Entry Aerodynamics

- Review of basic fluid parameters
- Heating rate parameters
- Stagnation point heating
- Heating on vehicle surfaces

Basic Fluids Parameters

$$M \equiv \text{Mach Number} = \frac{v}{a}$$

$$a \equiv \text{speed of sound} = \sqrt{\gamma R T} \qquad \left(R = \frac{\Re}{\bar{m}} \right)$$

$$\frac{\text{ordered energy}}{\text{random energy}} = \frac{\frac{1}{2} m v^2}{\frac{1}{2} m \bar{v}_g^2} = \frac{v^2}{3RT} = \frac{\gamma}{3} \frac{v^2}{a^2} = \frac{\gamma}{3} M^2$$

$$Re \equiv \text{Reynold's number} = \frac{\text{inertial force}}{\text{viscous force}}$$

$$Re = \frac{\dot{m} v}{\tau A} = \frac{\rho A v^2}{\mu \frac{v}{L} A} = \frac{\rho v L}{\mu}$$

More Fluid Parameters

$$K \equiv \text{Knudsen number}$$

$$K = \frac{\text{number of collisions with body}}{\text{number of collisions with other molecules}}$$

$$K = \frac{\lambda}{L}$$

$$\lambda \equiv \text{mean free path}$$

$$L \equiv \text{vehicle characteristic length}$$

Prandtl Number

$$Pr = \mu \frac{C_p}{K}$$

$$\text{where } C_p \equiv \text{specific heat at constant pressure}$$

$$K \equiv \text{thermal conductivity}$$

$$\mu \equiv \text{viscosity}$$

$$Pr \propto \frac{\text{frictional dissipation}}{\text{thermal conduction}}$$

$$Pr \approx 0.715 \text{ for air at standard conditions}$$

Sutherland's Law (empirical)

- viscosity depends on temperature

$$\frac{\mu}{\mu_{ref}} = \left(\frac{T}{T_{ref}}\right)^{3/2} \frac{T_{ref} + S}{T + S}$$

$$\text{for air:} \quad \mu_{ref} = 1.789 \times 10^{-5} \ \frac{kg}{m \cdot sec}$$

$$T_{ref} = 288 \ K$$

$$S = 110 \ K$$

- good to several thousand degrees

Stanton Number

- applies to boundary layer problems

$$S_T = \frac{\dot{q}_w}{\rho_e v_e (H_{aw} - H_w)}$$

$$H \equiv \text{enthalpy}$$

$$= C_p T \text{ for perfect gas}$$

$$H_w = \text{enthalpy at the wall}$$

$$H_{aw} = \text{enthalpy at an adiabatic wall}$$

$$\text{for } H_{aw}, \quad \left(\frac{\partial T}{\partial z}\right)_w = 0$$

Approximating H_{aw}

$$H_o = H_e + \frac{u_e^2}{2} \Longleftarrow \text{total enthalpy at edge of boundary layer}$$

$$H_{aw} = H_e + r\frac{u_e^2}{2} \qquad r \equiv \text{recovery factor}$$

$$H_{aw} = H_e + r(H_o - H_e)$$

$$\text{for incompressible flow, } r \approx \sqrt{Pr}$$
$$= 0.845 \text{ for std. air}$$

r decreases only 2.4% from M=0 to M=16

$$\Longrightarrow \text{fairly constant!}$$

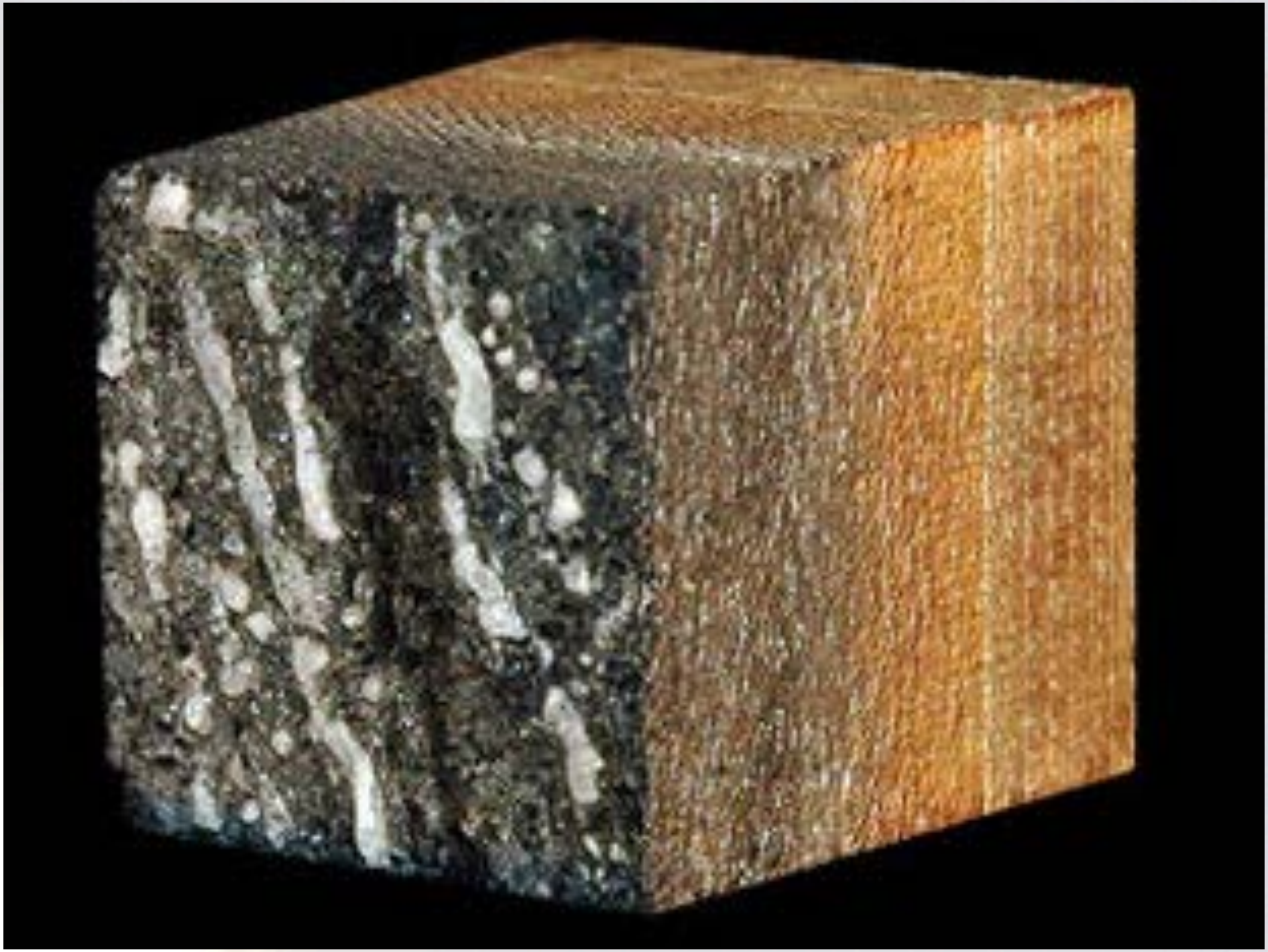
Reynold's Analogy

$$\frac{S_T}{c_f} = \frac{1}{2} Pr^{-2/3}$$

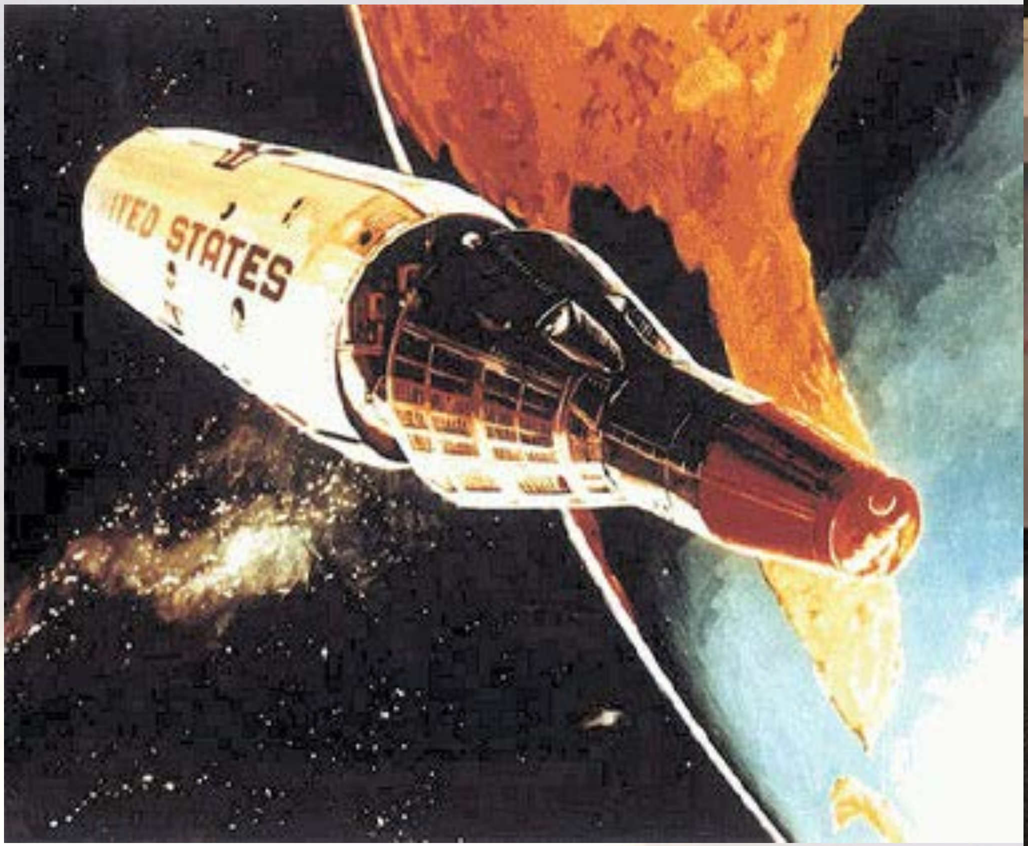
$$c_f \equiv \text{skin friction coefficient}$$

$$\text{since } Pr \approx 1, \quad S_T \approx \frac{c_f}{2} \qquad \Longleftarrow \text{Reynold's Analogy}$$

Mercury Heat Shield Section



Gemini MOL Heat Shield

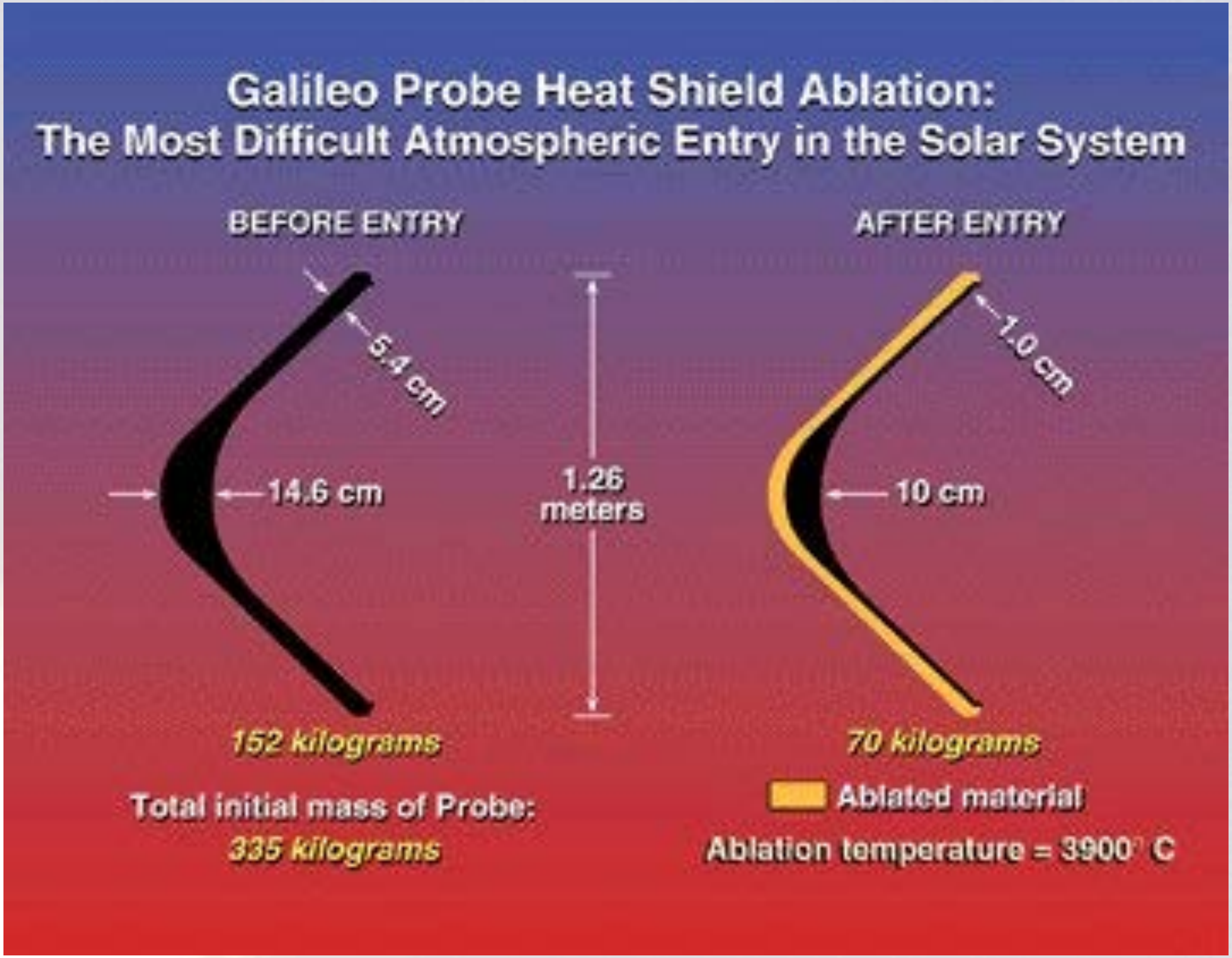


Apollo 11 Heat Shield

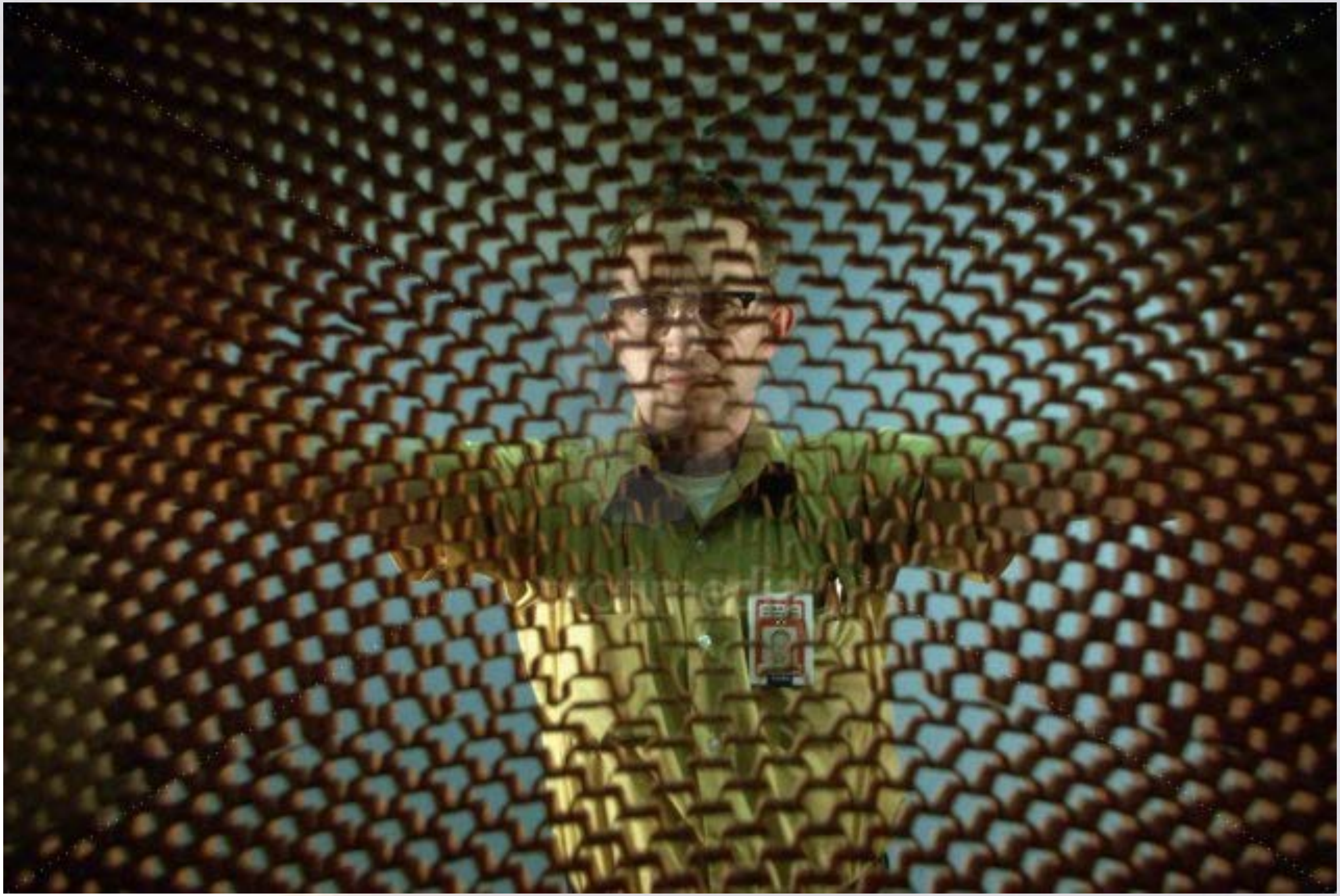
Orion Heat Shield

Phenolic Impregnated Carbon Ablator (PICA)

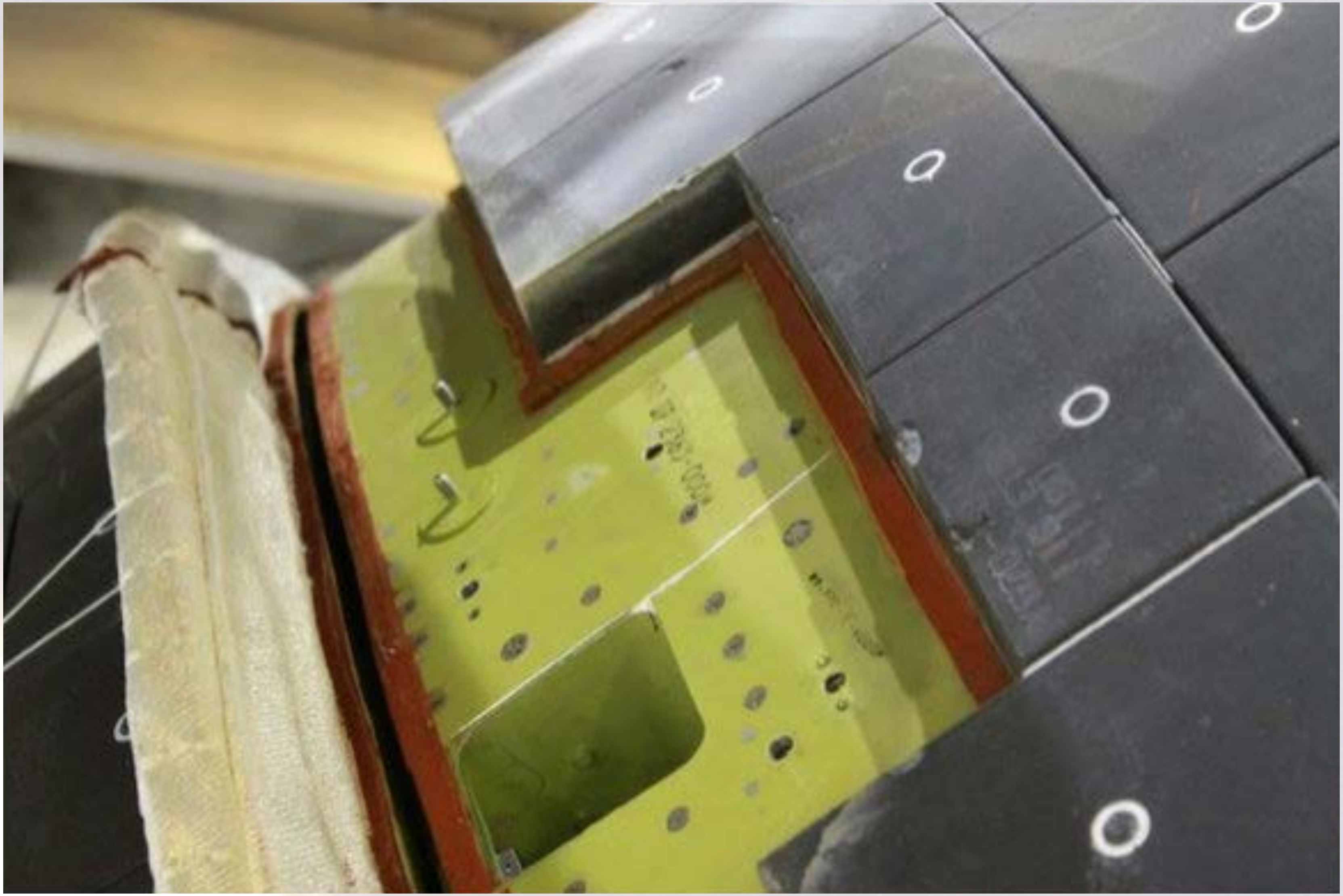
Galileo Jupiter Probe Heat Shield



Heat Shield Internal Structure



Shuttle Tile Installation



Inflatable Heat Shield (Suborbital Test)