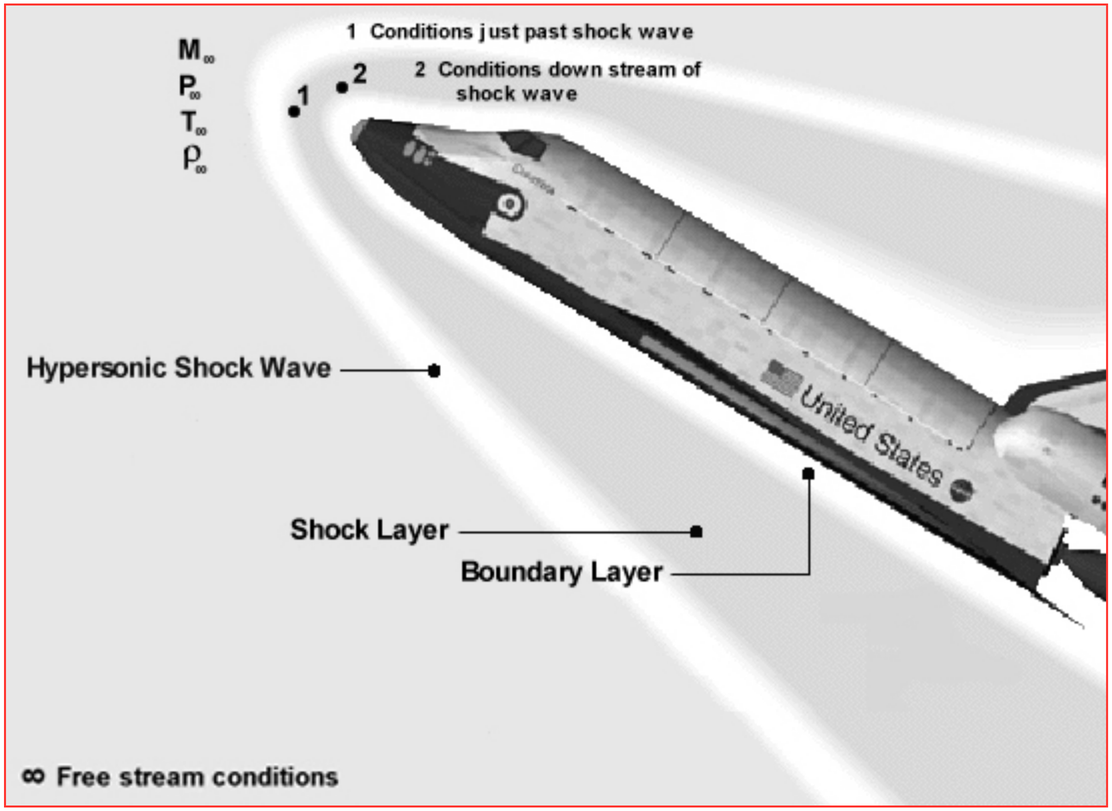
Appendix to Section 8: Space Shuttle Tile Thermal Protection System



Temperature Versus Heat (1)

• Often the concepts of heat and temperature are thought to be the same, but they are not.

• ***Temperature*** is a number that is related to the average kinetic energy due to the random motion of each molecule of a substance.

In Kelvin degrees, T is directly proportional to the average kinetic energy of the molecules.

• ***Heat*** is a measurement of the total energy in a substance. That total energy is made up of not only of the *kinetic energies* of the molecules of the substance, but total energy is also made up of the *potential energies* of the molecules.

Temperature Versus Heat (2)

- When heat, (i. e., energy), goes into a substance one of two things can happen:

1. The substance can experience a raise in temperature. That is, the heat can be used to speed up the molecules of the substance.

2. The substance can change state. For example, if the substance is ice, it can melt into water. This change does not cause a raise in temperature. The energy is used to change the bonding between the molecules. Ablative heat shields use this principal to protect reentering spacecraft

3. The degree of temperature change for a given heat input (loss) is the ***Heat Capacity***

Aerodynamic Heating on a Body

$$\frac{\partial}{\partial t}\iiint_{C.V.}\left(\rho\left(e+\frac{\left\|V^2\right\|}{2}\right)dv\right)+\iint_{C.S.}\rho\vec{V}\bullet d\vec{S}\left(e+\frac{\left\|V^2\right\|}{2}\right)=$$

$$\iiint_{C.V.}(\rho\vec{f}\,dv)\bullet\vec{V}-\iint_{C.S.}(pd\vec{S})\bullet\vec{V}+\iiint_{C.V.}\left(\rho\left(\dot{q}\right)dv\right)$$

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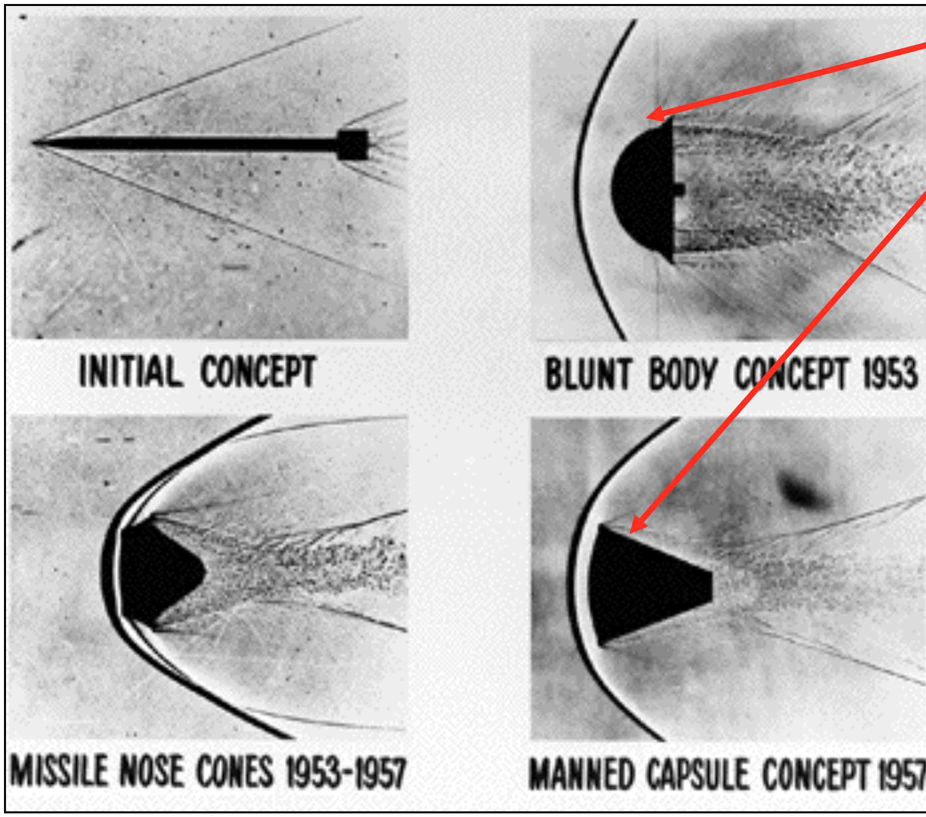
Hypersonic Vehicle Design

(cont'd)

- Heating vs. performance (Hypersonic Aerodynamics)

Heating is Minimized by Blunt Body
.. But so is Lift-to-Drag ratio



- Detached Normal Shockwave On Blunt Leading Edge Dissipates significant Portion of heat into flow

- But Also .. Produces High level of Drag

Heating proportional to

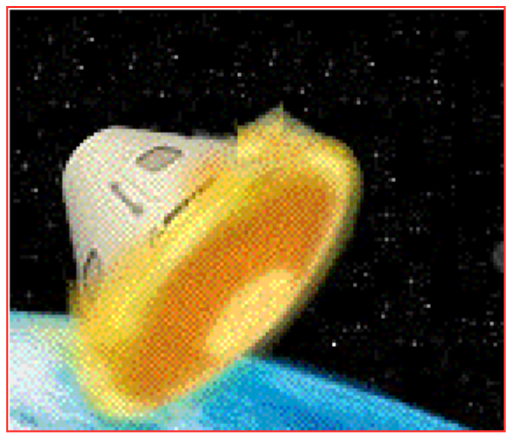
$1/R_{le}^{1/2}$

Stagnation Temperature for the Adiabatic Flow of a Calorically Perfect Gas (cont'd)

- Stagnation temperature is a measure of the Kinetic Energy of the flow Field.

- Largely responsible for the high Level of heating that occurs on high speed aircraft or reentering space Vehicles …

$$T_0 = T \cdot \left(1 + \frac{\gamma - 1}{2} \cdot M^2\right)$$



Compressibility Effects on Skin Friction Model (11)

$$\frac{u_{(y)}}{V_e} = \left(\frac{y}{\delta}\right)^{\frac{1}{7}}$$

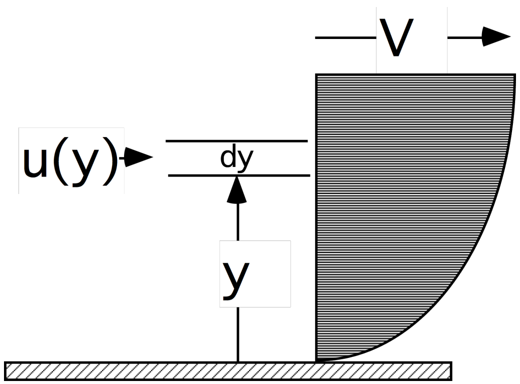
- Evaluating the Integral

$$T_{avg} = T_\infty + R_f \frac{V_\infty^2}{2 \cdot c_p} \cdot \frac{1}{\delta} \int_0^\delta \left[\left(1 - \frac{1}{R_f} \left[\left(\frac{y}{\delta} \right)^{1/7} \right]^2 \right) \right] \cdot dy = T_\infty + R_f \frac{V_\infty^2}{2 \cdot c_p} \cdot \frac{1}{\delta} \int_0^\delta \left[\left(1 - \frac{1}{R_f} \left(\frac{y}{\delta} \right)^{2/7} \right) \right] \cdot dy =$$

$$T_{avg} = T_\infty + R_f \frac{V_\infty^2}{2 \cdot c_p} \cdot \frac{1}{\delta} \left(y - \frac{1}{R_f} \frac{\delta \cdot \left(\frac{y}{\delta} \right)^{9/7}}{9/7} \right) \Big|_0^\delta = T_\infty + R_f \frac{V_\infty^2}{2 \cdot c_p} \cdot \left(1 - \frac{7}{9} \frac{1}{R_f} \right)$$

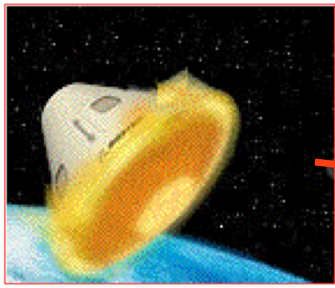
$$\boxed{T_{avg} = T_\infty + \frac{V_\infty^2}{2 \cdot c_p} \cdot \left(R_f - \frac{7}{9} \right)}$$

~ 2/9

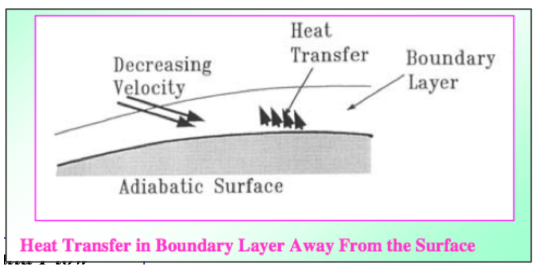


- ***Valid for 1/7 power Turbulent Flow***

Stagnation vs. Boundary Layer heating



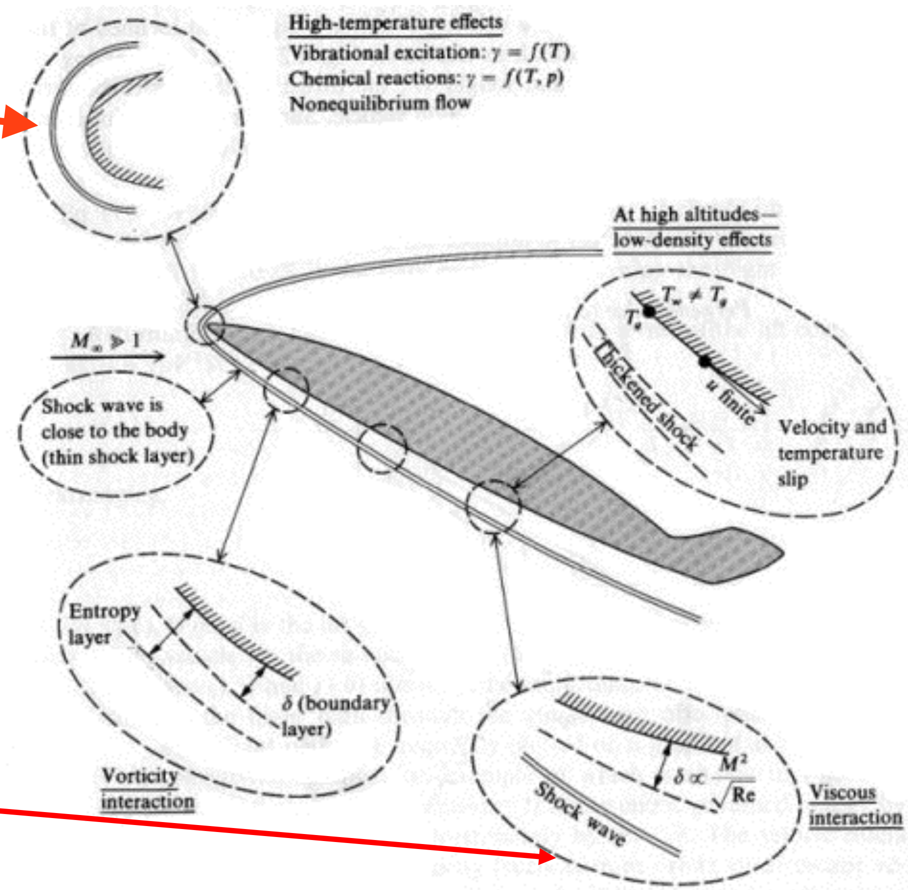
$$T_0 = T_\infty\left(1+\frac{\gamma-1}{2}M_\infty^{\;2}\right)$$



Heat Transfer in Boundary Layer Away From the Surface

$$T_{B.L.} = T_\infty + \left(R_f - \frac{7}{9}\right)\frac{V_\infty^{\;2}}{2\cdot C_p} =$$

$$T_\infty\left(1+\left(R_f-\frac{7}{9}\right)\left(\frac{\gamma-1}{2}\right)M_\infty^{\;2}\right)$$



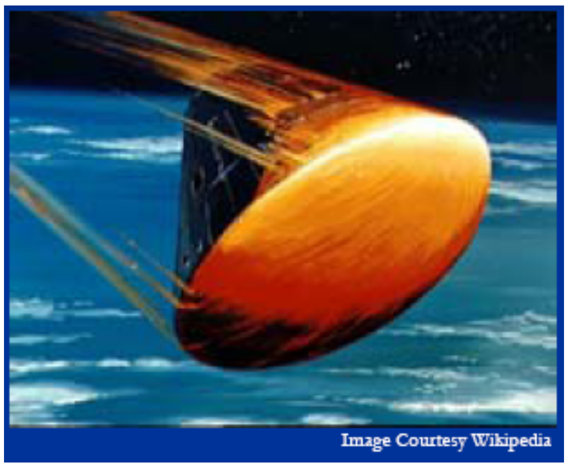
Ablation Example

-Heat shield consisting of phenolic resin in a metal “honeycomb” At high heat flux, resin

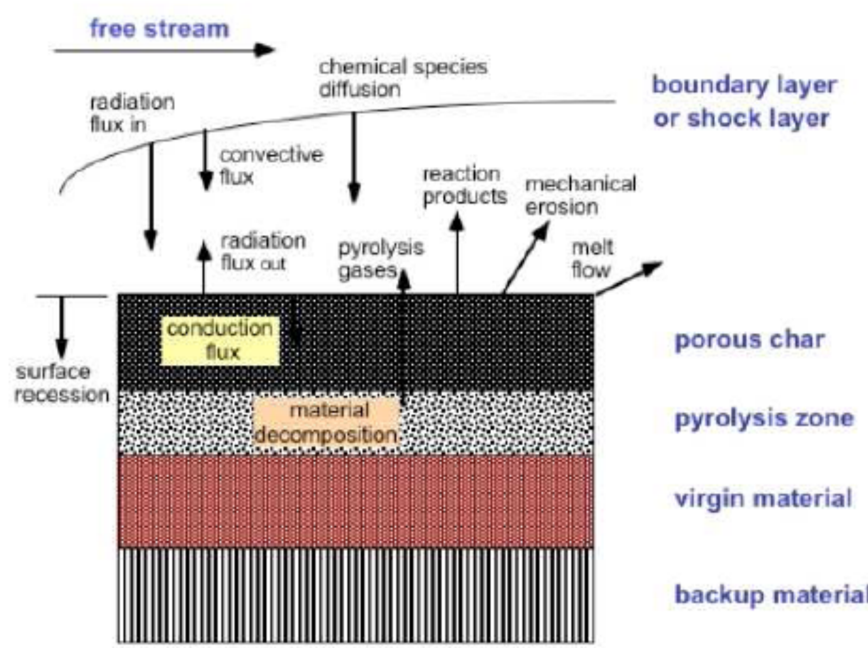
-Material decomposes via pyrolysis absorbing heat

-Products form a barrier between hot gasses and spacecraft structure

-Surface temperature remains low

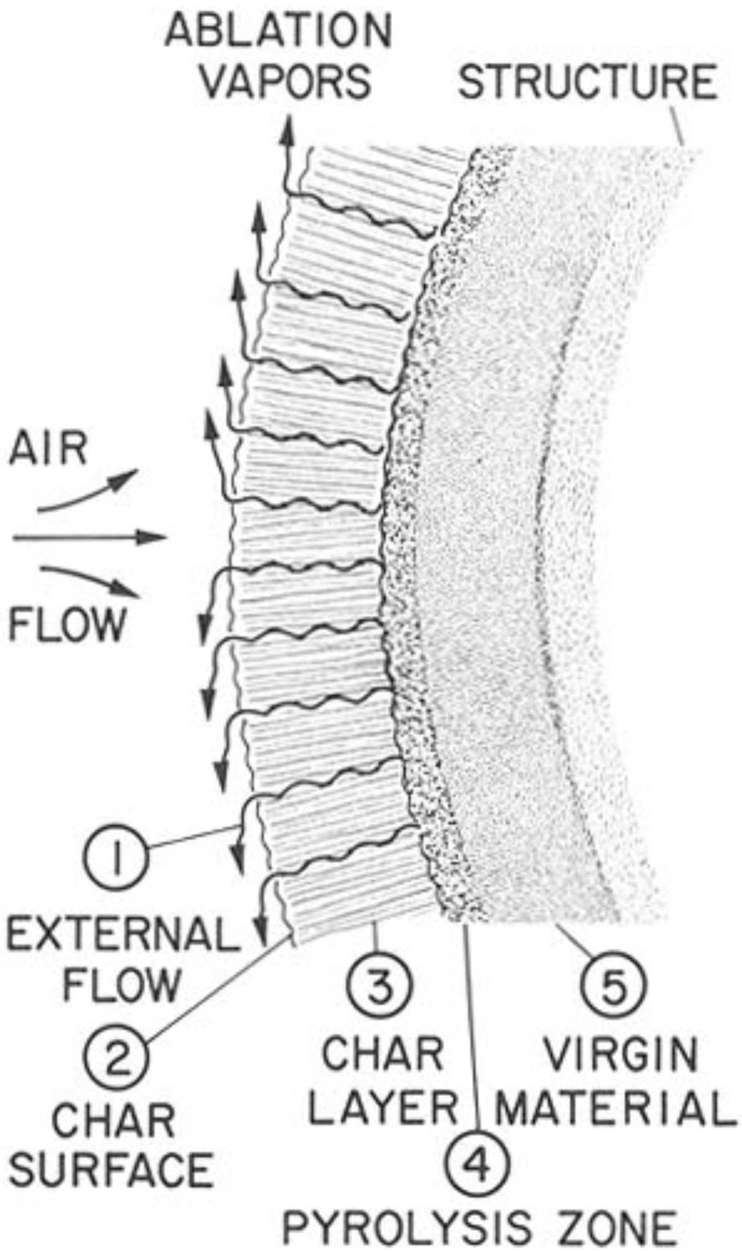


Laub, B. Thermal Protection Technology and Facility Needs for Demanding Future Planetary Missions, NASA Ames Research Center, October 2003



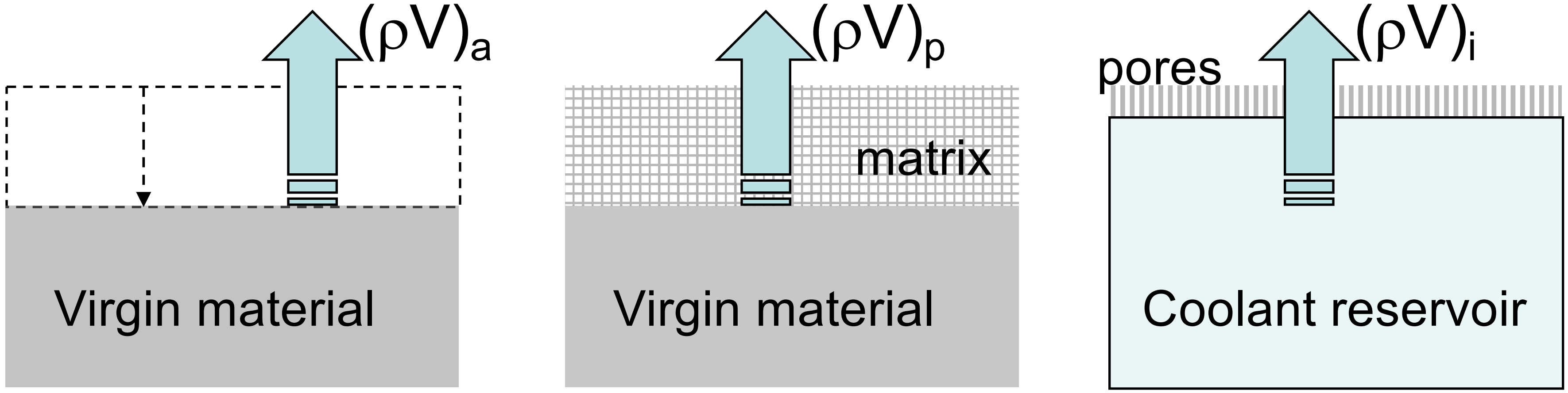
Energy accommodation mechanisms of ablative TPS materials

Heat blockage by mass transfer



- Direct injection of a coolant through a porous surface
- Vaporization of melted surface material
- Sublimation of the solid surface material
- Pyrolysis of surface material

Mass transfer mechanisms for TPS



Melting ablator | Pyrolitic surface | Porous surface

$$(\rho V)_a Q_a^* = (\rho V)_p Q_p^* = (\rho V)_i (h_i - h_w) = q_{c,w}$$

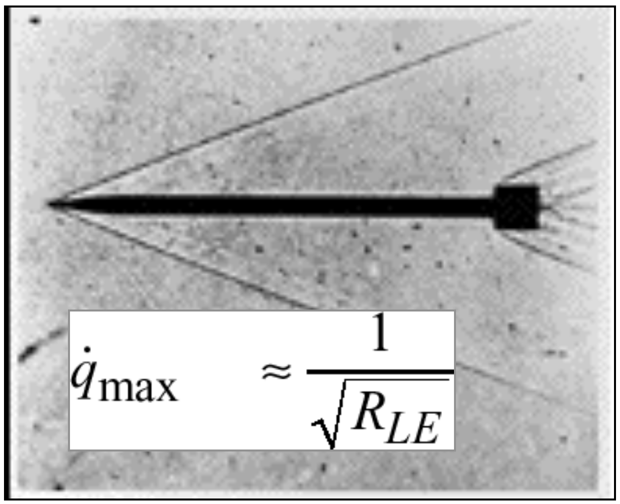
For Teflon, (in Btu/lb) an effective heat of ablation is

$$Q^* \approx 0.48(h_{s,e} - h_w) + 564$$

Hypersonic Vehicle Design

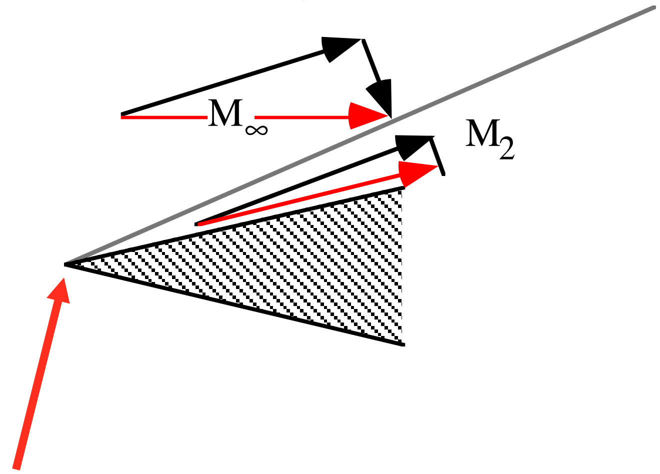
(cont'd)

- Sharp leading Edge has very high heating
  But Much Lower Hypersonic Supersonic Lift-to-Drag



$$\dot{q}_{max} \approx \frac{1}{\sqrt{R_{LE}}}$$

Oblique Shockwave

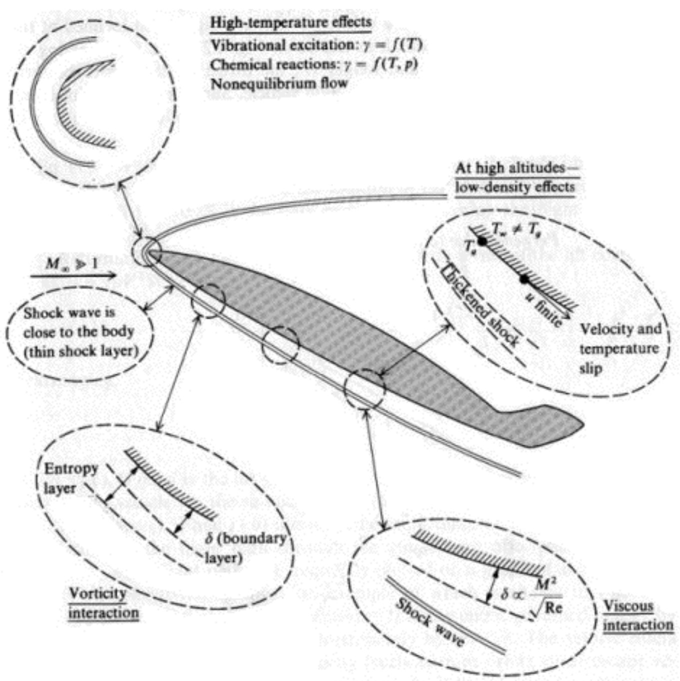


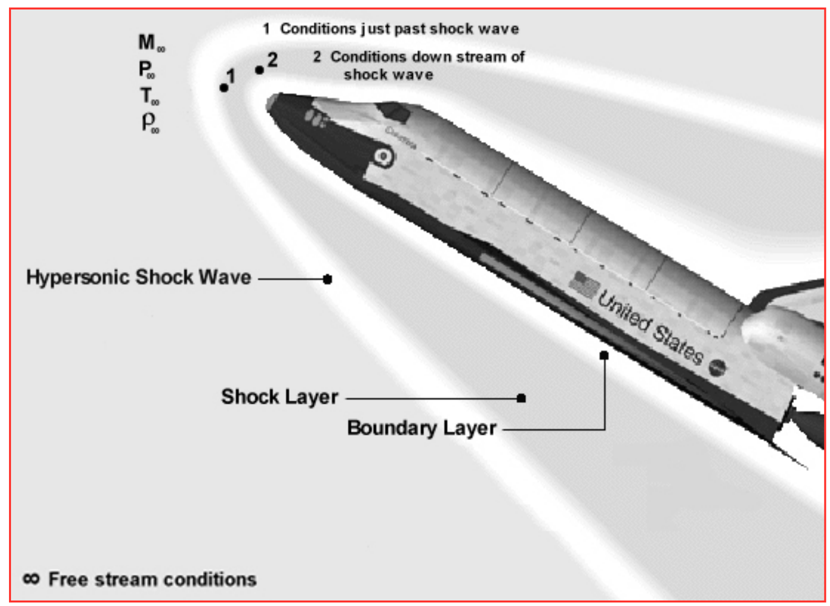
- Flow attached at leading edge
  Heating impinges directly

- More Exotic Thermal Protection
  Systems Required

Thermal Soak

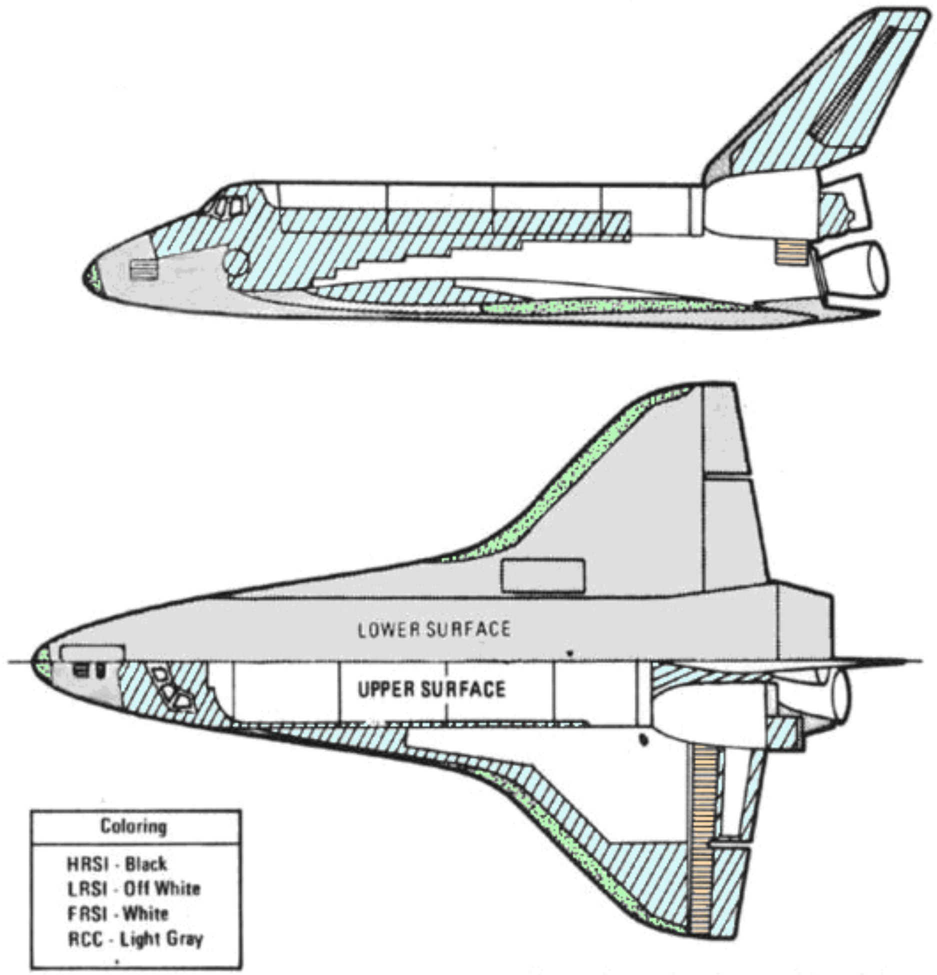
- Space Shuttle Thermal Protection System "soaks up" heat and stores it internally due to its very high heat capacity and low thermal conductivity

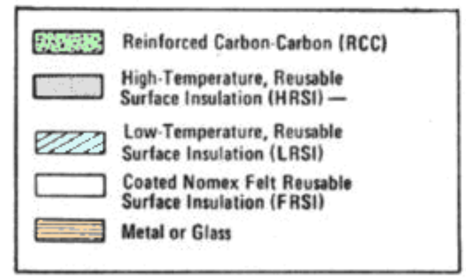




Thermal Soak (2)

- Space Shuttle Thermal Protection System (TPS) “soaks up” heat and stores it internally due to TPS very high heat capacity and low thermal conductivity





Element*	Area, sq m (sq ft)	Weight, kg (lb)
FRSI	332.7 (3581)	532.1 (1173)
LRSI	254.6 (2741)	1014.2 (2236)
HRSI	479.7 (5164)	4412.6 (9728)
RCC	38.0 (409)	1697.3 (3742)
Miscellaneous		918.5 (2025)
Total	1105.0 (11895	8574.7 (18,904

*Includes bulk insulation, thermal barriers, and closeouts

Thermal Protection System, Orbiter 102

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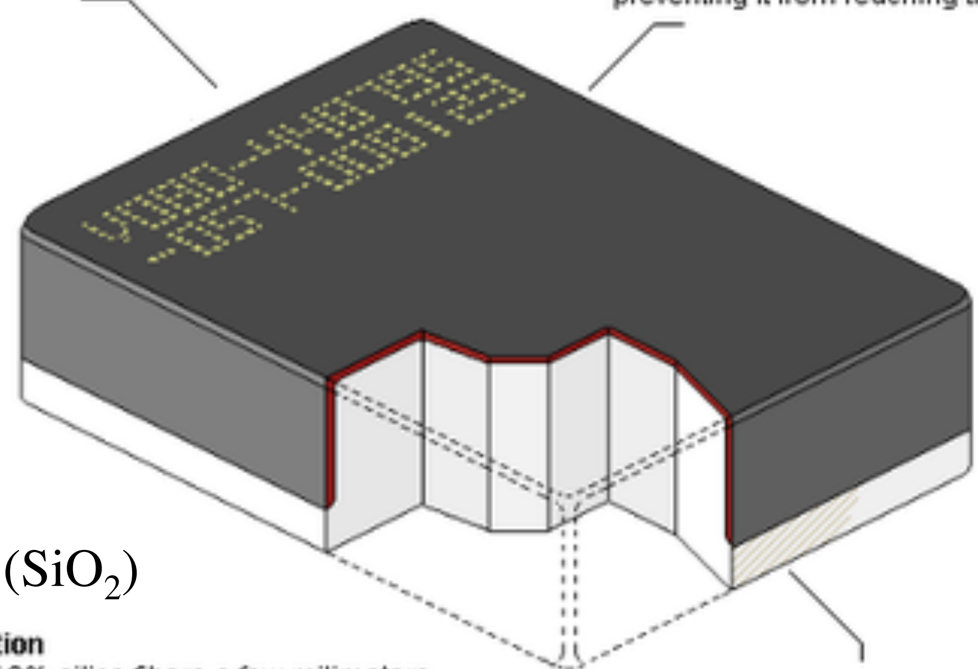
Mechanical & Aerospace Engineering

Thermal Soak (3)

Coating
The outer portion of a tile is covered with a black-glazed coating of borosilicate. These tiles do most of the coating job by shedding about 95% of the heat encountered. The remaining 5% is absorbed by the tile's interior, preventing it from reaching the orbiter's aluminum skin.

Identification number
Each tile has an identification number which tells batch and location. This number can be fed into a computer to produce an identical tile.



HSRI Shuttle Tile (High Temperature Reusable Surface Insulation)

One of the best "heat soaks" in the world

Mostly made up of empty space

Silica (SiO_2)

Composition
90% air, 10% silica fibers a few milimeters thick. The tiles feels similar to plastic foam. The silica fibers are derived from high-quality sand.

Glue
A silicon-rubber glue similar to common bathtub caulking, bonds a tile to a felt pad, that is in turn bonded to the orbiter's skin. The felt absorbs the stresses of airframe bending that could damage the tiles.

Thermal Soak (4)

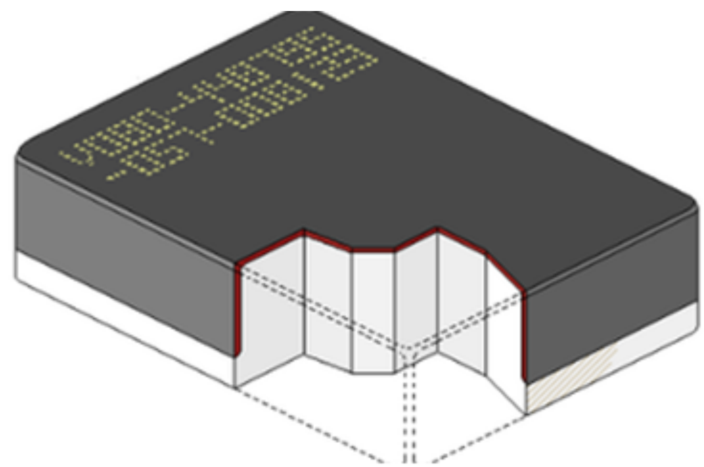
Density	144.2 kg/m^3 (9 lb/ft^3 LI-900) 352.5 kg/m^3 (22 lb/ft^3 LI-2200)
Specific heat	0.628 KJ/kg-K (0.15 BTU/lb-^{o}F)
Thermal conductivity	0.0485 W/m-k (0.028 BTU/ft-hr-^{o}F) at 21 ^{o}C) 0.126 W/m-k (0.073 BTU/ft-hr-^{o}F at 1093 ^{o}C)
Maximum reuse temperature	>1260 ^{o}C
Maximum single use temperature	1538 ^{o}C
Reusability at 2300 ^{o}F	>100 missions

Compare Shuttle Tile Thermal Conductivity to Conventional Materials

Material	Thermal conductivity W/(m·K)
Shuttle Tile (LI-900)	0.048-0.126
Air	0.025
Rubber	0.16
Thermal grease	0.7 - 3
Thermal epoxy	1 - 7
Glass	1.1
Concrete, stone	1.7
Sandstone	2.4
Stainless steel	12.11 ~ 45.0
Lead	35.3
Aluminium	220 (pure) 120--180 (alloys)
Gold	318
Copper	380
Silver	429
Diamond	900 - 2320

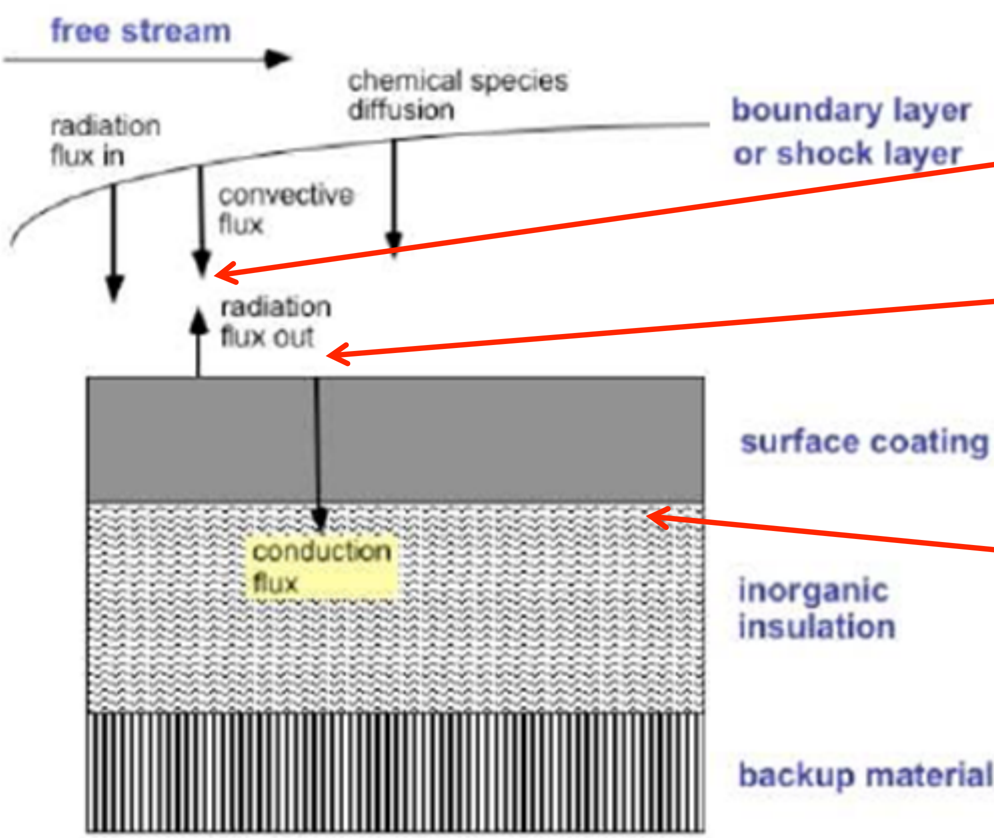
More or Less … Only Air is a better insulator (except for exotic materials like aero gels)

… a copper penny conducts heat almost 7000 Times faster than a shuttle tile



What Happens as Shuttle Tile is Heated?

"heat transfer rate per unit area"



$$\left(\dot{q}_{in}\right)_{convective} = \left(\varepsilon\sigma T^4\right)_{radiation\ back\ from\ surface} - \left(k\frac{\partial T}{\partial x}\right)_{conduction\ into\ tile\ (soak)}$$

$$\sigma = 5.670400(40) \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$$

What Happens as Shuttle Tile is heated? (2)

Because thermal conductivity of shuttle tile is so low … heat is radiated back from the surface faster than it is absorbed into the body

--- *Assume 1260 C surface temperature*

--- *80 C interior wall temperature*

--- *10 cm thick tile*

Always work in absolute temperature units

$$\left(\varepsilon\sigma T^4\right)_{\substack{radiation \\ back\ from \\ surface}} = 0.85 \cdot 5.6704\times10^{-8}\,(1260+273)^4\left(\frac{1}{100}\right)^2$$

= 26.62 W/cm²

Tile radiates back 180 times more heat than it Conducts into the structure!

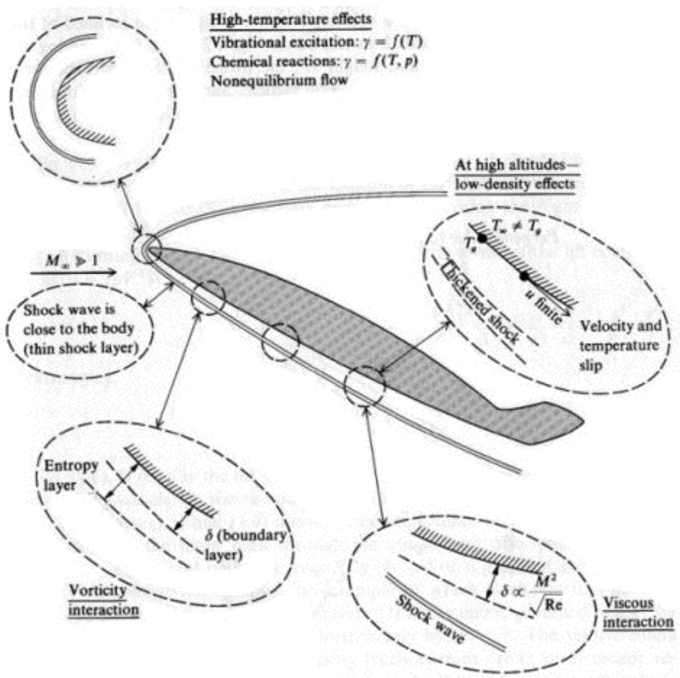
$$-\left(k\frac{\partial T}{dx}\right)_{\substack{conduction \\ into\ tile\ (soak)}} = 0.126\,\frac{(1260-80)}{0.1}\left(\frac{1}{100}\right)^2$$

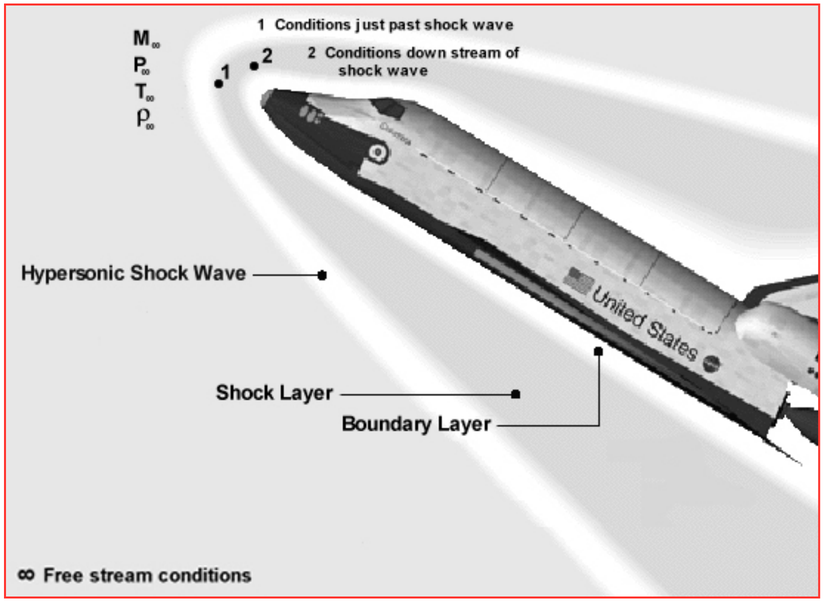
= 0.149 W/cm²

"heat transfer rate per unit area"

Thermal Soak (Revisited)

- Space Shuttle Thermal Protection System "soaks up" heat and stores it internally due to its very high heat capacity and low thermal conductivity



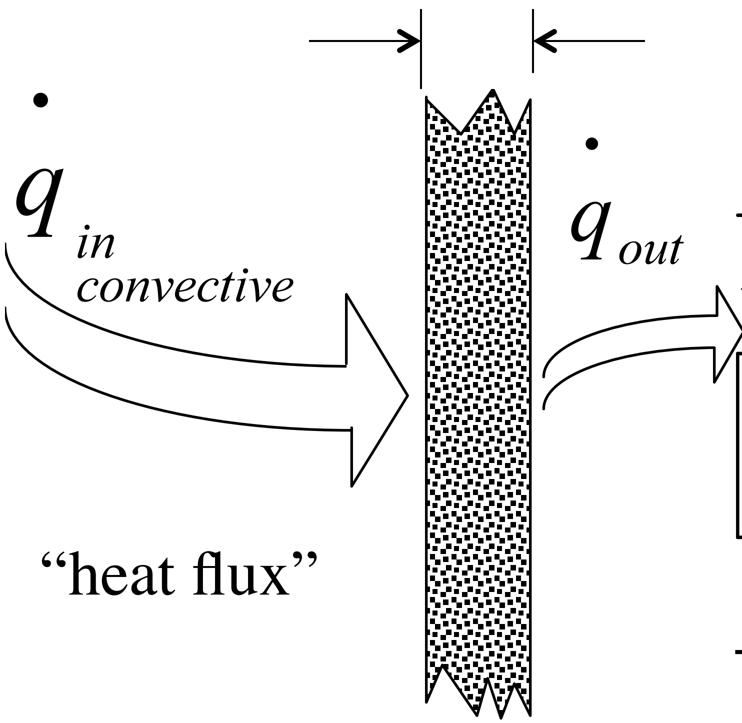


What Happens as Shuttle Tile is heated? (3)

But the Shuttle Tiles Still Stored a Lot of Heat That Had to be Removed Post Landing!

What Happens when a penny is heated? (2)

- Wall gradient is rapidly neutralized and whole penny heats up … no insulation properties at all



$$\frac{1}{A_{surf}}\left[\left(\frac{\partial q}{dt}\right)_{in} - \left(\frac{\partial q}{dt}\right)_{out}\right] = \frac{M \cdot c_p}{A_{surf}}\frac{\partial T}{dt} \rightarrow$$

$$\dot{Q}_{in} - \dot{Q}_{out} = \rho \cdot c_p \cdot \tau_{wall}\frac{\partial T}{dt}$$

$$\rightarrow \dot{Q} \sim \text{"heat flux"} \sim \frac{J}{m_2 \sec}$$

What Happens as penny is heated?

$c_p = 388 \frac{J}{kg^\circ K}$

$\rho = 7140 \frac{kg}{m^3}$

$\varepsilon \sim 0.85$

$k = 380 \ W/m-K$

$penny \sim 1.5 \ mm \ thick$

"heat transfer rate per unit area"

$$\left(\varepsilon\sigma T^4\right)_{\substack{radiation\\back\ from\\surface}} = 0.85 \cdot 5.6704\times 10^{-8}(1260+273)^4\left(\frac{1}{100}\right)^2$$

= 26.62 W/cm²

Penny would conduct almost 1000 times more heat into structure!

$$-\left(k\frac{\partial T}{dx}\right)_{\substack{conduction\\into\ tile\ (soak)}} = 0.380\frac{(1260-80)}{0.15}100$$

= 29,893 W/cm²

Ouch!