Thermal Properties for Accurate Thermal Modeling

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Outline

- **Thermal Properties**
  - Typical thermal property data
  - Typical thermal property measurement data
  - Thermal property measurement techniques

- **Insulation thermal property measurements & predictions at NASA LaRC**

- **Appendices**

Background

- **Author's background: Thermal modeling and thermal measurements for high temperature thermal protection systems**

- **Material presented here is from published and unpublished data on thermal properties of components of thermal protection systems**

Motivation

- **What is needed for accurate thermal modeling**
  - Correct geometry
  - Accurate thermal properties
  - Accurate boundary conditions
- **Will assume typical thermal analyst can model geometry & boundary conditions correctly**
- **Emphasis of this talk is on thermal properties**

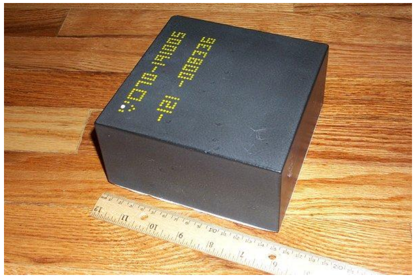
Thermal Property Resources

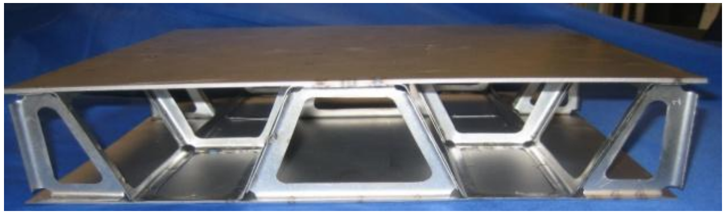
- **What sources does one use to obtain thermal properties**
  - Heat Transfer text book (undergraduate)
  - Handbook of Heat Transfer; Handbook of Radiation Heat Transfer
  - Thermophysical Properties of Matter, by Thermophysical Properties Research Center (1970)
  - NASA RP-1289, "Thermal Protection Systems-Thermophysical Property Data," (1992)
  - Aerospace Structural Metals Handbook (1994)
  - Other sources and references
  - Experimental thermal property measurements

- **How confident is an analyst that properties used in thermal analysis (from published data or experimental measurements) are accurate?**

Titanium Thermal Properties

- **Space Shuttle tiles mainly carry thermal loads**
- **Space Shuttle tiles do not carry structural loads (except normal pressure loads of ~ 2psi)**
  - Structural loads are carried by the underlying airframe structure
  - Airframe structural loads are de-coupled from the TPS by using strain isolation pads (between tile and airframe)
- **NASA is working on developing structurally integrated thermal protection systems (SITPS)**
  - Carries both thermal & structural loads
  - Is more damage tolerant
  - **A prototype SITPS concept is shown here**
    - Truss core structure (made of titanium for proof of concept) filled with flexible fibrous insulation



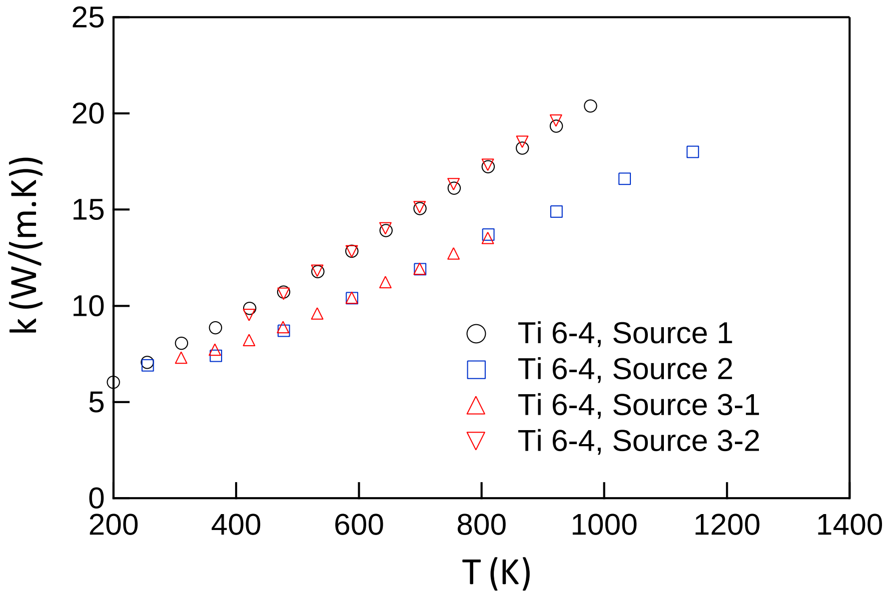


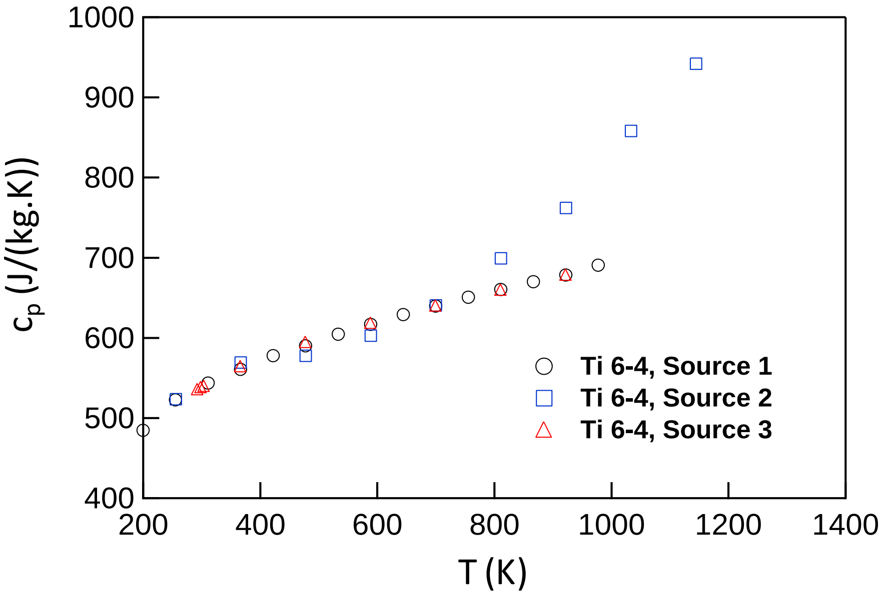
Titanium Thermal Properties

- **Performed transient thermal tests on the truss core SITPS concept (simultaneously varying surface temperature and pressure according to a typical reentry profile) at NASA LaRC's thermal vacuum facility**

- **Needed to perform thermal analysis of SITPS**
  - Needed thermal properties of Ti 8-1-1 (8%Al, 1Mo%, 1%V)
  - Could not find thermal properties on this specific titanium alloy
  - What does an engineer/thermal analyst do in this situation: look at thermal properties of other titanium alloys: Ti-6-4 (6% Al, 4% V)

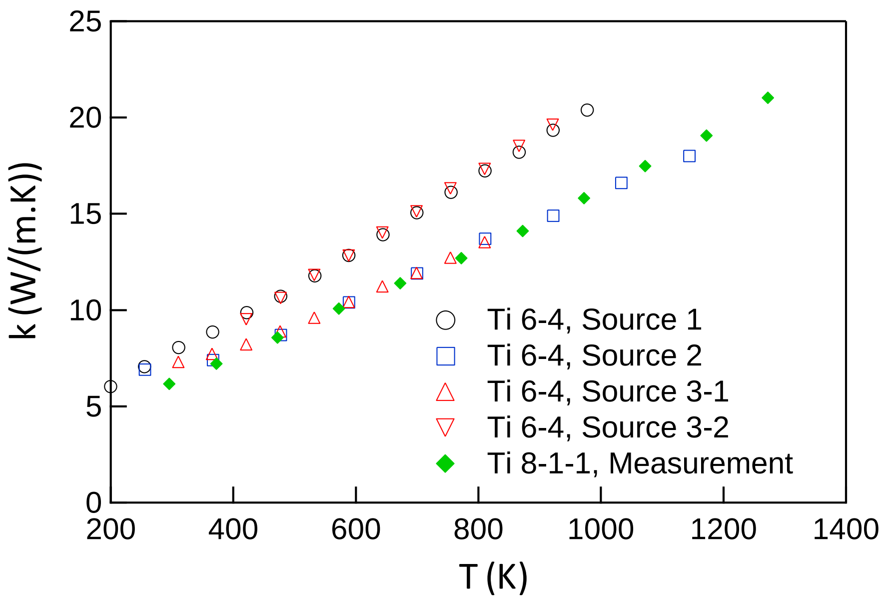
Thermal properties of Ti 6-4

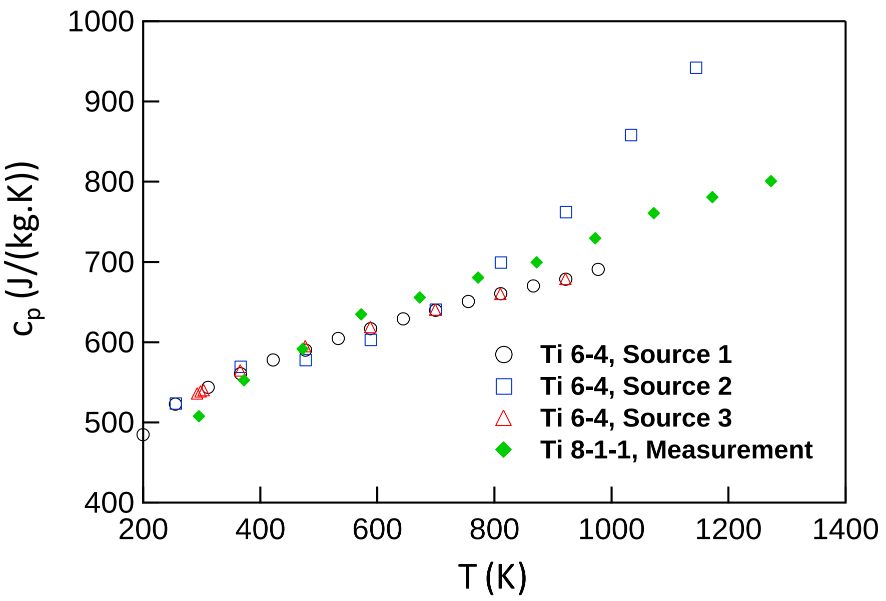




- **Two distinct sets of thermal conductivity data; difference between 2 sets increases with increasing temperature: 30% difference at 922 K**
  - Source 3-1 data matches Source 2
  - Source 3-2 data is for specially heat treated Ti, and matches data form Source 1
- **Specific heat data from Source 2 at temperatures above 800 K appears to be erroneous**
- **Which set of data shall we use?   Decided to perform property measurements on the specific Ti 8-1-1 at a laboratory**

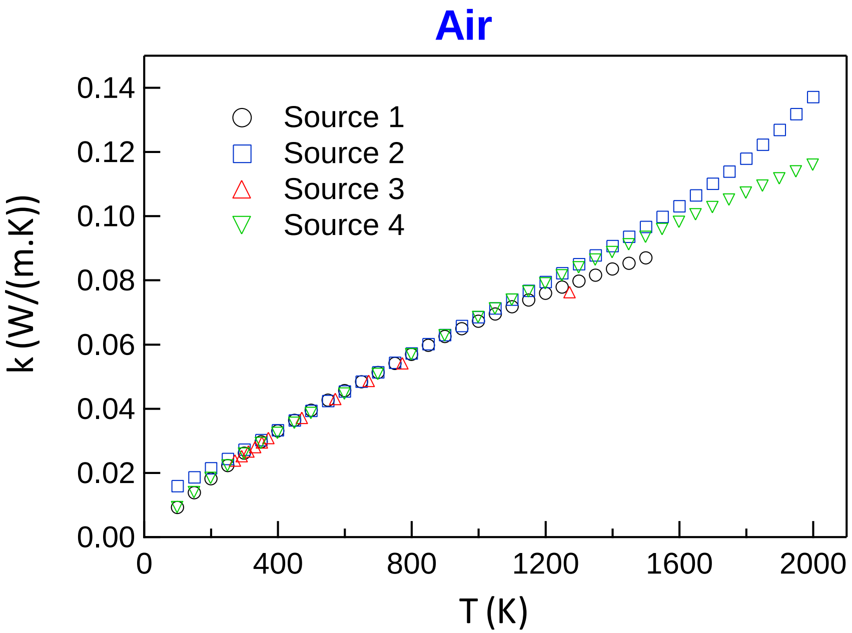
Thermal properties of Ti 8-1-1

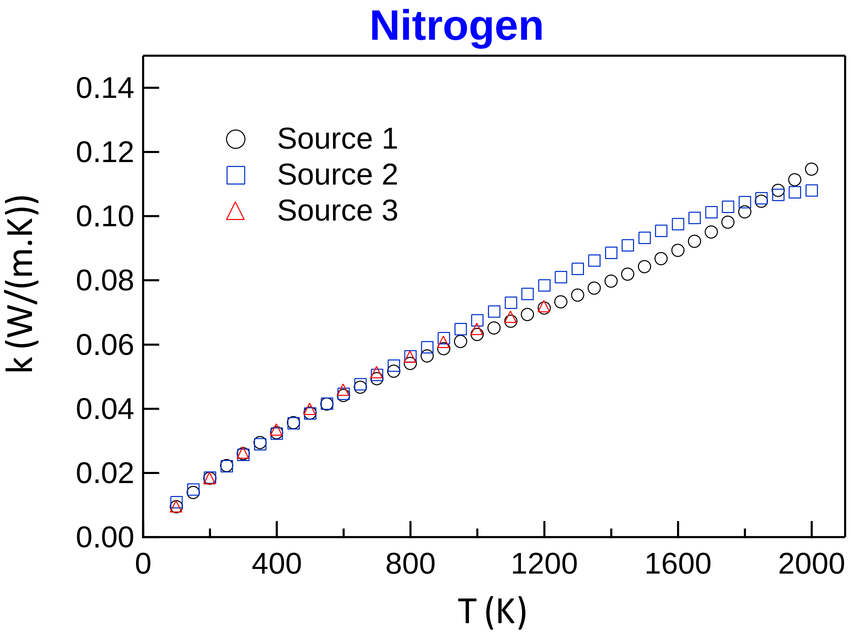




- **Thermal conductivity of Ti 8-1-1 matched thermal conductivity of Ti 6-4 from Sources 2 & 3-1**
- **Specific heat of Ti 8-1-1 was slightly higher than specific heat of Ti 6-4 from Sources 1 & 3**

Thermal Conductivity of Gases





- **Air:**
  - Source 1 & 3 are similar
  - Source 2 over-predicts both at cryogenic temperatures and above 1200 K
  - Source 4 over-predicts above 1200 K
- **Nitrogen:**
  - Source 1 over-predicts between 1000 -1900 K

Thermal Property Data

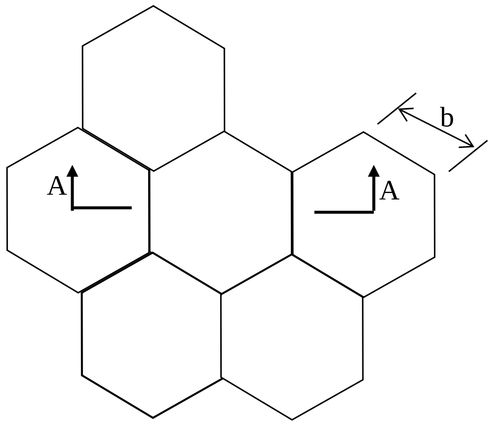
- **Do not rely on thermal property data from one source. Look up multiple sources. Do not necessarily trust manufacturer data**
- **Do not extrapolate thermal properties beyond the range of provided data, especially using curve-fits**
- **Thermophysical Properties of Matter (TPM) series (1970; published by IFI/Plenum) provide an extensive compilation of data from various sources, along with additional info**
  - Source of data
  - Method used to obtain data
  - Any special treatment of material
  - In some cases, provides the “recommended set of values”
  - Unfortunately does not contain data on newer materials, such as newer metallic alloys, ceramic matrix composites (CMC), polymer matrix composites (PMC)

Thermal Property Data

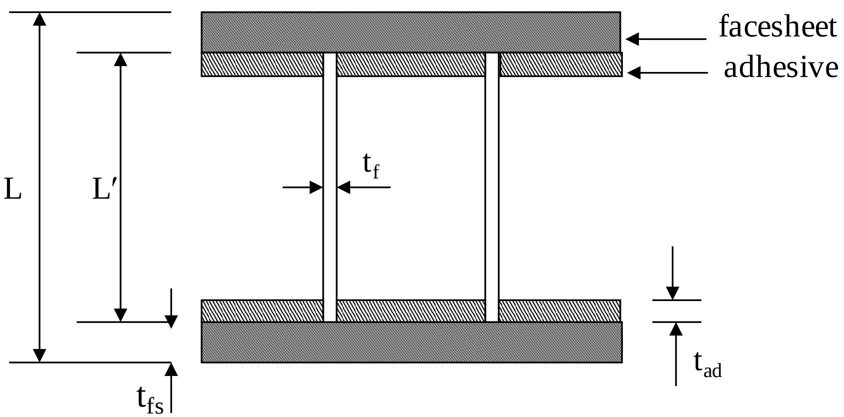
- **If can not find data for the specific material of interest, or not certain about the accuracy of available data, obtain thermal property measurements at a laboratory**
  Question: How reliable are the measurements?

Thermal Conductivity of Titanium Honeycomb Panel

- **Adhesively bonded titanium honeycomb panels (25.4 mm height, 4.8 mm cell size) were to be used as the wing structure of the High Speed Civil Transport**
- **Heat transfer through the honeycomb panel was critical to the design**



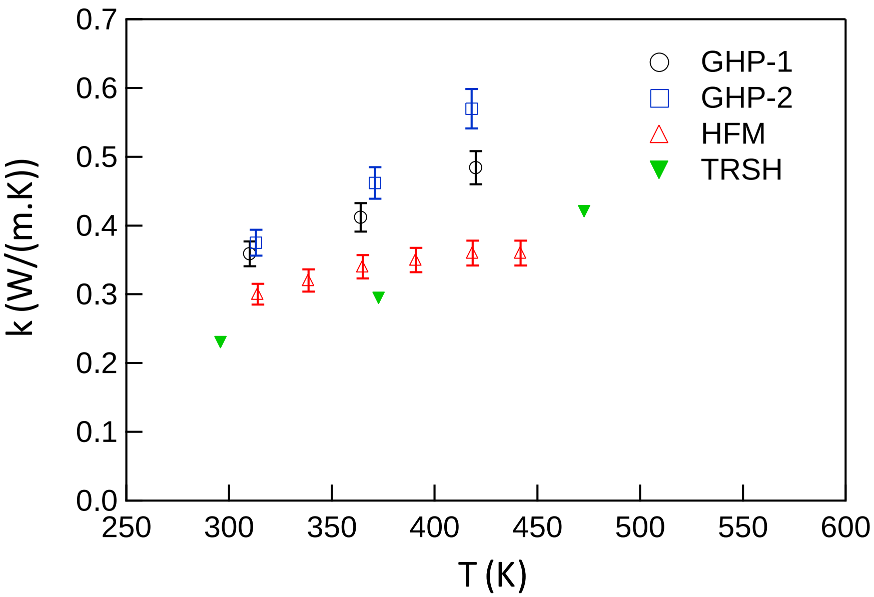
Plan view of honeycomb core



Section AA

Thermal Conductivity of Titanium Honeycomb Panel

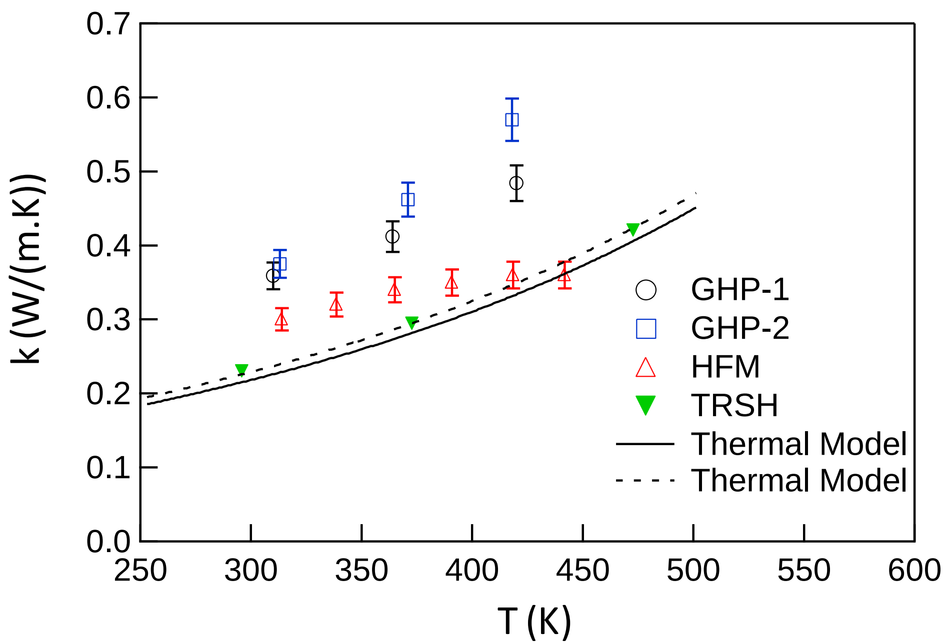
- **Effective thermal conductivity of honeycomb panels were measured at 4 laboratories using 3 different techniques**
  - Guarded Hot Plate (GHP)
  - Heat Flow Meter (HFM)
  - Transient Radiant Step Heating (TRSH)



- **4 sets of measurements were significantly different**
  - 2 GHP results were highest, and did not match at higher temperatures (17% difference at 420 K)
  - 45% difference between HFM & GHP data at 420 K
  - Dilemma: which set of data is more accurate

Thermal Conductivity of Titanium Honeycomb Panel

- **Performed numerical thermal modeling of heat transfer in honeycomb panel**
  - Solid & gas conduction, and radiation in cells
  - Obtained two sets of predictions based on lower & upper bound range of adhesive thermal conductivity (adhesive for bonding honeycomb to facesheets)



- **Numerical thermal model results matched TRSH data**
- **RMS deviations between average prediction and measurements**
  - **GHP-1: 58%**
  - **GHP-2: 76%**
  - **TRSH: 3%**

Thermal Conductivity of Saffil

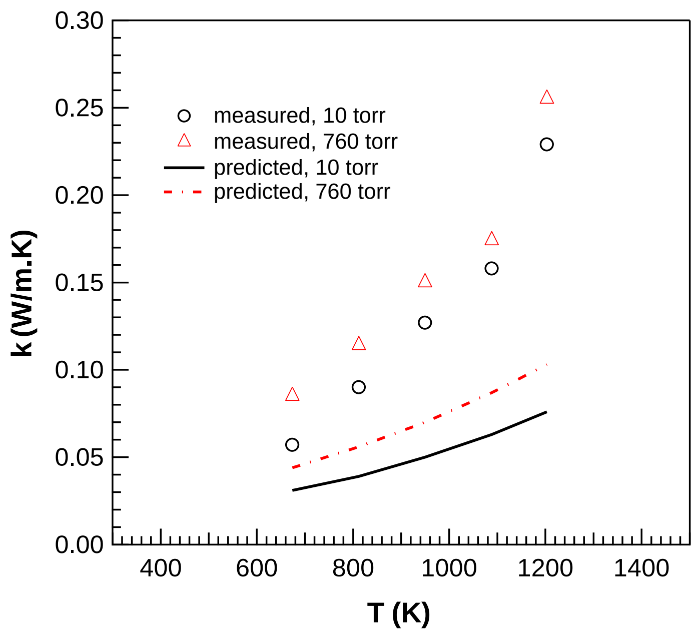
- **Author has developed high-fidelity thermal model for heat transfer in Saffil (high temperature Alumina-based flexible fibrous insulation) for the range of densities of 24 to 96 kg/m^3 (1.5 to 6 lb/ft^3)**

- **During Space Shuttle Return to Flight activities, a specially manufactured Saffil at a density of 144 kg/m^3 was considered for on-orbit repair of damaged tiles (fill the damaged area in tile with Saffil, then cover by a thin CMC sheet)**

- **Dilemma: could the thermal model be extended to this specially manufactured Saffil at higher density, or was a new model needed?**
  - Performed measurements using two different techniques
    - Guarded Hot Plate (GHP)
    - Transient Radiant Step Heating (TRSH)
  - Heat transfer mechanisms in these high porosity insulations are: gas conduction, solid conduction, and radiation, hence thermal properties are function of temperature, environmental pressure, and environmental gas

Thermal Conductivity of Saffil

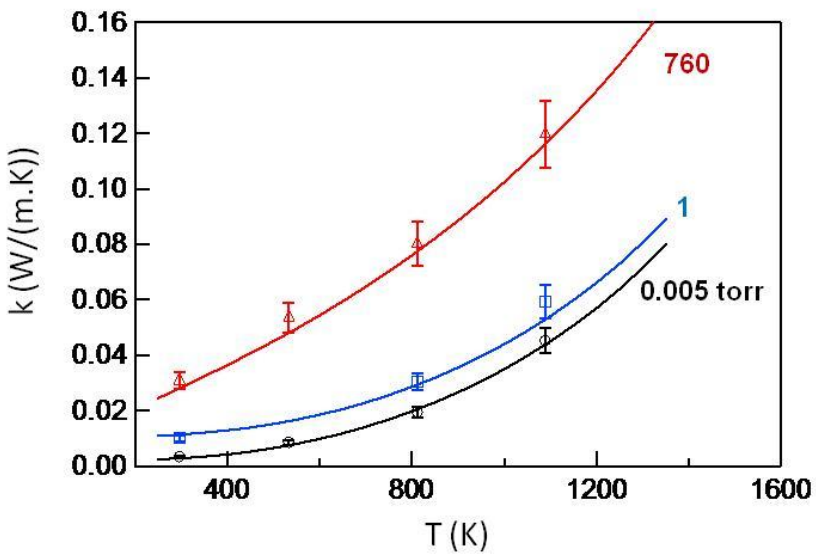
Guarded Hot Plate Technique (argon gas)



- **GHP data were on the average 78% higher than predictions**
- **Dilemma**
  - Either the thermal model is not applicable to this higher density specially manufactured Saffil
  - Or the thermal model developed for lower density regular Saffil is erroneous
  - Or GHP data is erroneous

Thermal Conductivity of Saffil

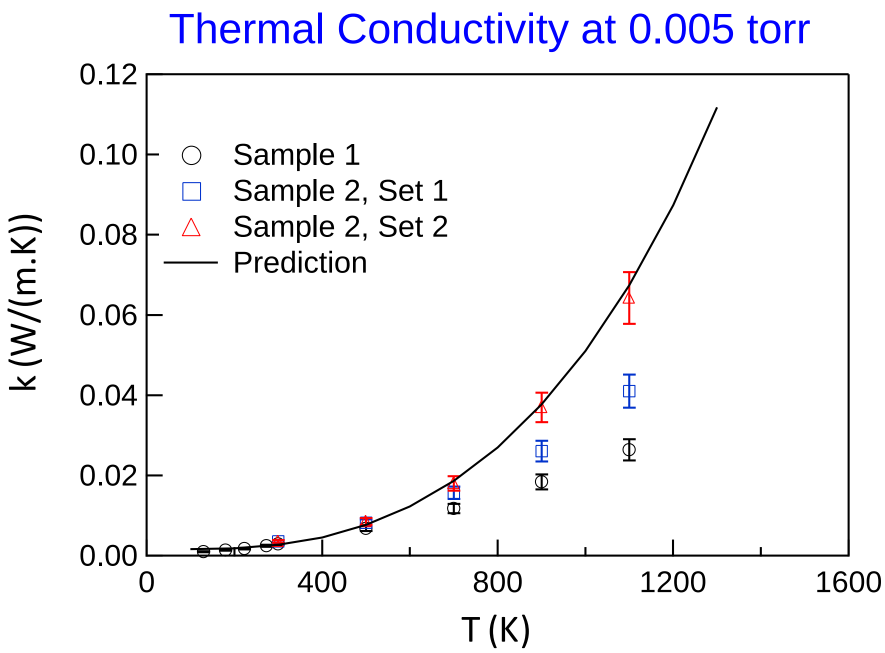
Transient Radiant Step Heating Technique (nitrogen gas)



- **Thermal model matched TRSH experimental data with rms deviation of 10%**
  - Thermal model was applicable for this higher density specially manufactured Saffil
  - GHP data were erroneous
  - GHP technique is fine - have seen lots of accurate data using GHP. Recent data generated using GHP appear to be erroneous. Could it be operator error?
  - TRSH has produced accurate results for both honeycomb and Saffil. Does it always produce accurate results?

Thermal Conductivity of APA

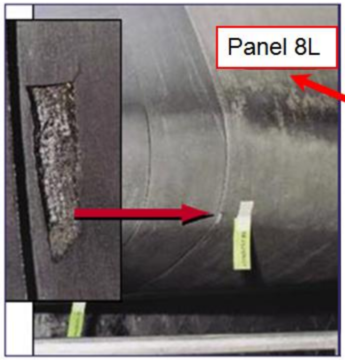
- **Author has developed heat transfer model for alumina paper fibrous insulation (APA). Performed measurements using TRSH technique**

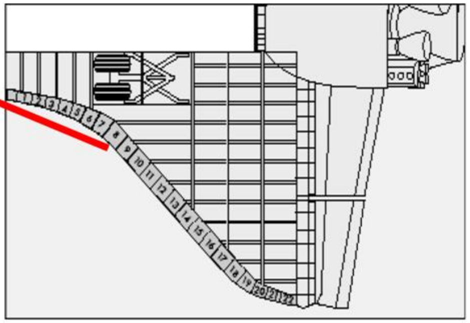


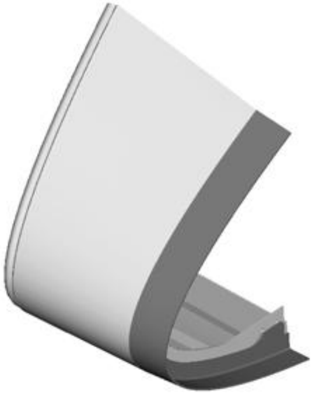
- **Sample 1 data deviated significantly form predictions above 700 K. Sample may have been contaminated during heat treatment prior to testing**
- **Sample 2 was heat treated in a clean oven. 1st set of data still deviated from predictions. Beaded thermocouples were used for temperature measurement. At this low pressure at higher temperatures, most of heat transfer is due to radiation. A beaded thermocouple may not provide accurate temperature measurement in a radiation dominated environment. Asked laboratory to switch to foil thermocouples (6 x 6 x 0.1 mm)**
- **Sample 2 Set 2 data (with foil thermocouples) provided data that closely matched predictions**

RCC Radiant Properties

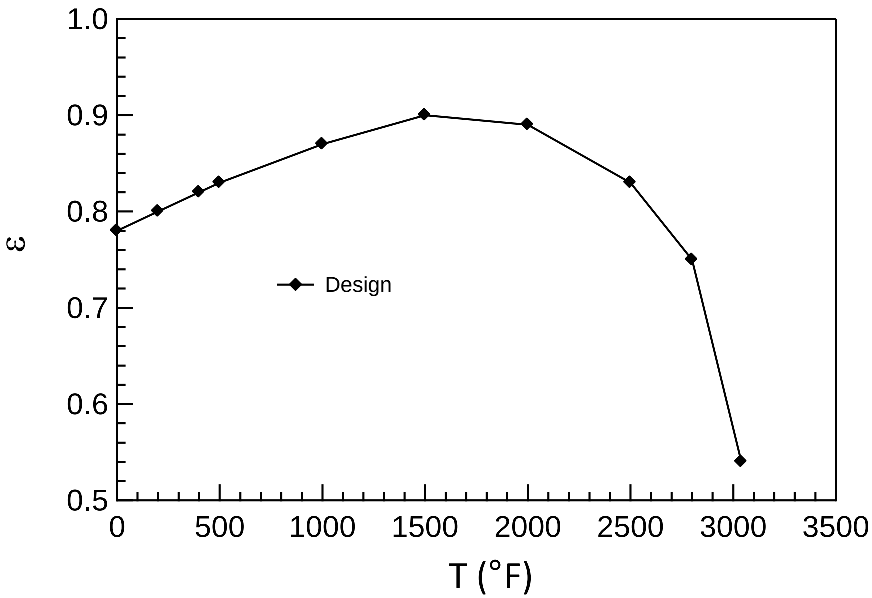
- Reinforced Carbon Carbon (RCC) panels were used as TPS on the wing leading edge of the Space Shuttle. The temperature of RCC panels during flight was highly sensitive to emittance of RCC
- Original design data showed sharp drop in emittance above 2000°F. The lower the emittance, the higher the resulting surface temperature





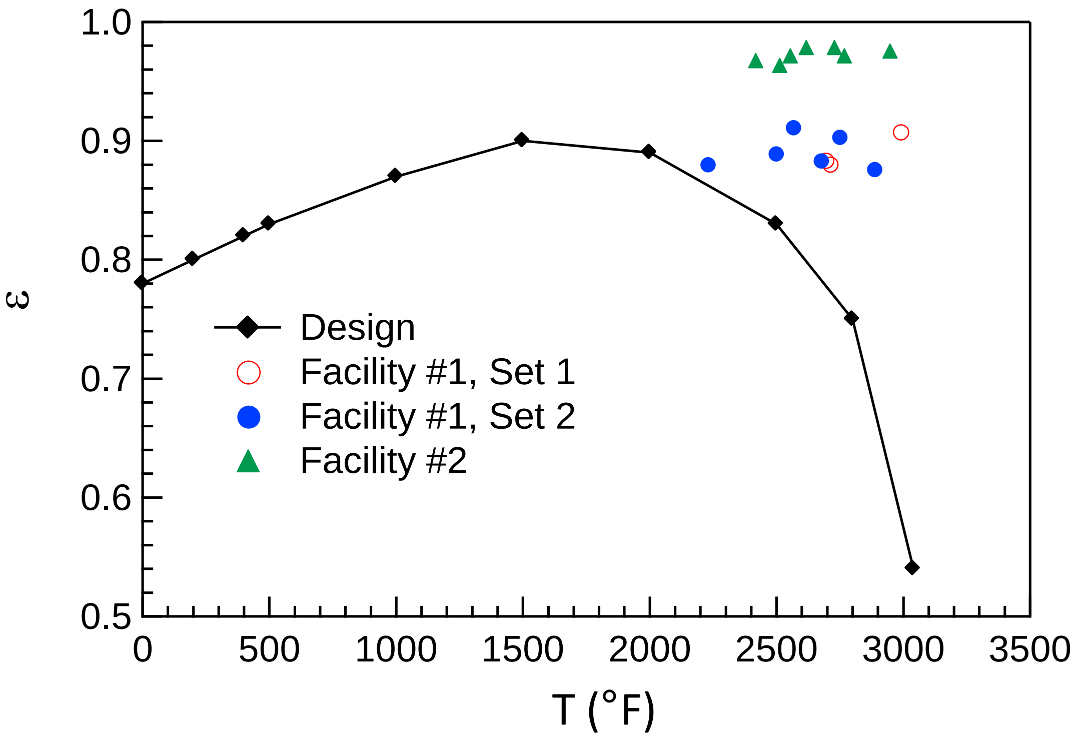


Total Hemispherical Emittance



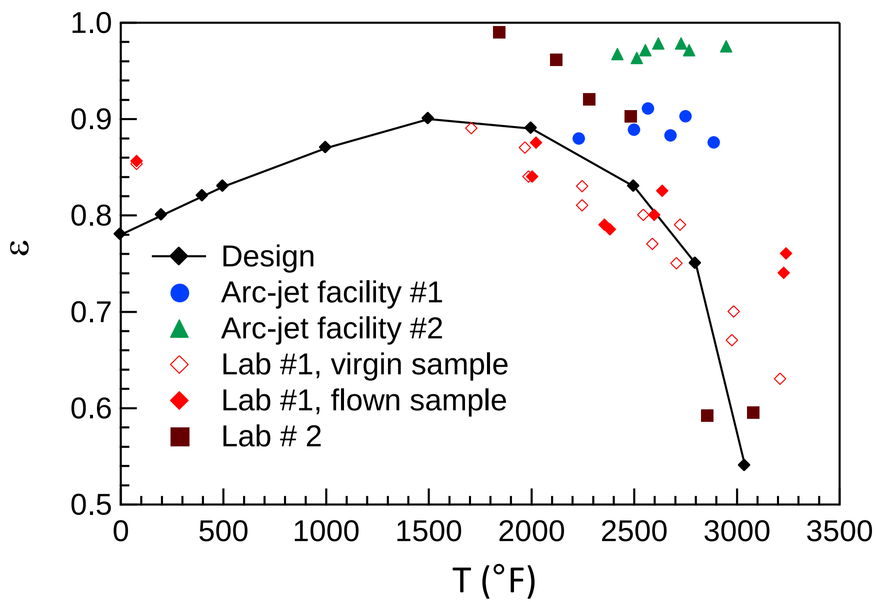
RCC Radiant Properties

- Recent arc-jet test data, using a spectro-radiometer to estimate emittance of test articles during arc-jet tests, showed much higher emittance values above 2000°F. Arc-jet emittance data show no significant variation with temperature
- Which set of data is more accurate?



RCC Radiant Properties

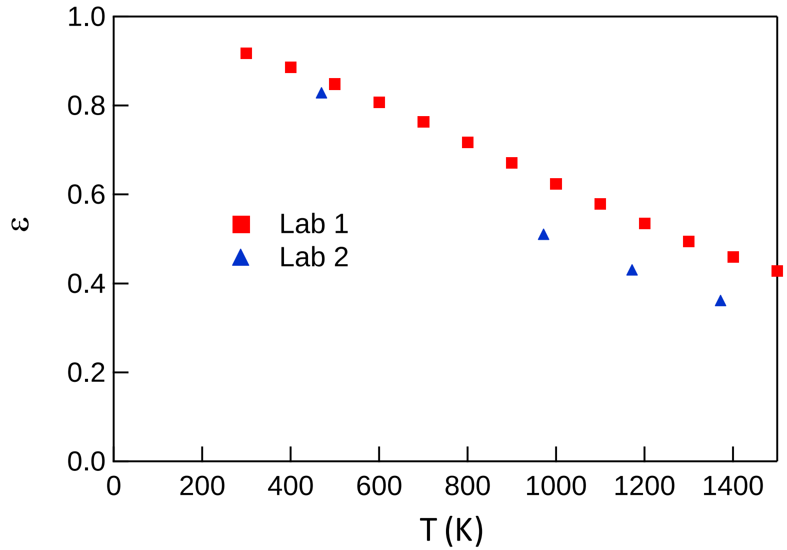
- Performed radiant property measurements in 2 different laboratories, using standard laboratory set-ups



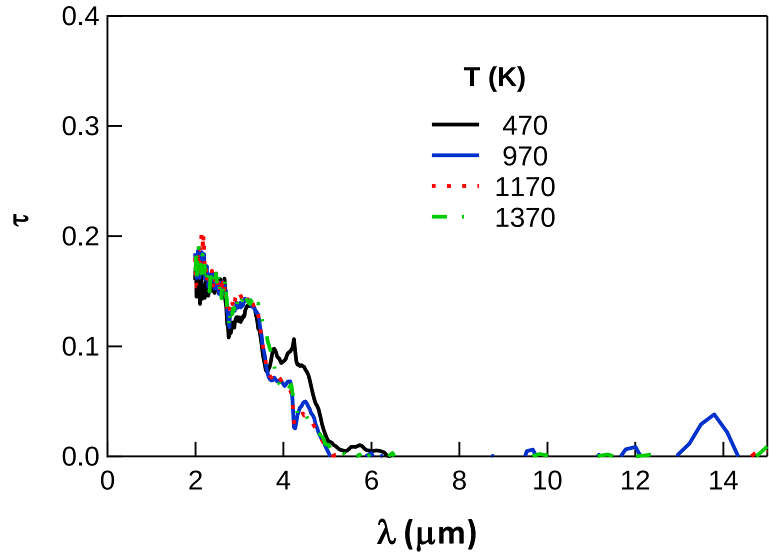
- Results from both labs followed the trend of original Design data, showing drop in emittance with increasing temperature above 2000°F

Radiant Properties of Nextel Fabric

Total Hemispherical Emittance



Spectral Hemispherical Transmittance



- **Nextel fabrics are used in blanket insulations (AFRSI blankets on Space Shuttle)**
  - Emittance of fabric is important for energy balance on the outer mold-line (OML) of blanket. Some engineers assume Nextel 440 has constant emittance of 0.8
  - Most fabrics have transmission at low wavelengths- this fact is ignored by most engineers
- **Total hemispherical emittance data from two labs show that emittance decreases with increasing temperature**
- **Spectral hemispherical transmittance show 20% transmittance at low wavelengths**
  - If fabric is heated radiantly (radiant source at low wavelengths), 20% the radiation will go right through the fabric and heat the underlying insulation
  - Some of the radiation from the underlying insulation (if its temperature is high enough to emit radiation at short wavelengths) will also exit through the fabric

Thermal Property Measurement Techniques

- **Specific Heat:**
  - Differential Scanning Calorimetry- ASTM E-1269

- **Thermal Conductivity:**
  - Guarded Hot Plate Technique, ASTM C-177
  - Heat Flow Meter Apparatus, ASTM C-518
  - Flash Diffusivity, ASTM E-1461
  - Transient Radiant Step Heating
  - Etc

- **Radiant Properties**
  - One laboratory in the U.S.A. that provides total hemispherical emittance measurement as a function of temperature (test sample must be electrically conducting)
  - Two laboratories in the U.S.A. that provide spectral hemispherical reflectance and transmission data as a function of temperature

Summary

- Thermal property measurements can be erroneous at times
- Can not simply rely on thermal properties from one laboratory using one technique
- It is always helpful to have a priori estimates of general trends of thermal data to evaluate accuracy of measured properties
- For the Space Shuttle tiles thermal properties were measured using various techniques at various commercial laboratories, aerospace companies, and government facilities. Compilation of all these data resulted in a set of average properties used for design

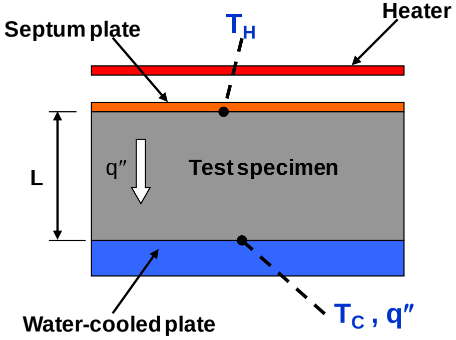
Insulation Thermal Property Measurements/Predictions at LaRC

- **Steady-sate test set-up at NASA LaRC for measuring/predicting thermal conductivity of high porosity insulations (rigid and flexible)**

- **Higher-fidelity models of heat transfer through high porosity insulations based on steady-state test set-up data- same model applies to both rigid and flexible insulations**

Thermal Measurements at LaRC

- **Effective thermal conductivity measurements**
  - Large temperature differences maintained across sample thickness
    - Cold side at room temperature (***T_C***)
    - Hot side from 530 to 1370K (***T_H***)
  - Pressure range of 0.001 to 760 torr, N_2 gas
  - Sample size: 30.5 × 30.5 × 2.5 cm
  - Provides accurate, repeatable, 1-D data



- **Measurements**
  - 9 heat flux gages on water-cooled plate & 23 thermocouples on septum plate
  - Use average data from central region (12.7 x 12.7 cm) to get ***q", T_C , T_H***
  - Effective thermal conductivity (***k_e***)

$$k_{e,\exp} = \frac{L \cdot q''}{T_H - T_C}$$

  - Relationship between ***k_e*** and ***k*** (for optically thick insulation)

$$k_e = \frac{1}{T_H - T_C} \int_{T_C}^{T_H} k.dT$$

- **Uncertainty:** detailed uncertainty analysis using bias**,** random, and spatial non-uniformity uncertainties. Average experimental uncertainty for ***k_e*** was 7% with RMS deviation of 16.6%

Thermal Model

- **Heat Transfer in high porosity insulations:**
  - Solid fraction ratio of typical insulations for aerospace application is typically less than 10%. Heat transfer mechanisms are: radiation, gas conduction, and solid conduction
  - If material is optically thick (radiation can be modeled as a diffusion process)

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}(k_c \frac{\partial T}{\partial y}) - \frac{\partial q_r''}{\partial y}$$

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}(k \frac{\partial T}{\partial y})$$

$$k = k_c + k_r = k_s + k_g + k_r$$

(k_s : solid conduction, k_g : gas conduction ; k_r : radiation)

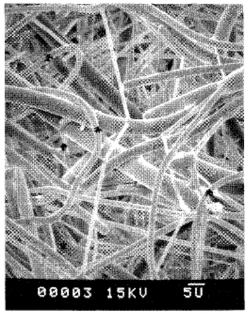
- **How to get *k(P, T)* from k_e measurements**

$$k_e(P, T_H, T_C) = \frac{1}{T_H - T_C} \int_{T_C}^{T_H} k(P,T).dT \quad \text{(Eq. 1)}$$

- **1. Simple approach: use measurements in vacuum (0.001 torr) to get combined contribution of solid conduction and radiation**
  - Assume k is a 3rd order polynomial function of *T*
  - Substitute Eq. 2 in Eq. 1, perform integration
  - Use at least 7 k_e measurements covering the range of temperatures, 7 equations and 4 unknowns

$$k_s + k_r = c_0 + c_1 T + c_2 T^2 + c_3 T^3 \quad \text{(Eq. 2)}$$

SEM of bonded fibers
Magnification =1200X



Thermal Model

- **2. Detailed Approach: Model solid conduction & radiation separately**

- **Solid Conduction: used semi-empirical model**
  - ***F_s* :** relates micro-scale geometric effects of fiber matrix with bulk dimensions
  - ***b:*** exponent , typically between 1 and 3
  - Need to estimate *b* & *F_s*
  - Need to know ***k^*_{bulk}*** (more complicated for multi-constituent fibrous insulation samples)

$$k_s = F_s \left(\frac{\rho}{\rho_{bulk}}\right)^b k^*_{bulk}$$

$$k_r = \frac{16\sigma n^{*2} T^3}{3e\rho}$$

- **Radiation Conductivity (diffusion approximation)**
  - *n** is not unity, and depends on fiber material, fiber volume fraction, gas, and can be obtained from literature
  - *e* is intrinsic property of material, and depends on composition and morphology of the medium
    - Fiber size distribution, orientation, volume fraction
    - Spectral complex refractive index of fibers
  - $e = a_0 + a_1 T + a_2 T^2 + a_3 T^3$, need to estimate coefficients a_i

Nomenclature:
e : specific extinction coefficient
T : temperature
n* : effective index of refraction
ρ : density
σ : Stefan-Boltzmann constant

- **Use 10 thermal conductivity measurement data points at 0.001 torr (negligible gas conduction) to get *F_s* , *b*, and coefficients for *e* (integration has to be performed numerically)**
  - 3 cryogenic data (90 – 130 K) – higher sensitivity to solid conduction. Typically use data from TRSH technique
  - 7 high temp. points (300 – 1400 K or higher) – higher sensitivity to radiation. Data from LaRC set-up

$$k_e(0.001, T_H, T_C) = \frac{1}{T_H - T_C} \int_{T_C}^{T_H} (k_s + k_r).dT$$

Thermal Model

- **Once contributions of solid conduction and radiation are known (simplified or detailed approach), all that is needed is to add the gas conduction contribution**

$$k_g = \frac{k_g^*}{1 + 2\dfrac{2-\alpha}{\alpha} \cdot \dfrac{2\gamma}{\gamma+1} \cdot \dfrac{1}{\Pr} \cdot \dfrac{\tilde{\lambda}}{L_c}}$$

Gas mean free path

$$\tilde{\lambda} = \frac{k_B \cdot T}{\sqrt{2} \cdot \pi \cdot d_m^2 \cdot P}$$

Nomenclature:

- D_f : mean fiber diameter
- d_m : gas collision diameter
- f_v : fiber volume fraction
- k_g^* : gas thermal conductivity (1 atm)
- k_B : Boltzmann constant
- Pr : Prandtl number
- α : thermal accommodation coefficient
- γ : specific heat ratio

- k_g^*, γ, *Pr* known for each gas; all other parameters are known. Used $\alpha = 1$. Only parameter needed is the characteristic length (pore size)
  - For fibrous insulations with single fiber composition (rigid or flexible) use empirical formulation
  - For more complicated materials, use up to 10 thermal conductivity data points at various pressures at one temperature to estimate L_c
- Once L_c is known, estimate k_g at any (T, P) & add contribution of k_g to ($k_r + k_s$)
- Can possibly estimate properties in any gas, only source of uncertainty is thermal accommodation coefficient

$$L_c = \frac{\pi}{4}\frac{D_f}{f_v}$$

Thermal Model Validation

- **Author has developed thermal model for following insulations:**
  - Flexible: Saffil and APA (alumina fibers), Q-fiber (silica fibers), Zirconia
  - Rigid: LI-900 (Space Shuttle tiles), Alumina Enhanced Thermal Barrier (AETB) tiles which are a higher temperature version of Shuttle tiles
  - Thermal models are applicable over a range of insulation densities: Saffil at 24 to 144 kg/m^3, Q-fiber at 48 to 96 kg/m^3, AETB at 128 to 256 kg/m^3
  - Validation of thermal model was generally accomplished by comparison with measurements using TRSH technique.

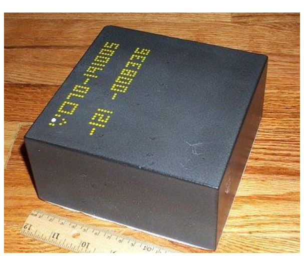
Saffil

APA

Q-fiber

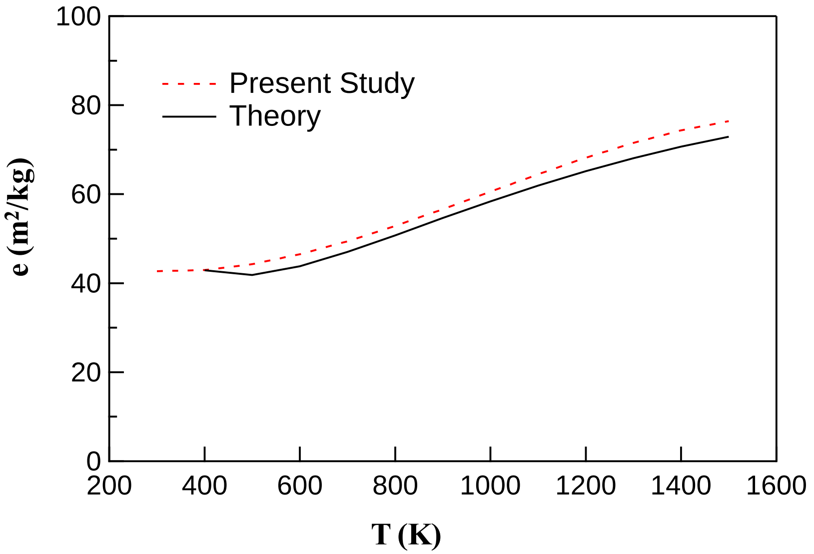
Zirconia

LI-900



Thermal Model Validation

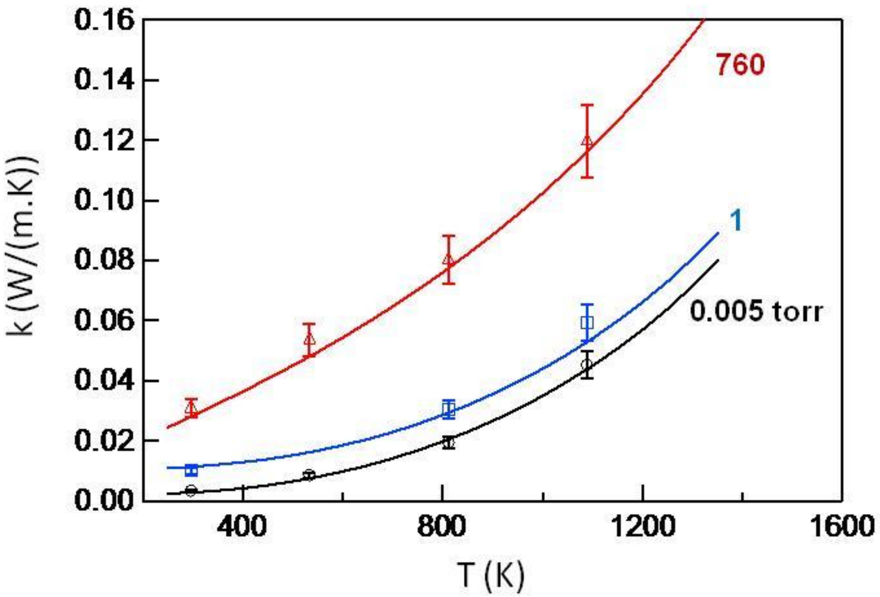
Specific Extinction Coefficient of Q-fiber



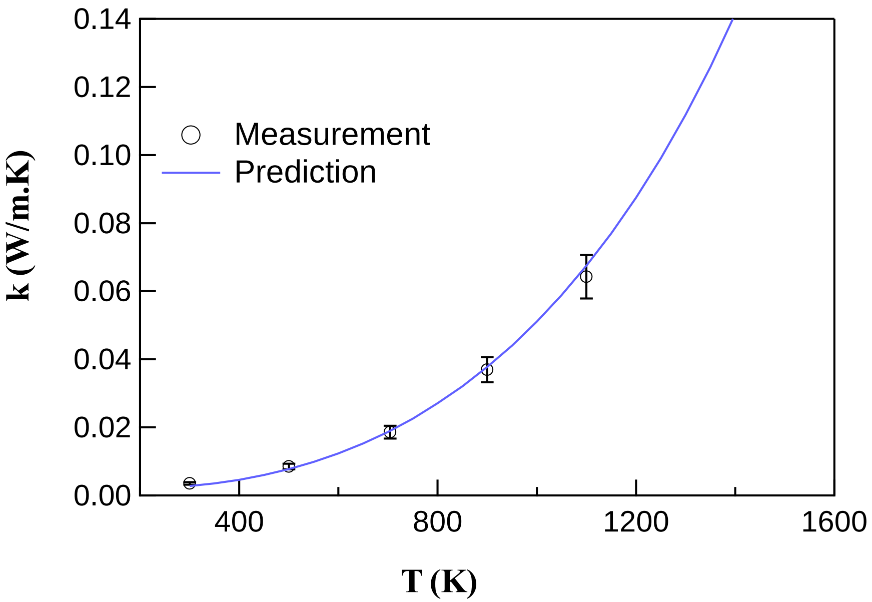
- **Compared predicted specific extinction coefficient of Q-fiber with theoretical data**
  - RMS deviation of 6%
  - Uncertainty of theoretical data: ± 4%

Thermal Model Validation-Comparison with TRSH data

Saffil (144 kg/m^3)



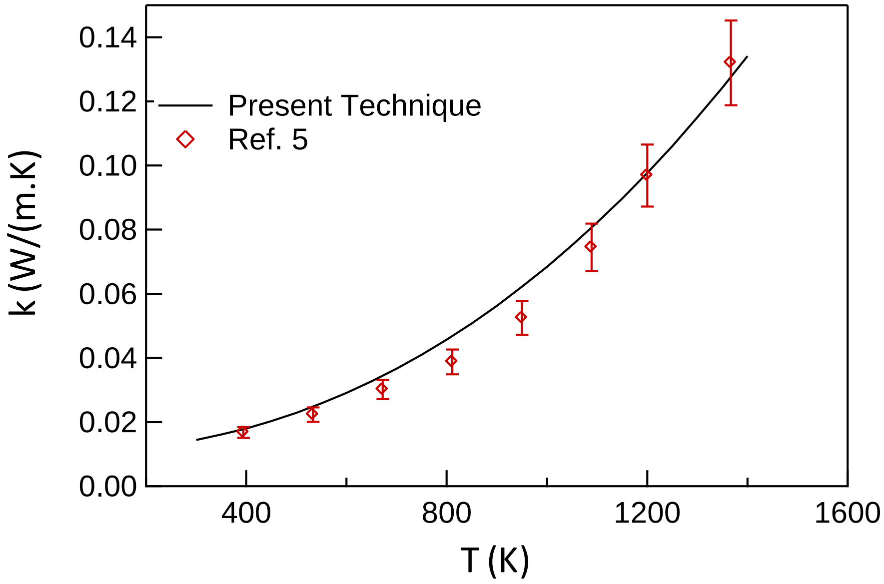
APA (107 kg/m^3) at 0.005 torr

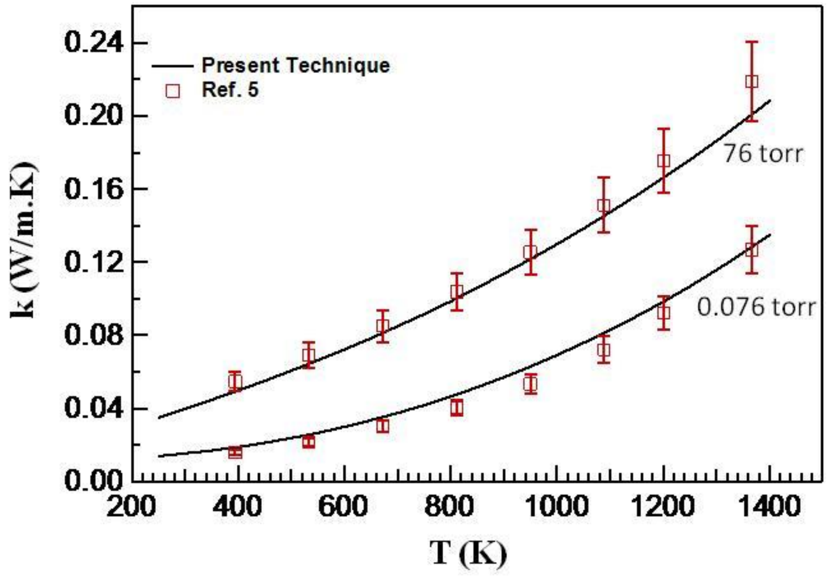


- **RMS deviation of**
  - 10% for Saffil at 3 pressures (0.005, 1, 760 torr)
  - 6.4% for APA at 0.005 torr

Thermal Model Validation- Rigid LI-900 tile

0.001 torr





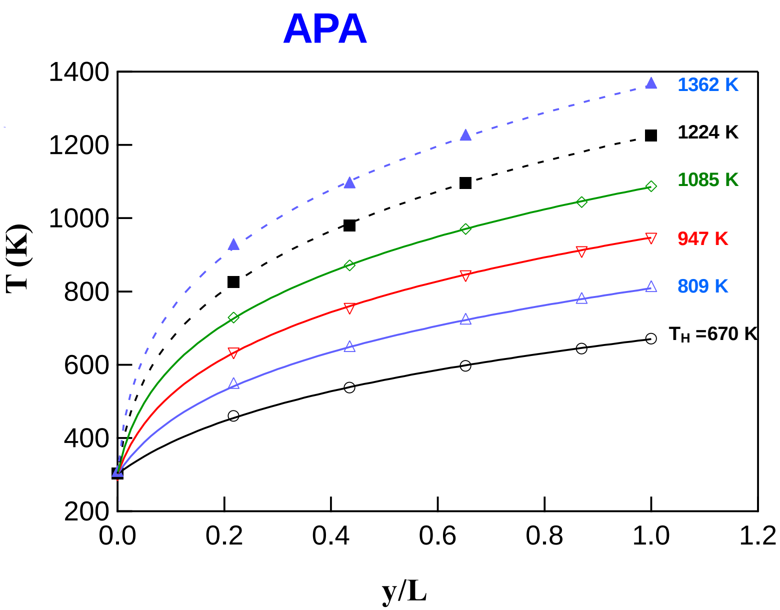
- **Comparison of predicted *k(T)* with published data* in air**
  - RMS deviations for all pressures: 10.5% Good overall agreement with published data

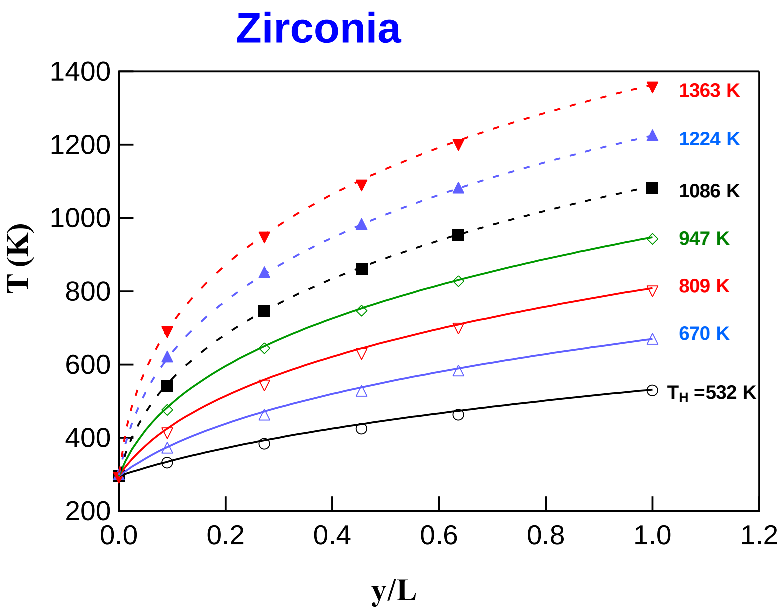
*Published data:

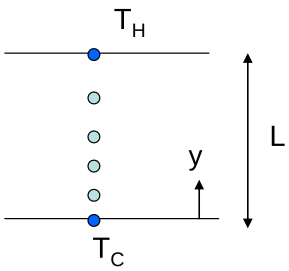
•Williams, S. D., and Curry, D. M., “Prediction of Rigid Silica Based Insulation Conductivity,” NASA TP-3276, January 1993

• Banas, R.P., and Cunnington, G. R.“Determination of Effective Thermal Conductivity for the Space Shuttle Orbiter’s Reusable Surface Insulation (RSI),” AIAA Paper 74-730, July 1974.

Thermal Model Validation- APA and Zirconia





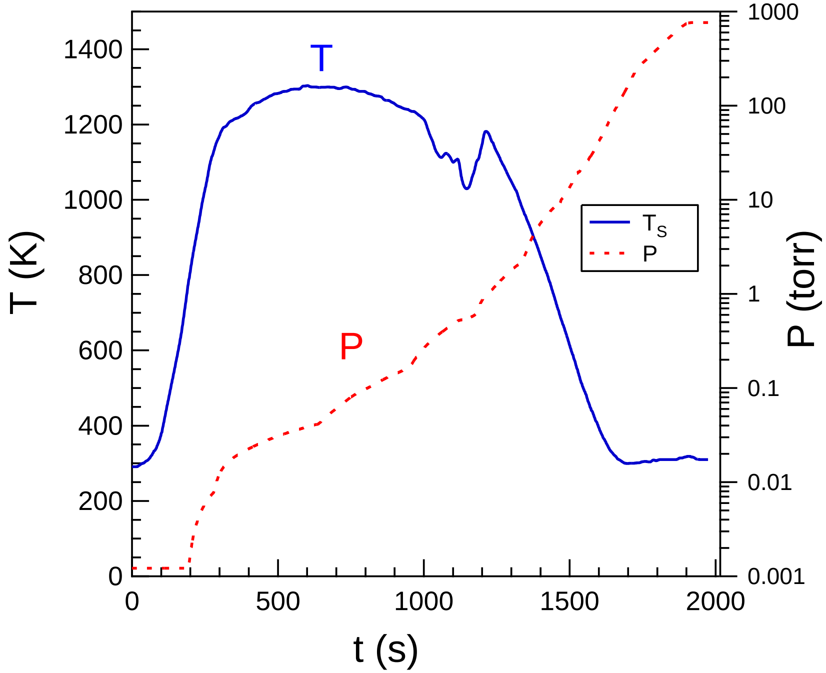


- **For steady-state tests on APA and zirconia, flexible insulations used 4 thermocouples through insulation thickness at various non-dimensional heights (0 & 1 corresponding to cold and hot side temperatures). Compared temperature measurements with steady state predictions using thermal model at P =0.001 torr at various hot-side temperatures (cold side temperature = 300 K)**
  - RMS and maximum deviations of
    - 0.5% and 1.2% for APA
    - 1.5% and 2.9%, for zirconia

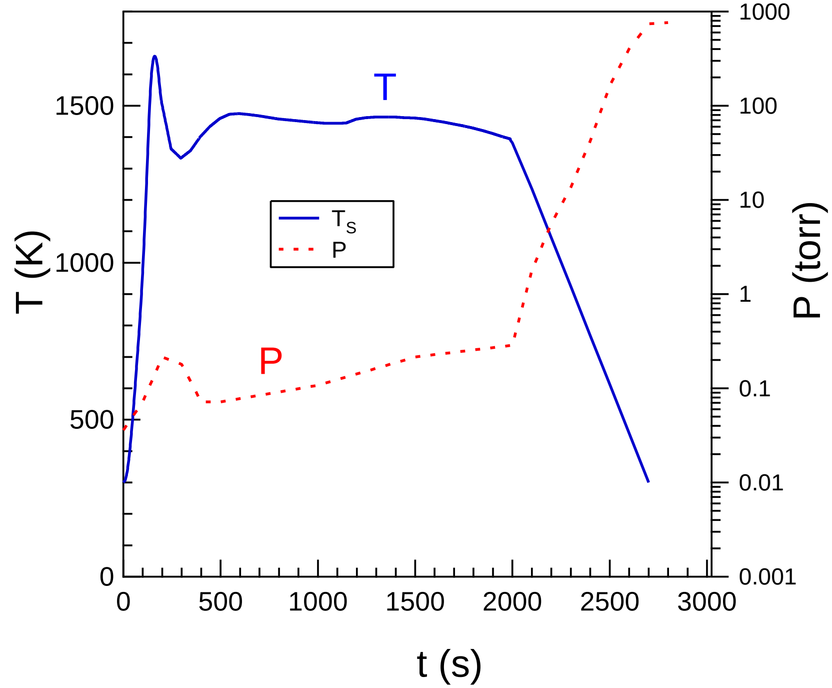
Generic Flight Profiles

- **Generic surface temperature and pressure profiles**

Lifting Body Reentry



Hypersonic Flight

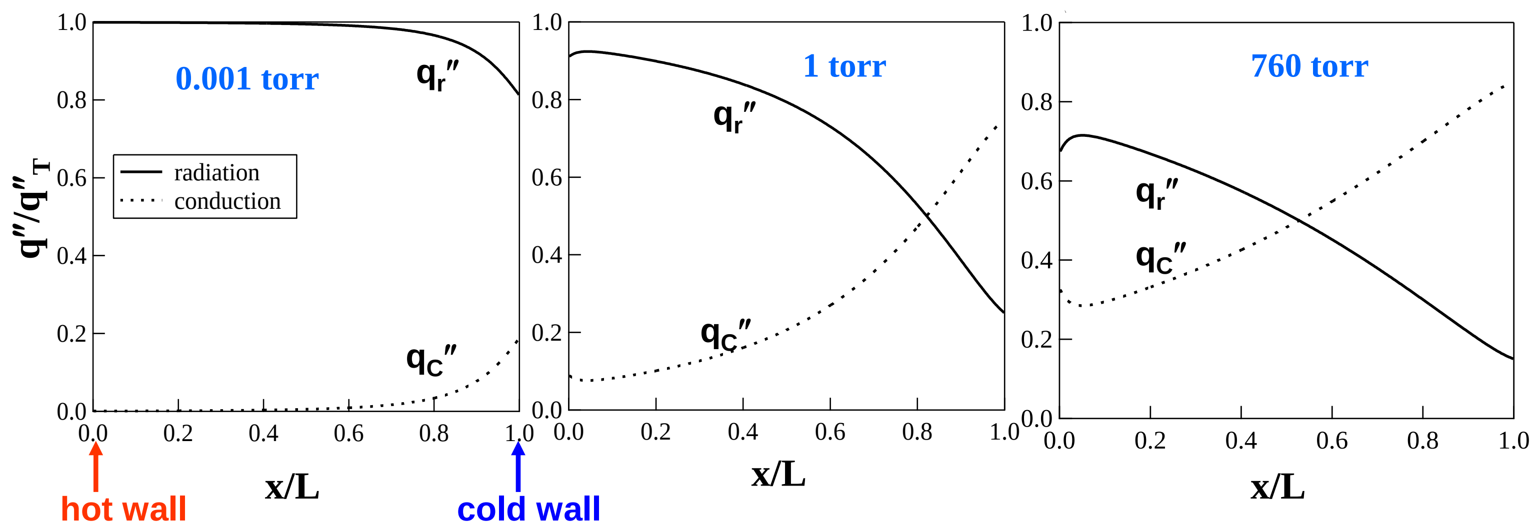


- **Heating portion of flight profiles are at low pressures (P < 1 torr)**

Heat Transfer in Insulations

- **Spatial (through-thickness) variation of ratio of radiation and conduction (gas and solid) heat fluxes to total heat flux**

Saffil, ρ = 48 kg/m^3 , L = 39.9 mm. T_H = 1300 K, T_C = 300 K



- **At very low P: radiation dominant mode of heat transfer; conduction close to cold wall is solid conduction**
- **Radiation is dominant close to hot wall, its relative magnitude decreases with increasing P**
- **As P increases gas conduction increases, and spatial location where conduction exceeds radiation moves from cold wall to mid-plane**
- **Sustained portion of hypersonic flight is at P ≤ 1 torr – radiation dominant in the top 80% portion of the insulation**
- **Knowing the relative contribution of various heat transfer modes is essential for developing optimized insulations**

Summary

- **Thermal property data from literature**
  - Do not rely on thermal property data from one source
  - Look up multiple sources
  - Do not necessarily trust manufacturer data

- **Thermal property measurements**
  - Can not simply rely on thermal properties from one laboratory using one technique
  - It is helpful to have a priori estimates of general trends of thermal data to evaluate accuracy of measured properties

- **Insulation thermal property measurements & predictions at NASA LaRC**
  - Use of a simple test technique with higher fidelity modeling of heat transfer can produce accurate results

Appendices

- List of Acronyms
- Thermal Property Measurement Techniques
- Author's Relevant Publications

Acronyms

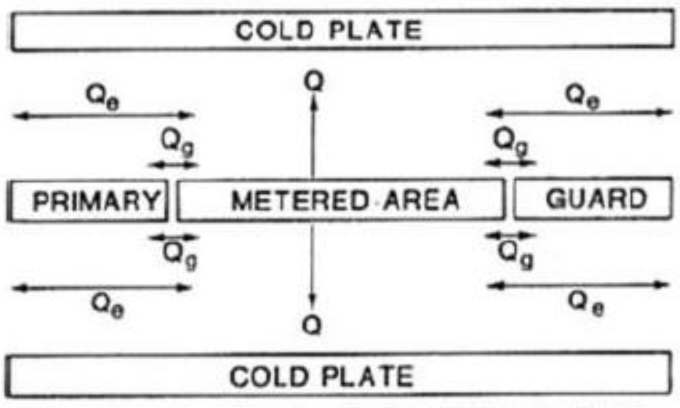
AETB	Alumina Enhanced Thermal Barrier
AFRSI	Advanced Flexible Reusable Surface Insulation
APA	Alumina Paper fibrous insulation
CMC	Ceramic Matrix Composite
GHP	Guarded Hot Plate technique
HFM	Heat Flow Meter technique
PMC	Polymer Matrix Composite
RCC	Reinforced Carbon Carbon
SITPS	Structurally Integrated Thermal Protection System
TPM	Thermophysical Properties of Matter
TPS	Thermal Protection System
TRSH	Transient Radiant Step Heating technique

Thermal Property Measurement Techniques

- **Specific Heat: Differential Scanning Calorimetry- ASTM E-1269**
  - Usually provides vary accurate results
  - Applicable to solids and liquids
  - Normal temperature range of -100 to 600°C; temperature range is extended at some laboratories

- **Thermal Conductivity:**
  - Guarded Hot Plate Technique, ASTM C-177
  - Heat Flow Meter Apparatus, ASTM C-518
  - Flash Diffusivity, ASTM E-1461
  - Transient Radiant Step Heating
  - etc

Guarded Hot Plate Techniques



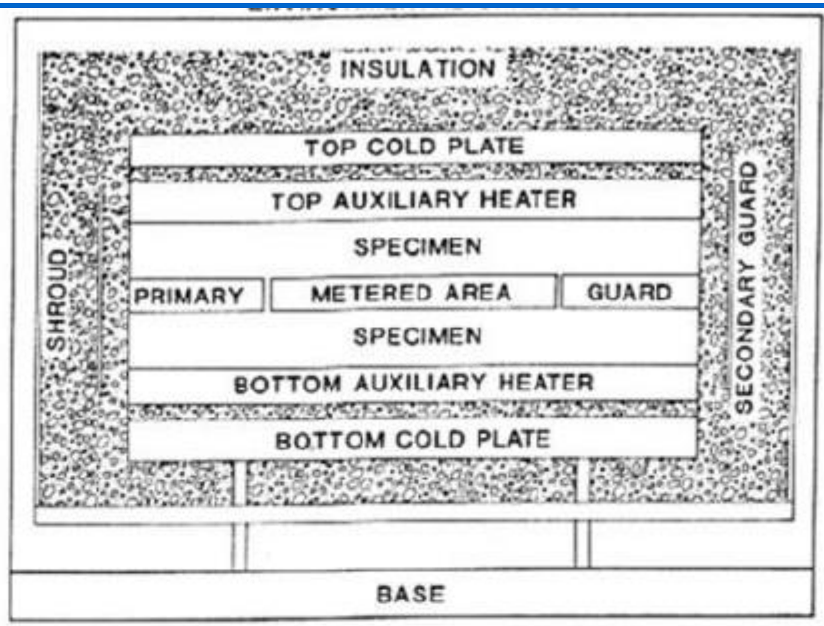


Figure source: ASTM

- An absolute measurement technique, typically used up to 800°C, but has been extended up to 1200°C
- Requires testing of two identical samples (typically 20 cm diameter)
- Requires balancing the main and guard heater to minimize lateral heat losses in the metered region
- Typically requires 12 to 24 hours of settling time for accurate measurement on low thermal conductivity insulations (some labs rush through 2 to 3 measurement points in one day!)

Heat Flow Meter Apparatus

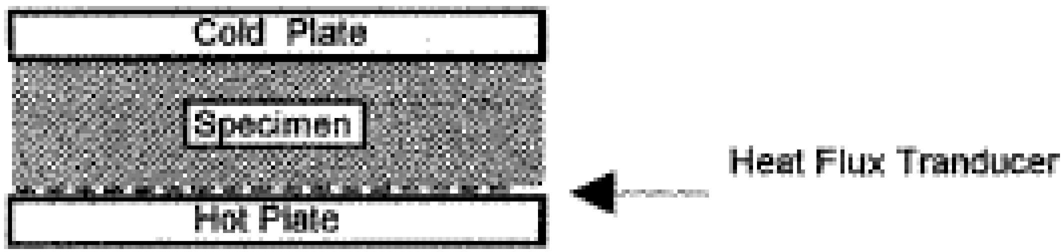
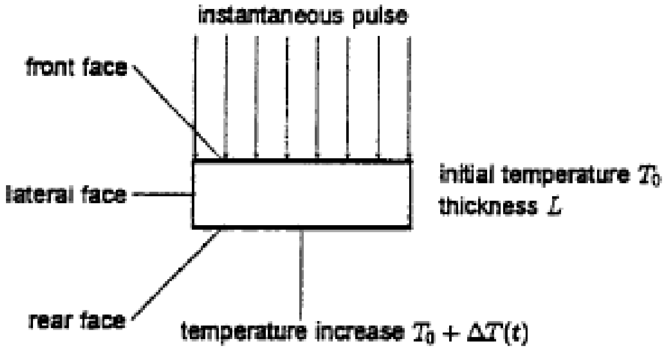


FIG. 1 Apparatus with One Heat Flux Transducer and One Specimen

Figure source: ASTM

- A relative measurement technique; requires test with a standard material at similar conditions as the test specimen
- Calibration should be carried out using a standard with similar thermal conductance, thickness, mean temperature, and temperature gradient as expected for the test sample
- The plate assemblies should be maintained at desired temperatures using fluid baths, electrical heaters, or thermoelectric coolers.
- Typically used from 10 to 540°C

Flash Diffusivity Technique



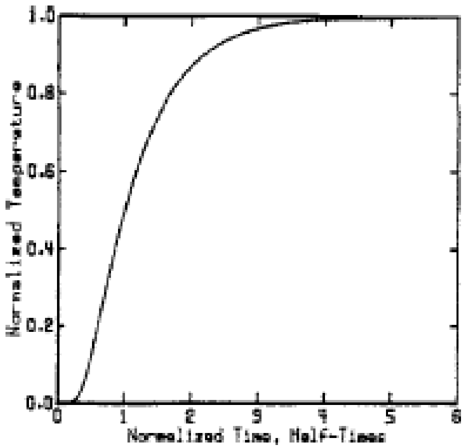


Figure source: ASTM

- Uses laser as flash heat source for front face of sample
- Determines thermal diffusivity from sample back face temperature rise
- Specific heat of sample is measured
- Thermal conductivity is determined from the measured thermal diffusivity and specific heat
- Temperature range: 80 to 2500 K

Transient Radiant Step Heating Technique

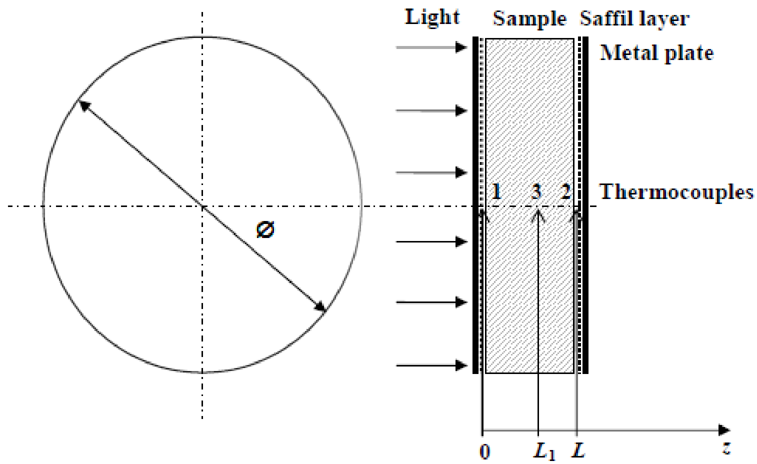


Figure source: Gembarovic & Taylor

- **Also known as "three point method"**
- **Similar to flash diffusivity technique, but specialized for testing insulations**
- **It uses a lamp as flash heat source, with sample installed in a furnace**
- **Used 3 thermocouples on test specimen: front face, back face, mid-plane**
- **Determines thermal diffusivity from temperature rises on front face, mid-plane and back face**
- **Temperature range: 90 to 1100 K**

- **For more details on technique refer to:** Gembarovic, J., and Taylor, R. E, "A Method for Thermal Diffusivity Determination of Thermal Insulators," *International Journal of Thermophysics*, Vol. 28, No. 6, 2007, pp. 2164-2175

Author’s Relevant Publications

Daryabeigi, K., Knutson, J. R., and Cunnington, G. R., “Heat Transfer Measurement and Modeling in Rigid High-Temperature Reusable Surface Insulation Tiles,” AIAA Paper 2011-345, January 2011.

Daryabeigi, K., Cunnington, G. R., Miller, S. D., and Knutson, J. R., “Combined Heat Transfer in High-Porosity High-Temperature Fibrous Insulations: Theory and Experimental Validation,” AIAA Paper 2010-4660, June 2010.

Miller, S.D., Cunnington, G. R., and Daryabeigi, K., “Advanced Multilayer And Opacified Fibrous Insulations For Hypersonic Vehicles,” JANNAF Air-breathing Propulsion Subcommittee Technical Session on Materials and Structures for Airframe and Propulsion Systems, Cocoa Beach, FL, January 26-29, 2009.

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Hanuska, A. R., Scott, E. P., and Daryabeigi, K., “Thermal Characterization of Complex Aerospace Structures,” *Journal of Thermophysics and Heat Transfer*, Vol. 14, No. 3, 2000, pp. 322-329, Also AIAA 1999-1053.