Thermal Protection Systems for Reusable Launch Vehicles

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Short Course: Thermal Control Hardware

Thermal & Fluids Analysis Workshop
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OUTLINE

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

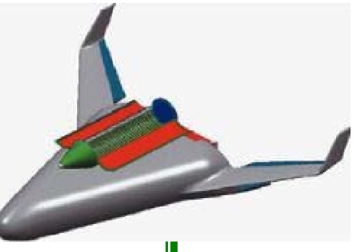
INTRODUCTION

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

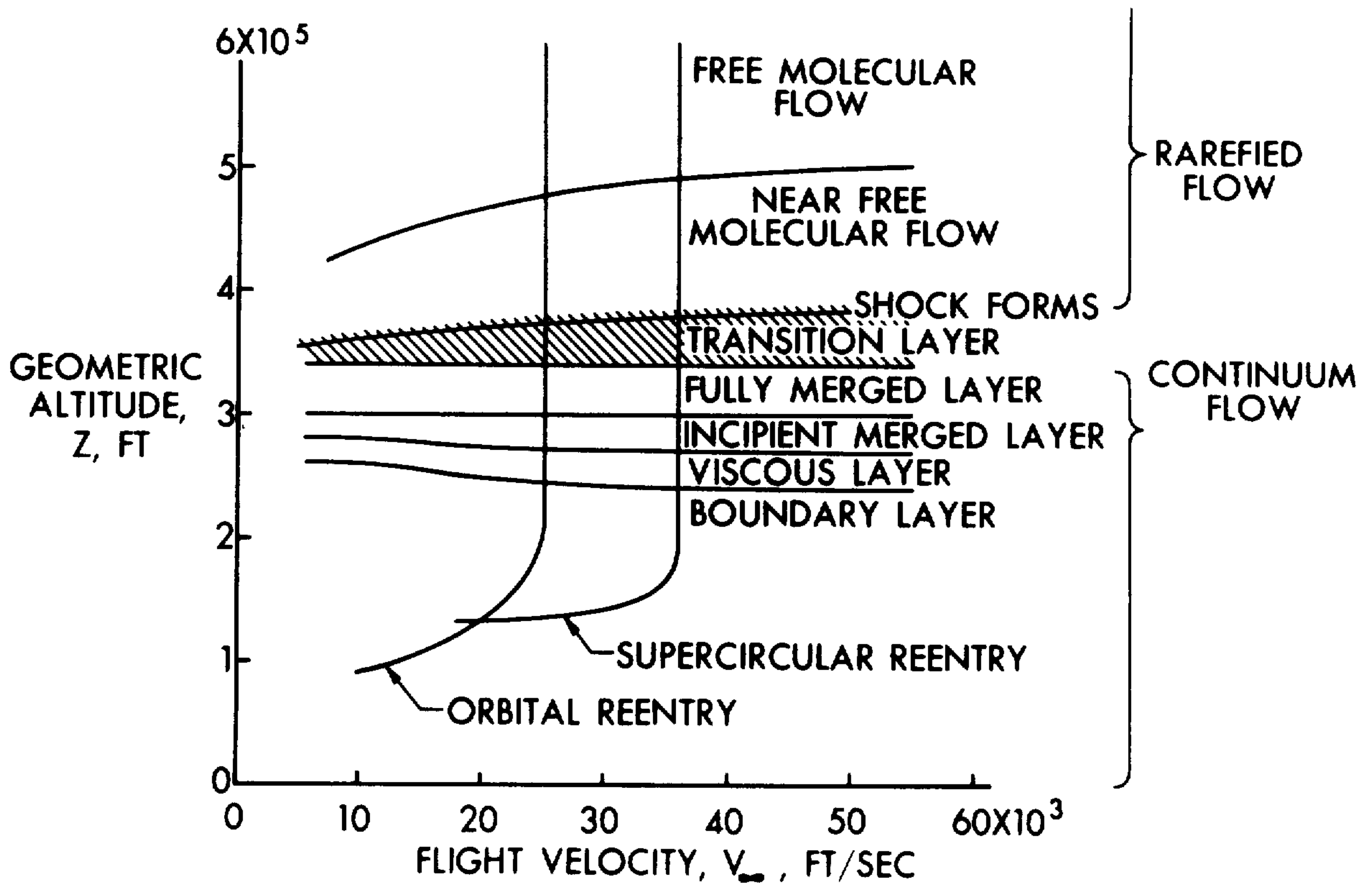
Vehicle Geometry
- Windward and leeward surfaces
- Stagnation region, leading-edge radius

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

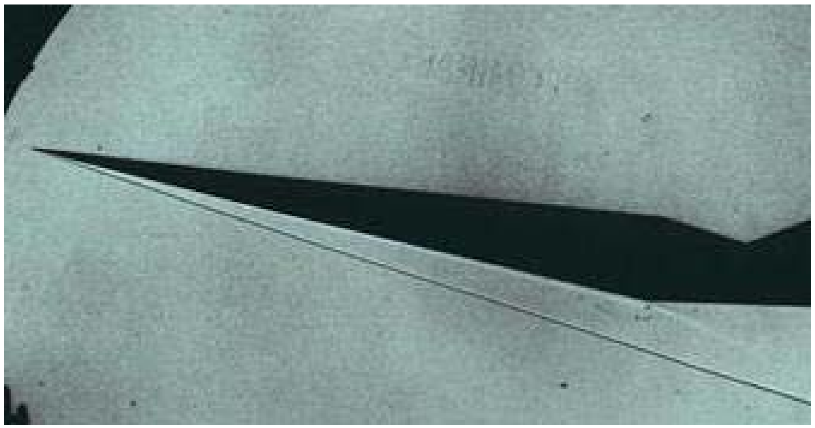
Heating Prediction
- Engineering codes
- Computational aerothermodynamics

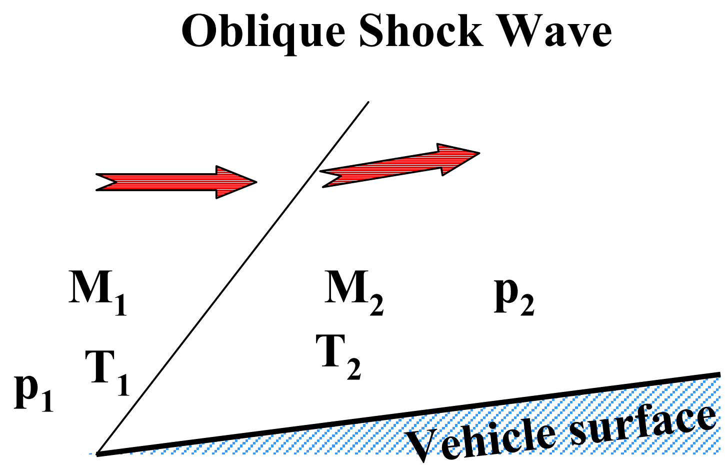
AERODYNAMIC HEATING FUNDAMENTALS

FLOW REGIMES



AERODYNAMIC HEATING FUNDAMENTALS
SHOCK WAVES





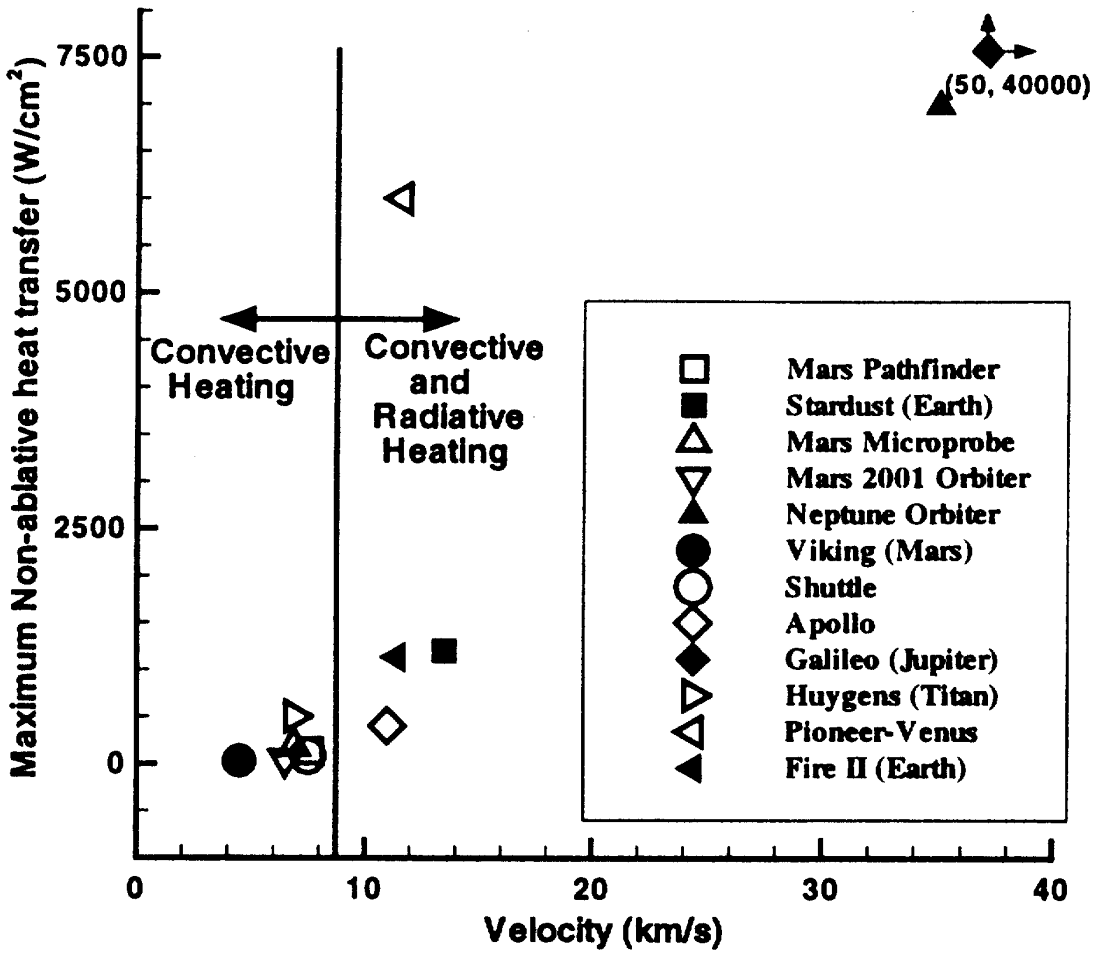
<u>**Normal Shock**</u>

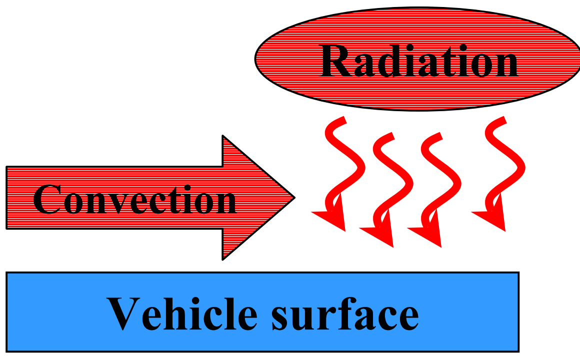
- **Supersonic to subsonic flow (M_2>1)**
- **Increase in pressure and temperature**

<u>**Oblique Shock**</u>

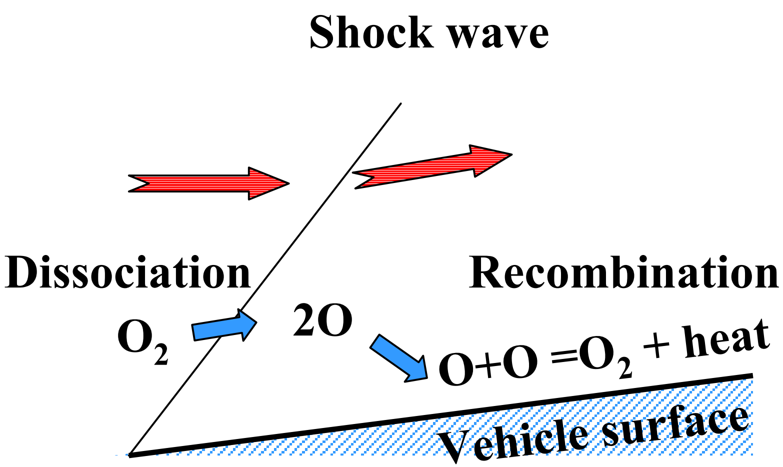
- **Parallel and normal components**
- **Calculate pressure and temperature changes for normal component**
- **M_2 can be supersonic**

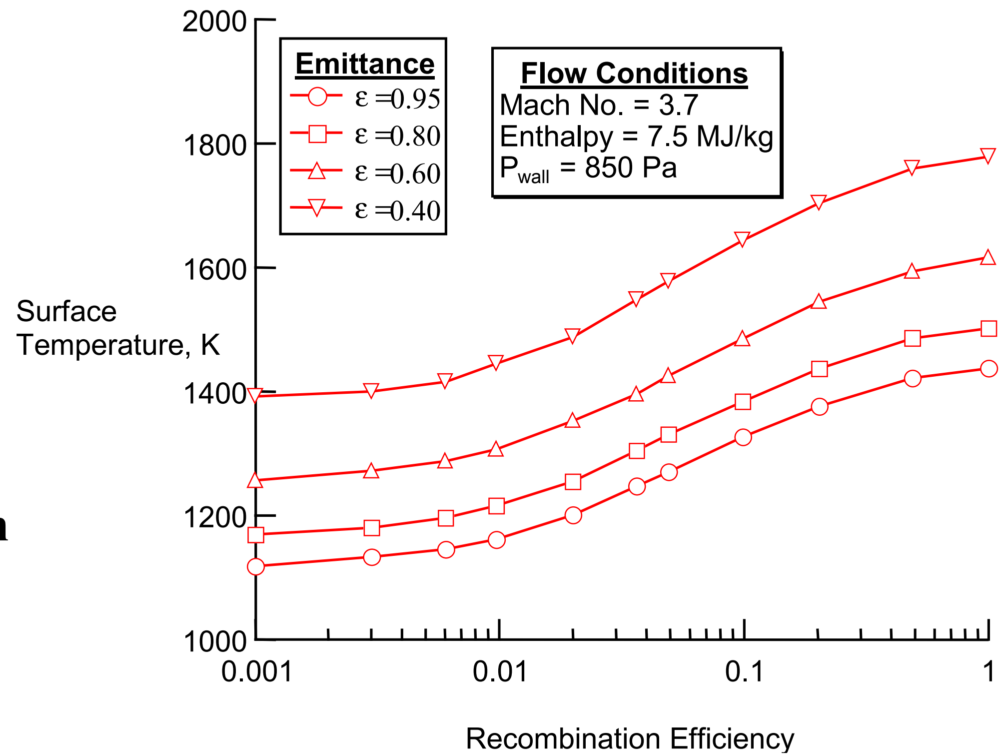
AERODYNAMIC HEATING FUNDAMENTALS
CONVECTIVE AND RADIATIVE HEATING





AERODYNAMIC HEATING FUNDAMENTALS
AERODYNAMIC HEATING OF TPS

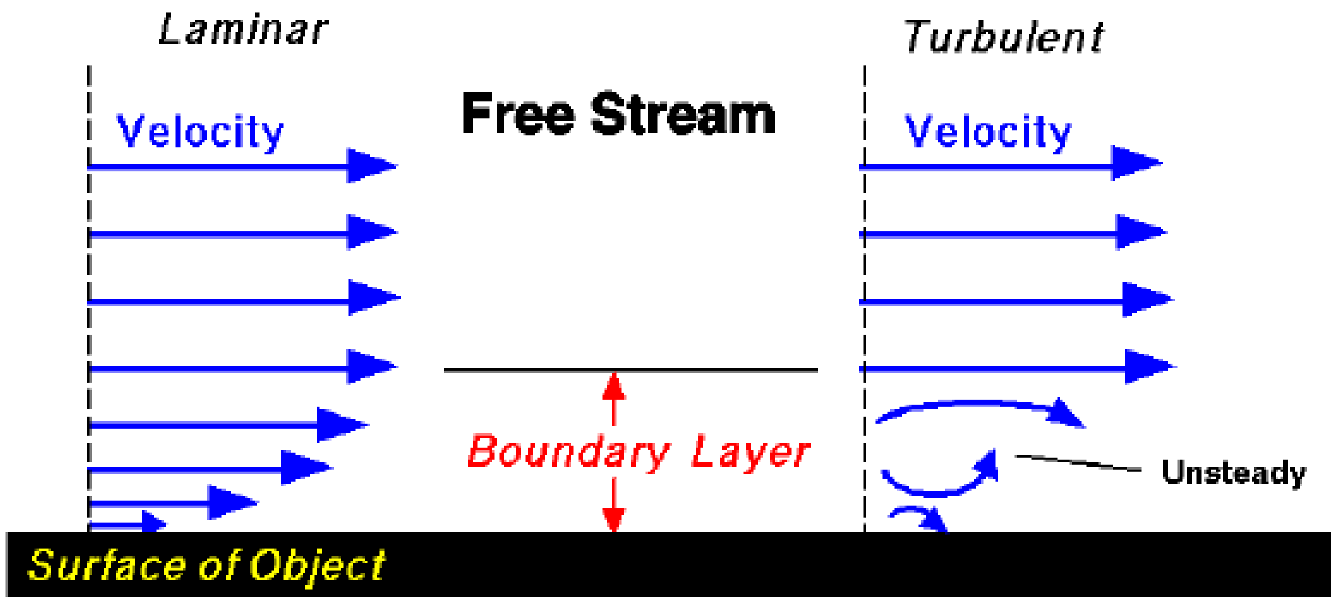




- Both oxygen and nitrogen can be dissociated when passing through a shock wave
- If the vehicle surface acts as a catalyst for recombination, additional surface heating can result

AERODYNAMIC HEATING FUNDAMENTALS

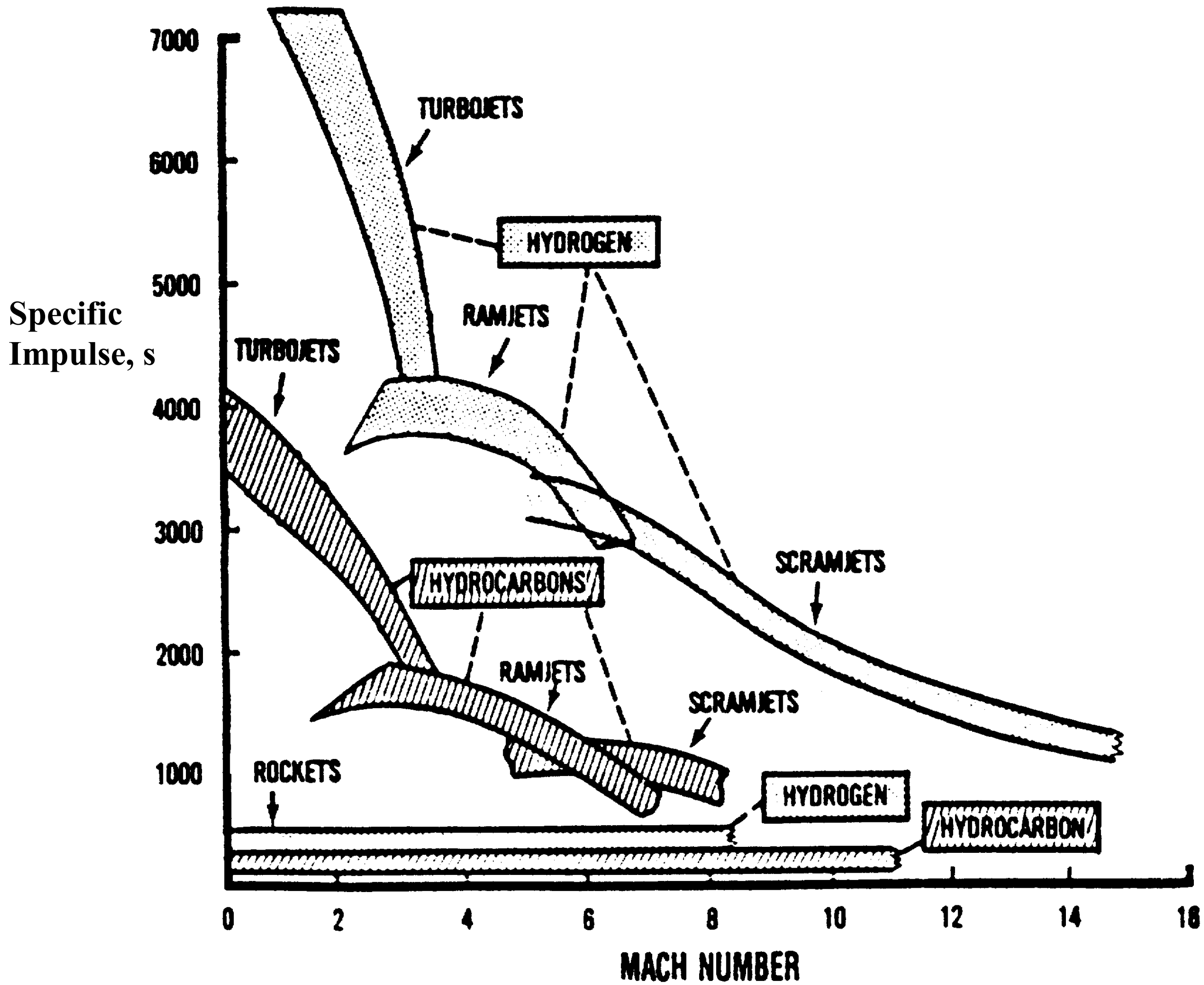
BOUNDARY LAYERS



<u>Laminar-to-Turbulent Boundary Layer Transition</u>

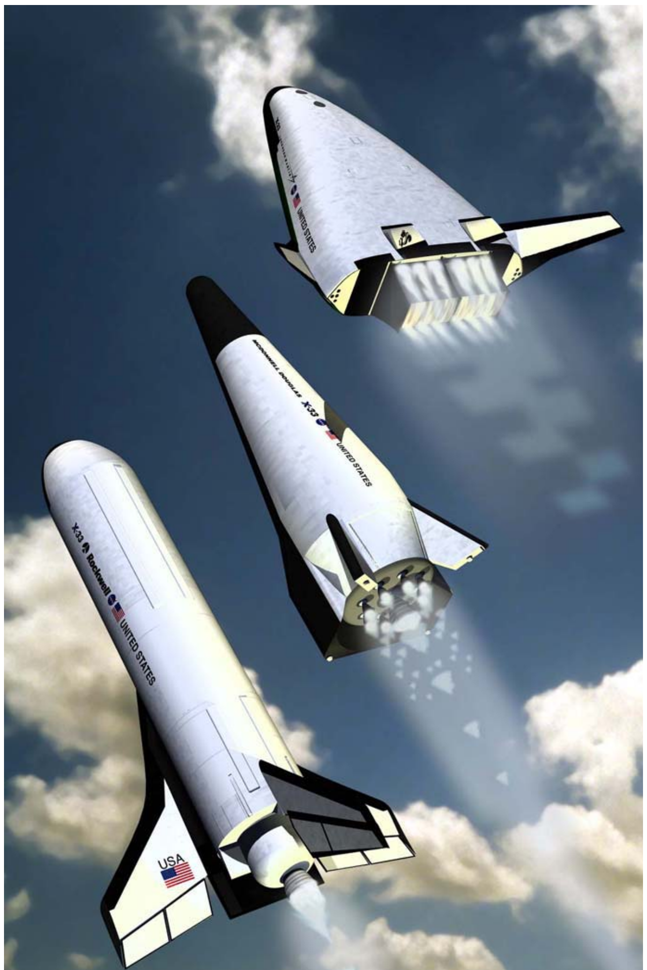
- **Flow is usually laminar for high altitude, high enthalpy flow**
- **Aerodynamic heating can be several times higher for turbulent flow**
- **Rough surface can cause premature transition to turbulent flow**
- **TPS design seeks to minimize surface roughness**

AERODYNAMIC HEATING FUNDAMENTALS
PROPULSION EFFICIENCIES



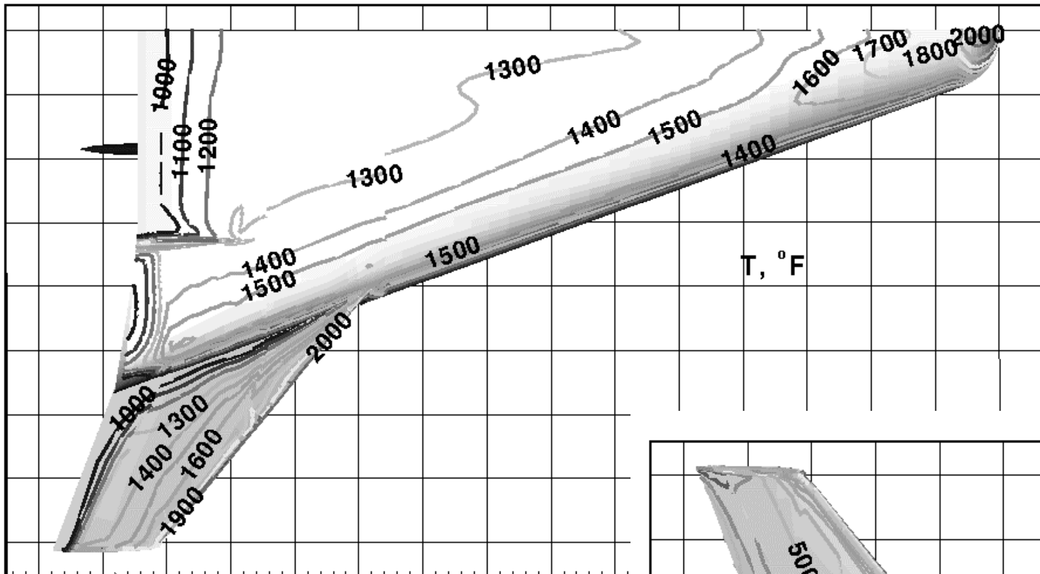
AERODYNAMIC HEATING FUNDAMENTALS
PROPULSION IMPACTS RLV CONFIGURATION

Rocket



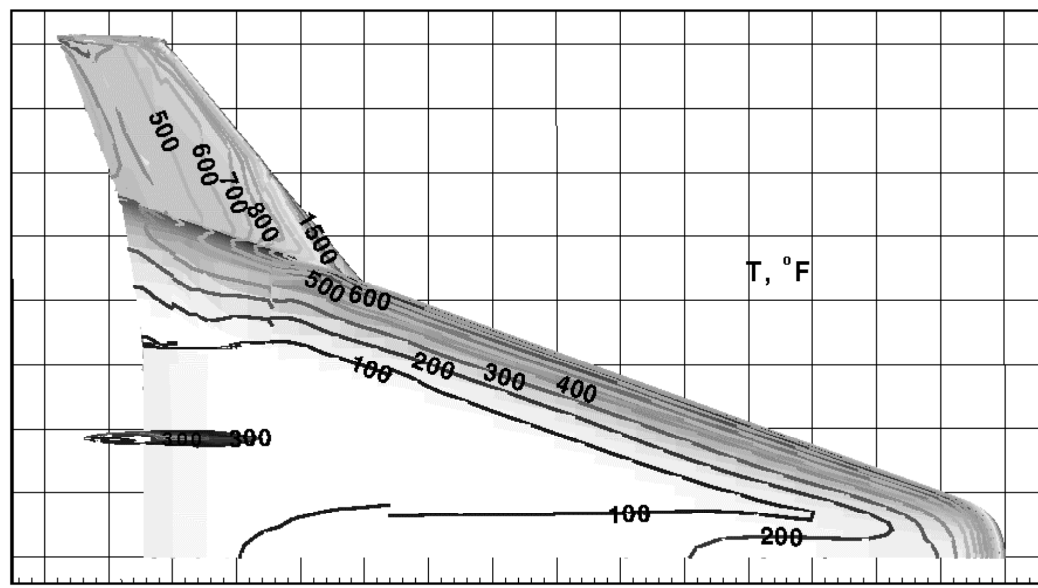
Airbreathing

AERODYNAMIC HEATING FUNDAMENTALS
HEATING VARIATION OVER A VEHICLE



Windward Surface

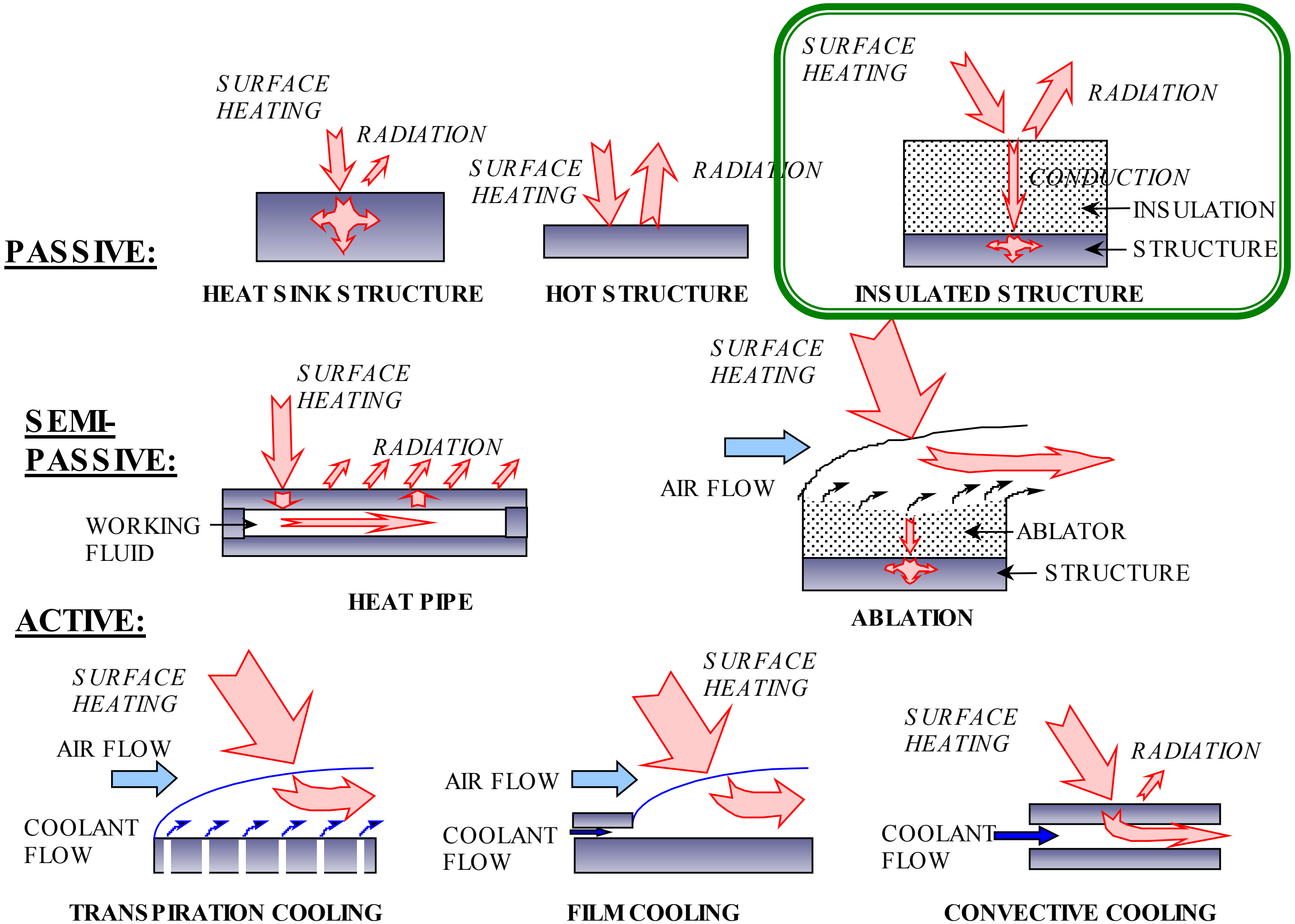
Leeward Surface



APPROACHES TO THERMAL PROTECTION

APPROACHES TO THERMAL PROTECTION

TYPES OF THERMAL PROTECTION SYSTEMS

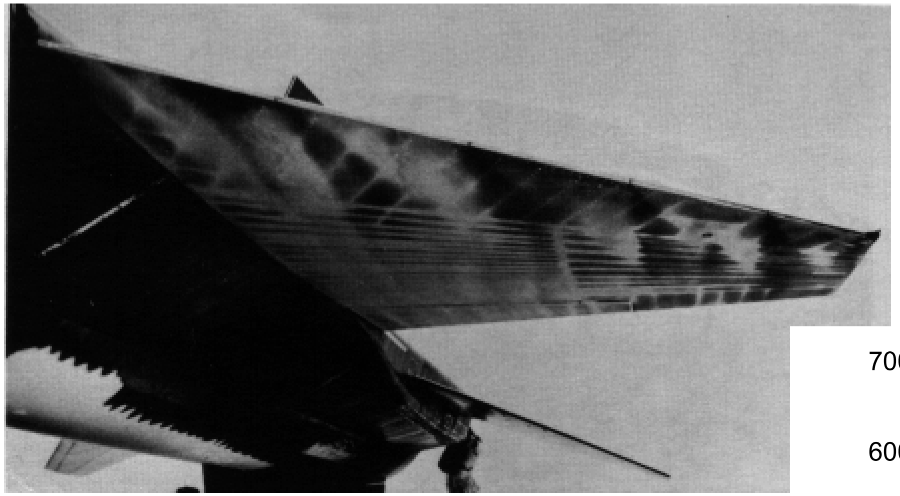


Preferred RLV approach

Choose the simplest and/or lightest that works

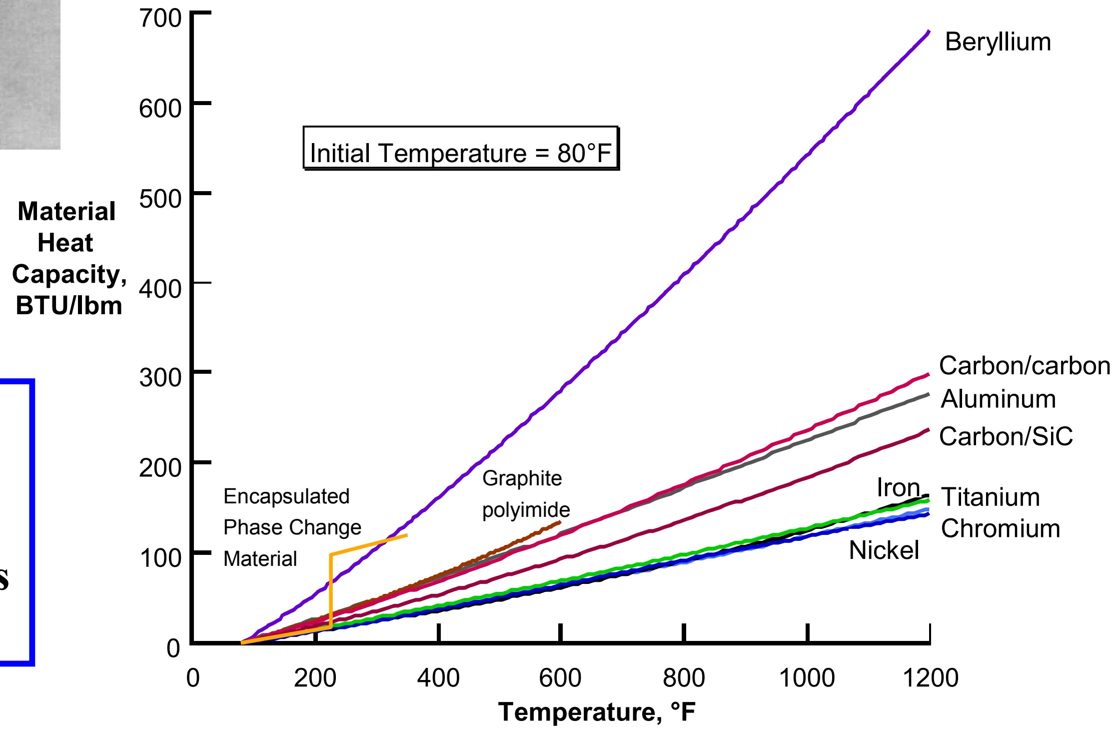
APPROACHES TO THERMAL PROTECTION
HEAT SINK STRUCTURE

X-15 WING STRUCTURE



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

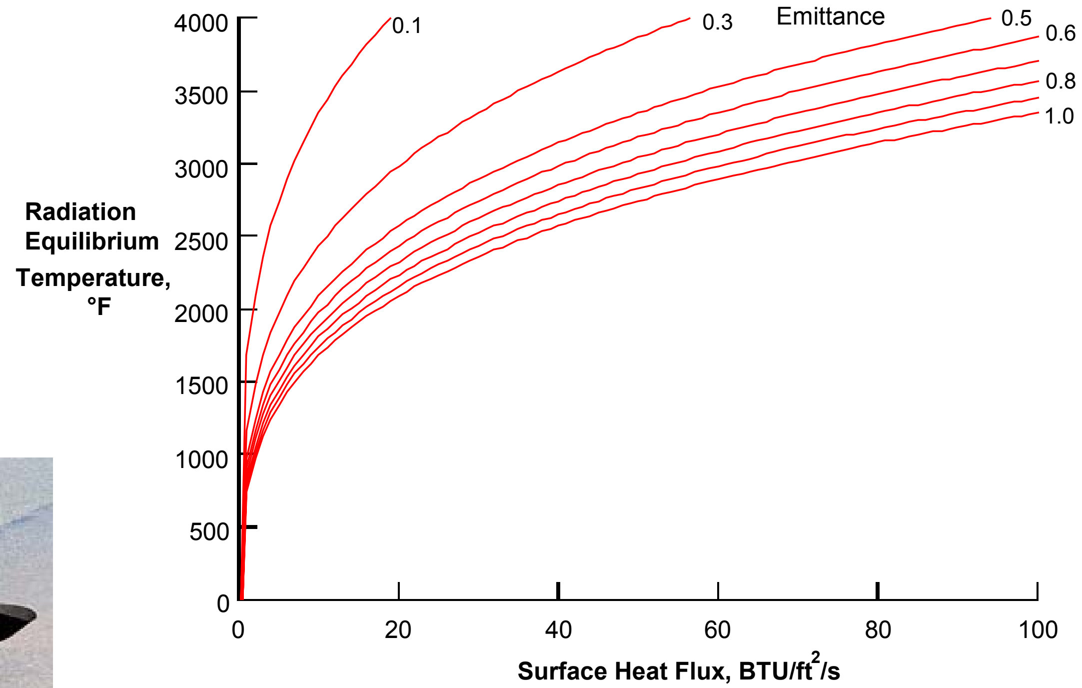
HEAT STORAGE IN STRUCTURES



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

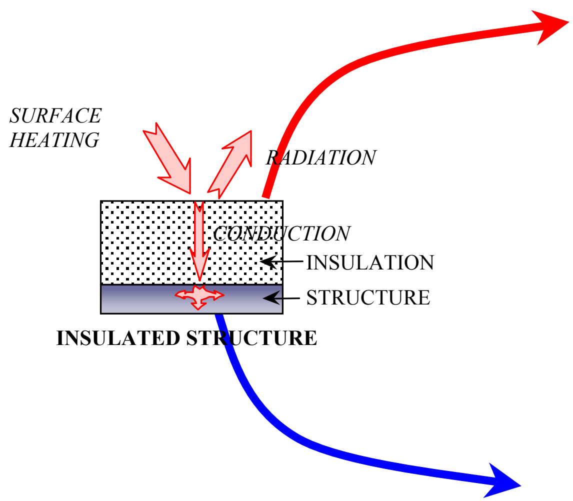
APPROACHES TO THERMAL PROTECTION
HOT STRUCTURE

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)

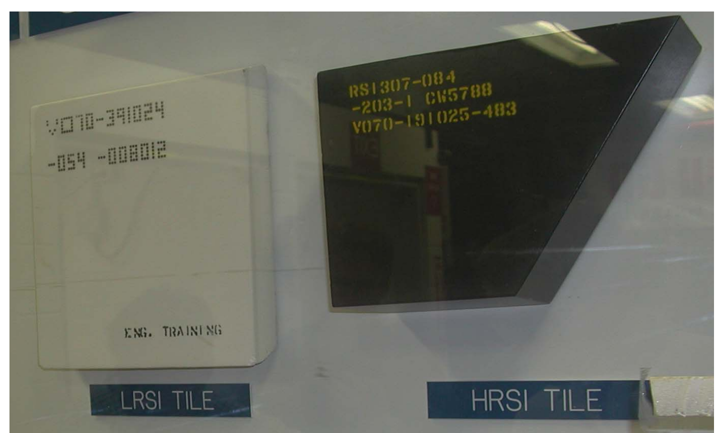
APPROACHES TO THERMAL PROTECTION
TPS INSULATING STRUCTURE



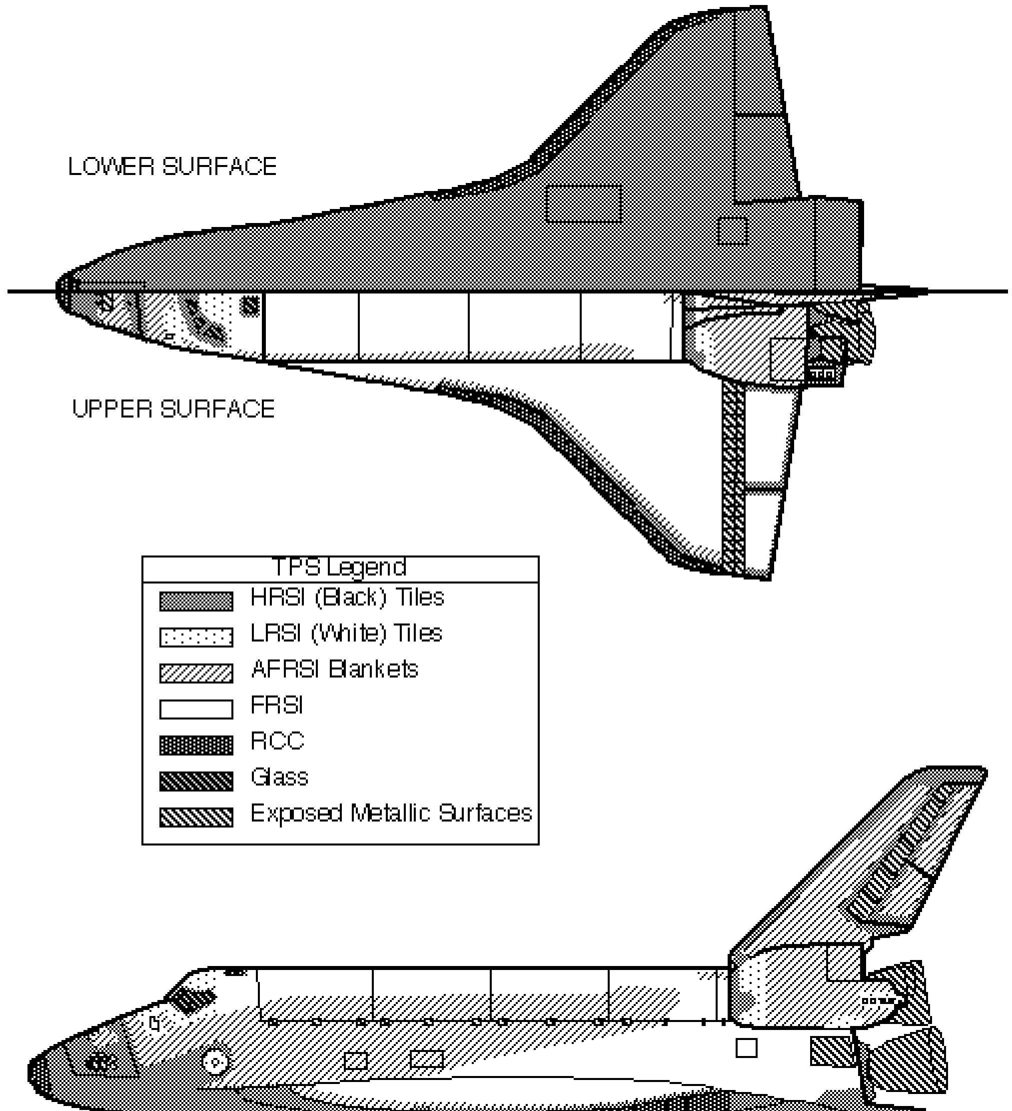
Surface acts like hot structure
- **Near radiation equilibrium temperature**
- **Reradiates most of incident heat**
- **Allows some heat to reach structure**

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

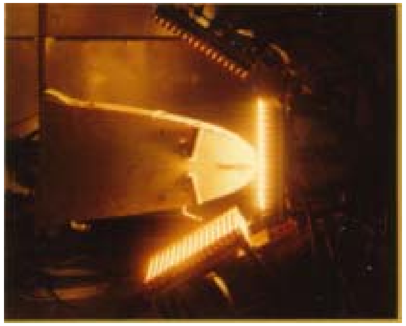
Applications:
- **Space Shuttle Orbiter**
- **Future RLV's**



APPROACHES TO THERMAL PROTECTION
TPS CONCEPTS VARY OVER VEHICLE SURFACE

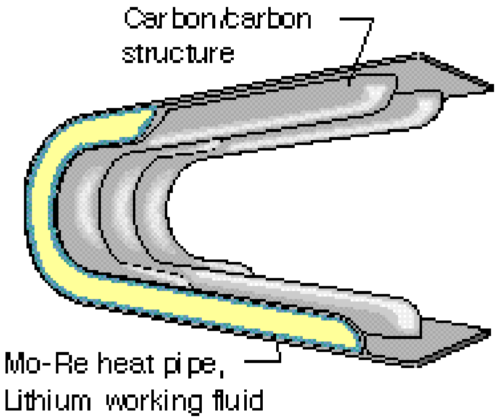


APPROACHES TO THERMAL PROTECTION
HEAT PIPE



Superalloy heat pipe leading edge for Shuttle wing

Operating liquid metal heat pipe



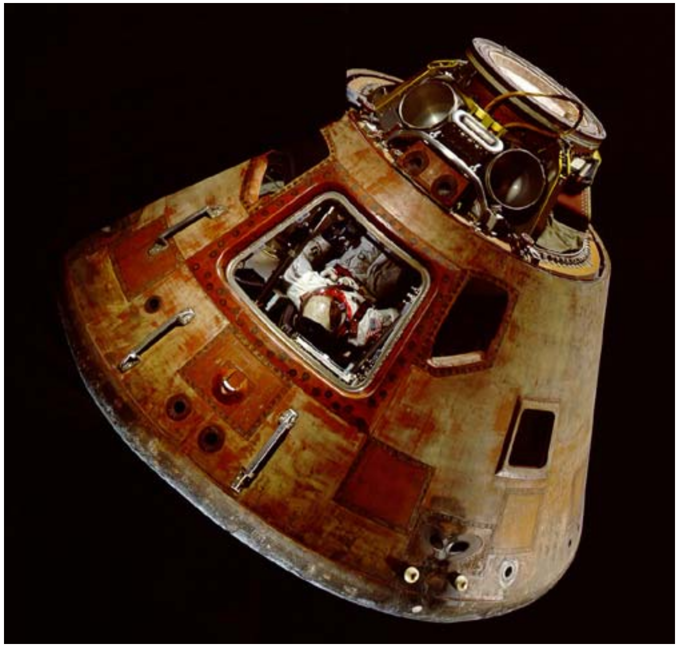
Carbon/carbon heat pipe leading edge for NASP wing

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

APPROACHES TO THERMAL PROTECTION
ABLATION

Apollo Capsule



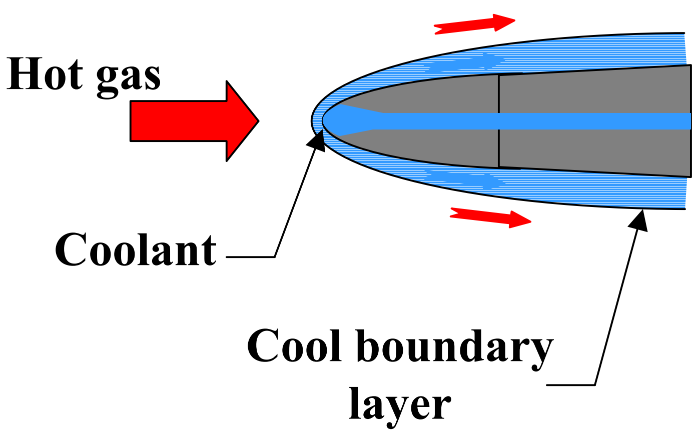
Ablator Operation
- Partially consumed by heating
- Heat absorbed as gases generated
- Gases block convective heating
- Ablator is also insulator
- Surface recedes with time
- Non-reusable

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**

Transpiration-cooled nose tip

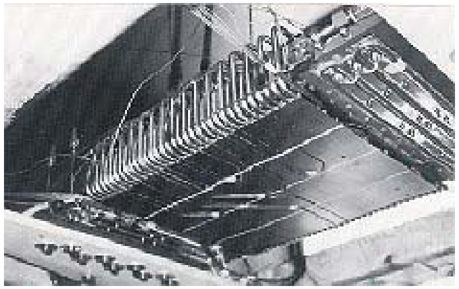


Applications of Transpiration and Film Cooling
- **Not mass-efficient for large areas**
- **Complex system, have to carry coolant**
- **Localized areas**
- **Nose tips**
- **Possibly sharp leading edges**
- **Airbreathing engine structures**

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 ⟷ **CONCEPT DEVELOPMENT**

METALS
- Structural properties
- Surface properties

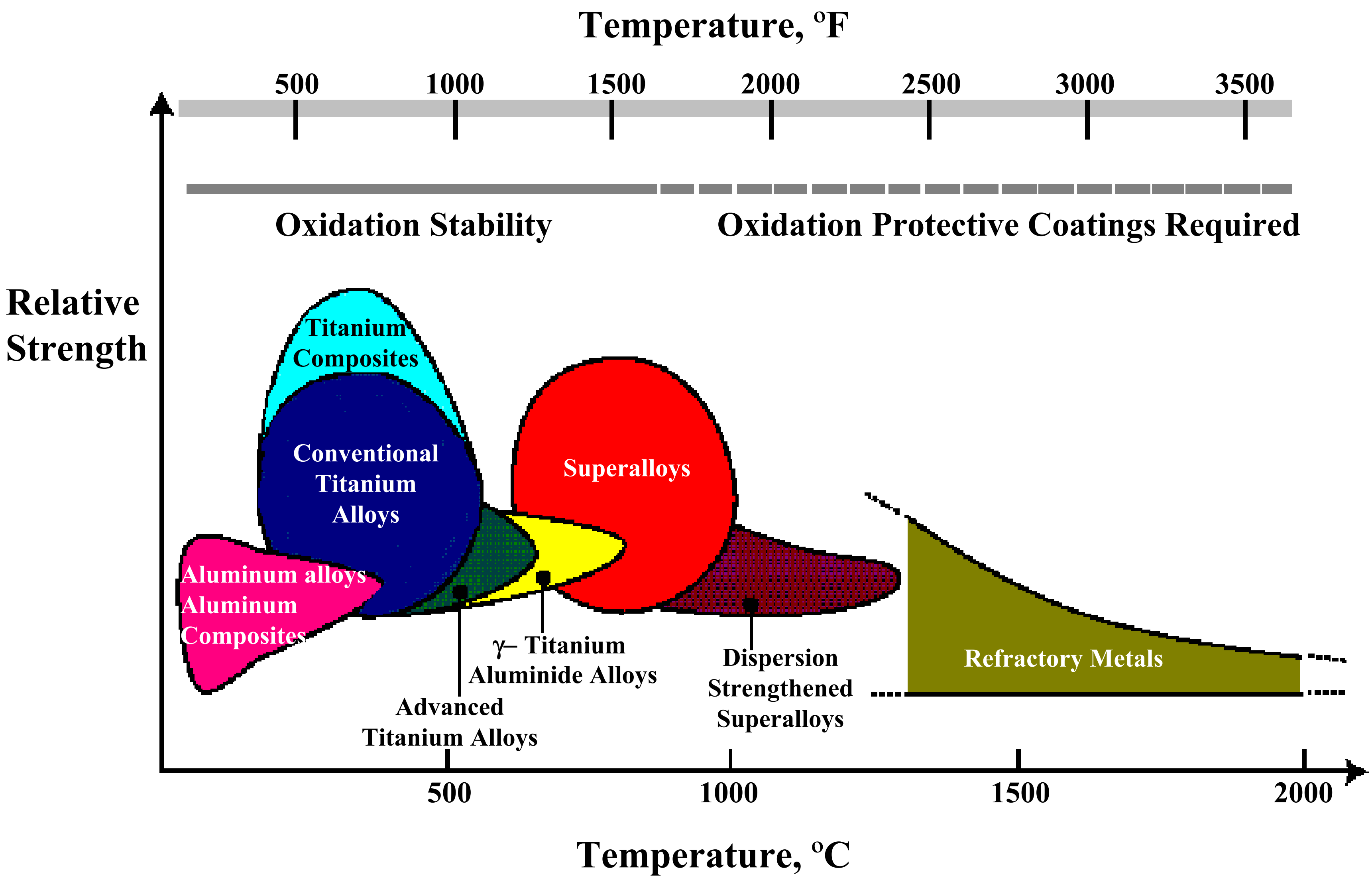
INSULATIONS
- Measured thermal properties
- Validated analysis
- Optimized combinations

CONCEPT DEFINITION
- Conception, design and analysis
- Vehicle integration

CONCEPT EVALUATION
- Coupon tests
- Panel tests

METALLIC TPS: MATERIALS

HIGH PERFORMANCE METALS FOR TPS



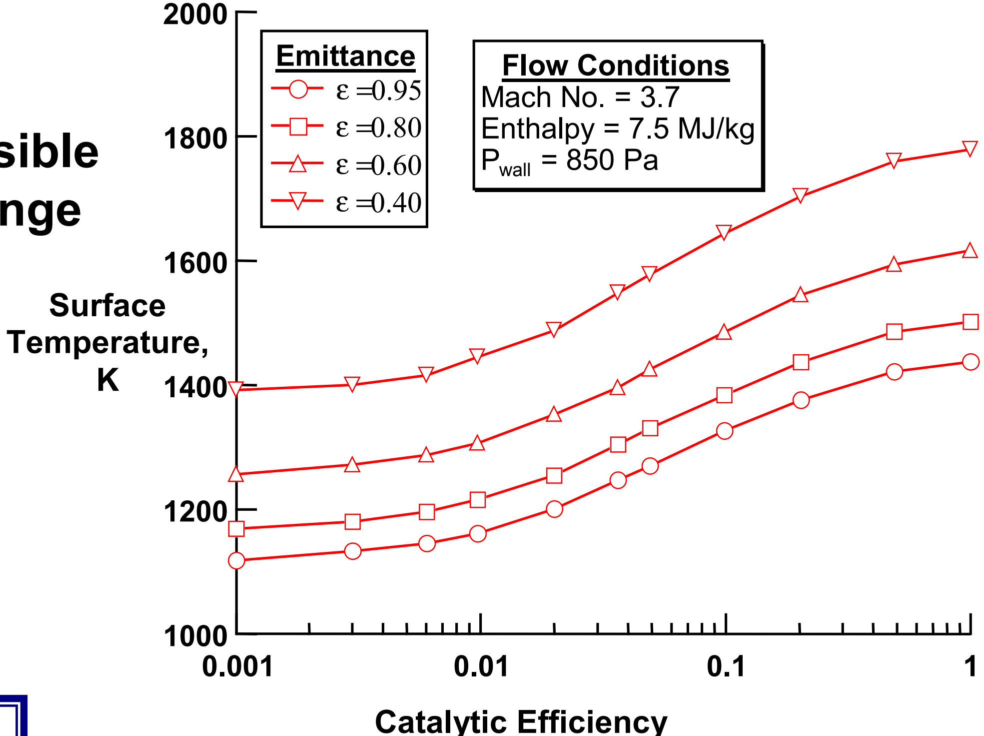
METALLIC TPS : MATERIALS
SURFACE PROPERTIES

Desired Surface Properties

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

Achieving desired surface properties may require coatings

Effects of Emittance and Catalytic Efficiency



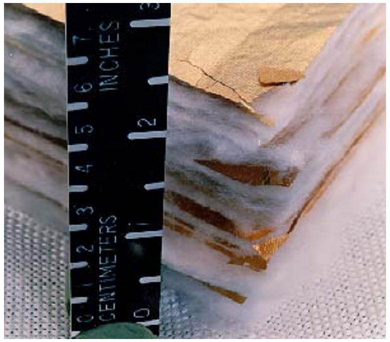
METALLIC TPS : MATERIALS
IMPROVED INTERNAL INSULATIONS

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

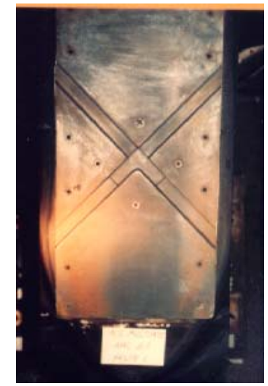
CANDIDATE INSULATIONS

- 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



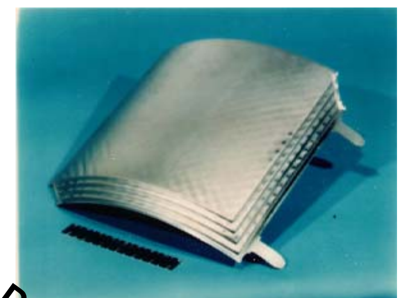
METALLIC TPS: CONCEPTS
EARLY TPS CONCEPTS

Metallic Standoff TPS



ACC Multipost

Metallic TPS Development



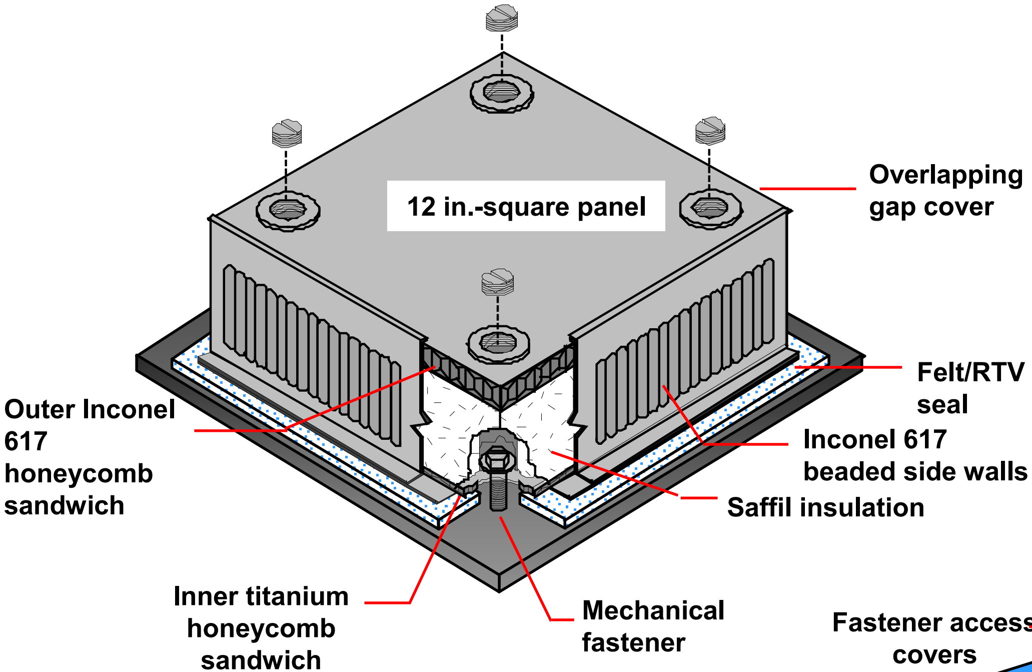
Titanium Multiwall

Superalloy Honeycomb

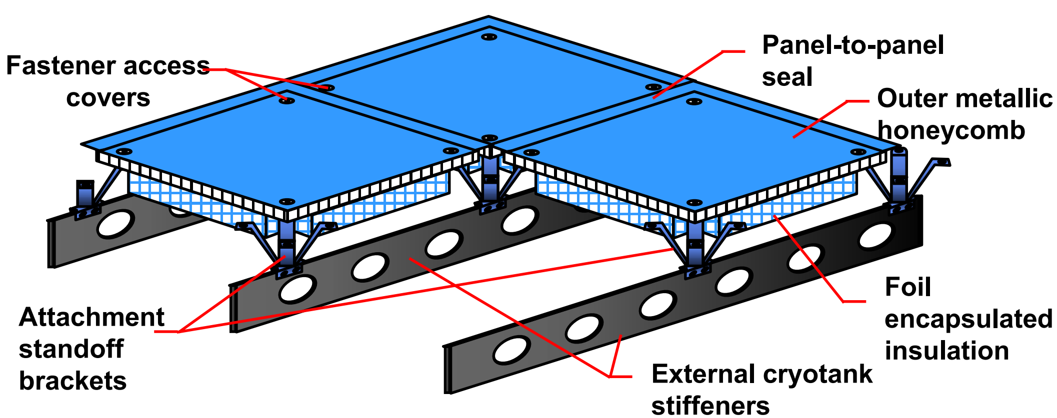
METALLIC TPS : CONCEPTS

RECENT TPS CONCEPTS

Superalloy Honeycomb TPS

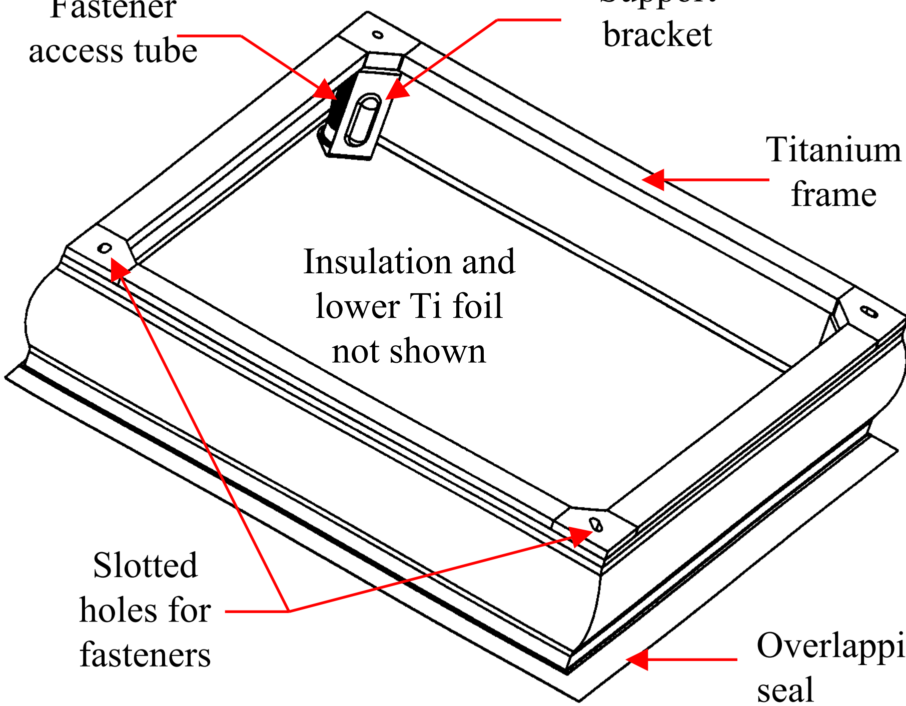


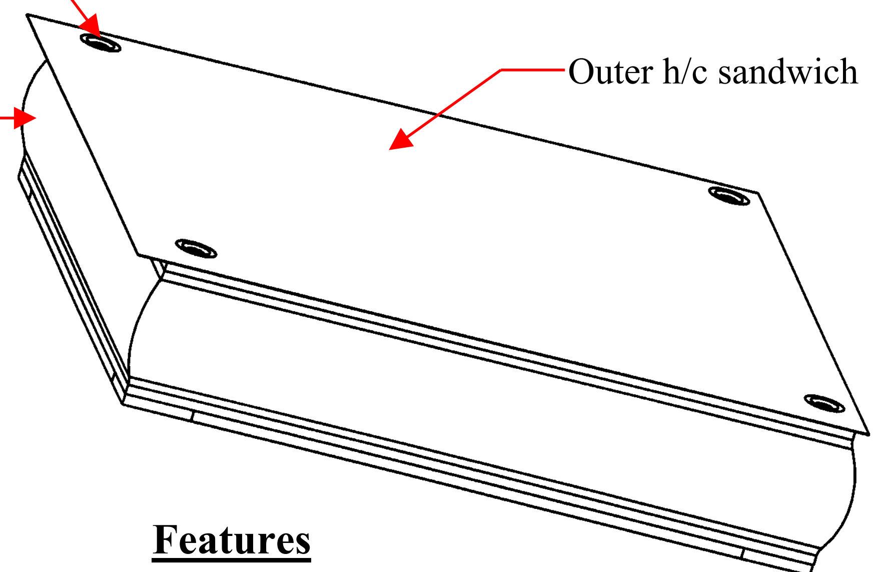
X-33 Windward Metallic TPS



METALLIC TPS : CONCEPTS

ARMOR TPS CONCEPT



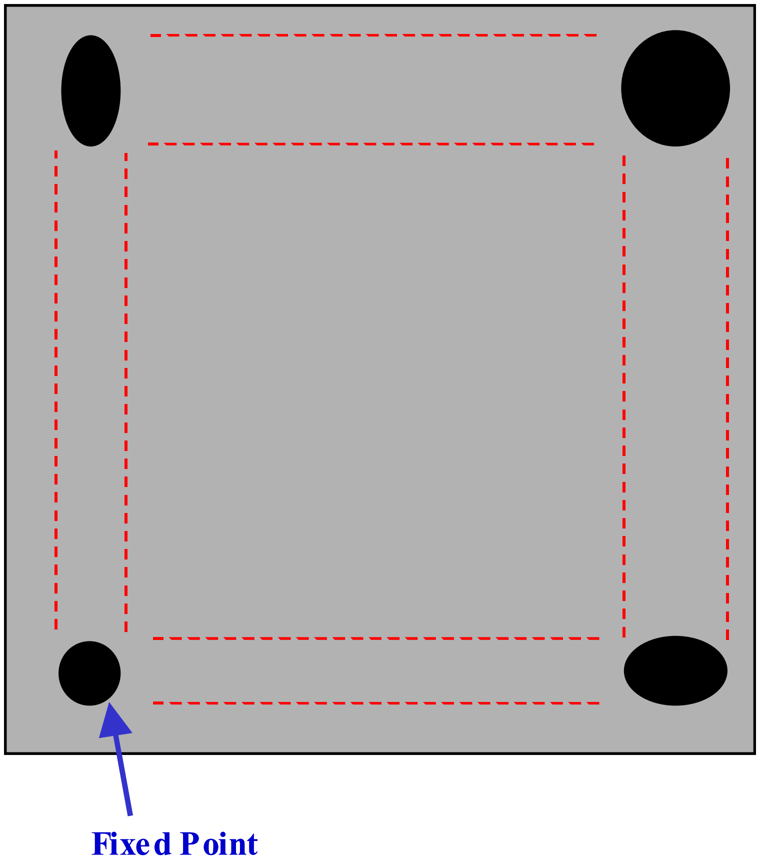


Features

- **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

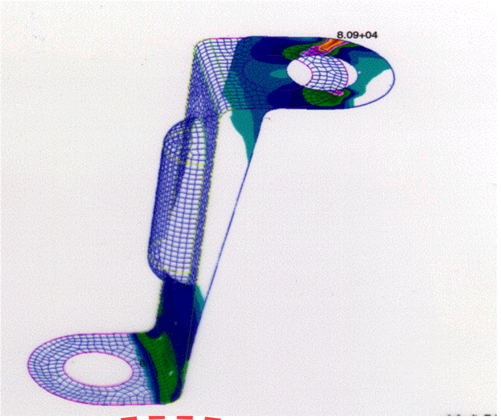
SIZING OF SLOTTED HOLES IN ARMOR TPS

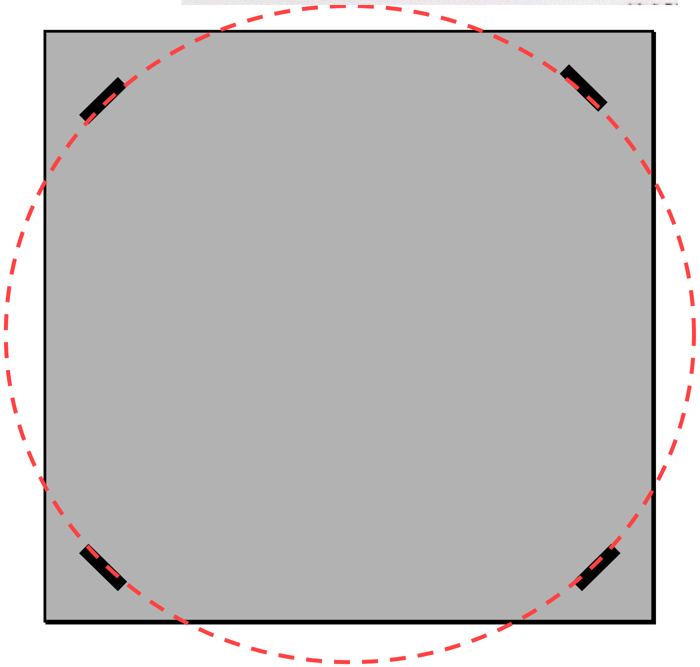


- Slotted holes were used for tank/TPS strain mismatch
- One corner of each panel was fixed and the others could move
- 14 load conditions considered
  - Tank pressures
  - TPS temperatures
  - Tank temperatures

METALLIC TPS : CONCEPTS

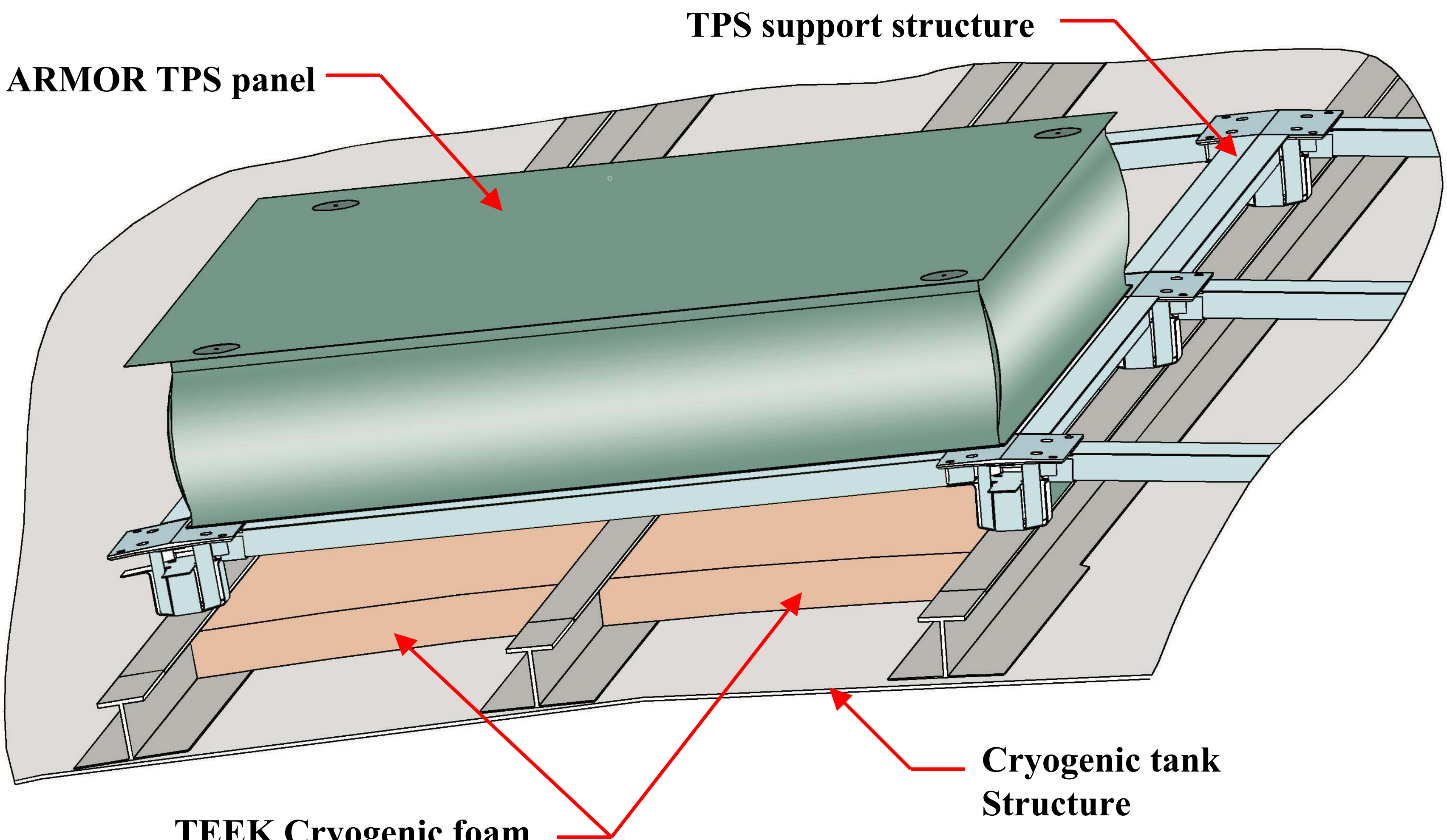
SUPPORT BRACKETS IN ARMOR TPS



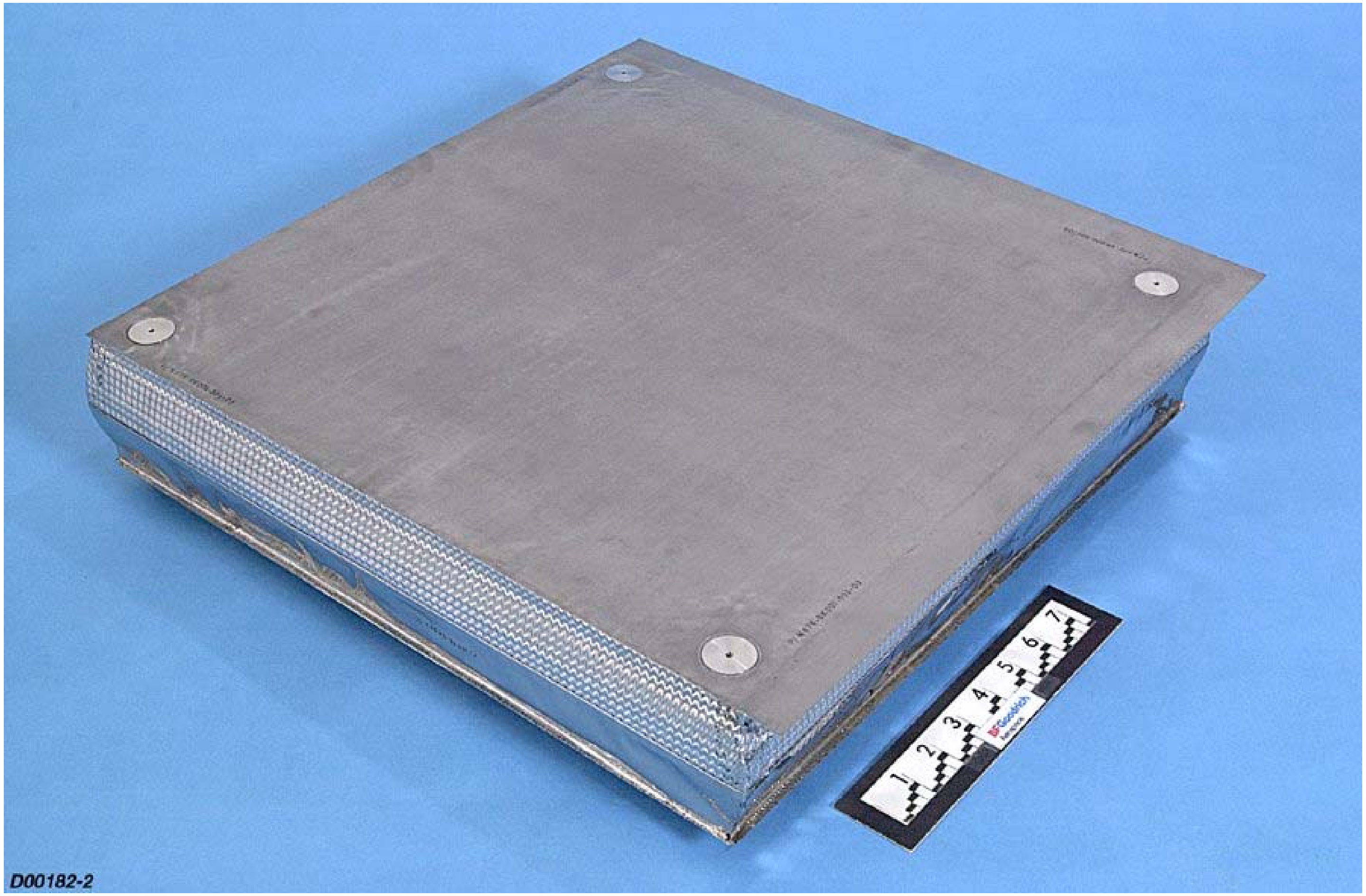


- Free thermal expansion of outer honeycomb layer
- Beaded to resist buckling
- Thin to reduce heat short
- Shear stiffness
- Critical structural element

METALLIC TPS : CONCEPTS
ARMOR TPS INTEGRATED WITH CRYOGENIC TANK

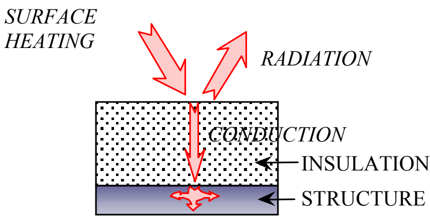


METALLIC TPS : CONCEPTS
FULLY ASSEMBLED ARMOR TPS PANEL



Four ARMOR TPS panels average 2.4 lb/ft^2

METALLIC TPS : ANALYSIS
THERMAL MODELING



Thermal Analysis

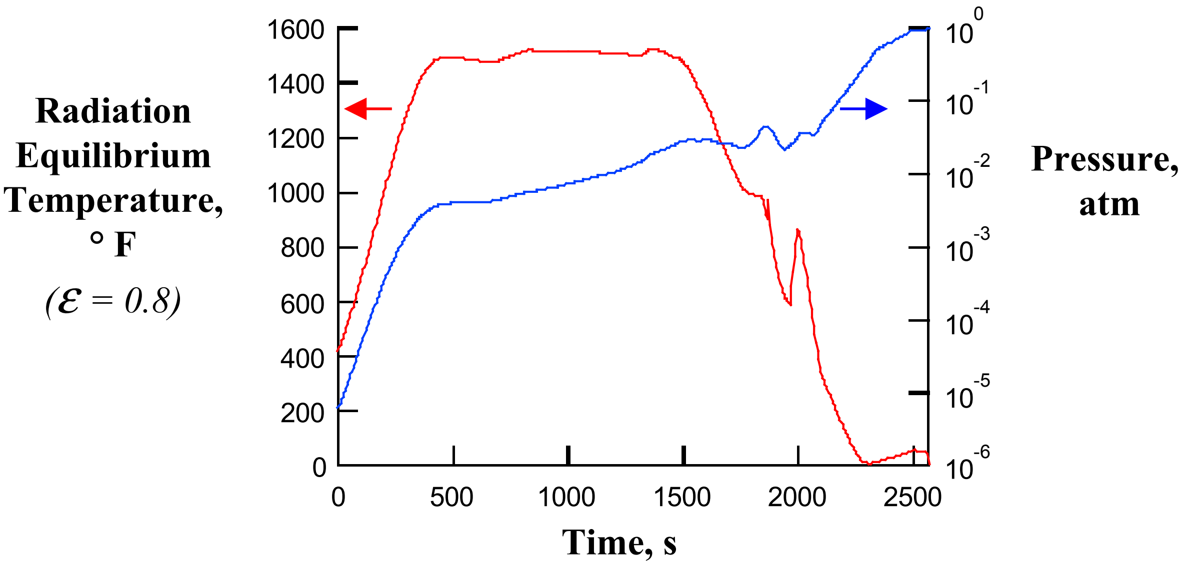
- **Transient Thermal Problem**
  - Surface temperatures vary from ambient to over 2000°F
  - Pressure varies from near vacuum to 1 atmosphere
  - Re-entry flight approximately 1/2 hour
  - Insulation sized to limit structural temperature
- **Nonlinear Material Properties**
  - Most TPS material thermal 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**

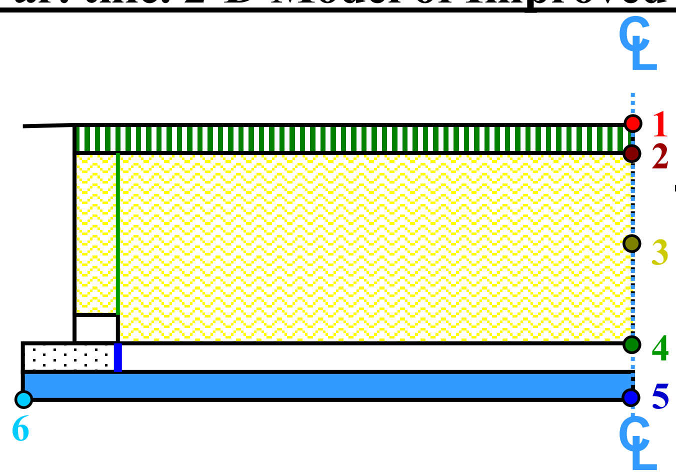
METALLIC TPS : ANALYSIS

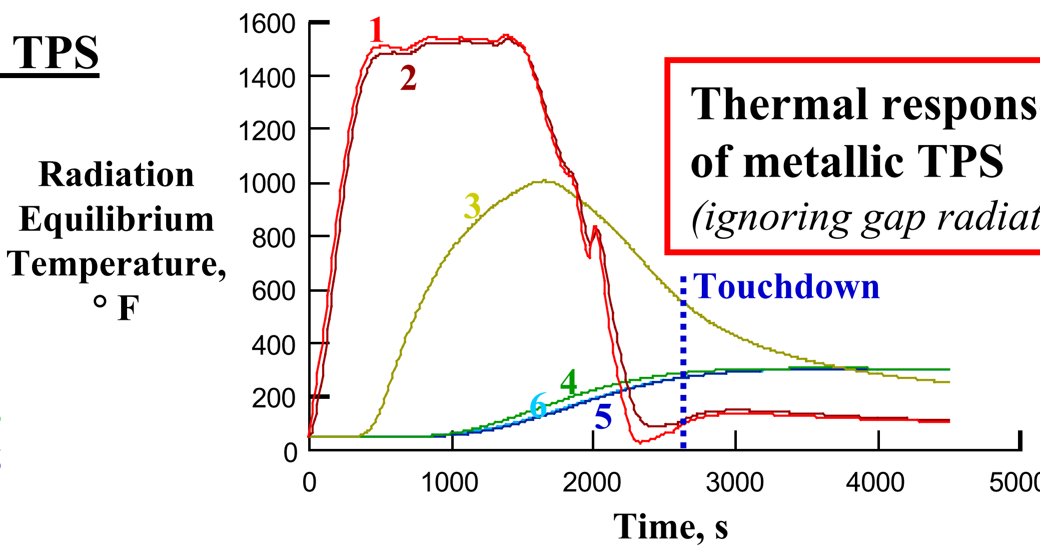
TYPICAL THERMAL RESPONSE OF METALLIC TPS TO RLV HEATING



Entry conditions typical of RLV with metallic TPS

Var. thic. 2-D Model of Improved TPS

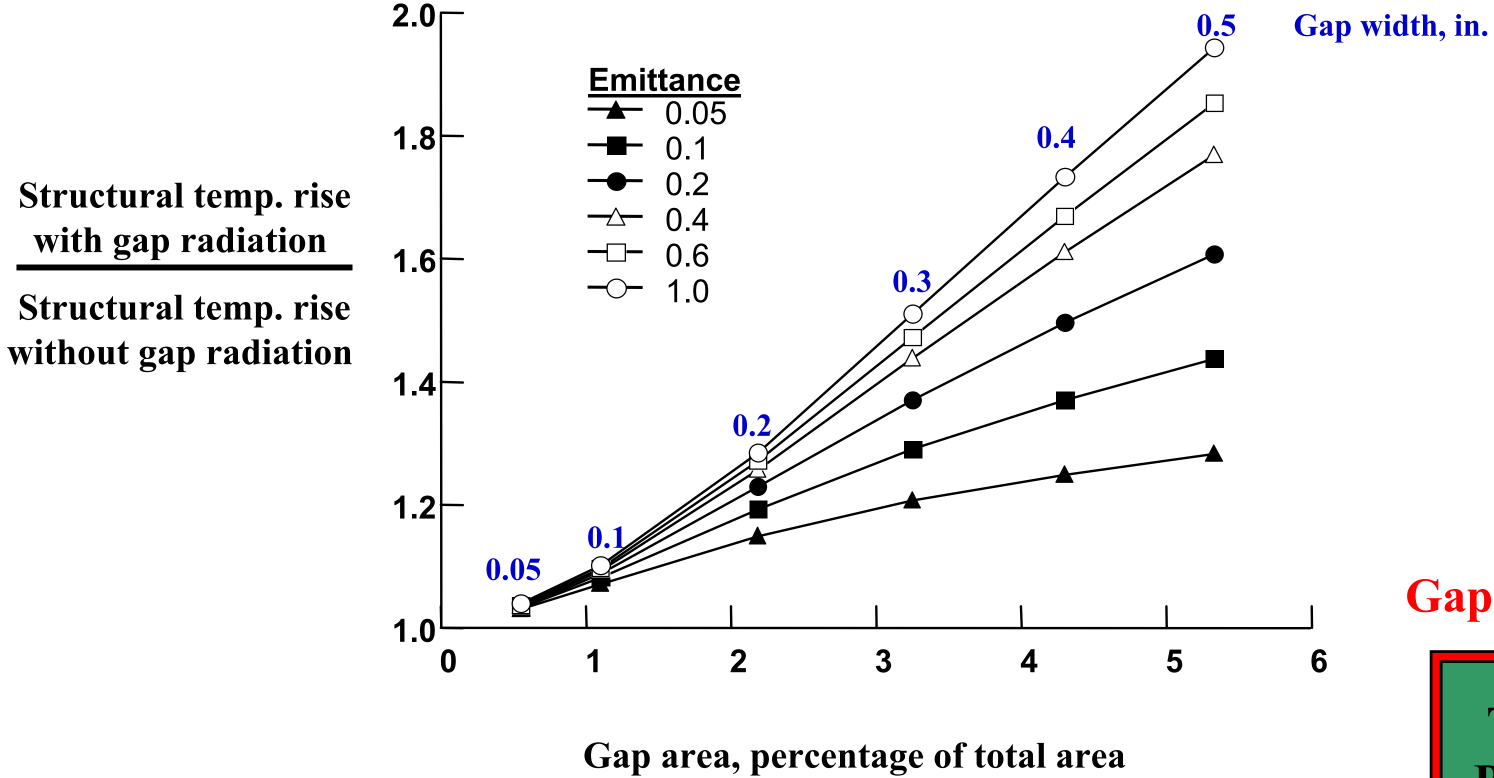


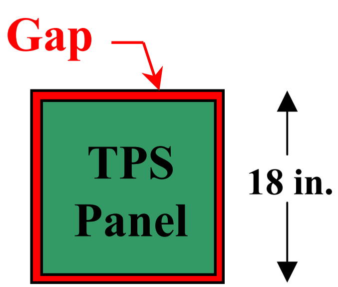


Thermal response of metallic TPS
(ignoring gap radiation)

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)**

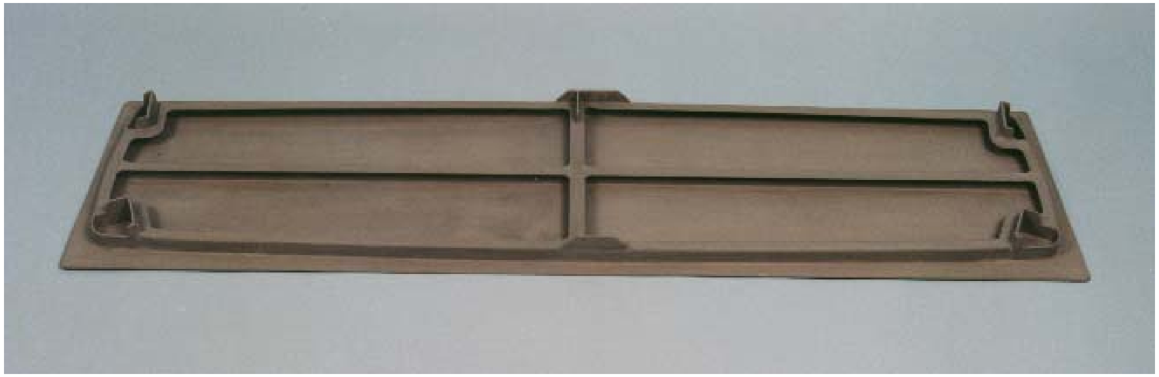
CURRENT TPS RESEARCH

CERAMIC TILES

- **AETB tile with TUFI/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**

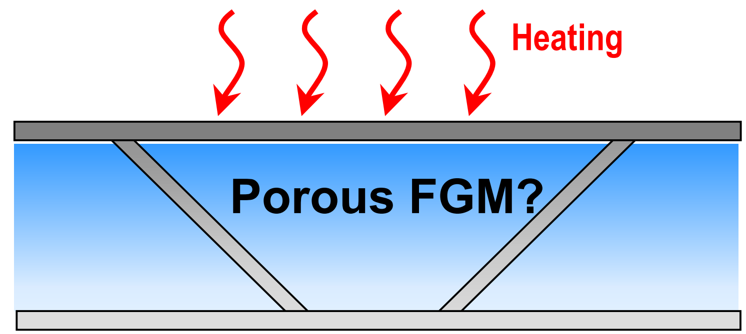
INTEGRATED MULTIFUNCTIONAL STRUCTURES

INTEGRATED MULTIFUNCTIONAL STRUCTURES

PRELIMINARY INTEGRATED CONCEPT CONSIDERATIONS

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

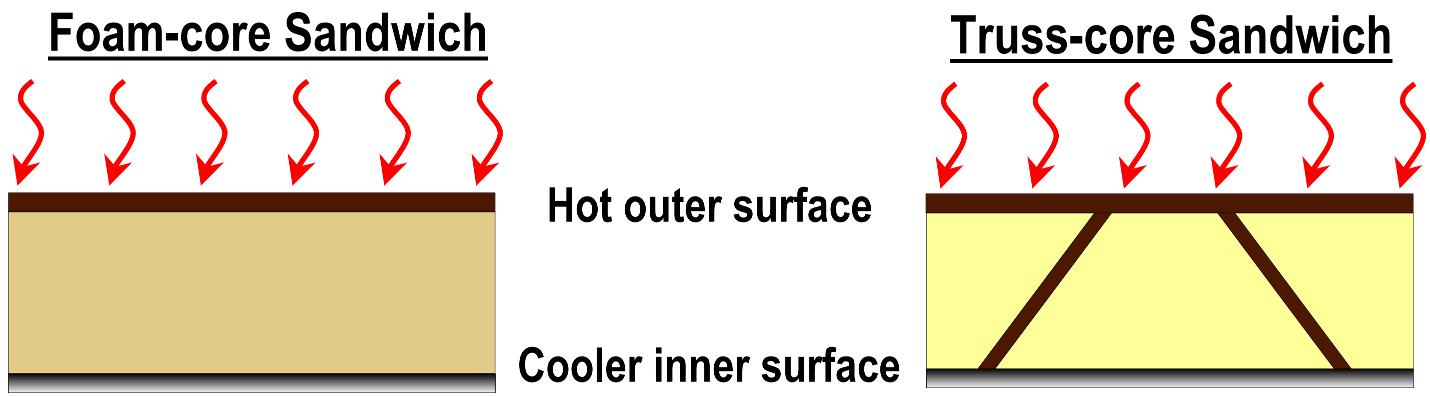
Intermediate material/structure
- Limits heat transfer
- Acceptable structural connection
- Candidate concepts
    - Discrete structural connections
    - Non-loadbearing insulation
    - Porous FGM
    - Structural foams
    - Enhanced heat storage (heat sponge)



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

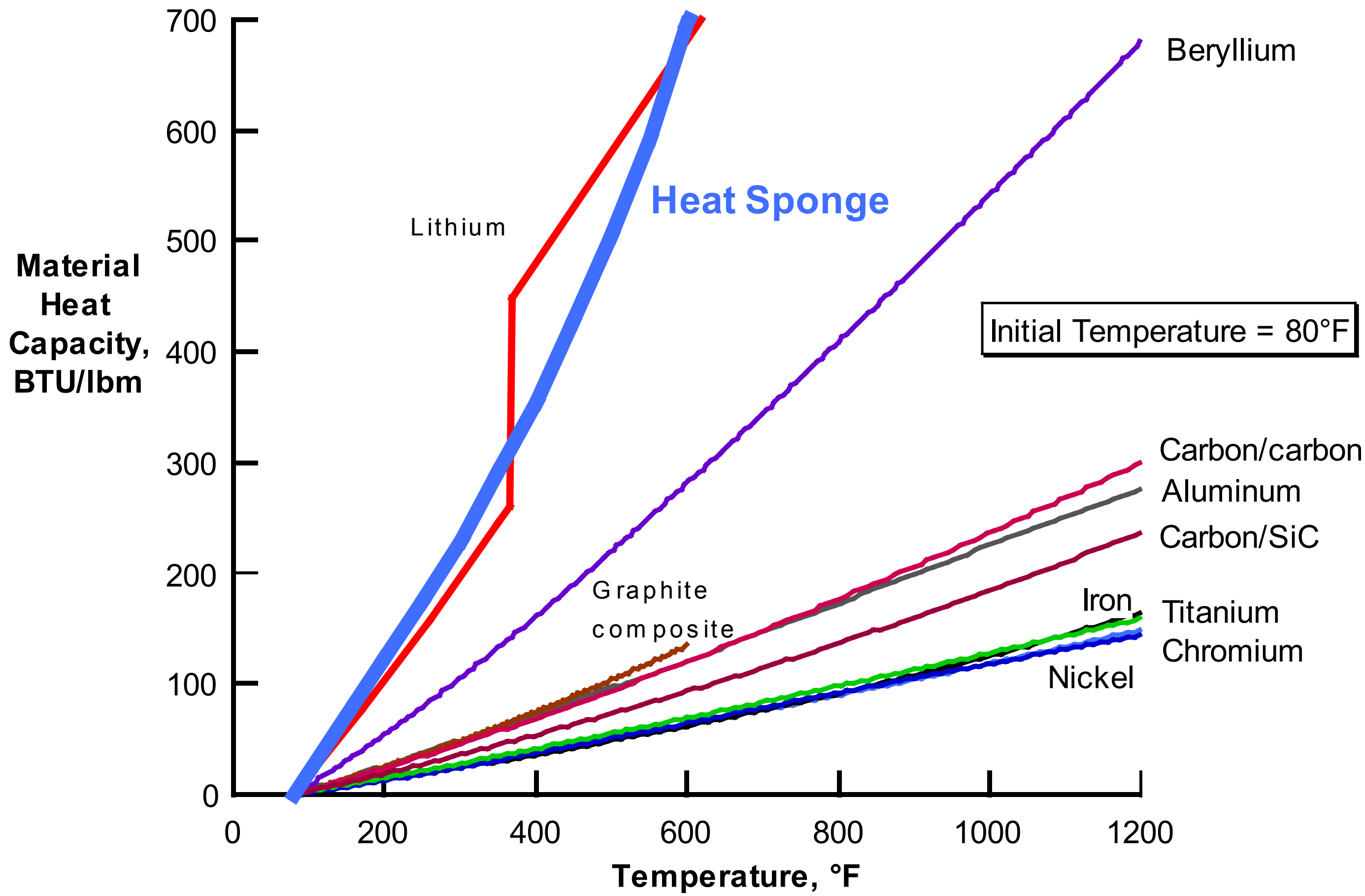


- **Insulating structural foam core**
  - **High temperature capability**
  - **Strain capability comparable to structural facesheets**
  - **Strength to perform as sandwich core**
  - **Low conductivity**

- **Truss core**
  - **Discrete connections between the hot and cool facesheets**
  - **Acceptable structural connections**
  - **Acceptable heat shorts**
- **Insulation**
  - **Load-bearing or non-load-bearing**

INTEGRATED MULTIFUNCTIONAL STRUCTURES

HEAT CAPACITY OF STRUCTURAL MATERIALS

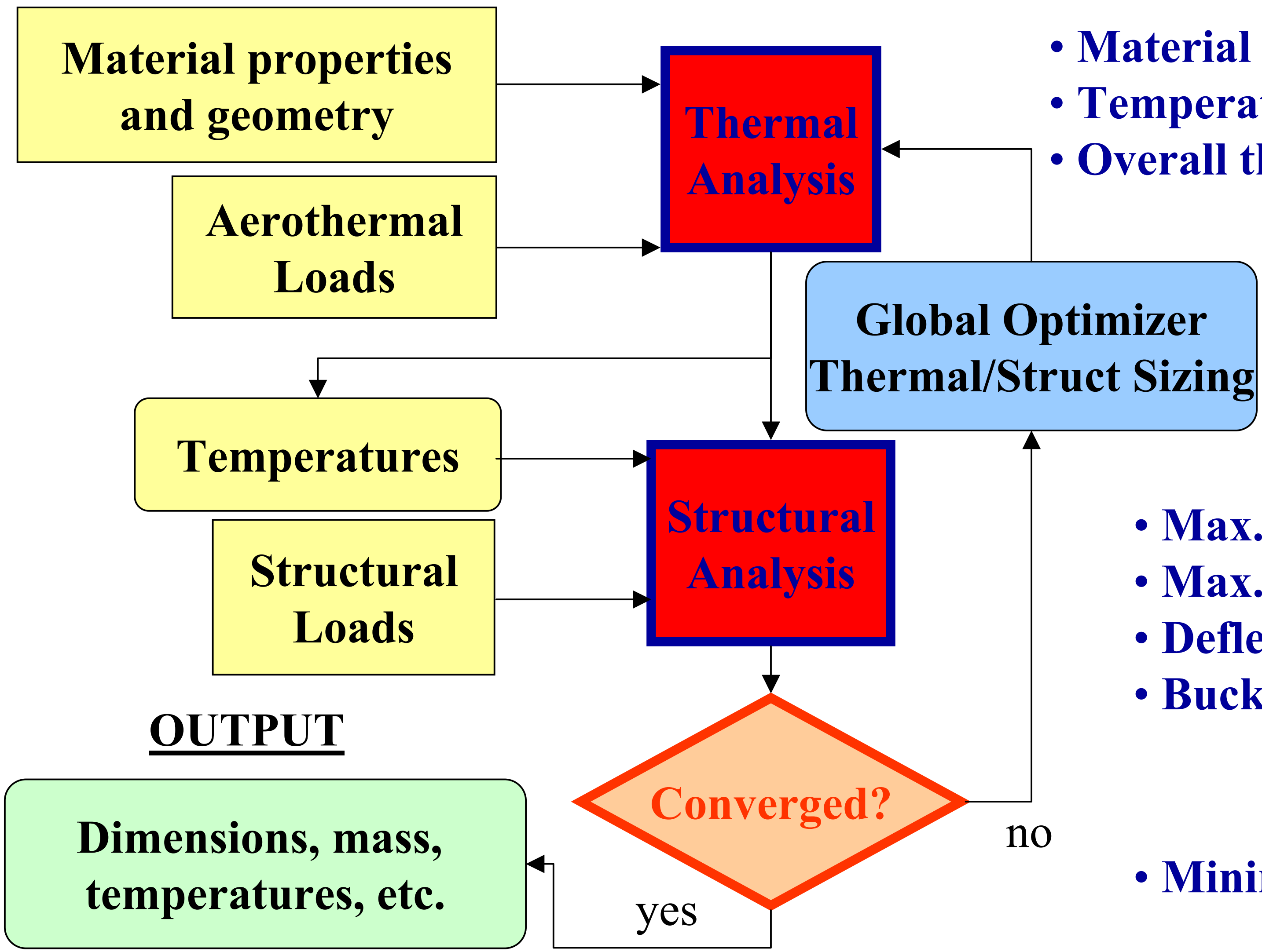


- **High heat capacity inner structure can reduce required insulation**
- **Heat capacity enhancement may be lighter than additional insulation**
- **Patent disclosure filed on Heat Sponge**

INTEGRATED MULTIFUNCTIONAL STRUCTURES

THERMAL/STRUCTURAL SIZING METHOD

INPUT **PROCESS** **CONSTRAINTS**



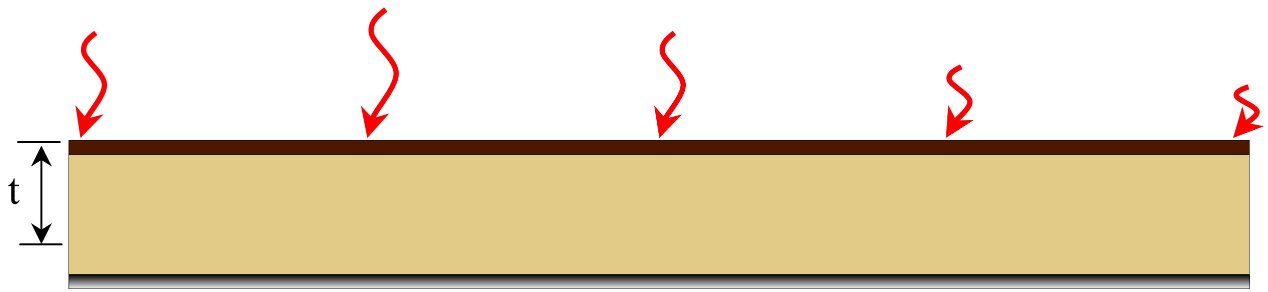
- Material temperature limits
- Temperature gradients
- Overall thickness?

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

- Minimize mass

INTEGRATED MULTIFUNCTIONAL STRUCTURES

HIGH THERMAL CONDUCTIVITY STRUCTURAL MATERIALS



High k inner structure

- 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

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

k_g^* - Thermal conductivity at 1 atm
Pr – Prandtl Number
L_c – characteristic length
α – accommodation coefficient
γ – ratio of specific heats
λ – mean free path

$$\lambda = \frac{\mathrm{K_B T}}{\sqrt{2}\pi\, \mathrm{d_g^2 P}}$$

P – pressure
T – temperature
K_B – Boltzman constant
d_g– gas collision diameter

METALLIC TPS : ANALYSIS

THERMAL CONDUCTIVITY OF HONEYCOMB SANDWICH

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

where:

$$f(\eta,\varepsilon) = 0.664(\eta+0.3)^{-0.69}\varepsilon^{1.63(\eta+1)^{-0.89}}$$

k_m – metal thermal conductivity
k_A – air thermal conductivity
t – thickness
T_o – temperature on outer surface
T_i – temperature on inner surface
ρ_{core} – h/c core density
ρ_m – metal density
ε – emittance
η – length/diameter of h/c core cell
σ – Stefan-Boltzman constant

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

where:

$$\Delta T = T_o - T_i$$

$$T_{av} = \frac{T_o + T_i}{2}$$

Neglecting this term

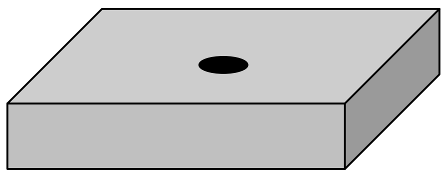
$$\boxed{k_{hc} = k_m\frac{\rho_{core}}{\rho_m} + 4t\sigma f(\eta,\varepsilon)T_{av}^3}$$

Modeled by separate conduction elements

METALLIC TPS : ANALYSIS

VENTING OF A METALLIC TPS PANEL

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

ρ_a – ambient air density

$P > P_a$

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

$P_a > P$

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

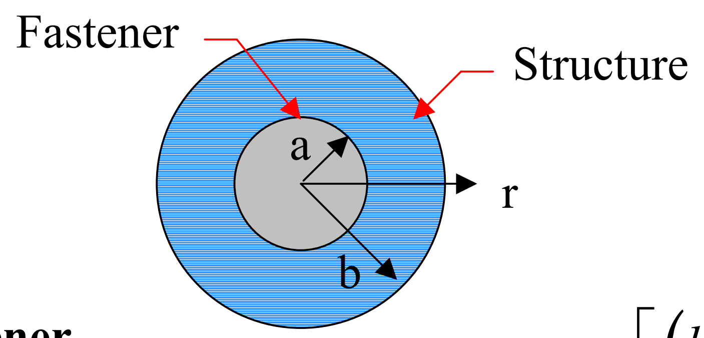
where

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

Internal insulation increases venting time

METALLIC TPS : ANALYSIS

THERMAL STRESS AROUND A CYLINDRICAL FASTENER



Fastener

$$\sigma_{r_f} = \sigma_{\theta_f} = -P$$

Structure

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

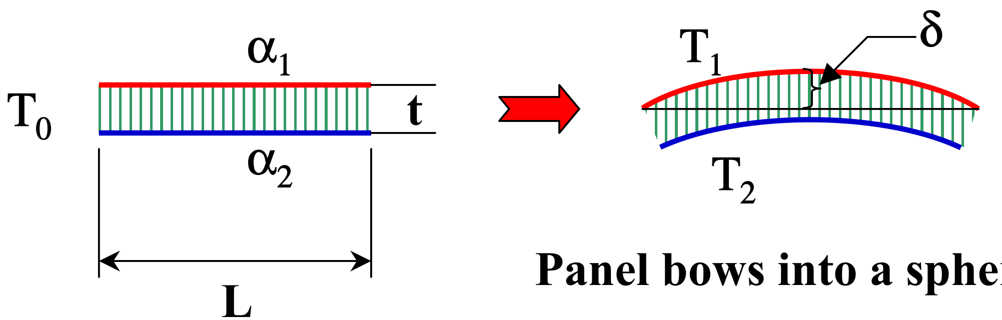
Where

$$P = \frac{E_s\left[\left(\frac{b}{a}\right)^2 - 1\right](\alpha_f - \alpha_s)\Delta T}{\left(\frac{b}{a}\right)^2(1+\nu_s) + (1-\nu_s) + \frac{E_s}{E_f}\left[\left(\frac{b}{a}\right)^2 - 1\right](1-\nu_f)}$$

METALLIC TPS : ANALYSIS

FREE THERMAL BOWING OF A SANDWICH PANEL

Sandwich Panel With Facesheets at Different Temperatures



Panel bows into a spherical segment

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

Simplifying: if $\alpha_1 T_1 << 1$ **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

$$q=\frac{k}{t}\Delta T \qquad \frac{m}{A}=t\rho$$

Minimize mass

Required thermal resistance

$$\frac{m}{A}=\boxed{\rho k}\,\frac{\Delta T}{q}$$

Minimize

- ***k – thermal conductivity***
- ***ρ – density***
- ***q – heat flux***
- ***m – mass***
- ***A – area***
- ***T – temperature***
- ***t - thickness***

Minimize ρk for minimum mass insulation in steady state

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