Extending Our Understanding of Compliant Thermal Barrier Performance

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Content of Discussion

- Introduction
  - Compliant Thermal Barriers (CTB) - What are they? Where are they used?
  - Treatment of CTB's – How are they implemented?
  - Construction, requirements, and characteristics of thermal barriers
- Current Efforts to Improve Understanding
  - Thermal
    - What we know
    - Modeling efforts
    - Case Study: Effect of core density on flow/leakage
  - Mechanical
    - What we know
    - Modeling efforts
    - Case Study: Effect of core density on loads
- Still more to do
- Summary

INTRODUCTION

An Integral Part of the TPS

Compliant Thermal Barriers

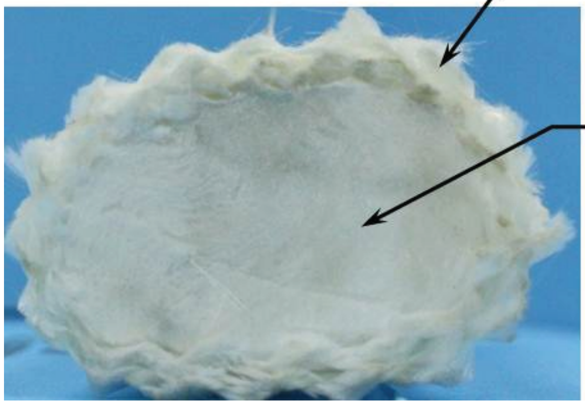
- Often referred to as “thermal seals” or “seals”
- One “class” of thermal barriers
- High-temp. ceramic-based fibrous materials
- Installed in TPS interface gaps
- Roles
  - Thermal – limit inboard temperatures
  - Structural – accommodate deflections
- Multitude of configurations…but share common elements

Vehicle Penetrations

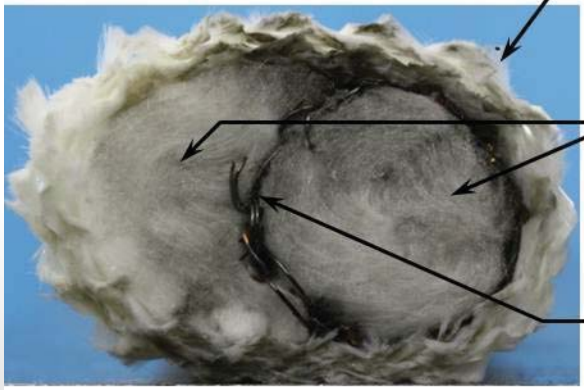
Doors

Control Surfaces

Compliant Thermal Barrier Construction

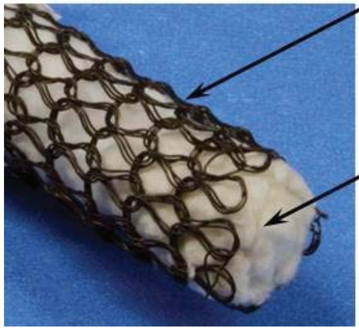


Blanket Thermal Barrier (BTB)



Hybrid Thermal Barrier (HTB)

- Outer sheath
  - 1+ layers of aluminosilicate woven fabric (e.g., Nextel™)
  - Coatings: RTV, emissivity, etc.
- Core
  - Aluminosilicate blanket (e.g., Saffil)
  - Metallic spring tube
- Other
  - Stitching to control shape/size and keep insulation in tact
  - End treatments/closeouts



Compliant Thermal Barrier Requirements & Characteristics

- General Requirements
  - Survive in harsh environments (thermally, chemically, tribologically)
  - Mitigate heat transfer
    - Good thermal insulators
    - Minimize convective flow (in combination with inboard environmental barriers)
    - Mitigate radiation heat transfer
  - Exhibit flexibility/conformability
  - Remain resilient
  - Meet load requirements

- Characteristics
  - Made of high temperature ceramic fiber-based materials
  - Utilize high-performance insulation
  - Permeable
  - Compliant
  - Exhibit set/compaction (even at ambient temperatures)
  - Non-linear hysteretic loading behavior

General Perception vs. Reality

More Art than Science???

- Typically considered as "gap fillers" to fill a space – design it to fit
- Often an "after-thought" in design of TPS
- Minimal effort to optimize design → need guidance
  - Thermally: How much insulation is needed? Is there an optimal orientation?
  - Mechanically: Are there load requirements for the interface? What level of durability does the barrier need? What kind of gap change does it need to accommodate?
- Strong reliance on heritage use

The Case for More Science

- Case studies
  - Door closure forces – Space Shuttle
  - Panel installation – MPCV
  - Potential tile debonding – MPCV

THE SCIENCE: CURRENT EFFORTS TO IMPROVE UNDERSTANDING OF THERMAL BEHAVIOR

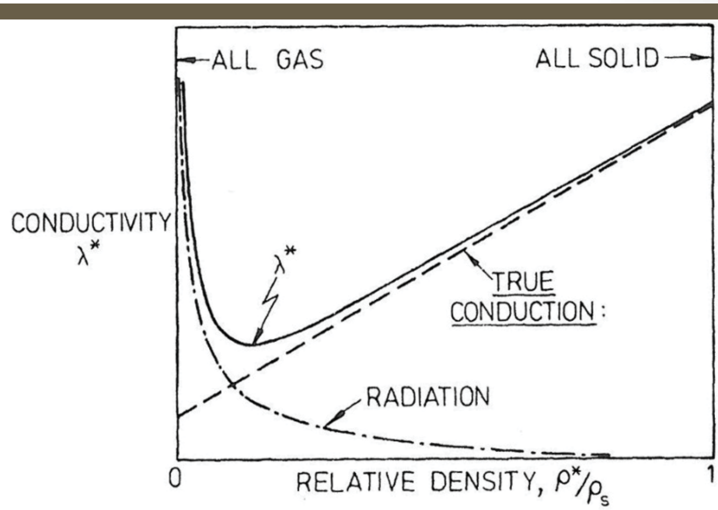
Thermal Behavior: What We Know

- Heat transfer occurs via several mechanisms
  - Conduction (solid and gas)
  - Convection (natural? and forced)
  - Radiation

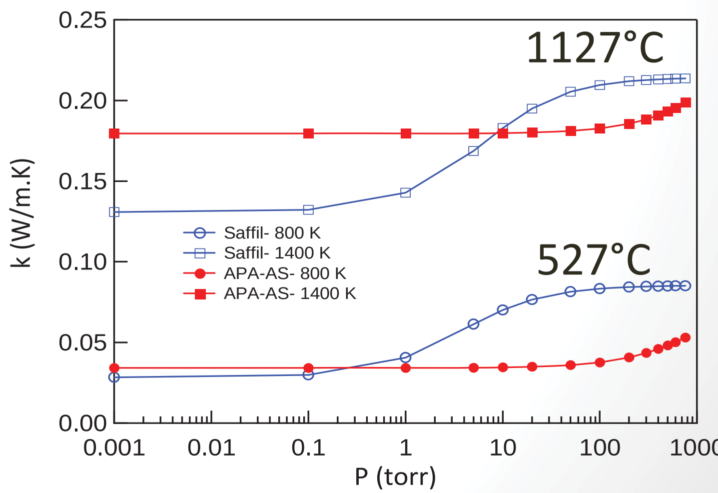
- Insulation density/pore size affect degree and modes of heat transfer

- Different modes are active/dominant under different conditions
  - Temperature (e.g., radiation dominant at high temperatures)
  - Pressure (e.g., gas conduction greater at higher pressures)

∴ **Heat transfer in porous soft good TPS is a complex interplay of mechanisms affected by many variables!**



(Gibson & Ashby, 1997)



(Daryabeigi *et al.*, 2010)

Energy Equation for Porous Media

- Generalized heat transfer equation

$$\left(\rho c_p\right)_g \left[\frac{(\rho c)_s}{\left(\rho c_p\right)_g}\frac{\partial T}{\partial t} + \vec{u}\cdot\nabla T\right] = \nabla\cdot\left(k_e \nabla T\right) + \cancel{q'''} + \frac{\mu}{K}\vec{u}^2$$

Thermal Inertia | Convection | Conduction + Radiation | Heat Generation | Viscous dissipation

Darcy Velocity: $\vec{u} = \frac{\dot{m}}{\rho_g} = \phi u_p$

- Heat transfer coefficients (Daryabeigi *et al.*, 2010)

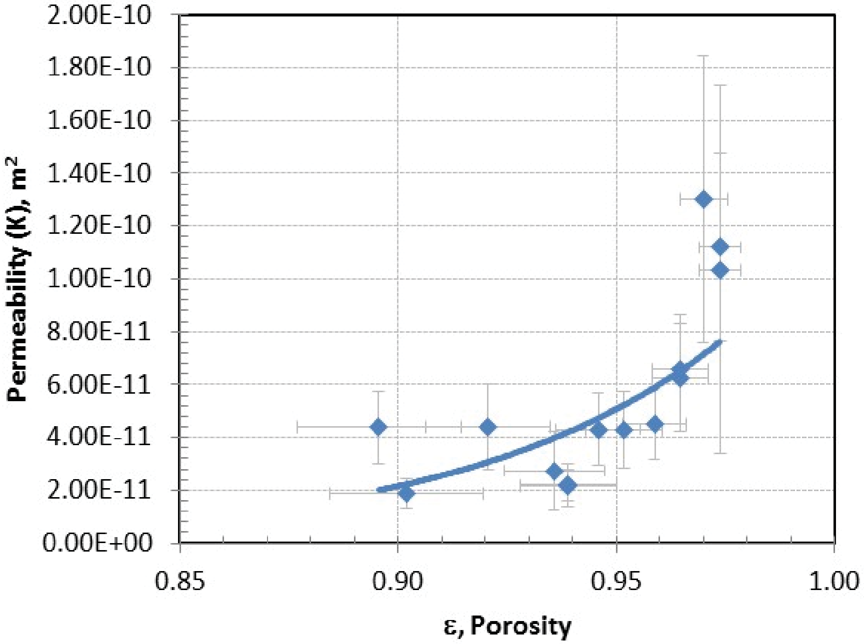
$$k_e = \underbrace{k_s + k_g}_{\text{Conduction}} + k_r$$

Radiation

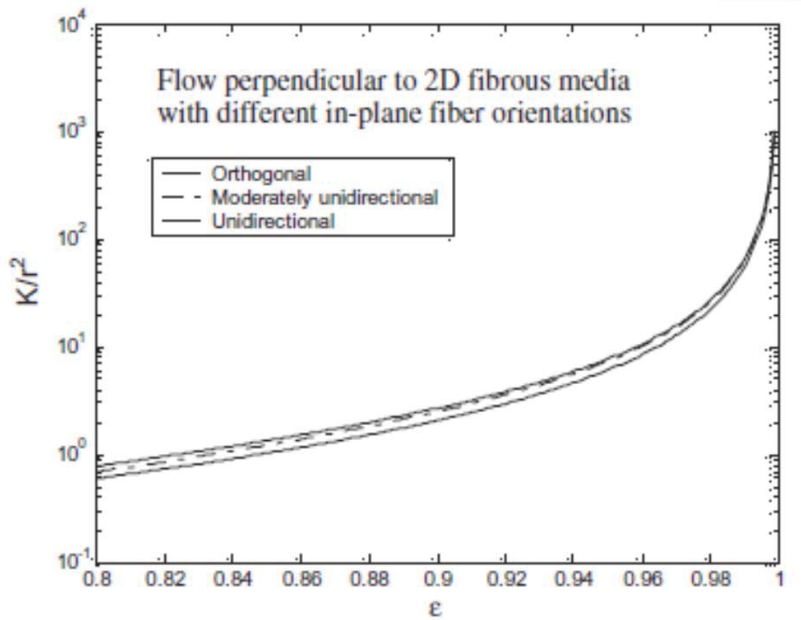
$$k_s(T) = F_s f_v^b k_s^*(T) \qquad k_g(T,P) = \frac{k_{g0}(T)}{\Phi + 2\Psi\frac{\beta}{Pr}Kn}$$

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

Case Study: Effect of Core Density on Flow



(DeMange, unpublished)



(Shuo *et al.*, 2011)

$$-\nabla P = \frac{\mu}{K}\vec{u} + \rho C|\vec{u}|\vec{u}$$

(Stanek & Szekely, 1974)

$$\frac{(P_1^2 - P_0^2)A}{2\dot{m}\mu RTL} = \frac{1}{K} + C\frac{\dot{m}}{A\mu}$$

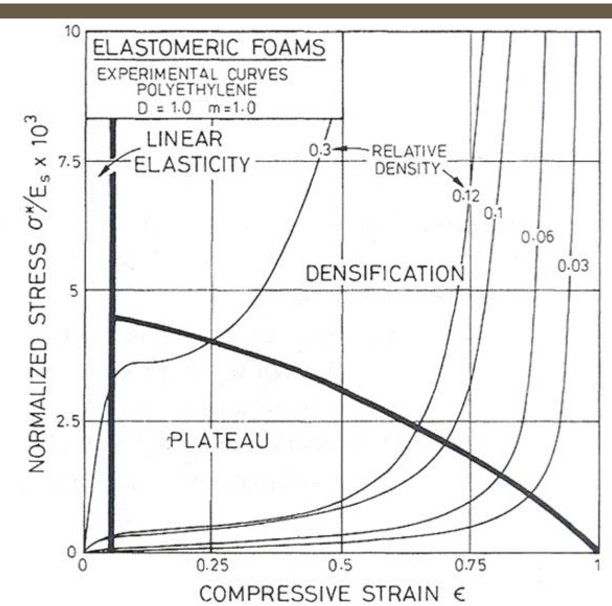
THE SCIENCE: CURRENT EFFORTS TO IMPROVE UNDERSTANDING OF MECHANICAL BEHAVIOR

Mechanical Behavior: What We Know

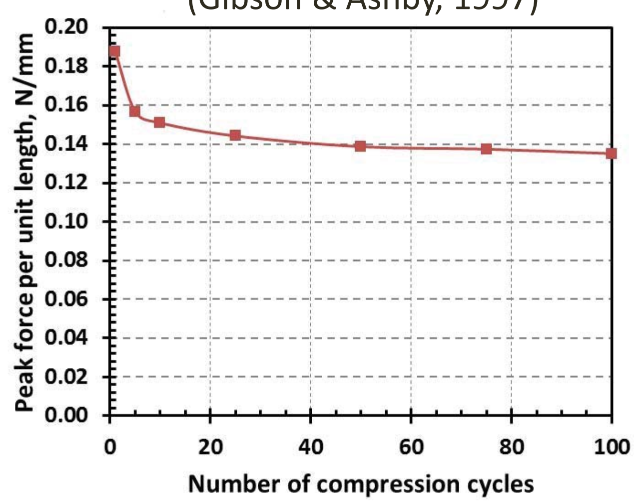
- Similar behavior to low-density porous foam materials
  - Linear elasticity (cell wall bending) → fiber bending
  - Plateau (cell wall buckling) → fiber breakage?
  - Densification (cell collapse) → pore collapse
- Strong effect of core density on mechanical performance (opposite to effect on insulating properties)

$$\sigma \propto \left(\frac{\rho^*}{\rho_s}\right)^n$$

- Exhibit hysteresis during loading, unloading
- Display compaction/set (even at RT) that decreases with number of cycles



(Gibson & Ashby, 1997)



(DeMange, 2012)

Modeling Efforts

- Van Wyk modeled compressibility of fibrous wool (1946)
  - Fiber as straight rod supported horizontally between 2 other rods
  - Many other studies based off Van Wyk's model
    - Komori, *et al.* (1977, 1992) – Orientation of fibers, fiber crimp
    - Beil, *et al.* (2002) – Friction of fibers
    - Barbier, *et al.* (2009) – Hysteresis and friction

$$p = \frac{kEm^3}{\rho^3}\left(\frac{1}{v_i^3} - \frac{1}{v_o^3}\right) = kE\left(SVF_i^3 - SVF_o^3\right)$$

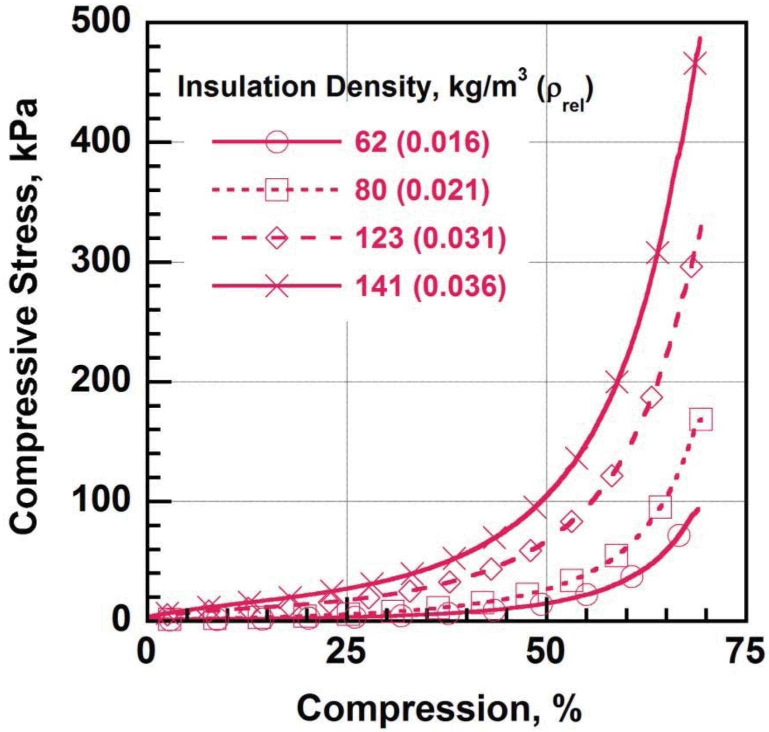
p = contact load
k = empirically determined constant (structure of fiber mass)
E = Young's modulus of fibers
m = mass of fibers
ρ = density of fiber
v_i = instantaneous bulk volume
v_o = initial bulk volume
SVF_i = instantaneous solid vol. fraction (volume fibers/bulk volume)
SVF_o = initial solid vol. fraction (volume fibers/bulk volume)

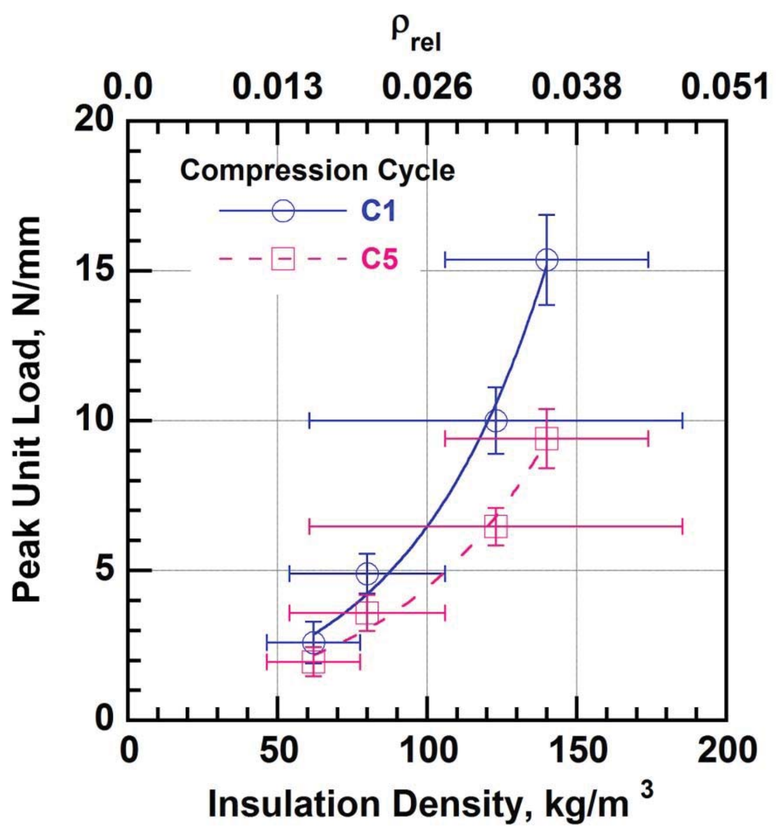
- Pineda (2014) modeled Saffil insulation using energy method

$$U_{4P} = C_{10}\left(\bar{I}_1 - 3\right) + C_{20}\left(\bar{I}_1 - 3\right)^2 + C_{30}\left(\bar{I}_1 - 3\right)^3 + C_{40}\left(\bar{I}_1 - 3\right)^4 \frac{K}{2}(\ln J)^2$$

$$\mathbf{T} = \frac{2}{J}\left[\left(\frac{\partial U}{\partial \bar{I}_1} + \bar{I}_1 \frac{\partial U}{\partial \bar{I}_2}\right)\overline{\mathbf{B}}' - \right]\frac{\partial U}{\partial \bar{I}_2}\overline{\mathbf{B}}'^2 + \frac{\partial U}{\partial J}\mathbf{1}$$

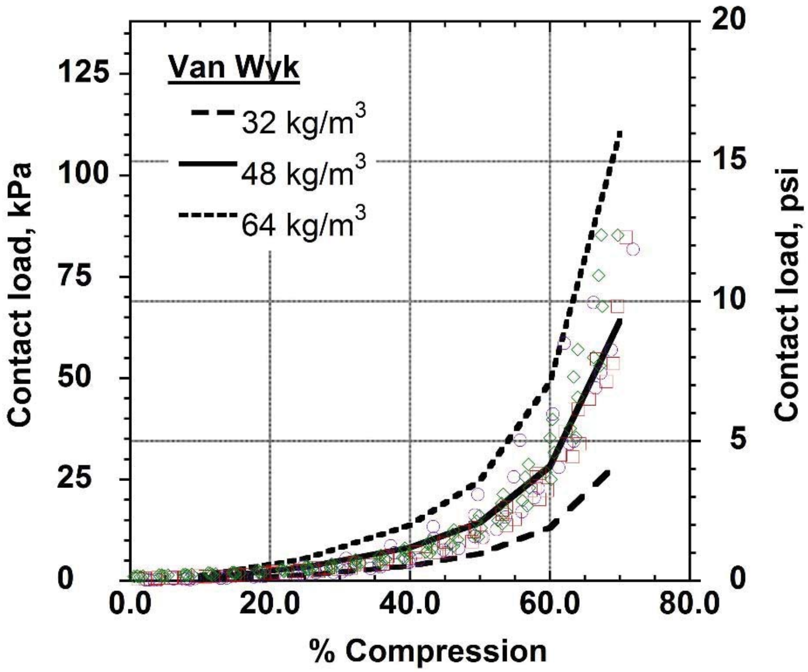
Case Study: Effect of As-Fabricated Core Density on Loads



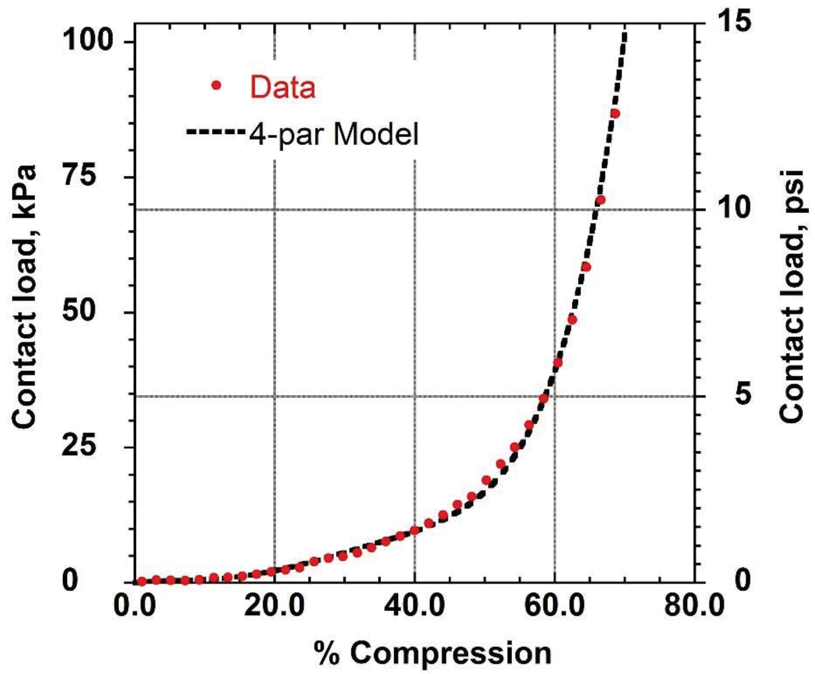


- Load behavior is highly nonlinear
- Nonlinear increase in peak load vs. as-fabricated density

Case Study: Initial Modeling Efforts



Van Wyk Model



Pineda Model

- Van Wyk provides a reasonable first approximation of behavior of CTB's
- Pineda model matches Saffil performance well
- Models need expansion and refinement to incorporate effects from various sources

Still so much to do...

- Heat transfer modeling
  - Need more data
    - Insulation – Effect of orientation (e.g., Saffil mat is transversely isotropic), other types (e.g., OFI, MLI, aerogels), how to reliably measure density
    - Effect of size/configuration – Hard to measure thermal properties on small samples
    - Variation between samples
  - Validation of models – How do we validate with combined conduction, convection, and radiation?
- Mechanical modeling
  - Need more data
    - Insulation – Basic mechanical material properties, effect of orientation (e.g., Saffil mat is transversely isotropic), other types (e.g., OFI, MLI, aerogels), how to reliably measure density
    - Effect of size/configuration (e.g., inclusion of spring tube, stitching, coatings)
    - Variation in samples
    - Effect of environment (temperature, pressure, space)
  - What's the best model?

Goal: Develop a thermal barrier thermo-mechanical design/sizing tool

Summary

- Thermal barriers are integral to successful TPS performance
  - ➢ Considered more art, but need more science
  - ➢ Vehicle designers need guidance in designing, implementing, and maintaining thermal barriers
- Behavior of thermal barriers
  - ➢ Thermal performance
    - o Heat transfer in porous soft goods is complex
    - o Good baseline understanding of heat transfer in porous TPS
    - o Challenges remain in characterization (e.g., lack of data, difficulty in testing small samples)
  - ➢ Mechanical performance
    - o Less studied and understood
    - o Very few models exist
    - o Multitude of configurations and implementations creates modeling challenges
- Still much to do

Points of Contact

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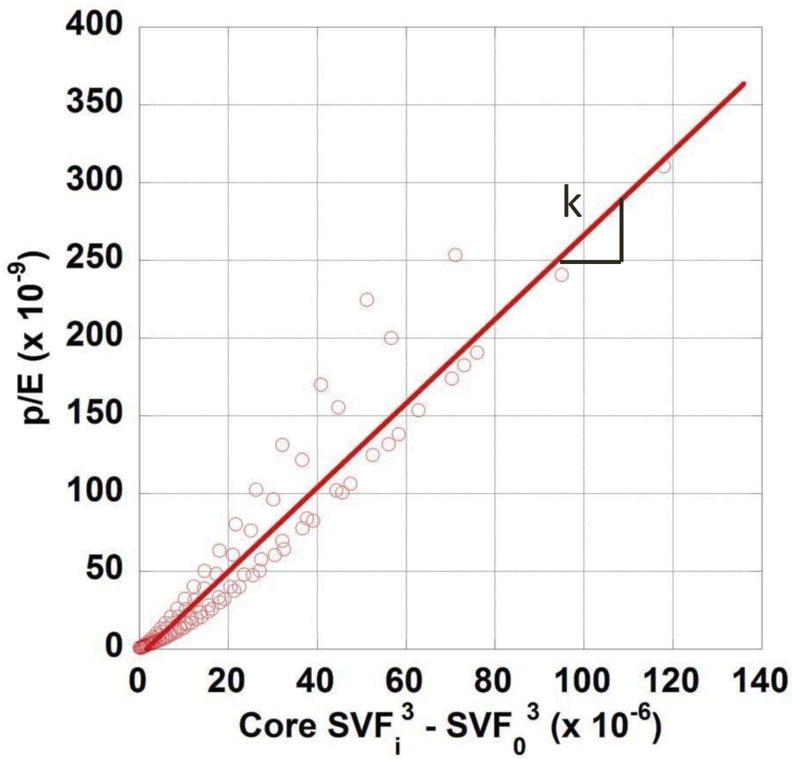
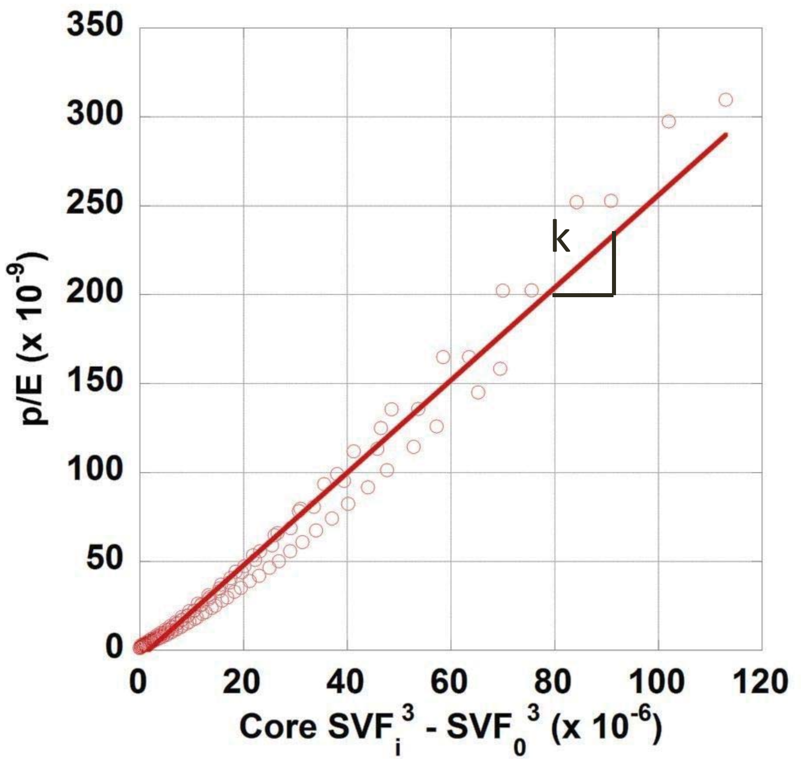
Appendix

Comparison to Van Wyk Model



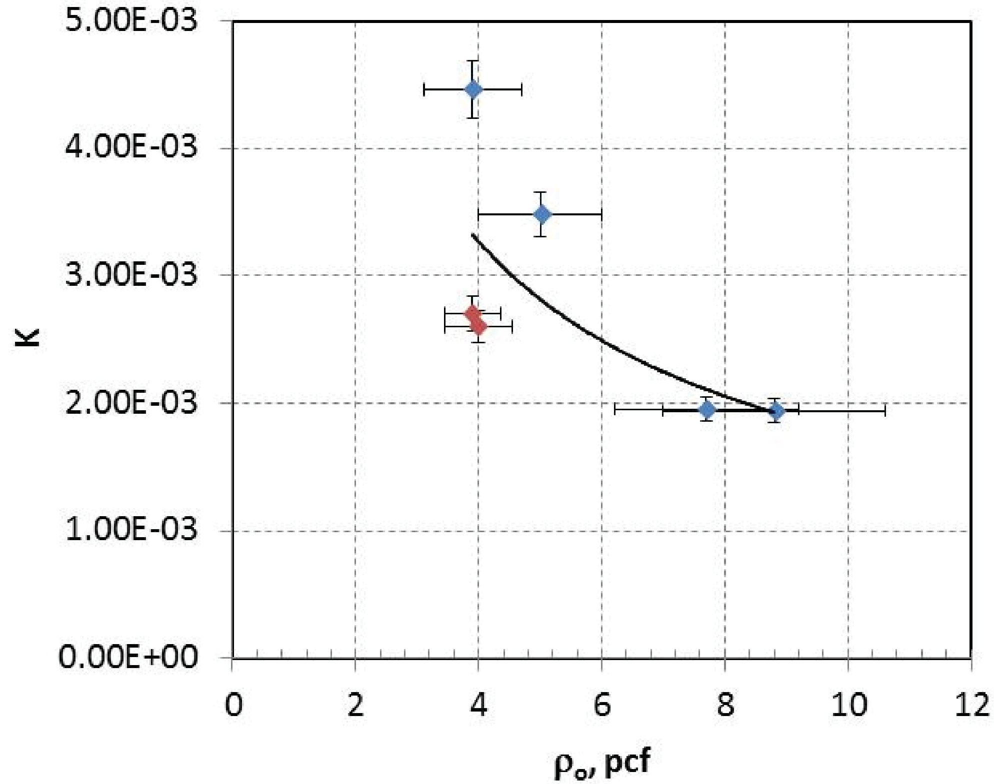
569 (HS-to-BS)



570 (PtoP)

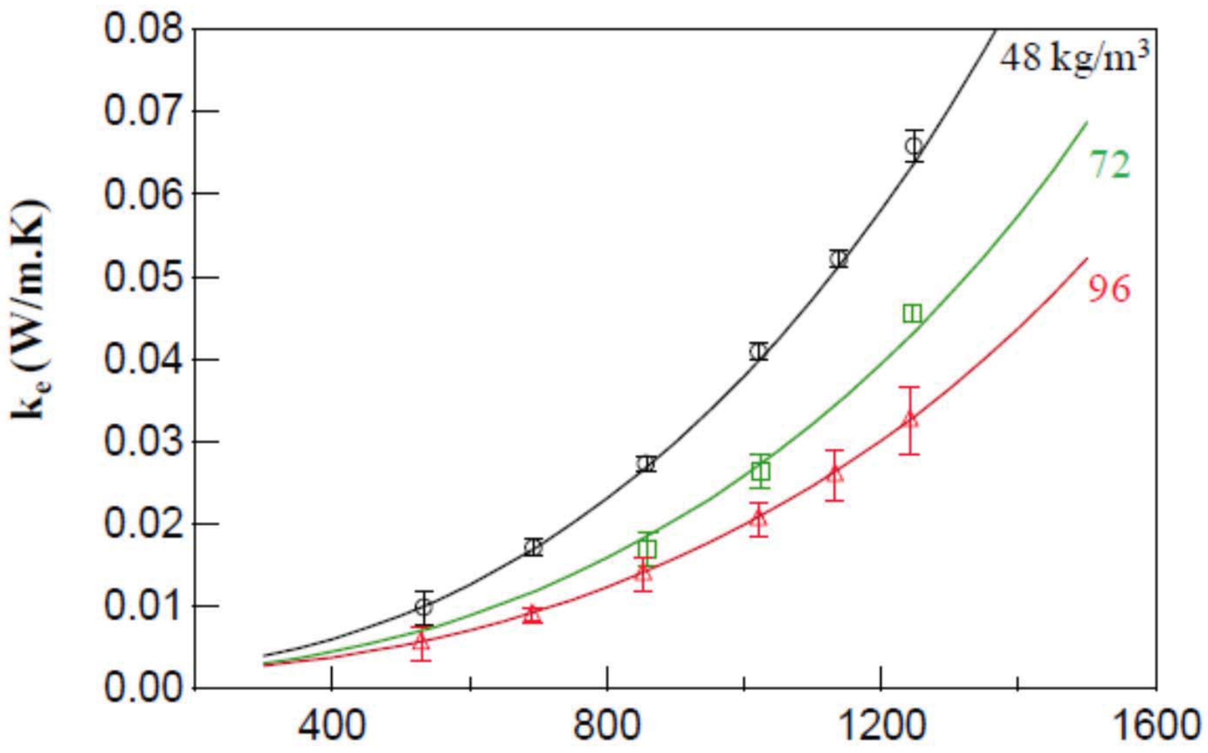
- Variability in compression performance of samples evident
- Suggest k varies from sample to sample (Van Wyk, 1946)
- Initial nonlinearity may be due to fiber slippage (Dunlop, 1974)

Variation of k for Samples



- k is function of initial density of core fibers (Dunlop, 1974)
- k is complex function of fiber configuration (e.g., layer orientation)

Effect of Insulation Density on Effective Thermal Conductivity



(Daryabeigi *et al.*, 2010)