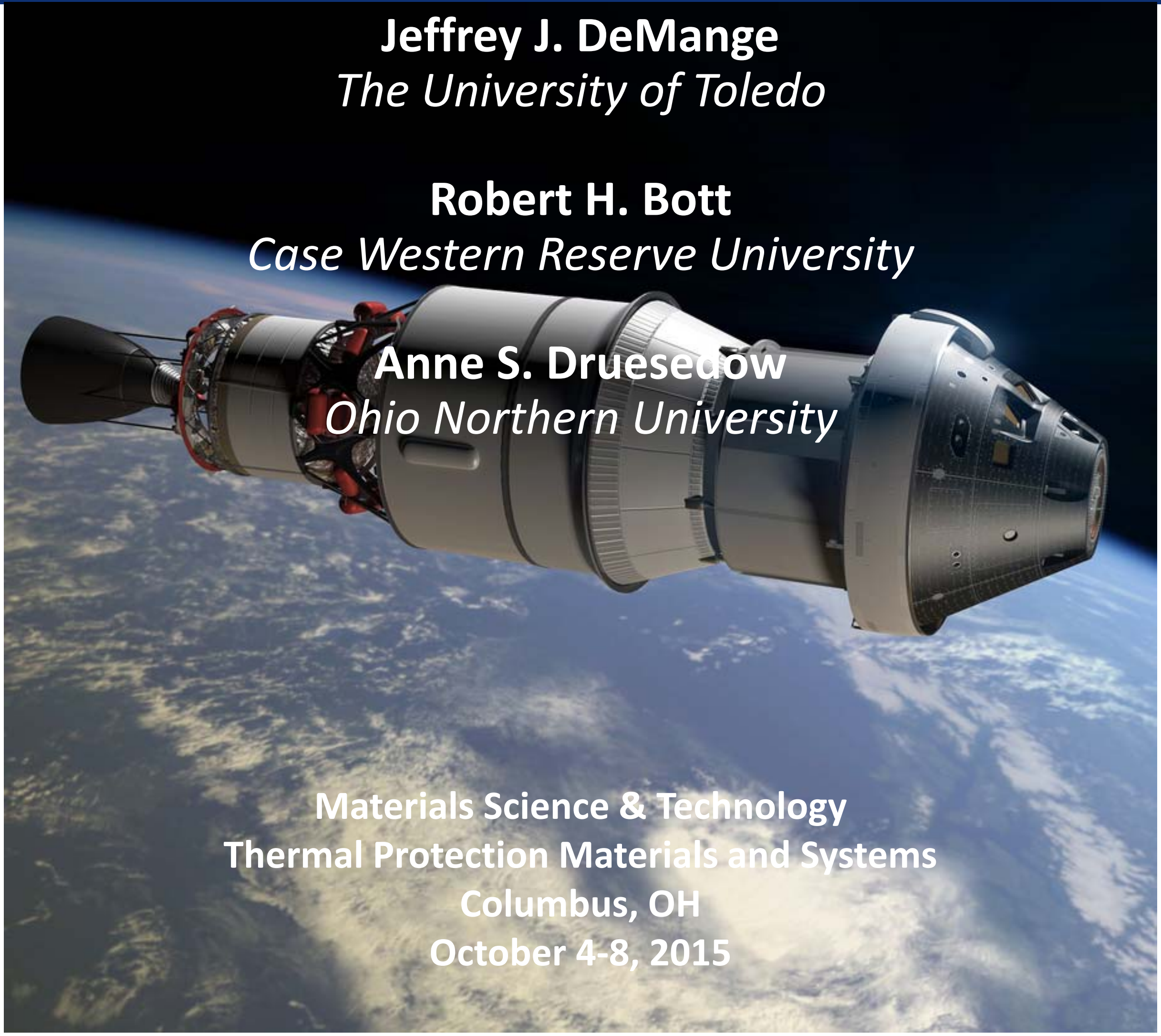
THE EFFECT OF CORE CONFIGURATION ON THERMAL BARRIER THERMAL PERFORMANCE



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Thermal Protection Materials and Systems
Columbus, OH
October 4-8, 2015

This research was funded by the U.S. Government under NASA Contracts NNC08CA35C & NNC13BA10B. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the U.S. Government.

CONTENTS OF DISCUSSION

- Introduction
  - Description of Compliant Thermal Barriers (CTB's)
  - Construction of CTB's
- Objectives
- Results
  - Experimental Studies
    - Measurement of core density
    - Effect of core density on flow/leakage → permeability
    - Thermal conductivity effect
  - Modeling Studies
    - Setup of model
    - Effect of various parameters on temperature
- Summary

AN INTEGRAL PART OF THE TPS

Compliant Thermal Barriers (CTB's)

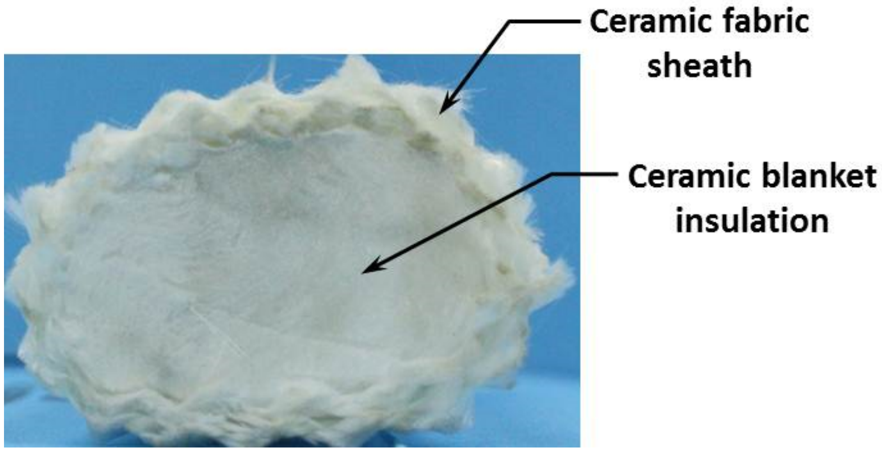
- Often referred to as "thermal seals" or "seals"
- One "class" of thermal barriers
- High-temp. ceramic-based fibrous materials
- Installed in TPS interface gaps
- Roles
  - Thermal – limit inboard temperatures
  - Structural – accommodate deflections

Vehicle Penetrations

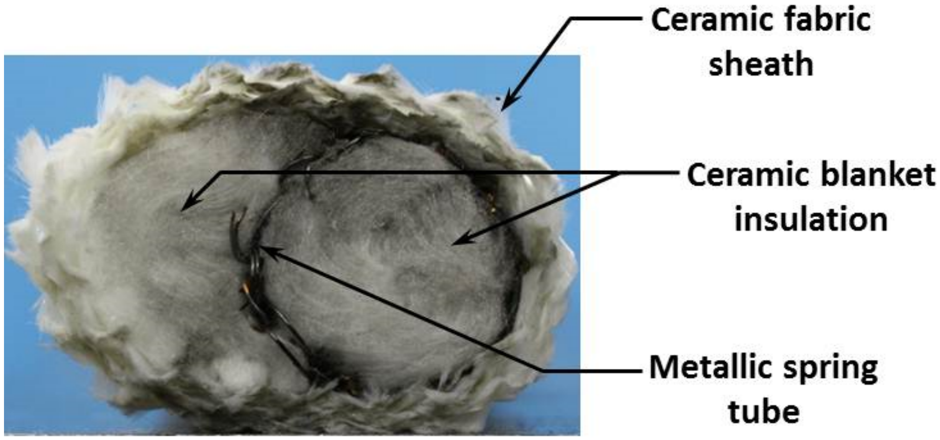
Doors

Control Surfaces

COMPLIANT THERMAL BARRIER CONSTRUCTION

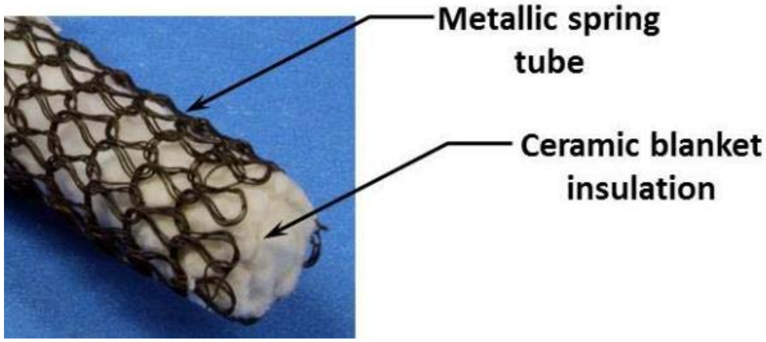


Blanket Thermal Barrier (BTB)



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 intact
    - End treatments/closeouts

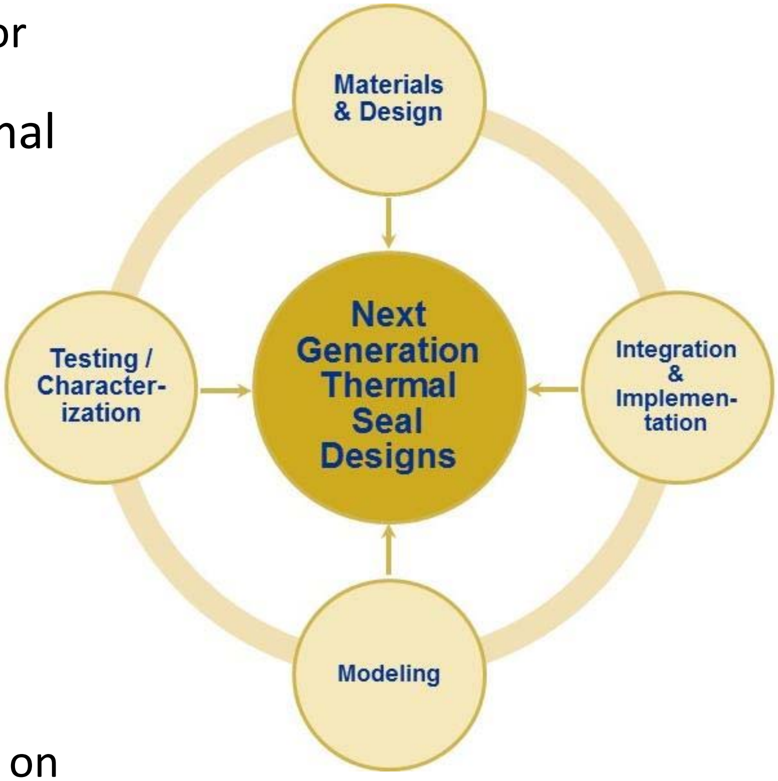


OBJECTIVES

- Thermal barriers are both simple and complex…
  - Simple in basic design and operation
  - Complex in fabrication and mechanistic behavior

- Vehicle designers need help in integrating thermal barriers
  - How big?
  - What configuration? Coatings?
  - How much insulation?
  - How to integrate?

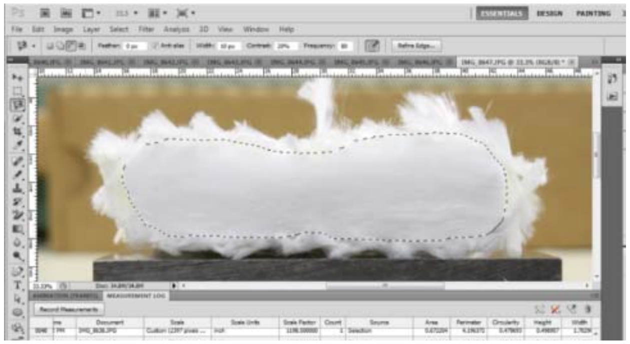
- Objectives: Utilize testing and modeling to
  - Improve understanding of thermal barriers
  - Facilitate improved and more efficient design practices
  - Determine effect insulation core characteristics on thermal barrier performance



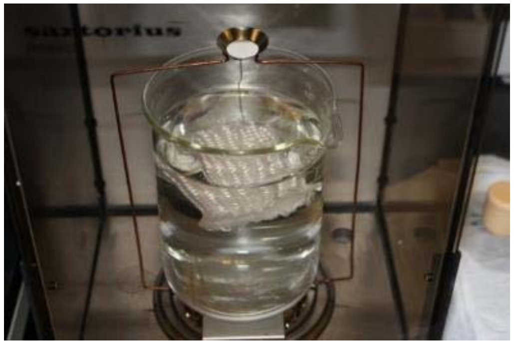
MEASUREMENT OF CORE DENSITY

- 3 different methods to measure core density
  - Laser dimensional measurement
  - Photographic dimensional measurement
  - Volume measurement (Archimedes' Principle)
- Each method has pro's and con's
  - Laser and photographic methods quick, but rely on assumptions about core shape
  - Archimedes' is most accurate, but more complicated
- Core density as a function of compression ("effective density") required for current study

Laser



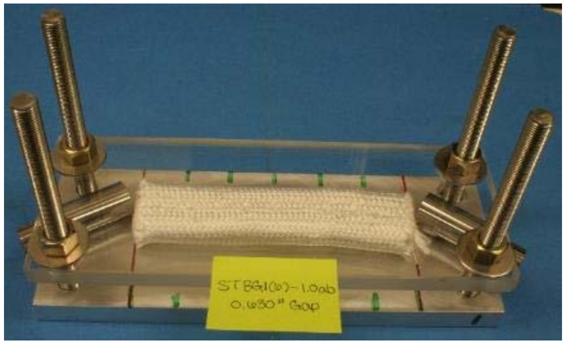
Photographic



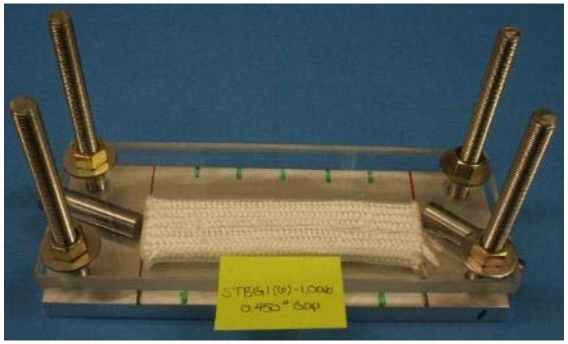
Archimedes

MEASUREMENT OF "EFFECTIVE DENSITY"

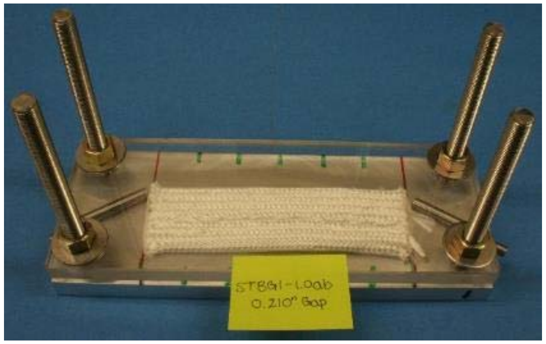
- "Effective density" accounts for volume change and densification of core with respect to compression
- Method
  - Compressed thermal barrier using thick Plexiglass plate to prescribed compression amount set by gage pins
  - Used 2D laser to measure width and thickness in 5 locations along length
  - Estimated core volume from "cross-sectional" and length measurements
- "Effective density" calculated for 3 compression levels (gaps)



Large Gap

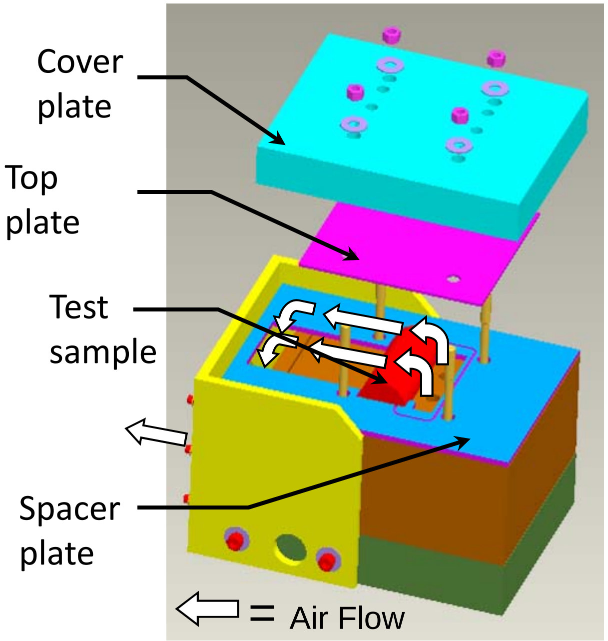


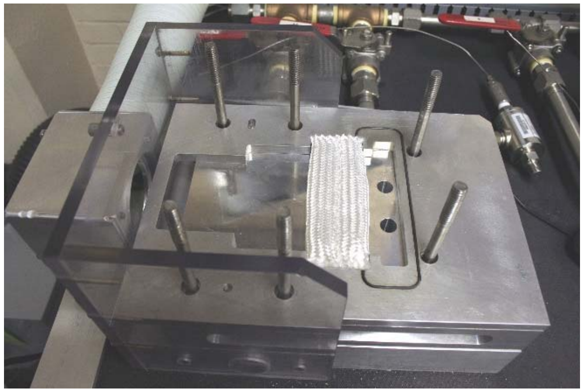
Medium Gap



Small Gap

MEASUREMENT OF LEAKAGE

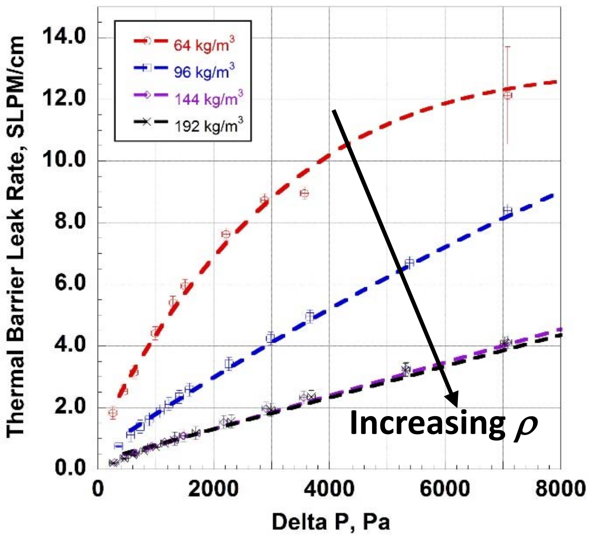




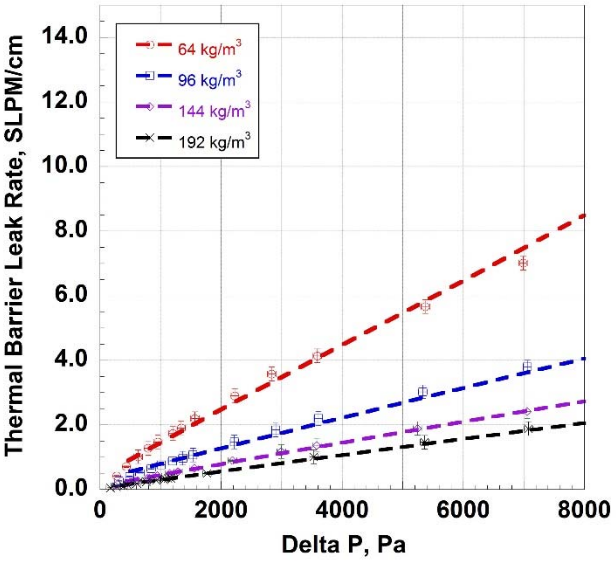
- Thermal barrier tested in Linear Flow Fixture #2 (LFF#2)
- 2 CTB types
  - ➢ Blanket (BTB): 64, 96, 144, 192 kg/m^3 nominal core density
  - ➢ Hybrid (HTB): 64, 144 kg/m^3 nominal core density
- Test parameters
  - ➢ Ambient temperature
  - ➢ 3 different gap/compression levels
  - ➢ Evaluated between smooth metal plates
  - ➢ Delta P: 0 – 7000 Pa
  - ➢ Flow measured as function of ΔP across seal

LEAKAGE RESULTS: BLANKET THERMAL BARRIER

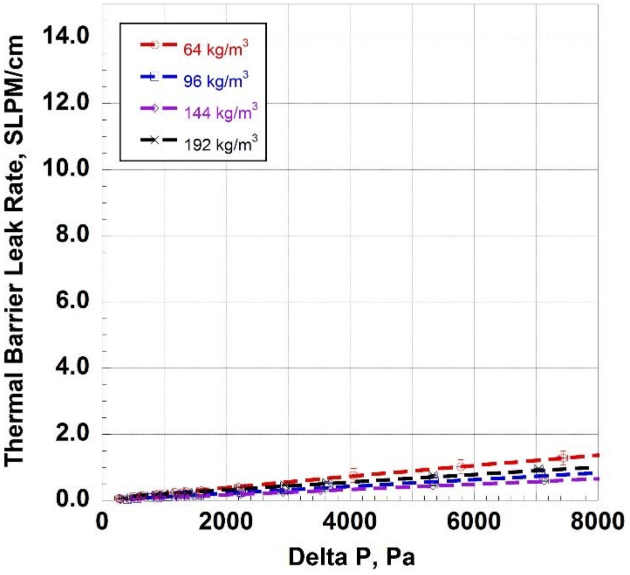
Large Gap



Medium Gap

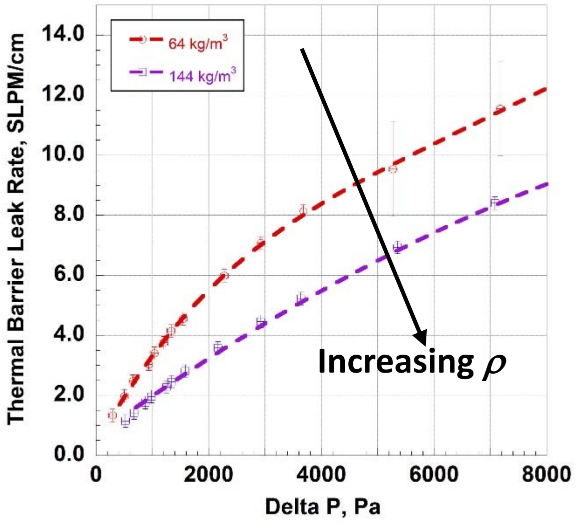


Small Gap



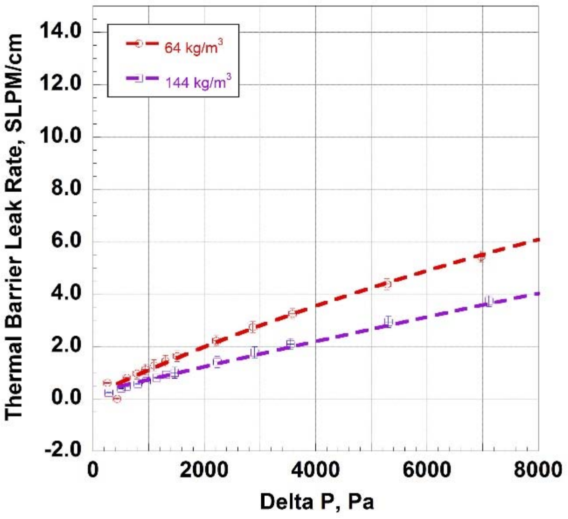
LEAKAGE RESULTS: HYBRID THERMAL BARRIER

Large Gap

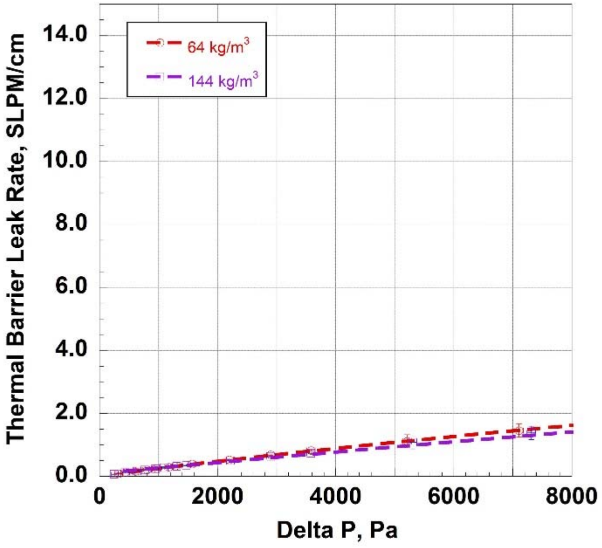


Increasing ρ

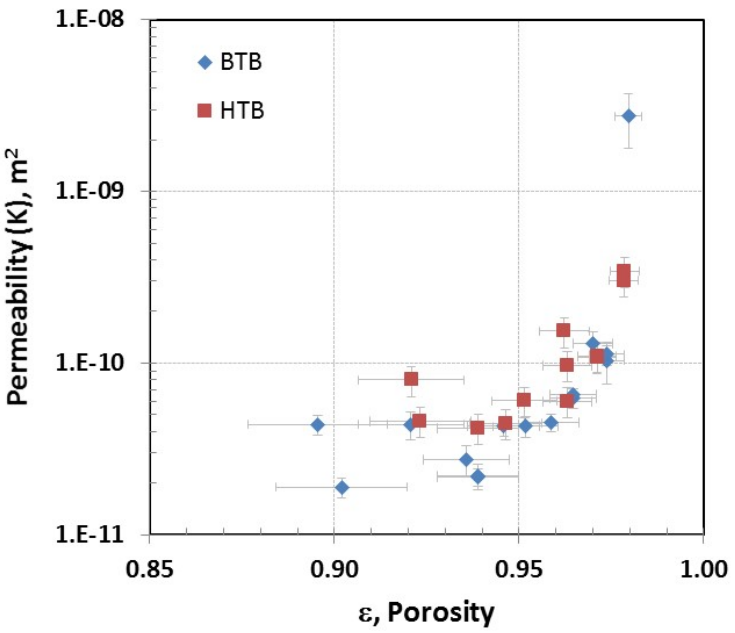
Medium Gap



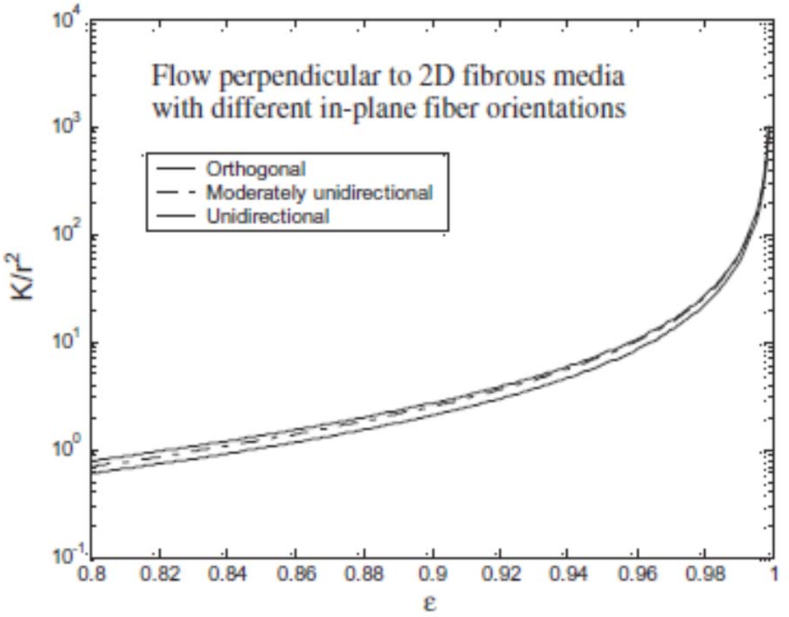
Small Gap



EFFECT OF CORE DENSITY ON PERMEABILITY



(DeMange, unpublished)



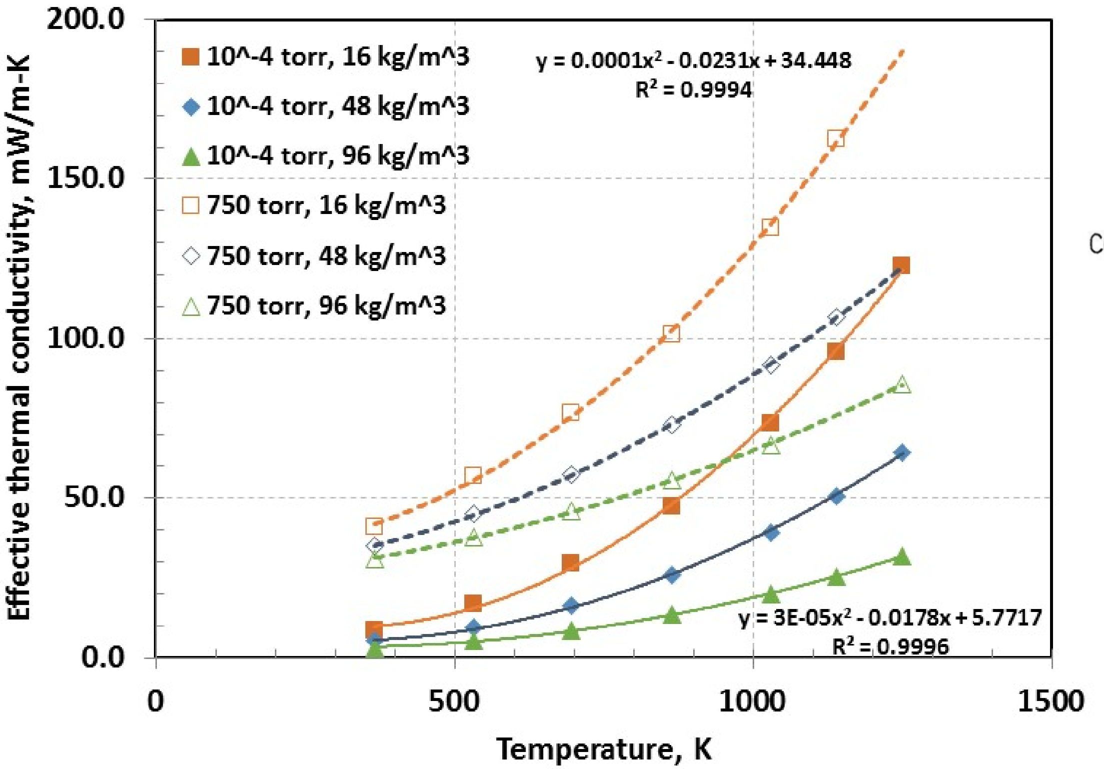
(Shuo *et al.*, 2011)

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

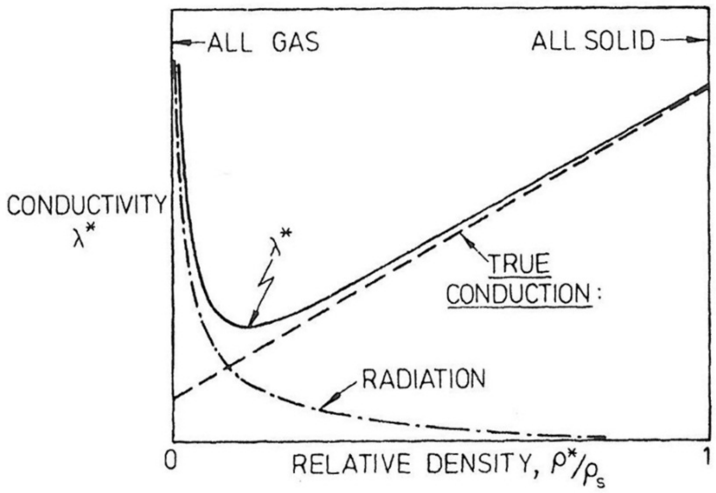
(Stanek & Szekely, 1974)

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

EFFECT OF CORE DENSITY ON EFFECTIVE THERMAL CONDUCTIVITY



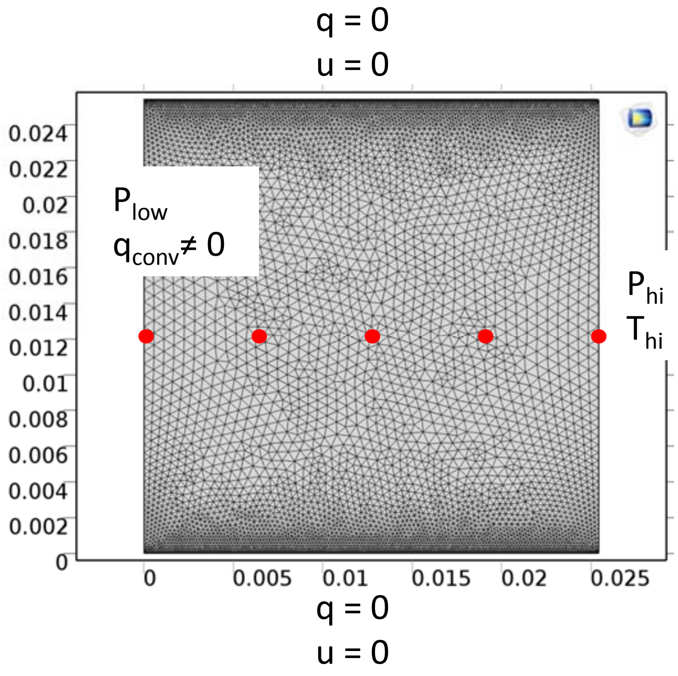
(Daryabeigi, 1999)



(Gibson & Ashby, 1997)

THERMAL MODELING OF SOFT GOOD THERMAL BARRIERS

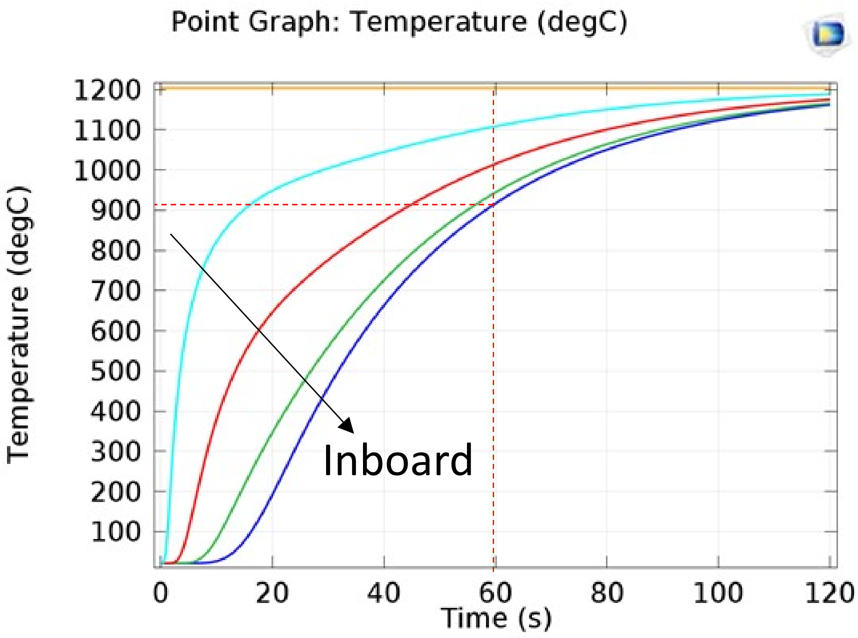
User-controlled mesh
Fluid dynamics – Extra fine
11524 Elements
DOF = 82300 (886 internal DOF)



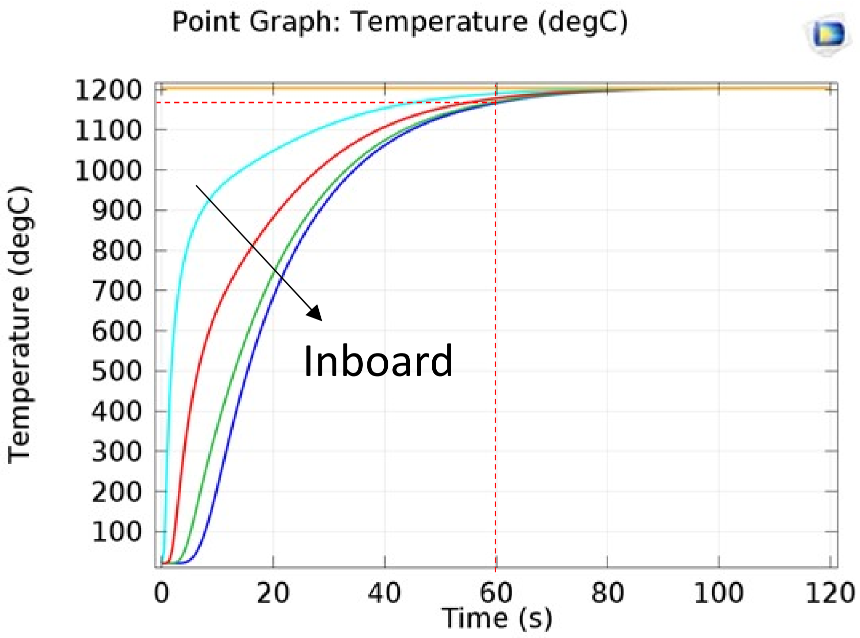
- Modeled using COMSOL 5.0
  - Heat Transfer in Porous Media
  - Free and Porous Media Flow
  - Standard Transient Navier-Stokes Formulation
- Geometry and Boundary conditions
  - Geometry: 2.54 x 2.54 cm square
  - Monitor pts: 5 equally spaced centrally along flow length
  - Outboard
    - P_{hi}: 1500 Pa - 3500 Pa
    - T_{hi}: 1204°C
  - Inboard
    - P_{low}: 100 Pa
    - T_{low}: Outflow (convection-dominated)
  - Top and bottom: Insulative, no slip
- Material properties
  - Density: 60 – 144 kg/m^3
  - Permeability: 0.20 x 10^{-10} – 27 x 10^{-10} m^2
  - Porosity: 90 - 95%
  - Thermal conductivity: High and low
  - Cp = 1000 J/kg-K

EFFECT OF POROSITY

$\varepsilon = 0.90$



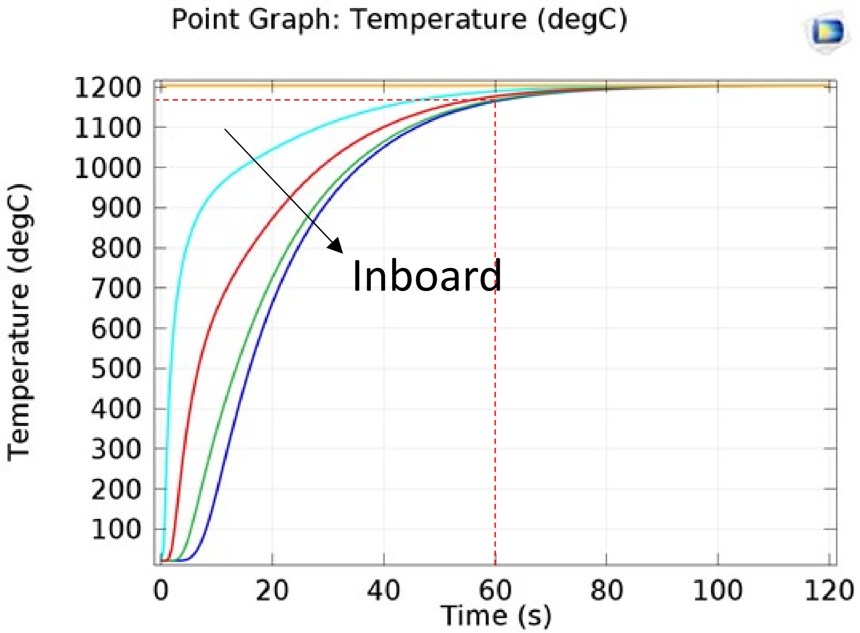
$\varepsilon = 0.95$



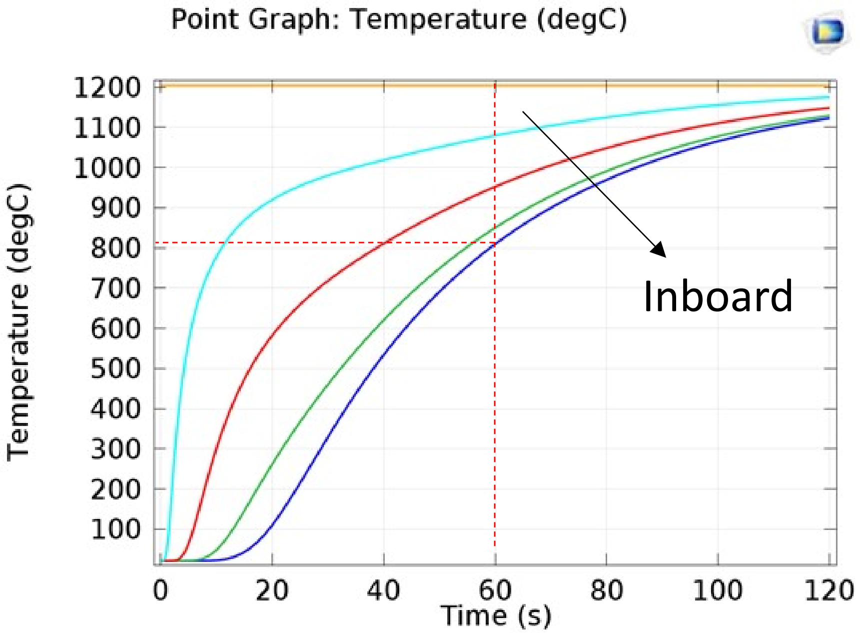
$\rho = 120\ \mathrm{kg/m^3}$
$K = 3.5\mathrm{E}{-10}\ \mathrm{m^2}$
$P_{hi} = 1500\ \mathrm{Pa}$
$P_{low} = 100\ \mathrm{Pa}$
$T_{hi} = 1204°\mathrm{C}$
$k = (3\mathrm{E}{-05}*T^2-0.0178*T+5.7717)/1000\ \mathrm{W/m\text{-}K}$

EFFECT OF INSULATION DENSITY

ρ = 60 kg/m^3



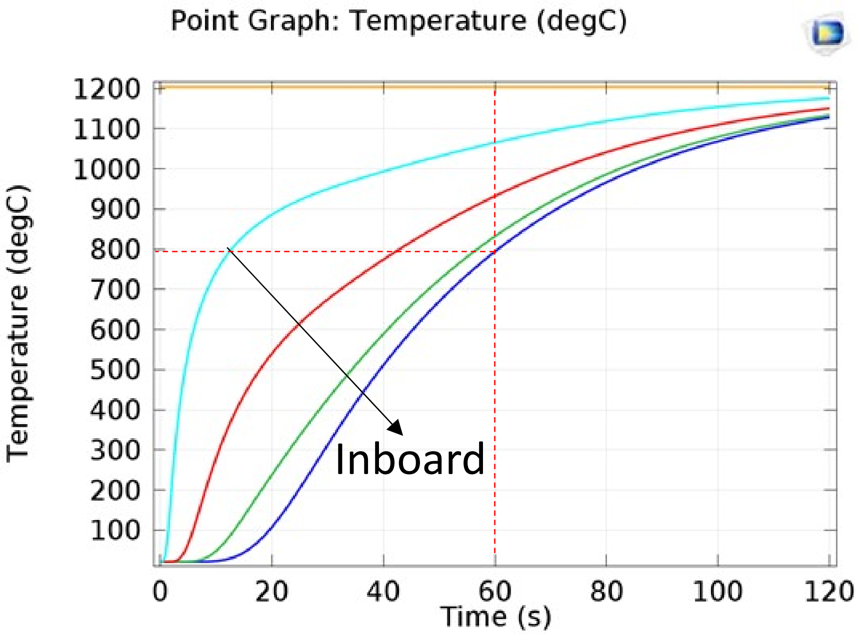
ρ = 144 kg/m^3



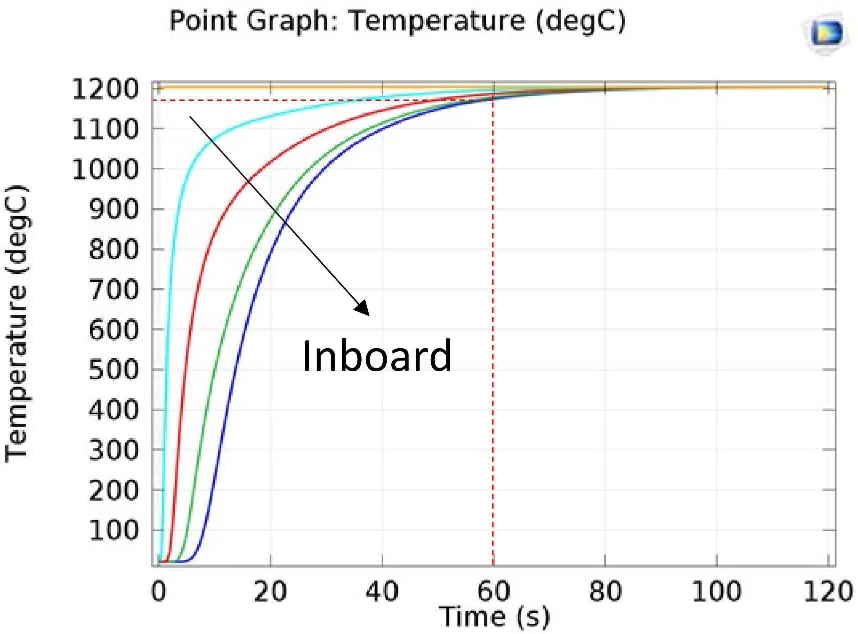
K = 3.5E-10 m^2
P_{hi} = 1500 Pa
P_{low} = 150 Pa
T_{hi} = 1204°C
k = (3E-05*T^2-0.0178*T+5.7717)/1000 W/m-K

EFFECT OF PERMEABILITY

K = 0.20 x 10^{-10} m^2



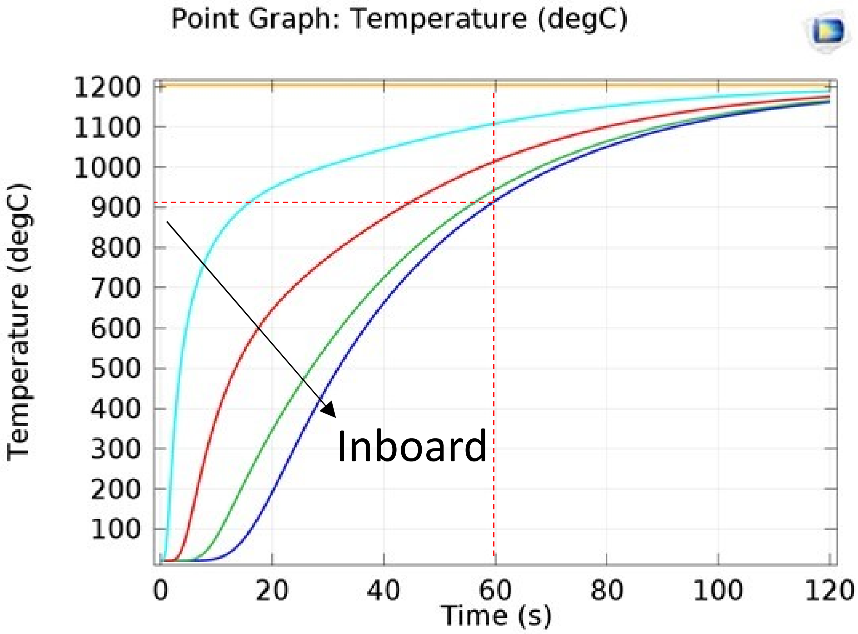
K = 27 x 10^{-10} m^2



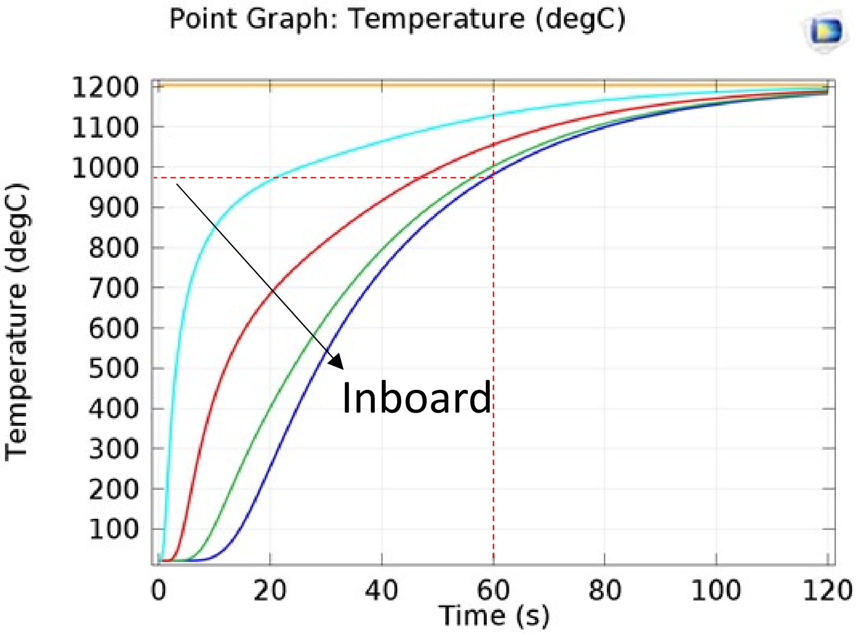
ρ = 120 kg/m^3
P_{hi} = 1500 Pa
P_{low} = 100 Pa
T_{hi} = 1204°C
k = (3E-05*T^2-0.0178*T+5.7717)/1000 W/m-K

EFFECT OF THERMAL CONDUCTIVITY

k = 3E-05*T^2 – 1.78E-2*T + 5.772 mW/m-K (lower)



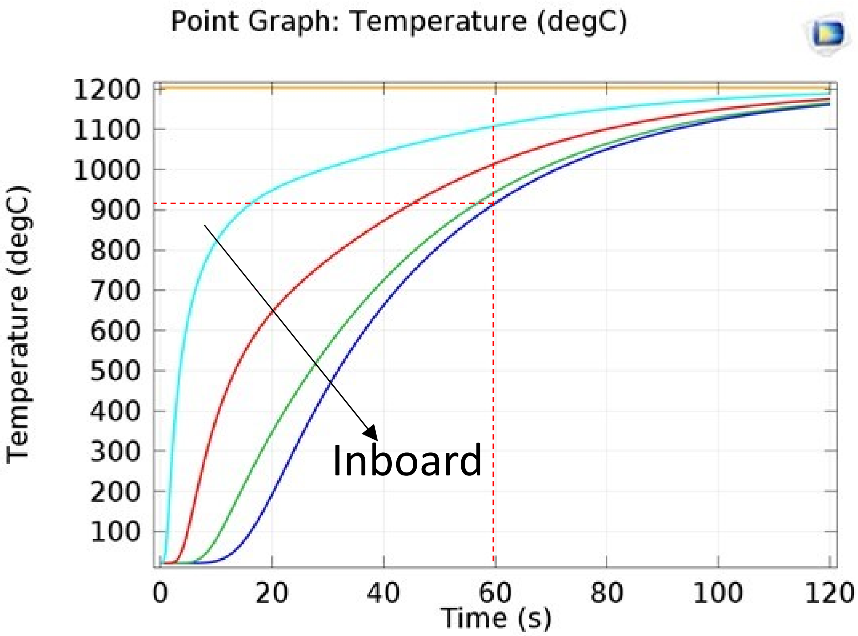
k = 1E-4*T^2 – 2.31E-2*T + 34.448 mW/m-K (higher)



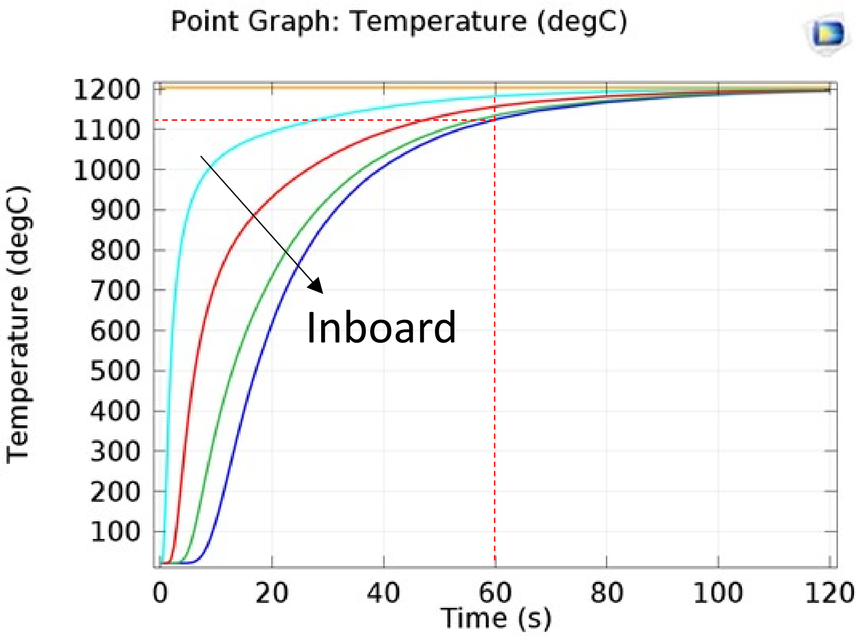
ρ = 120 kg/m^3
K = 3.5E-10 m^2
P_{hi} = 1500 Pa
P_{low} = 100 Pa
T_{hi} = 1204°C

EFFECT OF PRESSURE DIFFERENTIAL

P_{hi} = 1500 Pa



P_{hi} = 3500 Pa

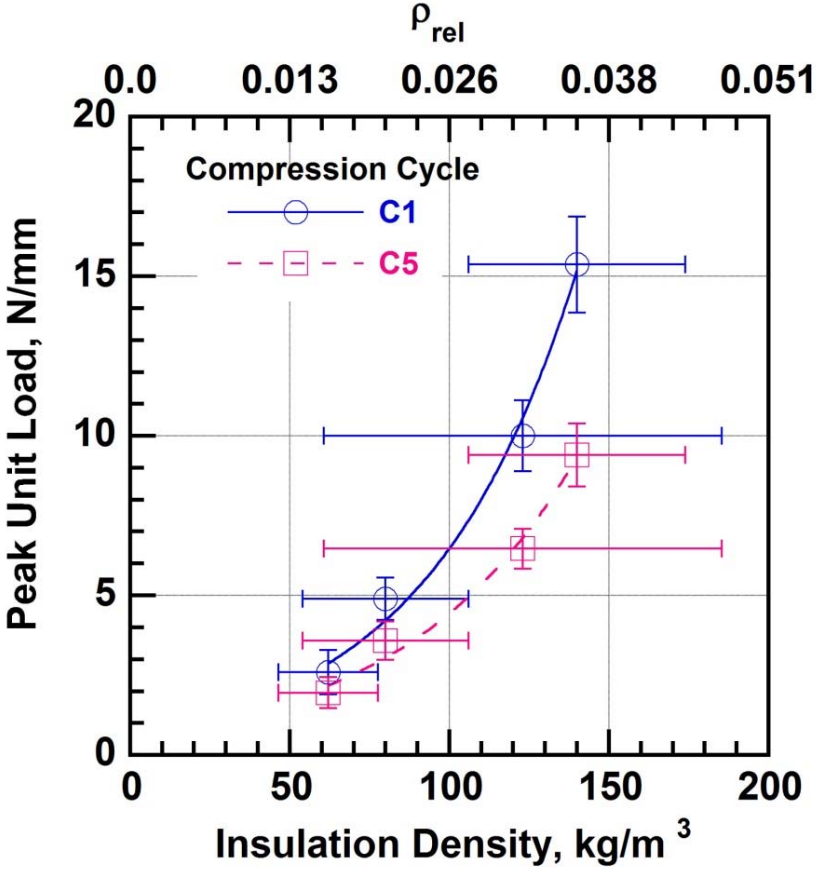


$K = 3.5E\text{-}10\ m^2$
$\rho = 120\ kg/m^3$
P_{low} = 100 Pa
T_{hi} = 1204°C
$k = (3E\text{-}05*T^2-0.0178*T+5.7717)/1000$ W/m-K

THE TRADEOFF

But…

What may be good thermally, may not be so good structurally.



SUMMARY & CONCLUSIONS

- More insulation = better thermal performance
  - Convective heat transfer
    - Flow testing and modeling
    - Lower porosity/higher density, higher compression → reduced permeability, reduced leakage
    - Higher pressure differential → more convective heat transfer
  - Conductive heat transfer
    - Thermal testing and modeling
    - Increasing density → lower k_{eff}
    - But…effect is likely asymptotic, may not improve much after a given core density
- More insulation = higher mechanical loads
  - 60 → 144 kg/m^3, peak loads increase by a factor of 3
  - May be issue if installed adjacent to delicate components (e.g., TPS)
- Vehicle designer/integrator needs to optimize design to account for both thermal and mechanical requirements
  - Integrated thermo-structural model would be beneficial
  - Efforts for both thermal and structural models are ongoing

REFERENCES

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APPENDIX

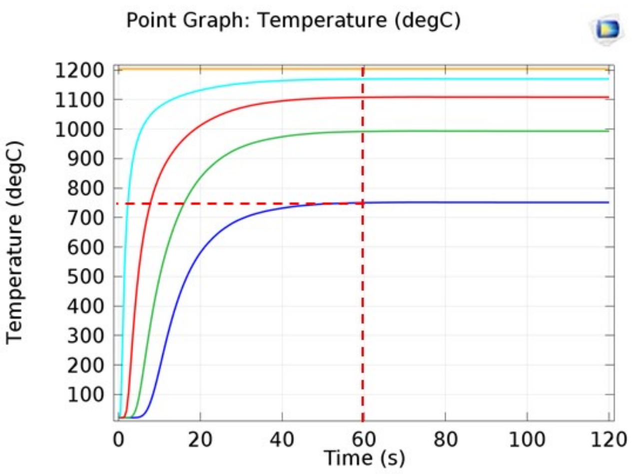
COMPLIANT THERMAL BARRIER REQUIREMENTS & CHARACTERISTICS

- 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

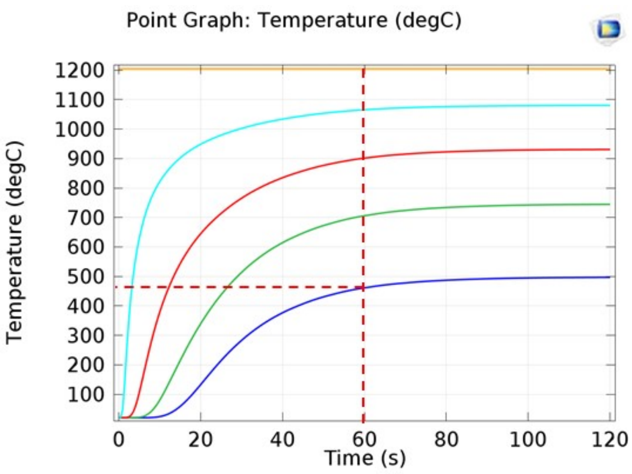
- Characteristics
  - Made of high temperature ceramic fiber-based materials
  - Utilize high-performance insulation
  - Permeable
  - Compliant
  - Exhibit set/compaction (even at ambient temperatures)
  - Non-linear hysteretic loading behavior

EFFECT OF PERMEABILITY AND REAR BOUNDARY CONDITION

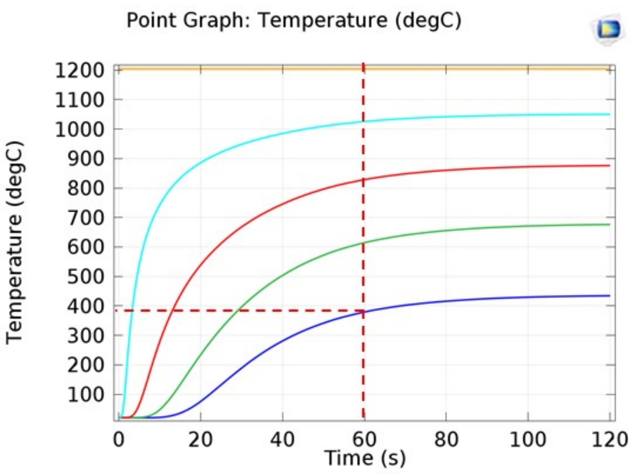
$K = 27 \times 10^{-10}\ m^2$



$K = 3.5 \times 10^{-10}\ m^2$



$K = 0.20 \times 10^{-10}\ m^2$



$\rho = 120\ kg/m^3$
$P_{hi} = 1500$ Pa
$P_{low} = 100$ Pa
$T_{hi} = 1204$°C
$k = (3E\text{-}05 * T^2 - 0.0178 * T + 5.7717)/1000$ W/m-K
Backside convective heat boundary ($h = 5\ W/m^2\text{-}K$)