Development of an Equation to Characterize Heat Flux Through IMLI and A Method to Implement in Thermal Desktop®

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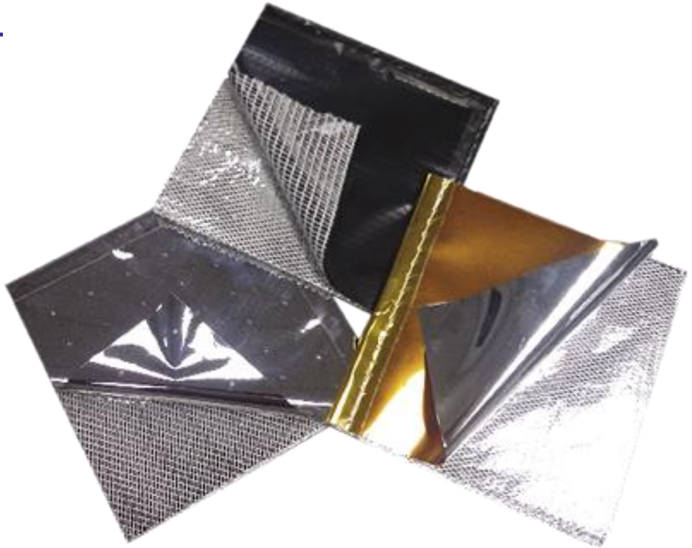
Introduction

- The goal is to create an empirical equation defining heat flux across IMLI for use in a system or vehicle level thermal model as a function of layer count, substrate temperature, and outer surface temperature

  - Multi-Layer Insulation (MLI) is a high performing thermal insulation solution for use in a vacuum and is often used for spacecraft and cryogenic systems
  - Traditional MLI installations have several layers of metalized polymer sheets separated by low conductivity polyester netting
  - Much work has been done creating empirical correlations, such as the Modified Lockheed Equation (MLE) for traditional MLI [1][2]

  - Integrated MLI (IMLI) is a system similar to traditional MLI with many layers of low emissivity sheets and spacer materials
  - IMLI employs spacers installed in a discrete matrix between each reflective layer instead of a continuous sheet of netting material
    - The spacer employment is intended to control layer spacing and density
    - IMLI promises to offer predictable performance and other benefits compared to traditional MLI[3]
  - Many test series have been conducted with IMLI and a variant Load Bearing MLI (LBMLI) over several years and different locations



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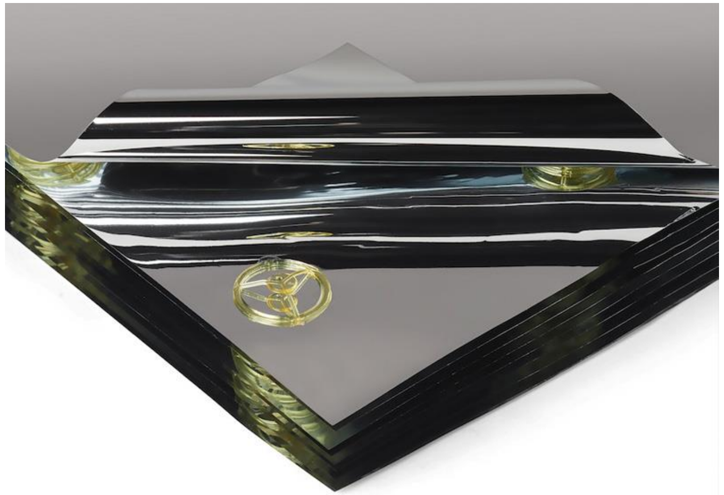


https://questthermal.com/

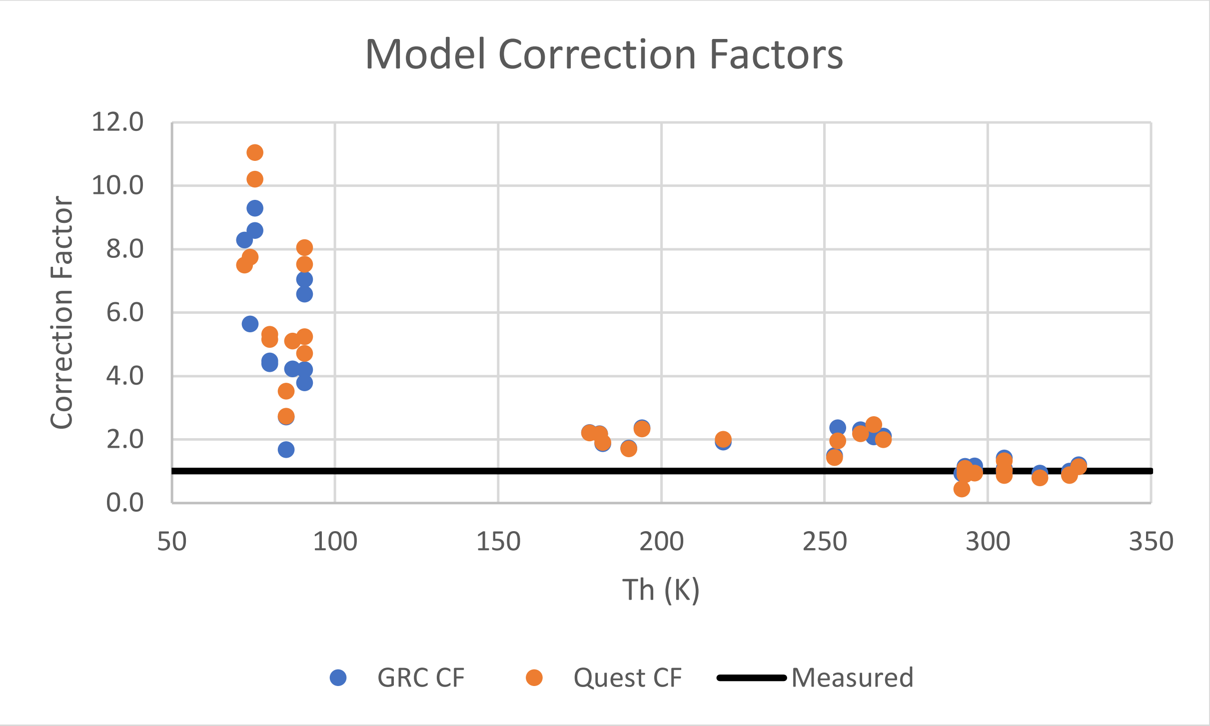
IMLI Test Data

- The test data consists of 37 different tests gathered from test series conducted at various NASA centers, universities, and aerospace corporations[3][4][5][6][7]
  - Aggregated data provided by Wes Johnson at Glenn Research Center (GRC)
- All test cases used a 5.5 layers/cm spacing
- Test cases 0-14 and 24-28 used the IMLI spacer
- Test cases 15-23 and 29-36 used the LBMLI spacer
  - Its design allows the IMLI to support to structures like Micrometeoroid/Orbital Debris (MMOD) Protection mounted to the outer layer
  - This limits the need for additional structural mounts that create thermal paths through the insulation
  - The more robust design should result in greater leak for a given layer count and boundary conditions

n	layers	Tc, K	Th, K	Measured Q, W/m^2
0	10	76	296	0.95
1	20	77	292	0.41
2	20	77	305	0.567
3	3	76	296	3.62
4	9	78	293	0.924
5	9	78	325	1.358
6	9	78	316	1.232
7	5	78	293	1.772
8	5	78	305	1.989
9	5	78	325	2.609
10	19	78	293	0.545
11	19	78	305	0.768
12	19	78	328	0.849
13	4	20	85	0.18
14	9	20	85	0.13
15	10	77	181	0.41
16	10	77	178	0.395
17	10	77	190	0.376
18	10	77	194	0.552
19	12	77	219	0.542
20	16	77	261	0.868
21	16	77	268	0.868
22	20	77	265	0.828
23	14	77	254	0.814
24	19	25	80	0.085
25	19	29.1	80	0.0788
26	19	32	182	0.219
27	19	25	87	0.097
28	19	23	253	0.453
29	10	20	74	0.186
30	10	20	90.7	0.206
31	10	20	72.3	0.168
32	10	20	90.6	0.185
33	20	20	75.5	0.158
34	20	20	90.6	0.169
35	20	20	90.6	0.158
36	20	20	75.4	0.146

IMLI Layer-by-Layer Models

- Wes Johnson of NASA Glenn Research Center and Quest Thermal Group LLC have developed layer-by-layer models of IMLI to predict the heat flux through a given IMLI configuration
  - Both have shared those model predictions for comparison purposes
  - These models predict flux through IMLI well at higher outer layer temperatures
  - Colder outer temperatures (<150K) result in the models underpredicting the flux through the IMLI
  - Correction Factors (CF) range from 1.5-11. CF = $Q_{measured}/Q_{predicted}$
    - This level of uncertainty at low temperatures can make Cryogenic Fluid Management predictions difficult
  - CF > 1 indicates a predicted heat flux < measured test data
  - CF = 1 signifies a match with test data
  - Layer-by-layer modeling can be computationally intensive in a system or vehicle level thermal model
  - By creating an empirical correlation, a vehicle level thermal model can more rapidly perform trade studies without the computation penalties of an explicit IMLI model



Empirical Data Fit - Modified Lockheed Equation

- The Modified Lockheed Equation was developed to characterize MLI performance from test data and has the form:

$$Q = \left(\frac{C_S \cdot T_m \cdot \bar{N}^{2.63} \cdot (T_h - T_c)}{N-1}\right) + \left(\frac{C_R \cdot \varepsilon \cdot (T_h^{4.67} - T_c^{4.67})}{N}\right) + \left(\frac{C_G \cdot P \cdot (T_h^{0.52} - T_c^{0.52})}{N}\right)$$

*Since this effort uses test data from high vacuum, the gas conduction term is not addressed

C_S	Conduction multiplier
C_R	Radiation multiplier
C_G	Gas conduction multiplier
ε	Layer emissivity
$\bar{N}$	Layer spacing
N	Layer count
P	Gas Pressure
T_c	Cold side temperature
T_h	Warm surface temperature
T_m	Mean temperature

- The conduction and radiation multipliers C_S and C_R can be fit to match test data from a particular insulation configuration and materials.
- The layer spacing term $\bar{N}^{2.63}$ adjusts linear conduction due to the number of netting layers between aluminized layers and compression of the blanket from staples during assembly
- This equation will be used as a starting point for comparison with test data

Empirical Data Fit - Modified Lockheed Equation

- A MathCAD solve block used to fit MLE to data
- The MLE was left in the original form (N-1 for linear term)

$$Q_{MLE}\left(N, T_C, T_H, C_S, C_R, T_{exp}, \bar{N}_{exp}\right) := \left(\frac{C_S \cdot \dfrac{\dfrac{T_C}{K} + \dfrac{T_H}{K}}{2} \cdot \bar{N}^{\bar{N}_{exp}} \cdot \left(\dfrac{T_H}{K} - \dfrac{T_C}{K}\right)}{N-1} + \frac{C_R \cdot \varepsilon \cdot \left(\left(\dfrac{T_H}{K}\right)^{T_{exp}} - \left(\dfrac{T_C}{K}\right)^{T_{exp}} \right)}{N} \right) \cdot \frac{W}{m^2}$$

$$resid_{MLE}\left(N, T_C, T_H, C_S, C_R, T_{exp}, \bar{N}_{exp}, Q_{TEST}\right) := \overrightarrow{Q_{TEST} - Q_{MLE}\left(N, T_C, T_H, C_S, C_R, T_{exp}, \bar{N}_{exp}\right)}$$

$$SSE_{MLE}\left(N, T_C, T_H, C_S, C_R, T_{exp}, \bar{N}_{exp}, Q_{TEST}\right) := \sqrt{\sum resid_{MLE}\left(N, T_C, T_H, C_S, C_R, T_{exp}, \bar{N}_{exp}, Q_{TEST}\right)^2}$$

Guess Values

$$C_s := 1$$
$$C_r := \blacksquare$$

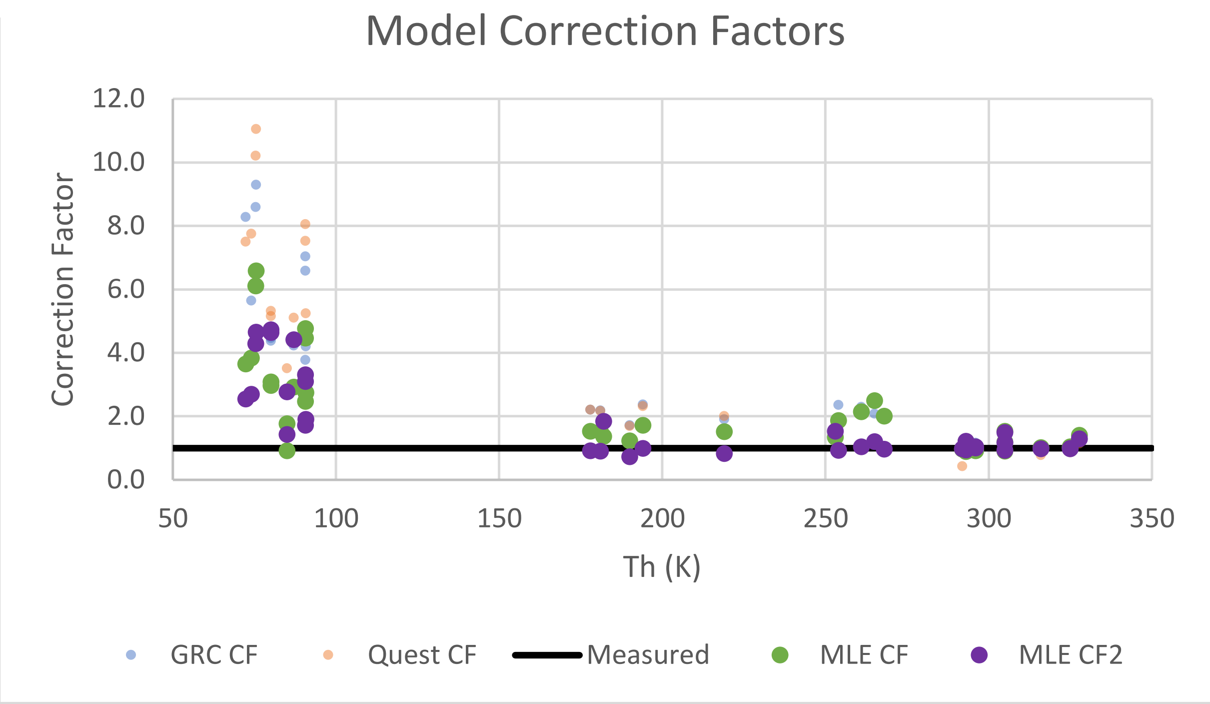
Constraints

$$C_r > 0 \qquad C_s > 0 \qquad \bar{N}_{exp} > 0$$
$$0 = \overrightarrow{resid_{MLE}\left(Layers, T_c, T_h, C_s, C_r, T_{exp}, \bar{N}_{exp}, Q_{test}\right)}$$
$$0 = SSE_{MLE}\left(Layers, T_c, T_h, C_s, C_r, T_{exp}, \bar{N}_{exp}, Q_{test}\right)$$
$$\overrightarrow{Q_{test} < Q_{MLE}\left(Layers, T_c, T_h, C_s, C_r, T_{exp}, \bar{N}_{exp}\right)}$$

Solver

$$\begin{bmatrix} C_{s\_MLE} \\ C_{r\_MLE} \end{bmatrix} := \mathbf{minerr}\left(C_s, C_r\right)$$

- C_S and C_R were solved treating cases 0-36 as single and separate populations
  - For a single group, correction factors for ranged from 0.9 – 6.6
    - C_S = 1.93e-6, C_R = 1.39e-10
  - Separating into IMLI and LBMLI groups gives correction factors from 0.75 to 4.9 with
    - IMLI: C_S = 1.23e-6, C_R = 3.88e-10
    - LBMLI : C_S = 2.51e-6, C_R = 9.91e-10
- Two sets of coefficients fit the data better than a single set of coefficients or either explicit model, but still has a lot of uncertainty at lower outer surface temperatures



IMLI Performance Characterization

- Is there an equation form with a better fit?
  - Removing T_{mean} from Conductive term linearizes that term
  - From McIntosh[2], the radiant transfer between 2 surfaces with many radiation shields having the same emissivity can be expressed as:

$$\dot{q} = \frac{1}{N+1} \cdot \frac{\sigma\left(T_1^{\,4} - T_2^{\,4}\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \quad \text{or} \quad \dot{q} = \frac{\sigma \cdot \varepsilon_{eq} \cdot \left(T_1^{\,4} - T_2^{\,4}\right)}{N+1} \quad \text{where} \quad \varepsilon_{eq} := \frac{1}{\frac{1}{\varepsilon} + \frac{1}{\varepsilon} - 1}$$

  - N is the number of shields, but the outer layers are counted in MLI systems, so it is equal to the number of the MLI layers, NL
  - Layer count in each term was left at N_L, instead of NL $\pm$ 1. Various papers use either an N_L or N_L $\pm$1 term. N_L resulted in best fit in this case
  - Layer spacing in all test data was constant at 5.5 layers/cm
    - The layer spacing and exponent terms effectively combine with the C_s term to form a single empirical constant
    - This will need to be revisited once test data with various layer spacing and grid spacing exists
  - The empirical coefficients **C_s** and **C_r**, temperature exponent terms **T_{exp_s}** and **T_{exp_r}**, and layer count exponents **N_{exp_s}** and **N_{exp_r}** were all solved for in the MathCAD block

$$Q_{IMLI} = \left(\frac{C_s \cdot T_m \cdot N^{2.63} \cdot \left(T_h - T_c\right)}{N_L}\right) + \left(\frac{C_r \cdot \sigma \cdot \varepsilon \cdot \left(T_h^{\,4.67} - T_c^{\,4.67}\right)}{N_L}\right)$$

$$Q_{IMLI} = \left(\frac{C_s \cdot N^{2.63} \cdot \left(T_h - T_c\right)}{N_L}\right) + \left(\frac{C_r \cdot \sigma \cdot \varepsilon_{eq} \cdot \left(T_h^{\,4} - T_c^{\,4}\right)}{N_L}\right)$$

$$Q_{IMLI} = \left(\frac{C_s \cdot \left(T_h^{T_{exp\_s}} - T_c^{T_{exp\_s}}\right)}{N_L^{N_{exp\_s}}}\right) + \left(\frac{C_r \cdot \sigma \cdot \varepsilon_{eq} \cdot \left(T_h^{T_{exp\_r}} - T_c^{T_{exp\_r}}\right)}{N_L^{N_{exp\_r}}}\right)$$

Guess Values

$$C_r := 1$$

$$C_s := 0.00011$$

Constraints

$$0 = \overrightarrow{resid2\left(Layers, T_h, T_c, C_s, C_r, T_{exp\_l}, T_{exp\_r}, N_{exp\_l}, N_{exp\_r}, Q_{test}\right)}$$

$$0 = SSE2a\left(Layers, T_h, T_c, C_s, C_r, T_{exp\_l}, T_{exp\_r}, N_{exp\_l}, N_{exp\_r}, Q_{test}\right)$$

$$\overrightarrow{Q_{IMLI}\left(Layers, T_h, T_c, C_s, C_r, T_{exp\_l}, T_{exp\_r}, N_{exp\_l}, N_{exp\_r}\right)} > \overrightarrow{Q_{test}}$$

Solver

$$\begin{bmatrix} C_{s1} \\ C_{r1} \\ T_{exp\_l1} \\ T_{exp\_r1} \\ N_{exp\_l1} \\ N_{exp\_r1} \end{bmatrix} := \mathbf{minerr}\left(C_s, C_r, T_{exp\_l}, T_{exp\_r}, N_{exp\_l}, N_{exp\_r}\right)$$

IMLI Performance Characterization

- Multiple initial guesses and coefficient constraints were investigated with little difference to the final RSS error of several solutions
  - N_{exp_s} and N_{exp_r} returned approximately **0.5** and **1**
  - T_{exp_s} and T_{exp_r} returned approximately **1** and **4** respectively
    - Conduction temperature exponent was near linear (exp ≈ 1)
    - Radiant temperature exponent was best fit with an exponent value near 4
    - Those integer values were selected for use with the IMLI flux equation

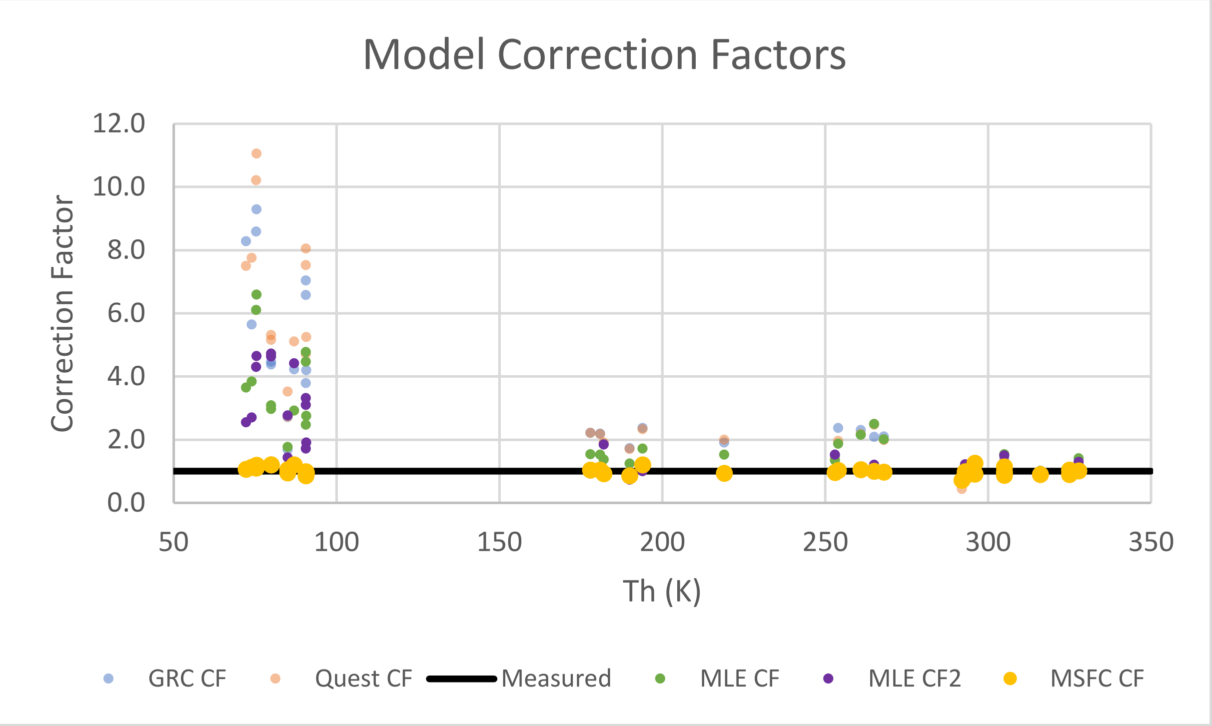
$$Q_{IMLI} = \left(\frac{C_s \cdot (T_h^{T_{exp\_s}} - T_c^{T_{exp\_s}})}{N_L^{N_{exp\_s}}} \right) + \left(\frac{C_r \cdot \sigma \cdot \varepsilon_{eq} \cdot (T_h^{T_{exp\_r}} - T_c^{T_{exp\_r}})}{N_L^{N_{exp\_r}}} \right)$$

$$Q_{IMLI} = \left(\frac{C_s \cdot (T_h - T_c)}{\sqrt{N_L}} \right) + \left(\frac{C_r \cdot \sigma \cdot \varepsilon_{eq} \cdot (T_h^4 - T_c^4)}{N_L} \right)$$

- As shown with the MLE, treating the test data as 2 populations has the best results

	C_S	C_R	Min CF	Max CF
All Data	0.0073	0.97	0.62	1.71
IMLI	0.005	1.031	0.71	1.24
LBMLI	0.01	1.3	0.75	1.30

- That C_R is near unity for each data set is encouraging as that matches the "book" answer
  - Setting C_R = 1 for LBMLI changes CF range to 0.77-1.28
  - This is a second "local minimum" for error which fits low temperature test data better

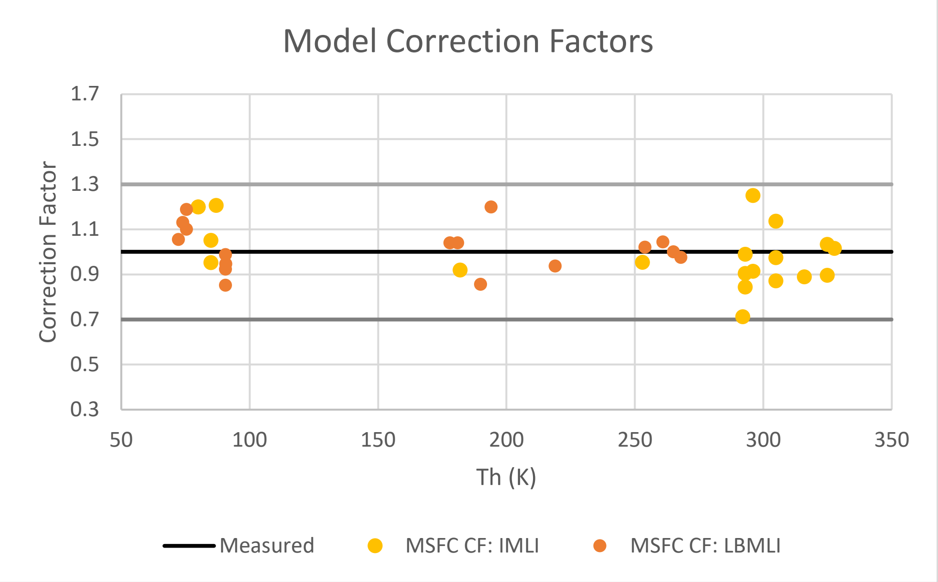


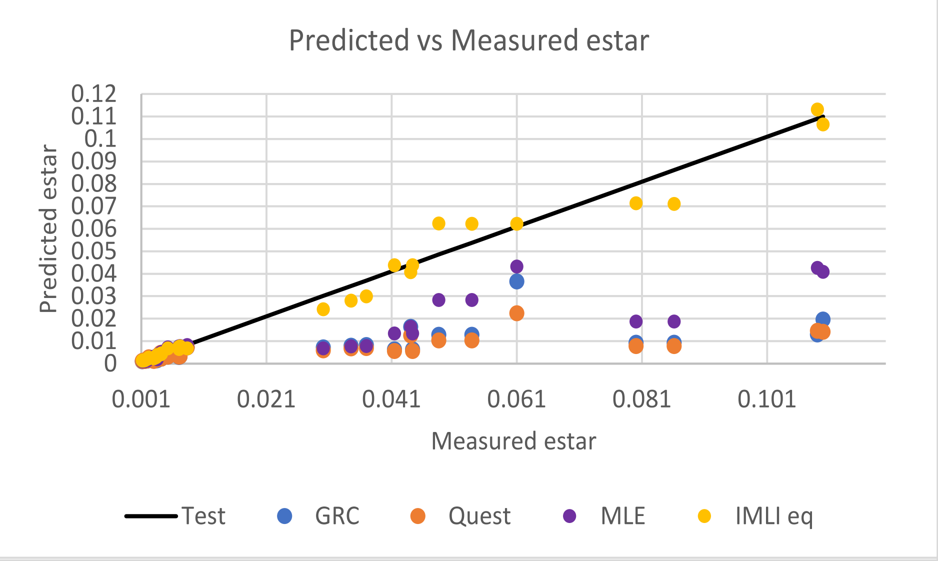
IMLI Performance Characterization

- Final suggested values:
  - $C_R = 1.0$, $C_{S\_IMLI} = 0.0053$, $C_{S\_LBMLI} = 0.0103$
  - Results in CF range of 0.72-1.28 or predictions within 30% of measured data
- Estar is another way to compare predictions to data
  - Proposed IMLI equation matches very well with measured test data
- Comparison of CF values between models and average error for test cases with an outer surface temperature >150K or <150K

	Min CF	Mean CF	Max CF	>150K Avg Error	<150K Avg Error
GRC model	0.92	2.90	9.29	28%	77%
Quest model	0.78	3.21	11.05	48%	82%
MLE data fit	0.89	2.13	6.59	31%	64%
IMLI eq data fit	**0.71**	**1.01**	**1.28**	**12%**	**11%**

$$Err_{avg} = \frac{\sum \frac{|Q_{predicted} - Q_{measured}|}{Q_{predicted}}}{n}$$

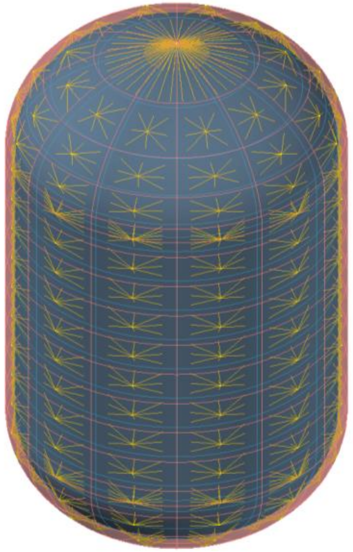


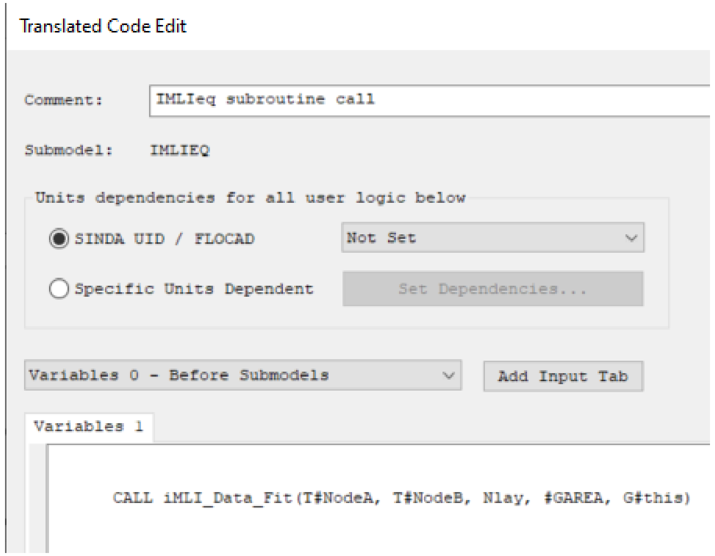


IMLI Equation Implementation in Thermal Desktop

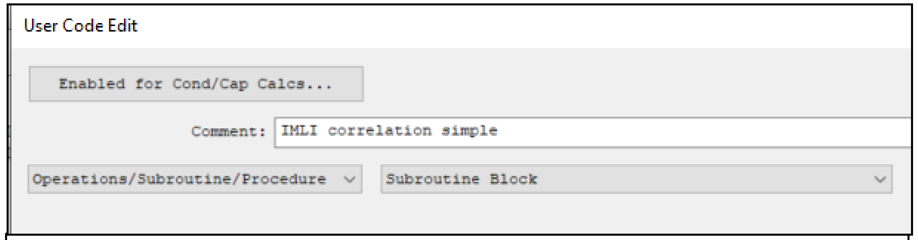
- For system/vehicle models with asymmetric environments (Orbits):
  - Create a surface representing the outer surface of the IMLI
  - Use a contactor to represent the thermal resistance through the IMLI
  - Utilizing Network Element Logic (NEL) in the contactor, call the provided user subroutine, shown on the right, as a function of the number of layers, substrate temperature, and IMLI surface temperature

  CALL iMLI_Data_Fit(T#NodeA, T#NodeB, Nlay, #GAREA, G#this)





- For applications where spatial resolution is not needed, the insulation tab may still be used with the estar defined in thermophysical properties as a register/expression




```
F    SUBROUTINE iMLI_Data_fit(TNodeA, TNodeB, Nlay, Area, Gval)

     CALL COMMON
C    Description
C    Calculate the effective IMLI conductance using the IMLI data fit equation.

FSTART
C
C   Declare Variable Types
     real :: TNodeA, TNodeB, Area, Gval
     real :: Th, Tc, Cs, Cr, Cg, emiss, emiss_eq
     real :: iMLIQ, iMLIQ_S, iMLIQ_R, iMLIQ_G

C   Define the temperature variables
       Th = max(NodeA, NodeB)
       Tc = min(NodeA, NodeB)

C   Define Variables based on Blanket_Type
C   Cs =0.005 IMLI or 0.01 for LBMLI, Cr = 0.01, Cg = unused for now
         Cs = 0.005 $ for IMLI or Cs = 0.01 for LBMLI
         Cr = 1.0
         Cg = 0.0

         emiss = 0.03
         emiss_eq = 1/((1/emiss)+(1/emiss)-1)

C   Calculate Terms of IMLIeq
       iMLIQ_S = (Cs*(Th-Tc))/(sqrt(Nlay))
       iMLIQ_R = (Cr*sigma*emiss_eq*(Th**4-Tc**4))/Nlay
       iMLIQ_G = 0 !(Cg_SR*Press*(Th**(0.52)-Tc**(0.52)))/Nlay
       iMLIQ =   iMLIQ_S + iMLIQ_R + iMLIQ_G)

C   Rearrange to generate and return estar
       Gval = ((iMLIQ * Area)/(sigma*(Th**4-Tc**4)))

     RETURN
     END
FSTOP
```

Acknowledgements

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- Sarah Nguyen / MSFC

Questions?

References

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