Quantifying MLI Thermal Conduction in Cryogenic Applications from Experimental Data

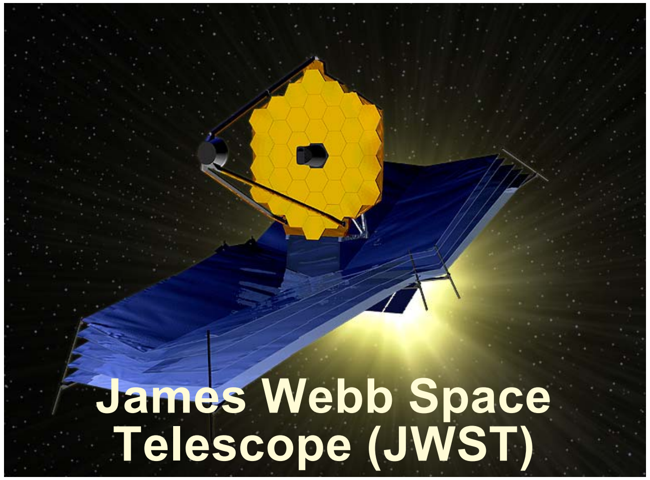
R.G. Ross, Jr.

Jet Propulsion Laboratory, California Institute of Technology

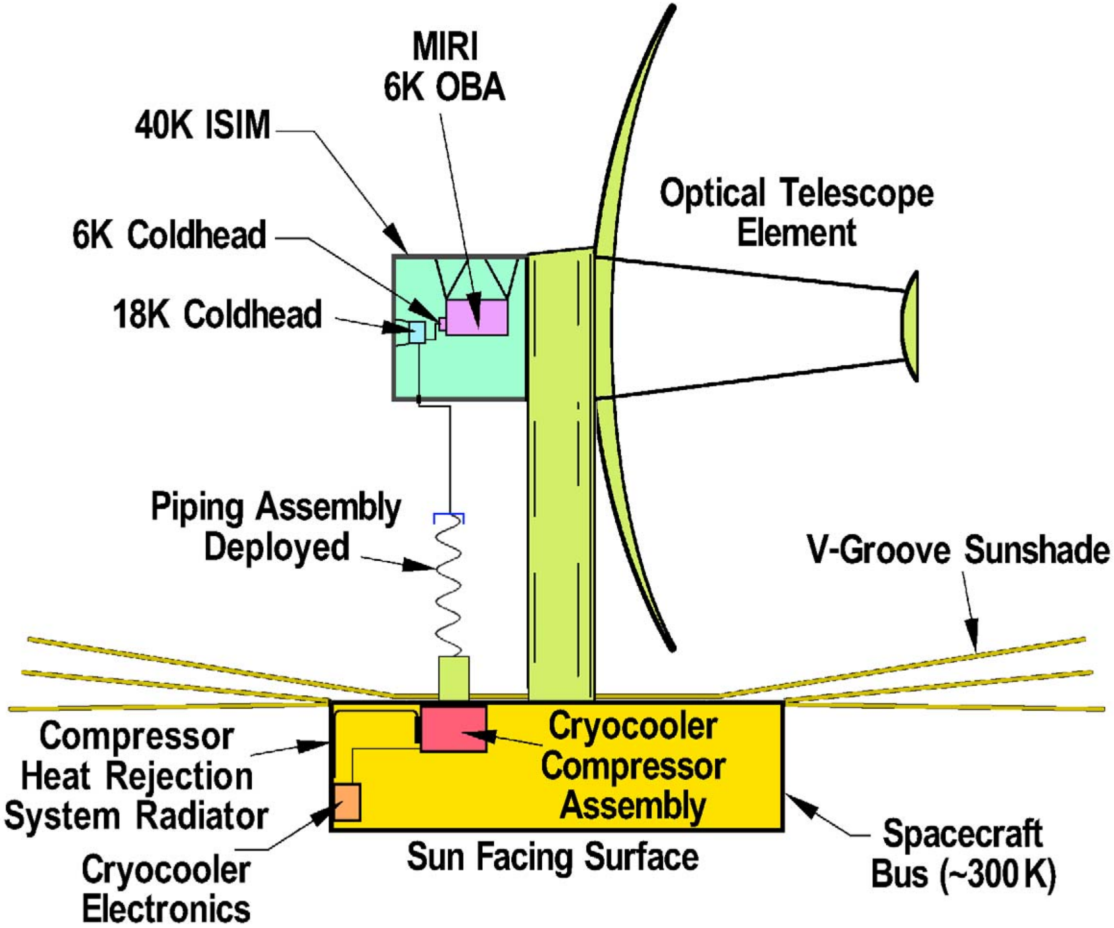
Topics

- Motivated by very cold (6 K) space telescope applications
  - Large MLI uncertainties observed in test data for Hot-side temperatures below 40 K
- Using modeling equations to Quantify (Extract) key parameters of existing MLI designs from test data
  - Conductivity of S/C versus Dewar versus Cryo MLI
  - Understanding Role of Conductivity in MLI performance
- Conclusions and Lessons Learned

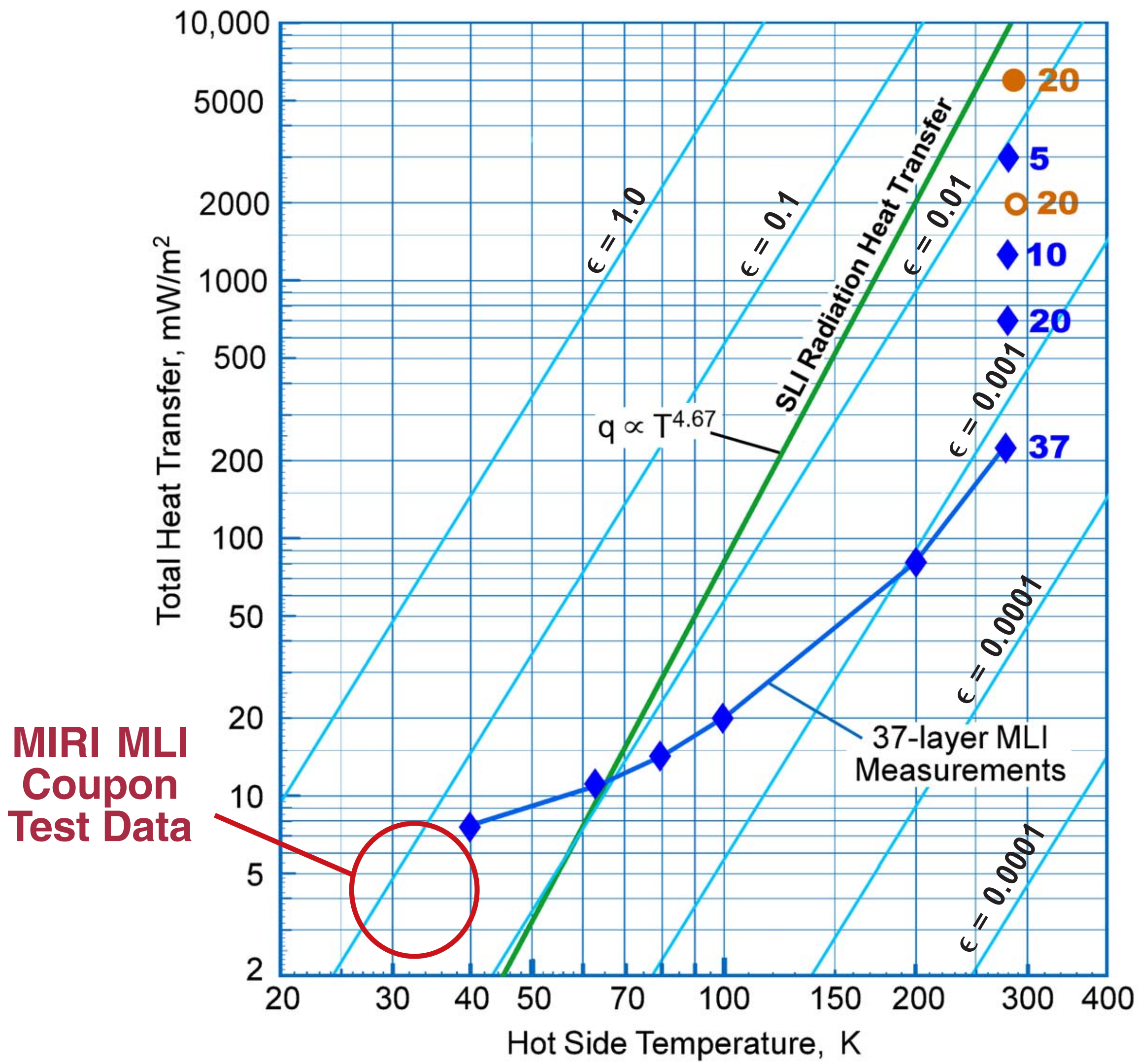
Cryogenic MLI Study Motivated by 6K MIRI Instrument on JWST



MIRI in its MLI



MLI Heat Transfer as a Function of Hot-Side Temperature



Key:

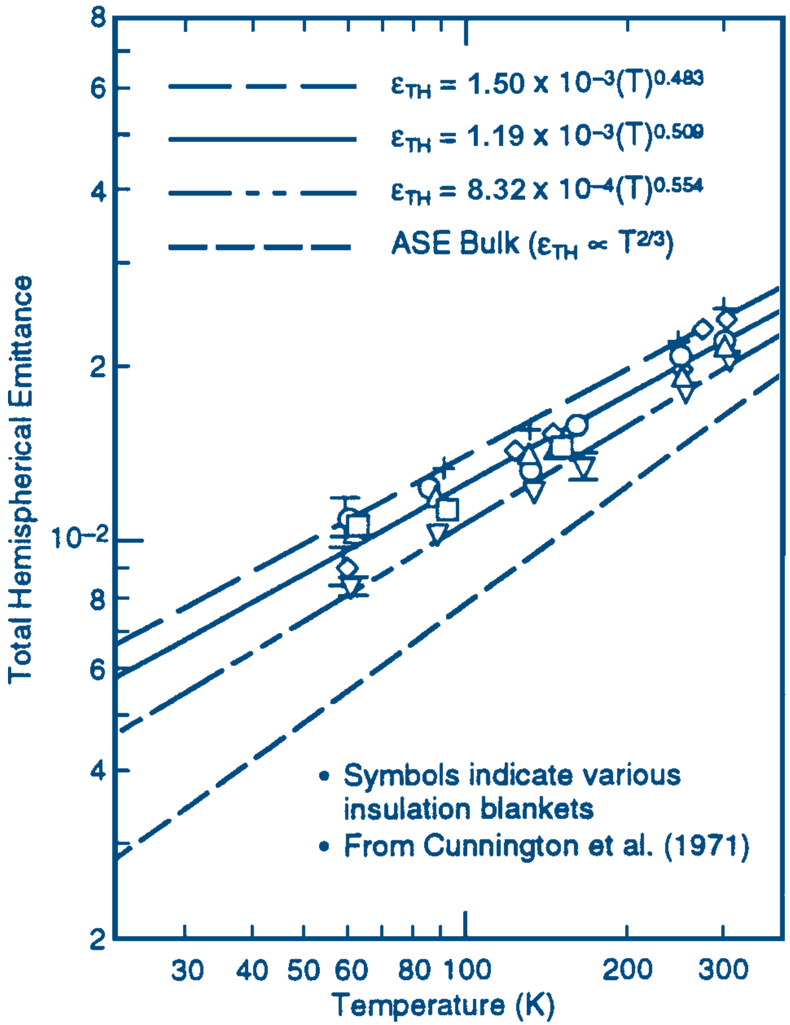
- SLI Radiation Absorbed ($\epsilon_H = 1$, $\epsilon_C = 6.8 \times 10^{-4} T_H^{0.67}$)
- Lines of constant Effective Emittance
- ● 20 JPL 20-layer Cassini (SSAK+5EK+15MN+AK)
- ○ 20 JPL Duo-layup Cassini (SSAK+5EK/15MN+A) (20 layers in 2 blankets with staggered seams)
- ♦ 10 Unperf. DAM 1-SN MLI (X = number of layers) (LMSC dewar minimum achiev. layer density)

Observations:

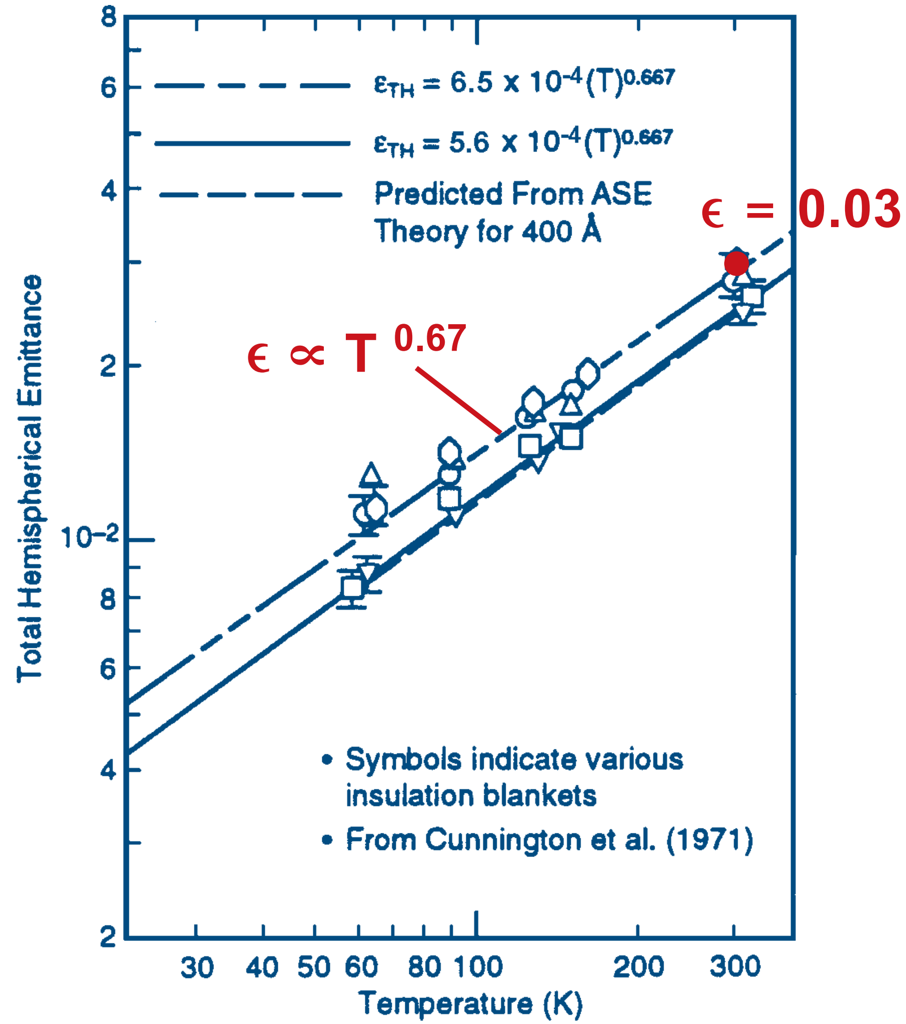
- Effective Emittance of Dewar MLI drastically degrades as hot-side temperature drops down to 40 K
- Spacecraft MLI has 10x greater effective emittance than dewar MLI

Lockheed Characterization of MLI Emittance as a Function of Temperature

Goldized Mylar



Aluminized Mylar



Lockheed Equation for Estimating MLI Thermal Radiation Loads

Classic Lockheed MLI Equation

MLI Conductivity

Conduction

Radiation

$$q = q_c + q_r = \frac{C_c N^{2.56} T_m}{n}(T_h - T_c) + \frac{C_r \epsilon_o}{n}(T_h^{4.67} - T_c^{4.67})$$

$\epsilon_o T^{0.67} \times T^4$

where

- q = total heat flux transmitted through the MLI (mW/m²)
- q_c = conductive heat flux transmitted through the MLI (mW/m²)
- q_r = radiative heat flux transmitted through the MLI (mW/m²)
- C_c = conduction constant = 8.95×10^{-5}
- C_r = radiation constant = 5.39×10^{-7}
- T_h = hot side temperature (K)
- T_c = cold side temperature (K)
- T_m = mean MLI temperature (K); typically $(T_h+T_c)/2$
- ϵ_o = MLI shield-layer emissivity at 300 K = 0.031
- N = MLI layer density (layers/cm)
- n = number of facing pairs of low-emittance surfaces in the MLI system

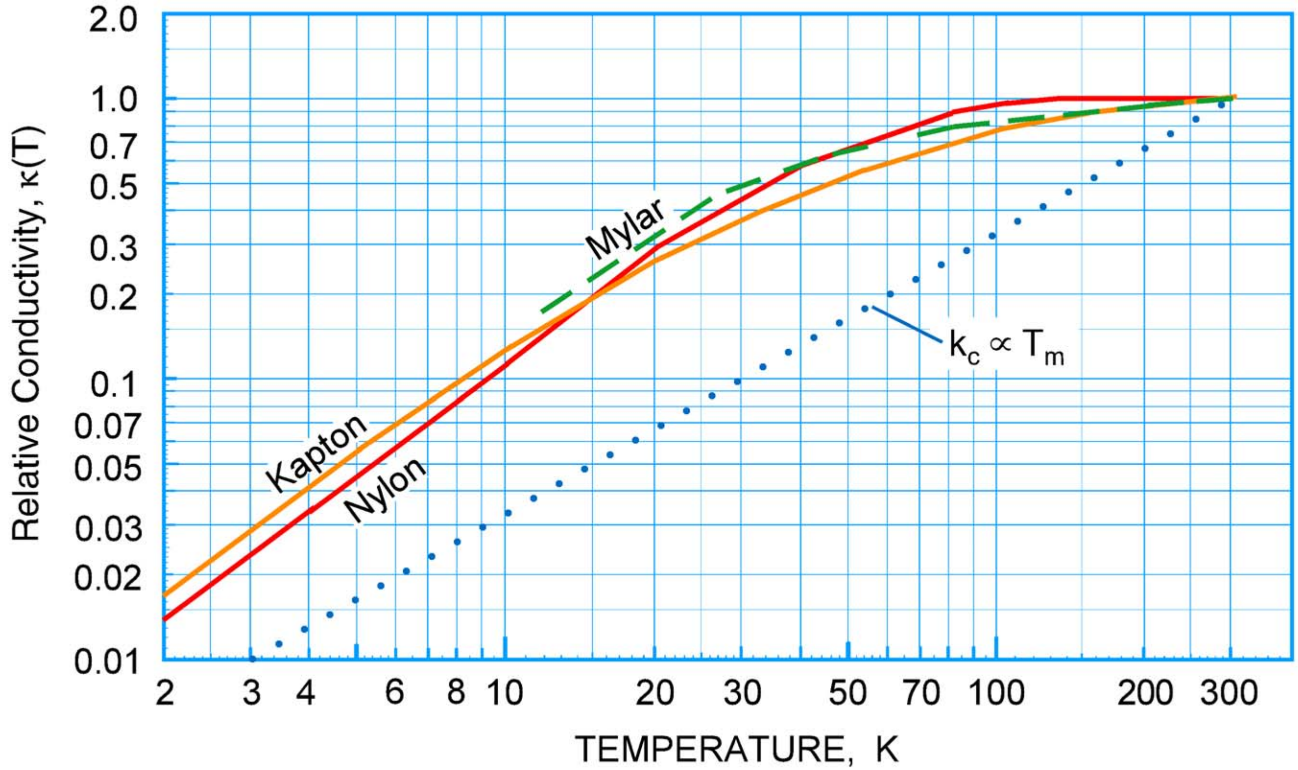
Estimation of Thermal Radiation Loads with Cryo MLI

Modified Lockheed MLI Equation

$C_c N^{2.56} T_m$

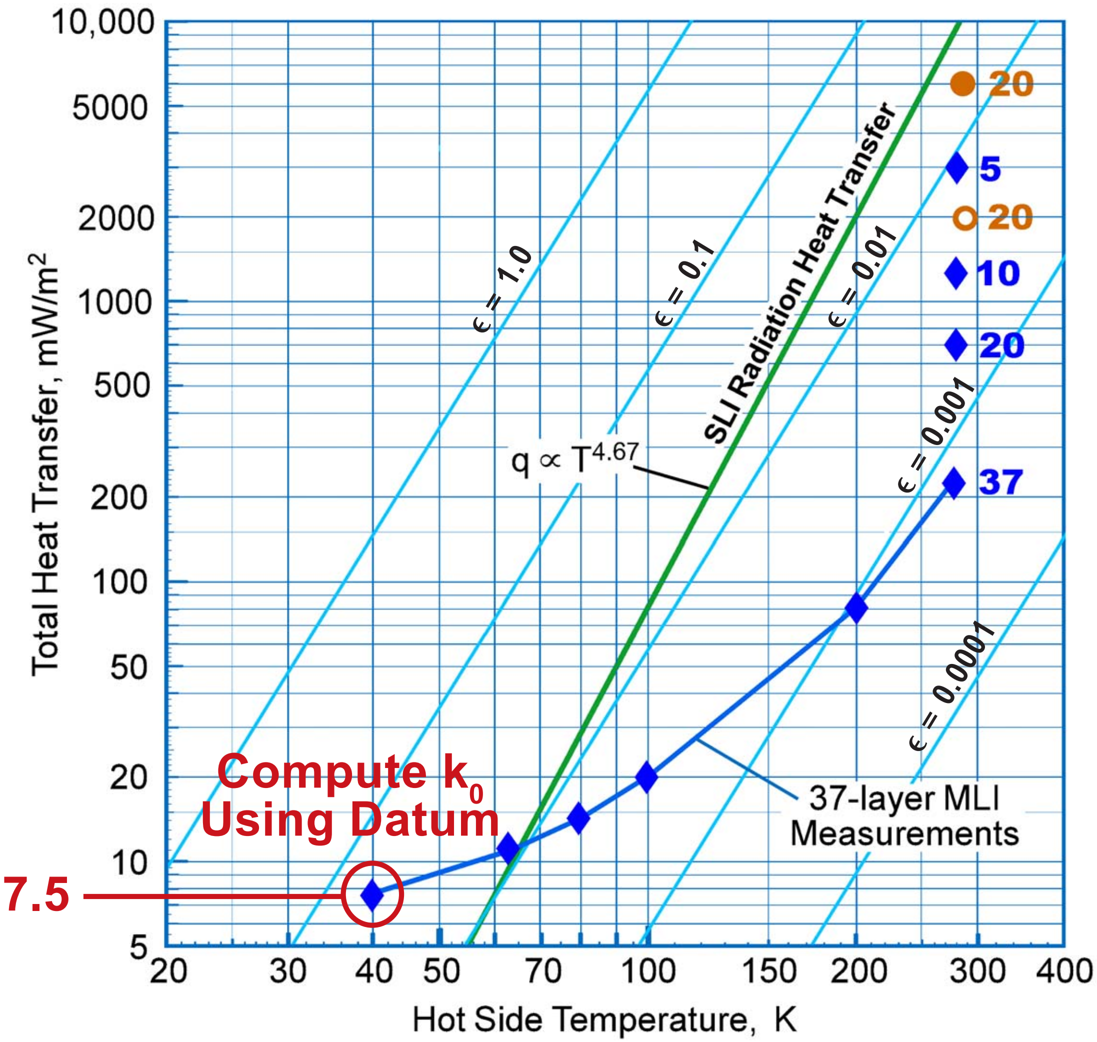
Conduction — Radiation

$$q = q_c + q_r = \frac{k_o\,\kappa(T)}{n}(T_h - T_c) + \frac{C_r\,\epsilon_o}{n}(T_h^{4.67} - T_c^{4.67})$$



Measured Thermal Radiation Loads with Room-Temperature MLI

Gold = JPL S/C MLI **Blue** = LMSC Dewar MLI



Key:

(green line)	SLI Radiation Absorbed ($\epsilon_H = 1$, $\epsilon_C = 6.8\times10^{-4}\,T_H^{0.67}$)
(blue line)	Lines of constant Effective Emittance
● 20	JPL 20-layer Cassini (SSAK+5EK+15MN+AK)
○ 20	JPL Duo-layup Cassini (SSAK+5EK/15MN+A) (20 layers in 2 blankets with staggered seams)
◆ 10	Unperf. DAM 1-SN MLI (**X** = number of layers) (LMSC dewar minimum achiev. layer density)

Observations:

- Room-temperature MLI quickly degrades at lower Hot-Side Temps.
- Spacecraft MLI 10x higher emittance than Dewar ML

Lockheed 37-Layer MLI Calculation for 40K Hot-side Temperature

Nonlinear Equation Set for Lockheed 37-layer Dewar MLI for T_H = 40K

$$q_2 = k_o \kappa(T_2)(T_2 - 4.2)/2 + C_r \epsilon_o (T_2^{4.67} - 4^{4.67})/2 = 7.5$$

$$q_3 = k_o \kappa(T_3)(T_3 - T_2)/3 + C_r \epsilon_o (T_3^{4.67} - T_2^{4.67})/3 = 7.5$$

$$q_5 = k_o \kappa(T_5)(T_5 - T_3)/5 + C_r \epsilon_o (T_5^{4.67} - T_3^{4.67})/5 = 7.5$$

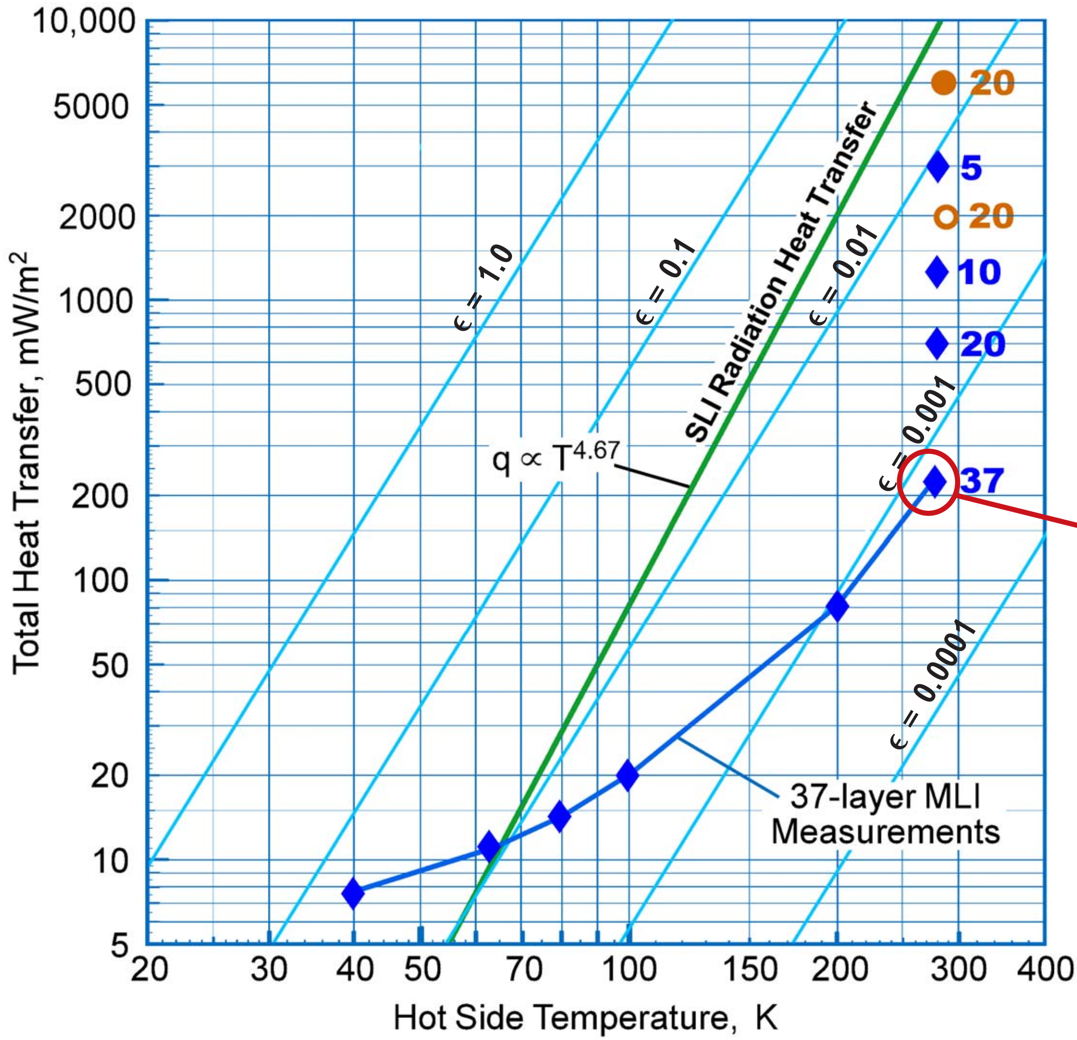
$$q_{10} = k_o \kappa(T_{10})(T_{10} - T_5)/10 + C_r \epsilon_o (T_{10}^{4.67} - T_5^{4.67})/10 = 7.5$$

$$q_{17} = k_o \kappa(40)(40 - T_{10})/17 + C_r \epsilon_o (40^{4.67} - T_{10}^{4.67})/17 = 7.5$$

No. Layers (ν)	T (K)	ΔT (K)	k_o ($mW/m^2 \cdot K$)	q_c (mW/m^2)	q_r (mW/m^2)	q_{Total} (mW/m^2)
cold wall	4.0	**Calc**	**Calc**	**99% Conduction!**		**Fixed**
2	11.5	7.5	25	7.5	0.06	7.5
3	16.5	5.0	25	7.5	0.06	7.5
5	22.0	5.5	25	7.5	0.06	7.5
10	30.0	8.0	25	7.5	0.06	7.5
17	40.0	10.0	25	7.5	0.06	7.5

Measured Thermal Radiation Loads with Room-Temperature MLI

Gold = JPL S/C MLI **Blue = LMSC Dewar MLI**



Key:

- SLI Radiation Absorbed ($\epsilon_H = 1$, $\epsilon_C = 6.8\times10^{-4}\, T_H^{0.67}$)
- Lines of constant Effective Emittance
- ● 20 — JPL 20-layer Cassini (SSAK+5EK+15MN+AK)
- ○ 20 — JPL Duo-layup Cassini (SSAK+5EK/15MN+A) (20 layers in 2 blankets with staggered seams)
- ♦ 10 — Unperf. DAM 1-SN MLI (**X**= number of layers) (LMSC dewar minimum achiev. layer density)

Next, Compute Heat Transfer for 278 K Point using k_o = 25

....and then compute for the other T_{HOT} points

Lockheed 37-Layer MLI Calculation for 278 K Hot-side Temperature

Nonlinear Equation Set for Lockheed 37-layer Dewar MLI for $T_H = 40K$

$$q_2 = 25 \times \kappa(T_2)\,(T_2 - 4.2)/2 + C_r \epsilon_o (T_2^{4.67} - 4^{4.67})/2 = Q_{278}$$

$$q_3 = 25 \times (T_3)\,(T_3 - T_2)/3 + C_r \epsilon_o (T_3^{4.67} - T_2^{4.67})/3 = Q_{278}$$

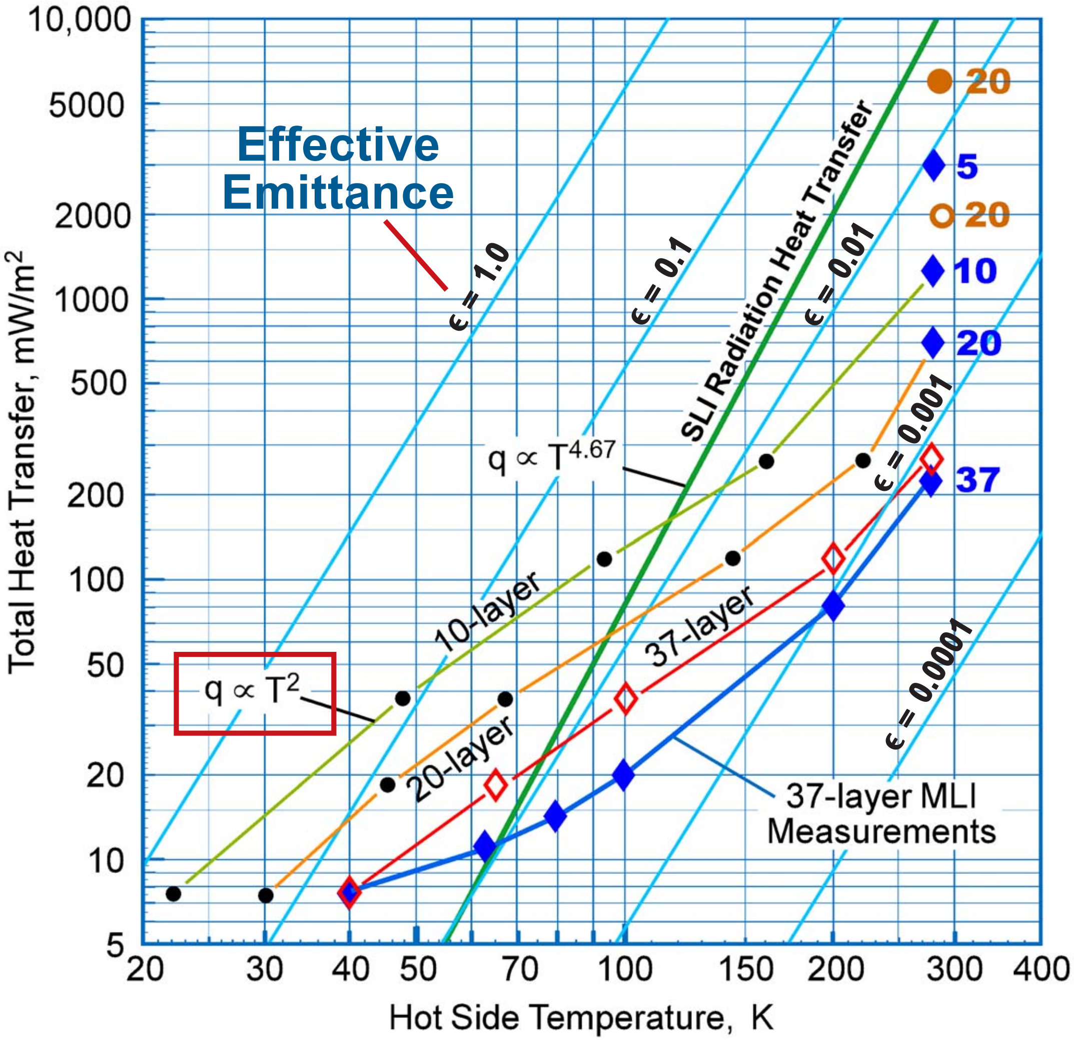
$$q_5 = 25 \times (T_5)\,(T_5 - T_3)/5 + C_r \epsilon_o (T_5^{4.67} - T_3^{4.67})/5 = Q_{278}$$

$$q_{10} = 25 \times \kappa(T_{10})\,(T_{10} - T_5)/10 + C_r \epsilon_o (T_{10}^{4.67} - T_5^{4.67})/10 = Q_{278}$$

$$q_{17} = 25 \times \kappa(40)\,(40 - T_{10})/17 + C_r \epsilon_o (40^{4.67} - T_{10}^{4.67})/17 = Q_{278}$$

No. Layers (ν)	T (K)	ΔT (K)	k_o ($mW/m^2 \cdot K$)	q_c (mW/m^2)	q_r (mW/m^2)	q_{Total} (mW/m^2)
cold wall	4.0	Calc	Fixed	Cond at low T		Calc
2	38	34	25	252	3	275
3	96	43	25	250	11	275
5	160	64	25	224	57	275
10	220	60	25	132	130	275
17	278	58	25	78	195	275

Computed Thermal Loads for Lockheed 37-Layer Dewar MLI



Key:

Green line	SLI Radiation Absorbed ($\epsilon_H = 1$, $\epsilon_C = 6.8 \times 10^{-4}\, T_H^{0.67}$)
● 20	JPL 20-layer Cassini (SSAK+5EK+15MN+AK)
○ 20	JPL Duo-layup Cassini (SSAK+5EK/15MN+A) (20 layers in 2 blankets with staggered seams)
◆ 10	Unperf. DAM 1-SN MLI (X= number of layers) (LMSC dewar minimum achiev. layer density)
◇	Modeled results for LMSC 37-layer DAM 1-SN
Orange line	Modeled results for LMSC 20-layer DAM 1-SN
Yellow-green line	Modeled results for LMSC 10-layer DAM 1-SN
Blue line	Lines of constant Effective Emittance

Bottom Line:

- Room-temperature MLI quickly degrades at lower Hot-Side Temps. Avoid using at T_H<100K
- Spacecraft MLI 10x higher emittance than Dewar ML

Conductance and Thermal Gradient Calculation for 21-layer Cassini MLI

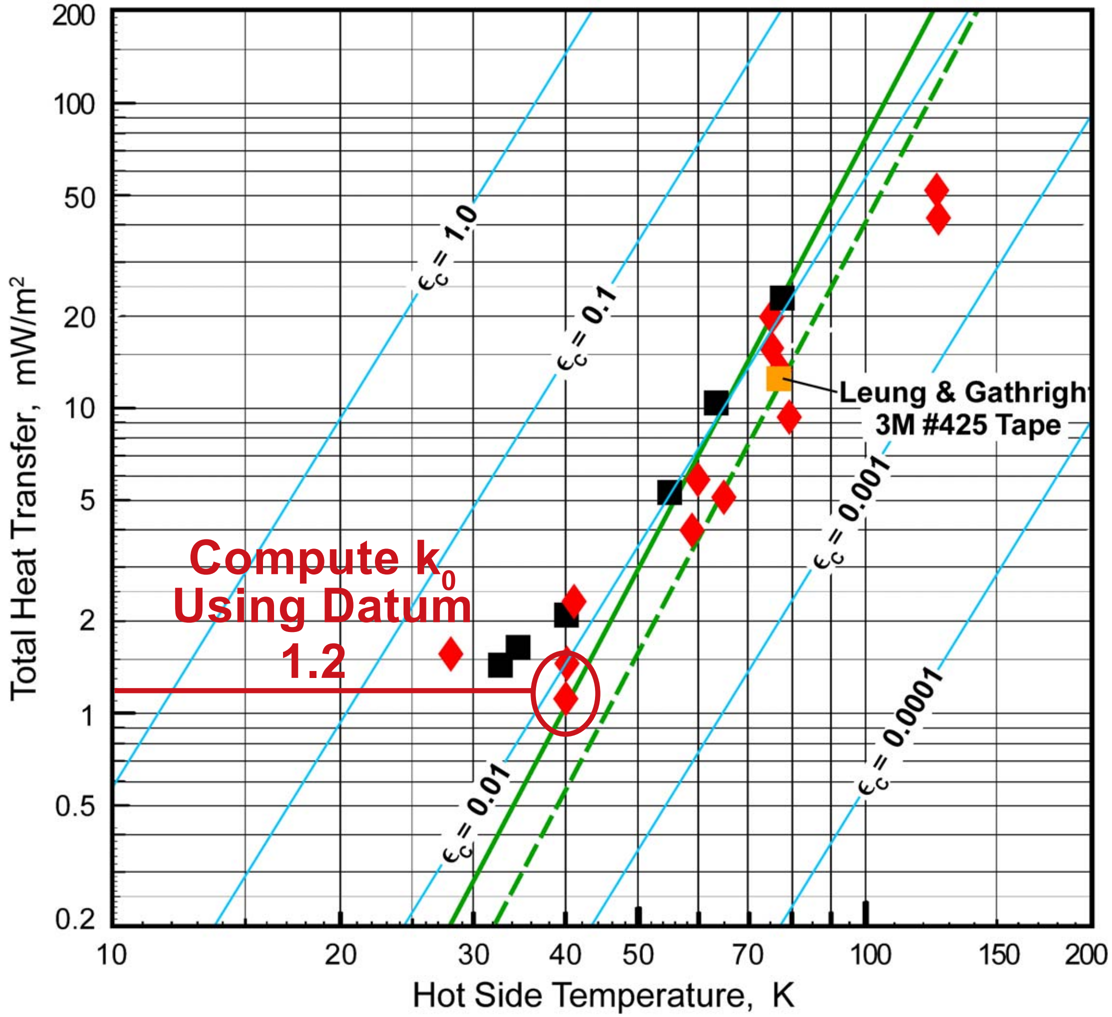
Calculations for JPL 21-layer S/C MLI with 328 K hotbox and 87K coldwall

No. Layers (ν)	T (K)	ΔT (K)	k_o (mW/m²·K)	q_c (mW/m²)	q_r (mW/m²)		q_{Total} (mW/m²)
cold wall	87	**Calc**	vacuum gap (ϵ=1)	**Mostly Cond**			**Fixed**
MLI out surface	121	34	n/a **Calc**	0	8720		8720
5	167	46	925	8635	85	**99%**	8720
15	304	137	925	8240	480		8720
1	313	9	925	7613	1107	**87%**	8720
inner hot box	328	15	vacuum gap (ϵ=0.08)	0	8720		8720

JPL Cassini MLI is 37x more conductive than Lockheed's Dewar MLI

Measured Thermal Radiation Loads with Lockheed Cryo-MLI & SLI

♦ = 9 Layer DAM with 3 silk nets



Key:

- SLI facing Black ($\epsilon_H = 1$, $\epsilon_C = 6.8 \times 10^{-4}\, T_H^{0.67}$)
- SLI facing SLI ($\epsilon_H = \epsilon_C = 6.8 \times 10^{-4}\, T_H^{0.67}$)
- Unperf. 9 Layer DAM with 3-SN (LMSC dewar minimum achiev. layer density)
- Bare tank taped with Double Alum Mylar (SLI)
- Lines of constant Effective Emittance

Observations:

- Cryo Dewar MLI is seen to improve upon SLI emittance down to 40 K Hot-Side Temps (but only by 2x)
- Spacecraft MLI has no hope at cryogenic Hot Side Temps
- 3M #425 tape is comparable to Cryo MLI

Measured Thermal Radiation Loads with Lockheed Cryo MLI

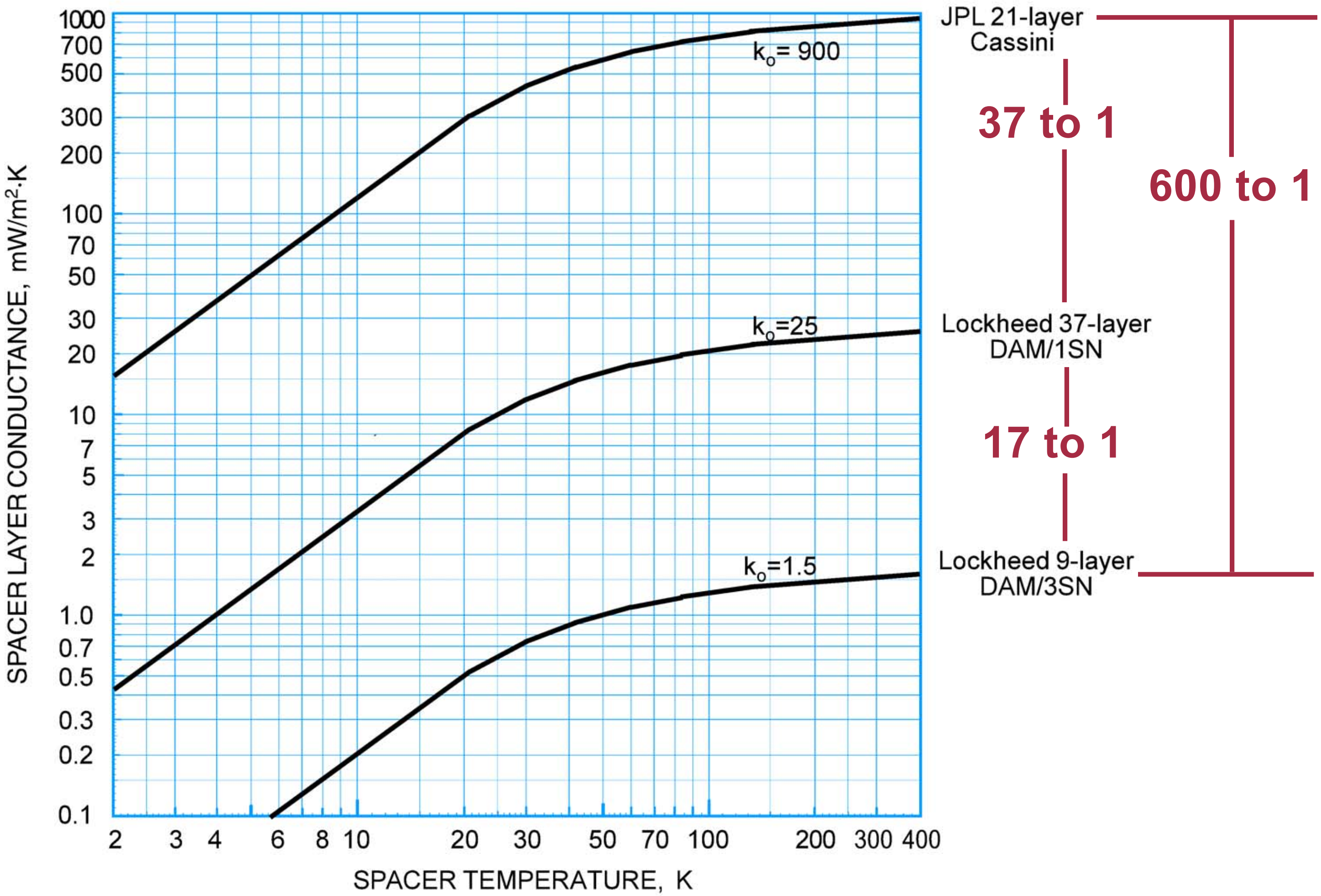
Calculations for Lockheed's 9-Layer 3-SN Cryo MLI with $T_H = 40K$

No. Layers (ν)	T (K)	ΔT (K)	k_o ($mW/m^2 \cdot K$)	q_c (mW/m^2)	q_r (mW/m^2)	q_{Total} (mW/m^2)
cold wall	4.2	**Calc**	**Calc**	**88% Conduction!**		**Fixed**
1	11.5	8.3	1.5	1.07	0.14	1.2
1	16.5	4.0	1.5	1.07	0.14	1.2
2	21.7	5.4	1.5	1.07	0.14	1.2
2	25.7	4.0	1.5	1.07	0.14	1.2
3	30.0	4.3	1.5	1.07	0.12	1.2
hot wall	40.0	10.0	-	0	1.2	1.2

Lockheed Cryo MLI is 17x less conductive than Lockheed's 37-Layer Conventional Dewar MLI

Measured Conductances of Various MLI Constructions

600 to 1 Variability in MLI Conductance between Cryo-dewar MLI and S/C MLI



Conclusions

- Calculation technique provides very useful insights into MLI performance
  - Layer Conductance (k_0)
  - Conduction/Radiation/Temp gradient thru MLI

- Lessons Learned: Estimating cryogenic heat loads with cryogenic MLI has LARGE uncertainties
  - 600 to 1 range of conductances (tough job to pick correct value for predictions)
  - MLI quickly degrades to SLI at $T_H < 100$ K as MLI conductance totally dominates below 100 K