

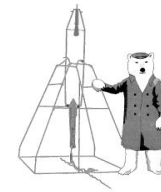
Cryogenic Thermal Conductivity Measurements on Candidate Materials for Space Missions

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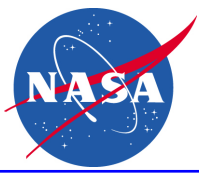
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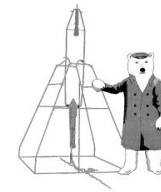
Introduction



- 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



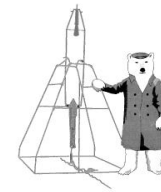
- For one-dimensional heat flow in a material,

$$\frac{\dot{Q}}{A} = \kappa \frac{dT}{dx}$$

- κ : thermal conductivity [W/m/K]
 - \dot{Q} : power [W]
 - A : cross sectional area [m²]
 - 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



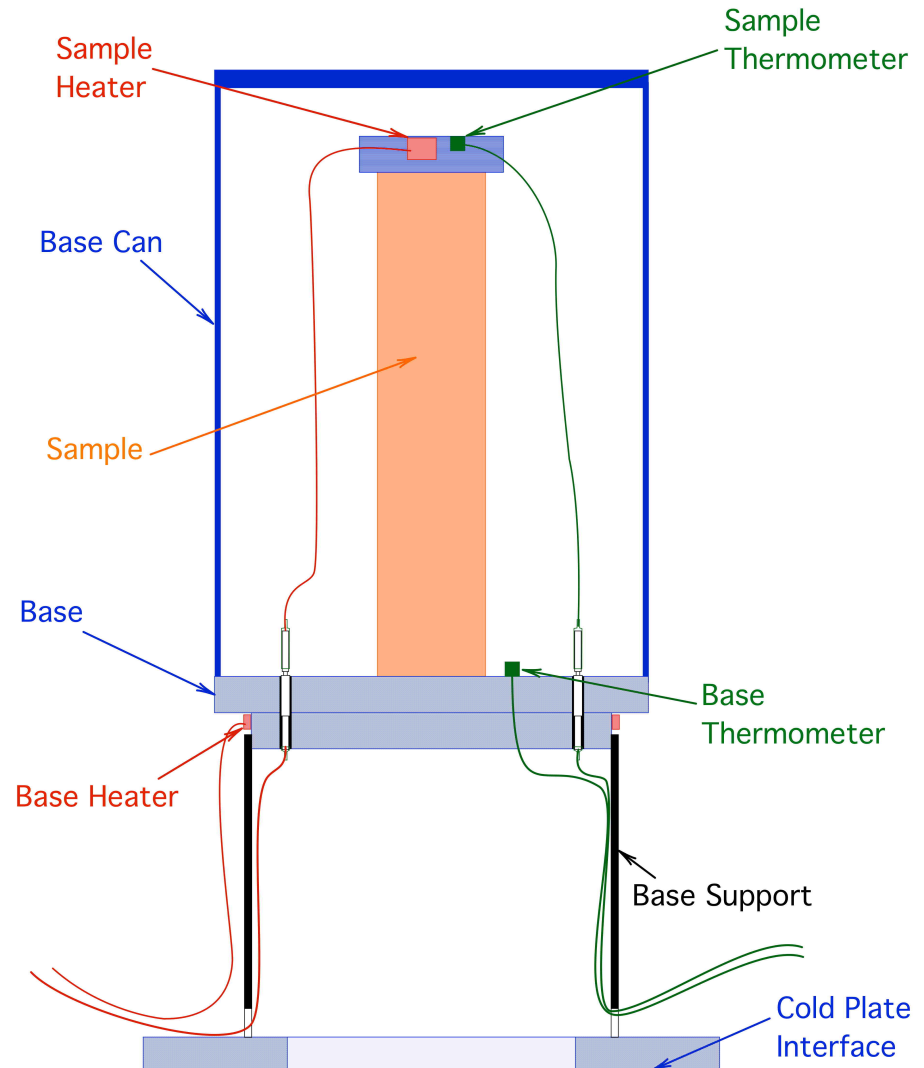
Simple Approach



- Control base temperature
- Apply heat to sample's free end
- Measure (small) ΔT

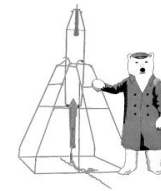
$$\kappa(\bar{T}) = \frac{L \dot{Q}}{A \Delta T}$$

- L : sample length [m]
- A : cross section [m²]
- $\bar{T} = (T_{\text{Sample}} + T_{\text{Base}})/2$





Complications



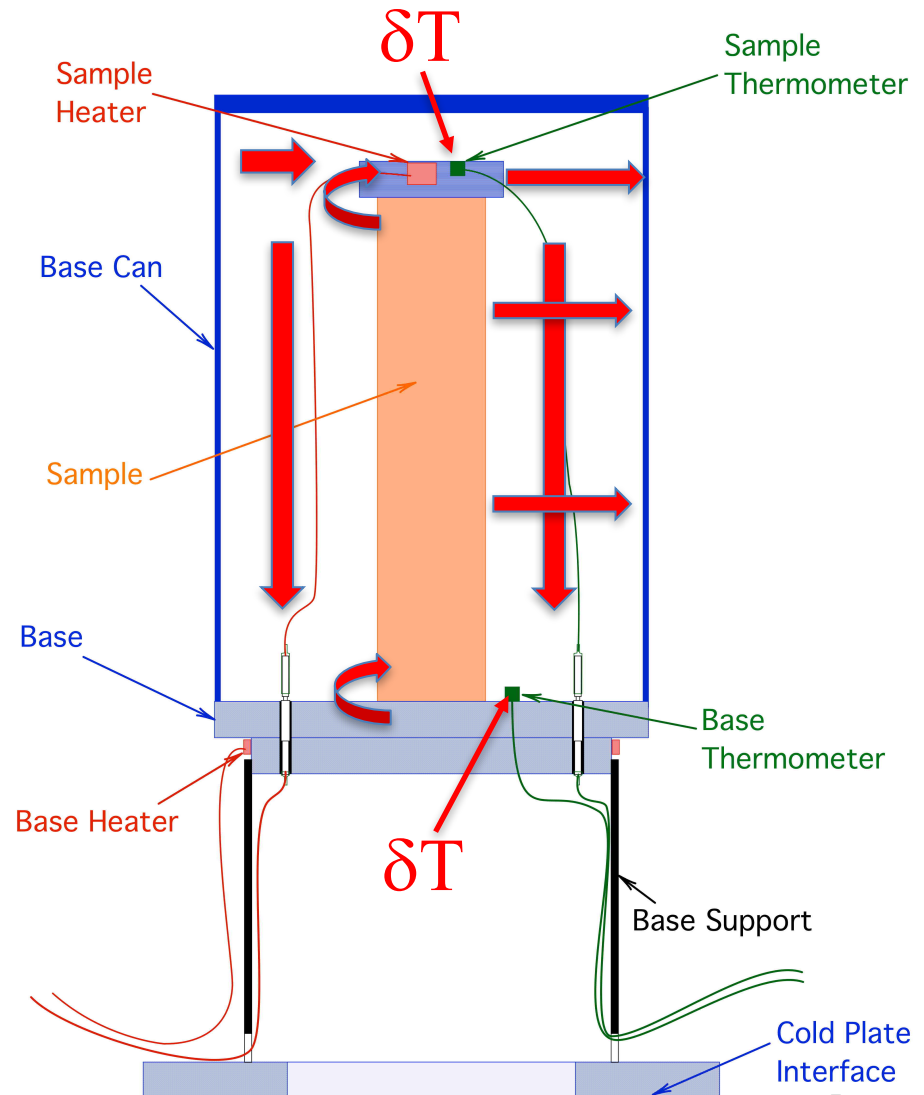
- Ohmic heating in heater leads
- Heat conducted in leads
- Heat radiated to surroundings

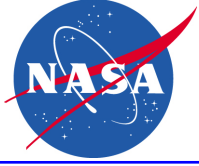
$$T_{Hot}^4 - T_{Cold}^4 \sim 4\bar{T}^3 \Delta T$$

- Joint resistance at base
- Joint resistance at floating end
- Absolute thermometer errors

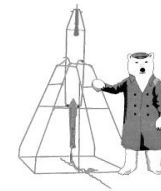
$$\frac{\dot{Q}_H - \dot{Q}_{TL} - \dot{Q}_{HL} - \dot{Q}_R}{A} =$$

$$\kappa(\bar{T}) \frac{(T_F - \delta T_F) - (T_B - \delta T_B) + \Delta T_F + \Delta T_B}{L}$$

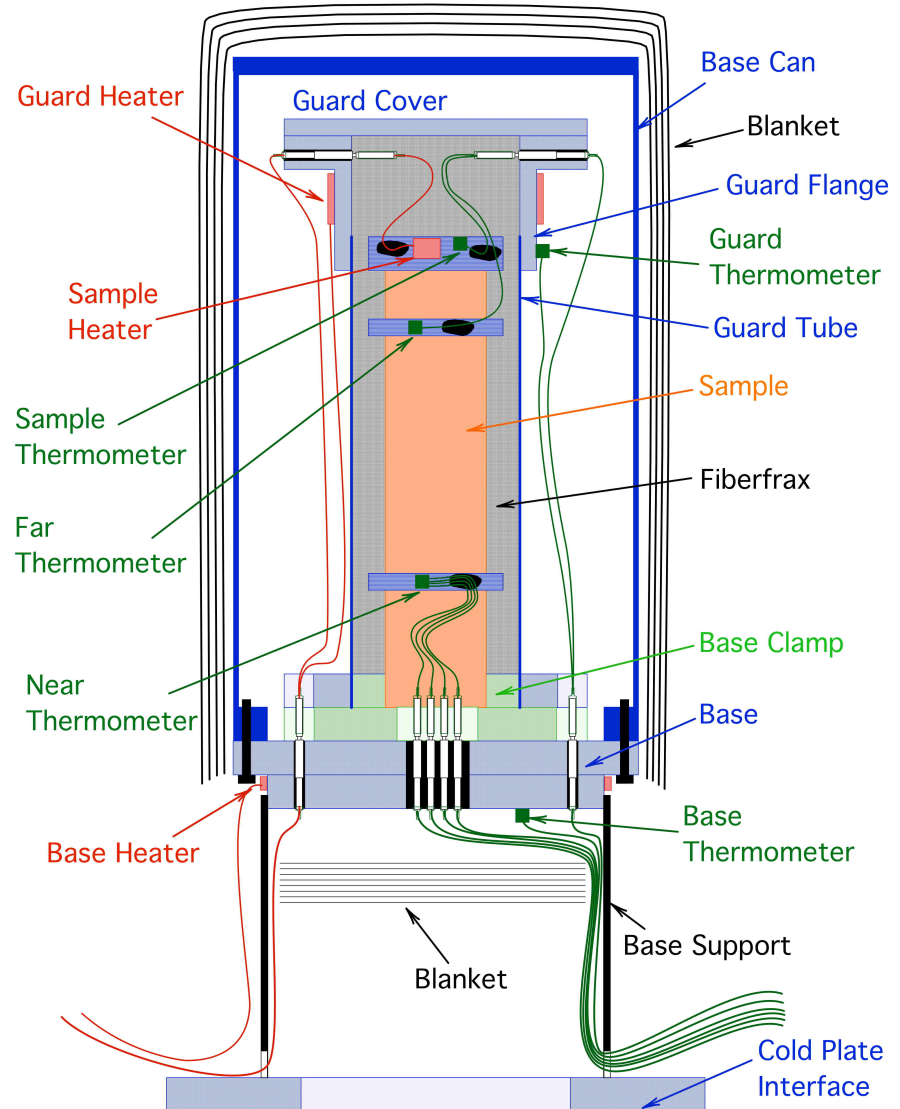




Our Test Configuration

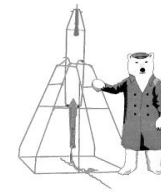


- Based on approach described in 1973 Moore, Williams and Graves RSI paper
- Guard surrounds sample:
Controlling $T_{\text{Guard Top}} = T_{\text{Sample Top}}$ reduces sample heat radiation
- “Fiberfrax” insulation eliminates remaining sample radiation
- Intermediate thermometers eliminate joint resistance effect
- Optimizing sample heater and leads minimizes ohmic heating in leads
- Lead heat-sinking minimizes lead heat conduction

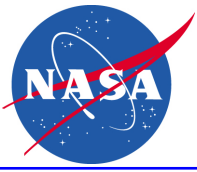




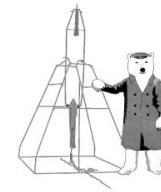
Instrumentation



- Thermometers
 - LakeShore Cryotronics SD-package Cernox™ sensors
 - Calibrated (resistance vs. T) from 1 to 325 K
- Heaters
 - Sample heater is 10 K Ω metal-film resistor
 - Leads: size, material chosen to give round-trip resistance less than $\sim 10 \Omega$ 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



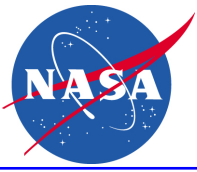
Data Acquisition and Analysis



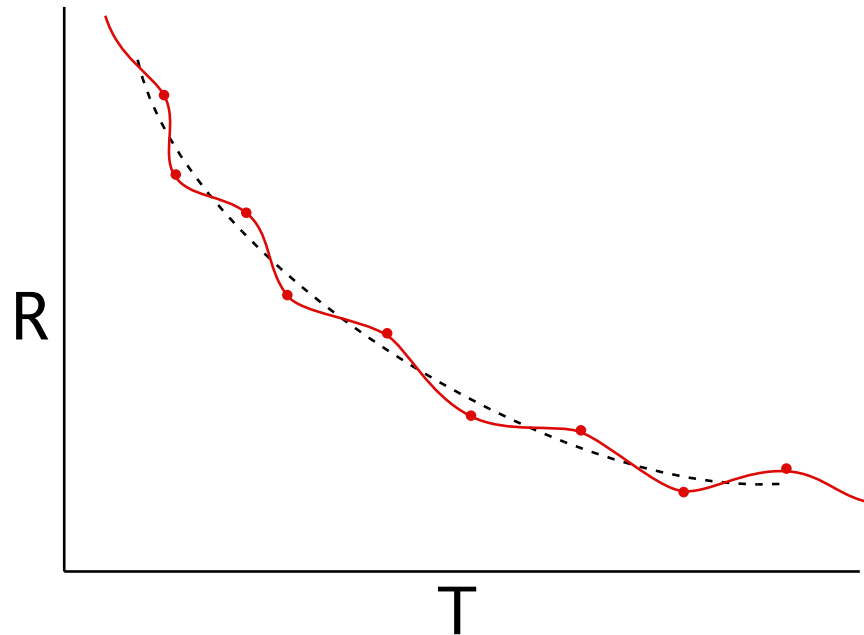
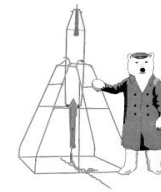
- For each value of $\bar{T} = (T_{\text{Sample}} + T_{\text{Base}})/2$:
 - Perform 4 different steady-state "balances"
 - For each balance, control $T_{\text{guard}} = T_{\text{Sample}} > T_{\text{Base}}$
 - Measure $\Delta T = T_{\text{Far}} - T_{\text{Near}}$
 - Measure \dot{Q} = sample control power

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

- 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 ΔT values provides statistical uncertainty in $\frac{d\dot{Q}}{d\Delta T}$



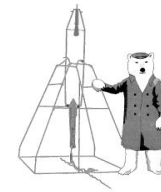
Effect of Cal. Curve “Scatter”



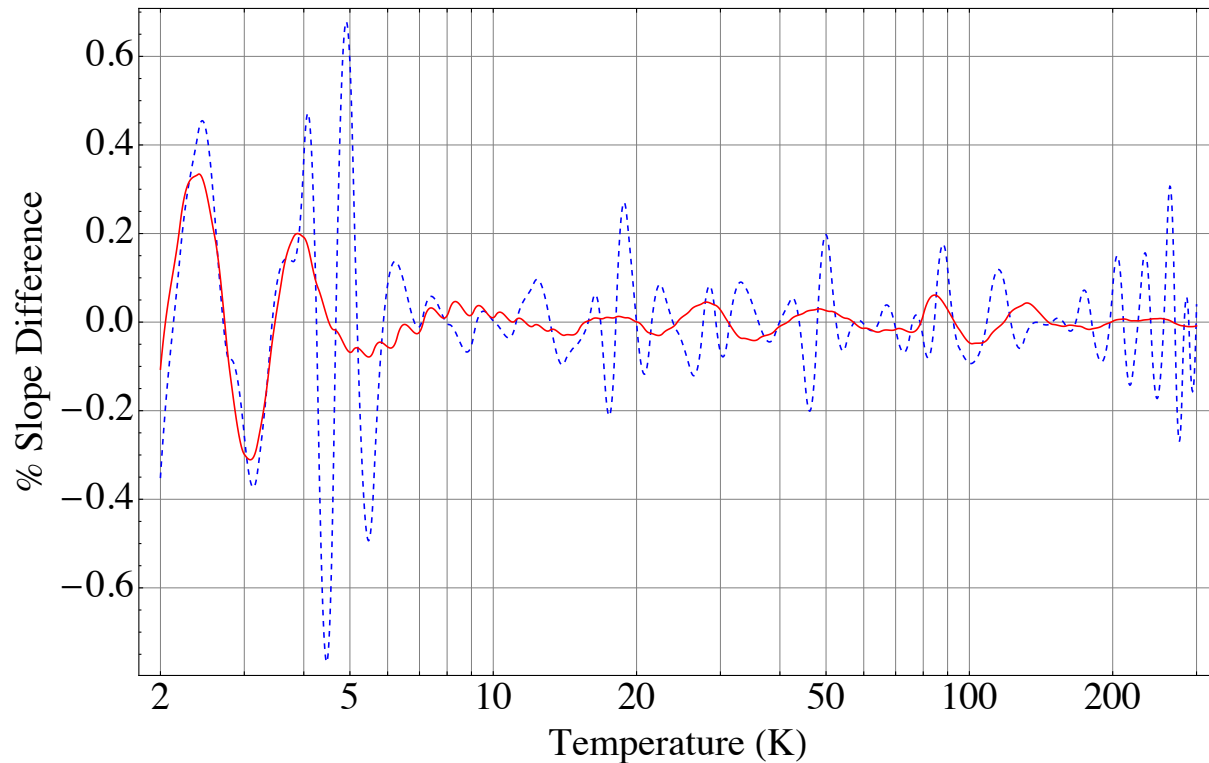
- Thermometer R vs. T calibrations have “scatter” due to measurement uncertainty
- Assume that “true” $R(T)$ is a smooth function approximated by a smoothing fit
 - LakeShore Cryotronics provides smoothing Chebyshev Polynomial fits
 - We performed cubic spline smoothing fit on a cal. curve
- Our readout 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 κ



Evaluation of Cal. Curve Slope

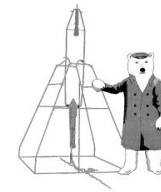


- Graphed slope difference between spline-smoothed curve and spline interpolations:
- Blue curve: interpolation of raw calibration points
- Red curve: interpolation of Chebychev fit points
- Above 6 K, raw points give max. slope error of 0.3% (mostly below 0.2%)
- Improvement is possible by loading Chebychev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





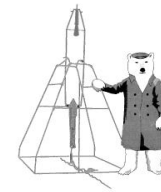
Sample/Guard Mismatch Error



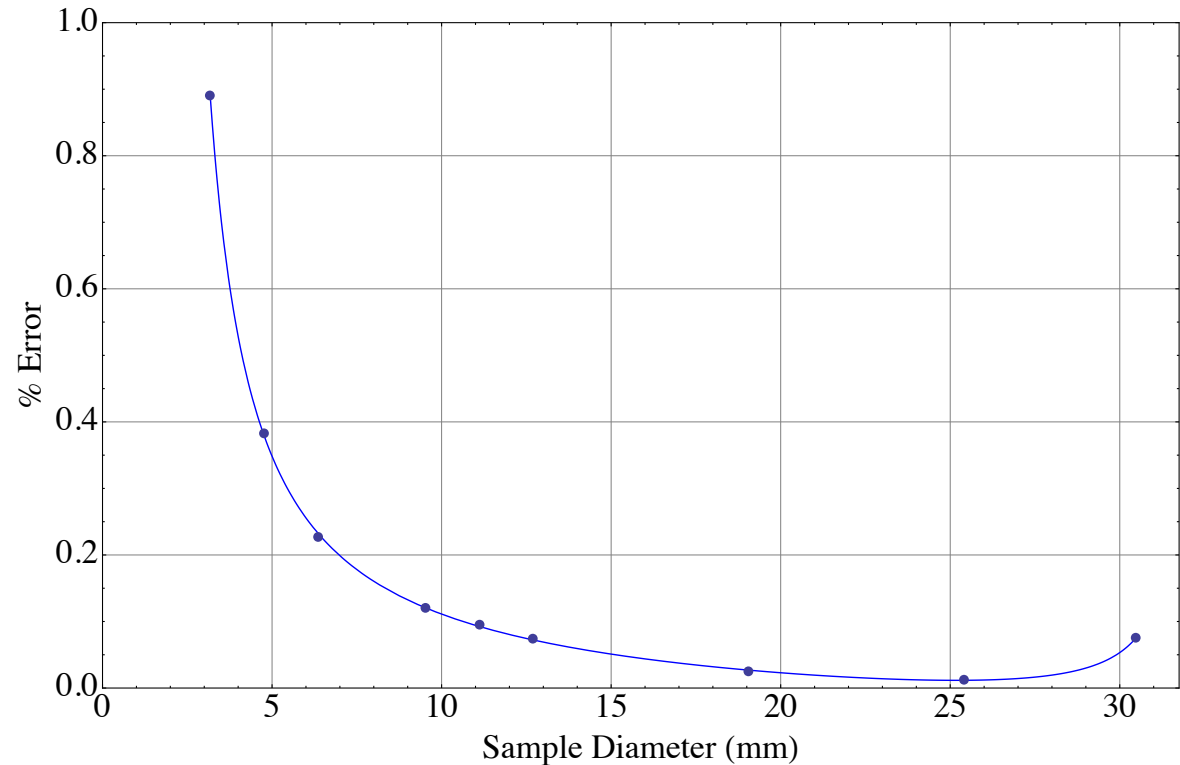
- To first order, keeping $T_{\text{Sample}} = T_{\text{Guard}}$ eliminates effect of sample-guard heat leaks
 - For small ΔT values, $T_{\text{Sample}} - T_{\text{Guard}}$ calibration curve mismatches are assumed constant for balances with a given \bar{T}
 - Constant mismatches result in constant sample-guard 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

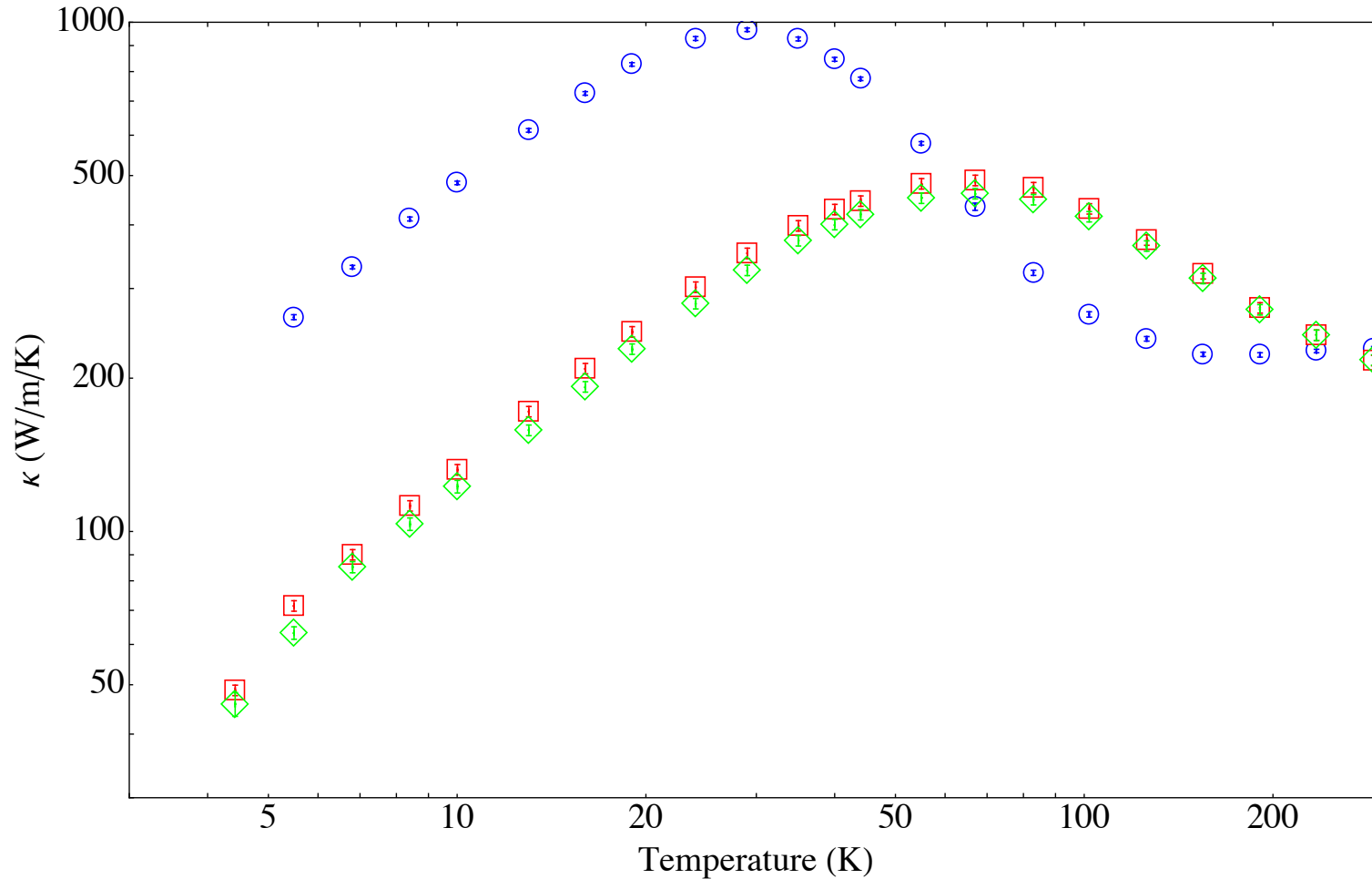
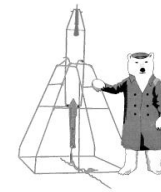


- Worst-case error at 300 K
- PVC has very low $\kappa = 0.16$ W/m/K at 300 K
- Modeled error vs. sample diameter inside 32 mm guard
- It's best to make sample diameter as large as practical
- This error is proportional to $1/\kappa$, so much lower for other materials





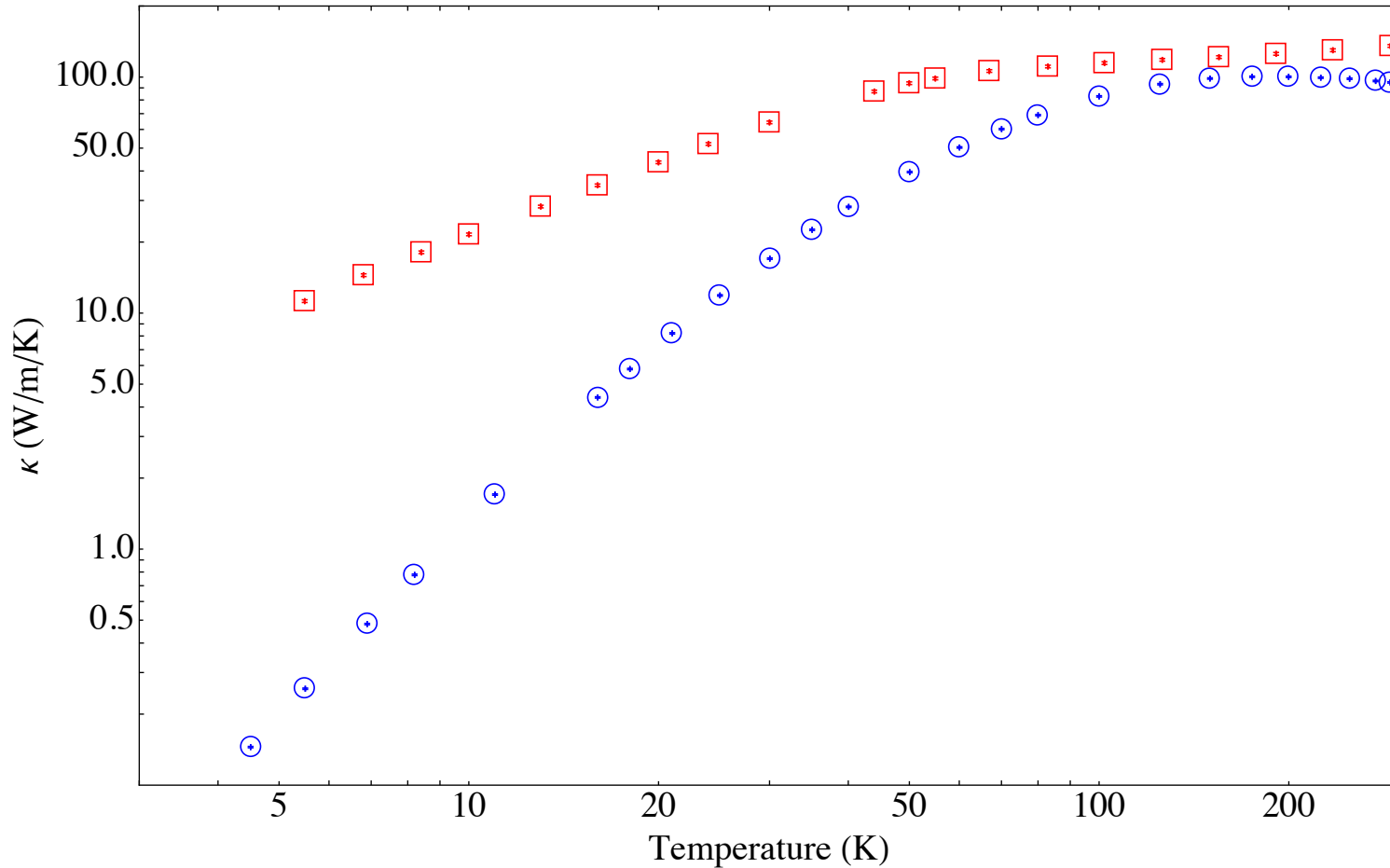
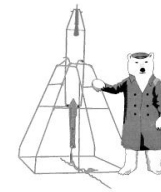
High Conductivity Samples



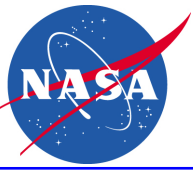
- aluminum 1350
- AlBeMet: longitudinal direction
- ◇ AlBeMet: transverse direction



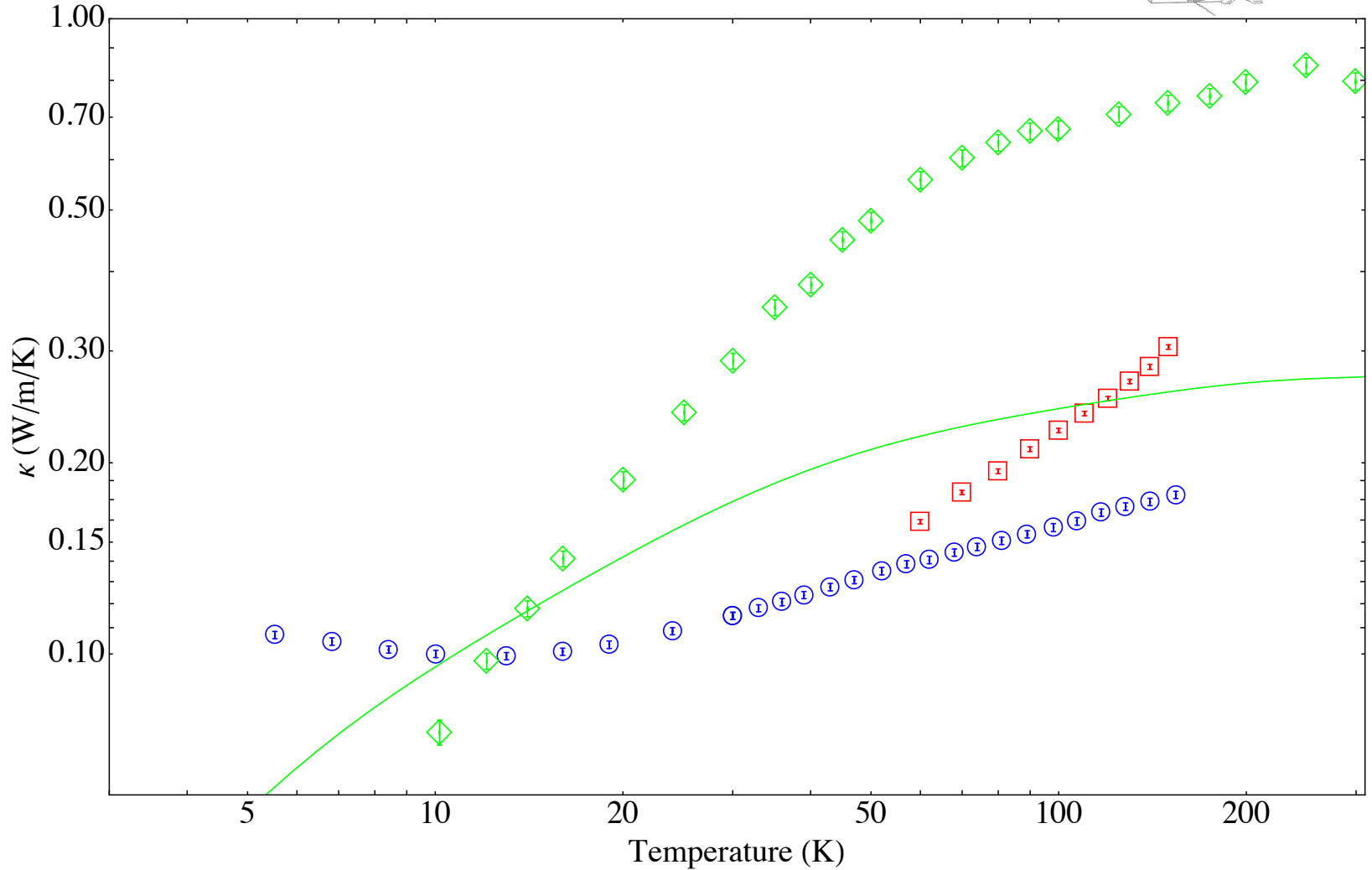
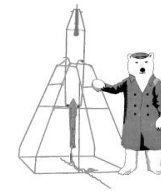
Medium Conductivity Samples



- aluminum nitride
- aluminum 6061-T6



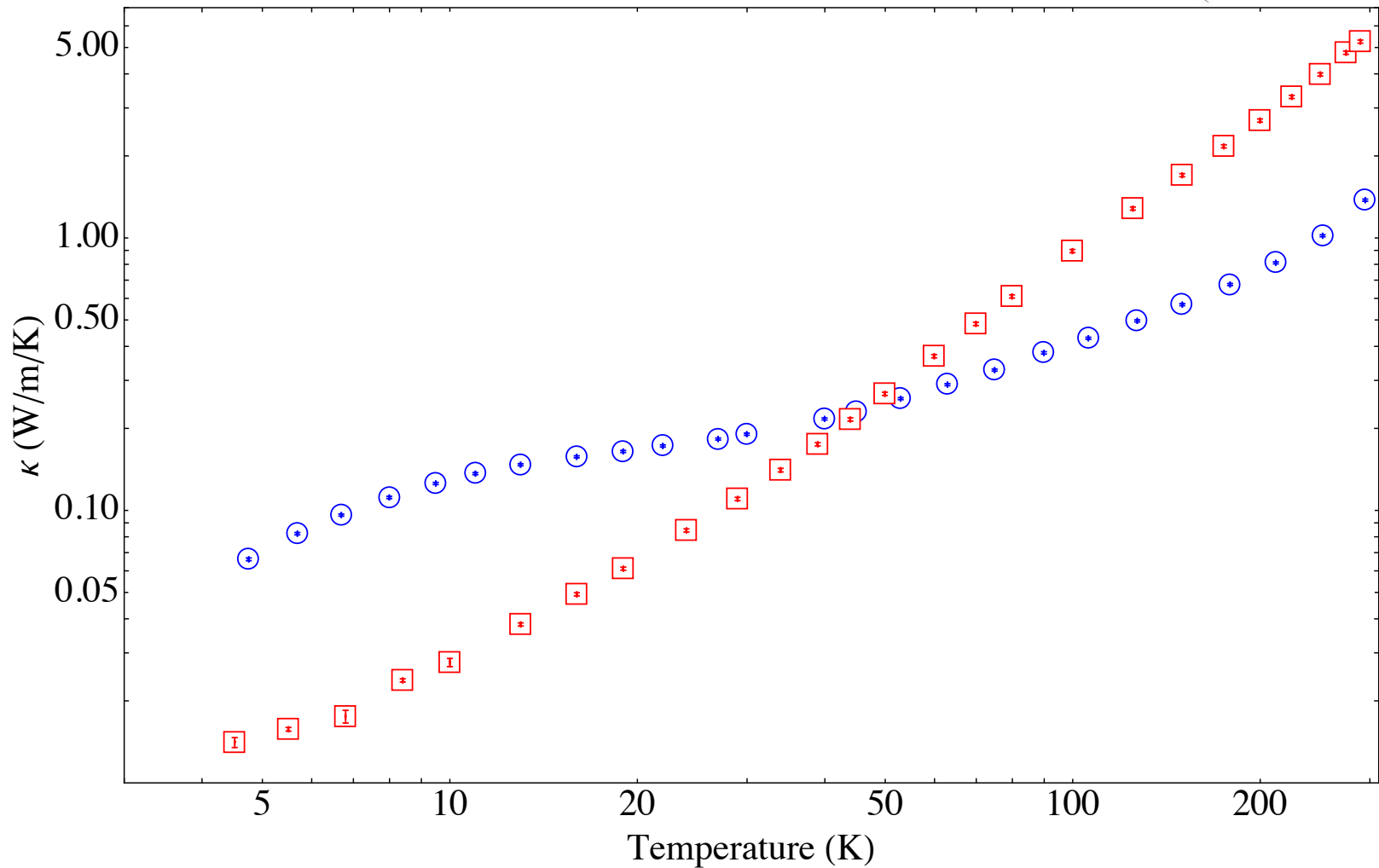
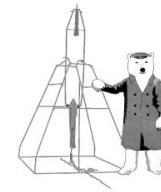
Polymer Samples



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

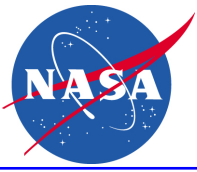


Composite Samples

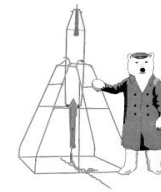


○ S-glass [(45,-45,0)4s layup, S2 glass in EX1522 epoxy matrix]

□ 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