Thermal Protection Systems for Reusable Launch Vehicles

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Short Course: Thermal Control Hardware

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OUTLINE

• Introduction
• Fundamentals of Aerodynamic Heating
• Approaches to Thermal Protection
• Metallic TPS
• Current TPS Research
• Integrated Multifunctional Structures
INTRODUCTION
INTRODUCTION

KEY TECHNOLOGIES FOR REUSABLE LAUNCH VEHICLES

Critical RLV Technologies
- More efficient propulsion
- Reusable cryogenic fuel tanks
- Improved thermal protection systems

TPS for RLV’s
- Large vehicle surface area
- Integration with vehicle structure
- Long life
- Rapid turnaround

TPS Design Goals
- Increase
  - Operability
  - Durability
  - Capability
- Decrease
  - Mass
  - Cost
  - Risk
INTRODUCTION

TPS DEVELOPMENT: A MULTIDISCIPLINARY CHALLENGE

Required Disciplines

- Aerothermodynamics
- Structures
- Materials
- Heat transfer
- Vehicle systems
- Acoustics
- Fatigue and creep
- Panel flutter
- Manufacturing
- Testing

Interactions

- Thermal-structural
  - Structural support often undesirable heat short
  - Thermal expansion -> stresses and deformations
  - Material properties change with temp. & press.
- Surface deformations may affect aerothermal heating
- Chemical changes (oxidation) degrade material
- Sizing TPS and structure separately not optimal
AERODYNAMIC HEATING FUNDAMENTALS
AERODYNAMIC HEATING FUNDAMENTALS

AERODYNAMIC HEATING OF TPS

Flow Phenomena
• Free molecular to continuum flow regimes
• Shock waves, shock interactions
• Convective and radiative heating
• Laminar to turbulent boundary layer transition

Interaction with Vehicle Surface
• Radiation equilibrium temperature
• Integrated heat load
• Surface emittance, catalysis and oxidation
• Surface roughness, steps, gaps, bowing

Vehicle Geometry
• Windward and leeward surfaces
• Stagnation region, leading-edge radius

Trajectory
• Rocket vs. airbreathing propulsion
• Quick, hot vs. longer, cooler trajectories

Heating Prediction
• Engineering codes
• Computational aerothermodynamics
AERODYNAMIC HEATING FUNDAMENTALS

FLOW REGIMES

GEOMETRIC ALTITUDE, Z, FT

FREE MOLECULAR FLOW
NEAR FREE MOLECULAR FLOW
SHOCK FORMS
TRANSITION LAYER
FULLY MERGED LAYER
INCIPIENT MERGED LAYER
VISCOS LAYER
BOUNDARY LAYER

SUPERCIRCULAR REENTRY
ORBITAL REENTRY

FLIGHT VELOCITY, V, FT/SEC

6X10^5
RAREFIED FLOW
CONTINUUM FLOW
AERODYNAMIC HEATING FUNDAMENTALS

SHOCK WAVES

Normal Shock
• Supersonic to subsonic flow ($M_2 > 1$)
• Increase in pressure and temperature

Oblique Shock
• Parallel and normal components
• Calculate pressure and temperature changes for normal component
• $M_2$ can be supersonic
AERODYNAMIC HEATING FUNDAMENTALS

CONVECTIVE AND RADIATIVE HEATING

Radiation

Convection

Vehicle surface

Graph showing the relationship between Maximum Non-ablative heat transfer (W/cm²) and Velocity (km/s). The graph includes data points for various spacecraft missions, such as Mars Pathfinder, Stardust (Earth), Mars Microprobe, Mars 2001 Orbiter, Neptune Orbiter, Viking (Mars), Shuttle, Apollo, Galileo (Jupiter), Huygens (Titan), Pioneer-Venus, and Fire II (Earth).
Both oxygen and nitrogen can be dissociated when passing through a shock wave.

If the vehicle surface acts as a catalyst for recombination, additional surface heating can result.
Laminar-to-Turbulent Boundary Layer Transition

- Flow is usually laminar for high altitude, high enthalpy flow
- Aerodynamic heating can be several times higher for turbulent flow
- Rough surface can cause premature transition to turbulent flow
- TPS design seeks to minimize surface roughness
AERODYNAMIC HEATING FUNDAMENTALS

PROPELLION EFFICIENCIES

Specific Impulse, s vs Mach Number chart

- Turbojets
- Hydrogen
- Ramjets
- Hydrocarbons
- Scramjets
- Rockets
- Hydrogen
- Hydrocarbons

Chart shows performance characteristics across different Mach numbers.
AERODYNAMIC HEATING FUNDAMENTALS
PROPULSION IMPACTS RLV CONFIGURATION

Rocket

Airbreathing
AERODYNAMIC HEATING FUNDAMENTALS
HEATING VARIATION OVER A VEHICLE

Leeward Surface

Windward Surface
APPROACHES TO THERMAL PROTECTION
APPROACHES TO THERMAL PROTECTION

TYPES OF THERMAL PROTECTION SYSTEMS

PASSIVE:
- Heat Sink Structure
- Hot Structure

SEMI-PASSIVE:
- Working Fluid
- Heat Pipe

ACTIVE:
- Transpiration Cooling
- Film Cooling
- Convective Cooling

Preferred RLV approach

Choose the simplest and/or lightest that works
APPROACHES TO THERMAL PROTECTION

HEAT SINK STRUCTURE

X-15 WING STRUCTURE

Range of Applicability Depends on:
• Integrated heat load
• Structural heat capacity
• Allowable structural temperature limits
• Structural heat loss mechanisms

• The heat sink approach is generally practical for only very short heating pulses
• Not appropriate for RLV’s

HEAT STORAGE IN STRUCTURES

Material

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat Capacity, BTU/lbm</th>
</tr>
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<tbody>
<tr>
<td>Aluminum</td>
<td></td>
</tr>
<tr>
<td>Carbon/carbon</td>
<td></td>
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<tr>
<td>Beryllium</td>
<td></td>
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<tr>
<td>Encapsulated Phase Change Material</td>
<td></td>
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<tr>
<td>Graphite polyimide</td>
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<tr>
<td>Iron</td>
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<tr>
<td>Nickel</td>
<td></td>
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<tr>
<td>Titanium</td>
<td></td>
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<tr>
<td>Chromium</td>
<td></td>
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<tr>
<td>Carbon/SiC</td>
<td></td>
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</tbody>
</table>

Initial Temperature = 80°F

Temperature, °F

0  200  400  600  800  1000  1200

Material Heat Capacity, BTU/lbm
APPROACHES TO THERMAL PROTECTION

HOT STRUCTURE

Hot Structure:
• Radiation equilibrium at surface ($q_{in} = q_{out}$)
• Can reach steady state
• High temperature material
• Temp. gradients, thermal stresses
• Interfaces to cooler structures
• Large integrated heat loads

Applications:
• Supersonic cruise
• Lightly loaded RLV structures (control surfaces)
APPROACHES TO THERMAL PROTECTION

TPS INSULATING STRUCTURE

Surface acts like hot structure
- Near radiation equilibrium temperature
- Reradiates most of incident heat
- Allows some heat to reach structure

Structure acts like a heat sink
- Integrated heat load through TPS
- Structural heat capacity
- Allowable structural temperature limits
- Structural heat loss mechanisms

Applications:
- Space Shuttle Orbiter
- Future RLV’s
APPROACHES TO THERMAL PROTECTION

TPS CONCEPTS VARY OVER VEHICLE SURFACE
APPROACHES TO THERMAL PROTECTION

HEAT PIPE

Heat Pipe Operation
- Sealed tubes containing working fluid
- Saturated wick lines interior
- Localized heating evaporates liquid
- Vapor travels to cooler region and condenses
- Liquid returns to hot spot through wick
- No pumps, sensors, or controls required

Heat Pipe Applications
- Diffuses a local hot spot
- Wing leading edges
- Nose caps

Superalloy heat pipe leading edge for Shuttle wing

Operating liquid metal heat pipe

Carbon/carbon heat pipe leading edge for NASP wing

Carbon/carbon structure

Mo-Re heat pipe, Lithium working fluid
**APPROACHES TO THERMAL PROTECTION**

**ABLATION**

**Ablator Operation**
- Partially consumed by heating
- Heat absorbed as gases generated
- Gases block convective heating
- Ablator is also insulator
- Surface recedes with time
- Non-reusable

**Ablator Applications**
- Can accommodate very high heating rates
- Hot side of ballistic reentry capsules (Apollo)
- Planetary probes
- Missile nose caps
- Less attractive for large areas on RLV’s
approaches to thermal protection

transpiration/film cooling

transpiration and film cooling

- coolant is injected into the boundary layer
  - porous surface – transpiration
  - discrete slots – film cooling
- prevents direct contact with hot flow
- removes heat from structure
- can accommodate large heating rates

applications of transpiration and film cooling

- not mass-efficient for large areas
- complex system, have to carry coolant
- localized areas
- nose tips
- possibly sharp leading edges
- airbreathing engine structures
APPROACHES TO THERMAL PROTECTION

CONVECTIVELY COOLED STRUCTURE

Convectively Cooled Structure
- Coolant flows through passages in the structure
- Surface below radiation equilibrium temperature
- Large heat flux through outer skin into coolant
- Heat in coolant must be removed
- Can accommodate large heat fluxes
- Can accommodate large integrated heat loads
- Requires pumps, controls and plumbing

Convectively Cooled Structure Applications
- Mainly considered for airbreathing RLV’s
  - High ascent heating
  - Fuel available for coolant/heat sink on ascent
- National AeroSpace Plane external structural skin
- Engine structures

NASP actively cooled panel
METALLIC THERMAL PROTECTION SYSTEMS
METALLIC TPS
MOTIVATION FOR DEVELOPMENT

Candidate TPS

- Ceramics
  - Tiles
  - Blankets
- Ceramic Matrix Composites (CMC’s)
- Metallic panels

Metallic TPS

- Ductile/damage resistant
- Mass efficient foil structures/insulations
- Much lower maintenance
- No re-waterproofing between flights
METALLIC TPS
TECHNOLOGY DEVELOPMENT

MATERIALS CHARTERIZATION/IMPROVEMENT

METALS
• Structural properties
• Surface properties

INSULATIONS
• Measured thermal properties
• Validated analysis
• Optimized combinations

CONCEPT DEVELOPMENT

CONCEPT DEFINITION
• Conception, design and analysis
• Vehicle integration

CONCEPT EVALUATION
• Coupon tests
• Panel tests
METALLIC TPS: MATERIALS

HIGH PERFORMANCE METALS FOR TPS

Temperature, °F

Relative
Strength

Oxidation Stability

Oxidation Protective Coatings Required

Temperature, °C

Titanium Composites

Conventional Titanium Alloys

Superalloys

Advanced Titanium Alloys

γ−Titanium Aluminide Alloys

Dispersion Strengthened Superalloys

Refractory Metals

Aluminum alloys

Aluminum Composites
METALLIC TPS : MATERIALS

SURFACE PROPERTIES

Desired Surface Properties

- Oxidation protection
- Emittance > 0.8
- Catalytic Efficiency - low as possible
- Reflectance - high in 1-2.5 μm range

Effects of Emittance and Catalytic Efficiency

Flow Conditions
Mach No. = 3.7
Enthalpy = 7.5 MJ/kg
P_{wall} = 850 Pa

Achieving desired surface properties may require coatings.
METALLIC TPS: MATERIALS
IMPROVED INTERNAL INSULATIONS

OBJECTIVES

• Characterize current and proposed insulations as function of temperature and pressure
• Develop and verify analytical tools to predict insulation performance
• Design, fabricate and verify performance of insulations optimized for RLV
• Incorporated improved insulations into TPS for reduced mass

CANDIDATE INSULATIONS

• FIBROUS INSULATIONS
  – Q-felt (quartz fibers)
  – Saffil (alumina fibers)
  – Coated saffil (reflective coatings on fibers)
• MULTILAYER INSULATIONS
  – Internal multiscreen insulation (IMI)
  – U.S. multilayer insulation (SBIR)
• OTHER INSULATIONS
  – Aerogel
  – Optimized combinations
METALLIC TPS: CONCEPTS

EARLY TPS CONCEPTS

Metallic Standoff TPS

Titanium Multiwall

ACC Multipost

Superalloy Honeycomb

METALLIC TPS Development
METALLIC TPS: CONCEPTS

RECENT TPS CONCEPTS

Superalloy Honeycomb TPS

- Outer Inconel 617 honeycomb sandwich
- Inner titanium honeycomb sandwich
- Mechanical fastener
- Felt/RTV seal
- Inconel 617 beaded side walls
- Saffil insulation
- Overlapping gap cover
- 12 in.-square panel

X-33 Windward Metallic TPS

- Outer metallic honeycomb
- Panel-to-panel seal
- Foil encapsulated insulation
- External cryotank stiffeners
- Fastener access covers
- Attachment standoff brackets
- Mechanical fastener
METALLIC TPS : CONCEPTS
ARMOR TPS CONCEPT

**Features**

- Compliant sides
  - Decouple h/c and frame
  - Can bulge to fill gap
- Stiffened corners accommodate thermal expansion mismatch
- Insulated fasteners
- Subsurface seals (felt gasket under panel perimeter)
- Fastener access from outer surface
- Encapsulated insulation
METALLIC TPS: CONCEPTS
SIZING OF SLOTTED HOLES IN ARMOR TPS

- Slotted holes were used for tank/TPS strain mismatch
- One corner of each panel was fixed and the others could move
- 14 load conditions considered
  - Tank pressures
  - TPS temperatures
  - Tank temperatures
METALLIC TPS : CONCEPTS
SUPPORT BRACKETS IN ARMOR TPS

- Free thermal expansion of outer honeycomb layer
- Beaded to resist buckling
- Thin to reduce heat short
- Shear stiffness
- Critical structural element
METALLIC TPS : CONCEPTS
ARMOR TPS INTEGRATED WITH CRYOGENIC TANK

ARMOR TPS panel
TPS support structure
Cryogenic tank
Structure
TEEK Cryogenic foam
METALLIC TPS: CONCEPTS
FULLY ASSEMBLED ARMOR TPS PANEL

Four ARMOR TPS panels average 2.4 lb/ft²
METALLIC TPS : ANALYSIS

THERMAL MODELING

Thermal Analysis

• Transient Thermal Problem
  - Surface temperatures vary from ambient to over 2000°F
  - Pressure varies from near vacuum to 1 atmosphere
  - Re-entry flight approximately 1/2 hour
  - Insulation sized to limit structural temperature

• Nonlinear Material Properties
  - Most TPS material thermal properties strongly temperature dependent
  - Insulation conductivity strongly pressure and temperature dependent
  - Gas conductivity in internal voids is complex
  - Heat transfer through honeycomb sandwich involves multiple modes

Desired Features of Thermal Model

• Accuracy: includes all important modes of heat transfer
• Flexibility: easily modified to represent modeling and design variations
• Efficiency: suitable for large numbers of iterative calculations
METALLIC TPS: ANALYSIS

TYPICAL THERMAL RESPONSE OF METALLIC TPS TO RLV HEATING

Entry conditions typical of RLV with metallic TPS

Var. thic. 2-D Model of Improved TPS

Thermal response of metallic TPS (ignoring gap radiation)

Radiation Equilibrium Temperature, °F ($\varepsilon = 0.8$)
METALLIC TPS : ANALYSIS

EFFECTS OF RADIATION IN PANEL-TO-PANEL GAP

- Need small gaps to avoid large temperature increases
- Substructure temp. not sensitive to practical emittance values
CURRENT THERMAL PROTECTION SYSTEMS RESEARCH
CURRENT TPS RESEARCH

CERAMIC BLANKETS

• DuraFRSI – AFRSI blanket with a metal foil outer surface

• CRI – blanket with rigidized outer surface

• High temperature FRSI (felt)
CURRENT TPS RESEARCH

CERAMIC TILES

• AETB tile with TUF1/cgs coating

• BRI – improved toughness, conductivity comparable to HRSI

• Tile leading edges

• Hybrid tiles with CMC outer layer

• SHARP leading edges – high temperature ceramics
CURRENT TPS RESEARCH

CERAMIC MATRIX COMPOSITE TPS

• X-33 Phase I C/SiC heat shield (1 ft x 4 ft)
CURRENT TPS RESEARCH
CERAMIC MATRIX COMPOSITE HOT STRUCTURES

• NASP control surface component

• X-33 body flap – incomplete design

• X-38 control surface

• X-37 control surface
CURRENT TPS RESEARCH

METALLIC TPS

• X-33 windward TPS – full vehicle TPS including seals and penetrations

• ARMOR TPS prototype panels

• Oceaneering metallic TPS
INTEGRATED MULTIFUNCTIONAL STRUCTURES
INTEGRATED MULTIFUNCTIONAL STRUCTURES
PRELIMINARY INTEGRATED CONCEPT CONSIDERATIONS

Intermediate material/structure
- Limits heat transfer
- Acceptable structural connection
- Candidate concepts
  - Discrete structural connections
  - Non-loadbearing insulation
  - Porous FGM
  - Structural foams
  - Enhanced heat storage (heat sponge)

Durable hot outer surface
- Low thermal expansion
- Strain compatibility
- Load sharing
- CMC’s, MMC’s, ?

Heating

Porous FGM?

Efficient inner structure
- Good structural properties
- Good thermal properties
  - High temperature limit
  - High heat capacity
  - High thermal conductivity
INTEGRATED MULTIFUNCTIONAL STRUCTURES

INITIAL GENERIC SANDWICH CONCEPTS

- **Foam-core Sandwich**
  - Hot outer surface
  - Cooler inner surface
- **Truss-core Sandwich**
  - Discrete connections between the hot and cool facesheets
  - Acceptable structural connections
  - Acceptable heat shorts

- **Insulating structural foam core**
  - High temperature capability
  - Strain capability comparable to structural facesheets
  - Strength to perform as sandwich core
  - Low conductivity
- **Insulation**
  - Load-bearing or non-load-bearing
INTEGRATED MULTIFUNCTIONAL STRUCTURES

HEAT CAPACITY OF STRUCTURAL MATERIALS

- High heat capacity inner structure can reduce required insulation
- Heat capacity enhancement may be lighter than additional insulation
- Patent disclosure filed on Heat Sponge
INTEGRATED MULTIFUNCTIONAL STRUCTURES
THERMAL/STRUCTURAL SIZING METHOD

INPUT

Material properties and geometry
Aerothermal Loads
Temperatures
Structural Loads

PROCESS

Thermal Analysis
Global Optimizer Thermal/Struct Sizing
Structural Analysis

CONSTRAINTS

- Material temperature limits
- Temperature gradients
- Overall thickness?

OUTPUT

Dimensions, mass, temperatures, etc.

Converged?

- Max. stress
- Max. strain
- Deflection limits
- Buckling

yes

no

- Minimize mass
INTEGRATED MULTIFUNCTIONAL STRUCTURES

HIGH THERMAL CONDUCTIVITY STRUCTURAL MATERIALS

- Large panels with variations in heating over surface
- High thermal conductivity inner structure:
  - Enables uniform thickness panel sized for average heat load
  - No need to taper insulation thickness for local variations in heating
  - Reduces temperature gradients (and thermal stress/distortions) on inner surface
  - Allows all of inner structure to approach temperature limits and use all available heat capacity
SUPPLEMENTAL SLIDES
METALLIC TPS : ANALYSIS

THERMAL CONDUCTIVITY OF A GAS IN A CAVITY

\[
k_g^* = \frac{k_g^*}{1+2\frac{2-\alpha}{\alpha} \left( \frac{2\gamma}{\gamma+1} \right) \frac{1}{\text{Pr}} \frac{\lambda}{L_c}}
\]

- Thermal conductivity at 1 atm
- Pr – Prandtl Number
- \( L_c \) – characteristic length
- \( \alpha \) – accommodation coefficient
- \( \gamma \) – ratio of specific heats
- \( \lambda \) – mean free path

\[
\lambda = \frac{K_B T}{\sqrt{2\pi} d_g^2 P}
\]

- P – pressure
- T – temperature
- \( K_B \) – Boltzman constant
- \( d_g \) – gas collision diameter
METALLIC TPS: ANALYSIS
THERMAL CONDUCTIVITY OF HONEYCOMB SANDWICH

\[ q = \frac{k_m \rho_{\text{core}}}{t} (T_o - T_i) - \frac{k_A}{t} (T_o - T_i) + f(\eta, \varepsilon) \sigma \left( T_o^4 - T_i^4 \right) \]

where:
\[ f(\eta, \varepsilon) = 0.664(\eta + 0.3)^{-0.69} \varepsilon^{1.63(\eta + 1)^{-0.89}} \]

\[ k_m - \text{metal thermal conductivity} \]
\[ k_A - \text{air thermal conductivity} \]
\[ t - \text{thickness} \]
\[ T_o - \text{temperature on outer surface} \]
\[ T_i - \text{temperature on inner surface} \]
\[ \rho_{\text{core}} - \text{h/c core density} \]
\[ \rho_m - \text{metal density} \]
\[ \varepsilon - \text{emittance} \]
\[ \eta - \text{length/diameter of h/c core cell} \]
\[ \sigma - \text{Stefan-Boltzman constant} \]

\[ f(\eta, \varepsilon) \sigma \left( 4T_{av}^3 \right) \left( 1 + \frac{(\Delta T)^2}{4T_{av}^2} \right) (T_o - T_i) \]

where:
\[ \Delta T = T_o - T_i \]
\[ T_{av} = \frac{T_o + T_i}{2} \]

\[ k_{hc} = k_m \frac{\rho_{\text{core}}}{\rho_m} + 4t \sigma f(\eta, \varepsilon)T_{av}^3 \]
Approximate Analysis for Venting of Cavity with No Internal Insulation

A – area of vent hole
V – internal volume of panel
P – pressure inside panel
$P_a$ – pressure outside panel
$\rho_a$ – ambient air density

$P > P_a$

\[
\frac{P(t)}{P_a} = \frac{1}{2} \left[ 1 + \left( 2 \frac{P_i}{P_a} - 1 \right) \cosh(\beta t) \right. \left. - 2 \sqrt{\frac{P_i}{P_a}} \left( \frac{P_i}{P_a} - 1 \right) \sinh(\beta t) \right]
\]

$P_a > P$

\[
\frac{P(t)}{P_a} = \frac{P_i}{P_a} + \beta \left( 1 - \frac{P_i}{P_a} \right)^{\frac{1}{2}} t - \frac{\beta^2}{4} t^2
\]

where

\[
\beta = \frac{A}{V} \left( \frac{2P_a}{\rho_a} \right)^{\frac{1}{2}}
\]

Internal insulation increases venting time
METALLIC TPS: ANALYSIS

THERMAL STRESS AROUND A CYLINDRICAL FASTENER

Fastener

\[ \sigma_{r_f} = \sigma_{\theta_f} = -P \]

Structure

\[ \sigma_{r_s} = -P \left[ \frac{(b/r)^2 - 1}{(b/a)^2 - 1} \right] \]

\[ \sigma_{\theta_s} = P \left[ \frac{(b/r)^2 - 1}{(b/a)^2 - 1} \right] \]

Where

\[ P = \frac{E_s \left[ \left( \frac{b}{a} \right)^2 - 1 \right] (\alpha_f - \alpha_s) \Delta T}{\left( \frac{b}{a} \right)^2 (1 + \nu_s) + (1 - \nu_s) + \frac{E_s}{E_f} \left[ \left( \frac{b}{a} \right)^2 - 1 \right] (1 - \nu_f)} \]
METALLIC TPS : ANALYSIS
FREE THERMAL BOWING OF A SANDWICH PANEL

Sandwich Panel With Facesheets at Different Temperatures

Panel bows into a spherical segment

\[ \delta = t \left( \frac{(1 + \alpha_1 T_1)}{(\alpha_1 T_1 - \alpha_2 T_2)} \right) \left( 1 - \cos \left( \frac{L}{2t} \left( \alpha_1 T_1 - \alpha_2 T_2 \right) \right) \right) \]

Simplifying: if \( \alpha_{1T} << 1 \) and \( \alpha_1 = \alpha_2 = \alpha \)

then

\[ \delta = \left( \frac{t}{(\alpha \Delta T)} \right) \left( 1 - \cos \left( \frac{L \alpha \Delta T}{2t} \right) \right) \approx \frac{L^2 \alpha \Delta T}{8t} \]
METALLIC TPS: MATERIALS
OPTIMUM INSULATION FOR STEADY STATE HEAT TRANSFER

\[ q = \frac{k}{t} \Delta T \]

Minimize mass
\[ \frac{m}{A} = t \rho \]

Required thermal resistance
\[ m = \rho k \frac{\Delta T}{q} \]

Minimize \( \rho k \) for minimum mass insulation in steady state

\( k \) – thermal conductivity
\( \rho \) – density
\( q \) – heat flux
\( m \) – mass
\( A \) – area
\( T \) – temperature
\( t \) – thickness
METALLIC TPS : MATERIALS
MEASURED INSULATION PERFORMANCE

• The product of density and conductivity is a good indicator of insulation mass efficiency for steady state heat transfer (transient case more complicated)
• Saffil (alumina) and Q-felt (quartz) fibrous insulations have similar thermal performance at a given density
• Insulations with multiple reflective layers offer improved performance