Characterization of Structurally Integrated TPS for Hypersonic Vehicles

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Fundamental Aeronautics 2008 Annual Meeting
October 7 – 9, 2008

Outline

- Structurally Integrated TPS
- Thermal Performance of Non-Rigid Insulations for Structurally Integrated TPS
- Concluding Remarks

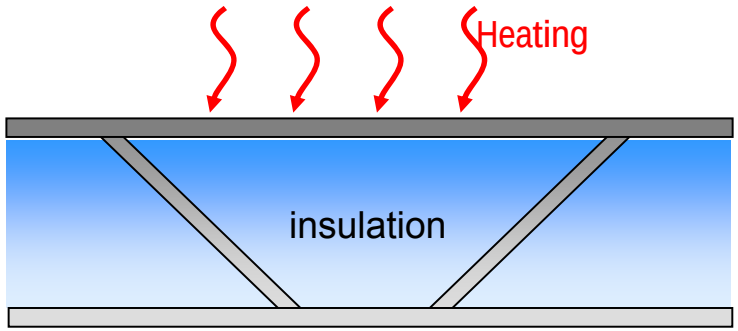
Structurally Integrated TPS - *Definition and Motivation*

Definition

Structural wall that carries airframe loads and maintains inner surface below acceptable maximum temperature *(Insulated wall)*

Motivation

- **Higher efficiency, lower maintenance**
- **Outer surface is robust structure**
- **Thermally integrated**

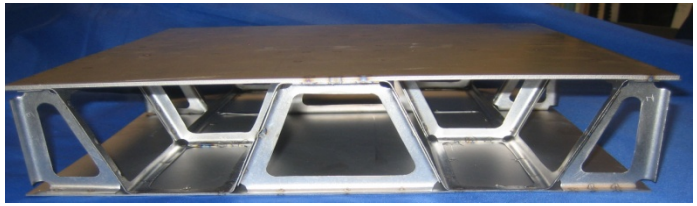


Challenges

- **Thermally induced stress due to CTE mismatch between various structural components**
- **Trade between structural and thermal performance**
- **Limited material selection**
- **Fabrication, scaling to large structures**

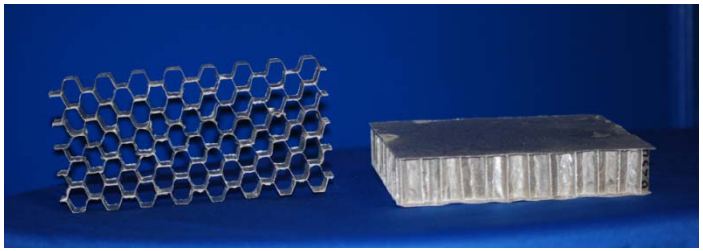
Preliminary Prototype Structurally Integrated TPS Concepts

- **Three concepts**
  - **Thermally Integrated Structural Sandwich Core (TISSC) – NASA concept**



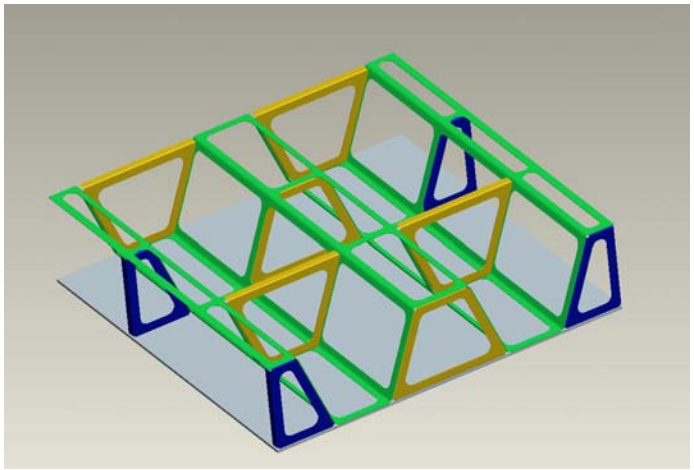
  - **Structurally Integrated TPS (SITPS) – NASA concept- manufactured by COI Ceramics Inc**

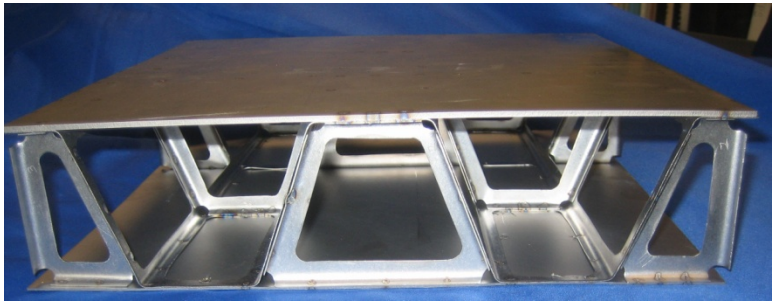
  - **Integrated Composite Structure TPS (ICSTPS) - developed by S. Miller & Associates Research Foundation (SMARF) under Hypersonic NRA**



- **Clarifications**
  - **These are prototype concepts used for preliminary thermal–structural evaluation.**
  - **None have been sized for a specific mission. Areal densities provided are for the prototypes, and should not be used for direct comparison of concepts**
  - **The preliminary thermal-structural test data will be used for evaluation of concepts, model validation and optimization, leading to specific designs for specific missions.**

Thermally Integrated Structural Sandwich Core (TISSC)





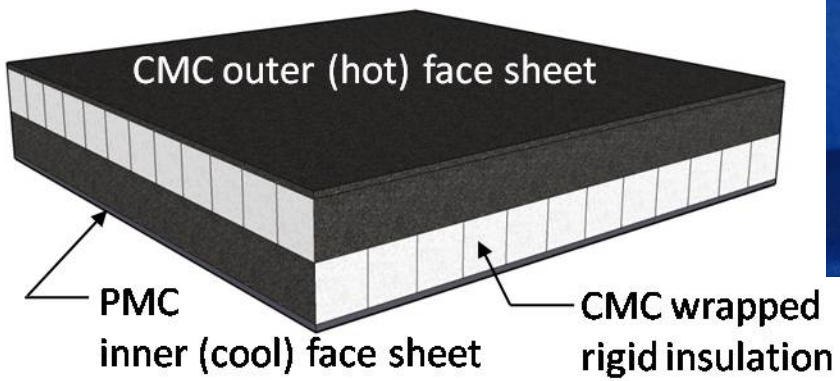
Features

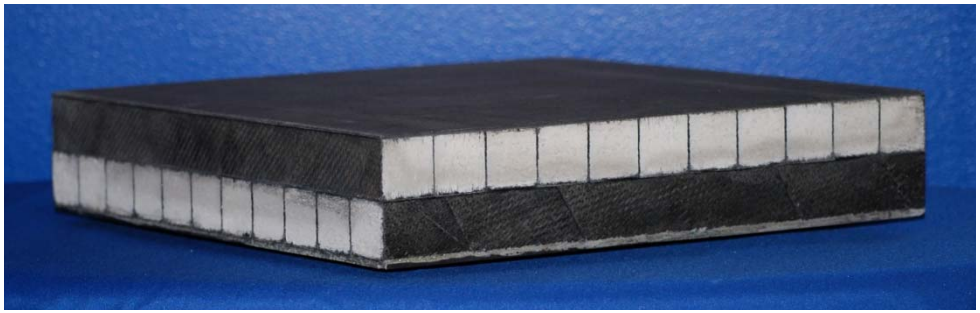
- **Tailorable structural core** (manufactured from titanium)
  - Biaxial shear & through-thickness stiffness
  - Volume for insulation (use efficient, non-load bearing insulation)
  - Cutouts, thicknesses, and number of reinforcements can be optimized
- **Areal density*: panel with 96 kg/m^3 (6 lb/ft^3) insulation: 26.1 kg/m^2 (5.4 lb/ft^2)**

* Typical areal density of combined TPS and structure on lifting bodies is ~ 4 – 6 lb/ft^2

* Areal densities are for preliminary prototypes without sizing for a specific mission; can not do direct comparison of areal densities of three prototype concepts

Structurally Integrated TPS (SITPS)

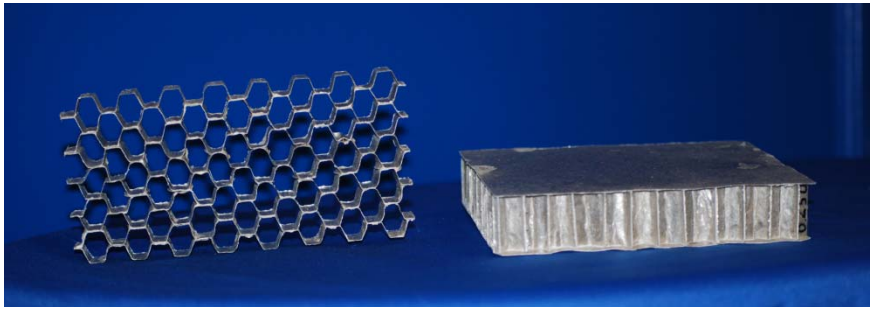




Features

- Rigid insulation bars wrapped with impregnated ceramic-fiber cloth
- Wrapped bars are stacked in a 0^0/ 90^0 configuration
- Layers of impregnated ceramic-fiber cloth stacked on top; co-cured and trimmed
- PMC bottom face sheet is bonded to panel
- Areal density = 28.7 kg/m^2 (5.9 lb/ft^2)

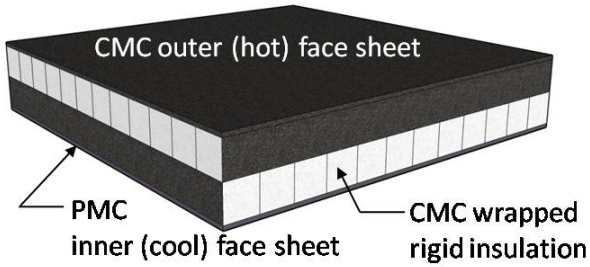
Integrated Composite Structure TPS (ICSTPS)



Honeycomb Filled With Chopped OFI

Features

- Honeycomb panel and facesheets fabricated from thin ceramic foils
- Extending application to CMC honeycomb, and CMC/PMC facesheets
- Honeycomb filled with non-load bearing OFI (Opacified Fibrous Insulation)
- Areal density* = 10.1 kg/m^2 (2.1 lb/ft^2) for ceramic honeycomb/facesheet with OFI
- ISCTPS could also be used as
  - Rigid insulation in Structurally Integrated TPS (SITPS) concept
  - Outer layer of a combined TPS (blanket insulation on backside)



Planned Tests for the Structurally Integrated TPS Concepts

- **Thermal Tests: for validation of thermal models**
  - Steady state
  - Transient
  - Thermal property data

- **Structural Tests: coupon testing at room & elevated temperatures**
  - Compression
  - Shear
  - Flat-wise tension
  - Three point bend

- **Validated thermal-structural model of concepts will be used for optimization**

Insulation Requirement for Hypersonic Vehicles

- TPS for long-duration hypersonic flight (including the structurally integrated TPS concepts) requires highly efficient insulation to withstand the high integrated heat loads
- Non-rigid, non-load bearing fibrous insulation is the most efficient insulation
- Present effort concentrates on thermal characterization (theoretical modeling and validation testing) of non-load bearing fibrous insulations for structurally integrated TPS

Candidate Non-Load Bearing Fibrous Insulations

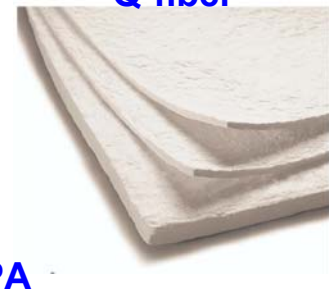
- **Silica (Q-fiber)**
  - Density: 64-96 kg/m^3 (4–6 lb/ft^3)
  - Max Temp: 1370 K (2000°F)
  - Used in AFRSI blankets on the Shuttle leeward side

- **Alumina (Saffil, Alumina Paper [APA])**
  - Density: 24-144 kg/m^3 (1.5–9 lb/ft^3)
  - Max Temp: 1760 K (2700°F)

- **Zirconia (ZYF)**
  - Density: 267-288 kg/m^3 (15–18 lb/ft^3)
  - Max Temp: 2200 K (3500°F)
  - Yttria stabilized zirconia

- **OFI (Opacified Fibrous Insulation)**
  - Density: 96–288 kg/m^3 (6–18 lb/ft^3)
  - Max Temp: ~1640 K (2500°F)
  - Mixture of opacifier in fibrous insulation mat (silica or alumina); opacifier significantly reduces radiation component of heat transfer
  - Developed by S. Miller & Associates Research Foundation (SMARF)

Q-fiber



AFRSI Blanket

APA

Zirconia

OFI

Thermal Characterization of Insulations

- **Heat transfer in fibrous insulations: combined radiation/conduction (gas and solid**

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

k_s	solid conduction
k_g	gas conduction
k_c	conduction (gas and solid)
k_r	radiation

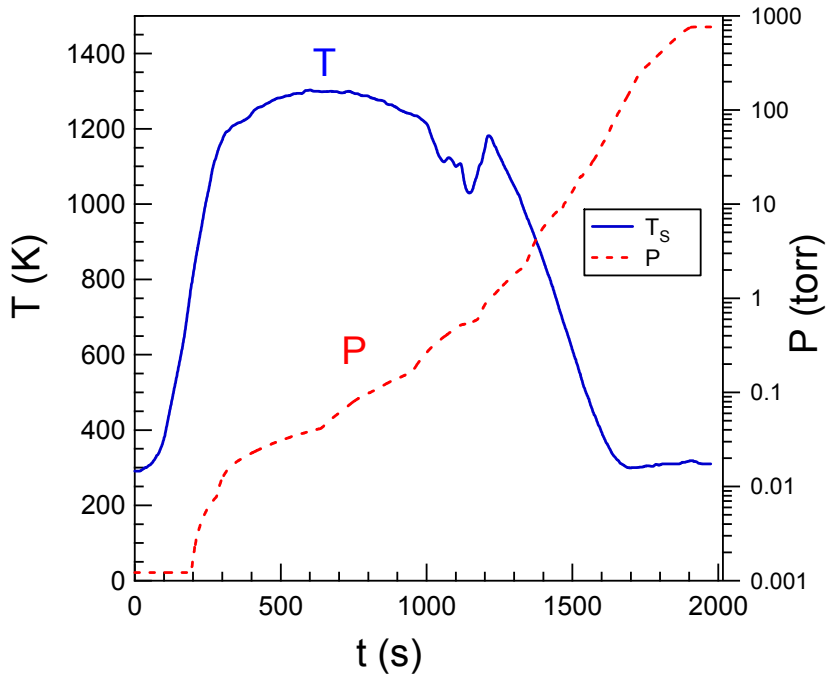
- **Traditional method (used for Space Shuttle)**
  - **Measure thermal conductivity as a function of T and P, Measure $c_P(T)$; use tabulated values in analysis and sizing**
  - **Shortcomings:**
    - **Measured values lump contribution of various modes, without any physics insight**
    - **Measured values only apply to the specific insulation composition (density, fiber diameter size), new set of data need to be generated for different composition**

- **New method**
  - **Use physics-based model to model heat transfer in high porosity fibrous insulations, validate model with steady-state experimental results: $k = k(T, P, \rho)$.**
  - **Advantages:**
    - **Applicable to any insulation composition (density, fiber diameter, etc)**
    - **Provides insight into contributions of various modes of heat transfer, can be used to optimize insulation stack-up**

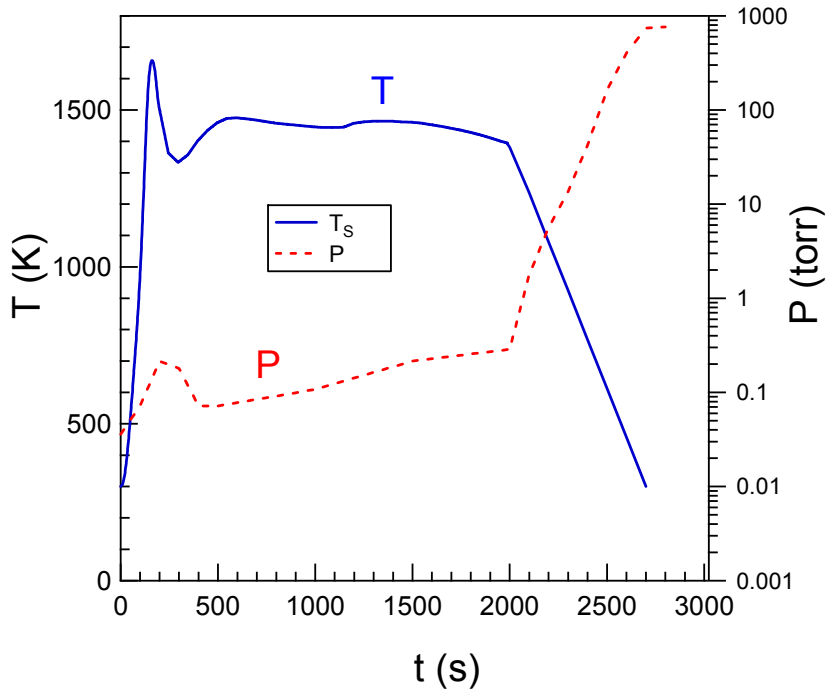
Generic Flight Profiles

- **Generic surface temperature and pressure profiles**

Lifting Body Reentry



Hypersonic Flight

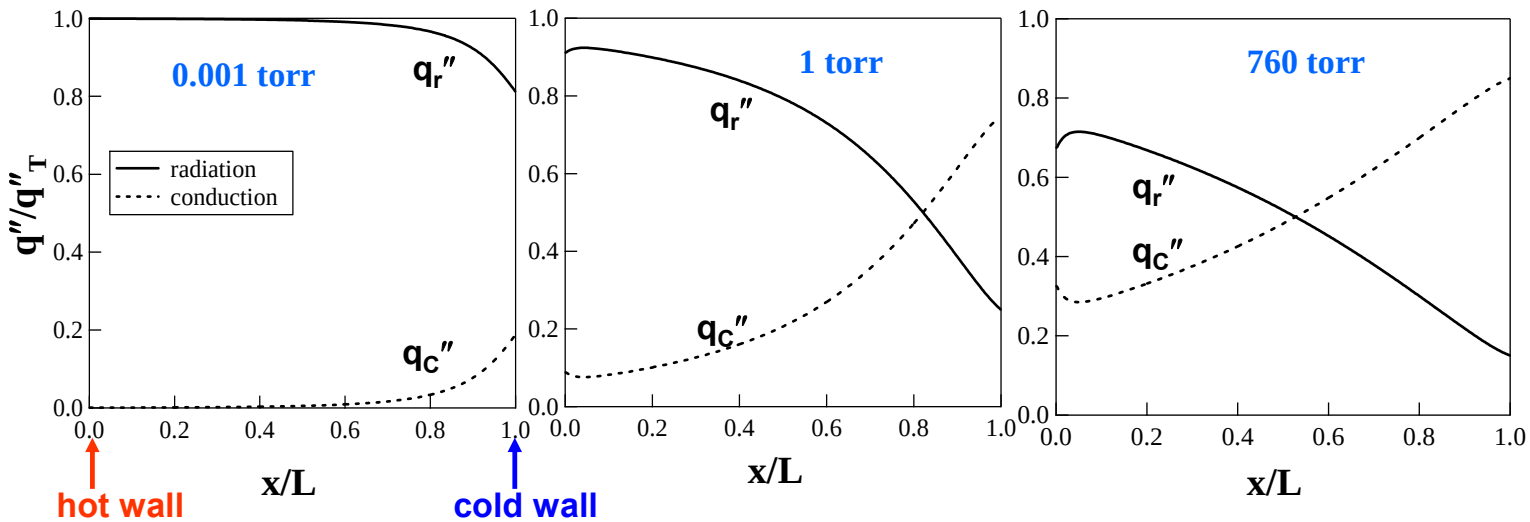


- Significant portion of flight, especially the peak heating portion, is at pressures below 1 torr

Heat Transfer in Insulations

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

Alumina (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 ↓ with increasing P**
- **As P ↑ 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**

Theoretical Model- Radiation & Solid Conduction

- **Radiation: for optically thick insulation, radiation can be modeled as diffusion**
  - **Modeling is based on pioneering work of Lee & Cunnington (1986- 2000). Radiative model accounts for 2-D scattering in fiber matrix, uses deterministic parameters that define composition and morphology of medium**
    - Fiber size distribution, orientation, volume fraction
    - Spectral complex refractive index of fibers
  - **Radiative conductivity from modified Rosseland absorption coefficient**

$$k_r = \frac{16\sigma \cdot n^2 \cdot T^3}{3} \int_0^\infty \frac{1}{\Gamma_\lambda} \frac{dI_{b\lambda}(T)}{dI_b(T)} d\lambda$$

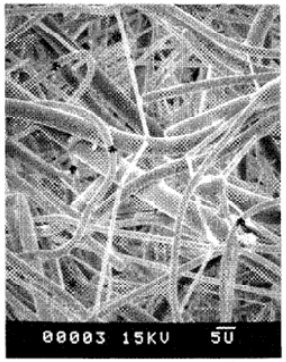
I	radiant intensity
n	index of refraction
ρ	density of fibrous insulation
σ	Stefan-Boltzmann constant
λ	wavelength
Γ_λ	modified absorption coefficient

- **Solid conduction: empirical model based on density and *k* of bulk material**

$$k_S(T) = F_S \cdot \rho \cdot k_{S-bulk}(T)$$

  - **F_s factor relating micro-scale geometric effects of fiber matrix and bulk dimensions. Obtained from steady state measurements in vacuum and at cryogenic temperatures**

SEM of bonded fibers
Magnification =1200X



Theoretical Model- Gas Conduction

- **Gas conduction: $k_g = f\,(T, P, \lambda, L_C)$:**

$$k_g = \frac{k_{g0}}{1 + 2\frac{2-\alpha}{\alpha}\cdot\frac{2\kappa}{\kappa+1}\cdot\frac{1}{\mathrm{Pr}}\cdot\frac{\tilde{\lambda}}{L_c}}$$

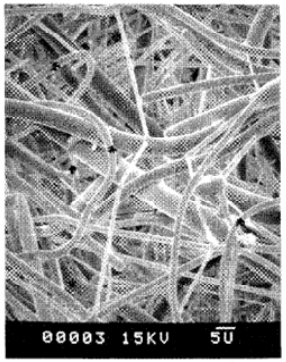
  - Gas mean free path

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

  - Empirical Pore size (characteristic length)
    - **θ = 0.524; fibers randomly oriented in space**

$$L_c = \theta\frac{D_f}{\rho/\rho_0}$$

SEM of bonded fibers
Magnification =1200X



k_{g0}	thermal conductivity of gas in free space	α	thermal accommodation coefficient
k	Boltzmann constant	ρ	felt density
D_f	fiber felt diameter	ρ_0	bulk density
d_m	gas collision diameter	κ	ratio of specific heats: c_P / c_v
Pr	Prandtl number		

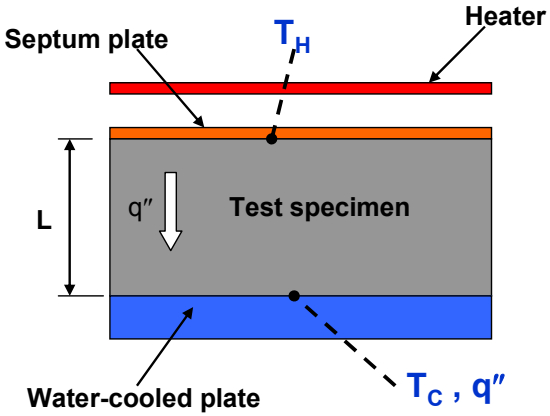
- **Contributions of various modes of heat transfer are then combined to yield thermal conductivity**

$$k = k_s + k_g + k_r$$

Steady State Test Apparatus

- **Steady-state thermal test apparatus at NASA LaRC**
  - Apparatus is based on ASTM C201
  - Measures **effective** thermal conductivity with
    - Large temperature differences maintained across sample thickness: cold side at room temperature, hot side up to 1370K (2000°F); being extended to 1920K (3000°F)
    - Pressure range of 0.001 to 760 torr
    - Sample size: 30.5 × 30.5 × 2.5 cm (12 × 12 × 1 in)

Schematic of Test Setup



- **Measurements**
  - T_H average hot side temperature
  - T_C average cold side temperature
  - q″ average cold side heat flux (thin film heat flux gages)

- **Calculation**

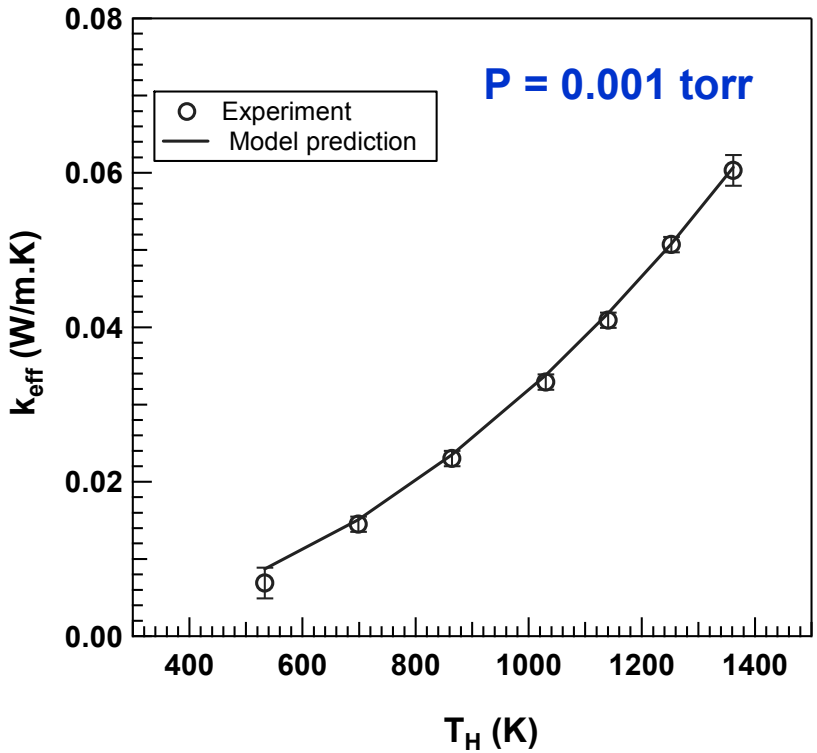
$$k_{eff,\exp} = \frac{L \cdot q''}{T_H - T_C}$$

- **Relation between analytical k_{eff} & k**

$$k_{eff} = \frac{1}{T_H - T_C} \int_{T_C}^{T_H} k(T, P, \rho)\, dT$$

- **Strategy**
  - Model k(T, P, ρ), calculate k_{eff}, compare to measured $k_{eff,exp}$

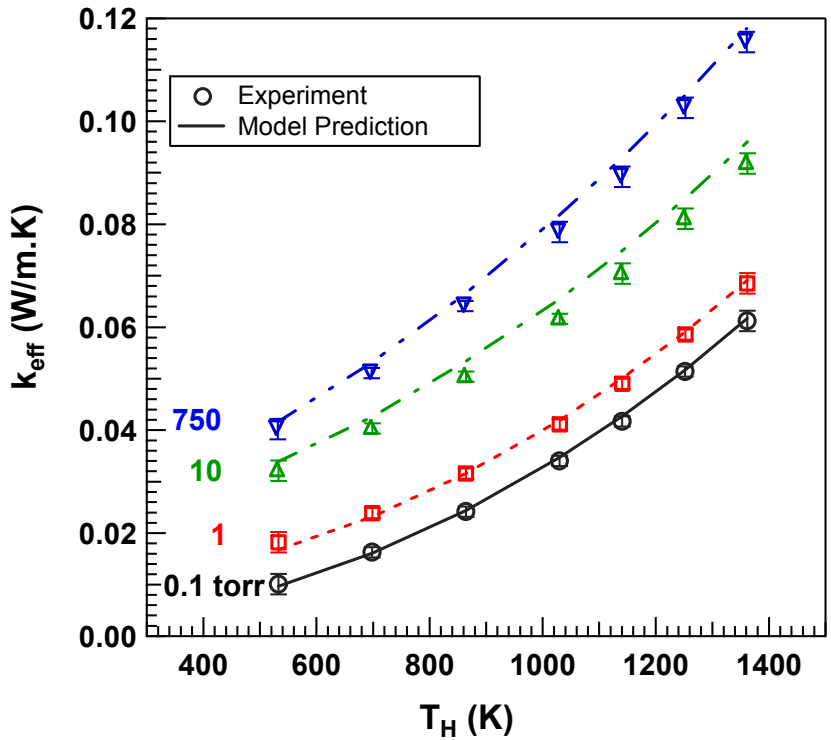
Comparison of Results –Silica



ρ = 68.8 kg/m^3

- Differences (exp. data & model prediction): 1 – 4% for 700 ≤ T_H ≤ 1360 K; 24% at 533 K
- Experimental Uncertainties: 1 – 6% for 700 ≤ T_H ≤ 1360 K; 29% at 533 K
- **Rms deviation** at 0.001 torr: 2.5% for 700 ≤ T_H ≤ 1360 K
  9.4% for 533 ≤ T_H ≤ 1360
- Higher experimental uncertainty at lower T at 0.001 torr due to low sensitivity of heat flux gages
- Close agreement validates modeling of radiation and solid conduction

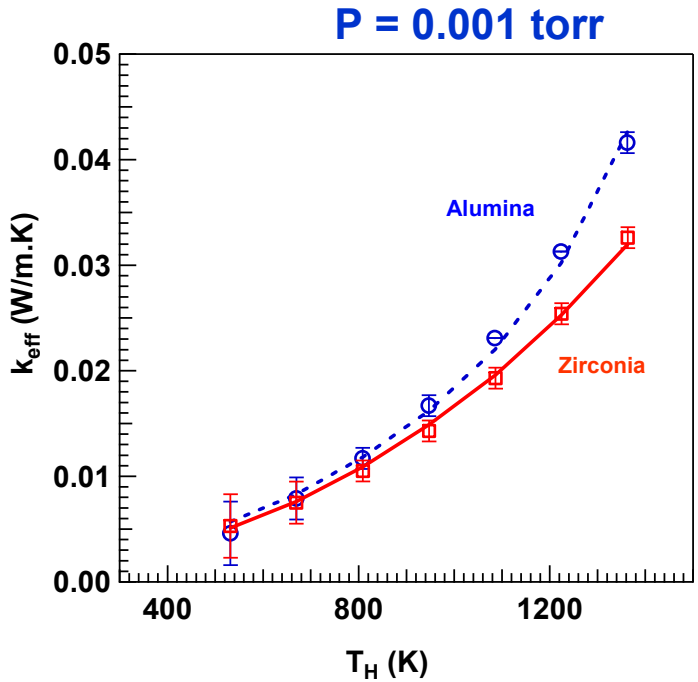
Comparison of Results –Silica



- **Rms deviations between experimental data and model predictions:**
  - **2.5% at 0.001 torr** — **validates radiation and solid conduction modeling**
  - **2.2% at 0.1 torr**
  - **3.8% at 1 torr**
  - **5.9% at 10 torr**
  - **3.8% at 750 torr**

  validates gas conduction modeling
- **Overall rms deviations at all T & P: 5.1% (close agreement)**

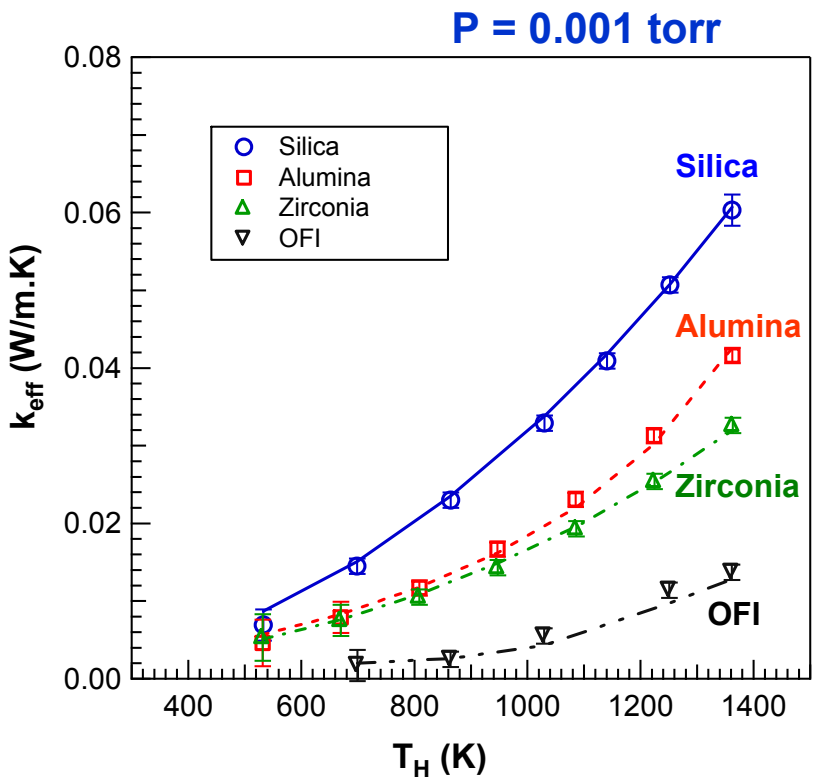
Comparison of Results – Alumina and Zirconia



Alumina, 107 kg/m^3
Zirconia, 267 kg/m^3

- Modeling of radiation and solid conduction for Alumina and Zirconia insulations is validated
- Rms deviations:
  - 8.1% for Alumina; 4.2% for Zirconia: $533 \le T_H \le 1360$
  - 4.8% for Alumina; 2.7% for Zirconia: $700 \le T_H \le 1360$
  - (2.5% for Silica: $700 \le T_H \le 1360$ K)
- Excellent agreement between theoretical model and experimental data for heat transfer in Silica, Alumina, and Zirconia fibrous insulations
  - Given any fiber composition, thermal properties can be generated as a function of T, P, ρ

Comparison of Results – OFI



Silica	68.8 kg/m^3
Alumina	107 kg/m^3
Zirconia	267 kg/m^3
OFI	204 kg/m^3

- **OFI significantly reduces the radiation component of heat transfer through insulation, has lowest k_{eff}**
- **Modeling radiation contribution of opacifiers in fiber matrix is not straightforward**
  - **Rms deviation for OFI: 15%**
  - **Newer, more detailed experimental data to be used to improve modeling of OFI**

Concluding Remarks

- **Structurally Integrated TPS**
  - **Three preliminary concepts briefly discussed**
  - **Planned Tests**
    - Perform steady state and transient thermal tests to validate numerical thermal models for various concepts
    - Generate necessary structural properties, and use validated thermal model for thermal-structural optimization of concepts

- **Thermal Modeling of various fibrous insulations for use in structurally integrated TPS for Hypersonic vehicles**
  - **Developed physics-based heat transfer models for various fibrous insulations, which was validated with experimental data**
    - Excellent agreement for Silica, Alumina and Zirconia fibrous insulations
    - Reasonable agreement for OFI. More experimental data and modeling refinement is required
  - **Given any fiber composition (size distribution, orientation, volume fraction & complex refractive index), thermal properties can be generated as a function of T, P, ρ**
  - **Verified performance of OFI as an effective non-rigid insulation for high temperature applications**