TFAWS Passive Thermal Paper Session

MLI Blanket Performance – Analytical Predictions and Quantitative Trends Measured in Testing

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Motivation and Objectives for Study

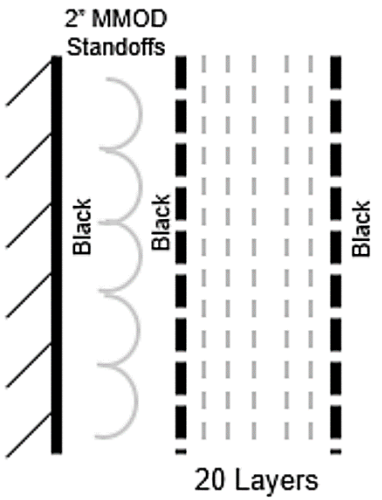
- **Motivation**
  - JPL's planned Europa Clipper mission and Europa Lander mission concept are both solar array powered and will travel to ~5.6 AU
  - Multi-layer insulation (MLI) blankets control the radiation heat loss to space, hence a better performing blanket could reduce the heater power required and result in significant power savings

- **Objectives**
  1. Characterize overall effective emittance, ε*, of several MLI blanket configurations, particularly those involving a "dual" blanket design
  2. Qualitatively determine sensitivity of blanket performance to artifacts of blanket construction that may negatively impact performance such as
     1. Seams
     2. Conductive losses caused by instrumentation, mylar standoffs, and test setup
     3. Dacron netting
  3. If a dual blanket configuration demonstrates significant reduction in heat loss over single blanket configurations, down-select a leading dual blanket configuration for use in large-scale testing

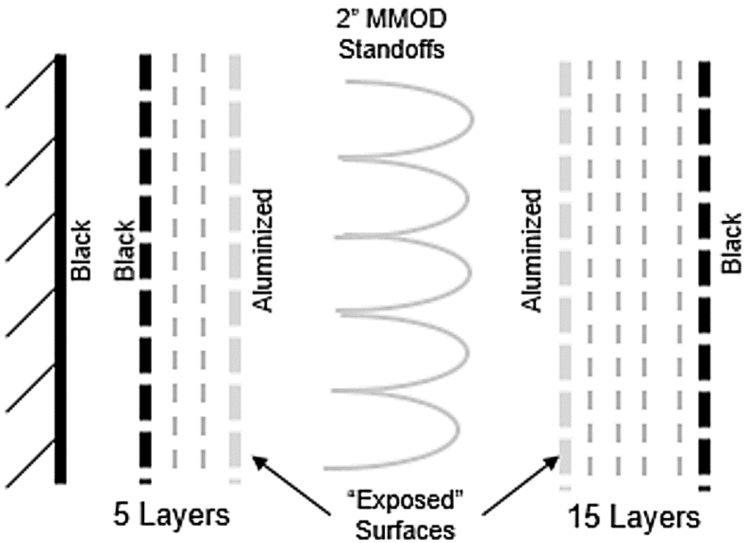
MLI Blanket Concepts

- **Single (*traditional*):**
  Increase the number of layers to improve overall ε*. There are diminishing returns beyond ~20 layers due to conductive shorting of layers contacting each other. There is a direct mass impact associated with the additional number of layers.

- **Dual (*proposed*):**
  Break into two blankets but keep the same number of total layers (mass neutral) and have low emissivity "exposed" interstitial surfaces of each blanket



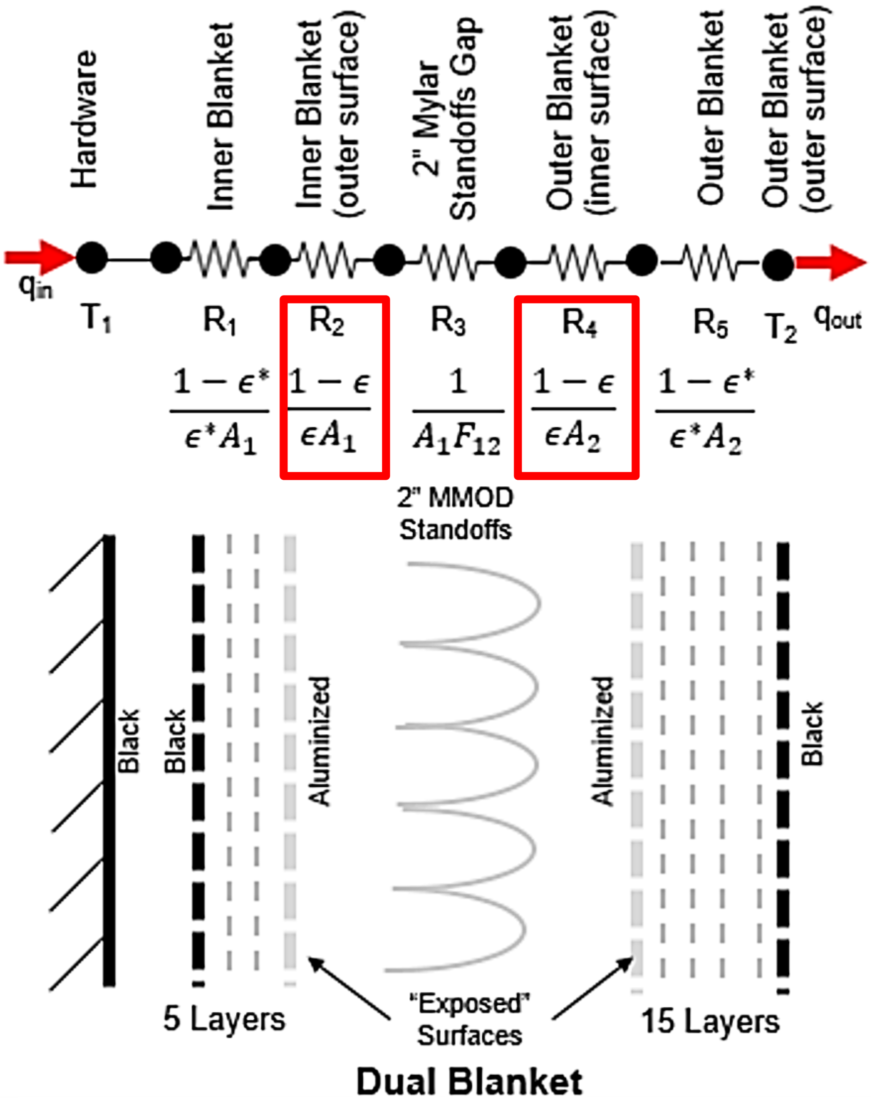
Single Blanket



Dual Blanket

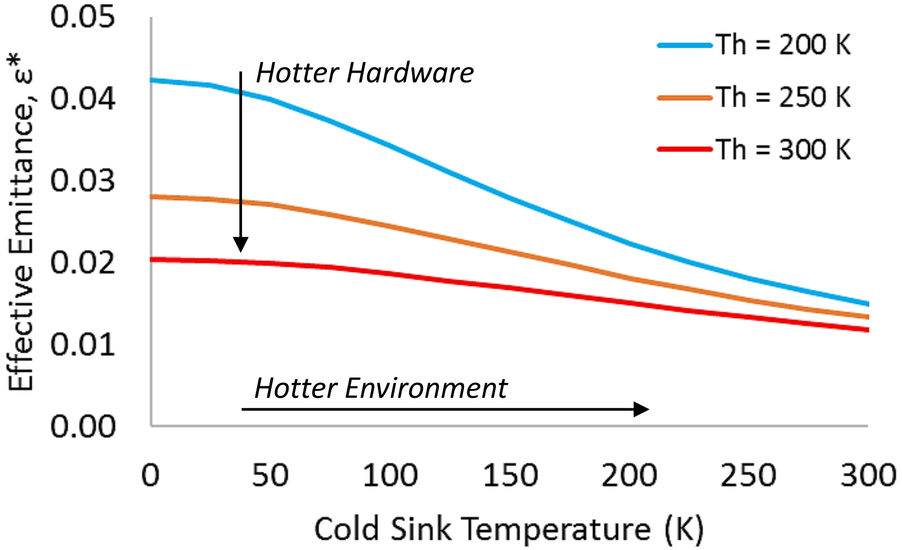
MLI Blanket Thermal Network

- The dual blanket concept leverages separated aluminized surfaces (shown in red boxes) on the “exposed surfaces” of the separated blankets to reduce the overall ε*
- In a single 20 layer blanket, these two adjacent layers would be conductively shorted by the seams and interstitial contact



Analytical Modeling

- The Lockheed equation* was developed as an empirical correlation to fit test data for various blankets designed at Lockheed Corporation (now Lockheed Martin)
- The equation accounts for seams, number of layers, and temperatures
  - $\varepsilon_{eff} = \frac{7.30*10^{-8}(N)^{2.63}}{\sigma(N_S+1)}\left(\frac{1}{T_H^2+T_C^2}\right) + \frac{7.07*10^{-10}(0.043)(2)}{\sigma N_S}\left(\frac{T_H^{4.67}-T_C^{4.67}}{T_H^4-T_C^4}\right)$
  - N = layers per thickness [#/cm]
  - N_S = number of layers
  - T_H = hardware sink temperature
  - T_C = cold sink temperature
  - Seams = factor of two for JPL blankets
- Performed analysis in Excel with a solver routine
- All predicts and test results for ε* in this package are defined from hardware to outermost MLI surface (*not space!*)



*JPL Memo 3547-TSE-86-214, October 27, 1986
Also see NASA CR-134477, April 5, 1974

Blanket Layup Test Matrix

- Wanted to investigate effects of…
  - Single vs dual blanket scheme (cases 3-9)
  - Black vs aluminized surfaces (case 3)
  - Dacron netting vs embossed (case 5)
  - Number of layers (cases 8, 9)
  - Staggering the seams (cases 6, 7, 9)
  - Locations of the standoffs (case 7)
- **Pre-test baseline** blanket design was a 20 layer dacron layup (case 1)
- **Leading dual blanket concept** was 5 layer embossed + 15 layer dacron with aluminized "exposed surfaces (case 4)
- Innermost and outermost layers were black for all tests to isolate the effect of single vs dual blankets
- All of the outer blankets included alternating layers of mylar and dacron netting (no embossed) since the outer blanket needs to be more mechanically robust for the Europa Clipper flight implementation

Pre-test baseline → case 1

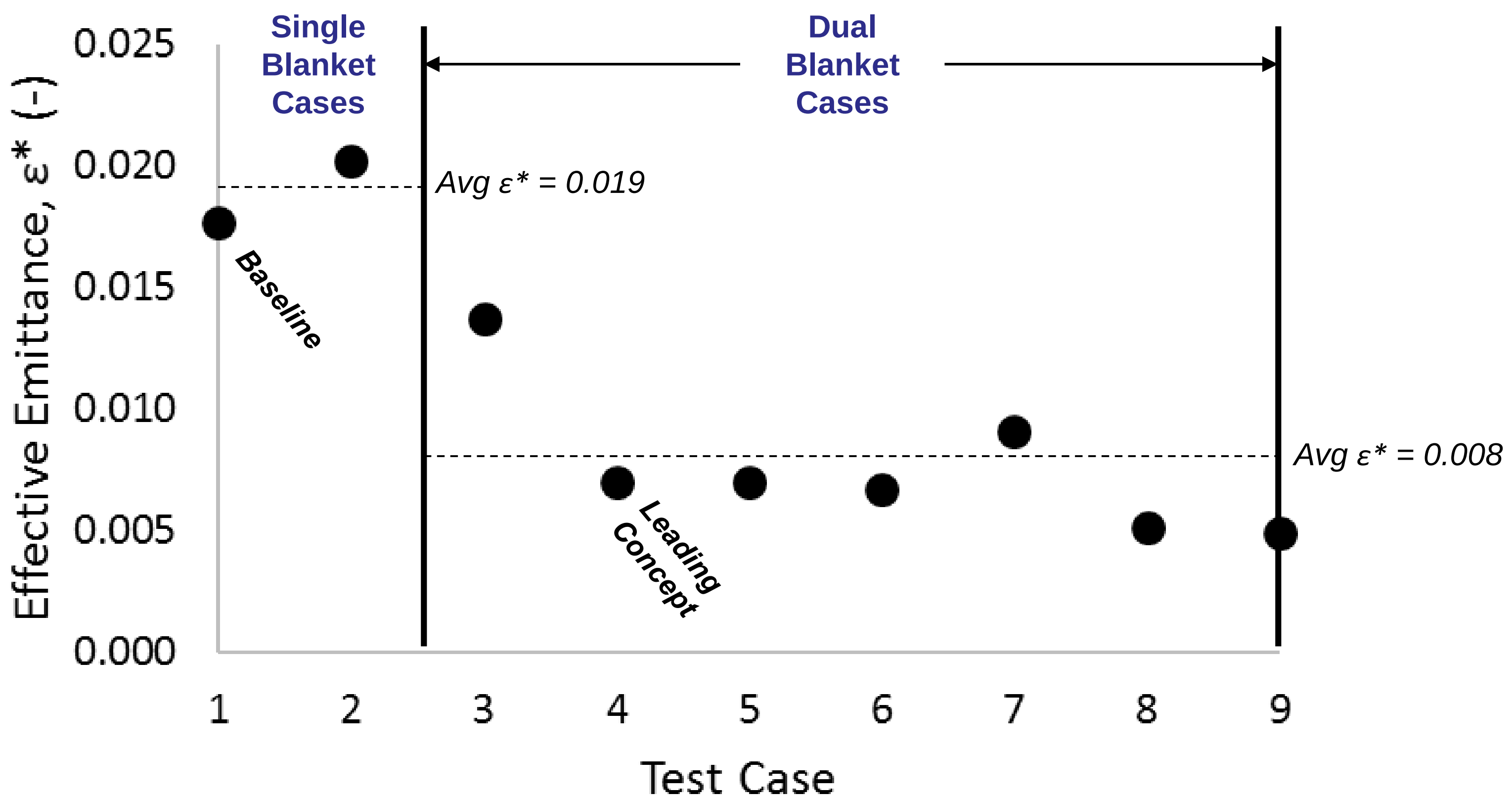
Leading concept → case 4

		Inner Blanket				Outer Blanket			
Case	2'' MMOD Standoffs	Inner Surface	# Layers	Outer Surface	2'' MMOD Standoffs	Inner Surface	# Layers	Outer Surface	Modifications to Seams
1	Yes					CK	20, DAM	CK	
2	Yes					CK	20, DAM	CK	Extra seams
3		CK	5, EAK	CK	Yes	CK	15, DAM	CK	
4		CK	5, EAK	AM	Yes	AM	15, DAM	CK	
5		CK	5, DAM	AM	Yes	AM	15, DAM	CK	
6		CK	5, EAK	AM	Yes	AM	15, DAM	CK	Staggered
7	Yes	CK	5, EAK	AM		AM	15, DAM	CK	Staggered
8		CK	15, EAK	AM	Yes	AM	15, DAM	CK	
9		CK	15, EAK	AM	Yes	AM	15, DAM	CK	Staggered

CK = carbon filled black kapton
AM = aluminized mylar
EAK = embossed aluminized kapton
DAM = dacron netting + aluminum mylar

Pre-Test Model Predictions

- **Model predictions suggest dual blanket schemes have roughly half the ε* value** of the baseline single blanket design
- Differences in blanket areas for dual blanket cases were accounted for in calculations



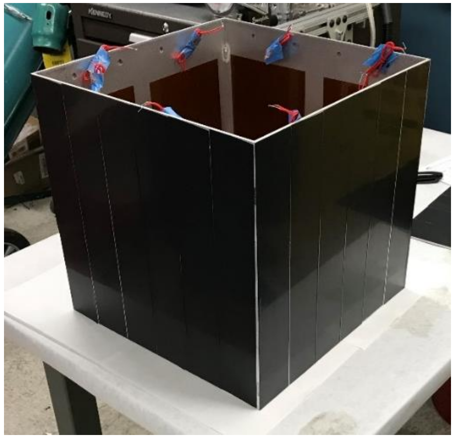
Testing Overview

Test Article

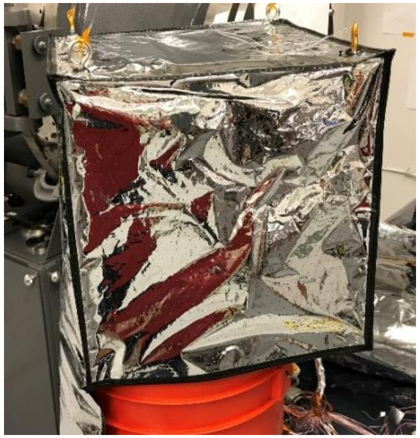
- 1ft x 1ft x 1ft aluminum cube with 1/8” thick panels
- Qty 2 heaters (wired in parallel) provided thermal control per side of the cube
- Qty 4 Type E, 36 AWG thermocouples per side of the cube
- Carbon filled black kapton tape exterior
- Cables exit from a 1” diameter hole of the bottom face of cube

Chamber Configuration

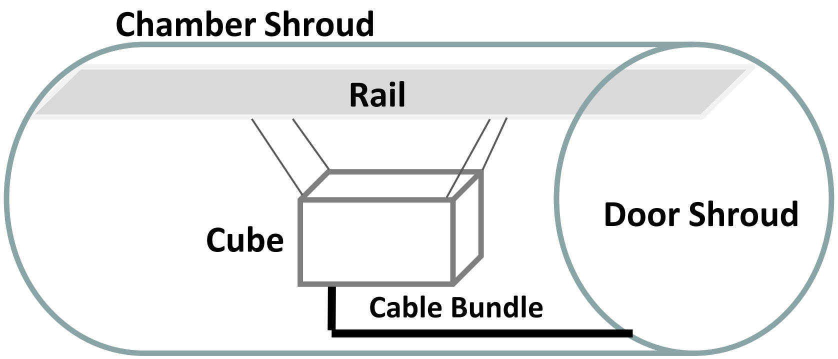
- 2 ft x 3 ft vacuum chamber pumped down to 10^{-5} torr or less with LN_2 flooded shroud to approx -175 ° C
- Test article suspended in chamber with four 0.020” diameter stainless steel wires
- Cable heat losses quantified and subtracted out to determine the heat loss through MLI only



Test Article
(Exterior, bottom missing)



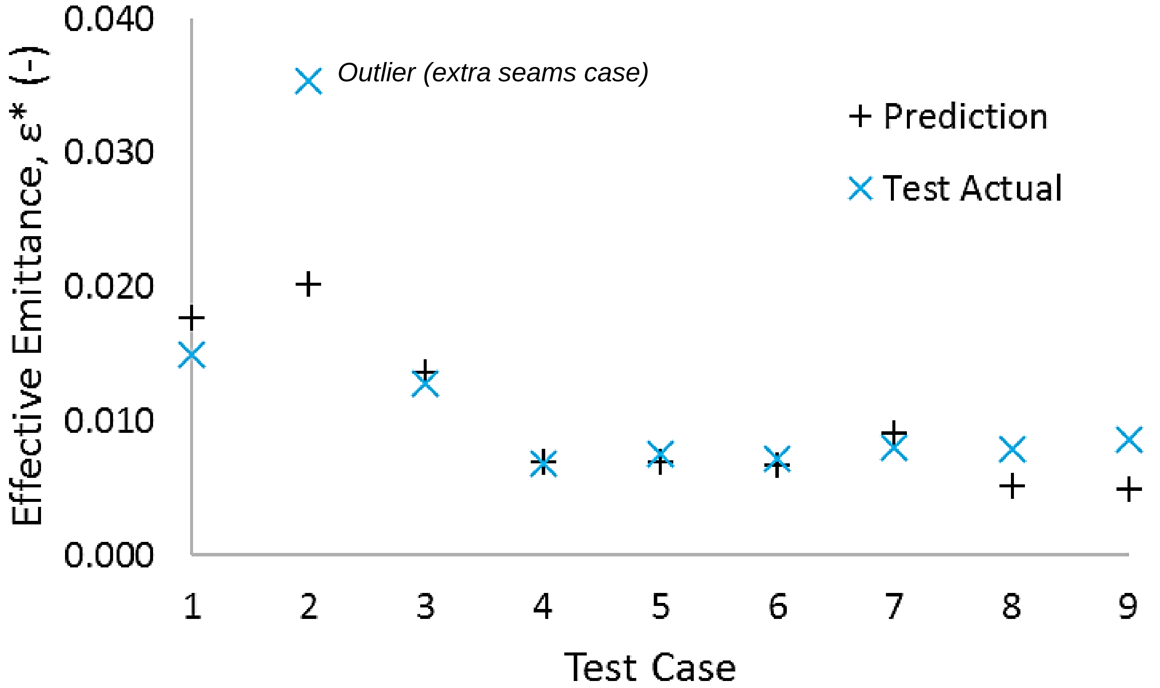
Blanketed Test Article
(inner blanket)



Chamber Schematic

Overview of Results

- ***Predicts and test data demonstrate that dual blanket designs had roughly half the ε* value of a single blanket design***
- Model predictions were surprisingly close to the test actuals
- Predicts for 6 of 9 cases within ±0.002 of test ε* value



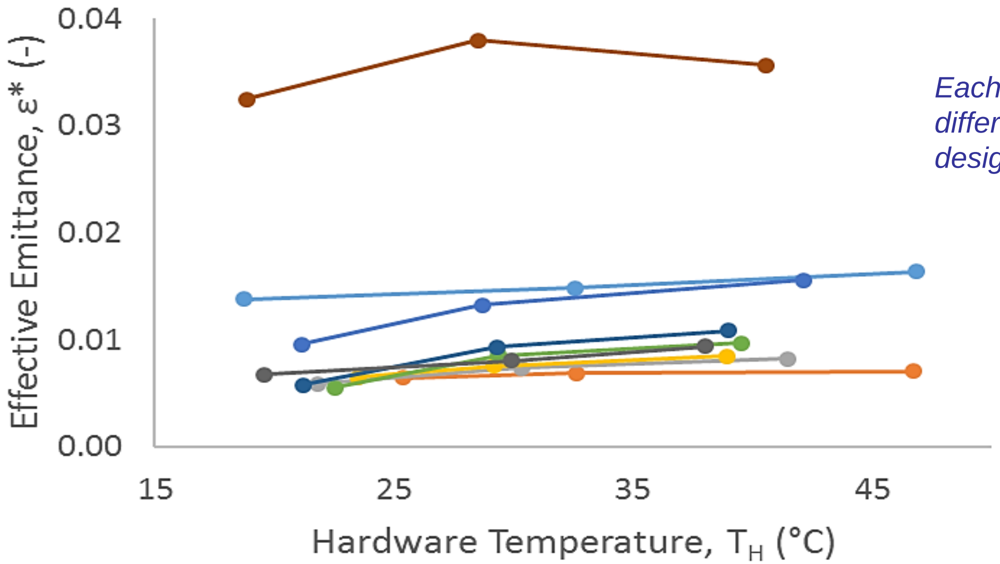
Ranked Results

- **Leading concept performed best overall in test**
- All dual blanket cases performed similarly, with averaged ε* values bound within a 0.0018 ε* range

Case	Rank	Blanket Layup	Predicted ε*	Test ε*	Test/ Predict	Test/ Baseline
1	8	2” + 20 CK, DAM, CK	0.0177	0.0150	0.85	-
2	9	2” + 20 CK, DAM, CK (extra seams)	0.0202	0.0354	1.75	2.36
3	7	5 CK, EAK, CK + 2” + 15 CK, DAM, CK	0.0137	0.0128	0.93	0.85
4	1	5 CK, EAK, AM + 2” + 15 AM, DAM, CK	0.0070	0.0068	0.97	0.45
5	3	5 CK, DAM, AM + 2” + 15 AM, DAM, CK	0.0070	0.0075	1.07	0.50
6	2	5 CK, EAK, AM + 2” + 15 AM, DAM, CK (staggered seams)	0.0067	0.0072	1.07	0.48
7	5	2" + 5 CK, EAK+ AM + 15 AM, DAM, CK (staggered seams)	0.0091	0.0080	0.88	0.53
8	4	15 CK, EAK, AM + 2” + 15 AM, DAM, CK	0.0051	0.0079	1.55	0.53
9	6	15 CK, EAK, AM + 2” + 15 AM, DAM, CK (staggered seams)	0.0049	0.0086	1.76	0.57

Results – Hardware Temperature

- Results suggest a slight increase in ε* with increasing temperature
  - Applying a linear best fit results in no correlation ($R^2 < 0.01$)
- This trend is counter to the predictions from the Lockheed equation, which suggests a decrease to ε* with increasing hardware temperature
- Possible explanations
  - *Temperature range of test article too small to measure appreciable differences*
  - Hysteresis effect from only doing upscale measurements
  - Non-linear heat loss through MLI vs cables



Each color is a different blanket design test case

Narrow hardware temperature ranges may exhibit negligible change to MLI performance

Results - Blanket Layup Design

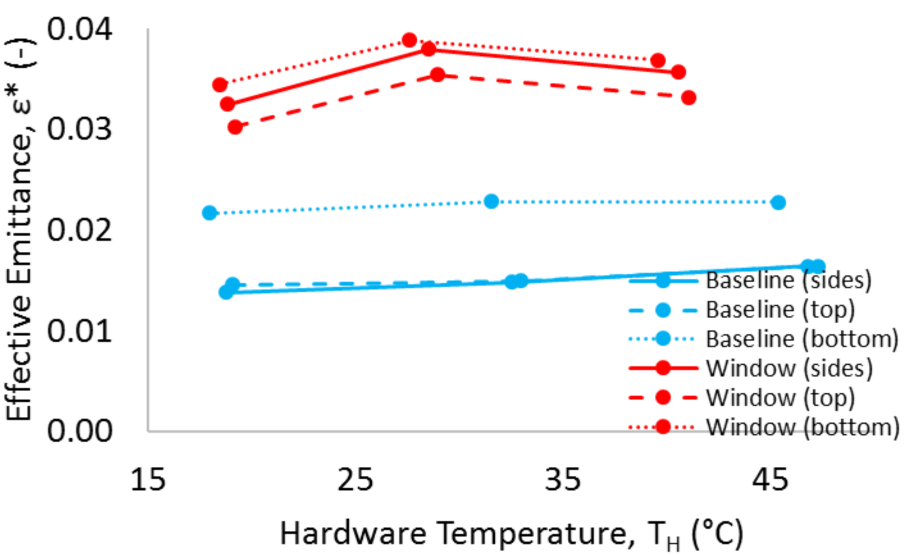
- Negligible difference in performance was measured between layup designs
  - Embossed designs, average ε* = 0.0068
  - Dacron designs, average ε* = 0.0075

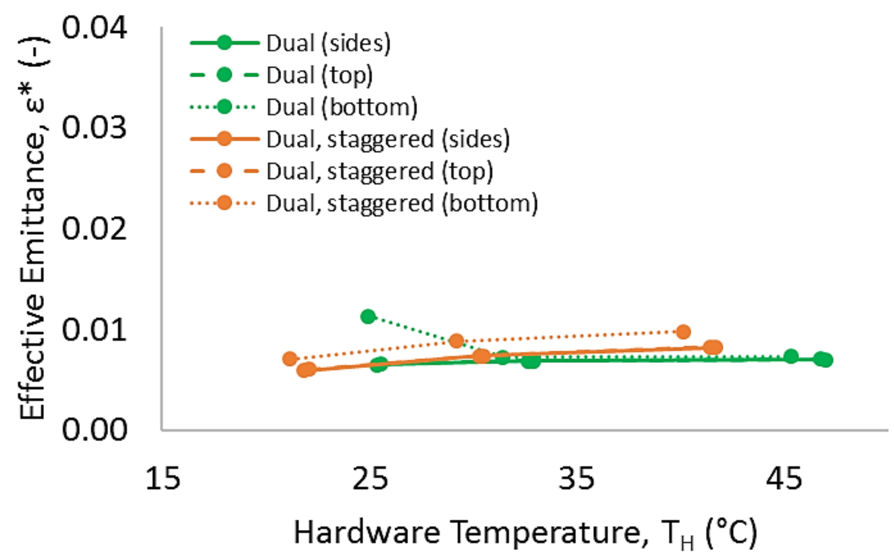
- Point-to-point contact conductance in the embossed layup may be comparable to conductance of the dacron netting layer
- Only the construction of the inner 5 layer blanket was varied, so this may be affecting the results

Dacron/mylar vs embossed layups exhibited negligible difference in MLI performance

Results - Seam Effects and Staggering

- MLI performance is negatively impacted by seams (conductive thermal shorts) at the edges of the blanket
  - Using tape to closeout the edges reduces this effect, but results in a less mechanically robust blanket
- ***Dual blanket performance may have been better in part because the seams of the inner blanket are blocked by the outer blanket, regardless of staggering them or not***
  - Even if seams are not staggered, the view factor from inner to outer is small when blankets are spaced 2” apart, so any improvement possible by staggering is reduced
- A comparison case between 20 layer blanket and 5+15 layer blanket with black kapton “exposed” layers resulted in slight performance improvement for the latter (0.015 vs 0.0128)
- Staggering the seams made negligible difference to performance
  - Possible artifact of having a cube test article – maybe a cylindrical shape would see an improvement

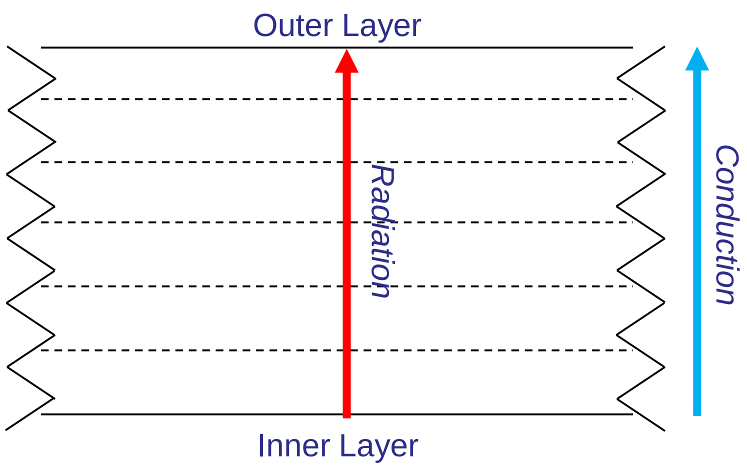




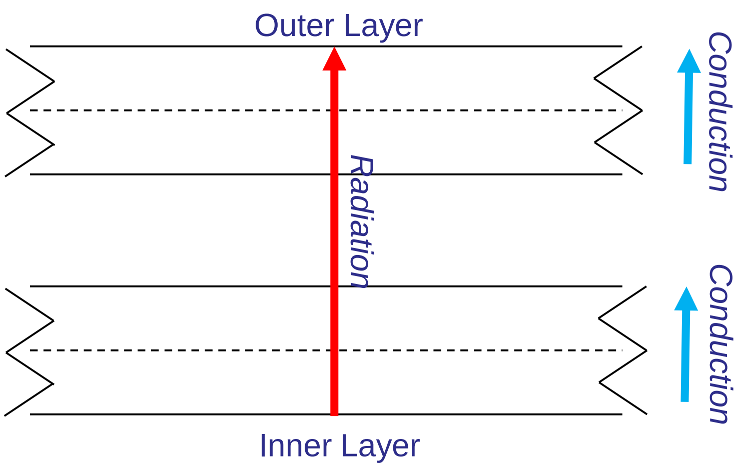
Seam inefficiencies significantly affected performance for single blanket schemes; less impactful for dual blanket scheme

Results - Seam Effects and Staggering

- Using a separated dual blanket design breaks the conductive thermal short from inner to outer layer at the seams
- This results in a larger thermal gradient from hardware to environment and better overall blanket performance



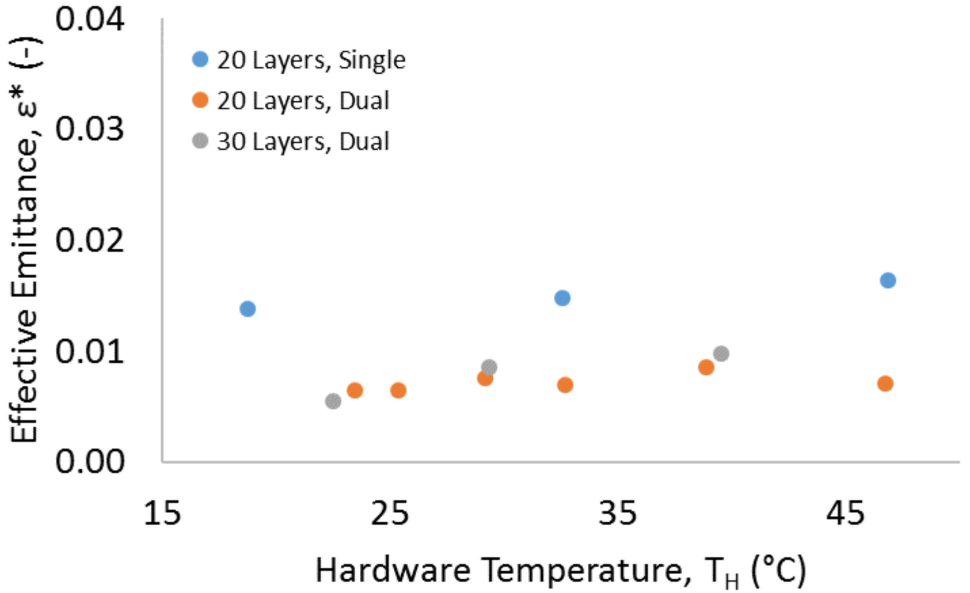
Single Blanket



Dual Blanket

Results – Number of Layers

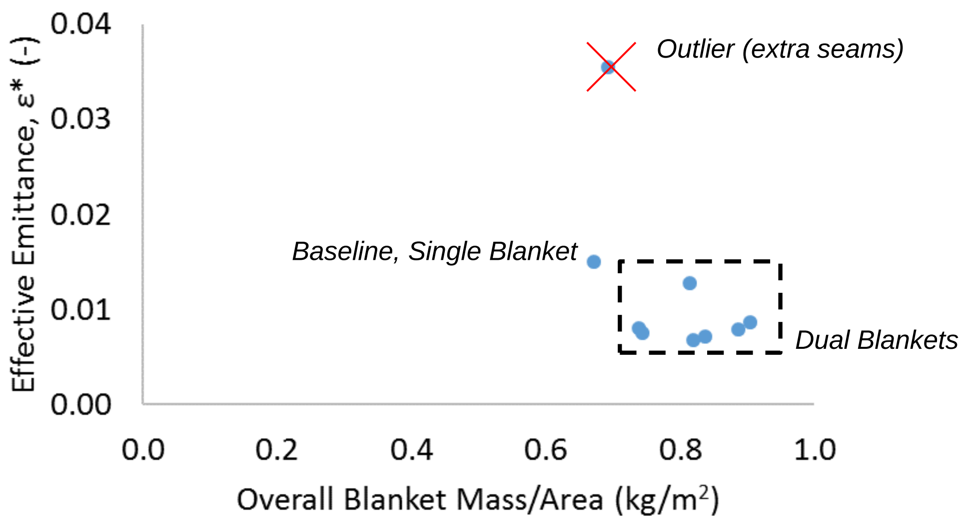
- Increasing the number of layers for dual blankets did not improve performance
- Would be nice to test a 5+5 dual blanket to see if performance compares with 20 layer blanket (power neutral but mass savings)
  - Needed to meet a 2” MMOD requirement on Clipper, so this wasn’t pursued



Dual blanket performance was similar for 20 and 30 total layers

Results – Mass Impact

- How much mass do I have to spend to get better blanket performance?
  - Excluding mylar standoffs and grounding straps
- ***Dual blanket mass/area was slightly higher***
  - Test article was small, so having more seams per unit area may have artificially influenced this
  - Larger blankets may see less difference in mass between dual and single blanket designs since the layers would dominate the mass instead of the seams
- ***Dual blanket layup performance was almost independent of mass***
- Blankets were too small for this test to make an appreciable differentiation of mass between different layups (i.e. dacron/mylar vs embossed)
  - On a larger scale, an embossed layup is expected to weigh less for the same area since it lacks the dacron netting



Implementing dual blanket scheme may slightly increase mass compared to single blanket scheme; dual blanket performance is nearly independent of mass

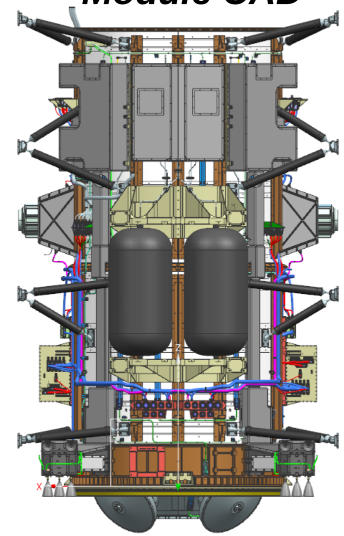
Lessons Learned

1. **Predictions from analytical models of MLI performance were better than expected**, but should still be used with caution until testing verifies the real performance
2. **During testing, steady state points need to be reached with some skill** and engineering judgment; waiting for a 0.2 C / hr type of criteria is not practical for a high thermal inertia test article in a development test
3. **Cooling below ambient temperature is not practical for a short development test**; better to extrapolate data if sub-ambient temperatures are not nominal for hardware design
4. **Combining larger heater wires** into a single cable bundle and running as one circuit **is much better for reducing parasitic heat loss** (disadvantage is loss of local heater control)

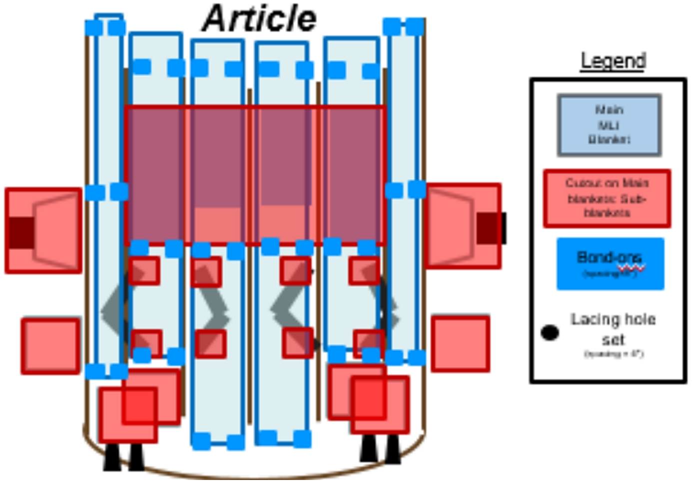
Work to Go

- Additional MLI testing on a large scale flight-like test article will be done for Europa Clipper in spring 2019
  1. Risk reduction for those areas where blanket performance may drive the heat loss and current level of conservatism is not enough
  2. Provides some practice with patterning and blanket interfacing before the flight build
- All test activities to be completed before Europa Clipper thermal CDR (May 2019)
- Will also incorporate additive manufacturing for test articles to improve model fidelity while saving cost and schedule (paradigm shift for thermal dev testing?)

Europa Clipper Prop Module CAD



Blanketed Test Article



Conclusions

- **Dual blanket performance was demonstrated to be about a 50% reduction in ε* (and power)**
- **Lockheed equation was effective for predicting MLI performance measured in test**

- Effect of temperature and blanket construction did not influence ε* value much, but more testing would be needed across more diverse test cases
- A mechanism for better dual blanket performance may be the reduction of the seams' influence

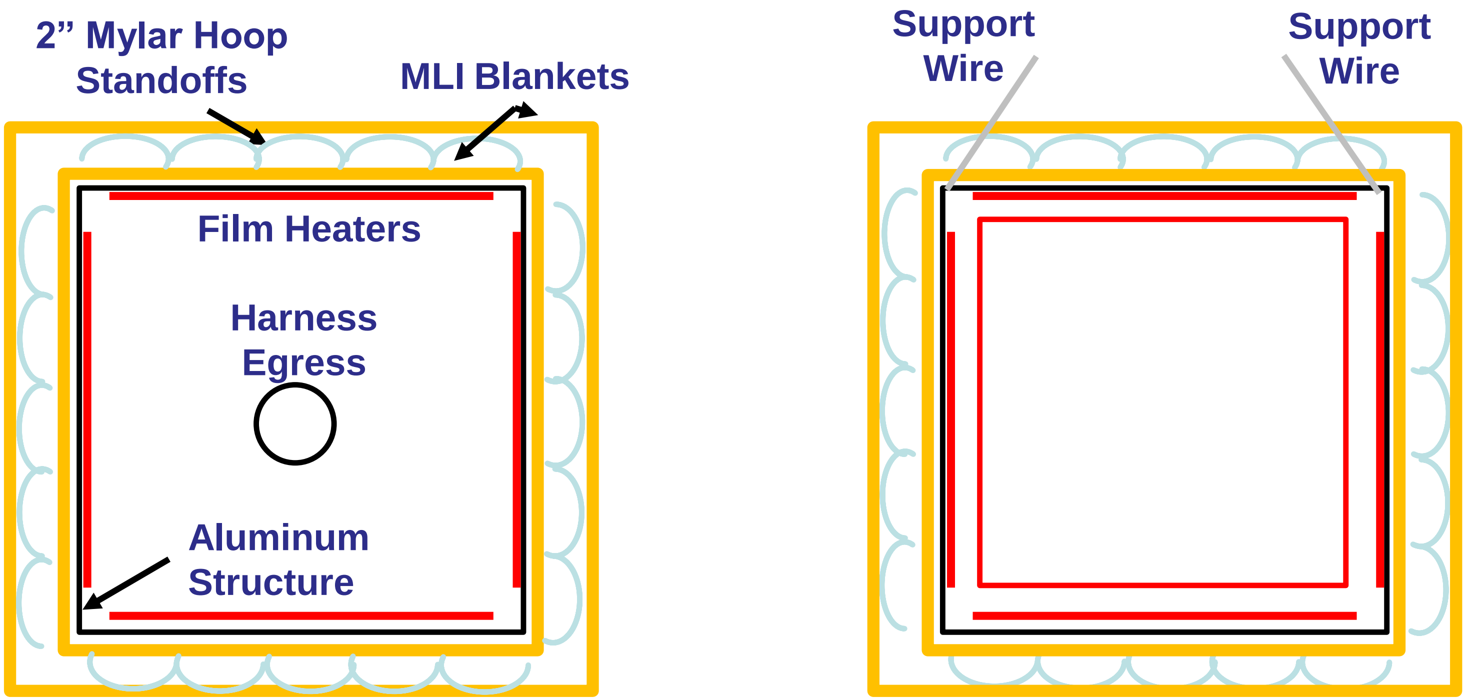
- Using a dual blanket design will be a mass upper, but power savings likely more beneficial for missions with large spacecraft

Acknowledgments

- The JPL shield shop was heavily involved with the design, fabrication, and delivery of the blankets used in this test
- Special thanks to Rich Frisbee and Mark Duran for blanket support and readily changing the blankets for each test case
- This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Backup

Test Article Schematic



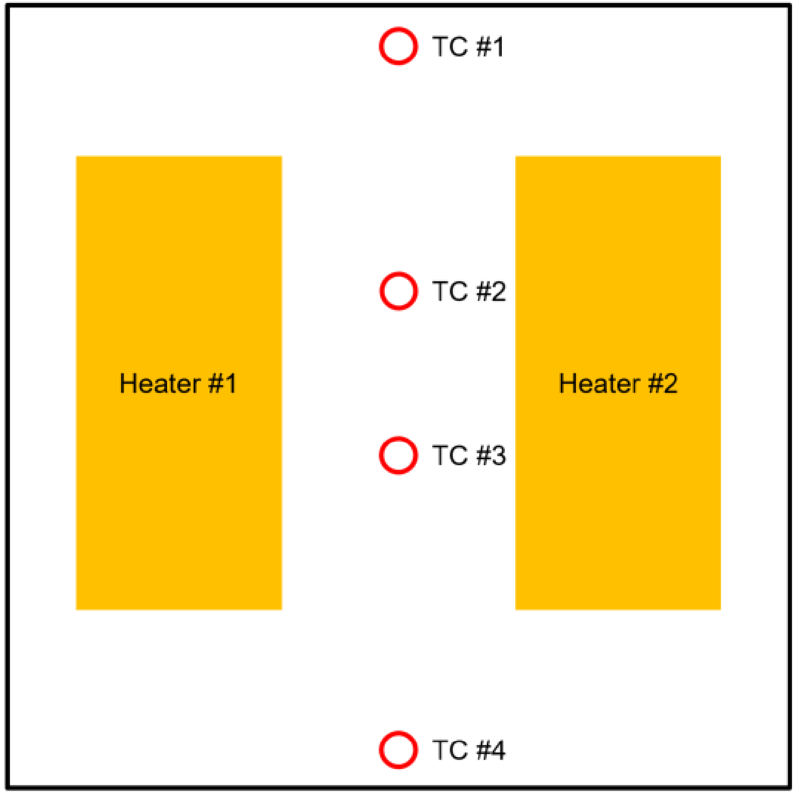
Top View

Side View

Instrumentation

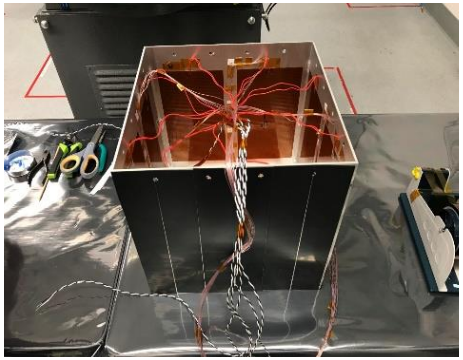
- Thermocouples
  - 24 on cube inside (4 per face x 6 faces)
  - 24 on MLI (4 per blanket face x 6 faces)
    - These were removed after the first test case
  - 5 on chamber shroud (top, bottom, left, right, rear)
  - 1 on chamber door shroud
  - **54 total (30 total for test cases 2-9)**

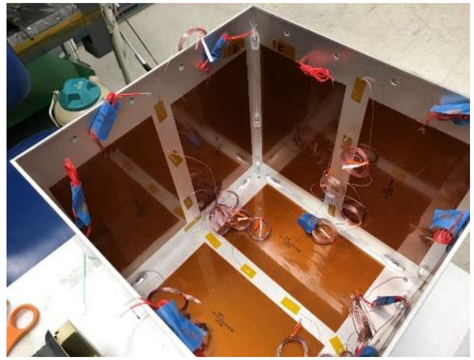
- Heaters
  - 12 on cube sides (2 per side of cube x 6 faces)
  - 1 guard heater for main cable bundle
  - **13 total**



Example Face of Cube

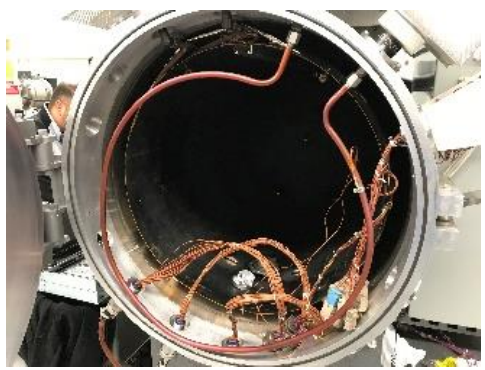
Test Photos

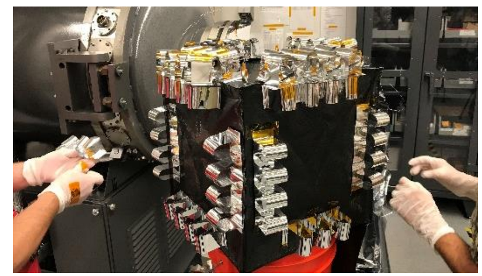


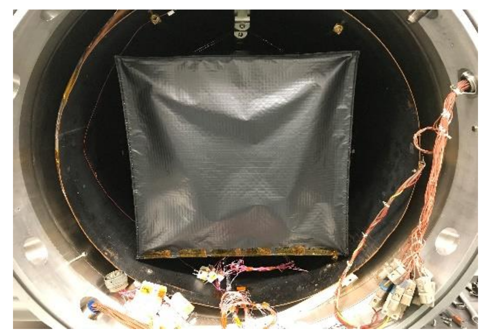


Test Article Setup

Chamber Setup







Testing

ε* Dependence on Temperature

- No correlation found between hardware temperature and effective emittance for the range of temperatures tested