Thermal Protection Systems for Aerospace Vehicles During Atmospheric Entry

Kamran Daryabeigi
Structural Mechanics and Concepts Branch
NASA Langley Research Center
Hampton, VA 23681

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Outline

- Biography
- Atmospheric Entry and Thermal Protection Systems
- Ceramic Insulations for Passive Thermal Protection Systems
  - Typical Applications
  - Ceramic Insulations
  - Heat Transfer Modeling
  - Thermal Performance Characteristics
  - Insulation Figures of Merit; Improving Thermal Performance
- Concluding Remarks
- NASA Employment Opportunities

Biography

- **Education**
  - B.S., Mechanical Engineering, Old Dominion University, Norfolk, VA, 1983
  - M.S., Mechanical Engineering, Old Dominion University, Norfolk, VA, 1986
  - Ph.D., Mechanical and Aerospace Engineering, University of Virginia, Charlottesville, VA, 2000

- **Work Experience**
  - Thermal Instrumentation Section, NASA Langley Research Center, Hampton, VA, 1986 -1995
    - Worked on thermal instrumentation and radiometric thermal (infrared) imaging
  - Structural Mechanics and Concepts Branch, NASA Langley Research Center, Hampton, VA, 1995 - present
    - Working on heat transfer in thermal protection systems
      - Thermal testing and modeling of high-temperature insulations
      - Developing improved high-temperature insulations

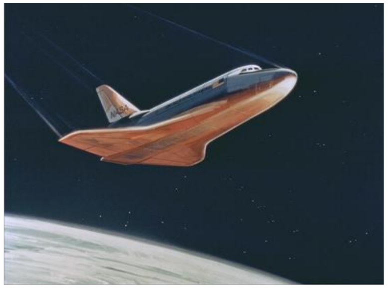
Atmospheric Entry

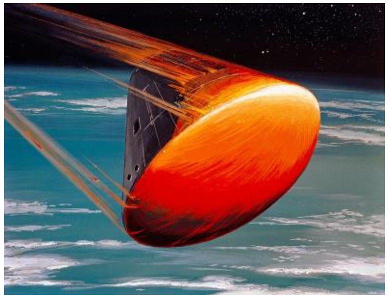
- **There are two types of planetary atmospheric entry**

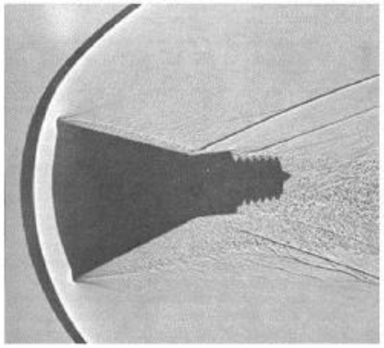
  - **Lifting body glided entry** for winged orbiter vehicles. Uses a delta wing for maneuvering during descent much like a conventional glider: Space Shuttle

  - **Controlled ballistic entry for capsules** (typically a sphere-cone). By flying at an angle of attack, the capsule has modest aerodynamic lift, providing some cross-range capability and widening its entry corridor: Apollo, Orion, Viking

  - Space vehicles have very high kinetic energy in orbit. Entering the high-density atmosphere at high velocities (7 km/s to 13 km/s), the vehicle will experience significant aerodynamic heating due to drag and compression of the air in front of the object.







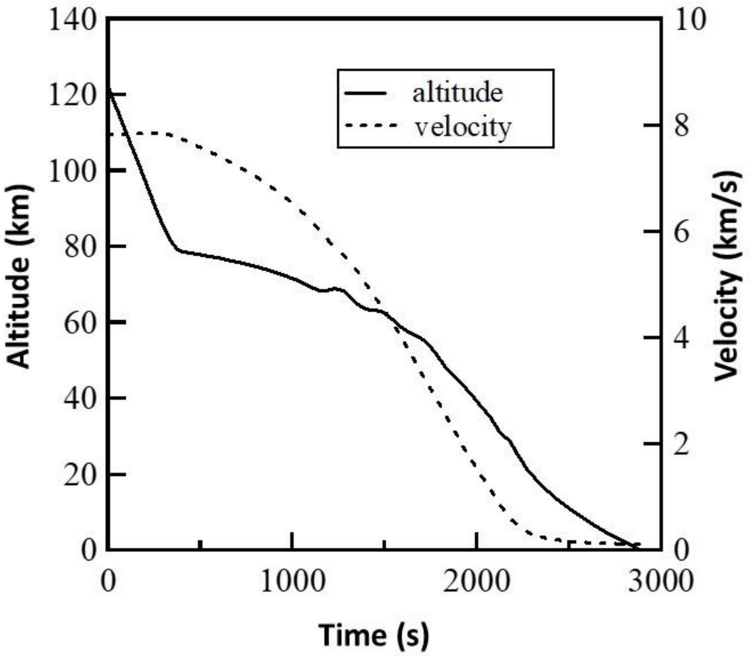
Atmospheric Entry

- Typical altitude for atmospheric entry
  - Earth: 120 km (62 mi.) above the surface
  - Venus: 250 km (155 mi.)
  - Mars: 80 km (50 mi.)

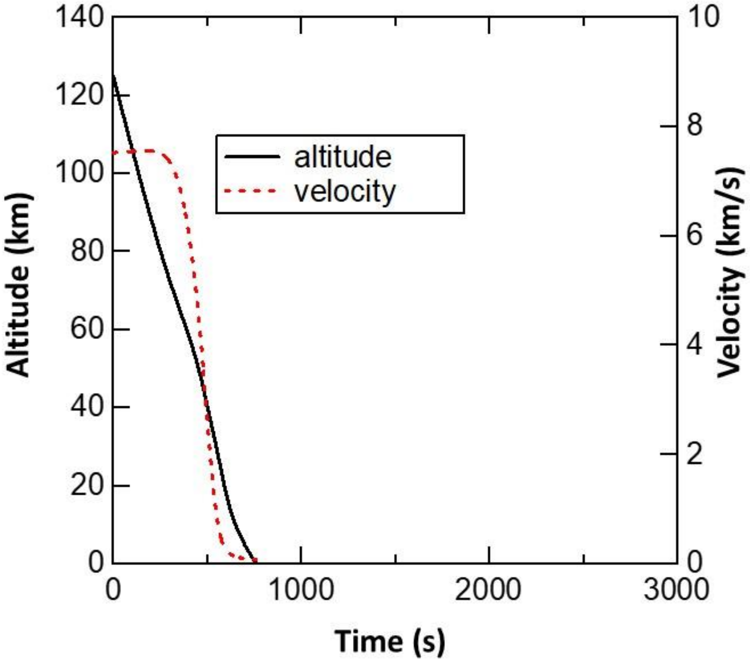
- Typical entry velocity
  - Space Shuttle (Earth): 8.1 km/s (Mach 25) ~18,000 mph
  - Apollo (Earth): 11.1 km/s (Mach 34)
  - Viking (Mars): 8 km/s

Typical Entry Trajectories

Lifting Body



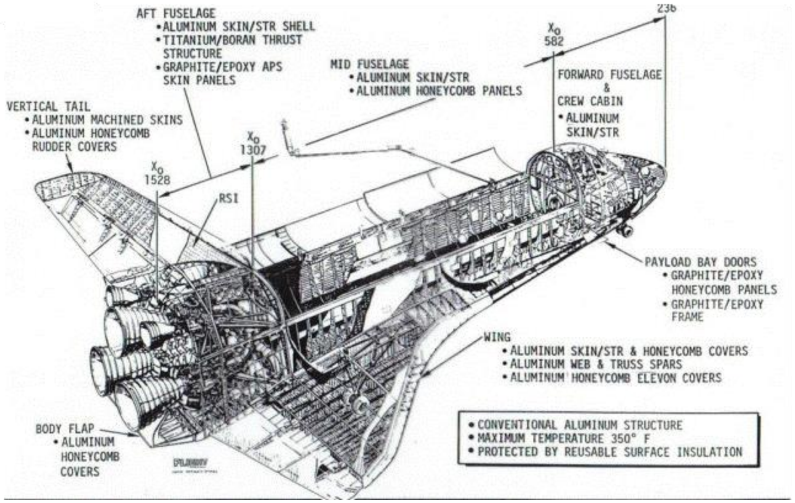
Capsule



- Corresponding maximum heat fluxes:
  - Lifting Body: 10 W/cm^2
  - Capsule: 110 W/cm^2
- **Capsules have a significantly shorter entry time with significantly higher heating rates**

Aerospace Vehicles

- Most aerospace vehicles’ primary structure consists of thin sheets of metal and/or metallic honeycomb panels with composite or metallic facesheets. Space Shuttle consisted of conventional aircraft skin/stringer structure (~0.1-inch thick aluminum)



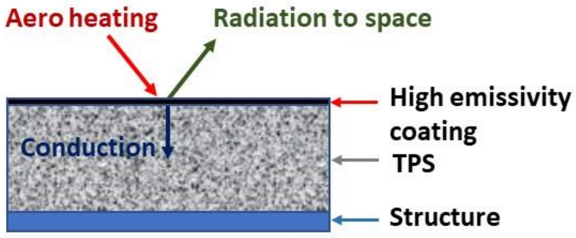
- These metals/composites can not be exposed to high heating rates during entry. Aluminum structure of Shuttle was designed not to exceed 170 ºC during re-entry due to fatigue considerations

- Need to protect the structure from aeroheating using efficient, light-weight insulations, referred to as **Thermal Protection Systems (TPS)**

Types of TPS

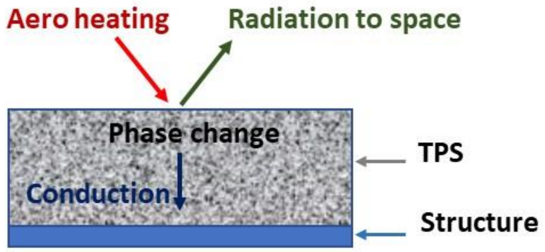
Passive TPS

- Use for lower heating rates for short and long duration entries
- Rigid or flexible ceramic insulations for surface temperatures up to typically 1700 ºC (3000 ºF)
- Radiates significant amount of heat back to space by using high emissivity outer surface
- Slows down heat transfer from surface to underlying structure using insulations



Ablative TPS

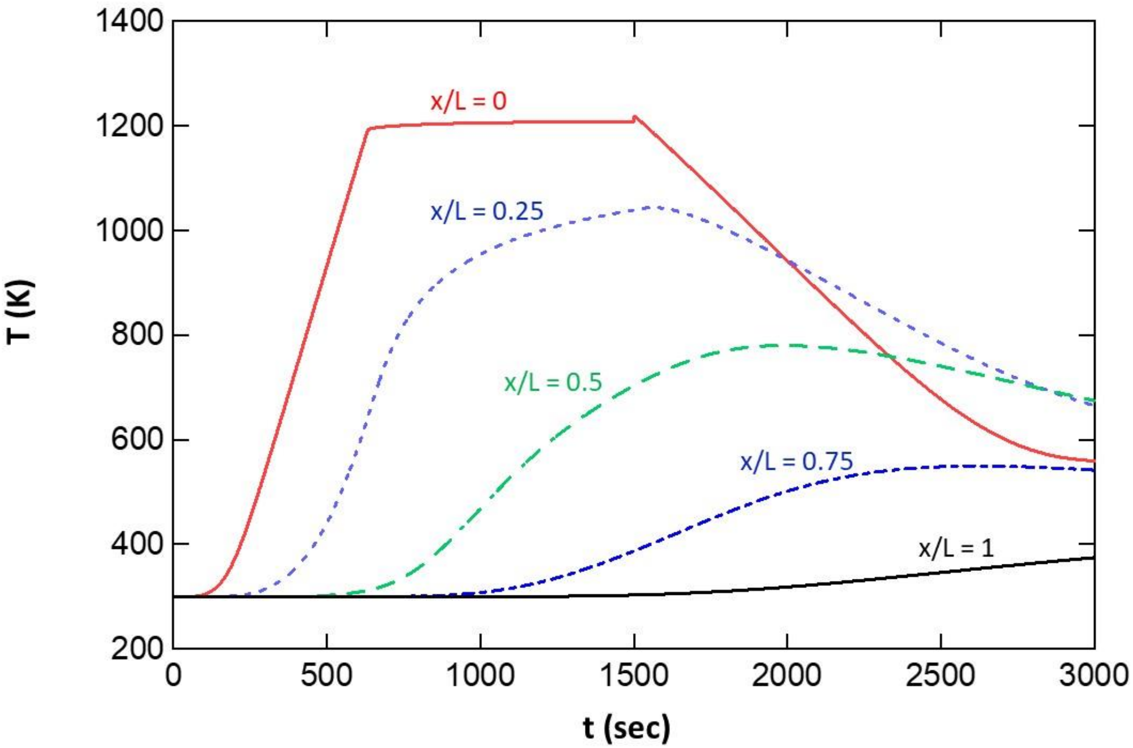
- Use for higher heating rates and short duration ballistic entries
- Typically carbon fibers with phenolic resin
- The resin ablates, most of the aeroheating is consumed in the phase change process, with some heat conducted to underlying substructure

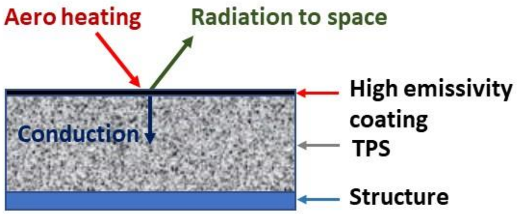


Passive TPS

Typical Temperature Distribution Through TPS thickness for a Glided Reentry

(TPS outer surface [x/L = 0] ; structure [x/L =1])



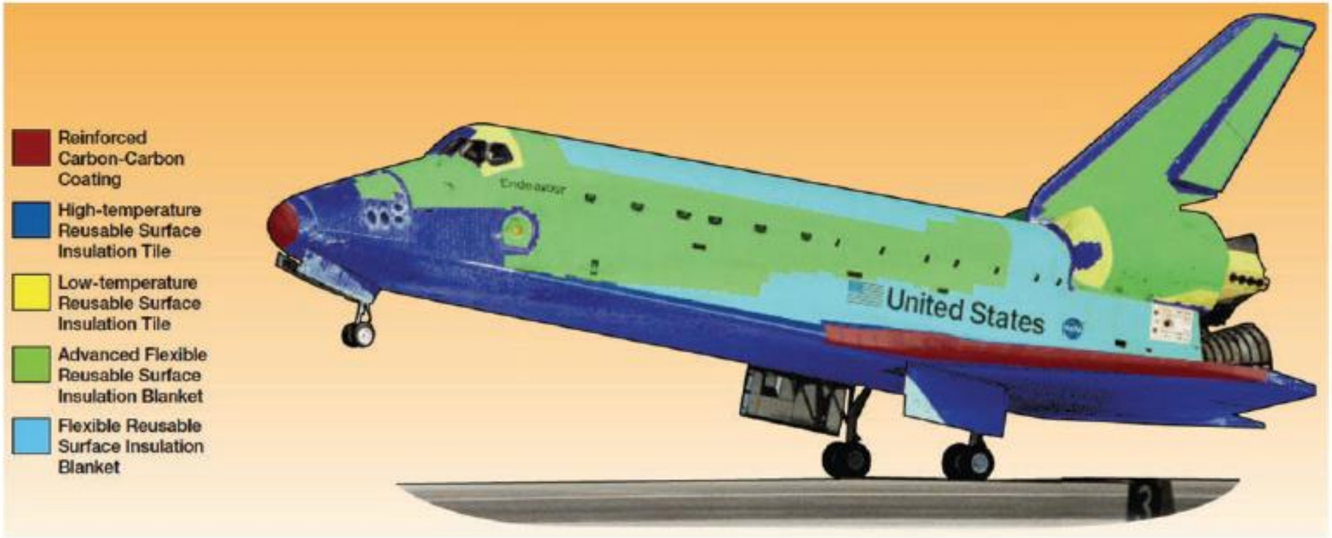


- Passive TPS slows down transfer of heat from outer surface to underlying structure

Passive TPS Applications

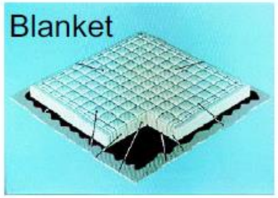
- **Rigid and flexible ceramic TPS**
  - **Space shuttle**
    - Rigid tiles on windward side (2300 ºF)
    - Flexible blankets on leeward side (1000 ºF)

Space Shuttle TPS



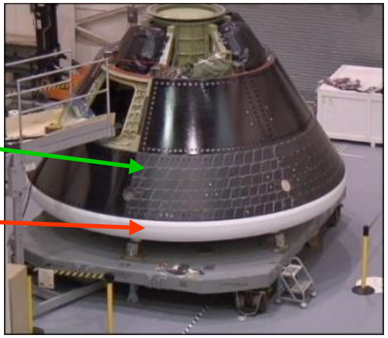
Rigid

Flexible



Passive TPS Applications

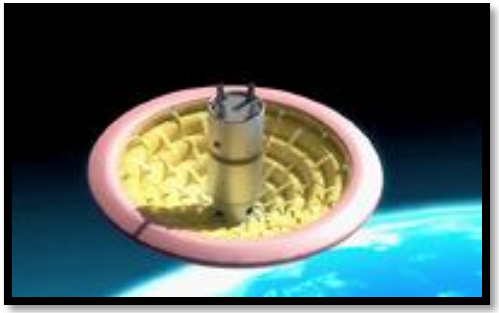
- **Orion**
  - Rigid ceramic tiles on back shell of Orion capsule (2300 ºF)
  - Ablators on windward surface

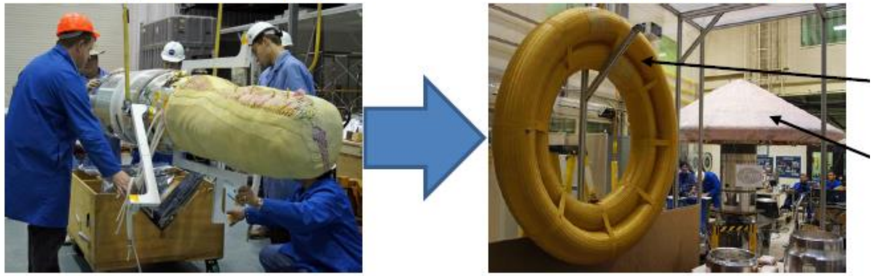


- **Fire shelter** for fire fighters (U.S. Forrest Service), flexible insulation layer- non aerospace (terrestrial) application
  - Existing shelter (M2002):
    - 2 layers of fabric with aluminum foil bonded to fabrics
    - Effective in reflecting radiation when flames are away from shelter
    - Not effective when flame is directly on shelter, since no insulation is used
    - 0.0197 in-thick, 0.35 g/in^2, overall weight: 4.3 lb
  - Worked with U.S. Forest Service to develop a 2nd generation fire shelter that included advanced flexible insulation between the fabrics

Passive TPS Application - HIAD

- Flexible TPS for Hypersonic Inflatable Aerodynamic Decelerator (HIAD)
- Capsules using traditional rigid TPS are limited by the payload shroud on launch vehicle (~5 m)
- HIAD heat shield can be
  - Packed and stowed in payload shroud
  - Inflated and deployed before entry, diameters 5 m - 10 m
- Why use HIAD
  - Mars atmosphere is much less dense than Earth, and is too thin to decelerate the spacecraft quickly
  - HIAD with ≥ 10 m diameter, acts as a giant brake, creates more drag, and decelerates vehicle at higher altitude, while experiencing less intense heating.
  - Ideal for delivering large payloads to Mars





Packaged: D < 22 (in)

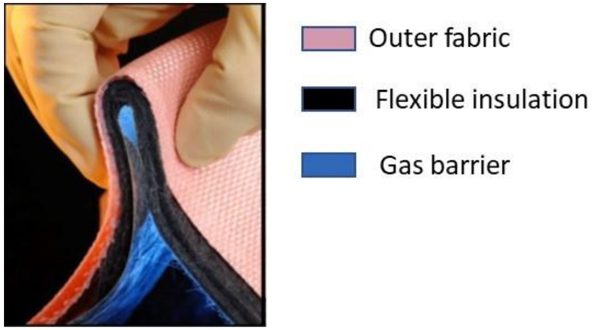
Deployed: D = 10 (ft)

Inflatable rings

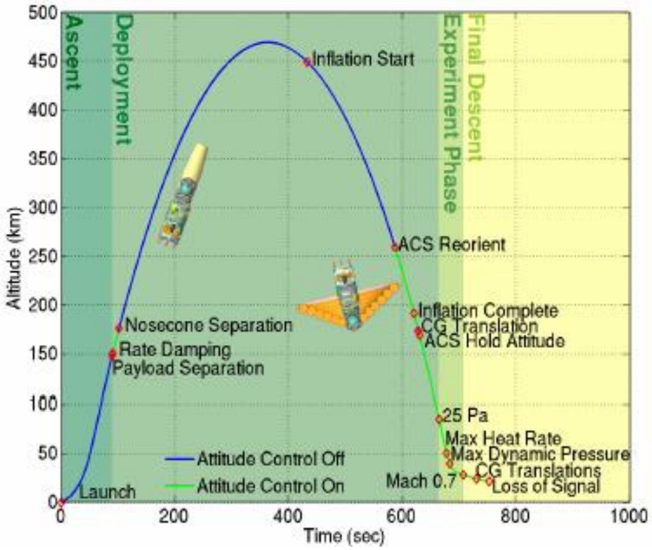
F-TPS installed

Passive TPS Application - HIAD

- **F-TPS requirements for HIAD application**
  - Foldable and durable
  - Thin: less than 25-mm thick
  - Light weight: areal density less than 4 kg/m^2
  - Withstand heat flux up to 100 W/cm^2
  - Handle surface temperatures of the order of 1700˚C, and maintain back face (gas barrier) temperatures at 400˚C or less.



- **Inflatable Reentry Vehicle Experiment (IRVE-3)**
  - Flight using sounding rocket, July 2012
  - 3-m diameter heat shield, re-entry heat flux of 14 W/cm^2



- **Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID)**
  - LOFTID is demonstrating a 6-m diameter inflatable aeroshell entry from low-Earth orbit for heat fluxes up to 30 W/cm^2. Flight scheduled for 2022

Ceramic Insulations

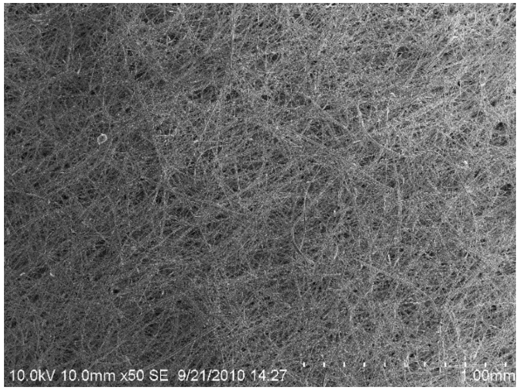
- **Three basic types of ceramic fibers for high temperature applications discussed here**
    - Silica/quartz : up to 2000˚F (1400 K)
    - Alumina: up to 3000˚F (1900 K)
    - Zirconia: up to 4500˚F (2750 K)

- **These insulations consist of fibers, with typical**
    - Fiber diameters of 2 μm to 10 μm
    - Fiber length to diameter ratios of 10 and higher

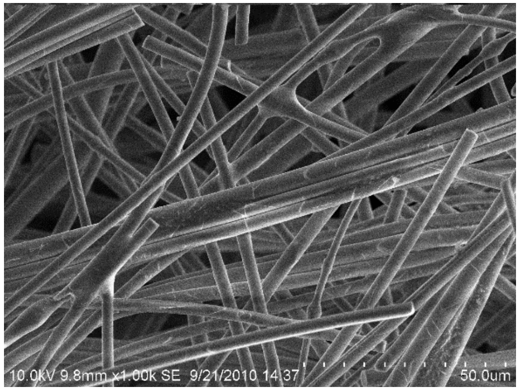
- **Photo and Scanning Electron Microscope (SEM) images of Alumina Paper (APA) insulation at 50 X and 1000 X magnification**
    - APA is a flexible insulation 1.3 mm (0.050 in.) thick with a density of ~100 kg/m^3; average fiber diameter of ~4.5 μm
    - Density of pure alumina is 3300 kg/m^3, so APA **porosity is ~97%.** Significant void volume

APA

APA; 50X Magnification



APA; 1000X Magnification



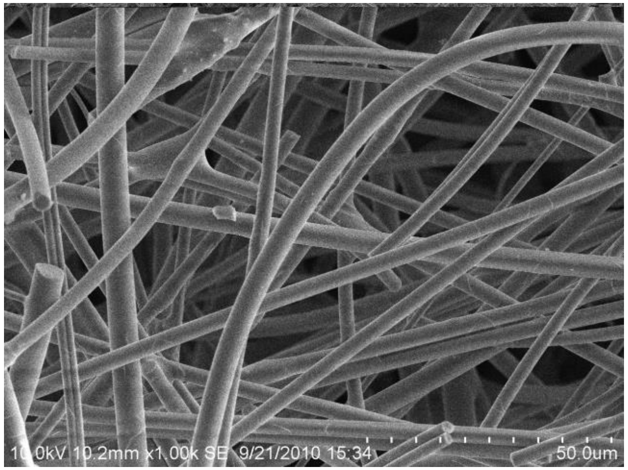
Ceramic Insulations

- **Rigid insulations are sintered and rigidized version of flexible insulations**
  - Fiber diameters of 1 μm to10 μm;
  - Porosity > 90%

- **SEMs of flexible (APA) and rigid (LI-900 tile) insulations at magnification of 1000 reveal similarity in basic structure**

- **Space Shuttle rigid tiles (LI-900) and flexible blankets were both manufactured from the same silica fibers (Q-fiber)**

Flexible APA;
1000 X Magnification

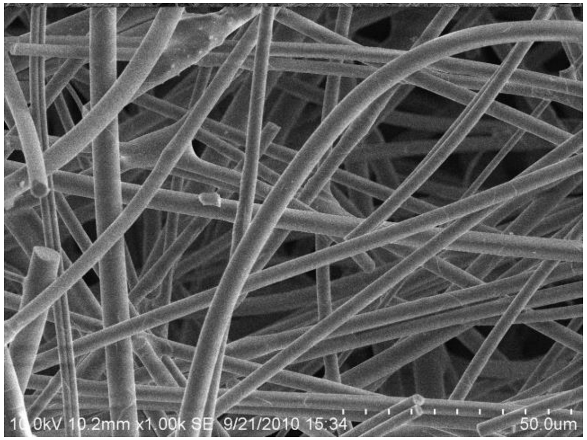


Rigid LI-900 Tile;
1000 X Magnification

Heat Transfer in Insulations

- **Because these insulations are highly porous, three modes of heat transfer are typically present**
  - **Solid conduction** along fibers and at fiber junctions
    - Varies directly with density ; ~ f (ρ)
    - Varies with temperature
  - **Radiation** between fibers
    - Fibers emit, absorb, and scatter radiation
    - Varies inversely with density; ~ f ($1/\rho$)
    - Varies with temperature to the fourth power; ~ f (T^4)

APA; 1000 X



  - **Gas conduction** in void spaces
    - Gas molecule collisions (with each other and with fibers) causing transfer of heat
    - Varies with pressure (altitude) and temperature
    - Varies with gaseous medium in the void (air, nitrogen, carbon dioxide, ...)
  - Natural convection is typically insignificant in insulations with densities of 20 kg/m^3 or higher

Heat Transfer in Insulations

- **Conservation of energy (1-D)** $$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(k_c \frac{\partial T}{\partial y}\right) - \frac{\partial q_r''}{\partial y}$$

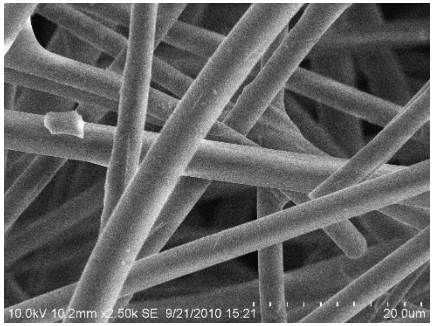
  - Fibers absorb, scatter, and emit radiation
  - Radiation hear transfer in fibrous insulation involves integral equations; difficult to setup and solve
  - Optical thickness is defined as: $\tau = \rho e L$
  - If $\tau >> 1$, then the material is optically thick, and radiant heat transfer can be modeled as a diffusion process

$$q_r'' = -k_r \frac{\partial T}{\partial y}$$

  - Resulting in $$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right)$$
  - Where $$k = k_c + k_r = k_s + k_g + k_r$$
  - The resulting equation is a non-linear partial differential equation that requires numerical solution
  - Will discuss models for k_s, k_r, and k_g

Nomenclature:

c : specific heat
e : specific extinction coefficient
k : thermal conductivity
k_c : conduction (gas + solid) thermal conductivity
k_g : gas thermal conductivity
k_r : radiant thermal conductivity
k_s : solid thermal conductivity
L : thickness
q_r'' : radiant heat flux
t : time
T : temperature
y : spatial coordinate
ρ : density
τ : optical thickness



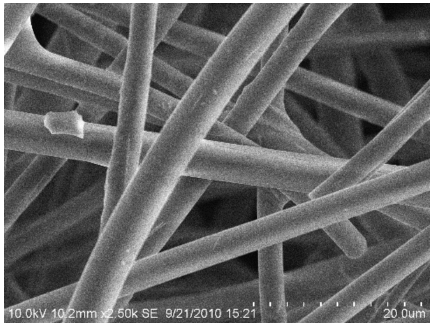
Thermal Model – Solid Conduction

- Exact formulation is nearly impossible due to multiple paths along fibers, and across fiber- to - fiber contacts

- An empirical formula is usually used which relates solid conduction thermal conductivity to bulk material thermal conductivity and fiber volume fraction (density ratio)

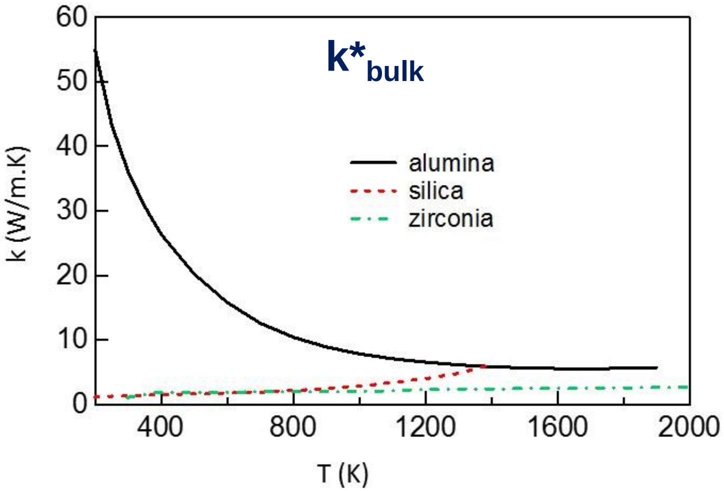
- Unknowns *b & F_s* can be obtained from thermal conductivity measurement of insulation sample in vacuum and cryogenic temperature (100 K – 150 K; insignificant radiation)

APA; 2500 X



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

Nomenclature:
F_s : scalar constant
b : scalar exponent
ρ : density



Thermal Model - Radiation

- Simplified approach assuming optically thick radiation

- Specific extinction coefficient, *e*, is an intrinsic property of fibers and is a function of
  - Temperature
  - Fiber material
  - Fiber diameter, length to diameter ratio
  - Fiber orientation in matrix

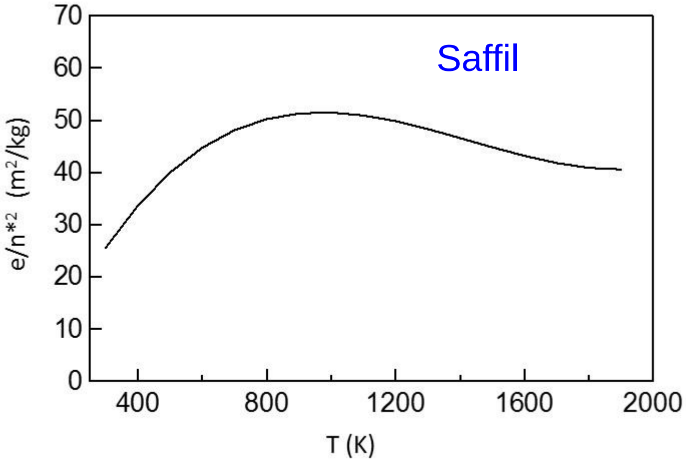
- Effective index of refraction, *n**, is strong function of fiber material, fiber volume fraction, and weak function of temperature; not easily known

- Combined quantity *e/n*²* can be inferred from thermal conductivity measurements of insulation sample in vacuum and at high temperatures

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

Nomenclature:

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

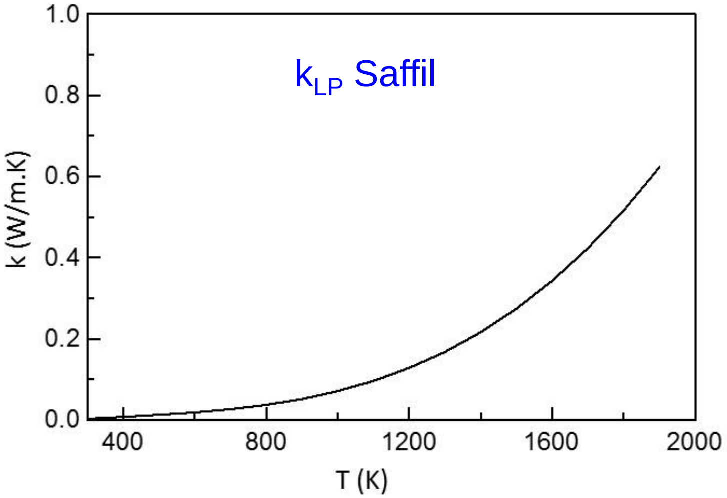


Thermal Model – Combined Radiation and Solid Conduction

- In vacuum (0.001 torr = 1.3 x 10^{-6} atm or lower) one gets the combined contribution of solid conduction and radiation (insignificant gas conduction)

$$k_s + k_r = F_s\left(\frac{\rho}{\rho_{bulk}}\right)^b k^*_{bulk}(T) + \frac{16\sigma T^3}{3\rho\frac{e}{n^{*2}}}$$

Measured *k* of Saffil in Vacuum

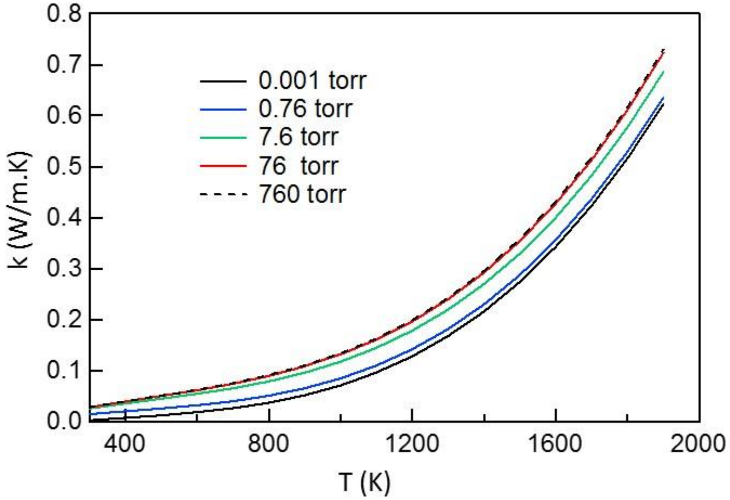


Thermal Model – Gas Conduction

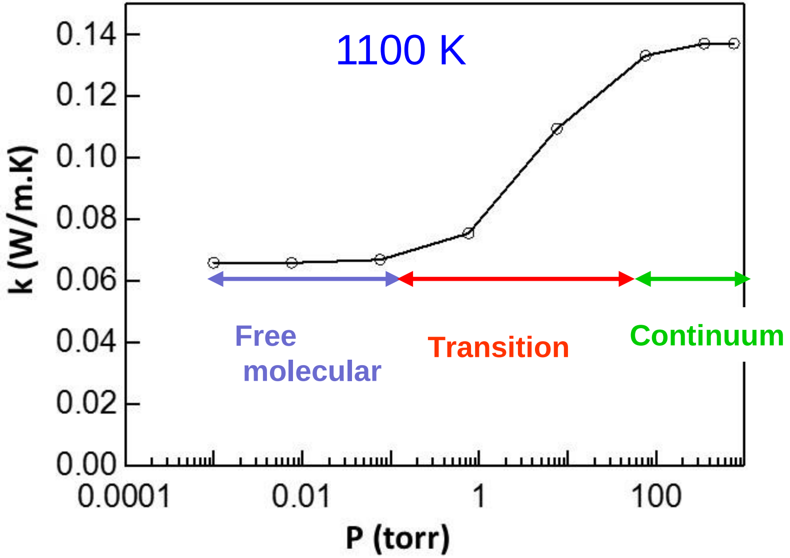
- **As pressure increases, the thermal conductivity increases**

- **Typical variation of thermal conductivity with pressure**
  - No pressure sensitivity at low pressures (free-molecular region)
  - Rise with pressure at intermediate pressures (transition region)
  - No pressure sensitivity at higher pressures (continuum region)
  - The pressure limits for the transition region depend on the characteristic pore size in fibrous insulation

Saffil in Nitrogen Gas



Measured *k* of Saffil as a Function of Pressure



Thermal Model – Gas Conduction

- Gas conduction heat transfer in fibrous insulation is a function of
  - Temperature
  - Pressure
  - Characteristic pore size, L_c
  - Type of gas
- All parameters in these equations are available from literature for any gas. Use semi-empirical formula for L_C as a function of mean fiber diameter and fiber volume fraction

Nomenclature:

D_f : fiber diameter
d_m : gas collision diameter
k_g^* : gas thermal conductivity (1 atm)
k_B : Boltzmann constant
P : pressure
Pr : Prandtl number
α : thermal accommodation coefficient
γ : specific heat ratio
L_c : characteristic pore size

$$k_g = \frac{k_g^*}{1 + 2\frac{2-\alpha}{\alpha} \cdot \frac{2\gamma}{\gamma+1} \cdot \frac{1}{\Pr} \cdot Kn}$$

Knudsen No: $Kn = \frac{L_0}{L_c}$

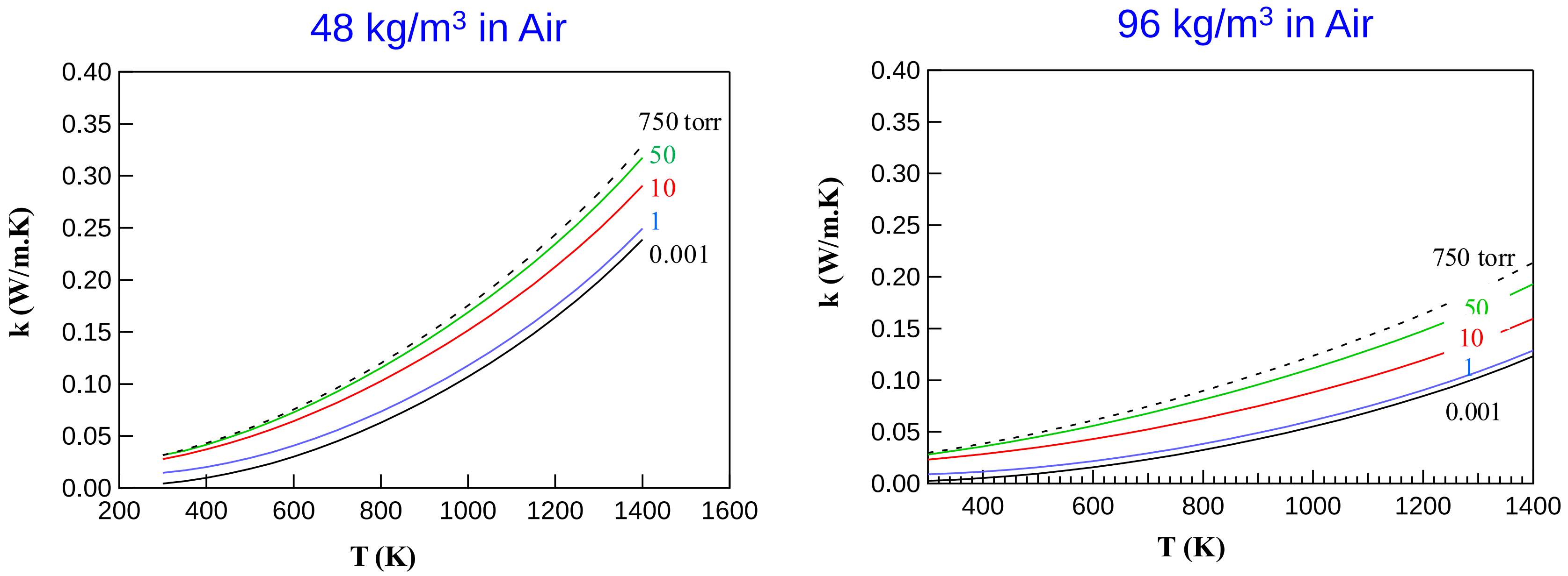
Gas Mean Free Path: $L_0 = \frac{k_B \cdot T}{\sqrt{2} \cdot \pi \cdot d_m^2 \cdot P}$

$$L_c = \frac{\frac{\pi}{4} D_f}{\frac{\rho}{\rho_{bulk}}}$$

Thermal Performance Characteristics – Density

- **Thermal conductivity of fibrous insulation generally decreases with increasing density**
  - Solid conduction increases with increasing density, but radiation decreases with increasing density

Thermal Conductivity of Q-fiber as a Function of Temperature and Pressure in Air at two Densities


48 kg/m^3 in Air

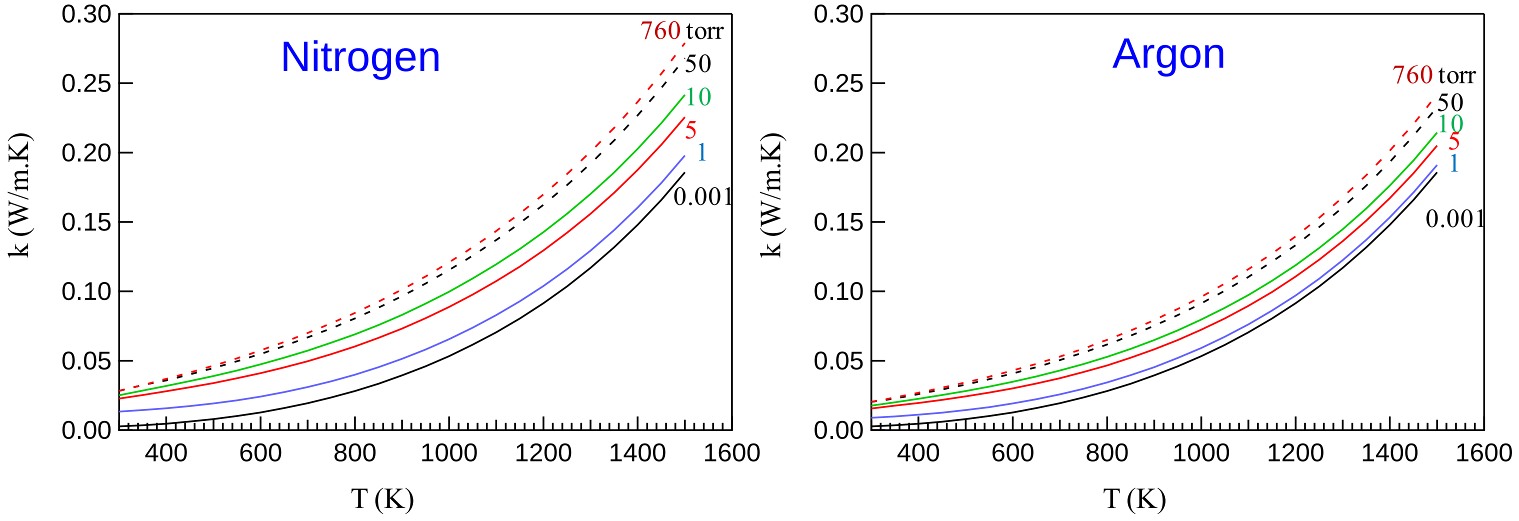
96 kg/m^3 in Air

- **Thermal conductivity is lower for sample with higher density**

Thermal Performance Characteristics – Gas Type

- **Thermal conductivity is a function of gaseous medium**
  - Argon has the lowest thermal conductivity compared to air, nitrogen, carbon dioxide
  - Helium has the highest thermal conductivity and overwhelms all other modes of heat transfer in fibrous insulation

Thermal Conductivity of APA as a Function of Temperature and Pressure in Nitrogen and Argon Gases



- **Thermal conductivity is lower in argon**

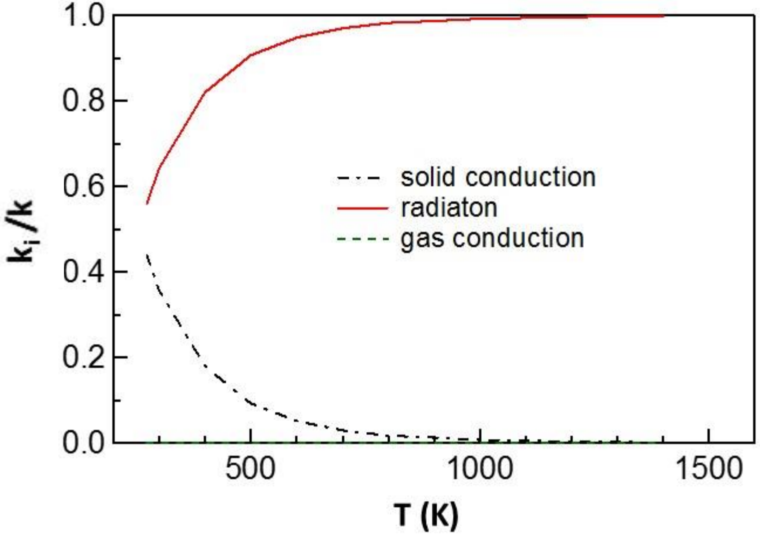
Relative Magnitude of Heat Transfer Modes – Flexible Insulation – Saffil at 96 kg/m³

- **Ratio of thermal conductivity for each mode to total thermal conductivity (sum of all three ratios equals unity)**

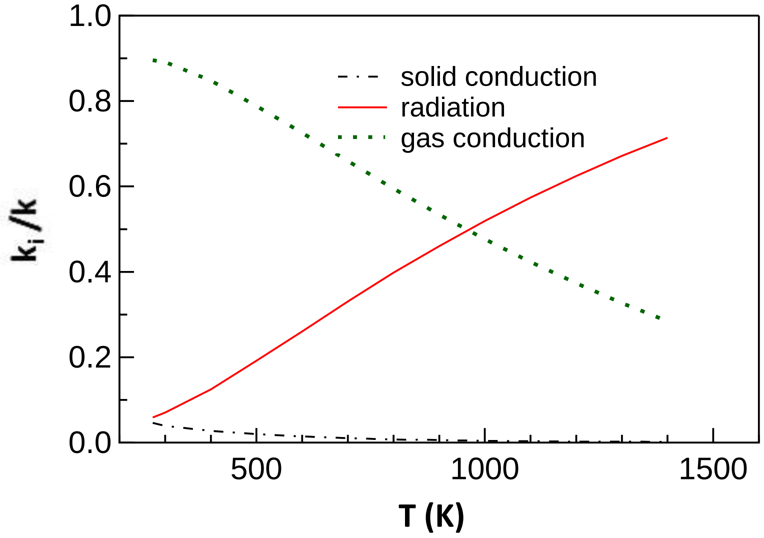
$$k = k_s + k_g + k_r$$

Plotting k_s/k ; k_g/k ; k_r/k

P =0.001 torr (1.3 x 10^{-4} kPa)



P =10 torr (1.3 kPa)



- Solid conduction is insignificant at higher temperature and pressures
- Low P: Radiation is dominant
- Intermediate P: Both radiation and gas conduction important
  - Gas conduction dominant at lower T
  - Radiation dominant at higher T

P (torr)	Altitude (km)
0.001	93 (300,000 ft)
10	30 (100,000 ft)
760	sea level

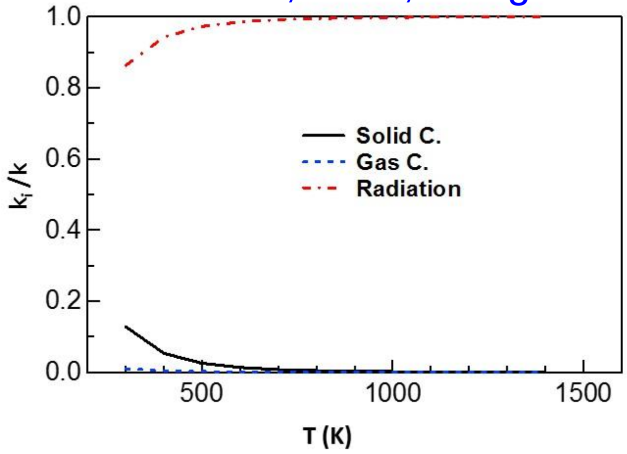
Relative Magnitude of Heat Transfer Modes – Flexible vs. Rigid

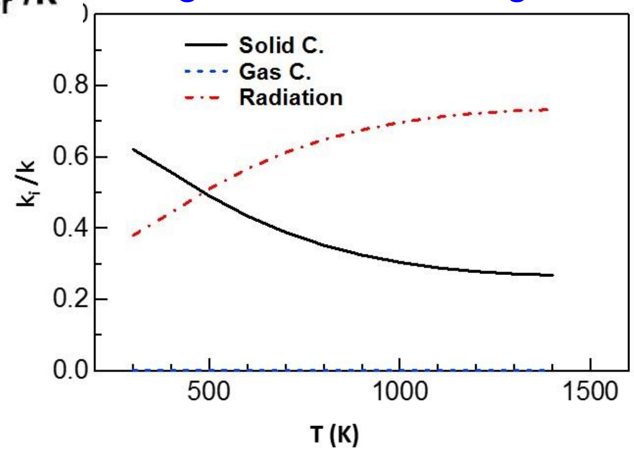
Flexible, Saffil, 48 kg/m^3

Plotting k_s/k ; k_g/k ; k_r/k

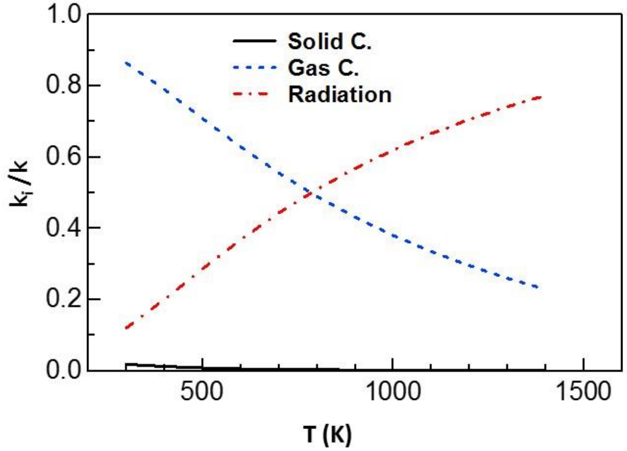
Rigid, LI-900, 144 kg/m^3

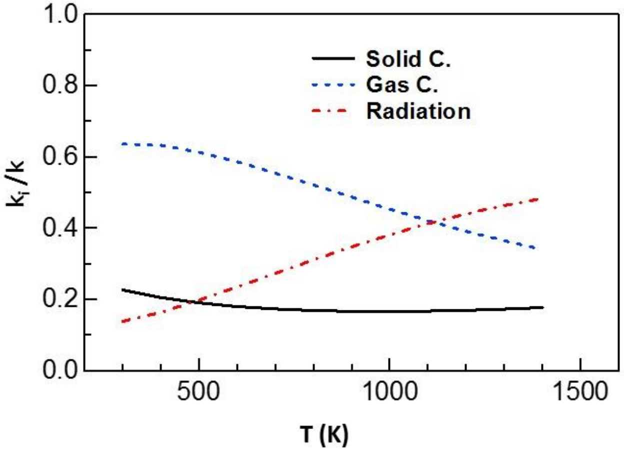
0.001 torr





50 torr





- Flexible insulations
  - Solid conduction is insignificant
  - Low P: Radiation is dominant
  - High P: Radiation is important at higher ***T***; Gas conduction at lower ***T***
- Rigid insulations
  - **Solid conduction is significant**
  - Low P: Radiation is dominant at higher ***T***
  - High P: Radiation is important at higher ***T***; Gas conduction at lower ***T***

Figures of Merit for Insulations

- **The product of density and thermal conductivity, ρk, is a figure of merit for insulations for a minimum mass solution***
  - For steady-state applications, minimizing ρk minimizes required insulation mass
  - For transient applications minimizing $\frac{\rho k}{\sqrt{c_p}}$ minimizes required insulation mass

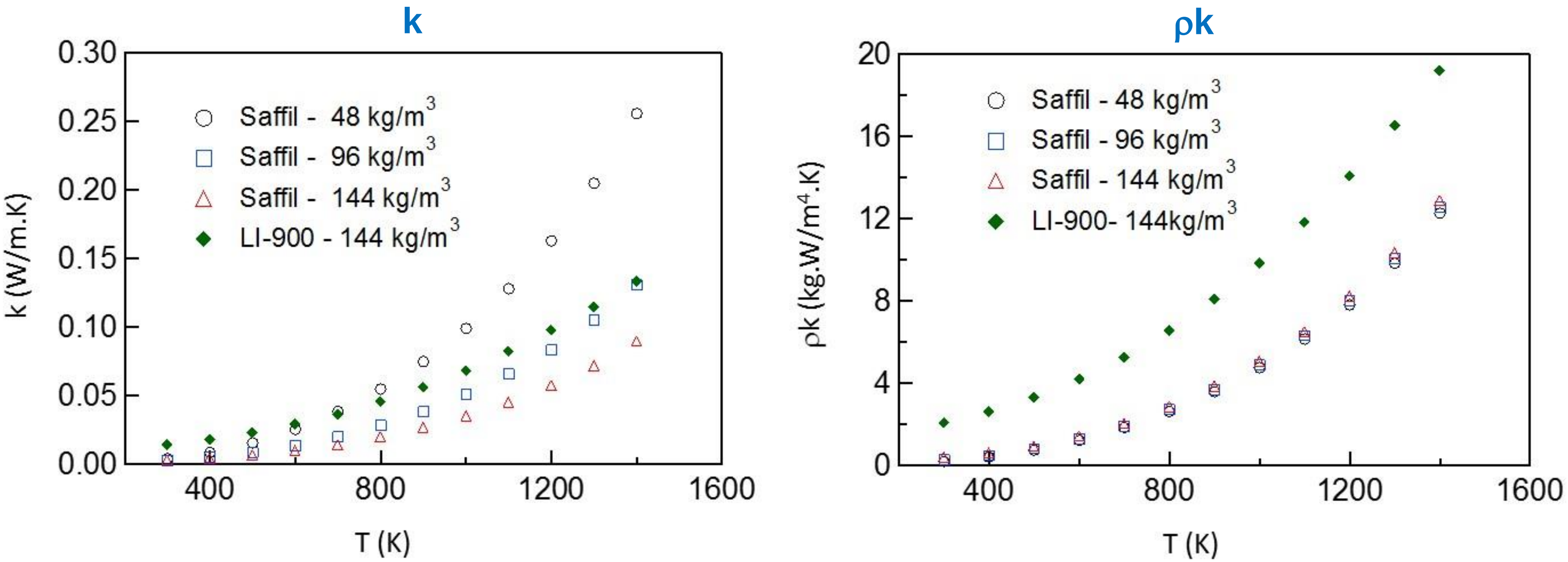
c_p : specific heat

- **ρk is also an appropriate figure of merit for comparing performance of insulations with different densities**

* Minimum mass solution may not necessarily be an optimum solution in presence of thickness constraints

Comparison of Flexible and Rigid Insulations

Saffil (flexible) and LI-900 (rigid) at 0.001 torr



- **Comparing *k***
  - Saffil *k* increases with decreasing density, especially at higher temperatures (due to radiation)
  - Saffil at 96 kg/m^3 and 144 kg/m^3 has lower *k* compared to LI-900 at 144 kg/m^3
- **Comparing *ρk***
  - Data for various Saffil densities collapse; all better than LI-900
  - Flexible insulations are more thermally efficient compared to rigid insulations in vacuum

Improving Thermal Performance

- Need to minimize ρk

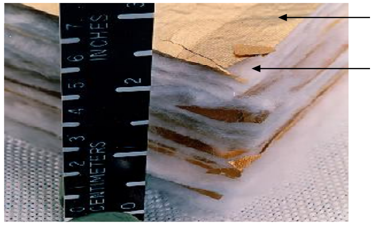
- Solid conduction is usually the least significant mode of heat transfer at higher temperatures, no need to optimize solid conduction

- Radiation is the dominant mode of heat transfer at high temperatures and at lower pressures; strategies have been successfully used to attenuate this mode of heat transfer

- Gas conduction is a significant mode of heat transfer at intermediate and high pressures; strategies have been successfully implemented to minimize this mode

Attenuating Radiation

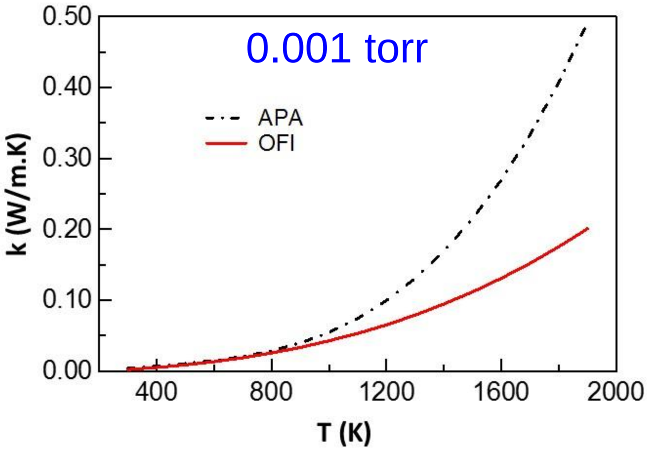
- **Use reflective foils – high temperature multi-layer insulation (MLI)**
  - Thin reflective foils made of high temperature materials coated with high reflectance coating (gold, platinum, etc.) separated by fibrous insulation spacers



Gold Coated Foil

Fiberous Insulation Spacer

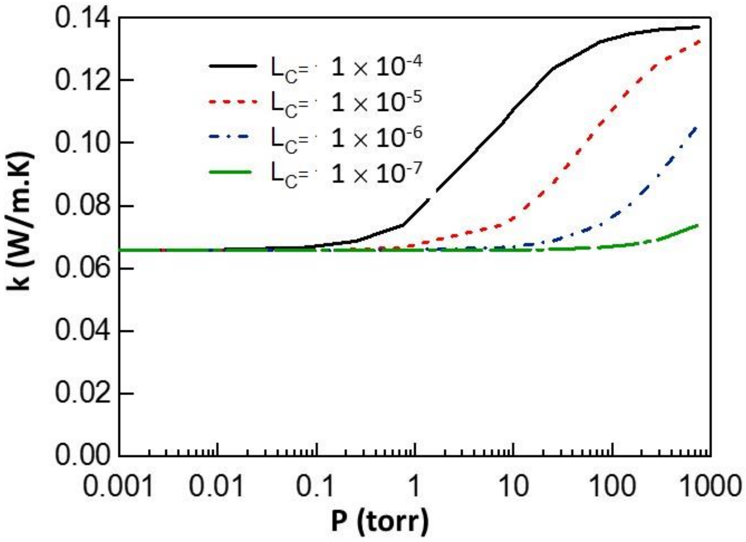
- **Use Opacifiers**
  - Use opacifer particles embedded in insulation
  - Shape, size, material of opacifiers; and distribution of opacifiers in fibrous insulation mat are critical factors
  - Type of opacifiers: Copper, Titanium oxide, Silicon carbide, Molydisilicide
  - One such insulation is OFI (Opacified Fibrous Insulation) manufactured by opacifying various flexible insulations

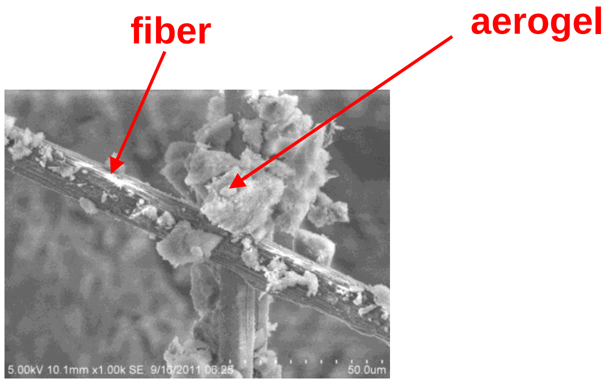


k(OFI) < 0.5 k(APA) at 1900 K (both at ~99 kg/m^3)

Gas Conduction Attenuation

- **Fibrous insulation pore size is typically 10^{-4} m**
- **As pore size decreases, gas conduction kicks in at higher pressures, and will plateau at higher pressures**
- **Aerogels have small pore size (10^{-6} m or lower); therefore, minimize gas conduction**
  - Aerogels are fragile and transparent to radiation
  - Install aerogel in fiber matrix to gain strength (enable flexibility and better handling) and reduce radiation transmission
- **Various fiber reinforced aerogels using silica (700˚C) or alumino-silicate aerogel (1100˚C) in silica or alumina fiber mats are available**

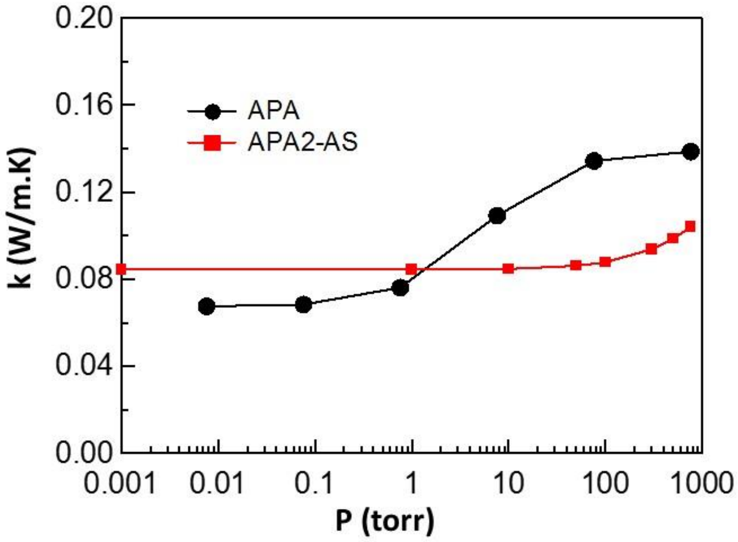


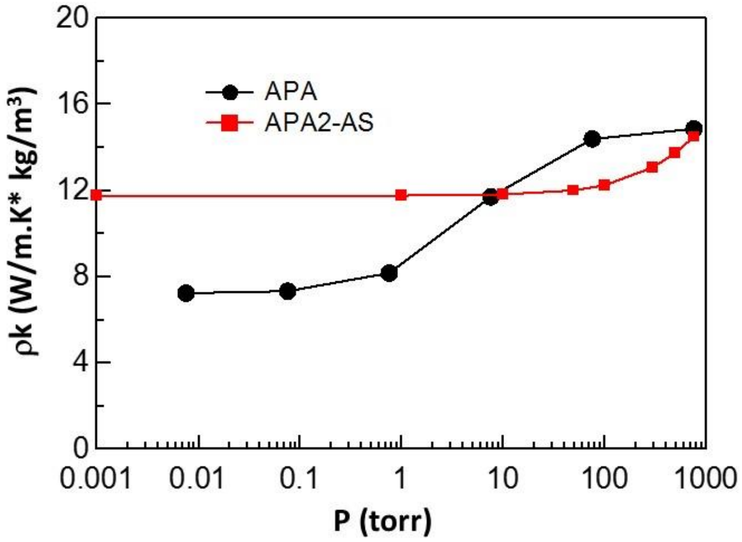


Fiber Reinforced Aerogel

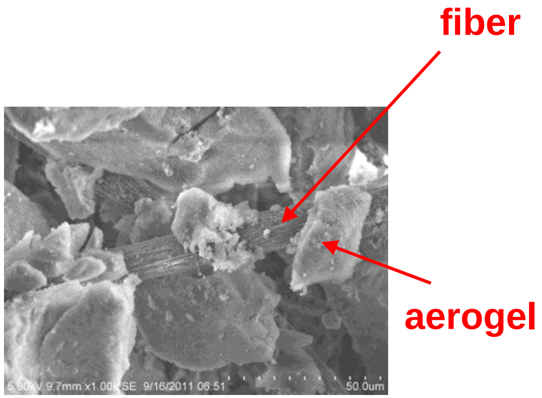
Alumina paper (APA) vs. alumino-silicate aerogel in alumina paper (APA2-AS); 1100 K

APA: 107 kg/m^3; APA2-AS: 139 kg/m^3



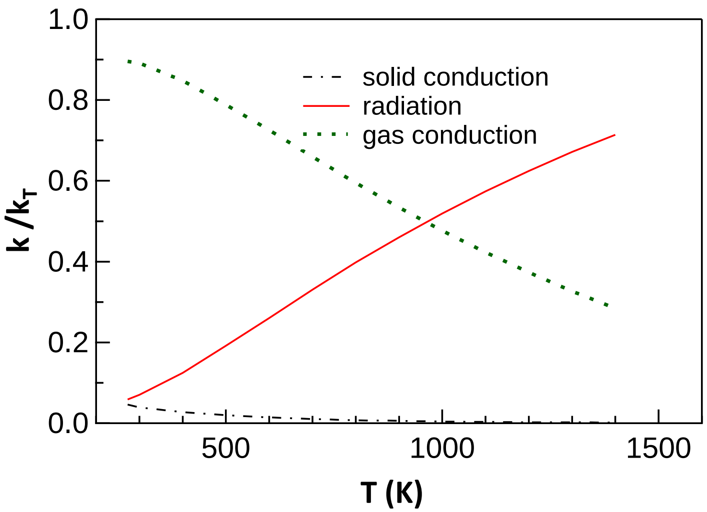


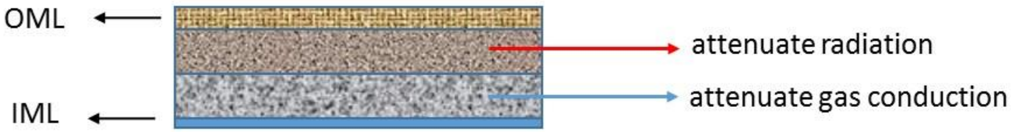
- **Comparison of fiber reinforced aerogel with APA**
  - k(APA2-AS) is flat up to 100 torr and is lower than k(APA) between 10 torr and 760 torr
  - k(APA2-AS) is higher than k(APA) at lower pressures: presence of aerogel particles around fibers cause an increase in radiation heat transfer
  - ρk (APA2-AS) is still lower than ρk(APA) between 10 torr and 760 torr, but advantage is not as significant



Improving TPS Thermal Performance

- **If application is at low pressures (P ≤ 1 torr) with T ≥ 400 K radiation is the dominant mode of heat transfer throughout the insulation thickness: attenuate radiation heat transfer using opacifiers or high temperature MLI**
- **If application is at high temperatures (T ≥ 800 K) and intermediate/high pressures (P ≥ 1 torr)**
  - Radiation is dominant at higher temperatures close to Outer Mold Line (OML): attenuate radiation in layers next to OML using opacifiers or high temperature MLI
  - Gas conduction is dominant at lower temperatures close to Inner Mold Line (IML): attenuate gas conduction in layers next to IML using aerogels





Concluding Remarks

- Discussed atmospheric entry and need for thermal protection systems
- Provided a brief overview of high-temperature ceramic insulations
- Discussed heat transfer in insulations; a simple high-fidelity thermal model; insight into significance of different heat transfer modes
- Described figures of merit for insulations, and methods to achieve optimized performance

Job Opportunities at NASA

- **Internships at NASA for undergraduate and graduate students:** **https://intern.nasa.gov/**
  - Intern: Semester-long internship. Postings in above link
  - Pathways: Multi-semester program that can lead to permanent employment. Postings in USA Jobs website:
    https://www.usajobs.gov/search/results?d=NN&hp=student&p=1
- **NASA job opportunities posted at USA Jobs website**
- **NASA Research Centers**
  - Ames (Mountain View, CA); Glenn (Cleveland, OH); Langley (Hampton, VA)
- **NASA Flight and Space Centers**
  - Armstrong (Lancaster, CA); Goddard (Greenbelt, MD); Johnson (Houston, TX), Marshall (Huntsville, AL); Kennedy (Cape Canaveral, FL)
- **Others:**
  - Jet Propulsion Laboratory (Pasadena, CA), …