Cryogenic Thermal Conductivity Measurements on Candidate Materials for Space Missions

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Introduction

• Many NASA missions include cryogenic instruments
• Spacecraft and instruments include optimized materials/assemblies
  - Highly-conductive annealed pure metals
  - Engineered materials
    Polymers
    Alloys
    Composites
    Ceramics
  - Customized electrical cables/harnesses

• Candidate materials often selected based on room temp. properties
• Often longitudinal cryogenic thermal conductivity is unknown
• We developed a thermal conductivity facility for JWST in 2004
• We have characterized ~ 30 samples since then
Concept

• For one-dimensional heat flow in a material,

\[ \frac{\dot{Q}}{A} = \kappa \frac{dT}{dx} \]

- \( \kappa \): thermal conductivity [W/m/K]
- \( \dot{Q} \): power [W]
- \( A \): cross sectional area [m\(^2\)]
- \( T \): temperature [K]
- \( x \): axial distance [m]

• Basic approach
  - Flow heat through sample
  - Measure temperature gradient

• We chose to perform “absolute” measurement
  - Relative measurements: lower precision
Simple Approach

- Control base temperature
- Apply heat to sample’s free end
- Measure (small) $\Delta T$

$$\kappa(\bar{T}) = \frac{L \dot{Q}}{A \Delta T}$$

- $L$: sample length [m]
- $A$: cross section [$m^2$]
- $\bar{T} = (T_{\text{Sample}} + T_{\text{Base}})/2$
Complications

- Ohmic heating in heater leads
- Heat conducted in leads
- Heat radiated to surroundings
  \[ T_{Hot}^4 - T_{Cold}^4 \sim 4\bar{T}^3 \Delta T \]
- Joint resistance at base
- Joint resistance at floating end
- Absolute thermometer errors

\[
\dot{Q}_H - \dot{Q}_{TL} - \dot{Q}_{HL} - \dot{Q}_R = \frac{A}{\kappa(\bar{T})} \left( (T_F - \delta T_F) - (T_B - \delta T_B) + \Delta T_F + \Delta T_B \right)
\]
Our Test Configuration

- Based on approach described in 1973 Moore, Williams and Graves RSI paper

- Guard surrounds sample:
  \[ T_{\text{Guard Top}} = T_{\text{Sample Top}} \]
  reduces sample heat radiation

- “Fiberfrax” insulation eliminates remaining sample radiation

- Intermediate thermometers eliminate joint resistance effect

- Optimizing sample heater and leads minimizes ohmic heating in leads

- Lead heat-sinking minimizes lead heat conduction
Instrumentation

• Thermometers
  - LakeShore Cryotronics SD-package Cernox™ sensors
  - Calibrated (resistance vs. $T$) from 1 to 325 K

• Heaters
  - Sample heater is 10 KΩ metal-film resistor
    - Leads: size, material chosen to give round-trip resistance less than ~10 Ω inside guard
  - Base and guard heaters: 50 Ω
    - made by winding stainless steel wire around flange
    - we don’t measure the power for these heaters

• Temperature readout/control boxes
  - Cryogenic Control Systems Cryocon Model 32B Controller

• Heater voltage and current readout
  - Keithley Model 2000 6.5-digit multi-meters
For each value of $\bar{T} = (T_{\text{Sample}} + T_{\text{Base}})/2$:

- Perform 4 different steady-state ”balances”
- For each balance, control $T_{\text{guard}} = T_{\text{Sample}} > T_{\text{Base}}$
- Measure $\Delta T = T_{\text{Far}} - T_{\text{Near}}$
- Measure $\dot{Q} = $ sample control power

\[
\kappa(\bar{T}) = \frac{L}{A} \frac{d\dot{Q}}{d\Delta T}
\]

To first order, differential measurement eliminates effect of absolute temperature errors

- $\frac{d\dot{Q}}{d\Delta T}$ is more accurate than any single $\frac{\dot{Q}}{\Delta T}$ value

- Least-squares fit of 4 different $\Delta T$ values provides statistical uncertainty in $\frac{d\dot{Q}}{d\Delta T}$
Thermometer $R$ vs. $T$ calibrations have “scatter” due to measurement uncertainty.

Assume that “true” $R(T)$ is a smooth function approximated by a smoothing fit:
- LakeShore Cryotronics provides smoothing Chebyshev Polynomial fits
- We performed cubic spline smoothing fit on a cal. curve

Our readout box uses cubic spline interpolation to get $T$ from $R$:
- Interpolation forces curve to go through every “scattered” point
- Causes local $dR/dT$ errors relative to slope of “true” smooth curve
- A local error in $dR/dT$ results in a proportional local error in $\kappa$
Evaluation of Cal. Curve Slope

- Graphed slope difference between spline-smoothed curve and spline interpolations:
  - Blue curve: interpolation of raw calibration points
  - Red curve: interpolation of Chebychev fit points
- Above 6 K, raw points give max. slope error of 0.3% (mostly below 0.2%)
- Improvement is possible by loading Chebychev fit points into readout box
Sample/Guard Mismatch Error

- To first order, keeping $T_{\text{Sample}} = T_{\text{Guard}}$ eliminates effect of sample-guard heat leaks
  - For small $\Delta T$ values, $T_{\text{Sample}} - T_{\text{Guard}}$ calibration curve mismatches are assumed constant for balances with a given $\bar{T}$
  - Constant mismatches result in constant sample-guard heat leak
  - This does not effect $\frac{d\dot{Q}}{d\Delta T}$

- However, Fiberfrax effective thermal conductivity has a strong $(T^3)$ temperature dependence

- We performed finite-element thermal model to evaluate second order effects in $\frac{d\dot{Q}}{d\Delta T}$
Mismatch Error for PVC Sample

- Worst-case error at 300 K
- PVC has very low $\kappa = 0.16 \text{ W/m/K}$ at 300 K
- Modeled error vs. sample diameter inside 32 mm guard
- It’s best to make sample diameter as large as practical
- This error is proportional to $1/\kappa$, so much lower for other materials
High Conductivity Samples

- Aluminum 1350
- AlBeMet: longitudinal direction
- AlBeMet: transverse direction
Medium Conductivity Samples

- aluminum nitride
- aluminum 6061-T6

Temperature (K)

\( \kappa \) (W/mK)
Polymer Samples

- Epon 815 epoxy
- Teflon sheet (rolled, longitudinal direction)
- Torlon (extruded)
- NIST fit for bulk Teflon

Temperature (K)

\( \kappa \) (W/m/K)
Composite Samples

- S-glass [(45, -45, 0)s layup, S2 glass in EX1522 epoxy matrix]
- T300 [(45, 0, -45)2s layup, T300 carbon fiber with 5HS weave in RS-3C epoxy matrix]
Conclusions

• It’s not too difficult to perform high-precision thermal conductivity measurements between 4 K and room temperature

• NASA/GSFC’s cryogenics group is equipped to perform such measurements for customers at any NASA center

• Thanks to the James Webb Space Telescope program, which funded the development of the technique and facility