Testing Seam Concepts for Advanced Multilayer Insulation

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Introduction

- Loss of performance in multilayer insulation systems due to joints and seams in the insulation blankets:
  - Recognized as a concern since the introduction of multilayer insulation.
  - When insulating large tanks more seams are required as tank dimensions exceed the roll widths available
- Over the years mitigation techniques have been developed
  - These include overlapping every layer, or precision cutting to minimize the gap
  - However labor intensive and time consuming.
- Recently Fesmire and Johnson re-examined the seams issue with a liquid nitrogen test rig at KSC and confirmed many of the previous findings.
- This effort extends the seams work into liquid hydrogen temperatures and studies a broader range of proposed seam configurations.

Seams Theory

- Hinckley set of equations for the direct radiation through an open butt seam

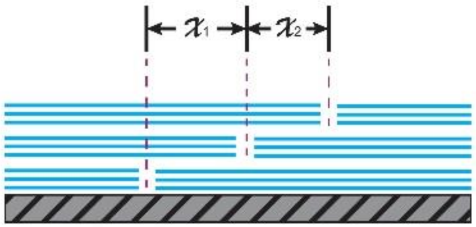
$$\frac{\dot{Q}_{seam}}{L_{seam}} = \frac{\delta_\varepsilon \sigma (T_H^4 - T_C^4)}{\left(\frac{2}{\varepsilon} - 1\right) n} \quad (1)$$

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

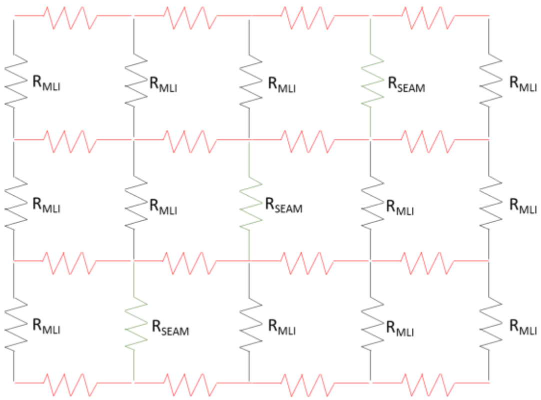
$$fn\left(\frac{\delta}{t}\right) = \sqrt{1+\varphi^2}\left(\frac{1}{3} - \frac{2\varphi^2}{3}\right) + \left(\frac{2\varphi^3}{3} - \frac{1}{3}\right) + \varphi^2 \ln\left(\frac{1+\sqrt{1+\varphi^2}}{\varphi}\right) \quad (3)$$

$$\varphi = \frac{\delta}{t} \quad (4)$$

Theory for a system with two staggers (m=2)



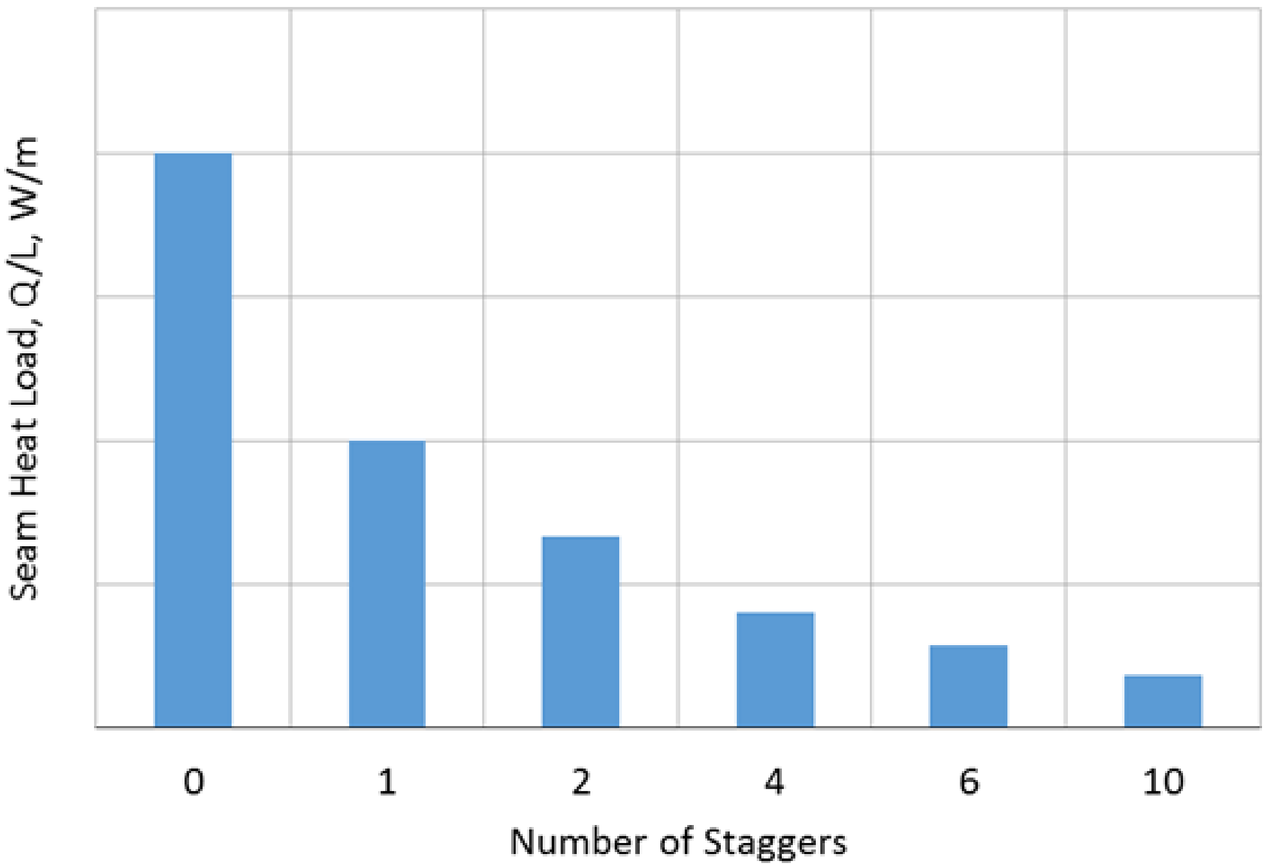
3 Blanket Staggered



$$\dot{q} \propto \frac{\epsilon\sigma\left(T_h^4 - T_c^4\right) + \dot{q}_{cond}}{n+1} \quad (5)$$

$$\frac{\dot{Q}}{L_{seam}} \propto \frac{\left(\dot{Q}/L_{seam}\right)_{m=0} + \dot{Q}_{cond}}{m+1} \quad (6)$$

Expected general performance of seam heat loads



Basic Design of Calorimeter

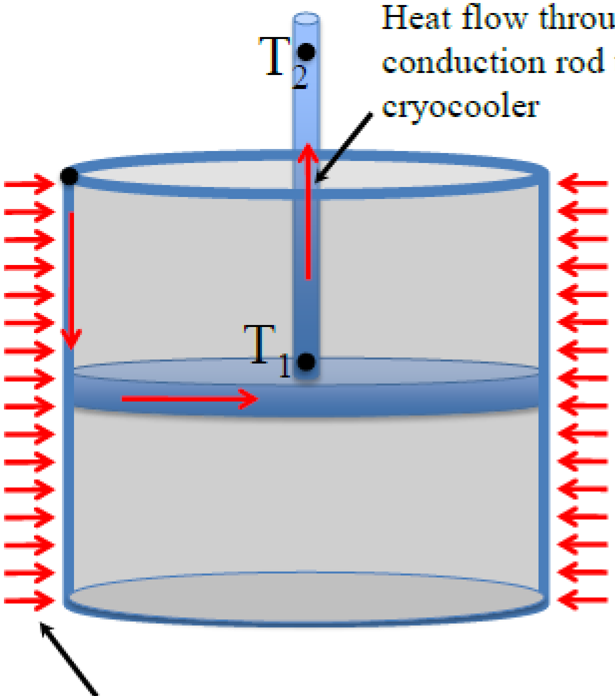
- Calorimeter was constructed to measure the performance of MLI using cryocoolers rather than cryogens.
- Key advantages include:
  - Not needing to use and top-off with cryogens,
  - Less safety restrictions on unattended operation and location of test rig since volatile cryogens are not present,
  - Wider range of boundary temperatures.
- Designed for boundary temperatures of 20K on the cold side and 90 K on the warm side
- Includes guards for top and bottom of measure cylinder
- Based on Conduction Rod system (explained on the next chart)

Calibrated Rod

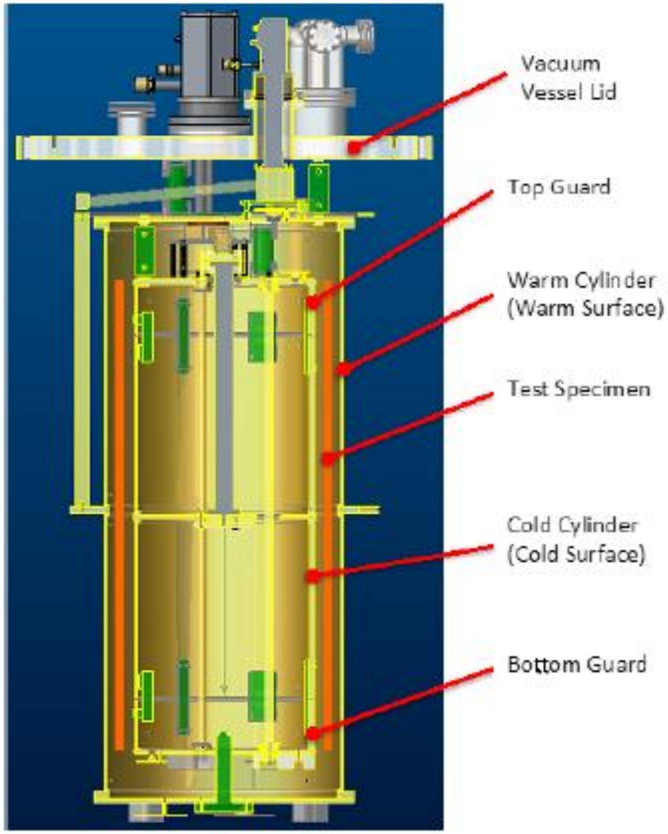
- Heart of the calorimeter –Measures heat flow through the measurement section (midsection of the cold cylinder)
- Heat flux through test specimen
- Heat flow through conduction rod to cryocooler
- Conduction rod has
  - hot end and cold end temperature sensors
  - known length between temperature sensors
  - known cross-sectional area
  - known material thermal conductivity
- Heat transfer rate calculated from Fourier conduction law

$$\dot{Q} = \frac{kA}{L}\Delta T = \theta \Delta T$$

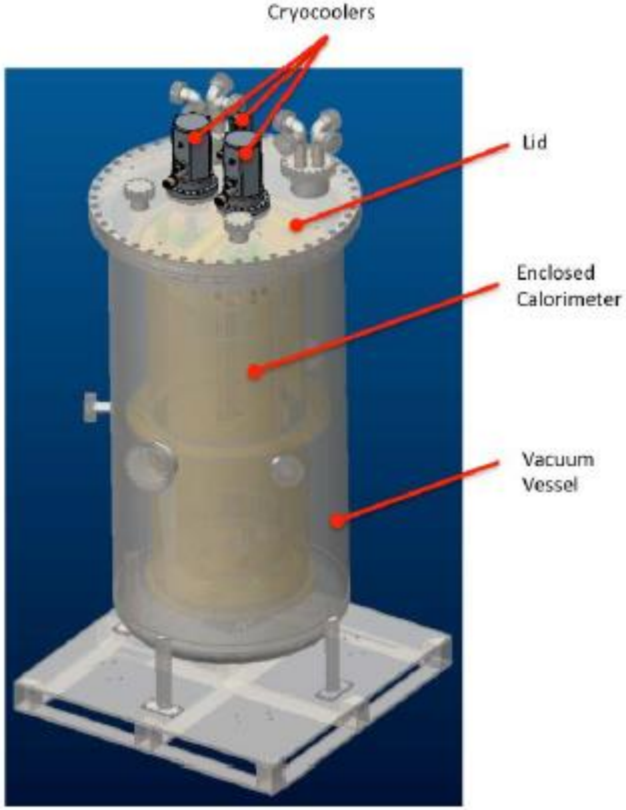
- Rod can be calibrated; k, A and L all temperature dependent
- Heat flux through MLI is heat transfer rate through conduction rod divided by MLI surface area



Concept Drawings of Calorimeter

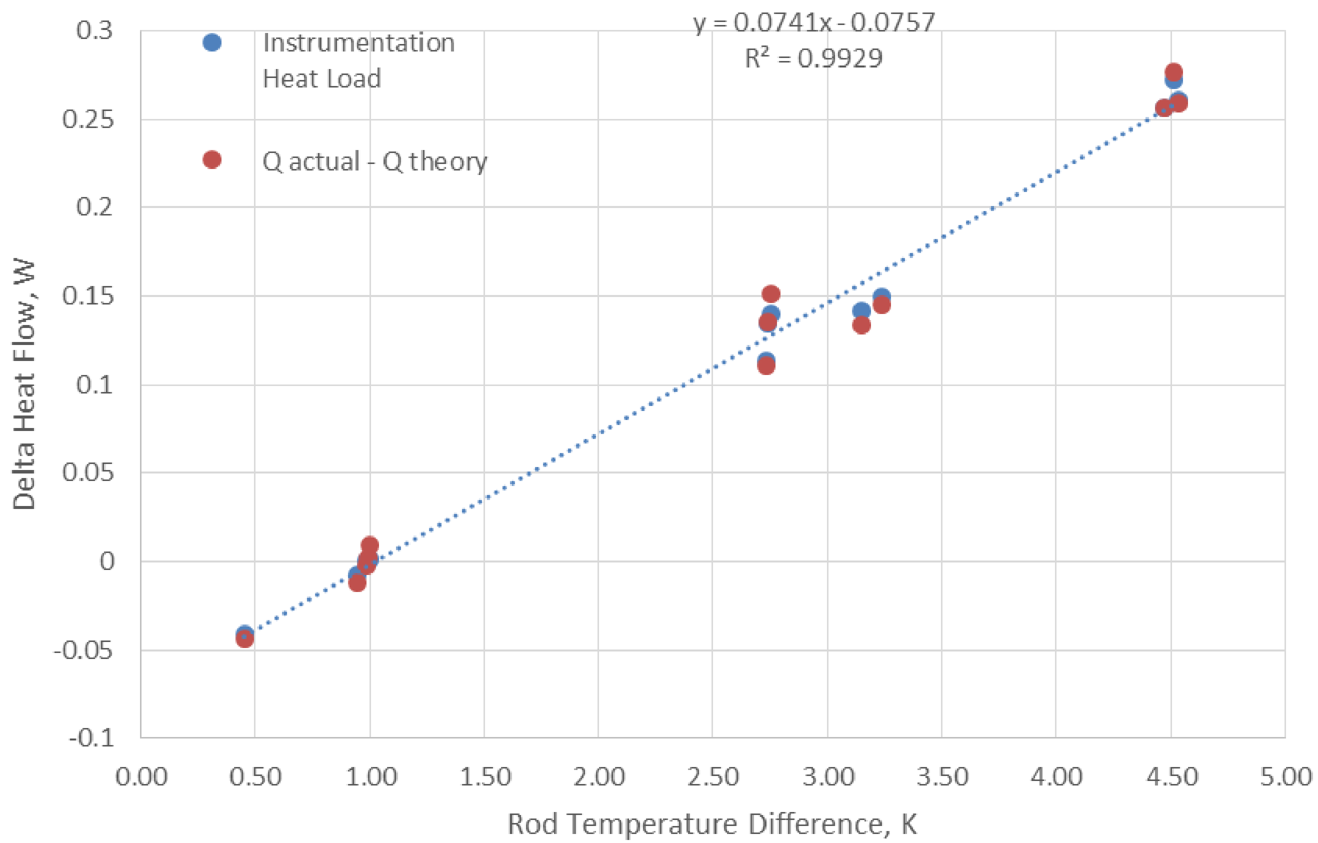


Cut through



Installation in Vacuum Vessel

Calibration with instrumentation heat loads adjusted

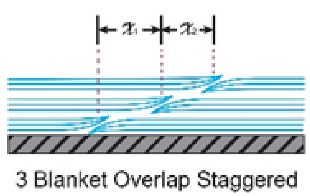


Test Data in red, calculated adjustments in blue.

Test Matrix as completed

Test Number	Description	MLI Layers	Seam Construction	Offset, x, (in)
1	Overlap seam	50	1 stagger (at layer 25)	2
2	Interleaved Seam	50	N/A	N/A
3	Butt seam	50	Single	0
4	Butt seam	50	1 stagger (at layer 25)	2
5	Butt seam	50	1 stagger (at layer 25)	4
6	Interleaved Seam	20	N/A	N/A
7	Overlap Seam	20	1 stagger (at layer 10)	2
8	Butt Seam	20	1 stagger (at layer 10)	2
9	Butt Seam	20	Single	0

(a)



(b)

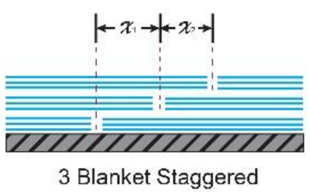


Figure 13: Diagram of overlapped seams (a) vs butt seams (b)

Cernox Sensors on both sub-blankets

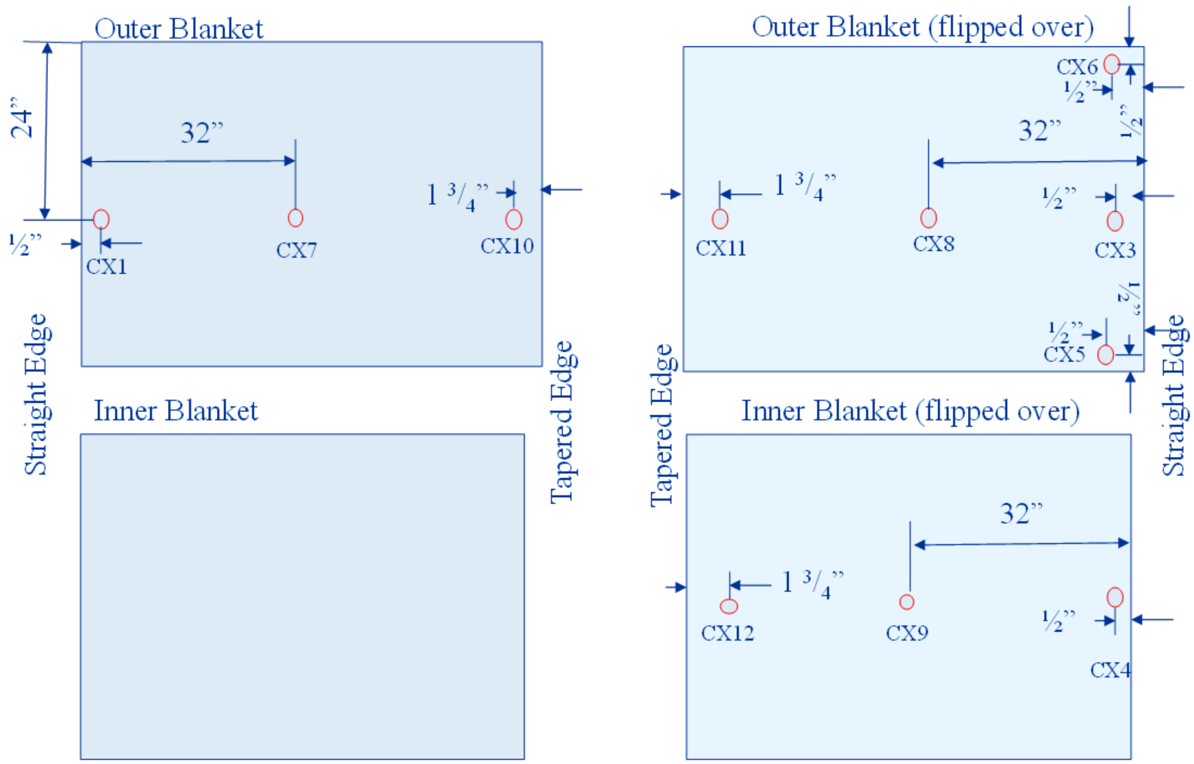


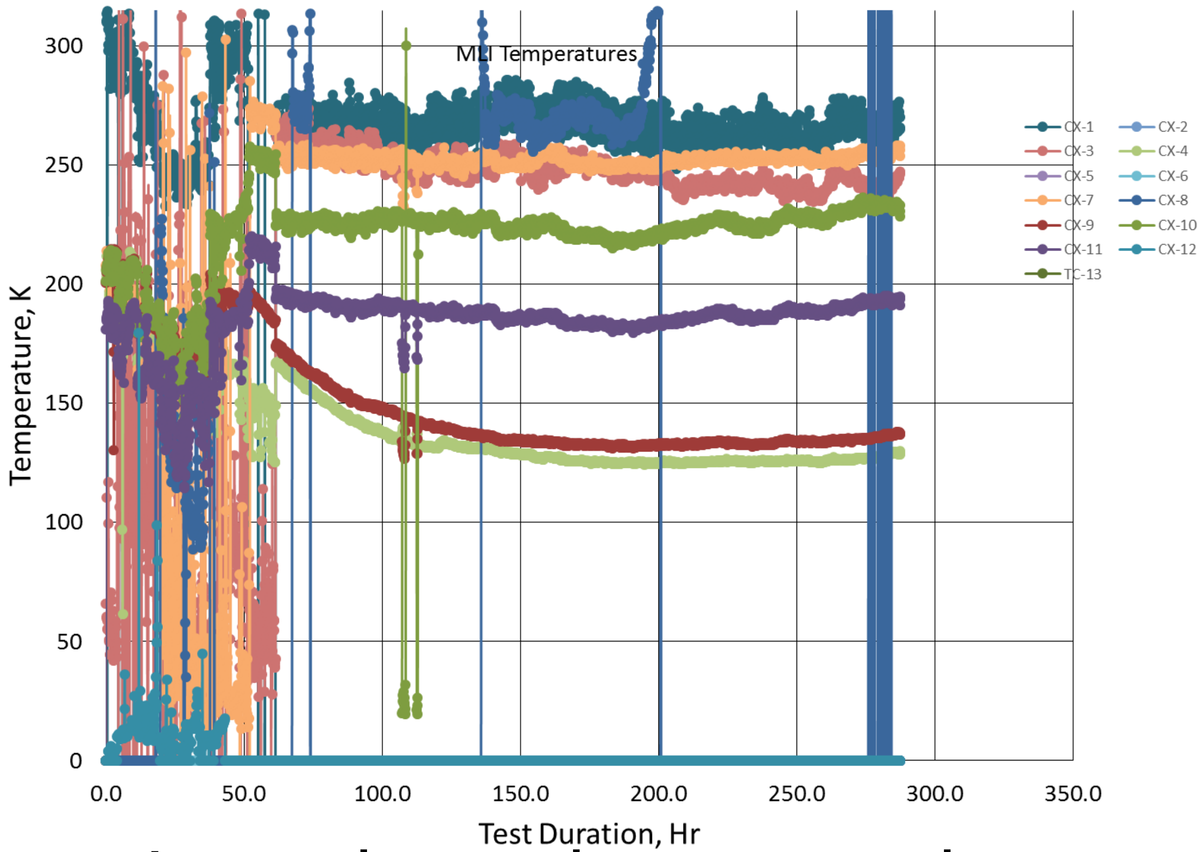
Figure 14:

Temperature data from testing

Position	Location:	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
CX-1	Outer Blanket	299.7	305.5	276.0	274.1	276.7	202.4	120.8		263.3
CX-7		263.8	300.2	230.0	215.3		120.4	255.1	257.4	250.3
CX-10		265.8	234.8	260.5	264.5	270.7	103.2	247.5	255.5	220.1
CX-4	Inner Blanket	91.3	205.2		208.6		81.0	87.3	103.1	125.1
CX-9		113.4	194.4		210.6	210.0		147.3	143.9	132.4
CX-12		101.6	170.4	181.8	219.1	210.0		148.9		
CX-11	Middle of Blanket	213.0	173.3	229.5	227.7	243.3	85.8	206.8	197.9	183.2
CX-8		209.9	208.2	230.0	215.3					
CX-3		221.3	201.9	213.4	219.4	224.6				245.6
CX-5	Top/Bottom	142.7	208.9	231.6	257.1	290.0				
CX-6		208.3		238.9	249.4	265.0				

Note– highlighted data indicates inner sensors actually in the middle.

MLI Temperatures for Test 9



Large swings are due to sensor noise.

Test results from 50 layer blankets

System Level Correction

Configuration	T_{avg}, K	K_{avg}, W/m/K	ΔT, K	Q_{theory} W	Q_{corr} W	Q_{net} W	Q_{seam}, W	Q_{seam}, W/m
Overlap Seams	21.06	29.8	2.56	0.453	0.317	0.770	0.075	0.082
Interleaved	19.16	27.3	2.43	0.393	0.302	0.695	0.000	0.000
Full Butt	18.85	26.9	2.51	0.400	0.312	0.712	0.017	0.018
Butt 2" Offset	18.85	26.9	2.52	0.401	0.312	0.713	0.018	0.019
Butt 4" Offset	19.37	27.8	2.56	0.418	0.317	0.735	0.040	0.044

Component Level Correction

Configuration	Q_{total}, W	Q_{net}, W	Q_{seam}, W	Q_{seam}, W/m
Overlap	0.472	0.356	0.022	0.024
Interleave	0.457	0.334	0	0.000
Butt	0.472	0.346	0.012	0.013
Butt - 2 in offset	0.472	0.346	0.012	0.013
Butt - 4 in offset	0.480	0.354	0.02	0.022

Test results for 20 layer blanket

System Level Correction

Configuration	T_{avg} K	K_{avg} W/mK	ΔT, K	Q_{theory}, W	Q_{corr}, W	Q_{total}, W	Q_{seam} W	Q_{seam} W/m
Interleaved	20.38	28.9	3.49	0.599	0.427	1.026	0.000	0.000
Overlap	18.62	26.6	3.65	0.573	0.445	1.019	-0.007	-0.007
Butt 2" Offset	17.52	25.0	4.21	0.625	0.512	1.137	0.112	0.122
Full Butt	17.25	24.7	4.09	0.597	0.497	1.095	0.069	0.075

Component Level Correction

Configuration	Q_{total}, W	Q_{net}, W	Q_{seam}, W	Q_{seam}, W/m
Interleave	0.599	0.376	0	0.000
Overlap	0.574	0.417	0.041	0.045
Butt - 1 stagger, 2 in	0.625	0.395	0.019	0.021
Butt - 0 stagger	0.597	0.387	0.011	0.012

Discussion of Results For the 50 layer blanket

- Layer by layer interleaved joint had the lowest heat leak
- Overlap joint had the same performance as the straight and staggered butt joints.
- Surprisingly staggering the butt joint did not decrease the heat load, and increasing the stagger distance didn't help.
- Test with the largest stagger was the worse than the straight butt joint
  - May be due to damage incurred by repeated handling rather the joint itself.
  - Even this seam results are only 5% more heat leak than the best performing seam.

Discussion of Results For the 20 layer blanket

- Tests are a bit less conclusive
- Overlap seam still performs very well,
- Offset butt joint is 10% worse than the interleaved blanket.
- Full butt joint outperforms the offset butt joint and is within 6% of the interleaved blanket.

Note: due to the lower thermal performance of the thinner blanket all delta temperatures on the rod are higher than our calibration range. The correction factors for the rod have been linearly extrapolated, but the heat load values should be considered relative to each other rather than absolute values.

Comparison to Theory

- The theoretical butt seam heat load from Hinckley:
  - 0.094 W/m for a 20 layer blanket
  - 0.050 W/m for a 50 layer blanket
- Same order of magnitude as measured:
  - 0.012 W/m to 0.075 W/m for 20 layers
  - 0.013 W/m to 0.018 W/m for 50 layers

CONCLUSIONS

- Work on multilayer insulation has shown the effectiveness of various seam approaches
- Better than expected performance for the blanket overlay seam
- Performance of a carefully constructed butt seam within 6% of a seam of individually overlapped.
- Repeatability testing of a similar number of layers has indicated a higher percentage blanket to blanket variation.

Thank you to the IFUSI team for their assistance!