performance from **CTD CryoBond 621**, **Masterbond EP29LPSP**, and **Scotchweld 2216**
  - Passed tensile and shear testing for multiple coupon materials
- Sound indicators of epoxy and standoff failures
- 5 of 6 standoff failures occurred above 25lbs
- 24 of 65 samples survived tensile and shear testing (not including standoff breaks)

Round 3, 5, & 6
coupons after testing

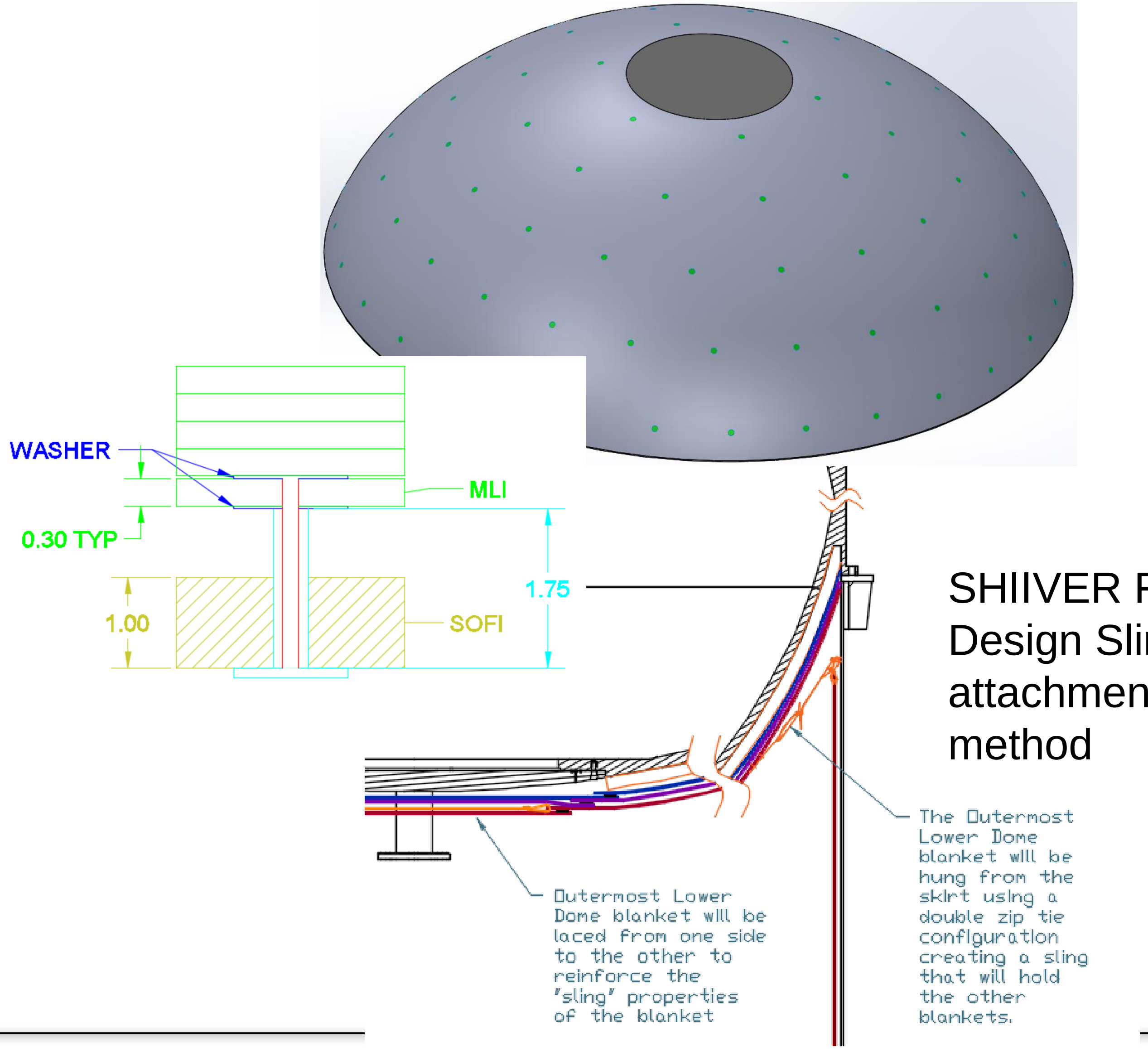


Alberts, S.J., Doehne, C.J., and Johnson W.L., **Testing Tensile and Shear Epoxy Strength at Cryogenic Temperatures**, presented at the 2017 Cryogenic Engineering Conference, Madison, WI, June 2017.

SHIIVER standoffs

- During the design of the SHIIVER MLI blankets, initially ClickBond posts were assumed to be used.
- Performed evacuation analysis
  - Average 5 Torr delta pressure across the blanket
  - 42 lb capacity per ClickBond
  - ~3000 lb force for SHIIVER
    - 90 ClickBonds for SHIIVER
  - ~13k lb force for 8.4 m upper stage
    - 397 ClickBonds – not reasonable

SHIIVER Top Dome Click-Bond Map at PDR

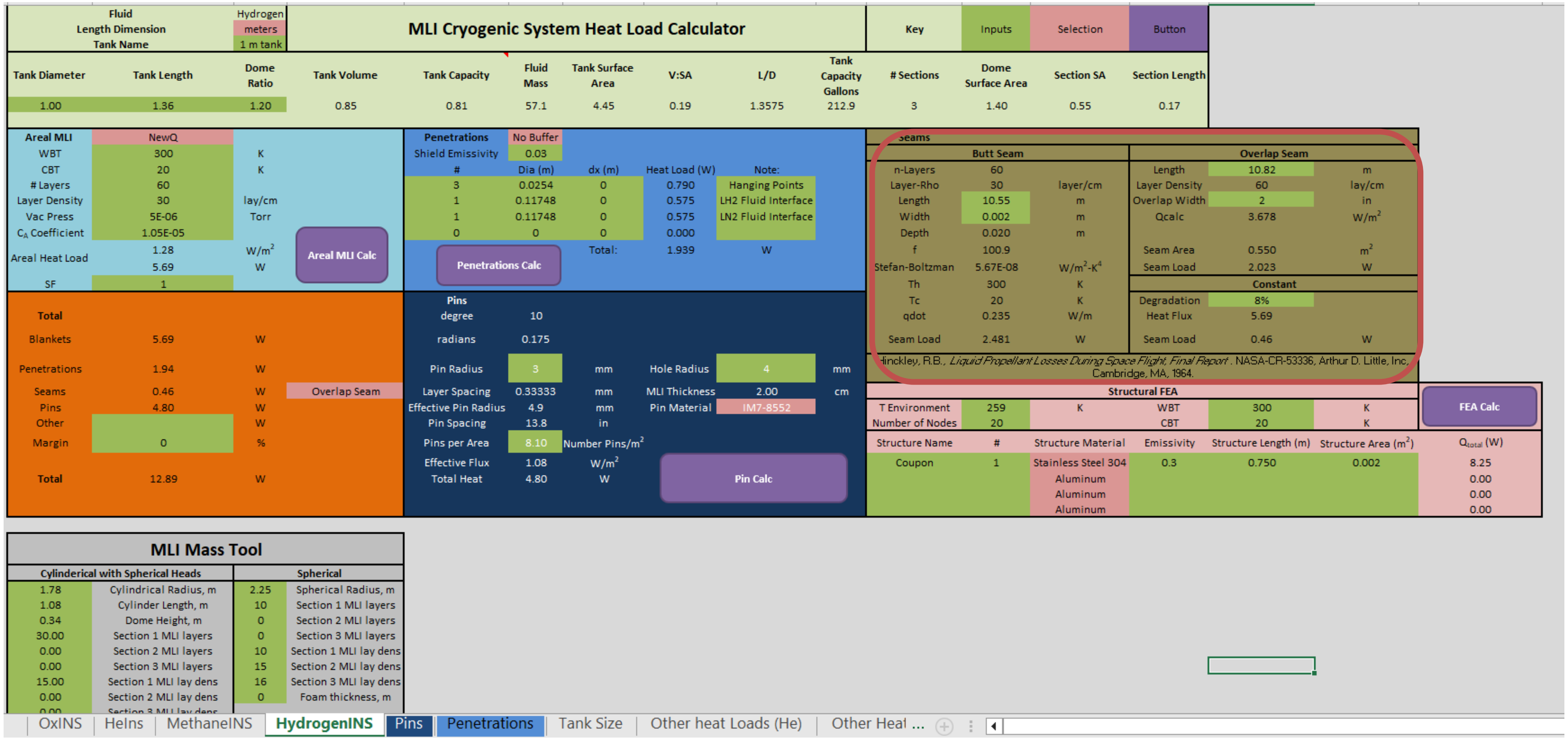


Outermost Lower Dome blanket will be laced from one side to the other to reinforce the 'sling' properties of the blanket

The Outermost Lower Dome blanket will be hung from the skirt using a double zip tie configuration creating a sling that will hold the other blankets.

SHIIVER Final Design Sling attachment method

MLI Cryogenic System Heat Load Calculator for Trad Cryo MLI



Fluid	Hydrogen
Length Dimension	meters
Tank Name	1 m tank

MLI Cryogenic System Heat Load Calculator

Key	Inputs	Selection	Button

Tank Diameter	Tank Length	Dome Ratio	Tank Volume	Tank Capacity	Fluid Mass	Tank Surface Area	V:SA	L/D	Tank Capacity Gallons	# Sections	Dome Surface Area	Section SA	Section Length
1.00	1.36	1.20	0.85	0.81	57.1	4.45	0.19	1.3575	212.9	3	1.40	0.55	0.17

Areal MLI	NewQ	
WBT	300	K
CBT	20	K
# Layers	60	
Layer Density	30	lay/cm
Vac Press	5E-06	Torr
C_A Coefficient	1.05E-05	
Areal Heat Load	1.28	W/m²
	5.69	W
SF	1	

Areal MLI Calc

Penetrations	No Buffer			
Shield Emissivity	0.03			
#	Dia (m)	dx (m)	Heat Load (W)	Note:
3	0.0254	0	0.790	Hanging Points
1	0.11748	0	0.575	LH2 Fluid Interface
1	0.11748	0	0.575	LN2 Fluid Interface
0	0	0	0.000	
		Total:	1.939	W

Penetrations Calc

Total			
Blankets	5.69	W	
Penetrations	1.94	W	
Seams	0.46	W	Overlap Seam
Pins	4.80	W	
Other		W	
Margin	0	%	
Total	12.89	W	

Pins					
degree	10				
radians	0.175				
Pin Radius	3	mm	Hole Radius	4	mm
Layer Spacing	0.33333	mm	MLI Thickness	2.00	cm
Effective Pin Radius	4.9	mm	Pin Material	IM7-8552	
Pin Spacing	13.8	in			
Pins per Area	8.10	Number Pins/m²			
Effective Flux	1.08	W/m²			
Total Heat	4.80	W			

Pin Calc

Seams

Butt Seam			Overlap Seam		
n-Layers	60		Length	10.82	m
Layer-Rho	30	layer/cm	Layer Density	60	lay/cm
Length	10.55	m	Overlap Width	2	in
Width	0.002	m	Qcalc	3.678	W/m²
Depth	0.020	m			
f	100.9		Seam Area	0.550	m²
Stefan-Boltzman	5.67E-08	W/m²-K⁴	Seam Load	2.023	W
Th	300	K	Constant		
Tc	20	K	Degradation	8%	
qdot	0.235	W/m	Heat Flux	5.69	
Seam Load	2.481	W	Seam Load	0.46	W

Hinckley, R.B., *Liquid Propellant Losses During Space Flight, Final Report*. NASA-CR-53336, Arthur D. Little, Inc., Cambridge, MA, 1964.

Structural FEA

T Environment	259	K	WBT	300	K
Number of Nodes	20		CBT	20	K

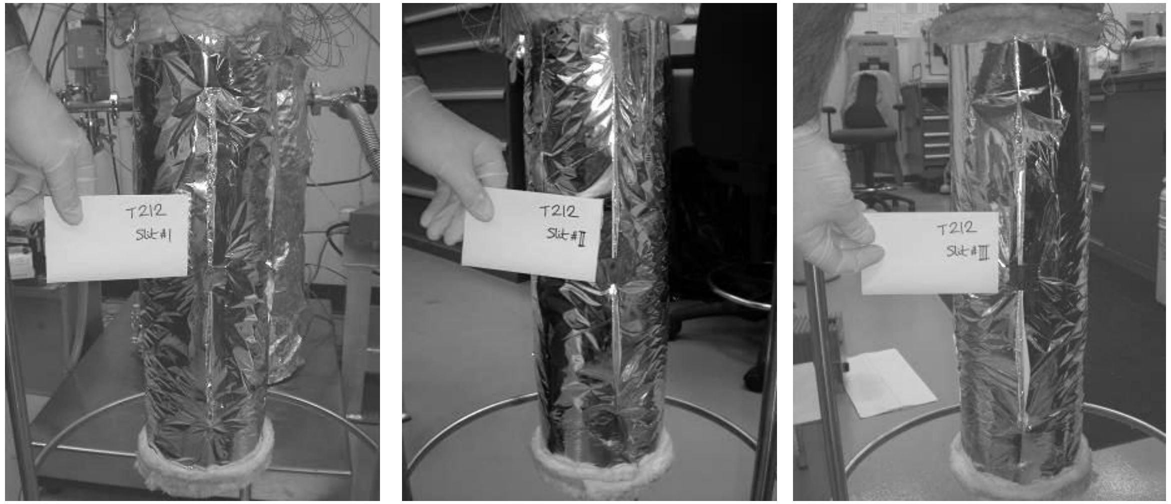
FEA Calc

Structure Name	#	Structure Material	Emissivity	Structure Length (m)	Structure Area (m²)	Q_{total} (W)
Coupon	1	Stainless Steel 304	0.3	0.750	0.002	8.25
		Aluminum				0.00
		Aluminum				0.00
		Aluminum				0.00

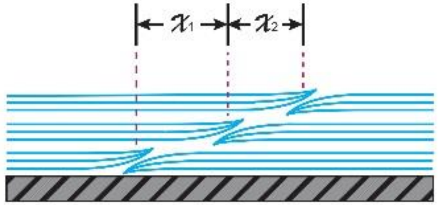
MLI Mass Tool

Cylinderical with Spherical Heads		Spherical	
1.78	Cylindrical Radius, m	2.25	Spherical Radius, m
1.08	Cylinder Length, m	10	Section 1 MLI layers
0.34	Dome Height, m	0	Section 2 MLI layers
30.00	Section 1 MLI layers	0	Section 3 MLI layers
0.00	Section 2 MLI layers	10	Section 1 MLI lay dens
0.00	Section 3 MLI layers	15	Section 2 MLI lay dens
15.00	Section 1 MLI lay dens	16	Section 3 MLI lay dens
0.00	Section 2 MLI lay dens	0	Foam thickness, m
0.00	Section 3 MLI lay dens		

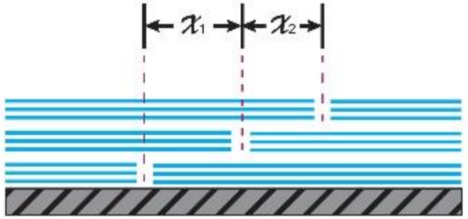
MLI Types of Seams



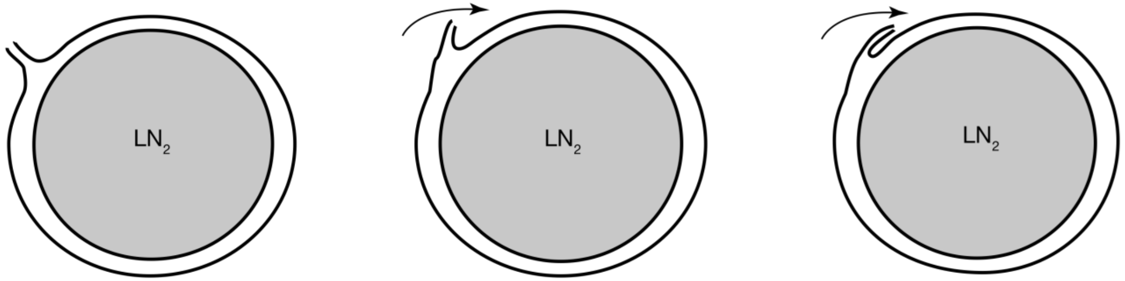
Butt Seams



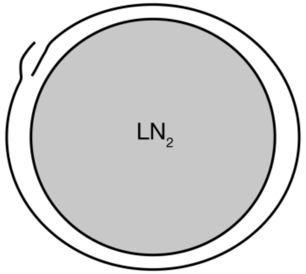
3 Blanket Overlap Staggered



3 Blanket Staggered



Method of fold-over seam installation



Overlapped seams

Butt Seam Analytical Solution

- **Hinckley came up with an analytical solution for the Butt Seam as shown on the right.**
- **Testing performed with liquid nitrogen has shown that this is a very good approximation.**
- **Equations are somewhat complicated and the variables may be hard to control in a real life application.**
- **Provides good estimate to use in initial design predictions and sensitivities.**

$$\frac{\dot{Q}_{seam}}{L_{seam}} = \frac{\gamma\sigma(T_H^4 - T_C^4)}{\left(\frac{2}{\varepsilon} - 1\right)n}$$

$$\frac{\gamma}{t} = \left(\frac{2}{\varepsilon} - 1\right)n * fn\left(\frac{\delta}{t}\right)$$

$$fn\left(\frac{\delta}{t}\right) = \sqrt{1+\varphi^2}\left(\frac{1}{3} - \frac{2\varphi^2}{3}\right) + \left(\frac{2\varphi^3}{3} - \frac{1}{3}\right) + \varphi^2 \ln\left(\frac{1+\sqrt{1+\varphi^2}}{\varphi}\right)$$

$$\varphi = \frac{\delta}{t}$$

Where Q is the heat leak through the seam, δ is the seam width, t is the seam depth, and L is the length of the seam.

Hinckley, R.B., *Liquid Propellant Losses During Space Flight, Final Report*. NASA-CR-53336, Arthur D. Little, Inc, Cambridge, MA, 1964.

Shu – MLI Cracks

- A series of tests on different heat load degradations was done on different cracks in a 30-layer blanket
  - Liquid nitrogen boil-off test method.
- Different ways to tape the cracks
- Different width of cracks
- Part 1 was a theoretical approach

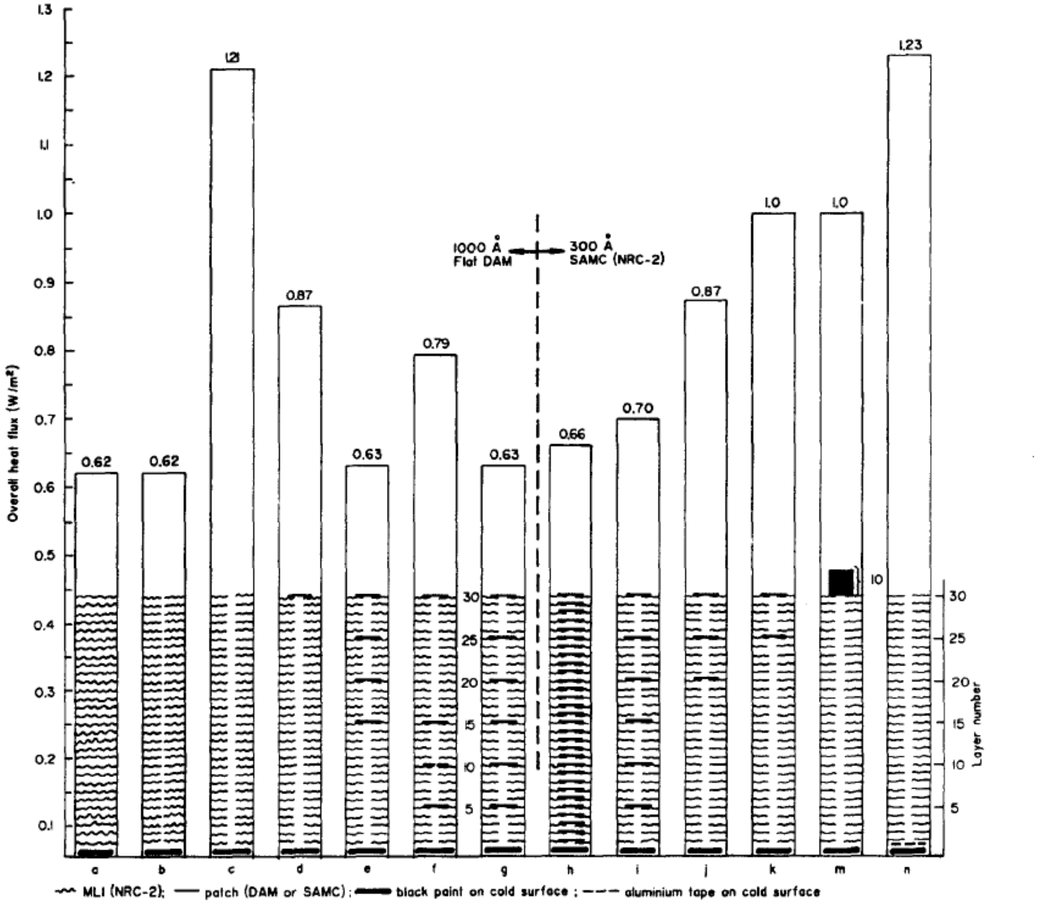


Figure 12 Graphic summary of heat flux results of patch study. a, No cracks; b, one-dimensional slits; c–m, runs 2 to 11; n, 0.09 mm aluminium tape on cold surface, no patches

Shu, Q.S., Fast, R.W., and Hart, H.L., Systematic study to reduce the effects of cracks in multilayer insulation, Part 2: experimental results, Cryogenics Vol 27, Issue 6, 1987

Overlap Seam Analytical Approach

In collaboration with Dave Frank (LMCO ret) the general thought process of treating an overlap seam as a double layer density was explored.

- **When a seam is overlapped, twice the layers of MLI are present at approximately the same thickness. Thus, the layer density is doubled.**
- **This is applied for the area of the seam using a Lockheed type equation (Modified Lockheed, NewQ, etc).**
- **It is assumed that the thermal gradients extending outside of the blanket are small in nature and do not affect the area of the blanket not a part of the seams. Thus, the rest of the blanket is treated as a nominal blanket area.**

50 Layer Test Results

- **Overlapped seams outperformed butt seams**
- **Offsetting butt seams didn't seem to provide any benefit**
  - By the time the butt seam is handled, radiation path becomes torturous
- **Minimal difference between the best and worst seams**

Test Number	Run	Q_{total}, watts	T_{avg}, K	K_{avg}, W/m/K	ΔT, K	Q_{net}, W	dQ, W	dQ, W/m
1	Overlap Seams	0.788	21.06	29.8	2.56	0.786	0.040	0.044
2	Interleaved	0.748	19.16	27.3	2.43	0.746	0.000	0.000
3	Full Butt	0.806	18.85	26.9	2.51	0.802	0.056	0.061
4	Butt 2" Offset	0.806	18.85	26.9	2.52	0.803	0.057	0.062
5	Butt 4" Offset	0.810	19.37	27.8	2.56	0.807	0.061	0.067

20 Layer Seam Results

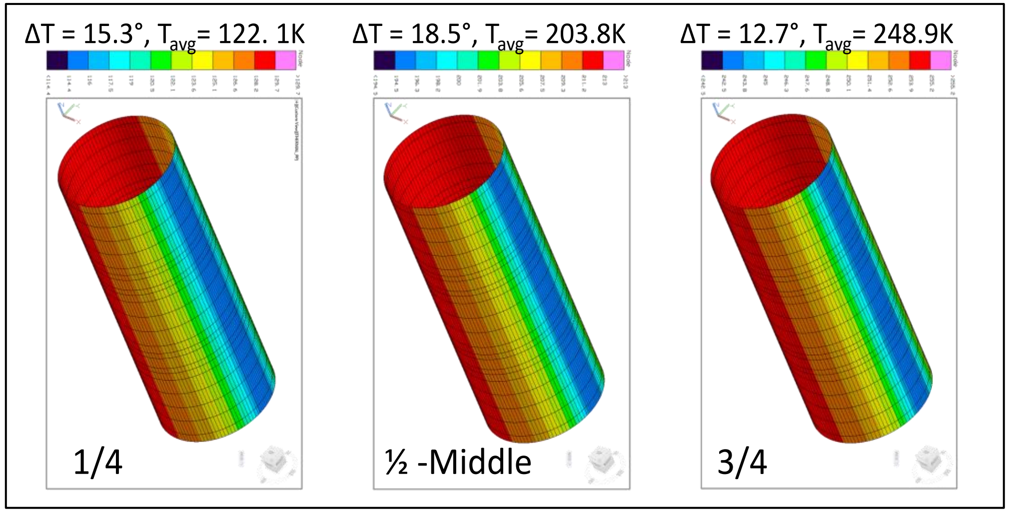
- **Once again, Overlap seam outperformed butt seam.**
  - Minimal heat gains into system
- **Offsetting butt seams didn't provide any benefit**

- **Much bigger difference between the best and worst seaming configurations**

Test Number	Run	Q_{total}, watts	T_{avg}, K	K_{avg}, W/m/K	ΔT, K	Q_{net}, W	dQ, W	dQ, W/m
6	Interleaved	1.033	20.38	28.9	3.49	1.012	0	0.000
7	Overlap	1.035	18.62	26.6	3.65	1.015	0.003	0.003
8	Butt 2" Offset	1.222	17.52	25.0	4.21	1.199	0.187	0.205
9	Full Butt	1.160	17.25	24.7	4.09	1.146	0.134	0.147

SHIIVER Seams Testing

- **Effect of seam measured by putting two seams into blanket**
- **Lockheed ATC analysis showed that two seams didn’t interfere with each other thermally.**
- **Effect of seam approximately 0.15 W/m in this configuration**
- **SHIIVER MLI designed to minimize seam length on 8.4 m tank**



Thermal Model by Lockheed ATC

Configuration	**Q_{total}, W**	**Q_{net}, W**	**Q_{seam}, W/m**	**% change**
Single Seam	0.928	0.923	0.147	
Double Seam	1.062	1.057	0.394	14.6%

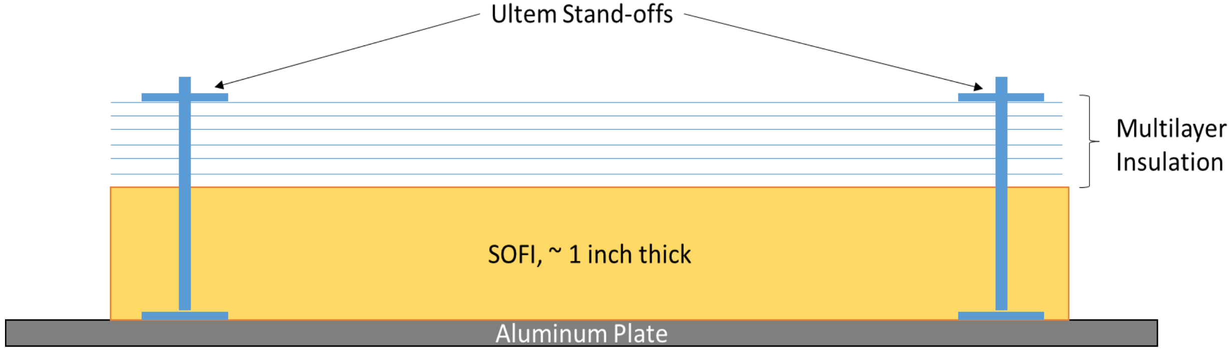
Conclusions

- **Measured heat loads for the nine tests conducted.**
- **Layer by layer interleaved joint showed the lowest heat leak.**
- **Overlap joint outperformed the straight and staggered butt joints.**
- **Surprisingly, staggering the butt joint did not decrease the heat load**
  - Increasing the stagger distance didn’t help.
  - In fact, the test with the largest stagger was worse than straight butt joint, (although this may be due to damage incurred by repeated handling rather the joint itself).
  - Technician installed by “stitch taping” joints every ~5 layers, may have shown that stitch taping is as good as full taping
- **Even worst performing seam only 5% more heat leak than best performing seam at 50 layers**
- **There are significant differences between 20 layers and 50 layers. This shows that the impact of seams is reduced with increased numbers of layers.**

1. Johnson, W.L., and Chato, D.J., **Performance of MLI Seams between 293 K and 20 K**, *IOP Conf. Series: Materials Science and Engineering* **755** 012152, 2020.
2. Johnson, W.L, and Fesmire, J.E., “**Testing of Various Seams in MLI**,” *Advances in Cryogenic Engineering*, Vol. 55B, American Institute of Physics, Melville, NY, 2010. Pg. 905-912.

MLI Charging Test Coupons

- **6 MLI samples were installed on an aluminum plate**
  - 1-inch-thick foam substrate (material not critical, but non-conductive)
  - Each sample was approximately 8 inches by 8 inches
  - 3 coatings:
    - Single Aluminized Kapton (2 mil, referred to film 1)
    - Germanium (~1500 Å) on 2 mil Kapton (film 2)
    - Indium Tin Oxide (~1.6 kohms/sq) on 2 mil kapton (aluminum coated underside, film 3)
  - 2 different numbers of reflective layers: 10 reflectors, 25 reflectors
  - Each sample had 3 polyetherimide (Ultem) Click-bond posts holding in place (i.e. foam was not bonded to aluminum plate)
  - 10 layer blankets each had individual grounding wires run



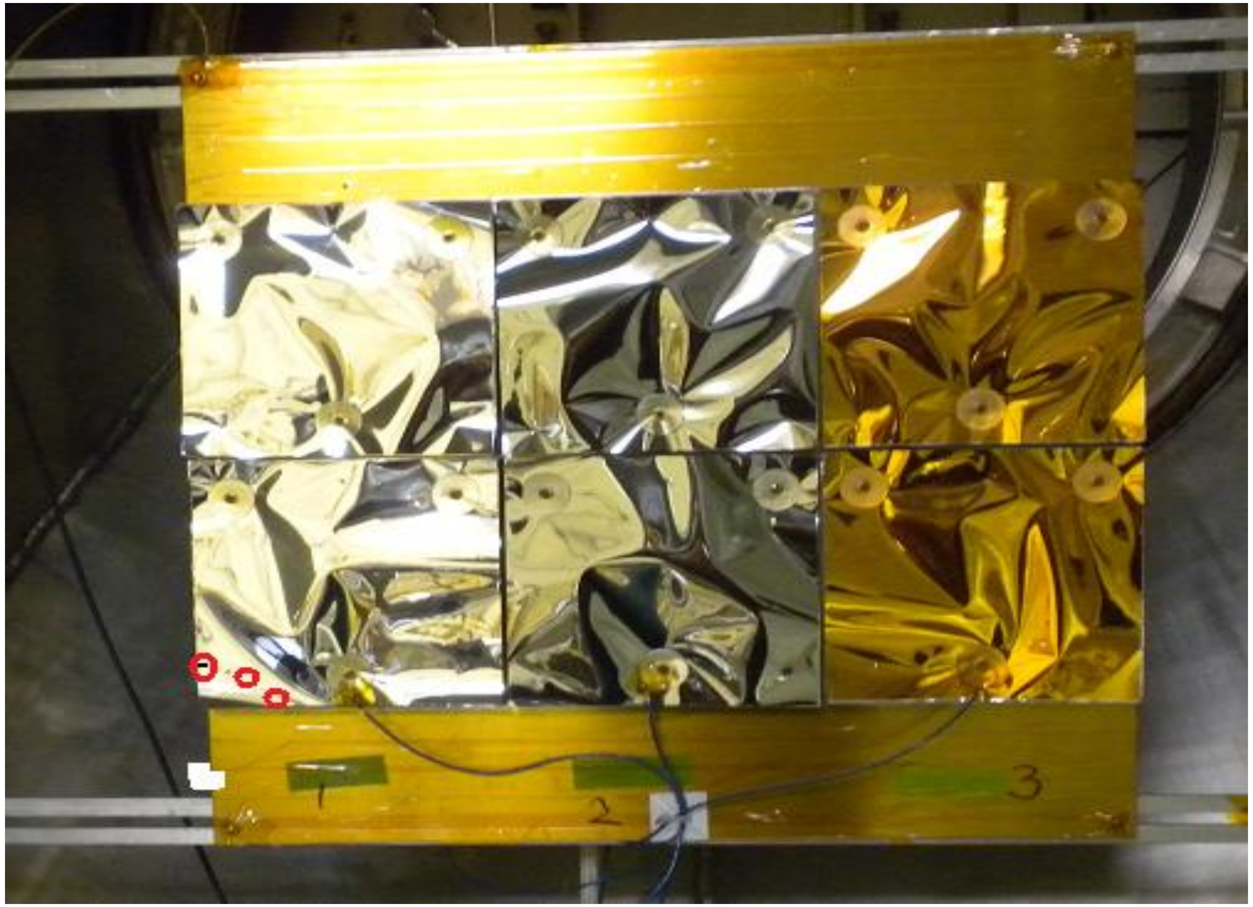
Vaynor, B.V., Galafaro, J.T., and Johnson, W.L., Electrostatic Testing of Multilayer Insulation for In-Space Cryogenic Vehicles, *IEEE Transactions on Plasma Science*, Vol 47, Issue 8, 2019, pp. 3810-3815.

Arcing Room Temperature Results – LEO environment

# arcs @ duration (min)	Ungrounded	Grounded	Film #1 (SAK) grounded only	Film #3 (ITO) grounded only
-200 V	0 arcs, 20 min			
-240 V	0 arcs, 30 min	0 arcs, 30 min	0 arcs, 30 min	0 arcs, 30 min
-270 V	3 arcs, 4 min			
-280 V	5 arcs, 15 min 3 arcs, 30 min*	0 arcs, 30 min	0 arcs, 30 min	0 arcs, 30 min
-320 V		0 arcs, 30 min	1 arc, 30 minutes	
-350 V	3 arcs, 30 min			
-360 V		0 arcs, 30 min		
-400 V	3 arcs, 5 min	2 arcs, 30 min	3 arcs, 1 minute	1 arc, 30 minutes
-440 V		3 arcs, 16 min		4 arcs, 30 minutes

Note 1: arcs were not seen, so it is unknown which sample they occurred on.
Note 2: arcing events decreased with time, indicative of destruction of arcing sites.
*Test was re-run at higher capacitance to try to see arcing events

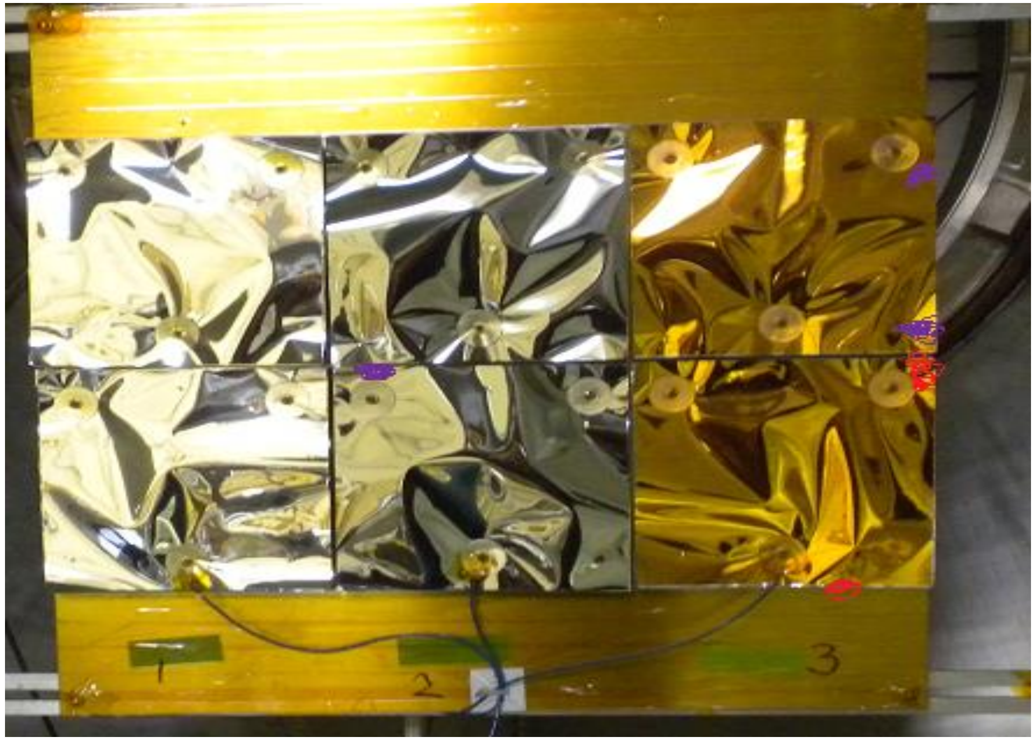
Arc locations



Film 1 (SAK) grounded only
Arcing locations shown with red circles
-400 V

Arcing Testing Results – GEO environment

# arcs @ duration (min)	Ungrounded	Films #2 and #3 grounded only	Film #1 (SAK) grounded only
2 nA/cm^2	0 arcs, 30 minutes	5 arcs, 10 s	0 arcs, 30 min
4 nA/cm^2	0 arcs, 30 minutes		0 arcs, 30 min
6 nA/cm^2			0 arcs, 30 min
8 nA/cm^2	3 arcs, 40 minutes		0 arcs, 30 min



Arcs are shown on coupon surface: red-films 2&3 grounded; violet-film 1 grounded.

Repeatability of MLI Systems

- Performed repeatability on two different sets of blanket:
  - NASA / Sierra Lobo
  - Yetispace
- Three different temperature regimes
- All testing done on same device.

NASA Test Matrix

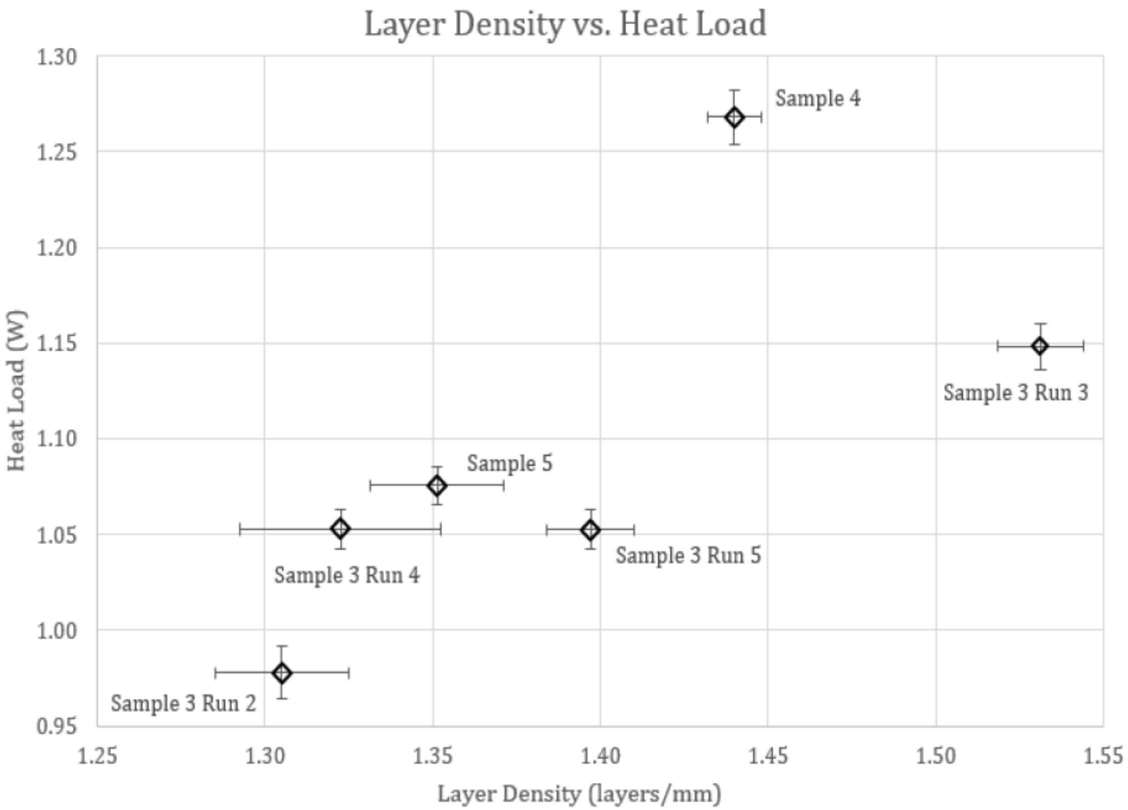
Test Series	Coupon #	Tc (K)	Th (K)
1	1	20	293
2	2	20	293
3	3	20	293
4	4	20	293
5	5	20	293
6	3	20	293
7	3	20	293
8	3	20	293
9	3	20	293
10	1	20	100
11	2	20	100
12	3	20	100
13	4	20	100
14	5	20	100
15	2	20	100
16	2	20	100
17	2	20	100

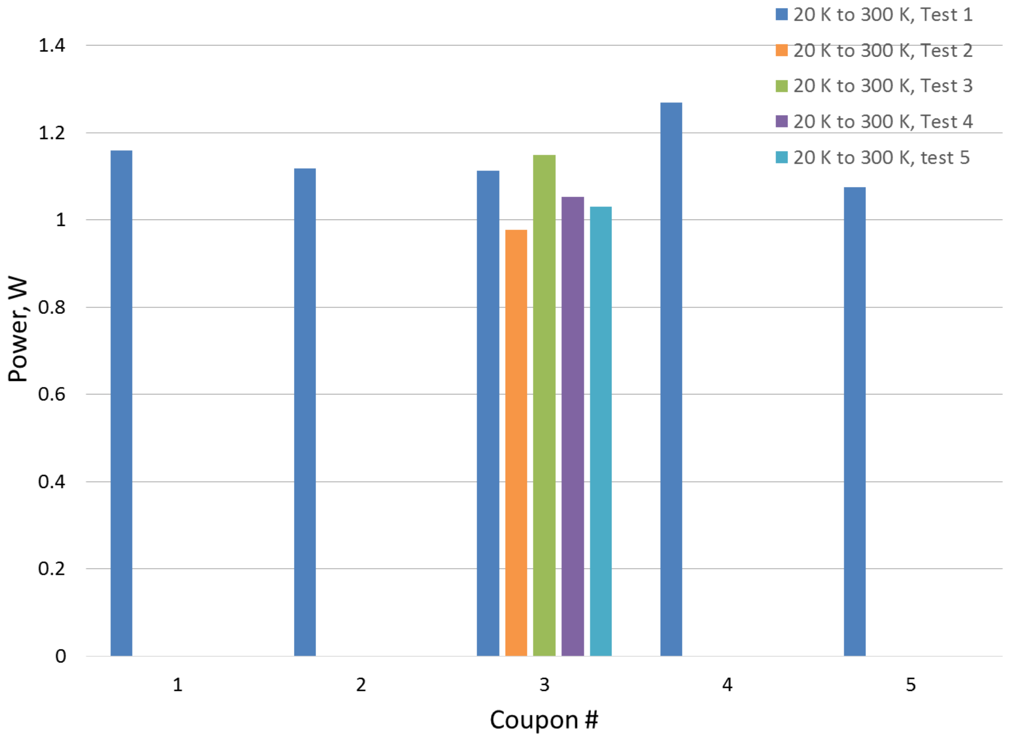
Yetispace Test Matrix

Test Series	Coupon #	Tc (K)	Th (K)
1	1	77	300
2	2	77	300
3	3	77	300
4	4	77	300
5	5	77	300
6	6	77	300
7	7	77	300
8	8	77	300
9	9	77	300
10	10	77	300

1. M. Vanderlaan, D. Stubbs, et. al. “Repeatability Measurements of Apparent Thermal Conductivity of Multi-Layer Insulation (MLI)” *IOP Conf. Series: Materials Science and Engineering* 278 012195, 2017
2. Johnson, W.L., Vanderlaan, M., et. al. Repeatability of Cryogenic Multilayer Insulation, *IOP Conf. Series: Materials Science and Engineering* 278 012196, 2017.
3. eCryo-RPT-0130

NASA coupon 300 K Test Results

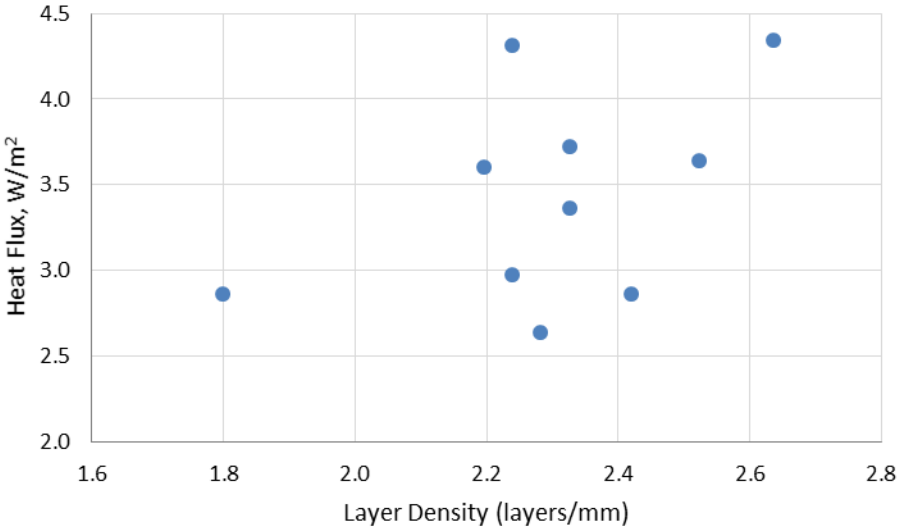




- Repeatability of single coupon installed 5 times similar to that of 5 different coupons installed:
  - Repeatability driven by installation, not coupon variability
- Small trend of performance with layer density.
- Nominally 25 reflective layers.

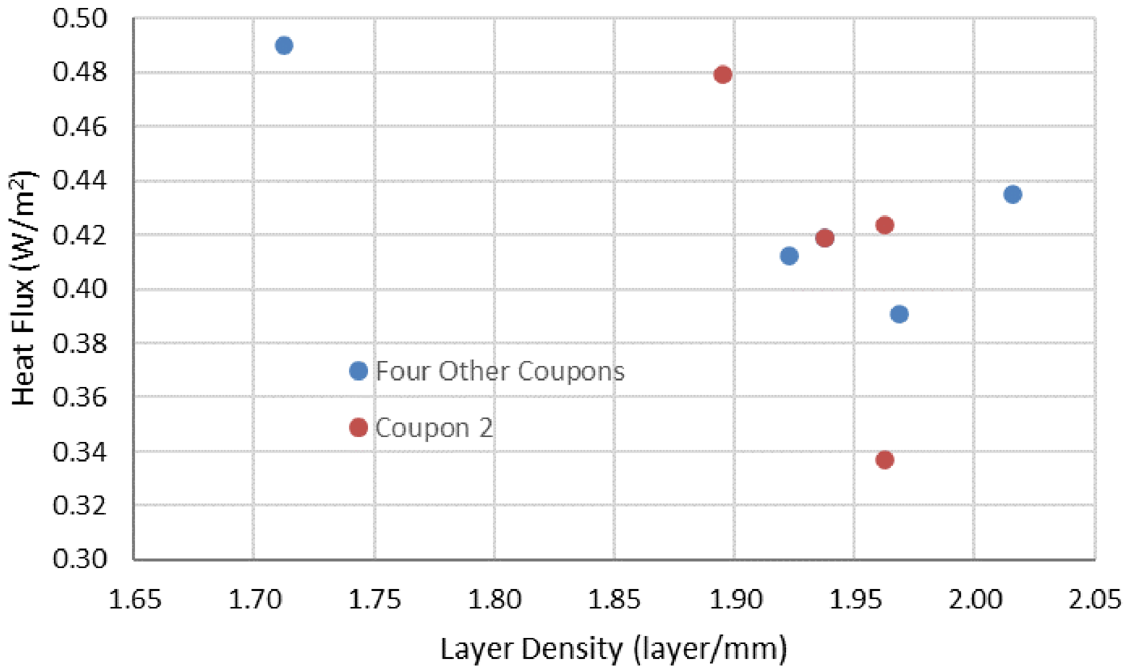
Yetispace Coupon 293 K Test Data

- No discernable trends with layer density
- 10 different coupons
  - Built in two different sets of 5 blankets
  - All materials from the same lots
- Nominally 11 reflective layers
- Less repeatable than NASA coupons
  - Repeatability driven by layer count.



NASA coupon 100 K Test Results

- Again, no heat flux trends with layer density
- Significantly lower repeatability:
  - Multiple different installers
  - Less experience with installers



Repeatability Results

Test Series	Mean, W	Min, W	Max, W	St. Dev, W	Range, W	Uncertainty
20 K to 300 K, All Five	1.15	1.08	1.27	0.066	0.19	+/-8.4%
20 K to 300 K, Coupon 3	1.06	0.98	1.15	0.061	0.17	+/-8.0%
77K to 293K, First Five	2.40	2.05	2.80	0.27	0.75	+/- 15.6%
77 K to 293 K, Second Five	2.93	2.22	3.36	0.42	1.14	+/- 19.5%
77 K to 293 K, All ten	2.66	2.05	3.36	0.44	1.31	+/- 24.6%
20 K to 115 K, All Five	0.35	0.31	0.40	0.028	0.083	+/- 12.0%
20 K to 115 K, Coupon 2	0.33	0.27	0.39	0.041	0.115	+/- 17.2%

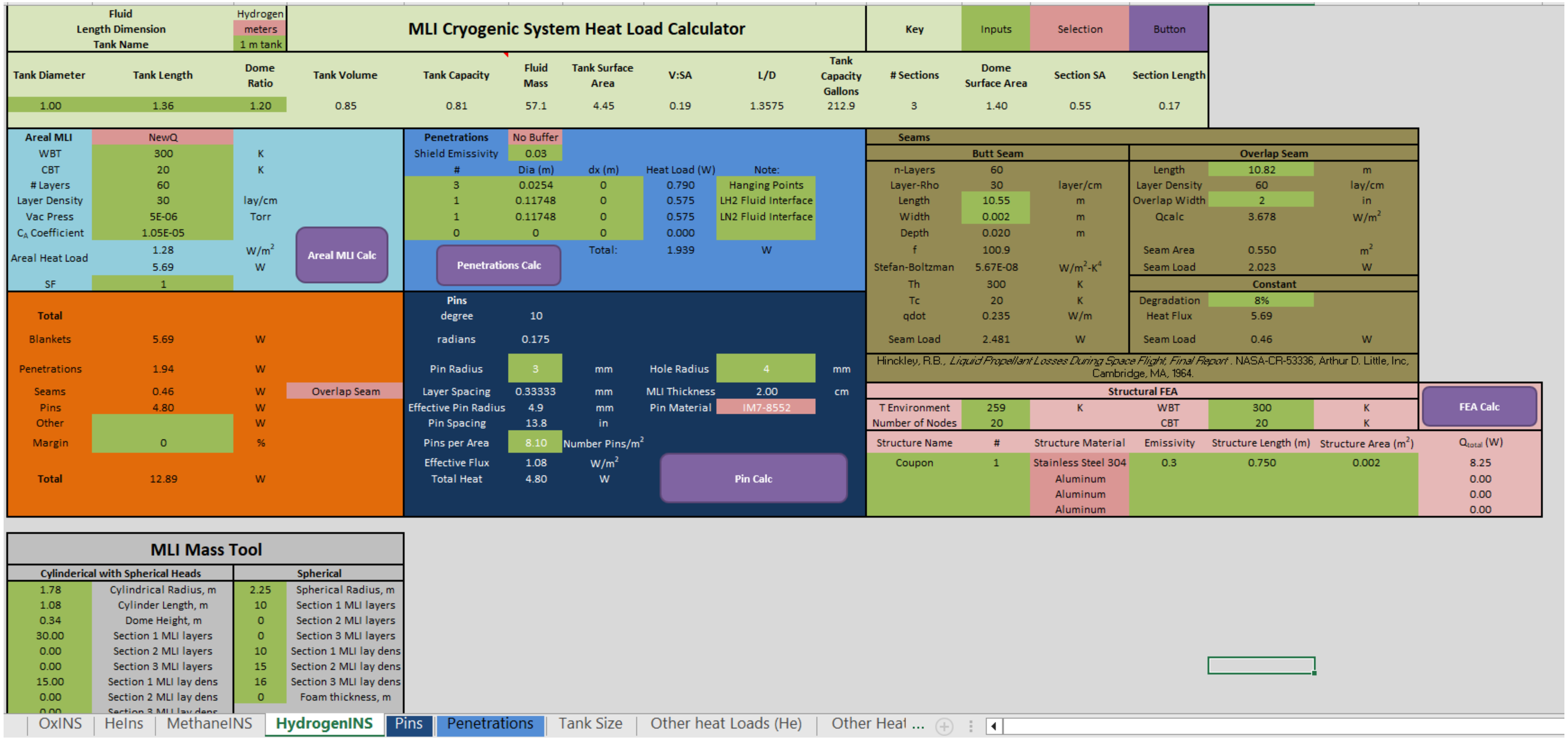
Evaluated per ASTM E-2586, Standard Practice for Calculating and Using Basic Statistics, 2014

Repeatability Significance

Test Series	Mean Standard Error, W	Mean SE as Percent of Mean	Calculated St. Dev, W	St. Dev Standard Error, W	St. Dev Calc – Meas, W	St. Error Greater?
20 K to 300 K, All Five	0.017	1.2%	0.083	0.023	0.017	YES
20 K to 300 K, Coupon 3	0.015	1.1%	0.074	0.021	0.013	YES
77K to 293K, First Five	0.064	2.7%	0.322	0.092	0.053	YES
77 K to 293 K, Second Five	0.098	3.3%	0.490	0.143	0.071	YES
77 K to 293 K, All ten	0.044	1.6%	0.426	0.102	-0.015	YES
20 K to 115 K, All Five	5.6×10^{-3}	1.6%	0.036	0.0095	0.0077	YES
20 K to 115 K, Coupon 2	8.2×10^{-3}	2.5%	0.056	0.016	0.015	YES

Evaluated per ASTM E-2586, Standard Practice for Calculating and Using Basic Statistics, 2014

MLI Cryogenic System Heat Load Calculator for Trad Cryo MLI



Fluid	Hydrogen
Length Dimension	meters
Tank Name	1 m tank

MLI Cryogenic System Heat Load Calculator

Key	Inputs	Selection	Button

Tank Diameter	Tank Length	Dome Ratio	Tank Volume	Tank Capacity	Fluid Mass	Tank Surface Area	V:SA	L/D	Tank Capacity Gallons	# Sections	Dome Surface Area	Section SA	Section Length
1.00	1.36	1.20	0.85	0.81	57.1	4.45	0.19	1.3575	212.9	3	1.40	0.55	0.17

Areal MLI	NewQ	
WBT	300	K
CBT	20	K
# Layers	60	
Layer Density	30	lay/cm
Vac Press	5E-06	Torr
C_A Coefficient	1.05E-05	
Areal Heat Load	1.28	W/m^2
	5.69	W
SF	1	

Areal MLI Calc

Penetrations	No Buffer			
Shield Emissivity	0.03			
#	Dia (m)	dx (m)	Heat Load (W)	Note:
3	0.0254	0	0.790	Hanging Points
1	0.11748	0	0.575	LH2 Fluid Interface
1	0.11748	0	0.575	LN2 Fluid Interface
0	0	0	0.000	
		Total:	1.939	W

Penetrations Calc

Seams					
Butt Seam			**Overlap Seam**		
n-Layers	60		Length	10.82	m
Layer-Rho	30	layer/cm	Layer Density	60	lay/cm
Length	10.55	m	Overlap Width	2	in
Width	0.002	m	Qcalc	3.678	W/m^2
Depth	0.020	m			
f	100.9		Seam Area	0.550	m^2
Stefan-Boltzman	5.67E-08	W/m^2-K^4	Seam Load	2.023	W
Th	300	K	**Constant**		
Tc	20	K	Degradation	8%	
qdot	0.235	W/m	Heat Flux	5.69	
Seam Load	2.481	W	Seam Load	0.46	W

Hinckley, R.B., *Liquid Propellant Losses During Space Flight, Final Report*. NASA-CR-53336, Arthur D. Little, Inc, Cambridge, MA, 1964.

Total			
Blankets	5.69	W	
Penetrations	1.94	W	
Seams	0.46	W	Overlap Seam
Pins	4.80	W	
Other		W	
Margin	0	%	
Total	12.89	W	

Pins					
degree	10				
radians	0.175				
Pin Radius	3	mm	Hole Radius	4	mm
Layer Spacing	0.33333	mm	MLI Thickness	2.00	cm
Effective Pin Radius	4.9	mm	Pin Material	IM7-8552	
Pin Spacing	13.8	in			
Pins per Area	8.10	Number Pins/m^2			
Effective Flux	1.08	W/m^2			
Total Heat	4.80	W			

Pin Calc

Structural FEA						
T Environment	259	K	WBT	300	K	
Number of Nodes	20		CBT	20	K	
Structure Name	#	Structure Material	Emissivity	Structure Length (m)	Structure Area (m^2)	Q_{total} (W)
Coupon	1	Stainless Steel 304	0.3	0.750	0.002	8.25
		Aluminum				0.00
		Aluminum				0.00
		Aluminum				0.00

FEA Calc

MLI Mass Tool

Cylinderical with Spherical Heads		Spherical	
1.78	Cylindrical Radius, m	2.25	Spherical Radius, m
1.08	Cylinder Length, m	10	Section 1 MLI layers
0.34	Dome Height, m	0	Section 2 MLI layers
30.00	Section 1 MLI layers	0	Section 3 MLI layers
0.00	Section 2 MLI layers	10	Section 1 MLI lay dens
0.00	Section 3 MLI layers	15	Section 2 MLI lay dens
15.00	Section 1 MLI lay dens	16	Section 3 MLI lay dens
0.00	Section 2 MLI lay dens	0	Foam thickness, m
0.00	Section 3 MLI lay dens		

National Aeronautics and Space Administration

Quest xMLI Products

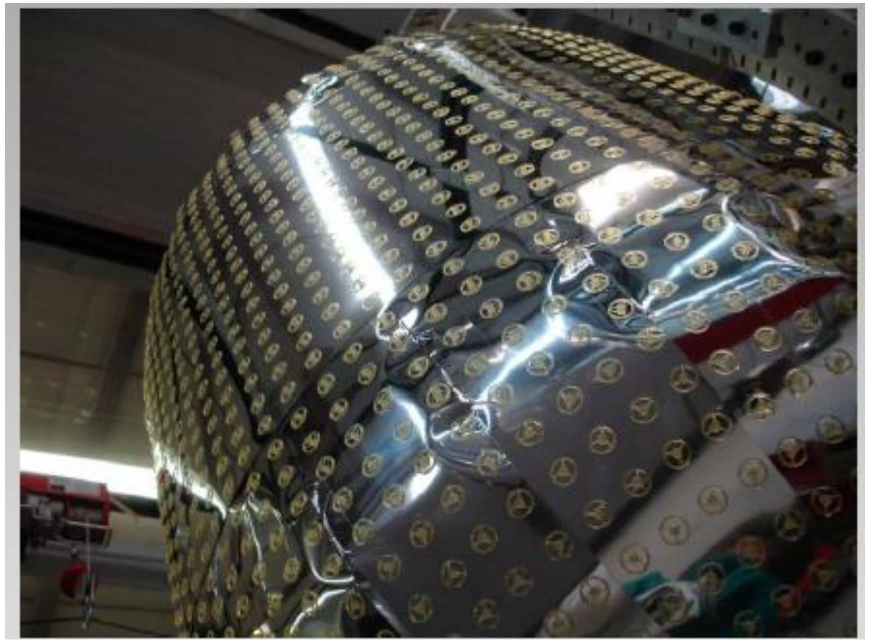
Evolvable Cryogenics (eCryo)
GRC MSFC
DVAT ◆ IFUSI ◆ SHIIVER ◆ RFMG ◆ IVF

A summary of the History of the xMLI family

- **Integrated MLI was the first of the xMLI family developed**
  - Funded through an SBIR contract in 2006
  - Joint effort between Quest Product Development (spun off Quest Thermal Group) and Ball Aerospace
  - Phase 2 awarded in 2006, multiple Phase 3 awards since
- **Load Responsive MLI (LR-MLI) was funded as a Phase 1 SBIR in 2008**
  - Developed to allow insulations to structurally carry vacuum jackets for science dewars.
  - Phase 2 subsequently awarded with multiple Phase 3 awards
- **Wrapped MLI was funded as a Phase 1 SBIR in 2009**
  - Insulate vacuum jacketed lines
  - Phase 2 was awarded – no NASA work past this contract
- **Multiple other Phase 1 and 2 SBIRs were awarded to Quest between 2010 and the present**
  - Complex shapes
  - MMOD-IMLI
  - Launch Vehicle IMLI
  - Vapor Cooled Shield -MLI
  - Advanced Cooled Shield – IMLI
  - Vapor Cooled Structure MLI
  - Multi-Environment MLI
  - Variable Conductance Radiators
  - Etc
- **Load Bearing MLI developed in response to the Self-Supporting MLI solicitation that lead to the 2nd round of Reduced Boil-off Testing as a part of CPST in 2012.**

IMLI Physical Implementation

- **For IMLI, the tripod spacers are on an approximately 2-inch square grid**
- **For LR-MLI, the dual-tripod spacers are on an approximately 1-inch square grid (holds 15 psid)**
- **For LB-MLI/SS-MLI, the dual-tripod spacers are on an approximately 2-inch square grid**
  - Holds much less than 15 psid



IMLI / LB-MLI Testing – Bulk Blankets

- **There are on the order of 30 test data points on bulk blankets that have been published outside of Quest in-house testing.**
- **Most of these have been done by NASA either at KSC on Cryostat-100 or GRC during either the Reduced Boil-off 2 testing or on the CoMPACT calorimeter.**
  - MSFC VATA-2 testing was also conducted in parallel to the RBO-2 testing, but the data was not cleaned up or evaluated. If done so, this could provide interesting data points in the mid warm boundary temperature range.
- **Tank testing has been done on RBO-2 and VATA-2**
- **The presenter has been a part of all of these tests.**

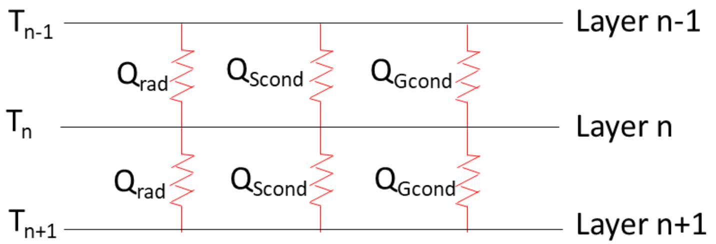
Non-Quest Testing

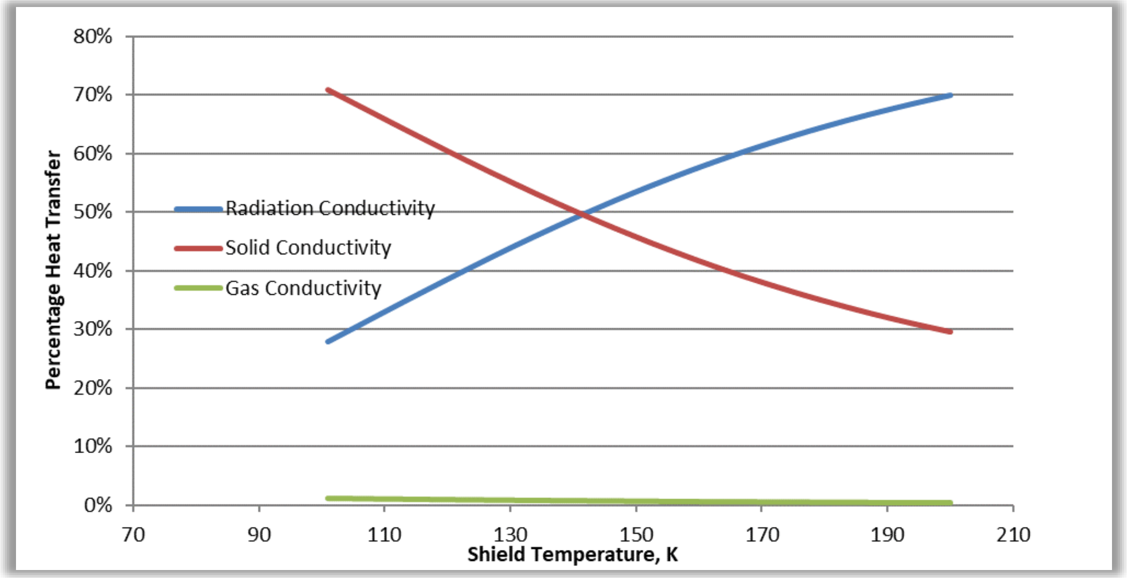
Test Site	layers	Tc, K	Th, K	Measured Q, W/m^2
Ball	10	76	296	0.95
KSC	20	77	292	0.41
KSC	20	77	305	0.567
Ball	3	76	296	3.62
KSC	9	78	293	0.924
	9	78	325	1.358
	9	78	316	1.232
KSC	5	78	293	1.772
	5	78	305	1.989
	5	78	325	2.609
KSC	19	78	293	0.545
	19	78	305	0.768
	19	78	327.8	0.849
FSU	4	20	85	0.18
	9	20	85	0.13
KSC	10	77	181	0.41
	10	77	178	0.395
	10	77	190	0.376
	10	77	194	0.552
	12	77	219	0.542
	16	77	261	0.868
	16	77	268	0.868
	20	77	265	0.828
	14	77	254	0.814
GRC RBO	19	25	80	0.085
	19	29.1	80	0.0788
	19	32	182	0.219
	19	25	87	0.097
	19	23	253	0.453
GRC	10	20	74	0.186
Calorimeter	10	20	90.7	0.206
	10	20	72.3	0.168
	10	20	90.6	0.185
	20	20	75.5	0.158
	20	20	90.6	0.169
	20	20	90.6	0.158
	20	20	75.4	0.146

LB-MLI in green

IMLI / LB-MLI / LR-MLI Analysis

- **NASA and Quest have independently developed similar analysis approaches**
- **Both employ a "layer by layer" model approach where conduction, radiation, and convection are accounted for between each layer.**
  - The temperature of each layer is iterated upon until uniform heat flux achieved through each layer.
  - Conductors modeled as an A/L and number of spacers per square meter.
- **Results are generally good for IMLI**
- **LB-MLI / LR-MLI harder due to trying to model if any contact is made between center tripod and previous layer (much higher A/L).**
  - If no contact, IMLI model works for these too

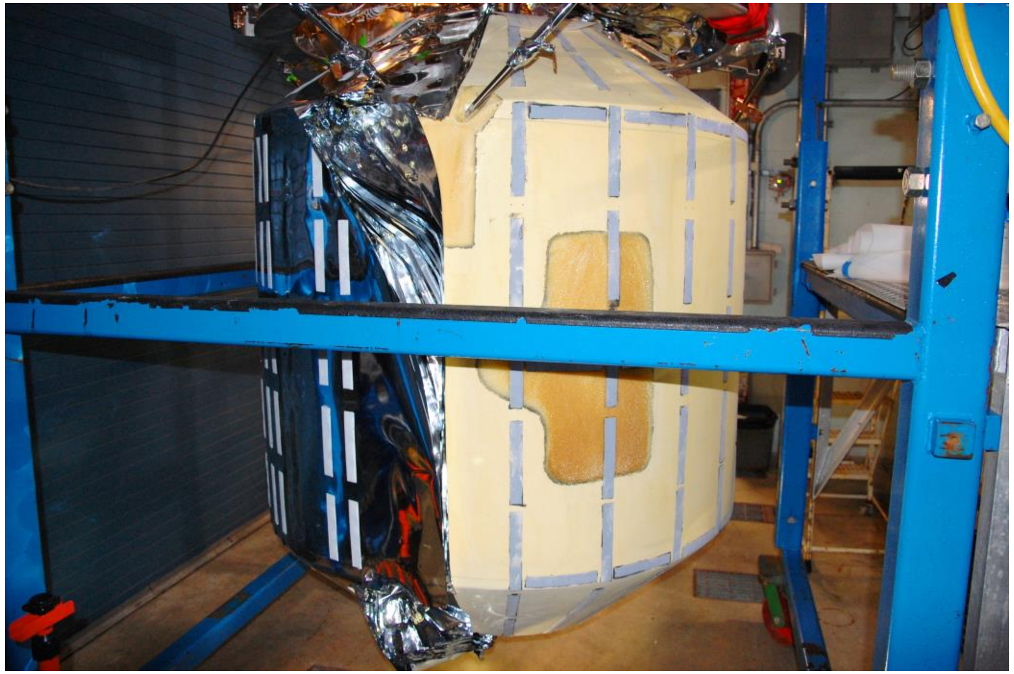




IMLI / LB-MLI / LR-MLI flights

- **IMLI has flown or is getting ready to fly on multiple missions:**
  - Green Propellant Infusion Mission (Ball Aerospace prime) as a secondary mission demonstration
  - Robotic Refueling Mission 3 on the receiver dewar
    - Note that no methane transfer occurred on this mission, though ground test data indicated the IMLI functioned as planned.
  - Lucy (Jupiter Trojan Asteroids)
    - On L'Ralph Instrument Package

- **Planned for several other missions:**
  - Near Earth Object Surveyor (2027)
  - The Lunar Environment Monitoring Station (LEMS)
  - Roman Space Telescope (mid-2020s)



IMLI /LB-MLI Other Test Data

Test data has been gathered on:

- Seaming technic: result showed no change between 1 and 2 seams
- Perforations: For RBO-2/VATA-2, Quest perforated their blanket at less than 0.01% open area
  - 0.25-inch diameter holes on 24 inch spacing
  - < 5% change in performance degradation during calorimeter testing, within the uncertainty of the test hardware.
  - Successfully survived all testing, even with SOFI outgassing
- Penetrations:
  - Small penetrations – wires, etc. characterized similar to traditional cryogenic MLI
  - Medium penetrations tested on 0.25”, 0.5” diameter penetrations
    - Vacuum gaps and cryolite filler
    - 6 tests, data analysis partially performed but never published
    - Was not modeled like traditional MLI was
- Vibration survivability
  - Qualification testing for GPIM
  - As a part of RBO-2/VATA-2
- Acoustic survivability
  - As a part of RBO-2/VATA-2
- Performance as a function of pressure
- Rapid depressurization (see RBO-2)

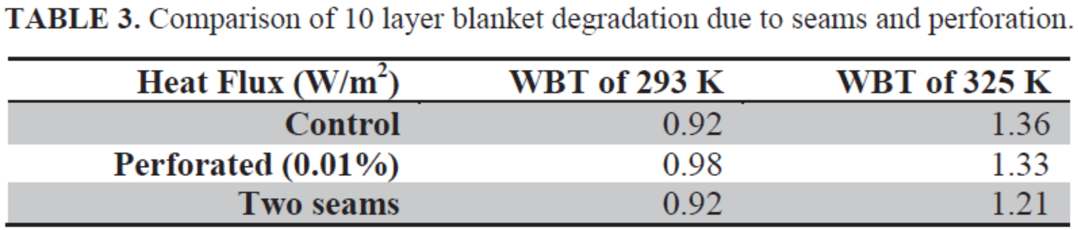


TABLE 3. Comparison of 10 layer blanket degradation due to seams and perforation.

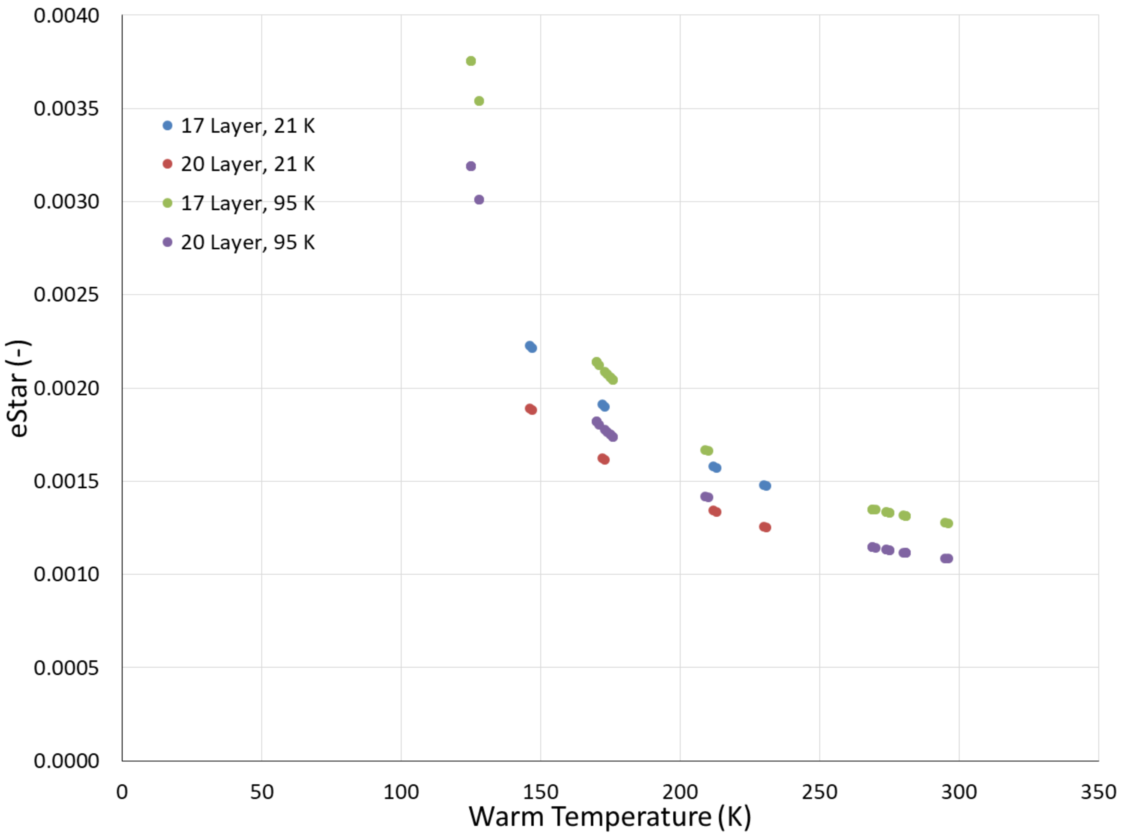
Heat Flux (W/m^2)	WBT of 293 K	WBT of 325 K
Control	0.92	1.36
Perforated (0.01%)	0.98	1.33
Two seams	0.92	1.21

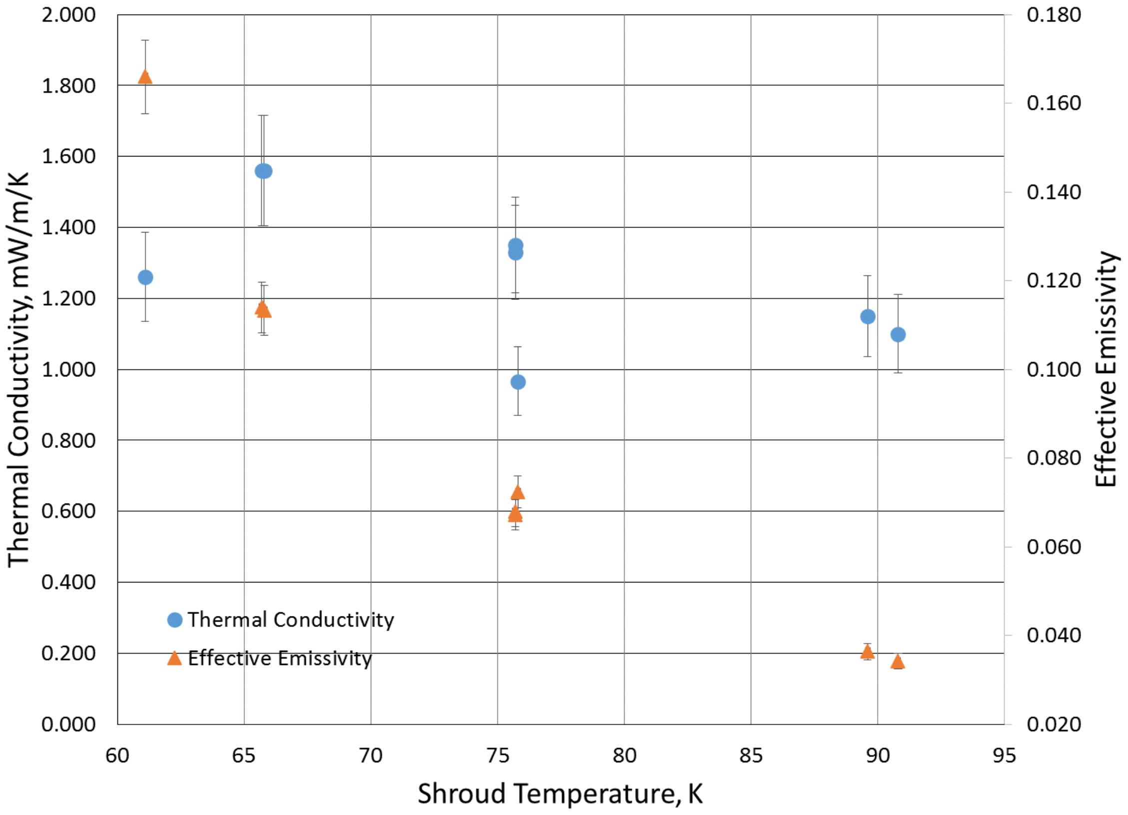
Conclusions

Other Somewhat Related Lessons Learned

- **How do you specify MLI**
  - Layer count?
  - Performance (effective emissivity, heat flux, etc.)?
  - How do you verify the specification
- **How do you normalize MLI performance? Why?**
- **If you use data – does that data describe how it was tested?**
  - How do you test MLI?
- **Read NASA TP- 20205008233, Appendix J for thorough discussion of lessons learned from SHIIVER (how to apply high performance MLI to a large tank)**

Estar with Temp





Summary

- **MLI performance is driven by many variables, all of which must be controlled in some manner.**
- **The expected performance of a blanket must be anchored in some manner to an analytical justification:**
  - How is the system being installed?
  - How is the system being fabricated?
  - What are the driving requirements and environments to consider?
- **The aerospace industry has a long history behind current MLI development that is often not well remembered.**
- **Much of the data that has been generated more recently is considered company proprietary data.**

National Aeronautics and Space Administration

Questions?

LIQUID OXYGEN ZERO BOIL-OFF TEST MLI PERFORMANCE

MLI Heat Load

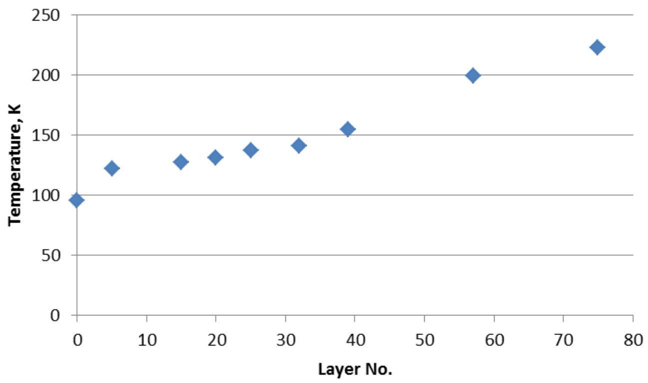
- **Tank Surface area: 6.18 m^2**
- **MLI inner SA: 6.23 m^2**
- **MLI thickness: 1.25 inch**
- **MLI outer SA: 6.87 m^2**
- **Mean Insulation SA: 6.57 m^2**
- **MLI temperature gradient essentially constant through all tests at 220 K– indicates nearly identical heat load**

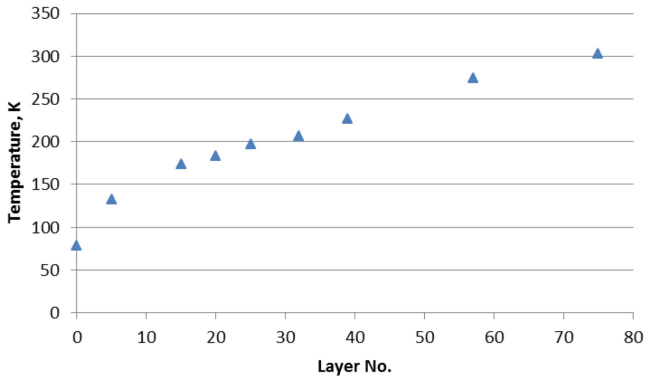
Warm Boundary Temperature (K)	220	300
Cold Boundary Temperature (K)	95.4	78.6
MLI/remainder Heat Load (W)	2.6	4.8
Heat Flux (W/m^2)	0.38	0.74
Effective emissivity, ε*	0.0029	0.0016

MLI Blankets

		Temperatures	
Sensor	Layer (from bottom	220 K WBT	300 K WBT
Shroud		218.8	298.4
TC-51	75	222.8	302.8
TC-52	57	199.1	274.0
TC-53	39	154.2	226.9
TC-59	32	140.8	206.3
TC-58	25	137.3	197.6
TC-57	20	131.1	183.0
TC-56	15	127.4	174.0
TC-55	10	Off Scale High	
TC-54	5	121.6	132.8
CBT	0	95.4	78.6

- **MLI was split into 2 blankets**
- **38 layers in each blanket**
  - TC-53 in between two blankets
  - Gives boundary temperature
- **Intermediate Temperature:**
  - 154 K @ 220 K WBT
  - 227 K @ 300 K WBT
- **Effective emissivities (ε*):**
  - Outer blanket:
    - 0.0037 @ 220 K WBT
    - 0.0023 @ 300 K WBT
  - Inner blanket:
    - 0.014 @ 220 K WBT
    - 0.0050 @ 300 K WBT
  - Bunching of the inner blanket may have caused issue
  - Appears to be a temperature/emissivity issues
    - Data later shows that this may be captured in existing models





Conventional MLI Heat Leak Calculations

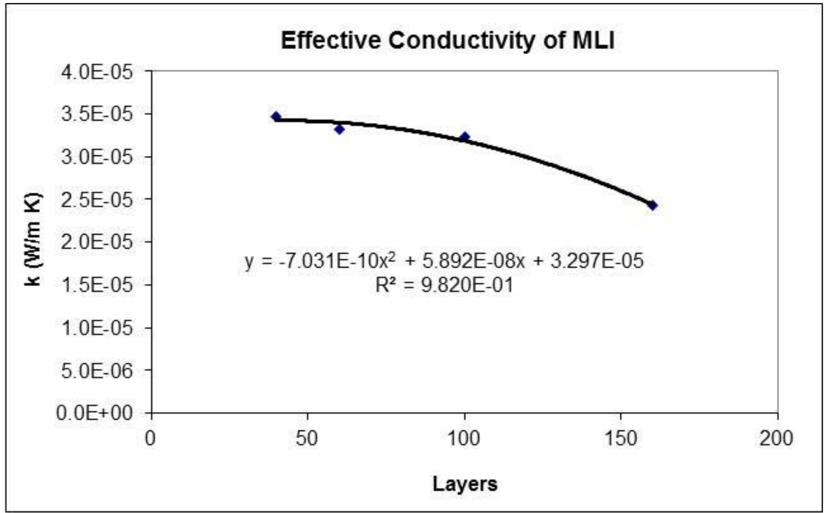
- Number of Layers: 75
- Blanket Thickness: 3.8 cm (1.5 inches)
- Layer Density: 20 lay/cm
- Perforations: Only in outer/inner layer of sub-blankets
- Used four different methods to calculate acreage heat loads:
  - Thermal conductivity from Stochl[1]
    Note: The effective conductivity model is intended to use for calculation heat leak through MLI blanket (not temperature profile)
  - NewQ Equation[2]
  - Lockheed Equation[3]
  - Modified Lockheed Equation[4]

[1] Stochl, NASA TN-D-7659

[2] Johnson, W.L. ***Thermal Performance of Cryogenic Multilayer Insulation at Various Layer Spacings***, Master's Thesis, University of Central Florida, Dec. 2010.

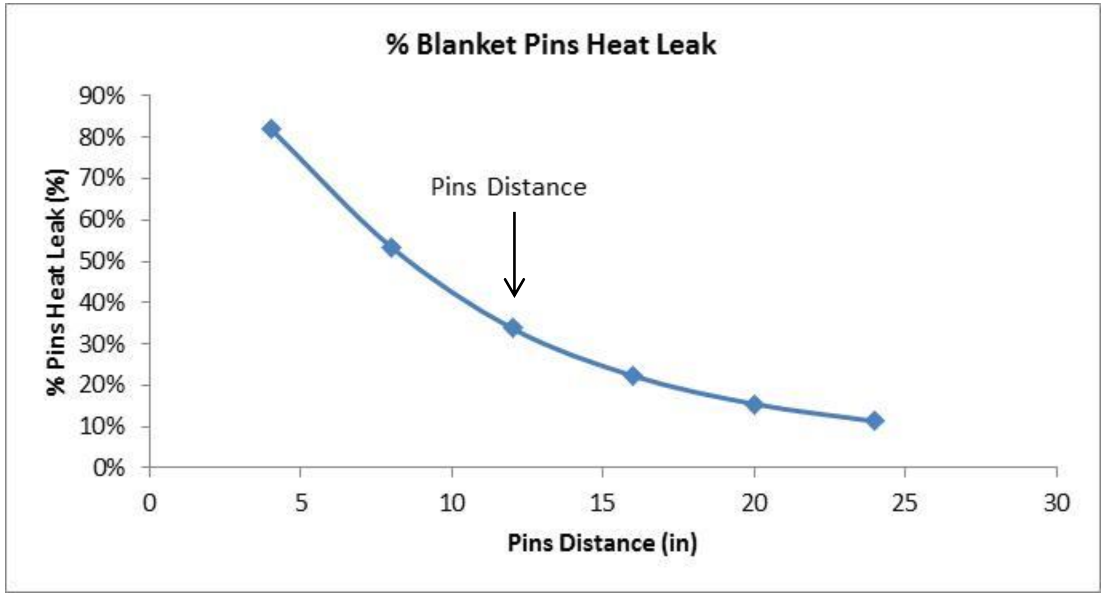
[3] Eq 4-56 from NASA CR-134477

[4] Eq 13 from NASA TM-2004-213175



Thickness (cm)	Layers	Effective k (W/m-K)
1.95	40	3.47E-05
2.93	60	3.31E-05
4.88	100	3.23E-05
7.82	160	2.43E-05

LZBO Tank MLI Heat Leak



- LZBO tank MLI is reinforced using 0.080” nylon blanket pins for ***structure support***
- Pin spacing a trade between structural integrity and thermal performance.
- Design distance between pins is 12” which results 33.7% additional heat leak compared to conventional MLI or 10% overall additional heat leak into the tank

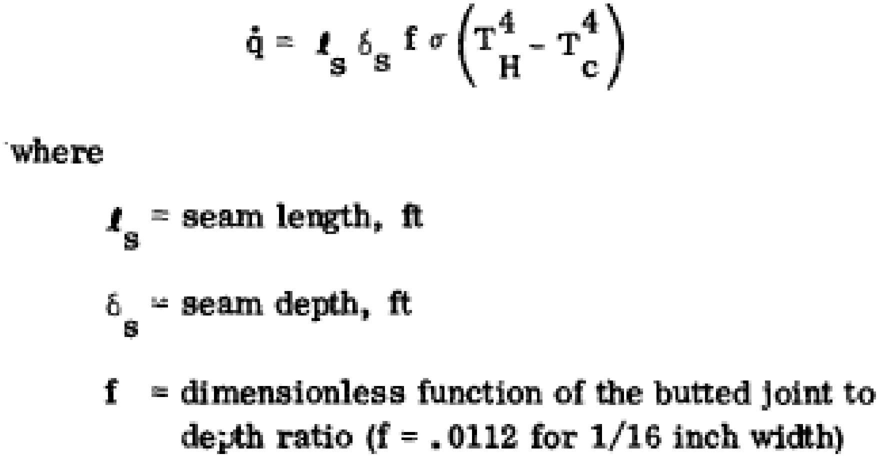
LZBO Tank Conventional Blanket Heat Leak Break-up

Th = 250 K, Tc = 90 K, 75 layers, 0.080" diam, Nylon Pin, 1.1" length

Pin Distance (in)	Blanket (W/m^2)	Pins/m^2 (#/m^2)	Pins (W/m^2)	Total (W/m^2)	% Pins Heat Leak (%)
4	0.146	97	0.668	0.814	82.1%
8	0.146	24	0.167	0.313	53.4%
12	0.146	11	0.074	0.220	33.7%
16	0.146	6	0.042	0.188	22.2%
20	0.146	4	0.027	0.173	15.5%
24	0.146	3	0.019	0.165	11.3%

MLI seams

- **Design (scaled from Sumner, TN D-8229)**
  - Butt joint
  - 3.2 mm gap
  - Offset with each blanket
  - 0.06 W/m
- **Check with Hinkley (CR-53336, pg II-29)**
  - 0.13 W/m for upper blanket
  - 0.03 W/m for lower blanket
  - 0.11 W/m for full blanket (if seams aligned)
- **3.5 m seam length**
- **0.39 W @ 220 K WBT**



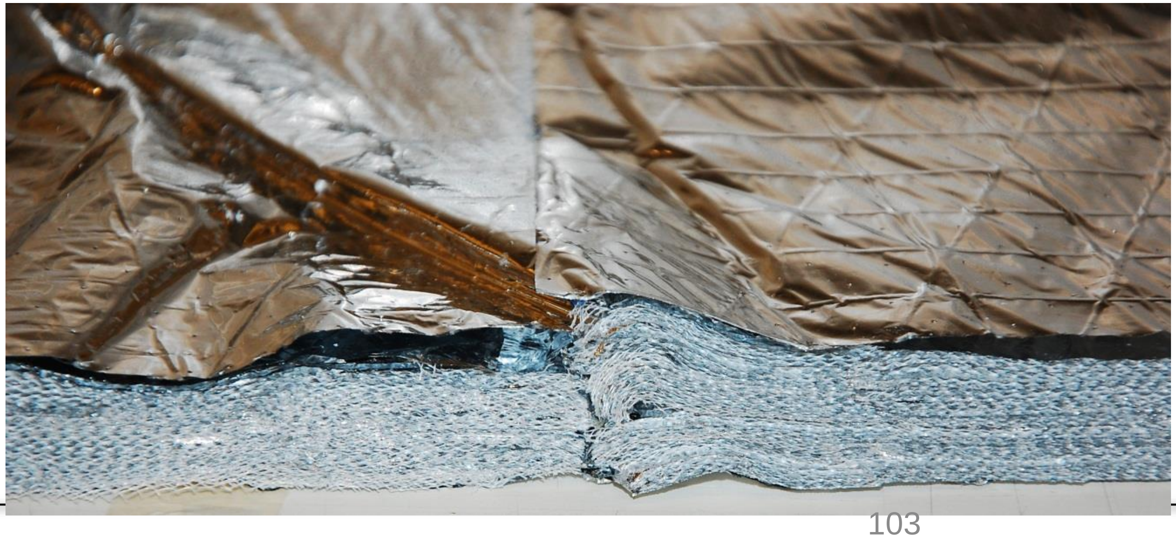
$$\dot{q} = \ell_s \delta_s f \sigma \left(T_H^4 - T_c^4\right)$$

where

ℓ_s = seam length, ft

δ_s = seam depth, ft

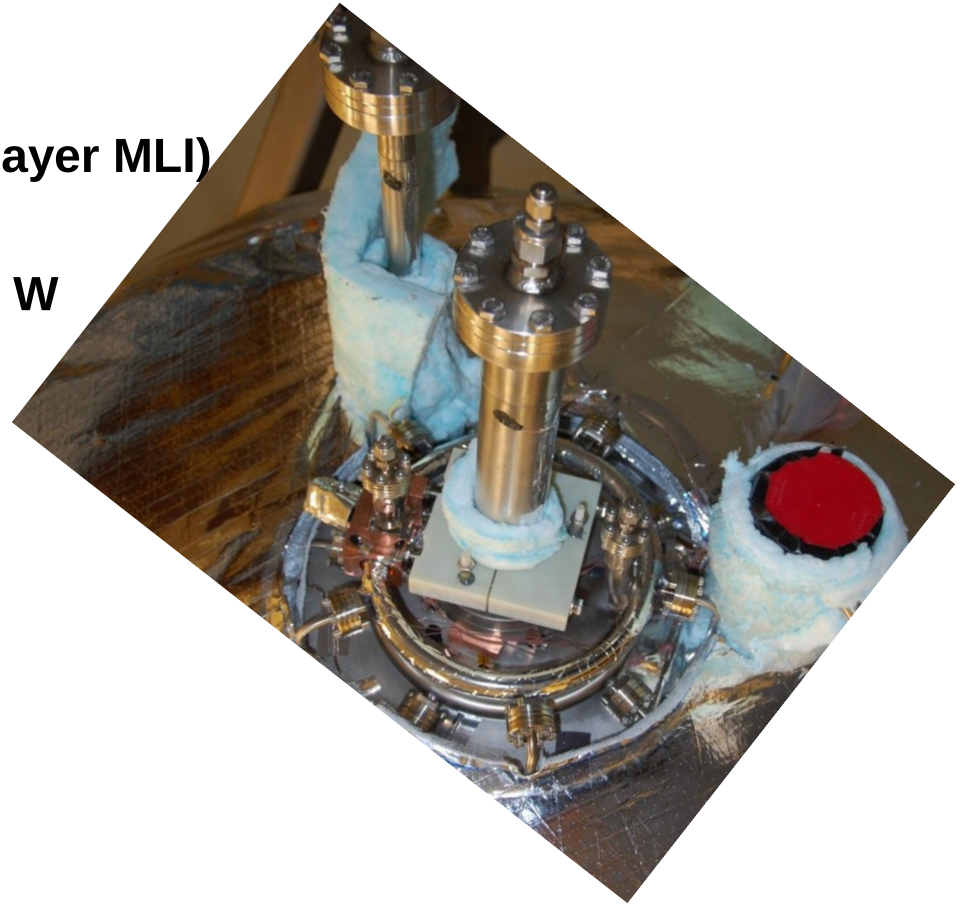
f = dimensionless function of the butted joint to depth ratio (f = .0112 for 1/16 inch width)



MLI Penetrations

- **Fluid/electrical penetrations isolated from MLI**
  - 0.5” (12.5 mm) thick Cryolite
  - 75 layers of MLI
- **2 inch OD vent line: 0.10 W (only 35 layer MLI)**
- **1 inch OD fill line: 0.02 W**
- **~3 inch OD instrumentation leg: 0.04 W**
- **1 inch OD struts (6): 0.09 W**
- **Total 0.25 W @ 220 K WBT**

- **NASA TP-2012-216315**



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

Compiled MLI Heat Loads at 220K WBT

Heat Load Method	Heat Load (W)	Total System Heat Load (W)	Ins. System Scale Factor	Blanket Scale Factor
NASA TN-D-7659 1	0.861	1.80	1.5	3.0
Lockheed Equation[3]	0.657	1.59	1.7	4.0
New Q Equation[2]	1.60	2.53	1.0	1.6
Modified Lockheed[4]	1.58	2.51	1.0	1.7
Pin Heat Load*	0.298			
Seam Heat Load	0.39			
Penetrations Heat Load	0.25			
Actual Heat Load		2.6		

$$SF_{blanket} = \frac{Q_{actual}}{Q_{MLI}}$$

$$SF_{system} = \frac{Q_{actual}}{Q_{MLI} + Q_{pin} + Q_{seam} + Q_{pen}}$$

As engineering design of MLI blanket matures, accounting for components allows for more accurate MLI heat load calculation.

High layer density (20 lay/cm) caused conduction through Dacron netting to be increasingly important.

Compiled MLI Heat Loads at 300 K WBT

Heat Flux Method	Heat Load (W)	Total System Heat Load (W)	Ins. System Scale Factor	Blanket Scale Factor
NASA TN-D-7659 [1]	1.55	3.80	1.3	3.1
Lockheed Equation[3]	1.66	3.91	1.2	2.9
New Q Equation[2]	3.02	5.27	0.92	1.6
Modified Lockheed[4]	3.21	5.46	0.89	1.5
Pin Heat Load*	0.53			
Seam Heat Load	1.32			
Penetrations Heat Load	0.40			
Actual Heat Load		4.8		

$$SF_{blanket} = \frac{Q_{actual}}{Q_{MLI}}$$

$$SF_{system} = \frac{Q_{actual}}{Q_{MLI} + Q_{pin} + Q_{seam} + Q_{pen}}$$

As engineering design of MLI blanket matures, accounting for components allows for more accurate MLI heat load calculation.

High layer density (20 lay/cm) caused conduction through dacron netting to be increasingly important.