Cryocoolers for Space Applications #2

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Topics

- **Space Cryocooler Historical Overview and Applications**
- **Space Cryogenic Cooling System Design and Sizing**
- **Space Cryocooler Performance and How It's Measured**
- **Cryocooler-Specific Application and Integration Example: The AIRS Instrument**

Topics

- Spacecraft Design and Qualification Requirements Overview
- Cryogenic Load Estimation and Management Practices
- Estimating Cryocooler Off-State Conduction
- Vacuum Level Considerations for Cryogenic Applications
  - Gaseous Conduction, Cryopumping, High Emittance Films
- Estimating Structural Support Thermal Conduction Loads
  - Load Estimating "Rule of Thumb"
  - MLI and Gold Plating Lateral Conductivity
- Estimating Thermal Radiation Loads
  - Radiation Heat Transfer in Cryogenic Applications
  - Effect of Material properties and Contaminant Layers
  - MLI Performance (Room Temperature vs Cryo)

References

- Donabedian, M., “Thermal Uncertainty Margins for Cryogenic Sensor Systems,” AIAA-91-1426, AIAA 26th Thermophysics Conference, June 24-26, 1991, Honolulu, Hawaii, pp. 1-14 (doi: 10.2514/6.1991-1426)
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- General Environmental Verification Specification for STS & ELV Payloads, Subsystems, and Components, GEVS-SE, Rev A, NASA Goddard Space Flight Center, Greenbelt, MD, 1996, 233 p.
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- Nast, T.C., “A Review of Multilayer Insulation Theory, Calorimeter Measurements, and Applications,” *Recent Advances in Cryogenic Engineering - 1993*, ASME HTD-Vol. 267, ASME, New York (1993), pp. 29-43. (17 references).
- Ross, R.G., Jr., “Chapter 6: Refrigeration Systems for Achieving Cryogenic Temperatures,” *Low Temperature Materials and Mechanisms*, Y. Bar-Cohen (Ed.), CRC Press, Boca Raton, FL (Scheduled to be published in Nov. 2015). (79 references).
- http://www2.jpl.nasa.gov/adv_tech/ JPL website with 103 JPL cryocooler references as PDFs (R. Ross, webmaster)

Principal Cryogenic System Development Challenges

- 5 to 10 YEAR LIFE with >0.95 RELIABILITY
  - This corresponds to 2,000,000 miles for an automobile with no breakdowns or servicing
  - Also requires compatibility with spacecraft environments and environmental changes over mission life
- Compatibility with Sophisticated Science Instruments
  - S/C science instruments demand low levels of vibration and EMI and highly stable temperatures
- Compatibility with S/C environments and interfaces
  - Reasonable size and weight
  - Compatible thermal interfaces and heat dissipation levels
  - Compatible electrical interfaces (power level, inrush, ripple current)
  - Compatible with digital communication interfaces

Cryocooler Technology Drivers

- 5 to 10-year (50,000 hour) operational life mechanical mechanism
  - Huge potential for wear and mechanical fatigue (~10^{10} cycles)
- Sensitive mechanical construction
  - Precision part fit and alignment
  - Fragile cold-end construction
  - Strong sensitivity to leakage of working fluid (Helium)
- High sensitivity to contamination
  - Lubricants or rubbing surfaces generate contaminants (Typically, No lubricants allowed in long-life coolers)
  - Cold surfaces getter contaminants from all sources
- Complex drive electronics to provide AC waveforms and closed-loop control of piston motions, vibration, and coldtip temperature
  - AC drive generates vibration, EMI, and high ripple currents
- Difficult failure analysis
  - Operation obscured by pressure vessels and vacuum jackets
  - Observation and rework require resealing, decontamination, and refilling — often requiring several weeks

Programmatic Lessons Learned

- Simplicity, Maturity and Broad Usage are Critical to Success
  - Simplicity = shorter devel., improved reliability, lower cost
  - Development level-of-effort needs to match sponsor/mission time window and funds allocation
  - Successful technologies generally funded by multiple sources over many-year time periods before critical maturity reached. Broad interest base key to multiple-sponsor continuity

- Development Time-Constant vs. Mission-Life-Cycle a Key Issue
  - Often requirements/need changes before cryosystem completed
  - 2x change in cryogenic loads = major redesign

- Key to Achieving a Successful Space Application
  - All S/C requirements fully factored into R&D phase (launch loads, system interfaces, temperatures, EMI, safety, etc.)
  - Analytical and test methods for flight, developed in R&D phase
  - S/C timeline matched to cooler development time/maturity level
  - Stable S/C requirements to accommodate long cooler devel. time
  - Simple program interfaces to allow focus on technical challenges

Cryocooler R&D Development Process

- Establish detailed generic cooler requirements for target missions including system operational interfaces, environmental and operational stress levels, reliability, and life
- Develop preliminary design able to meet requirements
- Analyze performance and determine principal failure modes and failure-mechanism parameter dependencies
  - Develop and conduct Reliability Physics Analyses
  - Develop and conduct mechanism-specific Characterization and Life Tests of brassboard hardware
- Resolve or design-out requirement shortfalls
- Fabricate engineering model
- Conduct product performance verification tests
  - Full set of Qualification Tests
  - System-level functional tests
  - Multi-year Life Tests
- Feed back results into next-generation hardware and cooler Specification

Characterization and Accelerated Life Testing Objectives and Attributes

OBJECTIVE

- To understand and quantify the fundamental interdependencies between performance (failure level), environmental and operational stress level, hardware materials and construction features, and time

ADVANTAGES

- Mechanism-level understanding achieved by selecting specialized tests and facilities targeted at specific degradation stress environments and construction material parameters
- Carefully controlled parameters (generally at parametric levels) with acceleration consistent with accurate extrapolation to use conditions

LIMITATIONS

- Expensive and time consuming — requires specialized testing equipment and modestly long test durations (2 weeks to 5 years)
- Requires multiple tests to address the total spectrum of degradation mechanisms and levels
- Number of specimens insufficient to quantify random failures

Cryocooler Flight Development Process

- **Establish detailed mission-specific cooler requirements** including all system operational interfaces, environmental and operational test levels, electronic parts, reliability, and life
- **Assess heritage design's ability to meet requirements** and modify accordingly
- **Carefully reevaluate principal failure modes and determine compliance with mission requirements**
  - Reliability Physics Analyses (previously proven techniques)
  - Characterization and Life Tests of flight-like components
- **Resolve or design-out requirement shortfalls**
- Fabricate engineering model and flight units (typically in same build sequence)
- **Conduct product performance verification tests**
  - Full set of Qualification Tests
  - System-level functional tests
  - Life Tests often not done (too late, no units, no money)

Qualification Testing Objectives and Attributes

OBJECTIVE

- To rapidly and economically screen hardware designs and flight articles for prominent (non-wearout) failure mechanisms
- To rapidly assess the relative durability of alternative designs

ADVANTAGES

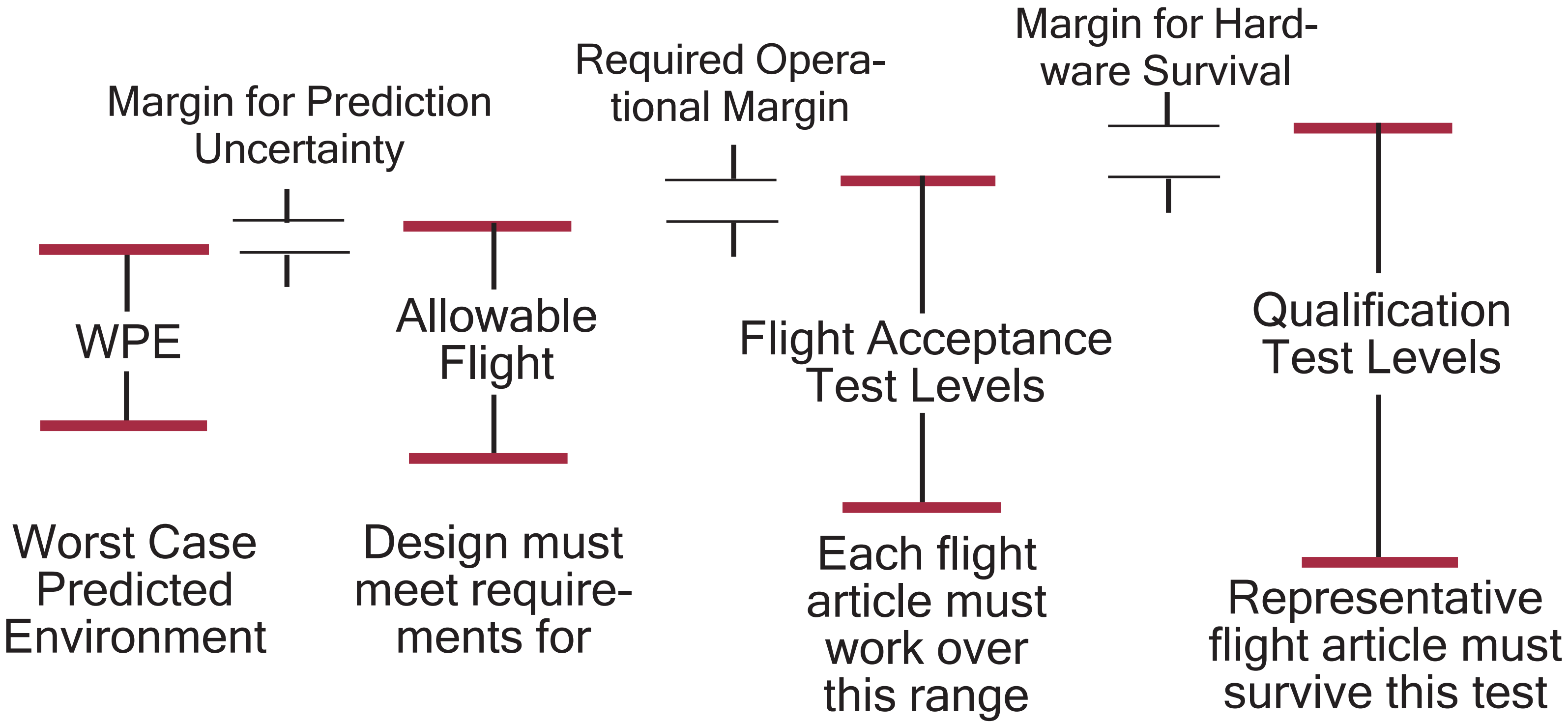
- Quick turnaround — relatively inexpensive
- Relatively standard procedures allows intercomparison with historical data
- Separate tests (vibe and thermal vac) for important environmental and operational stresses aids identification of high-risk mechanisms

LIMITATIONS

- Minimal life-prediction capability (a relative measure of robustness, generally does not quantify life attributes)
- Requires multiple tests and specialized facilities to address the total spectrum of stressing environments
- Number of specimens insufficient to quantify random failures

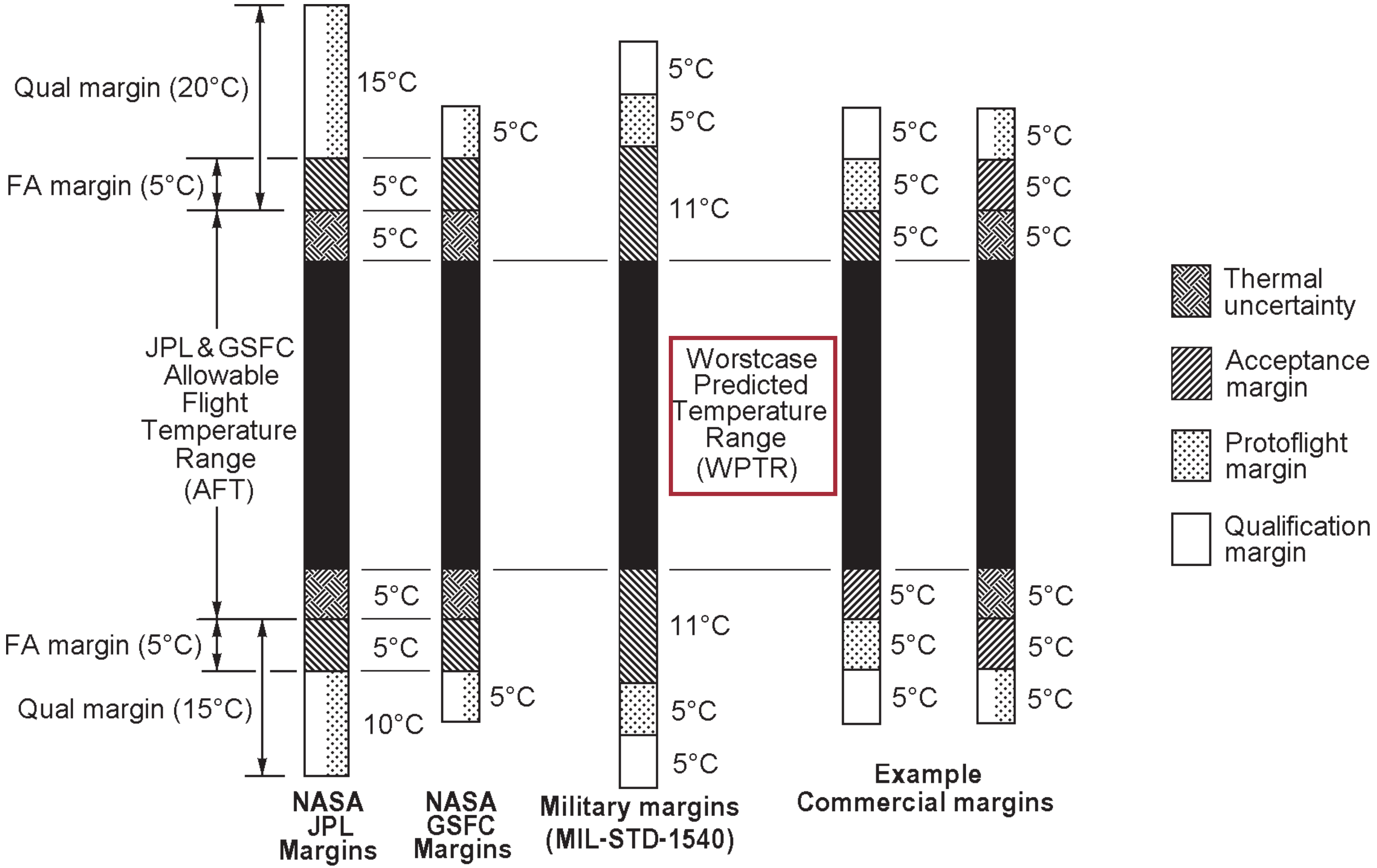
Typical Space Design and Qualification Requirements

- **Aerospace organizations follow a set of institutional requirements for thermal and structural design margins and Qualification test levels.**
  - **Start with Worstcase Predicted Environments (WPE) throughout the space mission (mission specific)**
  - **Flight Acceptance (FA), Protoflight and Qualification (Qual) test levels for the hardware are then defined with respect to WPE**



Typical Space Thermal Design Margin Requirements

For "Room Temperature" Hardware



Full-Up System-Level Testing Objectives and Attributes

OBJECTIVE

- To accurately assess hardware functionality and reliability with special emphasis on system synergisms, interactions, and interfaces

ADVANTAGES

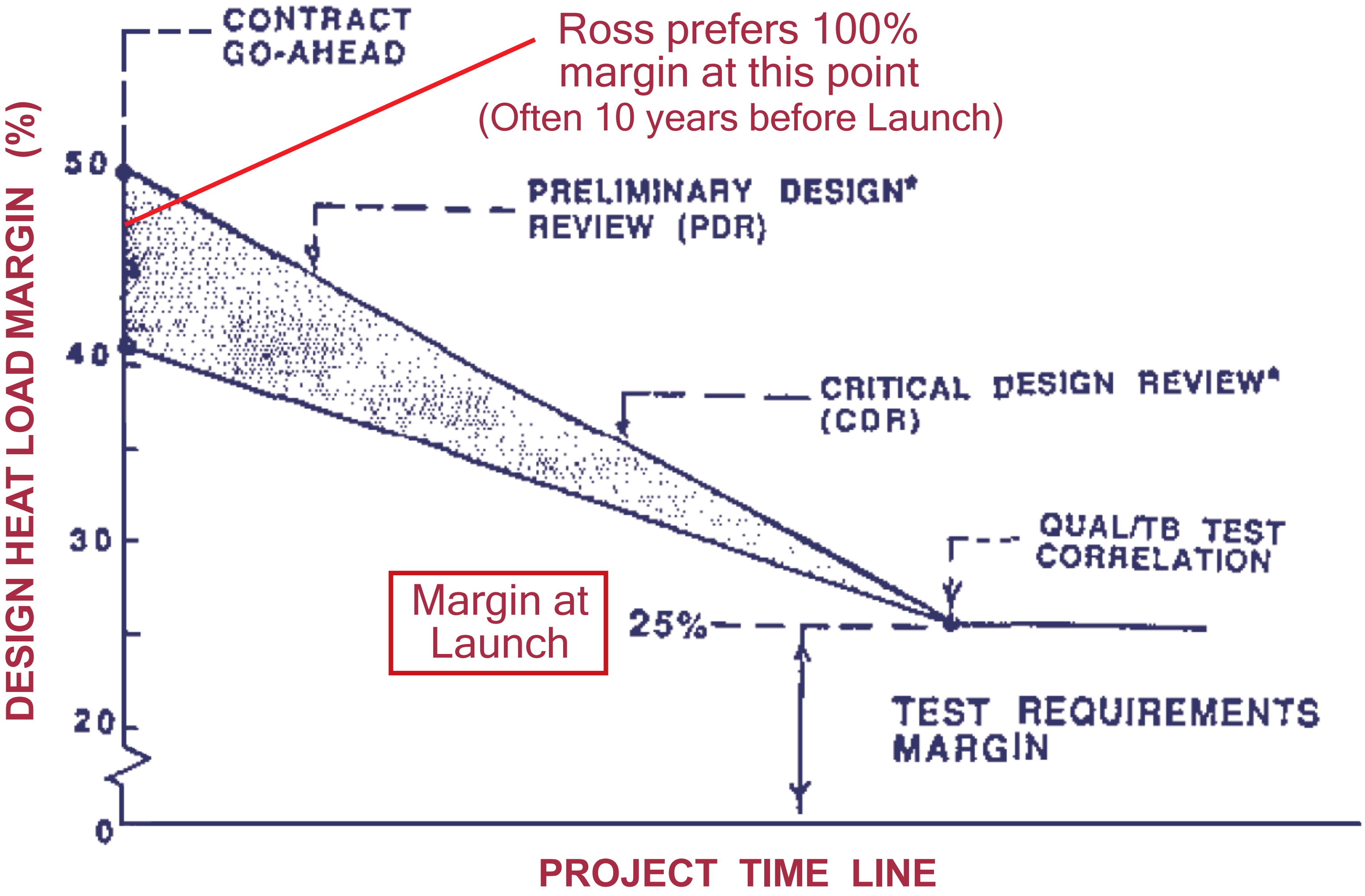
- Complete system interfaces and operating conditions provides reliable assessment of subsystem compatibility issues and degradation mechanisms associated with system interactions or operational stresses
- Inclusion of balance-of-system hardware provides data and confidence in complete functional system

LIMITATIONS

- Requires complete system with all important balance-of-system components and interfaces
- Occurs very late in the design cycle; changes at this point are difficult and expensive
- Significant added complexity in constructing and testing complete system

Recommended Thermal Design/Test Margins for Cryogenic Systems

From Donabedian, M., "Thermal Uncertainty Margins for Cryogenic Sensor Systems," AIAA-91-1426, AIAA 26th Thermophysics Conference, June 24-26, 1991.



Ross prefers 100% margin at this point
(Often 10 years before Launch)

Margin at Launch

Estimating Cryogenic Loads (The Critical Cryosystem Activity)

- One of the most important and difficult tasks in cryogenic system design
  - Needed to select cryocooler design
  - Needed to scope required power and heat dissipation to S/C
  - Needed to identify system thermal design drivers
  - Needed to scope the development risk and cost

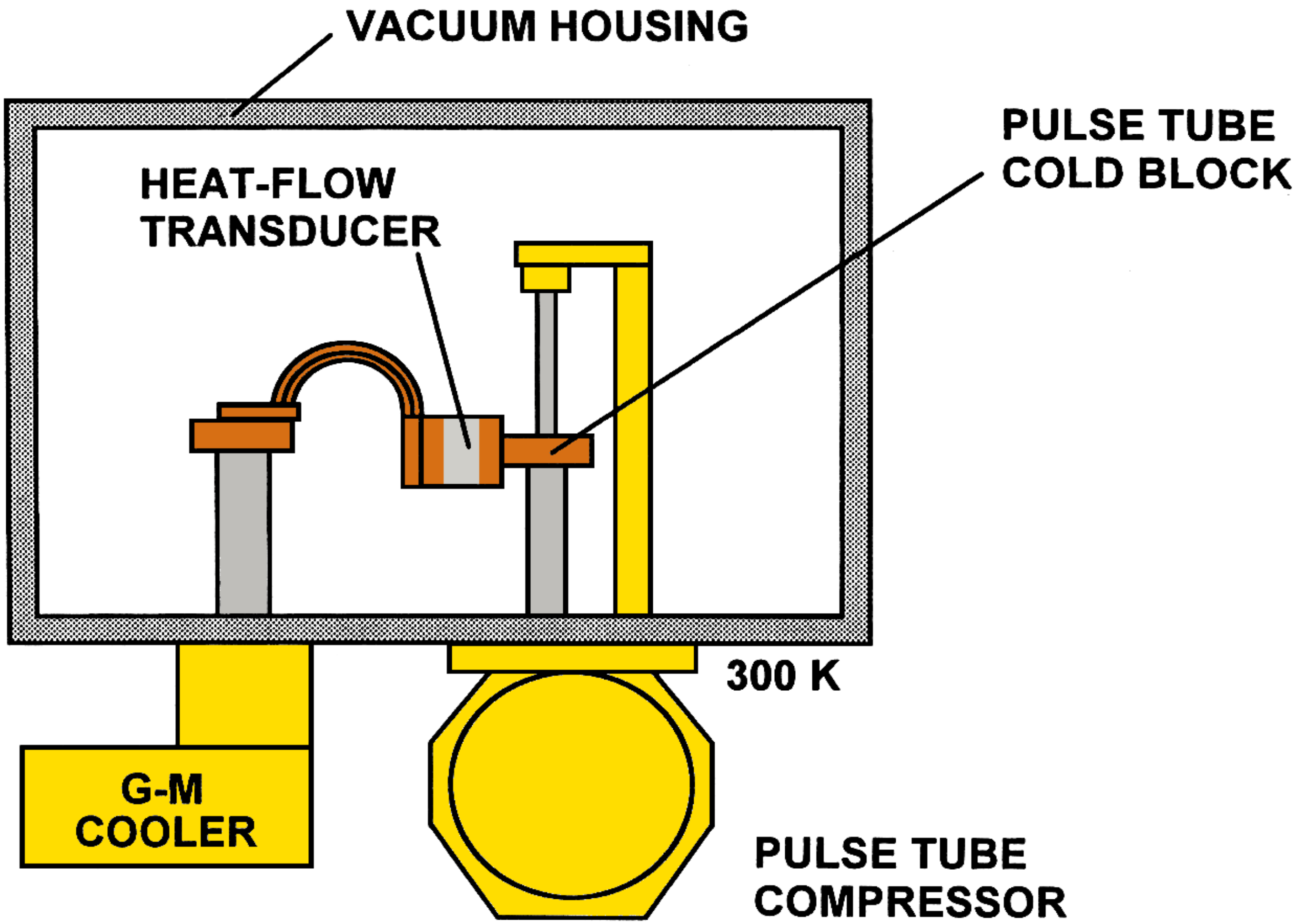
- Needs to be accurate to 2x, AND stay within bounds for entire development period (perhaps 10 years)
  - Exceed 2x: generally implies new cooler system design
  - Very difficult to do for an entirely new system w/o prior history

- Key Steps
  - Derive a strawman cryogenic system design
  - Estimate the total cooling load over total operating range
  - Acquire performance data for the candidate cryocooler
  - Iterate load projections & cooler selection to get workable design
  - Validate design with detailed calculations and engineering tests

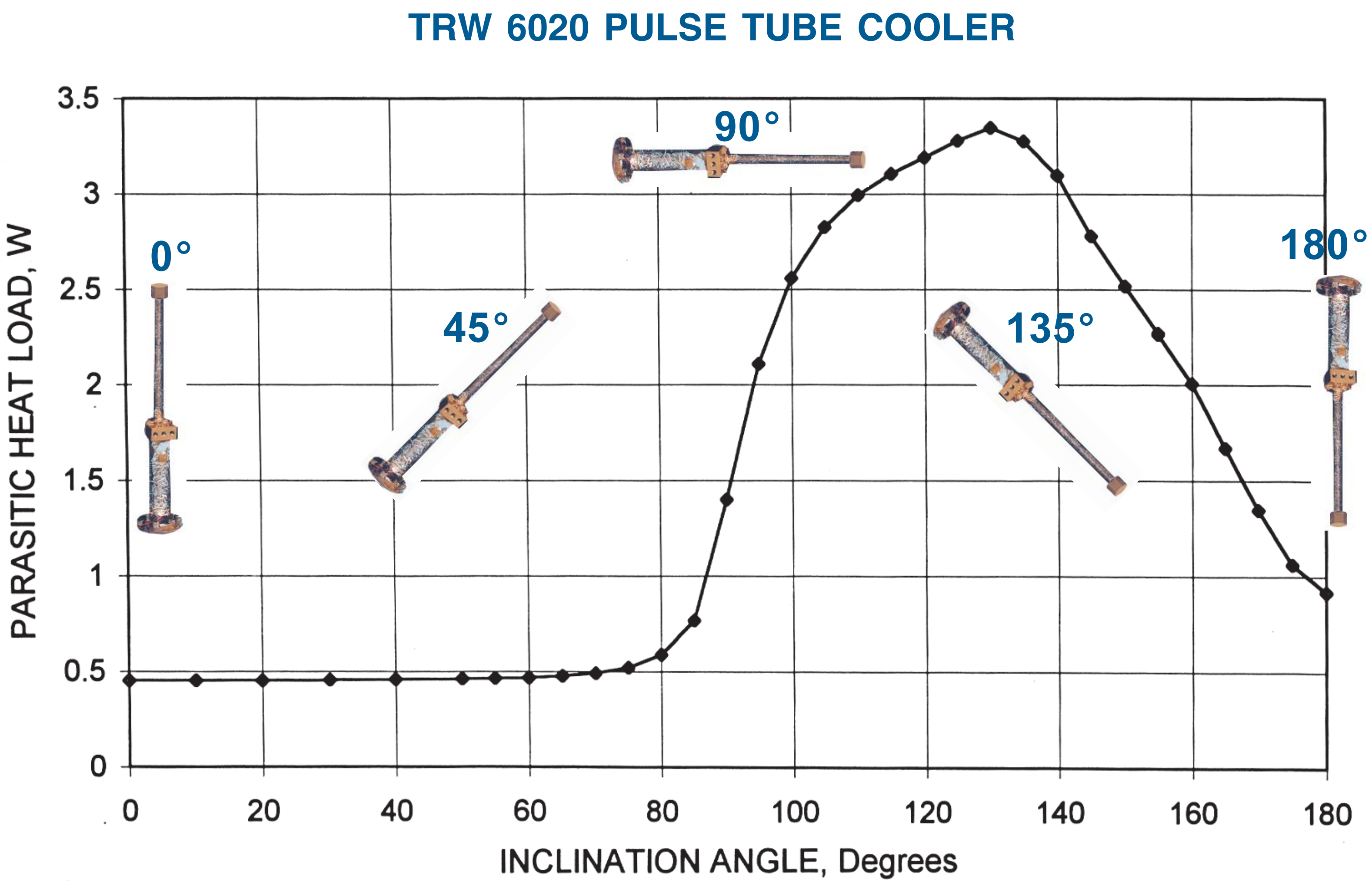
Principal Space Cryocooler Load Contributors

- Active Loads
  - Direct I^2R from detectors, motors, electronics, etc
  - Cryogenic load (liquefying gases or cooling a fluid or solid)
- Parasitic conduction loads of cryosystem interconnections
  - Conduction down plumbing and wiring including convection
  - Conduction down standby non-operating cryocoolers
- Parasitic conduction down cryosystem structural supports
  - Conduction down struts and structural members used to support the cryosystem during launch and in space
  - Requires structural support concept design
- Parasitic radiation from exterior of cryosystem
  - Strong function of the surface emittance of application materials
  - Strong function (T^4) of exterior surface temperatures
  - Strongly dependent on surface cleanliness and material purity
  - Strongly dependent on MLI construction and compaction

Cryocooler Off-State Conduction Test Setup

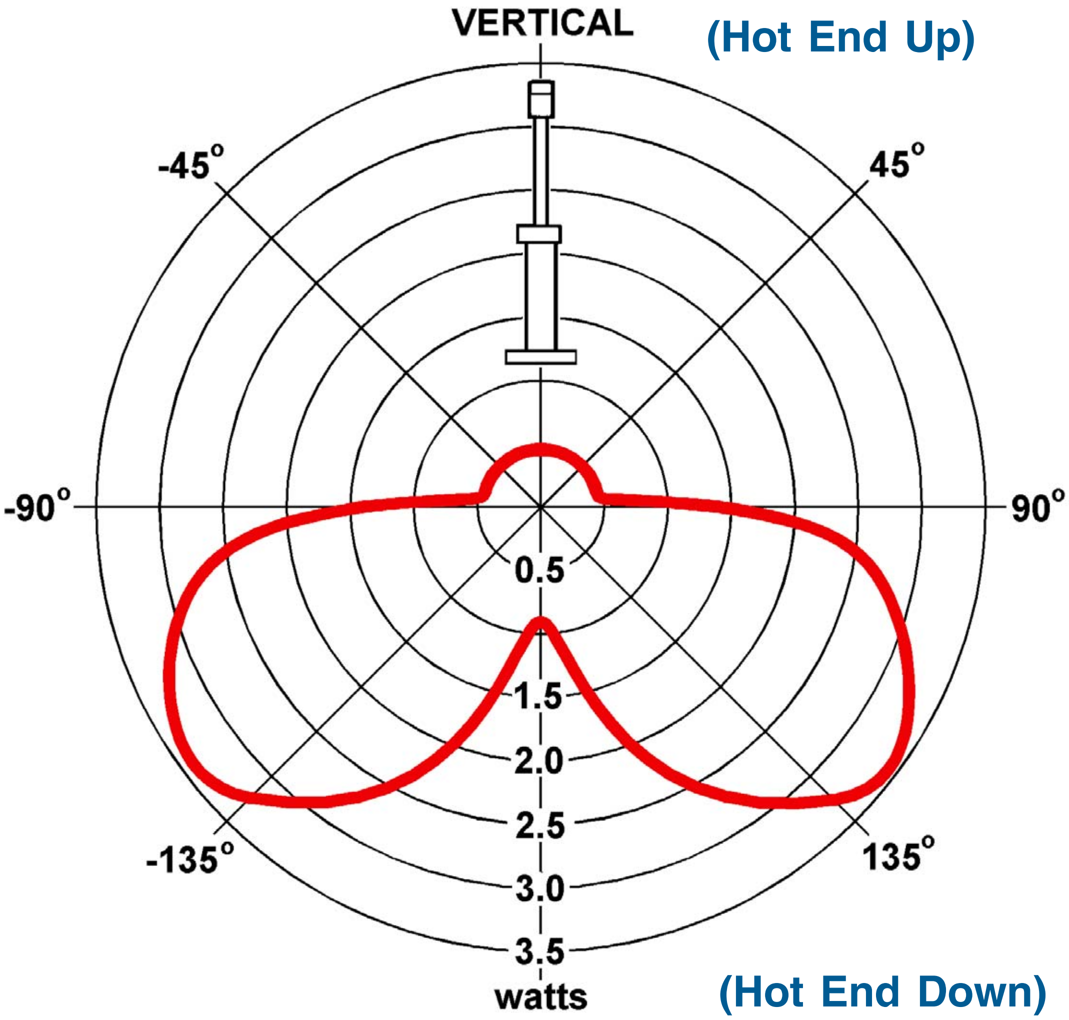


Coldfinger Off-State Conduction Sensitivity to Inclination Angle



PT Off-State Conduction at 60K vs Inclination Angle in 1-G Field

TRW 6020 PULSE TUBE COOLER

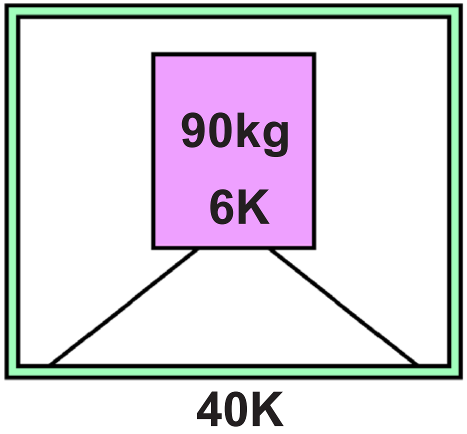


(Hot End Up)

(Hot End Down)

Estimation of Thermal Conduction Loads for Structural Supports

OBJECTIVE



- To rapidly and economically estimate structural conduction loads in the early feasibility design phase
- To assess the quality of a structural design against historical benchmarks for achieved conductance

APPROACH

- Use scaling equations built on known relationships between:
    - Material conductivity and temperature
    - Launch acceleration level and assembly mass
    - Support-member cross-sections and launch acceleration level
    - Conductive load and support-member cross-section
- Scaling Equations calibrated using a database of successful flight designs.

Conductive Load Dependences

$$Q = \kappa \, \Delta T \, (A / L)$$

where

Q = Conducted heat (watts)

κ = Average Material conductivity (watts/cm·K)

ΔT= Differential temperature along member length, K

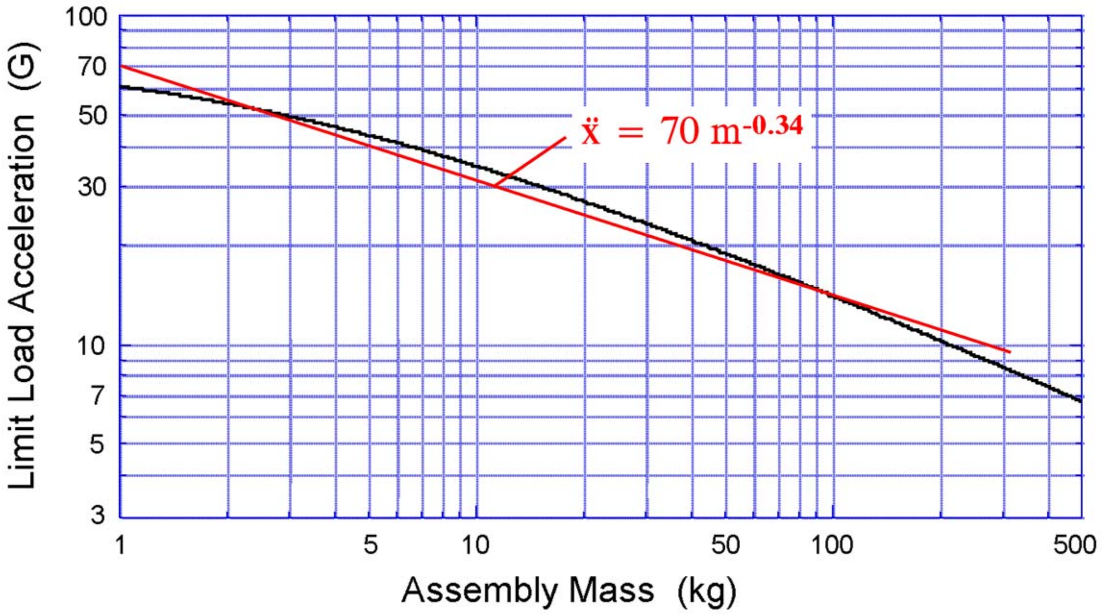
A = Structural member cross-sectional area (cm^2)

L = Structural member length (cm)

PROBLEM: Need Estimate for A/L

A/L Scaling Dependences

- Stress in support material (σ) = Force/Area
- For constant material stress: Area must increase $\propto$ Force
- Force $\propto$ supported mass (m) x launch acceleration ($\ddot{x}$)
- Acceleration ($\ddot{x}$) from Mass Acceleration Curve ($\ddot{x} \propto m^{-0.34}$)
- Thus: A/L $\propto m^{-0.34} \times m$; i.e. $\boxed{(A/L)_2 = (A/L)_1 \times (m_2/m_1)^{0.66}}$



Overall Scaling Equation for Structural Conductance

Thus:

$$Q_2 = Q_1\,(\kappa_2/\kappa_1) \times (m_2/m_1)^{0.66} \times (\Delta T_2/\Delta T_1)$$

where

$Q =$ Conducted heat (watts)

$\kappa =$ Average material conductivity (watts/cm·K)

$m =$ Supported mass, kg

$\Delta T =$ Differential temperature between mass and support point, K

If we define:

$\mathcal{A} =$ Empirical scaling factor $= Q_1 / (\kappa_1\, m_1^{0.66}\, \Delta T_1) = (A_o/L_o)/m_o^{0.66}$

Then:

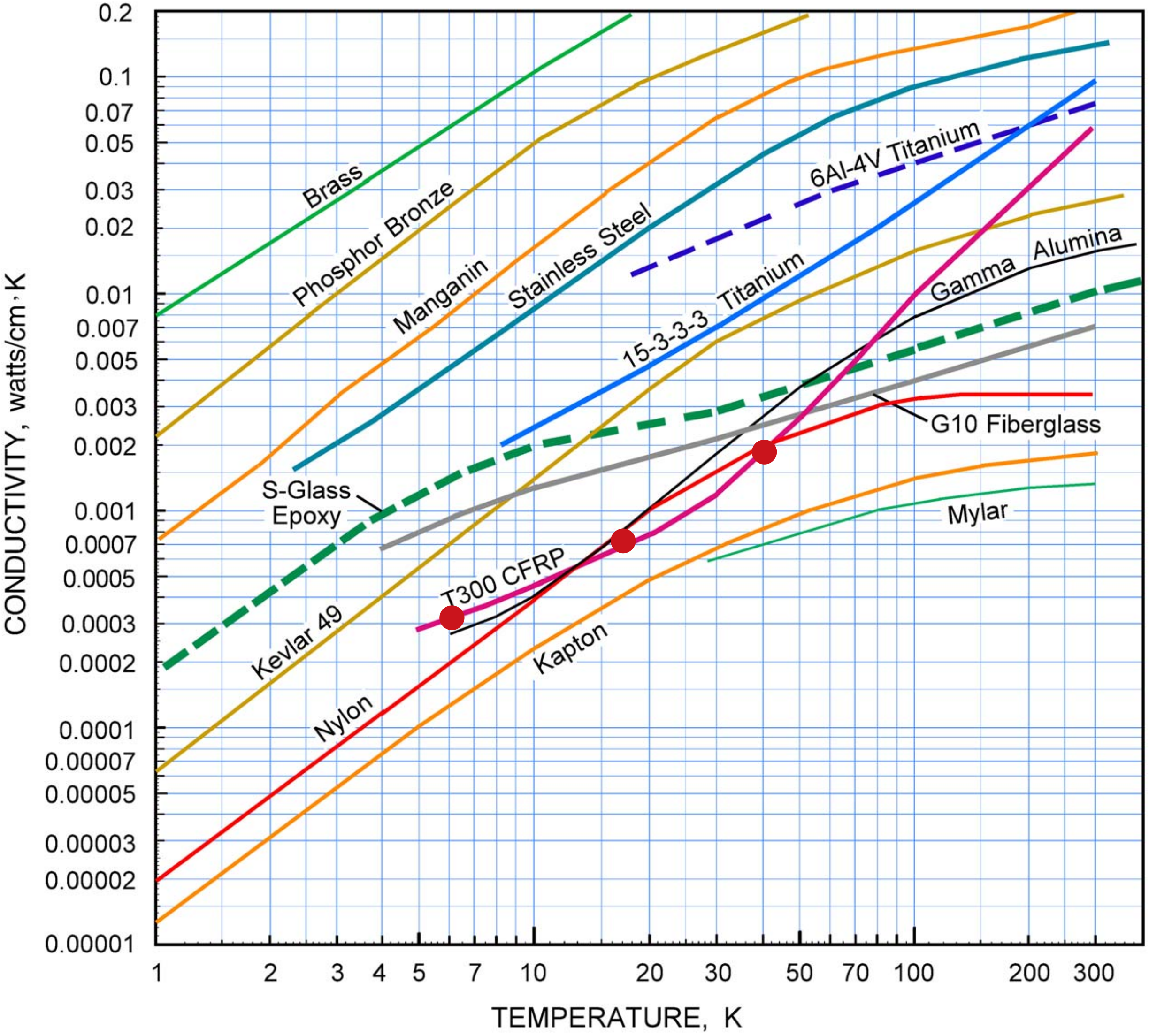
$$\boxed{Q = \mathcal{A}\,\kappa\, m^{0.66}\,\Delta T}$$

From Historical Examples:

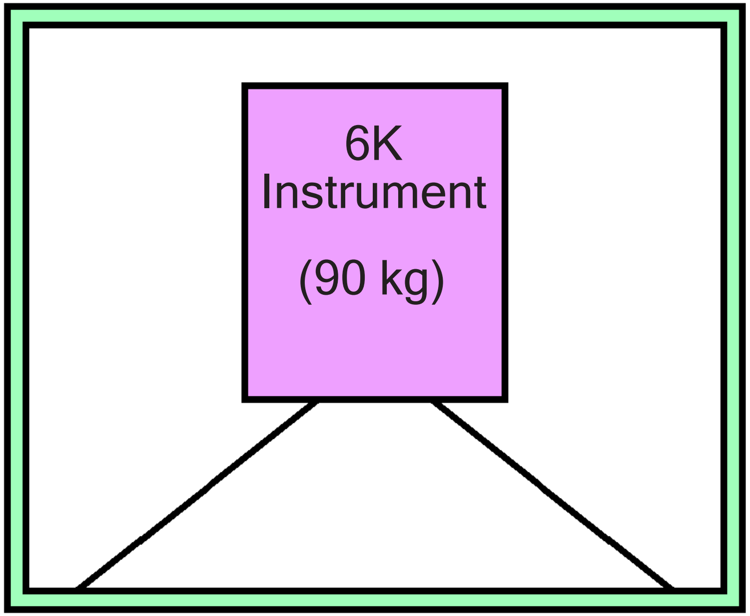
$\mathcal{A} \approx$ 0.28 for non-optimized (cantilevered) structures

$\mathcal{A} \approx$ 0.02 for high-efficiency axially loaded members

Thermal Conductivity of Common Low-Conductivity Structural Materials



Example Space Cryogenic Structure Conduction Estimation Problem



40 K Primary Structure

PROBLEM: Estimate the structural conduction loads:

$$Q = \mathcal{A}\ \kappa\, m^{0.66}\, \Delta T$$
$$= 0.02\,(0.0007)(90)^{0.66}\,(34)$$
$$= 9.3 \text{ mW to } 130 \text{ mW}$$

(corresponding to $\mathcal{A} = 0.02$ to 0.28)

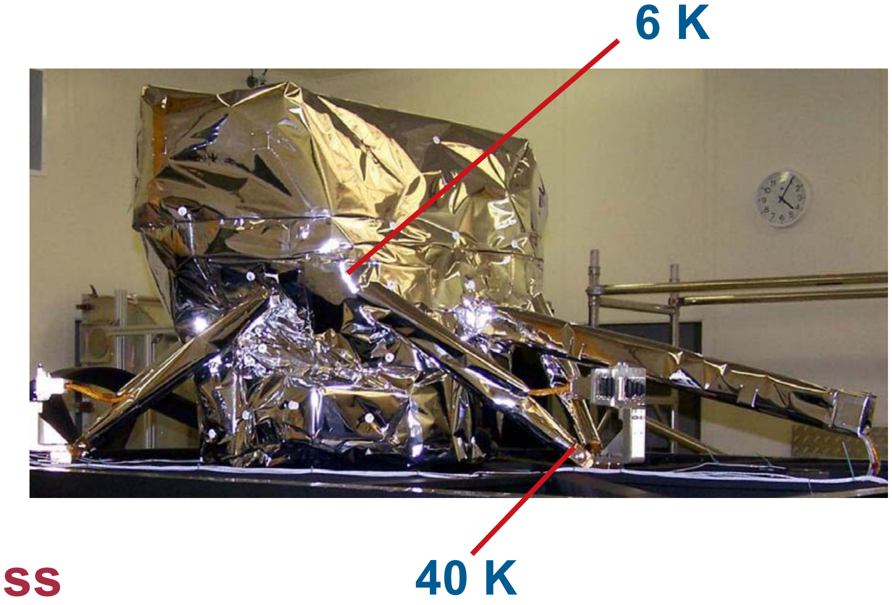
Watch Out for MLI and Gold Plating Lateral Conductivity

PROBLEM

- MLI and Gold Plating have relatively high in-plane conductivity
- These materials can create a thermally conductive path between hardware elements with significantly different temperatures

LESSONS LEARNED

- Be very careful about gold plating or wrapping thermally isolating members with MLI
- Conductivity of MLI Aluminized layer is about equal to that of 6061-T6 aluminum of equal thickness



Vacuum Level Considerations for Cryogenic Applications

Three Vacuum Level Issues:

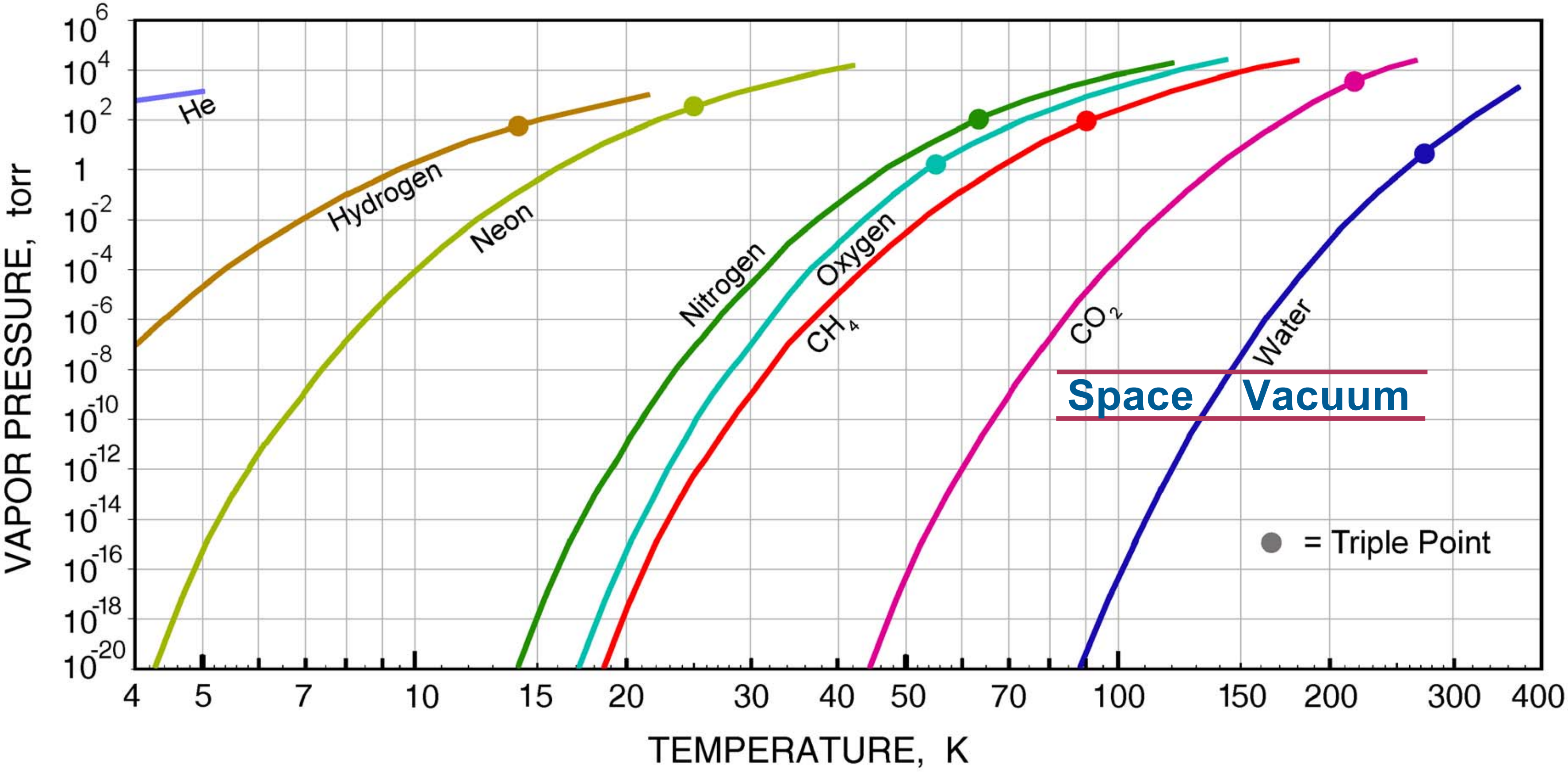
- **Gaseous Conduction** from hot surfaces to cold surfaces (Free molecular gaseous heat transfer)
- **Cryopumping heat loads** onto cold surfaces from gases condensing on cold surfaces (heat of fusion added to gaseous conduction)
- **Increased radiation heat loads** on cold surfaces from high emittance condensed gases on cold surfaces

Typical Vacuum Levels:

10^{-4} torr:	Run of the mill vacuum chamber
10^{-4} torr:	In space in open Shuttle Bay
10^{-4} torr:	**Inside spacecraft bus** in space (Ross estimate)
10^{-6} torr:	Good quality vacuum chamber
10^{-8} torr:	Inside ultrahigh vacuum chamber
10^{-8} torr:	**Exterior to spacecraft sunlit surfaces** (long term)
10^{-10} torr:	Exterior to spacecraft shaded-side surfaces (long term)

Vapor Pressures and Condensation Temperatures for Common Gasses

To remain contaminant-free in space requires T>150K



Vacuum Gas Transport and Heat Transfer Considerations

Key Vacuum Physics Considerations:

- Gas motion in vacuum is free-molecular ... line-of-sight, wall-to-wall with very few gas-gas impacts
  - To pump it, one must intercept the molecules before they reach sensitive cold surfaces
  - Cryopumping with cold shields (<100K) is highly effective

- From gas transport physics:
  - Rate of H_2O arrival (thickness buildup): $\dot{\delta}$ (µm/s) = 160 P (torr)
  - Cryopumping Heat Transfer Rate: $\dot{Q}$ (W/m^2) = 34 P (torr)

So, for vacuum pressure levels of water:

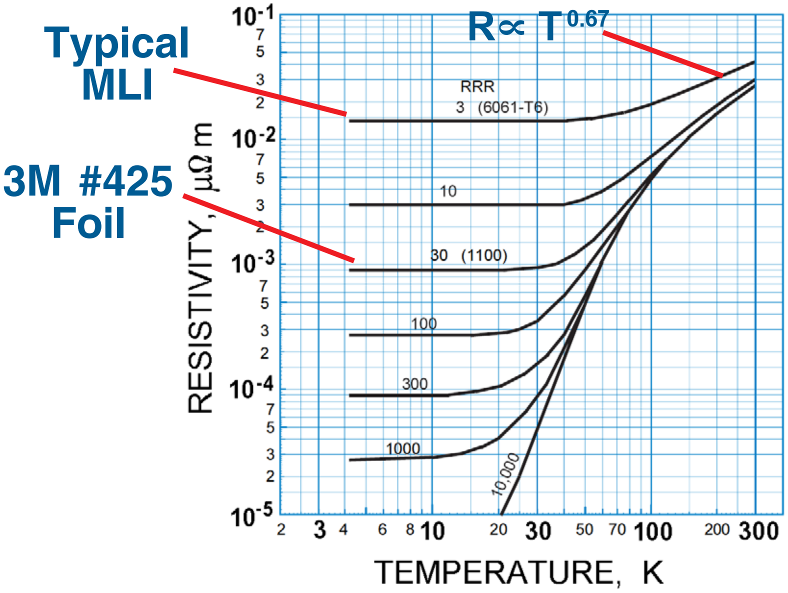
Vacuum Level	Time for 1 µm H_2O	H_2O Cryopumping Heat Transfer
10^{-4} torr	1 minute	34,000 mW/m^2
10^{-6} torr	1.7 hours	340 mW/m^2
10^{-8} torr	7 days	3.4 mW/m^2
10^{-10} torr	2 years	0.034 mW/m^2

Radiation Heat Transfer Considerations

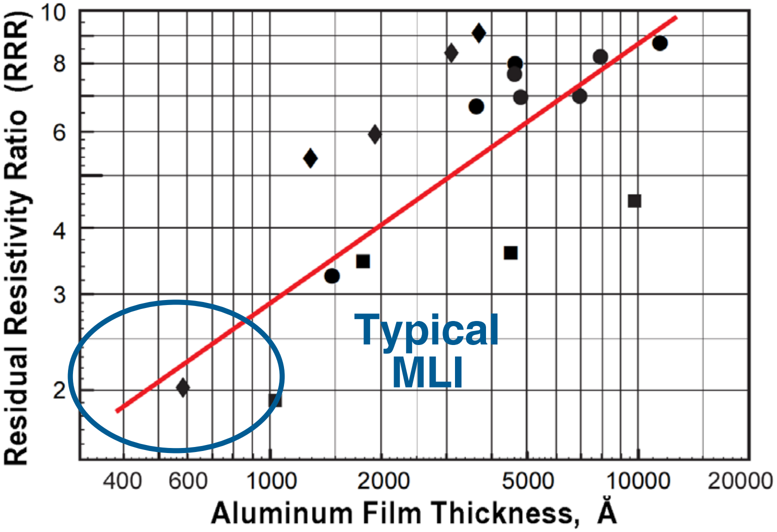
Key Issues:

- Heat transfer proportional to $A \epsilon (T_{Hot}^4 - T_{Cold}^4) \approx A \epsilon T_{Hot}^4$
- Emittance (ϵ) (IR absorptance) is dependent upon:
  - Material Surface Electrical Resistance ($\epsilon \propto R$)
  - Surface thickness and purity/atomic structure (RRR)
  - Temperature
  - Presence of surface contaminants

R of Aluminum vs. RRR

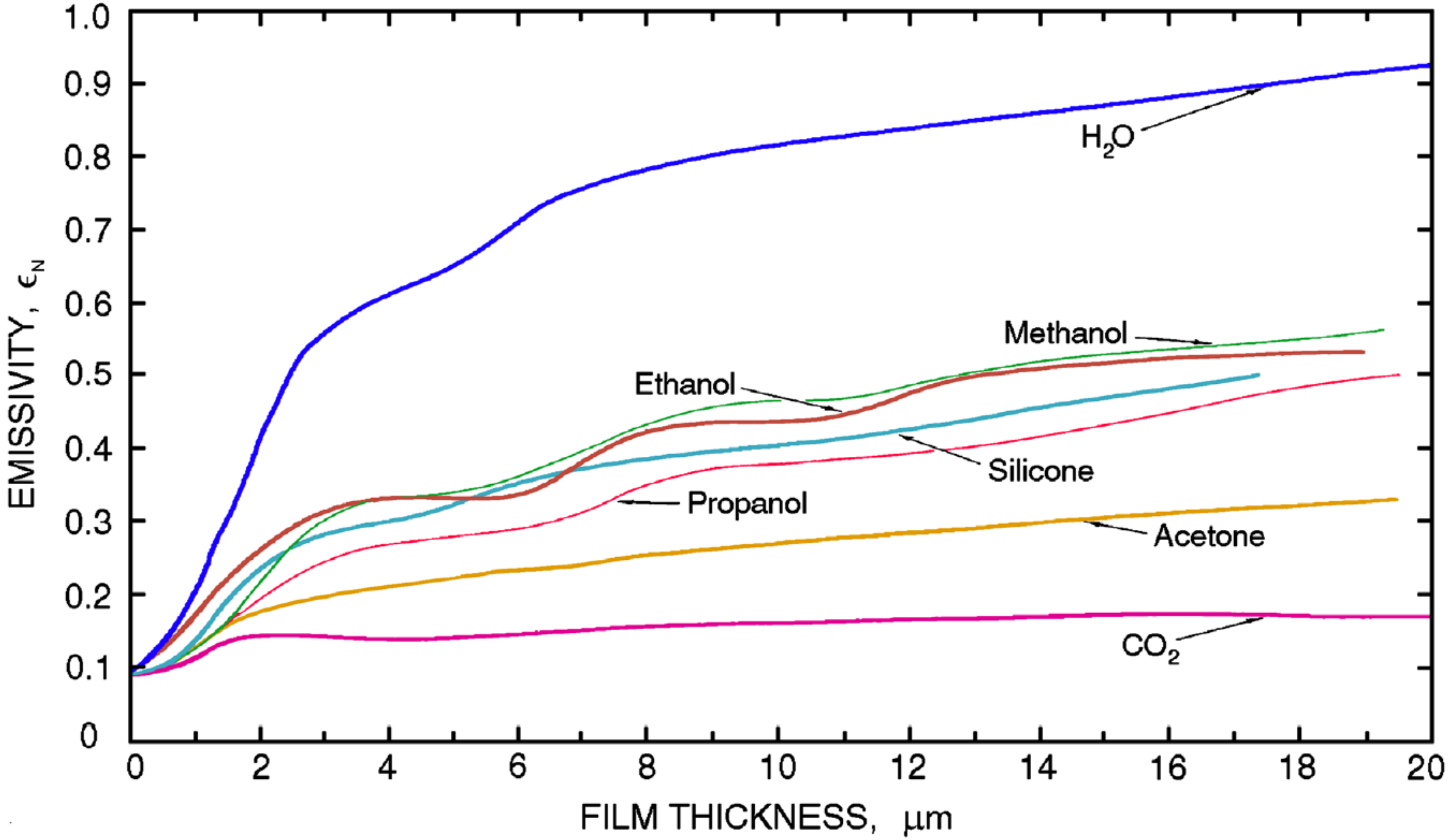


RRR of Aluminum films on MLI

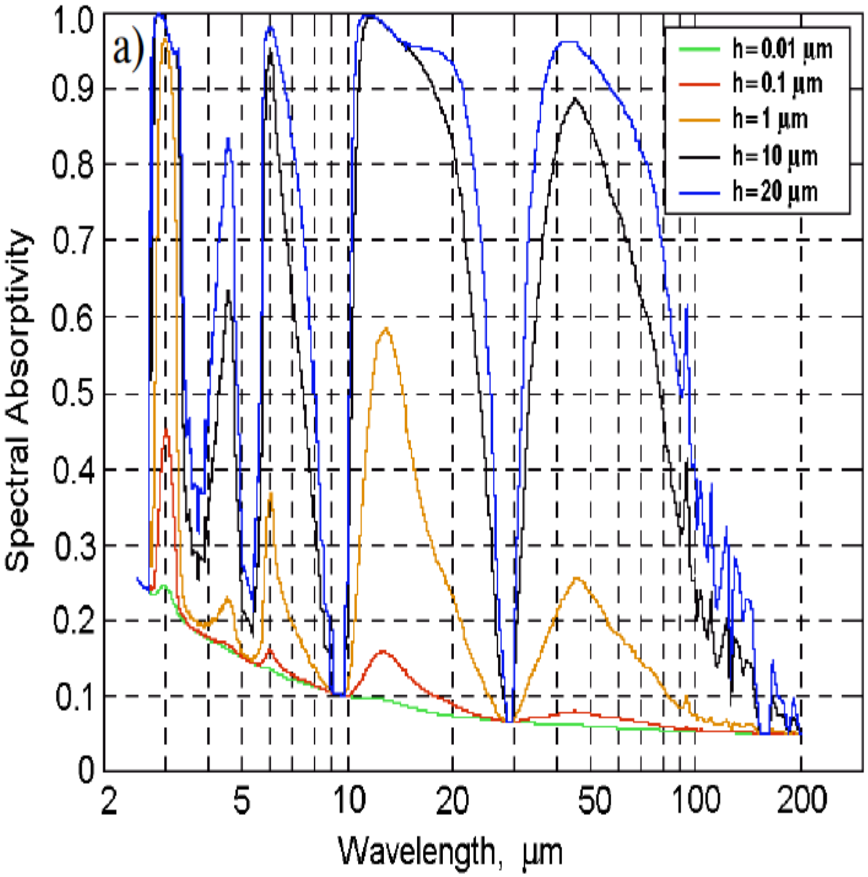


Emittance Dependence on Contaminant Film Thickness

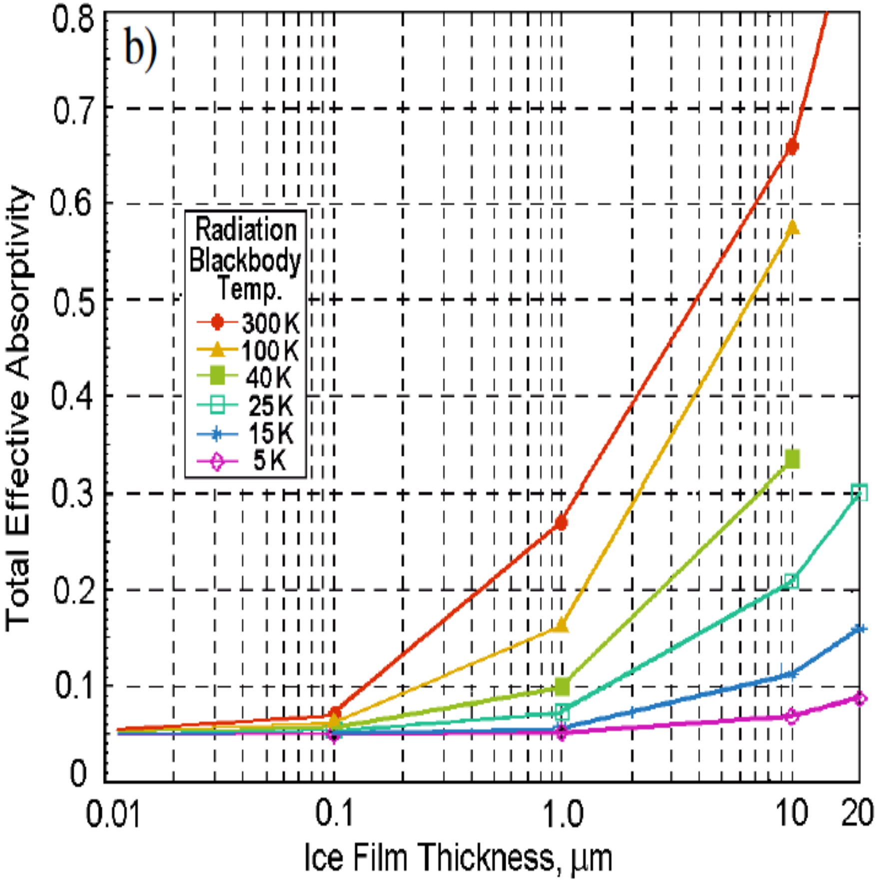
IR Absorptivity of Contaminant films on Polished Stainless Steel to 300K Blackbody Radiation



IR Absorptivity of H_2O Film (Thickness and Temperature)



- Spectral absorptivity of various thicknesses (h) of water ice



- Total IR absorptivity as a function of film thickness for incident radiation from noted blackbody temperatures.

Estimation of Thermal Radiation Loads with Conventional MLI

Classic Lockheed MLI Equation

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

where

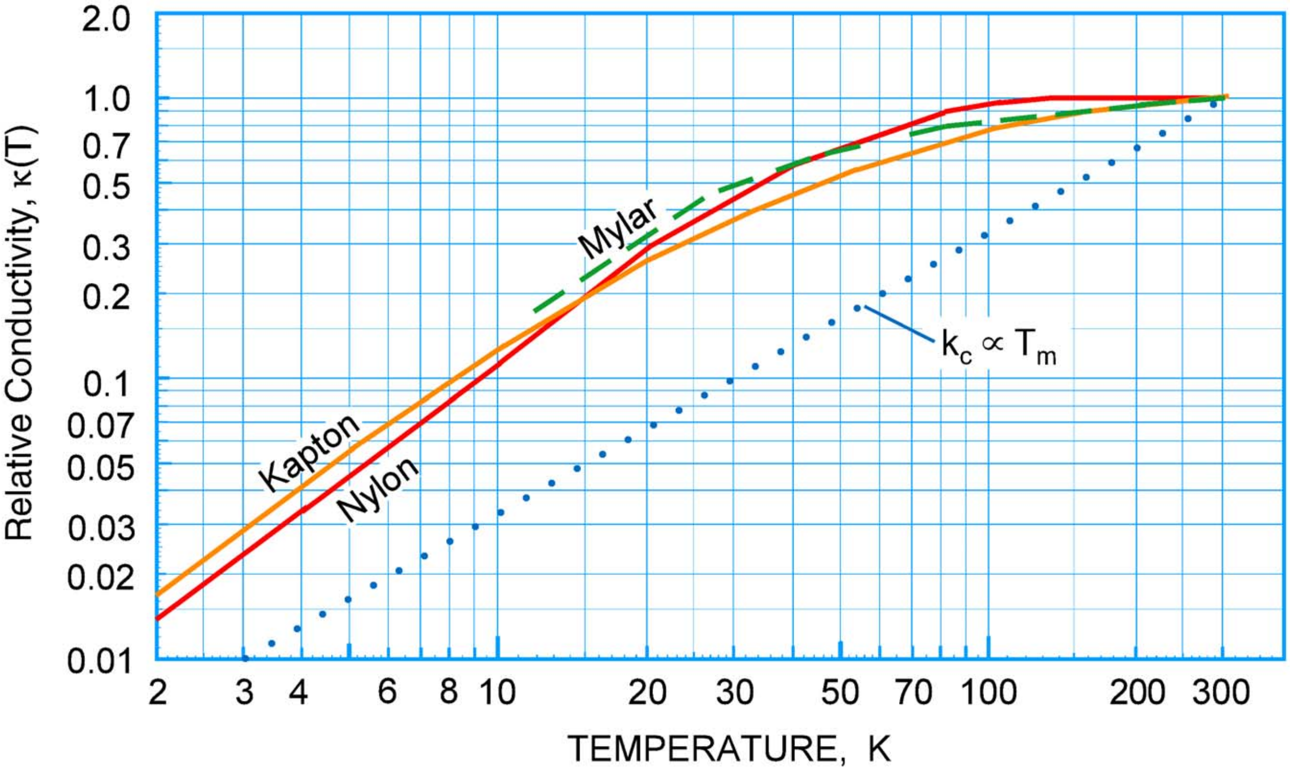
q = total heat flux transmitted through the MLI (mW/m^2)
q_c = conductive heat flux transmitted through the MLI (mW/m^2)
q_r = radiative heat flux transmitted through the MLI (mW/m^2)
C_c = conduction constant = 8.95×10^{-5}
C_r = radiation constant = 5.39×10^{-7}
T_h = hot side temperature (K)
T_c = 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

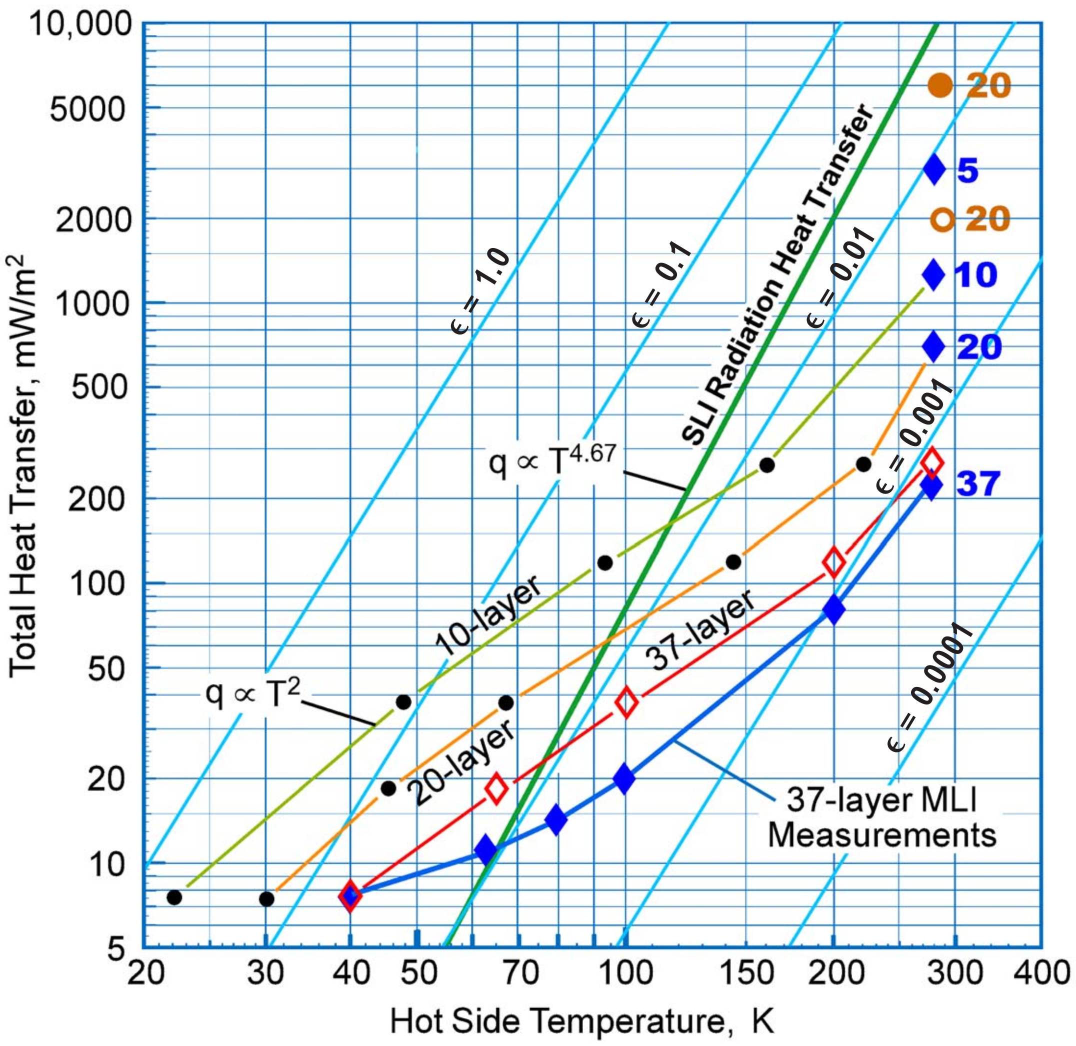
Conduction **Radiation**

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



Measured Thermal Radiation Loads with Room-Temperature MLI

As a function of Hot Side Temperature



Key:

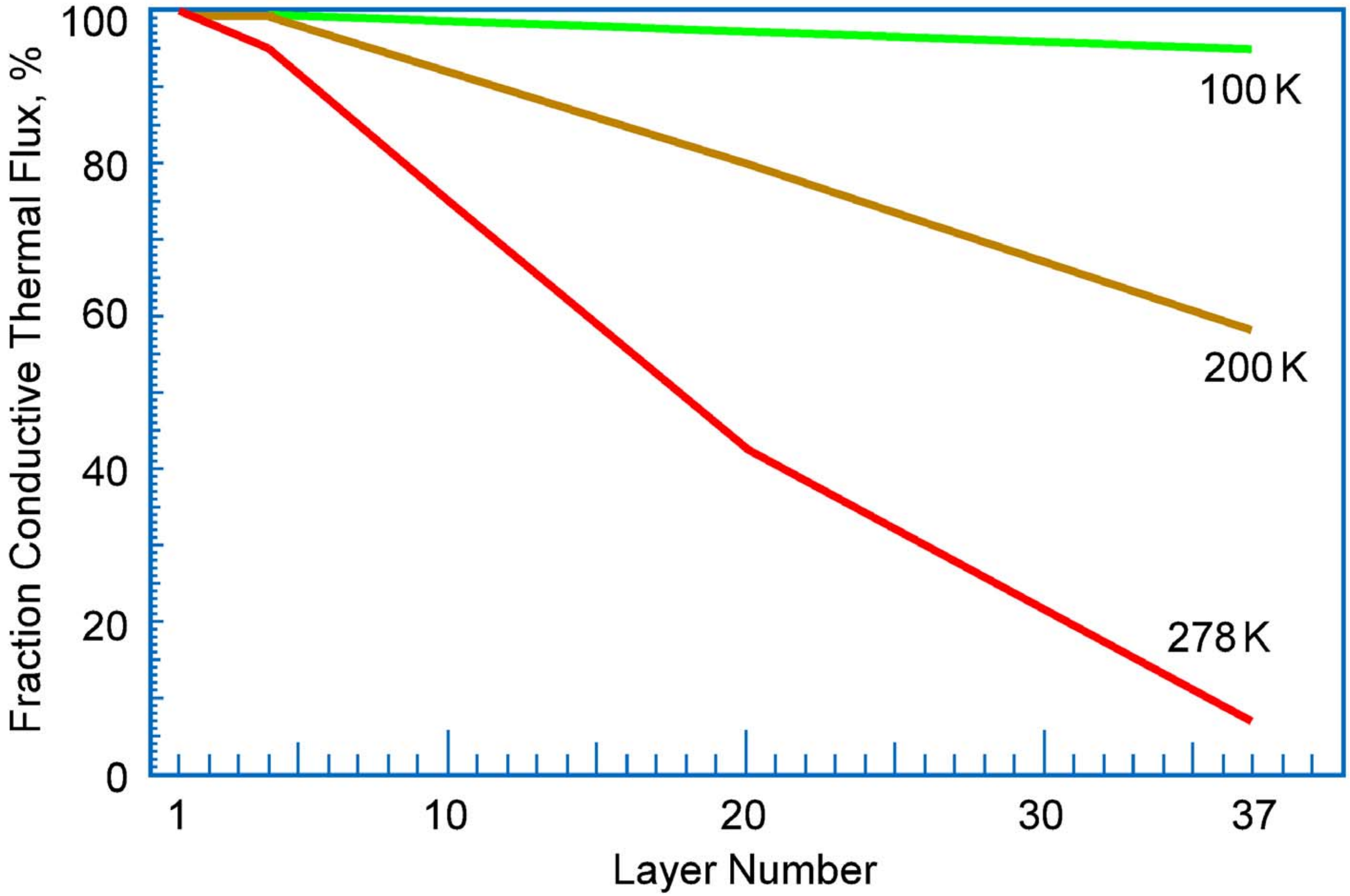
▬	SLI Radiation Absorbed ($\epsilon_H = 1$, $\epsilon_C = 6.8\times10^{-4}\,T_H^{0.67}$)
● 20	JPL 20-layer Cassini (SSAK+5EK+15MN+AK)
○ 20	JPL Duo-layup Cassini (SSAK+5EK/15MN+A) (20 layers in 2 blankets with staggered seams)
◆ 10	Unperf. DAM 1-SN MLI (**X** = number of layers) (LMSC dewar minimum achiev. layer density)
◇	Modeled results for LMSC 37-layer DAM 1-SN
▬	Modeled results for LMSC 20-layer DAM 1-SN
▬	Modeled results for LMSC 10-layer DAM 1-SN
▬	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 MLI**

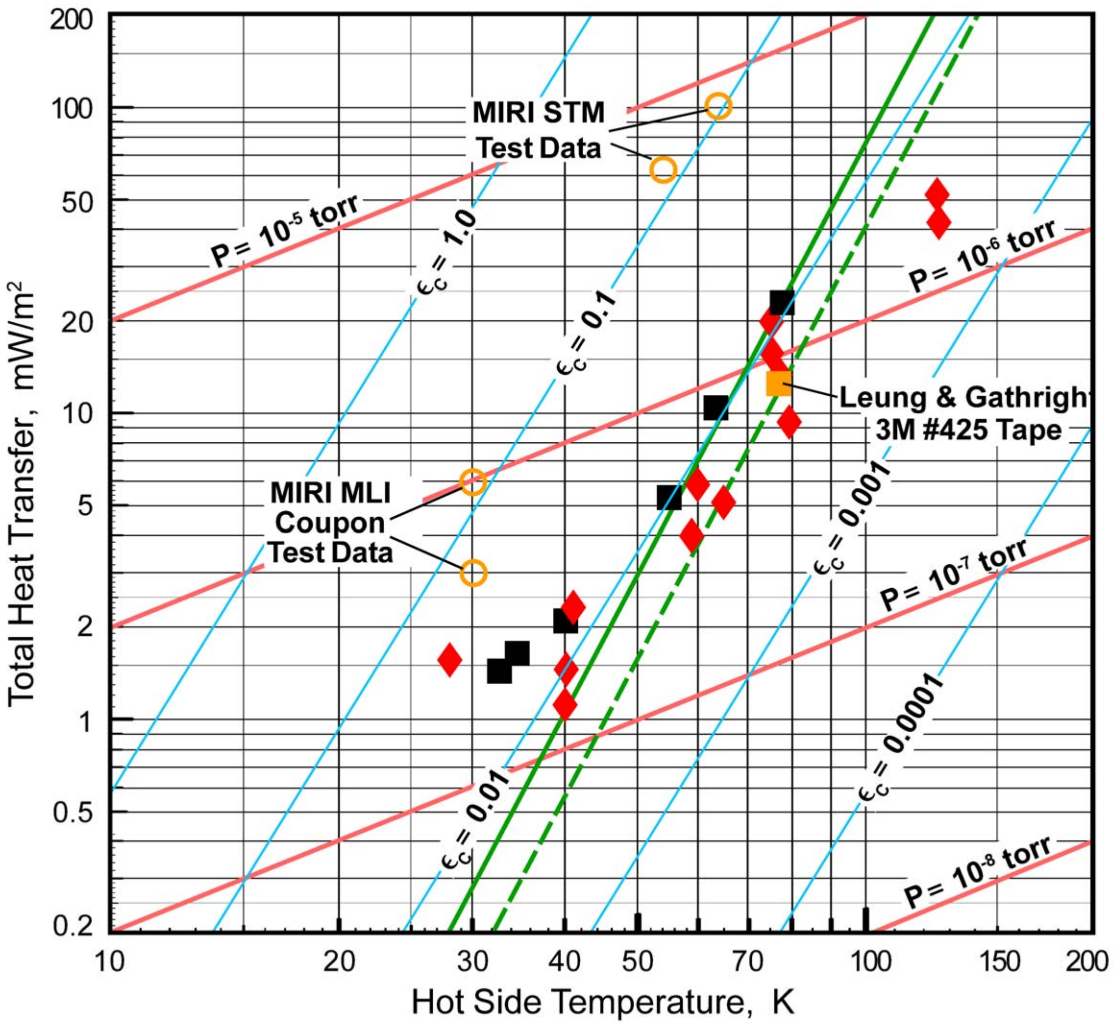
Relative Role of MLI Conductance as a function of Hot Side Temperature

Lockheed 37-layer Dewar MLI ($k_0 = 25$)



Hotside Temp

Measured Thermal Radiation Loads with Cryo-MLI & SLI



Key:

▬ SLI facing Black ($\epsilon_H = 1$, $\epsilon_C = 6.8\times10^{-4}\, T_H^{0.67}$)

▬ ▬ SLI facing SLI ($\epsilon_H = \epsilon_C = 6.8\times10^{-4}\, T_H^{0.67}$)

◆ 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

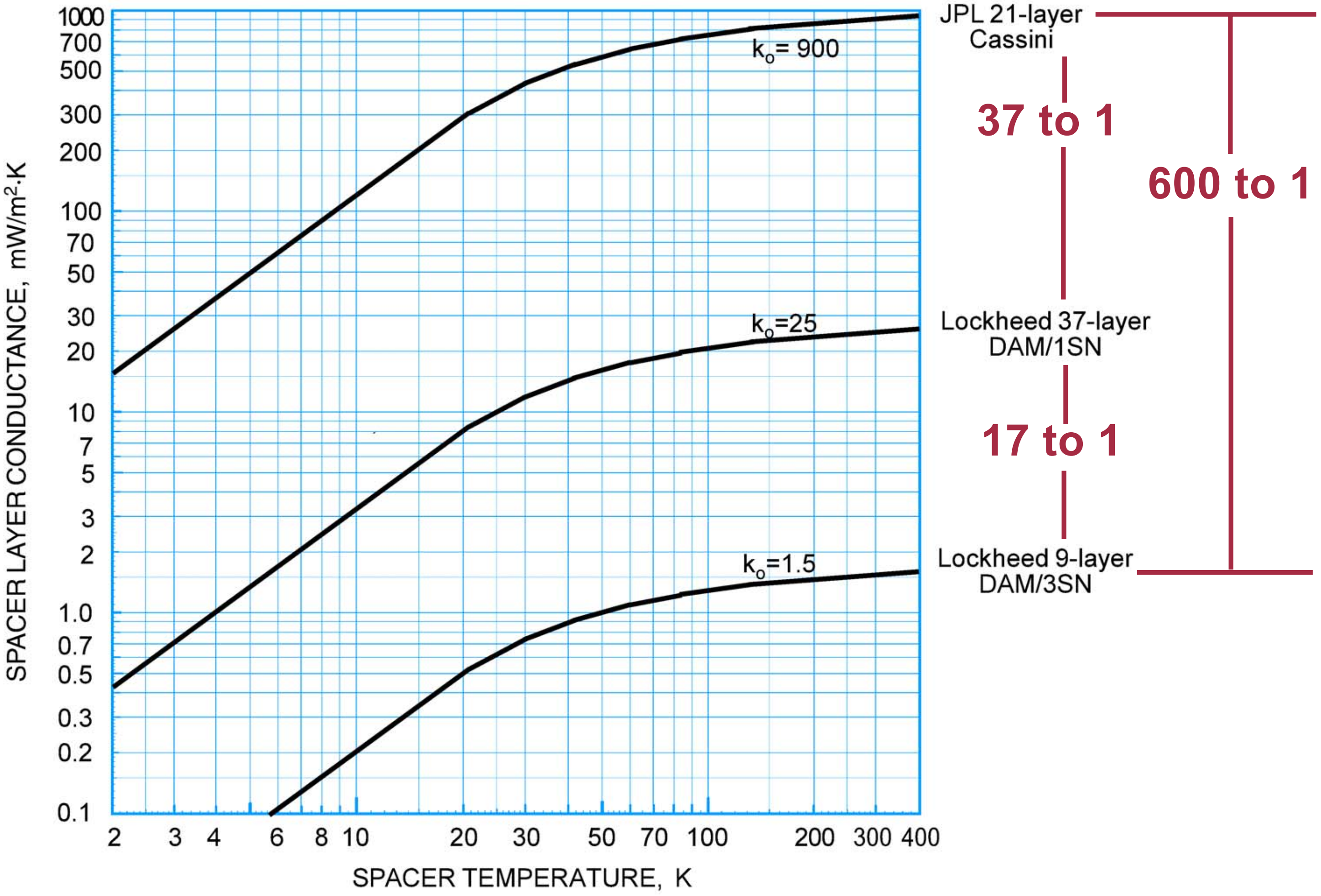
▬ Lines of constant Vacuum Pressure

Bottom Line:

- Cryo Dewar MLI can 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
- Gas conductance seen to impact heat transfer for $T_H < 50$ K

Measured Conductances of Various MLI Constructions

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



JPL 21-layer Cassini

37 to 1

600 to 1

Lockheed 37-layer DAM/1SN

17 to 1

Lockheed 9-layer DAM/3SN

System Design and Sizing Summary

- Designing cryogenic systems for space (or for ground) is a complex process requiring careful management
  - Accurate early identification of system requirements
  - Conservative margins applied for inevitable changes associated with improved design fidelity
  - Systematic Characterization & Qualification of system to burn-down margins and reduce risk

- Cryogenic system designs typically have LARGE uncertainties
  - Structural conduction loads
  - Vacuum level (gaseous conduction & cryopumping)
  - Emittances (surface material properties & contaminant levels)
  - MLI effective emittance (conductance, unintended contact)