# Thermal Properties – Do We Trust Them?

# Yes'ish

## Panel Discussion

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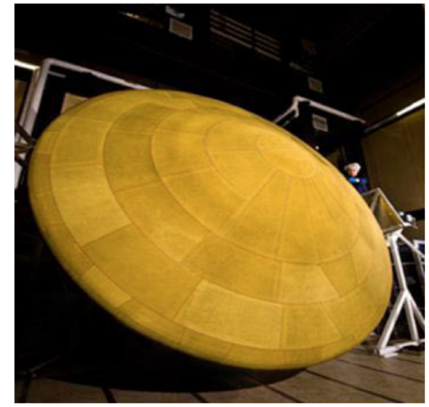
Newport News, VA

# Perspective

- Materials science vs analysis perspective
- Focus on ablative TPS materials
  - Low – mid density, porous materials
  - Carbon Phenolic based materials
  - PICA and HEEET
- Focus on Thermal Conductivity
- Primarily based on experience from:
  - Crew Exploration Vehicle (CEV) Thermal Protection System (TPS) Advanced Development Program (ADP)
  - Heatshield for Extreme Entry Environment Technology (HEEET) Project

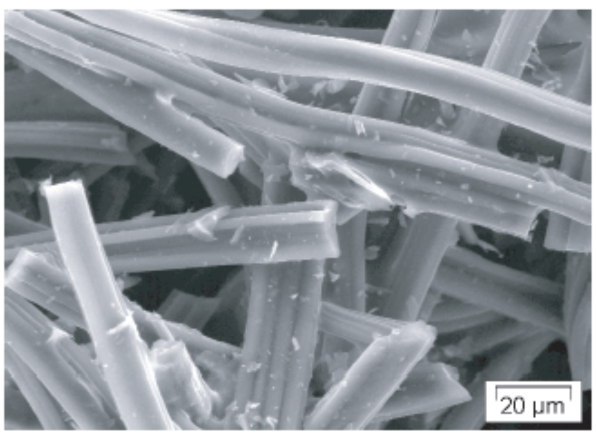
# What is PICA?

- Phenolic Impregnated Carbon Ablator (PICA)
  - Used on Stardust, MSL, OSIRIS, Mars 2020
  - Low Density Carbon Phenolic Ablator

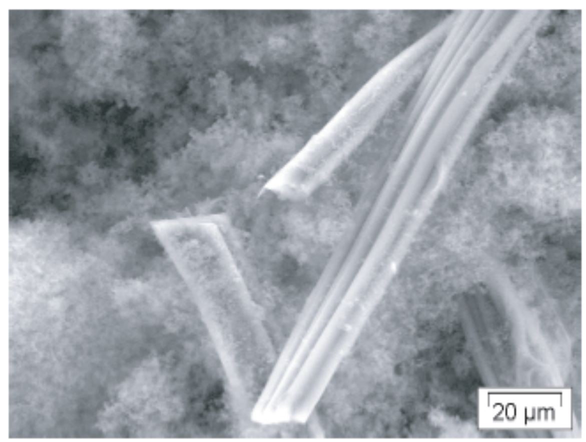


MSL Heatshield (4.5m diameter)

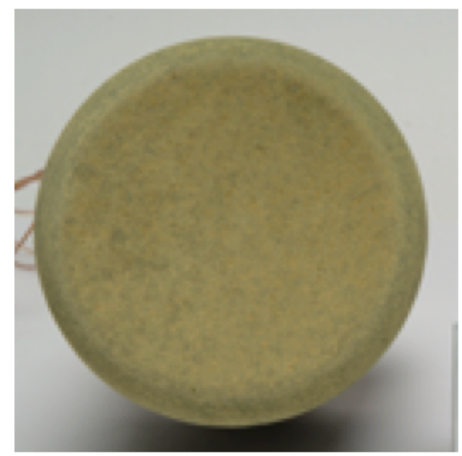
OSIRIS-REx forebody TPS. (~0.8m diameter)




Fiberform before impregnation

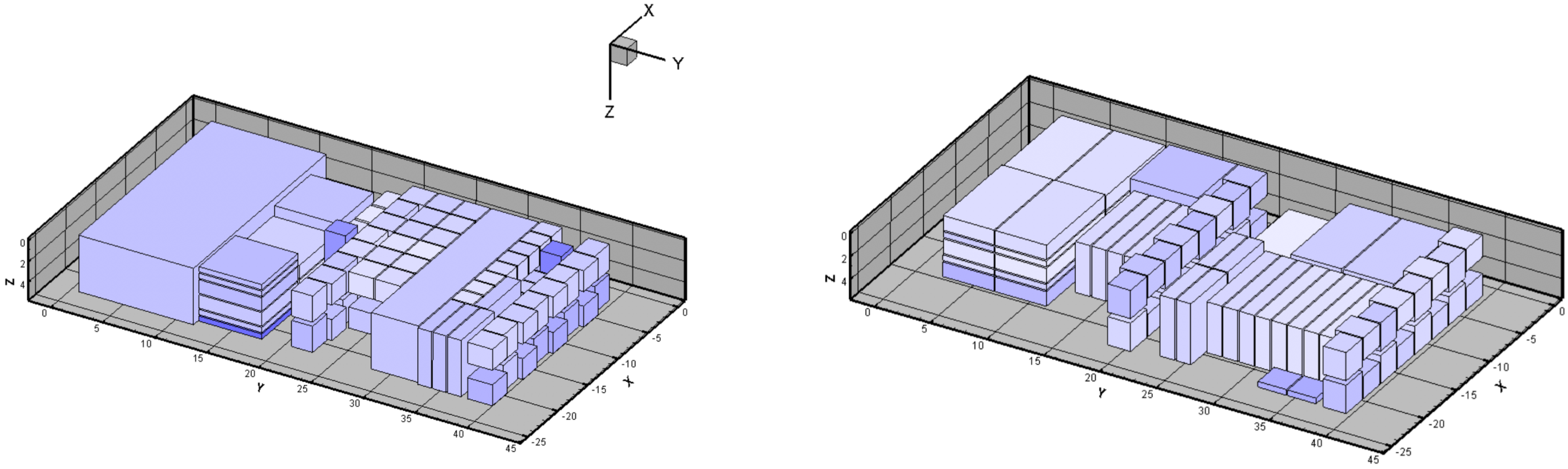


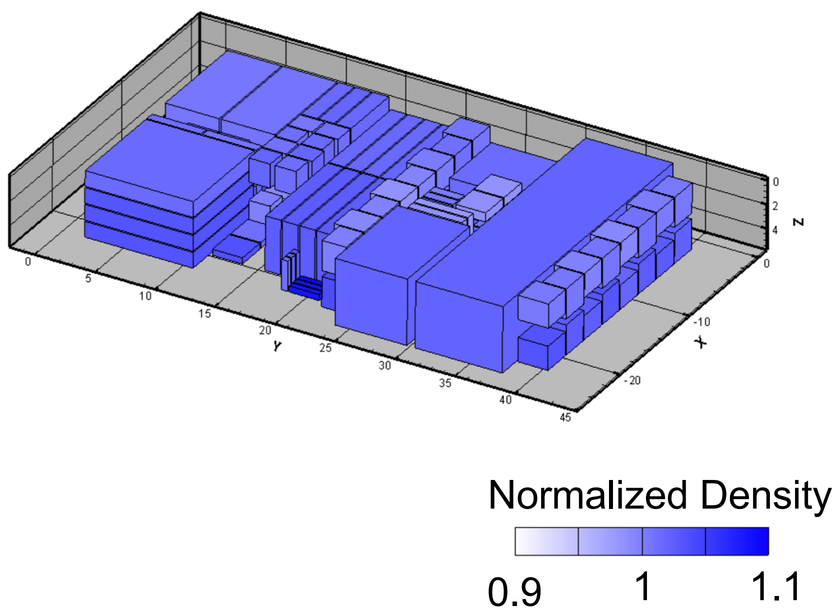

PICA with phenolic resin impregnated



PICA Billet

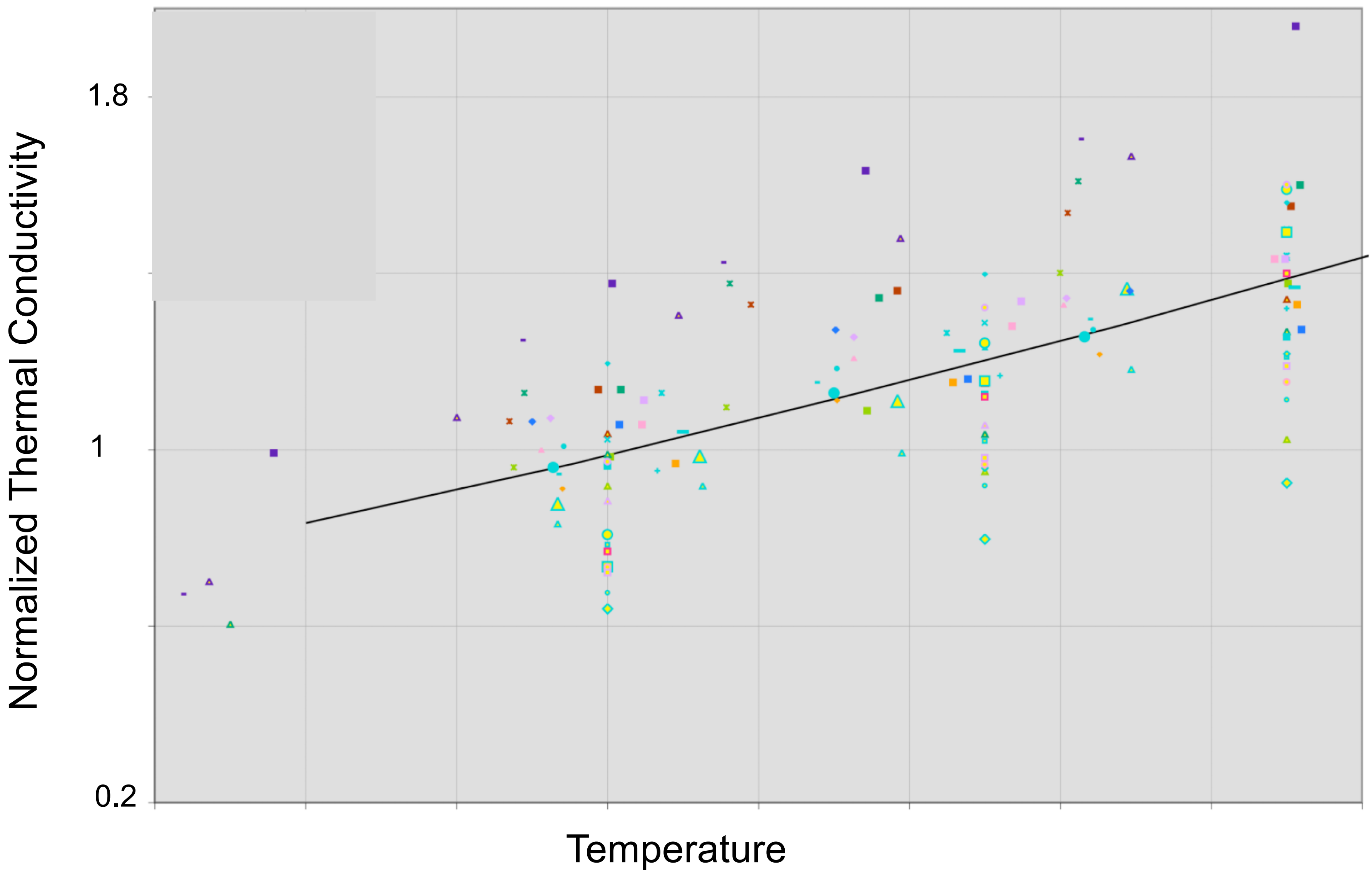
# PICA Billet Has Significant Variability in Density



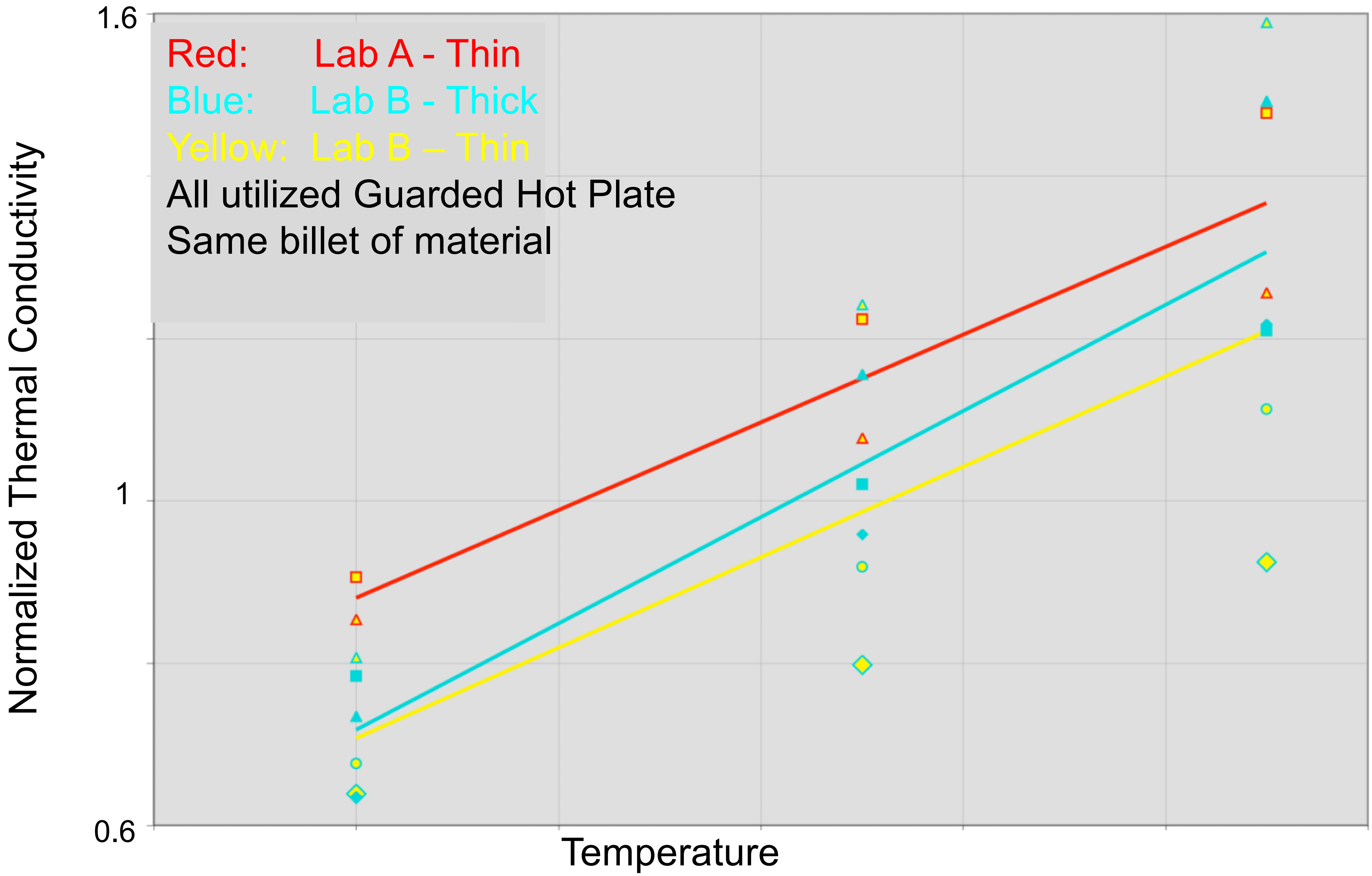

- Density of individual test specimens were measured and used to create a density map for PICA billets
- Density variation exists within a single billet and from billet to billet
- Manufacturing process results in preferred fiber alignment but not perfect fiber alignment
    - Thermal Conductivity in X/Y (in-pane) is ~2 times in Z (thru the thickness, TTT)

# PICA Thermal Conductivity Spans a Wide Range



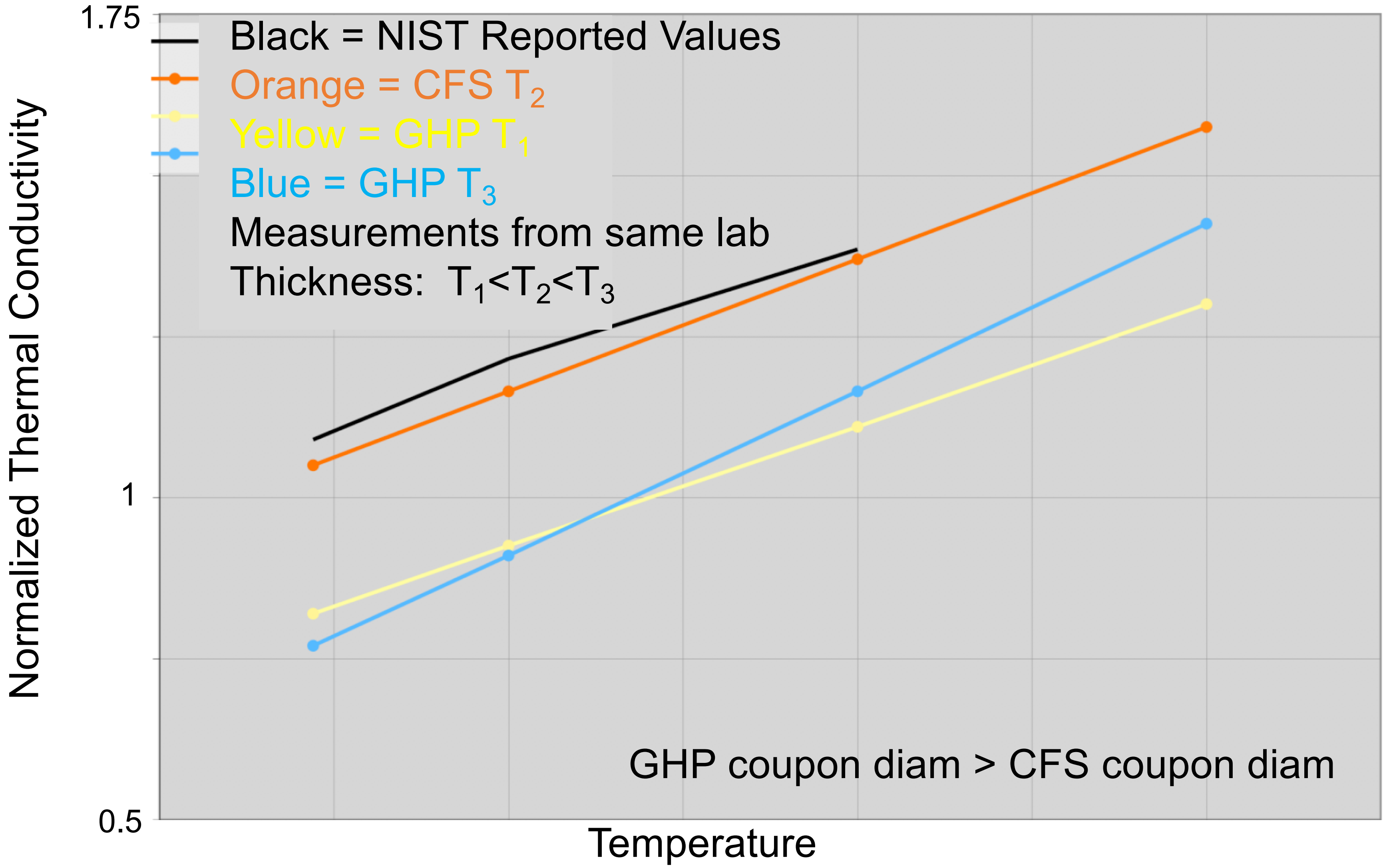

- Data pooled from 2 different labs utilizing 3 different test approaches
- What value do you use for design?
- If thermal conductivity is utilized for lot acceptance what value do you use?

# PICA Thermal Conductivity Measurements Are Test Technique Dependent



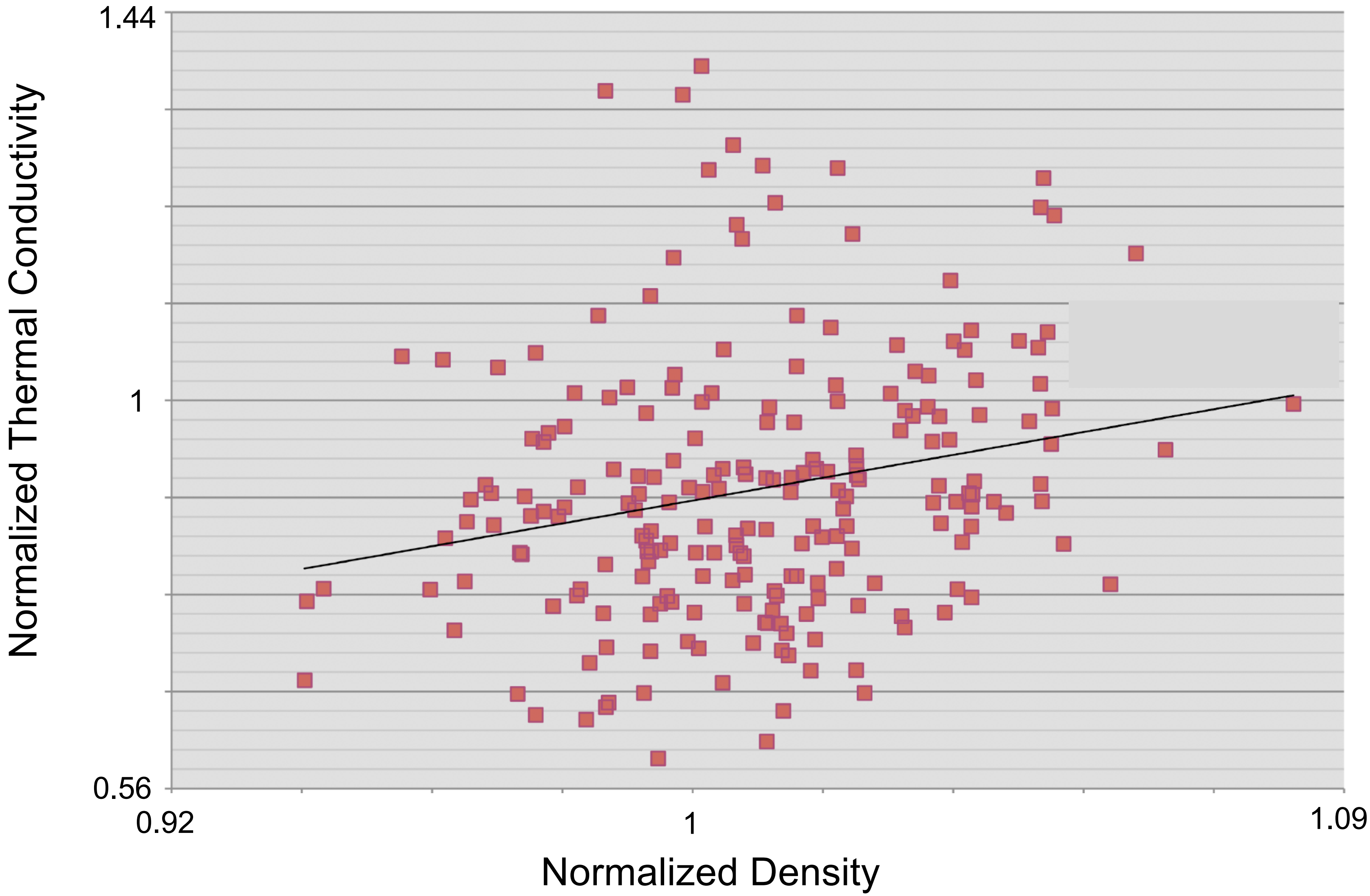

- Thick specimens had less variation (from this limited test pool)
- Lab A appears to have less variability

# NIST Standard Material Thermal Conductivity Measurements Are Test Technique Dependent

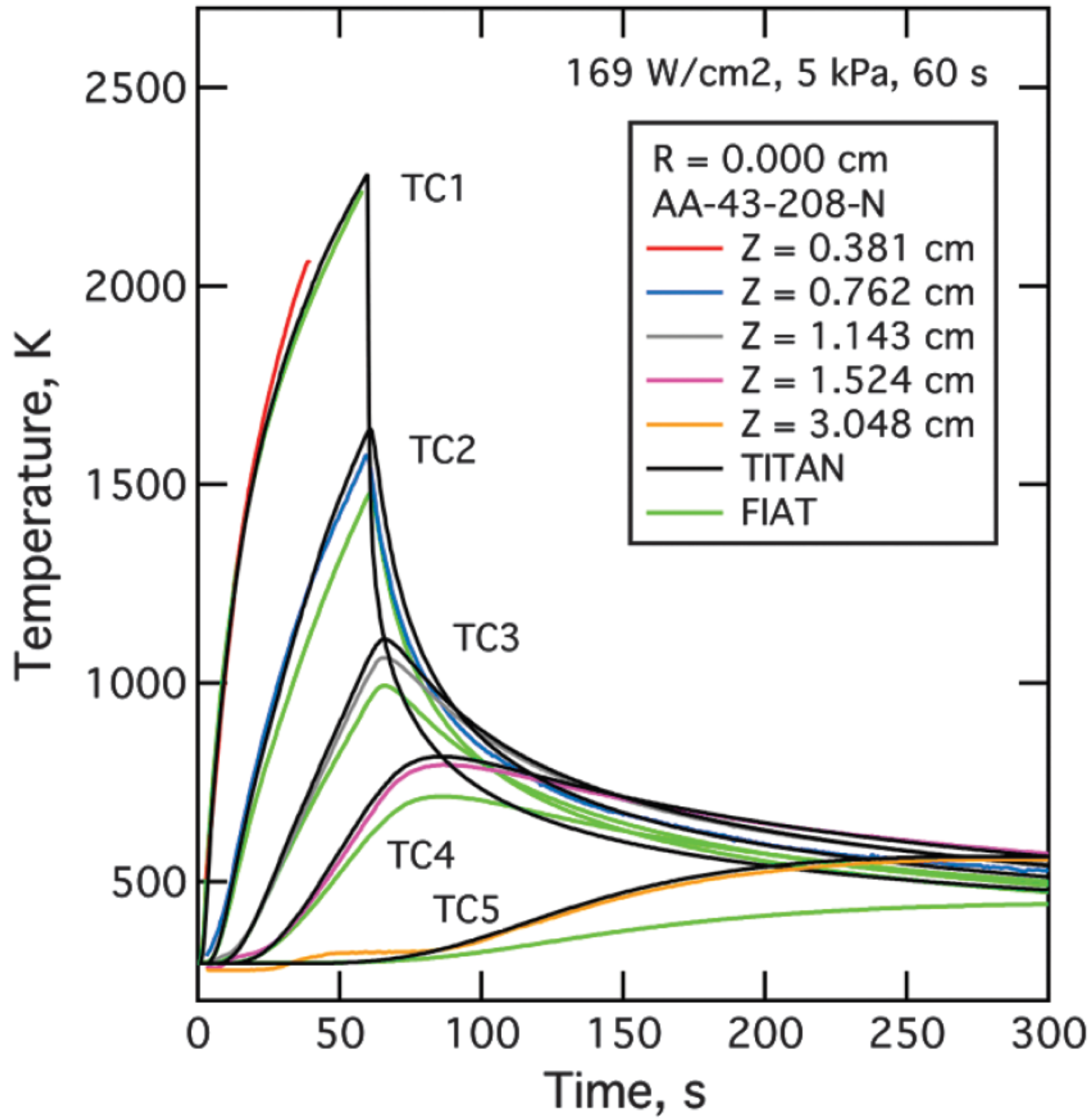



- For the standard material GHP consistently lower than CFS
- CFS closer to NIST standard values

# No Strong Trend in Thermal Conductivity as Function of Density



# Given All That – We Still Do a Reasonably Good Job of Predicting In-Depth Temperatures




- 4” ISO-Q arcjet test article with in-depth thermocouples
- Z = TC distance from surface

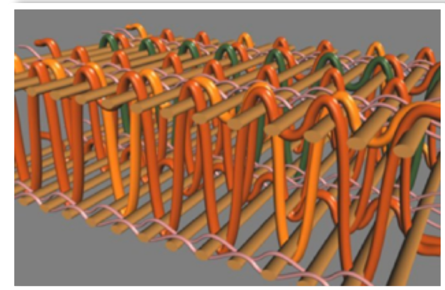
Milos and Chen
JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 47, No. 5, September–October 2010

# PICA Summary

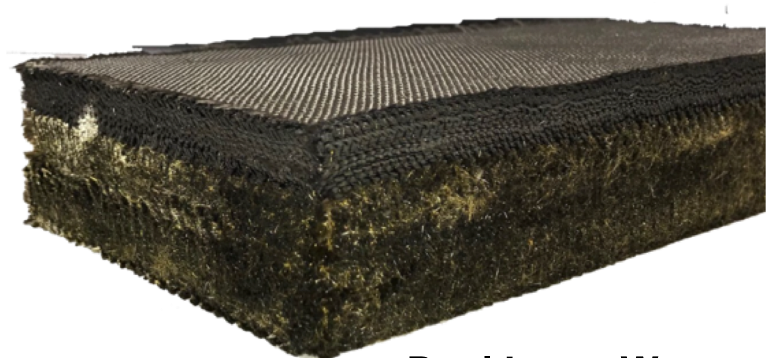
- Inherent variability in the material is contributing to wide range of thermal conductivity values measured
  - Density appears to have only minor effect
  - Local variability in fiber orientation is contributing
- Variations are likely averaging out through the thickness
  - Thicker specimens appear to have lower variation
- However, thick specimens are more difficult to use for lot acceptance due to limited material availability
- The worst case value is going to depend on the analysis being performed
  - For TPS sizing = high thermal conductivity
  - For thermal stresses in a material – driven by low thermal conductivity
- Absolute value of the conductivity in PICA is very small compared to metals, C-C etc…

# What is the HEEET Material?

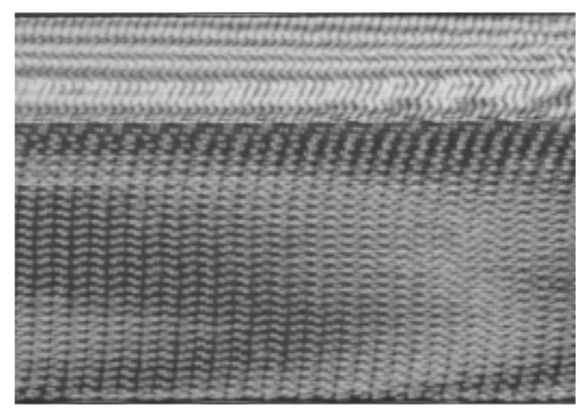
- Mid-density 3D woven dual layer carbon phenolic
  - 3D layer to layer weave
  - Dual Layer:
    - OML Layer = Recession Layer (RL) – manages recession
      - Higher density all carbon fiber weave, exposed to entry environment
    - IML Layer = Insulation Layer (IL) – manages heat load
      - Lower density, lower thermal conductivity, blended carbon/phenolic yarn
    - 2 layers are integrally woven together,
      - mechanically interlocked (not bonded)
  - Woven material has medium density phenolic resin infusion
    - Higher phenolic loading than PICA
    - Open porosity



**3D Weave**



**Dual Layer Weave**

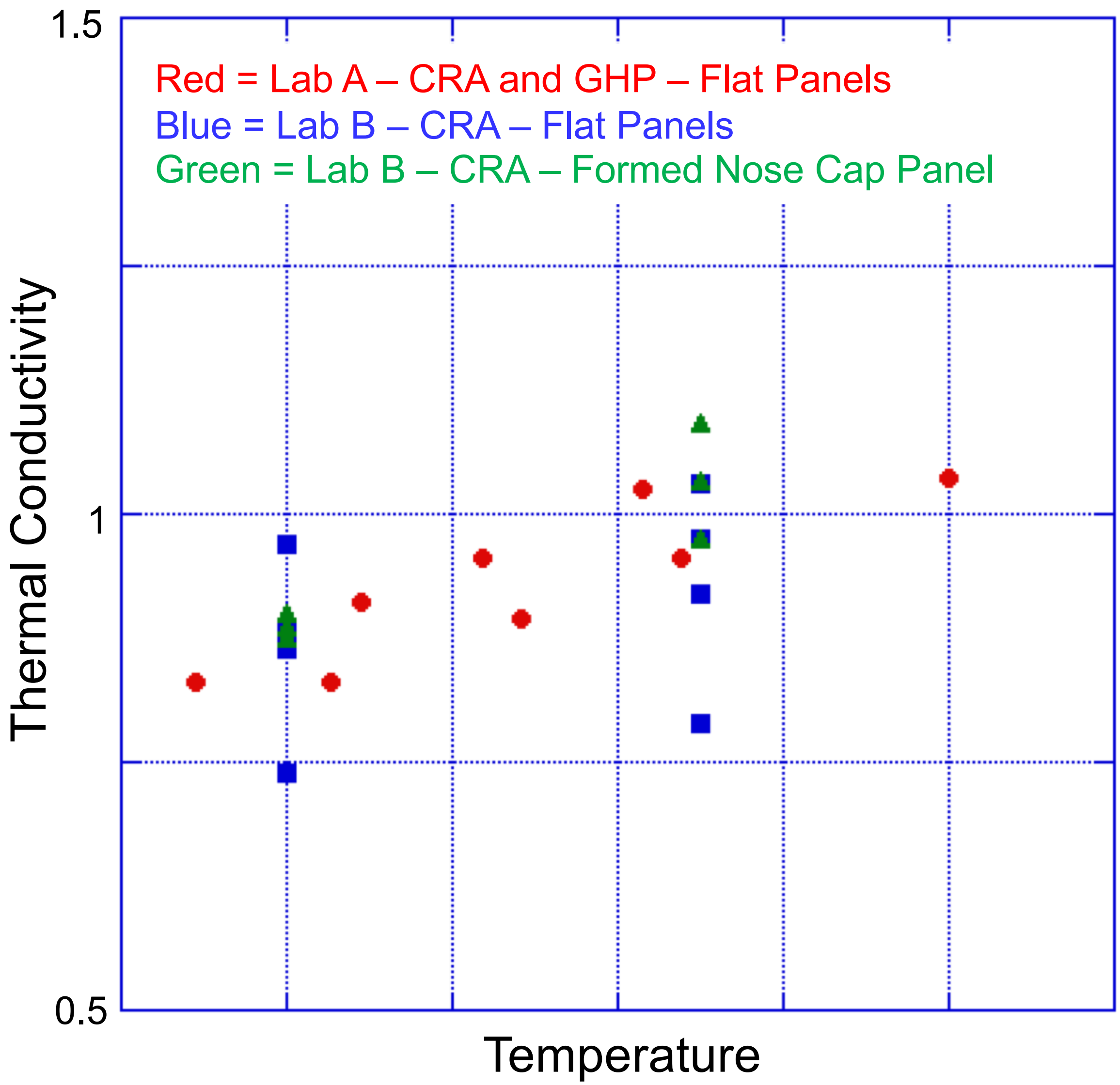


**CT Scan HEEET Weave**

# Challenges with Thermal Conductivity Measurement in HEEET

- RL and IL are transversely isotropic materials
  - IP conductivity higher than TTT conductivity
- Recession layer tends to be thin, thickest woven to date ~0.6 inches
  - Makes it a challenge to measure IP thermal conductivity
  - Extracting coupons parallel or perpendicular to primary fiber direction is challenging given material thickness limitations
- Even IL layer is not very thick, ~1.5 inch max thickness demonstrated to date making coupon extraction challenging
- Limits the diameter and thickness of specimens that can be tested
  - At times multiple layers of RL could be stacked to get sufficient thickness to cut out IP specimens – is this representative?
- However HEEET microstructural variability appears less pronounced than in PICA so results are more consistent: billet to billet, within billet and when using different techniques

# HEEET Thermal Conductivity Comparisons

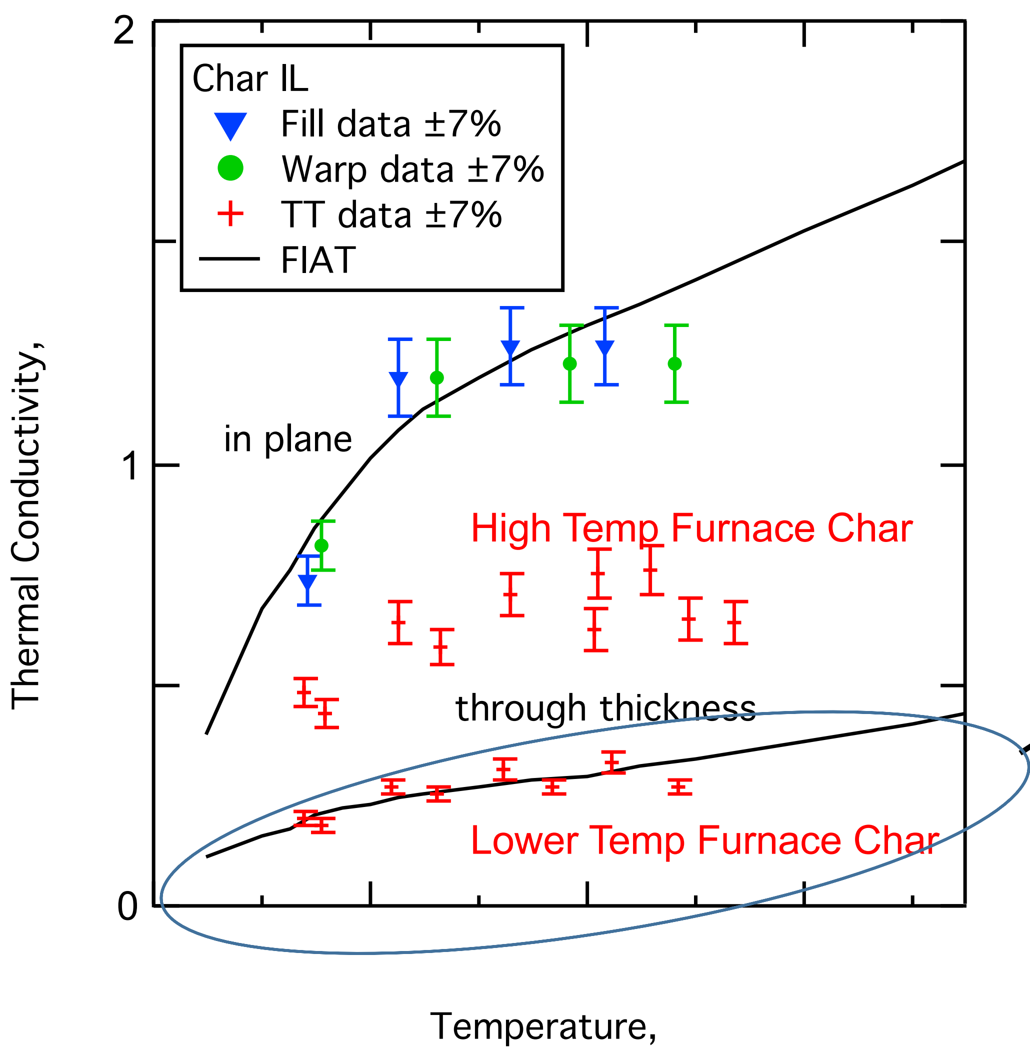


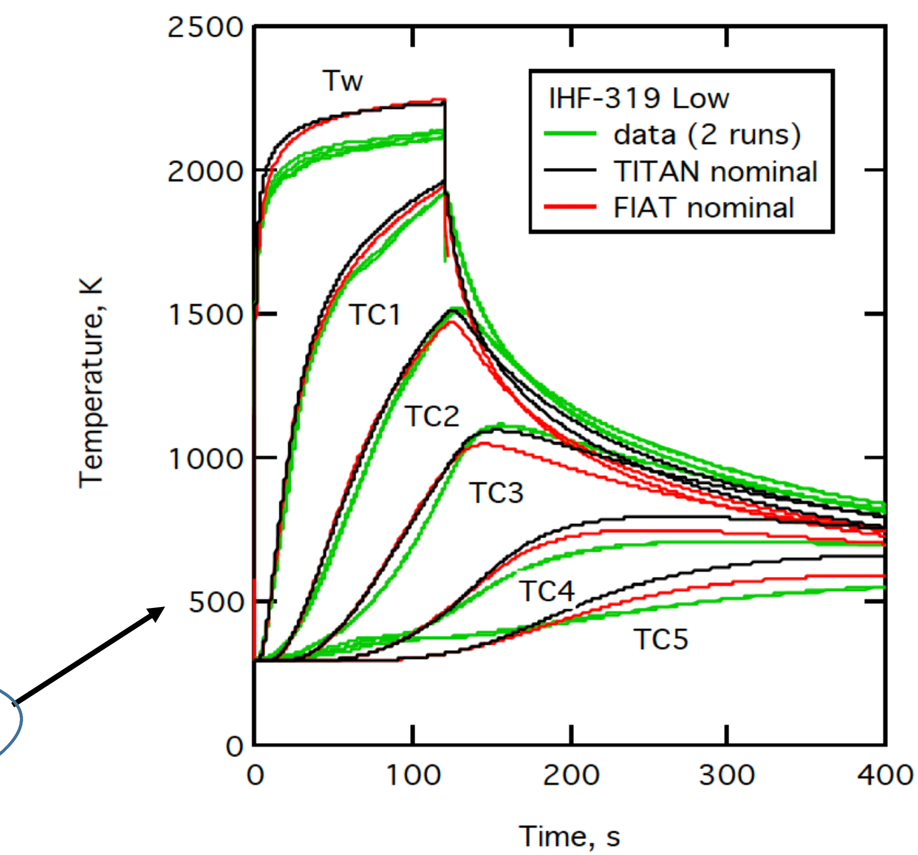

- HEEET material is woven flat and formed to follow OML of heatshield
- Forming does not appear to significantly effect conductivity

# HEEET Char Thermal Conductivity

- Ablative materials char during heating
- Char conductivity is different than that of virgin material
- Char is often developed in a furnace at lower temperatures than during entry, then conductivity is measured and used in material response models
- HEEET project looked at heat treating char to flight relevant temperatures and then measured thermal conductivity
  - Challenge is that time at temperature during entry is minutes versus hours during a high temperature furnace heat treatment
    - Furnace allows for change in structure of carbon (graphitize) that may not occur during entry
    - High temperature furnace char (2361K) is ~2X higher than lower temp char (1473K)

# HEEET Char Thermal Conductivity




Thermal response model with Low Temp Furnace Char matches in-depth TC measurements well

- Use of high temperature furnace char measurements would result in larger discrepancies

# HEEET Summary

- Thin layers in HEEET material system can pose challenges in conductivity measurements
  - Some missions may have thicknesses of 0.1” of the RL
- Depending on radius of curvature forming may influence properties
- Char thermal conductivity is difficult to measure
  - Not currently feasible to measure char conductivity in realistic environment:  appropriate temperature transients, which pyrolysis gases percolating through, etc…
- Even with these challenges current HEEET material response models provide good agreement