Thermal Analysis and Design

- Lecture #22 – November 9, 2023
- Update of ENAE 484 project assignments
- Fundamentals of heat transfer
- Radiative equilibrium
- Surface properties
- Non-ideal effects
  - Internal power generation
  - Environmental temperatures
- Conduction
- Thermal system components

Collaborative Exploration Rovers (GSFC)

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Gustavo Lang Jr
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Section 0101: TuTh 11:00-12:15

Mars Simulation at the Moon (RASC-AL)

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Section 0103: MW 12:00-1:15

Large-Scale Lunar Prospector (RASC-AL)

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Section 0104: MW 3:30-4:45

Sustained Lunar Infrastructure (RASC-AL)

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Ethan Goldberg

Zachary Argo

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Section 0105: TuTh 2:00-3:15

Classical Methods of Heat Transfer

- Convection
  - Heat transferred to cooler surrounding gas, which creates currents to remove hot gas and supply new cool gas
  - Don't (in general) have surrounding gas or gravity for convective currents
- Conduction
  - Direct heat transfer between touching components
  - Primary heat flow mechanism internal to vehicle
- Radiation
  - Heat transferred by infrared radiation
  - Only mechanism for dumping heat external to vehicle

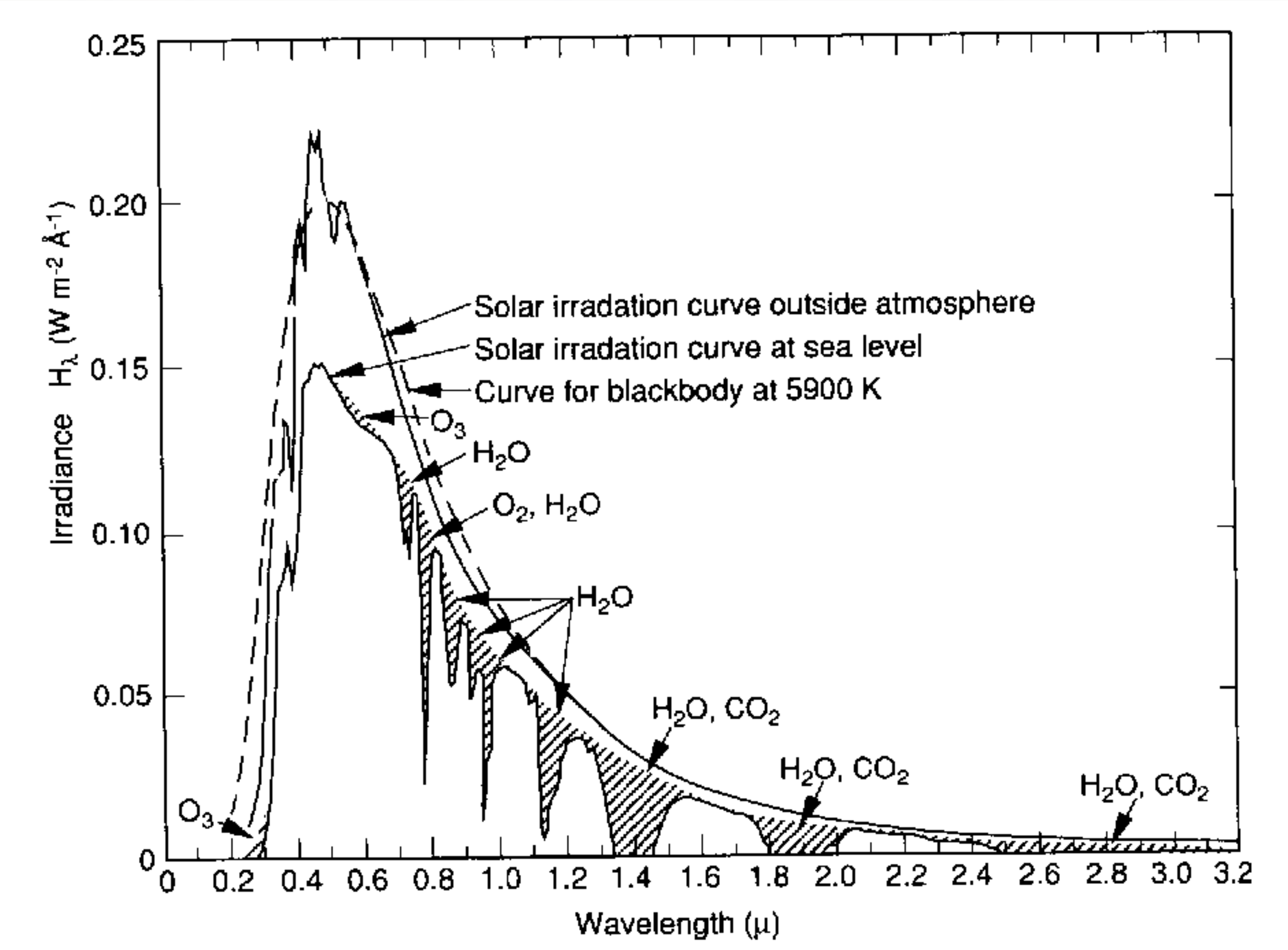
Ideal Radiative Heat Transfer

Planck's equation gives energy emitted in a specific frequency by a black body as a function of temperature

$$e_{\lambda b} = \frac{2\pi h C_0^2}{\lambda^5 \left[\exp\left(\frac{-hC_0}{\lambda k T}\right) - 1\right]}$$

(Don't worry, we won't actually use this equation for anything…)

The Solar Spectrum



Ref: V. L. Pisacane and R. C. Moore, Fundamentals of Space Systems   Oxford University Press, 1994

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- Stefan-Boltzmann equation integrates Planck's equation over entire spectrum

$$P_{rad} = \sigma T^4 \qquad \sigma = 5.67x10^{-8} \frac{W}{m^2 K^4}$$

("Stefan-Boltzmann Constant")

Thermodynamic Equilibrium

- First Law of Thermodynamics

$$Q - W = \frac{dU}{dt}$$

heat in -heat out = work done internally

- Heat in = incident energy absorbed
- Heat out = radiated energy
- Work done internally = internal power used
  (negative work in this sense - adds to total heat in the system)

Radiative Equilibrium Temperature

- Assume a spherical black body of radius r
- Heat in due to intercepted solar flux

$$Q_{in} = I_s \pi r^2$$

- Heat out due to radiation (from total surface area)

$$Q_{out} = 4\pi r^2 \sigma T^4$$

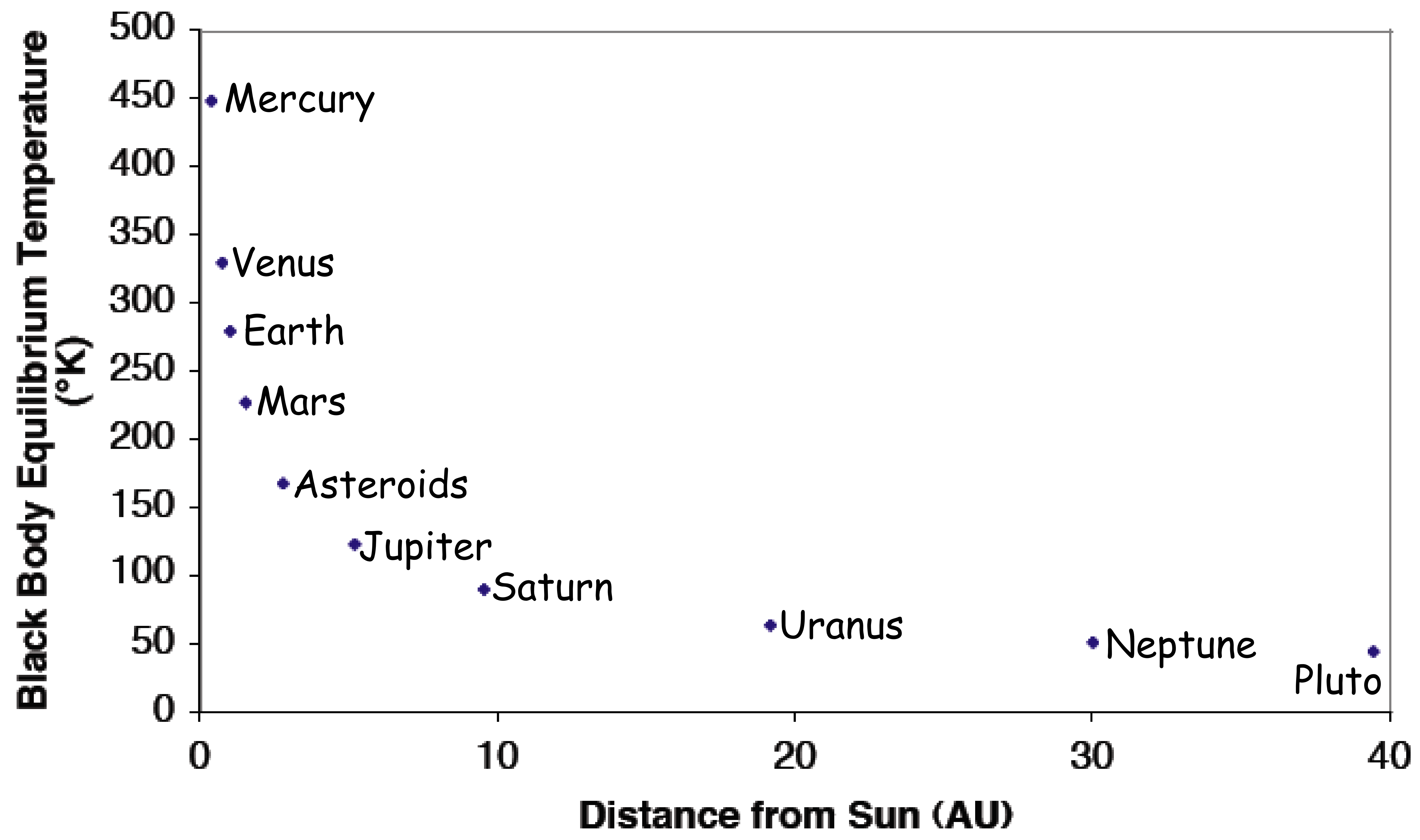
- For equilibrium, set equal

$$I_s \pi r^2 = 4\pi r^2 \sigma T^4 \Rightarrow I_s = 4\sigma T^4$$

- 1 AU: I_s=1394 W/m²; T_{eq}=280°K

$$T_{eq} = \left(\frac{I_s}{4\sigma} \right)^{1/4}$$

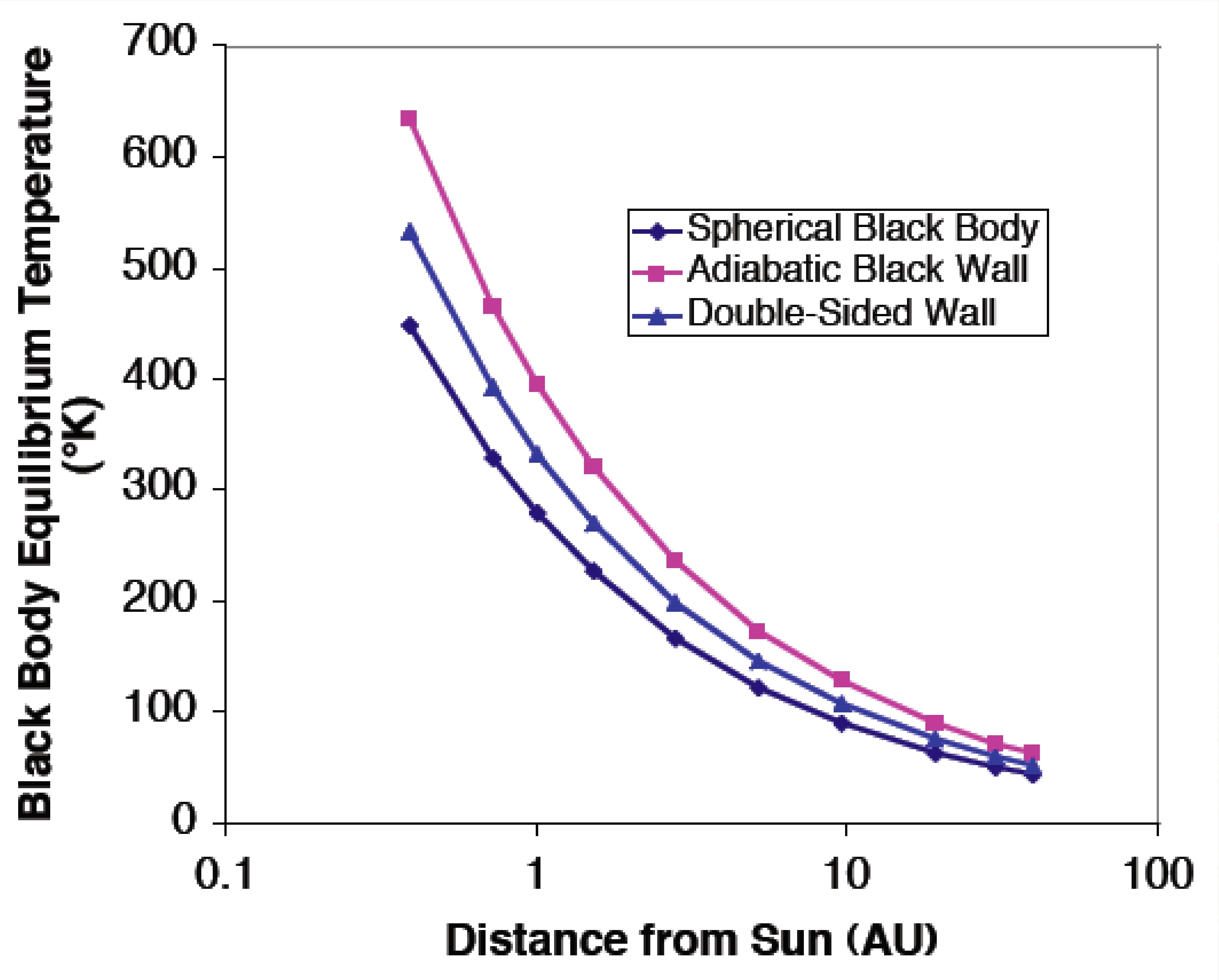
Effect of Distance on Equilibrium Temp



Shape and Radiative Equilibrium

- A shape absorbs energy only via illuminated faces
- A shape radiates energy via all surface area
- Basic assumption made is that black bodies are intrinsically isothermal (perfect and instantaneous conduction of heat internally to all faces)

Effect of Shape on Black Body Temps



Incident Radiation on Non-Ideal Bodies

Kirchkoff's Law for total incident energy flux on solid bodies:

$$Q_{Incident} = Q_{absorbed} + Q_{reflected} + Q_{transmitted}$$

$$\frac{Q_{absorbed}}{Q_{Incident}} + \frac{Q_{reflected}}{Q_{Incident}} + \frac{Q_{transmitted}}{Q_{Incident}} = 1$$

$$\alpha \equiv \frac{Q_{absorbed}}{Q_{Incident}}; \quad \rho \equiv \frac{Q_{reflected}}{Q_{Incident}}; \quad \tau \equiv \frac{Q_{transmitted}}{Q_{Incident}}$$

where

- α =absorptance (or absorptivity)
- ρ =reflectance (or reflectivity)
- τ =transmittance (or transmissivity)

Non-Ideal Radiative Equilibrium Temp

- Assume a spherical body of radius r
- Heat in due to intercepted solar flux

$$Q_{in} = I_s \alpha \pi r^2$$

- Heat out due to radiation (from total surface area)

$$Q_{out} = 4\pi r^2 \varepsilon \sigma T^4$$

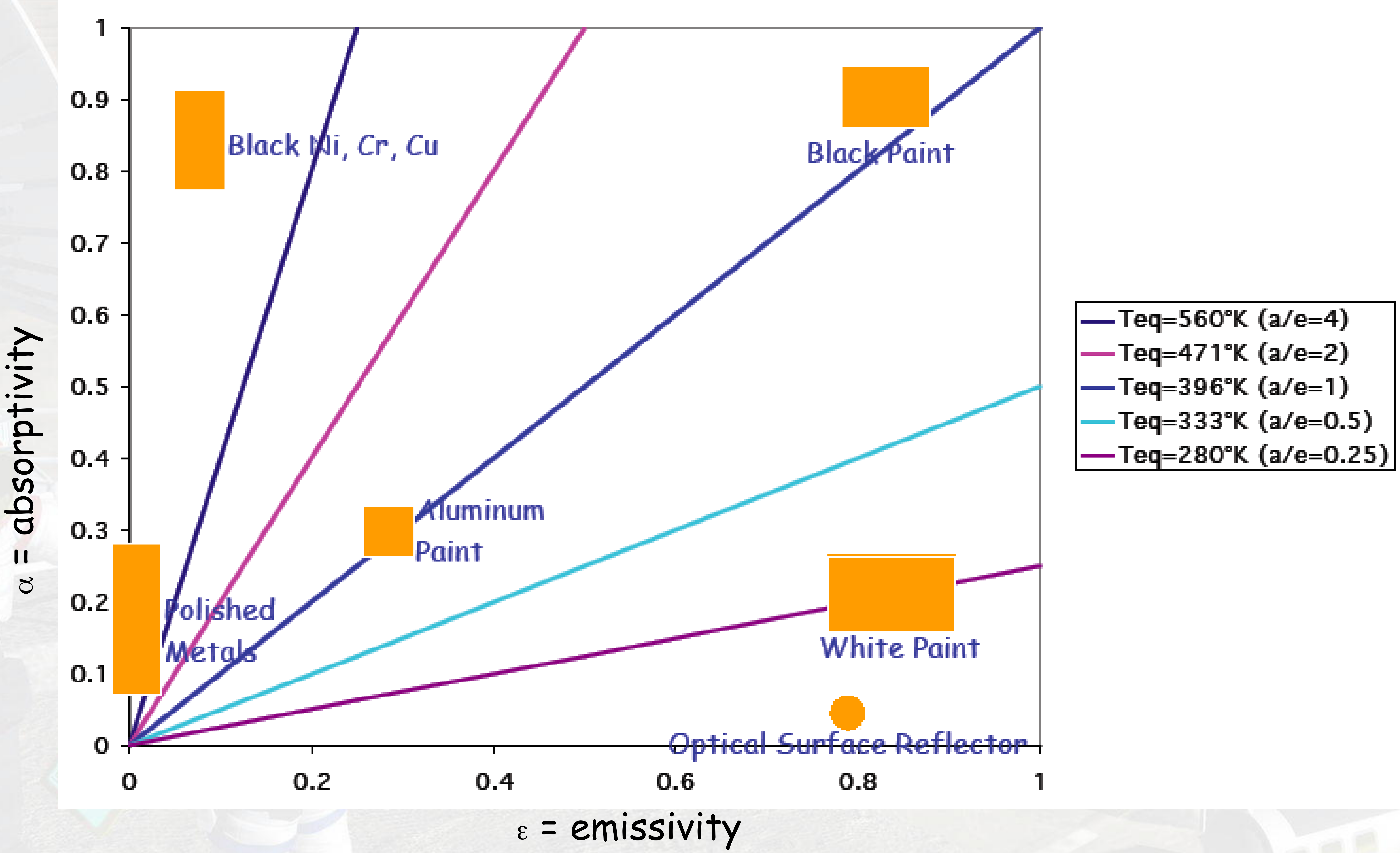
(ε = "emissivity" - efficiency of surface at radiating heat)

- For equilibrium, set equal

$$I_s \alpha \pi r^2 = 4\pi r^2 \varepsilon \sigma T^4 \Rightarrow I_s = 4\frac{\varepsilon}{\alpha}\sigma T^4$$

$$T_{eq} = \left(\frac{\alpha}{\varepsilon}\frac{I_s}{4\sigma}\right)^{1/4}$$

Effect of Surface Coating on Temperature



Non-Ideal Radiative Heat Transfer

- Full form of the Stefan-Boltzmann equation

$$P_{rad} = \varepsilon \sigma A \left(T^4 - T_{env}^4 \right)$$

where T_{env}=environmental temperature (=4°K for space)

- Also take into account power used internally

$$I_s \alpha A_s + P_{int} = \varepsilon \sigma A_{rad} \left(T^4 - T_{env}^4 \right)$$

Example: AERCam/SPRINT

- 30 cm diameter sphere
- $\alpha=0.2$; $\varepsilon=0.8$
- $P_{int}=200W$
- $T_{env}=280°K$ (cargo bay below; Earth above)
- Analysis cases:
  - – Free space w/o sun
  - – Free space w/sun
  - – Earth orbit w/o sun
  - – Earth orbit w/sun

AERCam/SPRINT Analysis (Free Space)

- A_s=0.0707 m^2; A_{rad}=0.2827 m^2
- Free space, no sun

$$P_{\text{int}} = \varepsilon\sigma A_{\text{rad}} T^4 \Rightarrow T = \left(\frac{200W}{0.8\left(5.67\times 10^{-8}\frac{W}{m^2K^4}\right)\left(0.2827m^2\right)} \right)^{1/4} = 354^{\circ}\text{K}$$

AERCam/SPRINT Analysis (Free Space)

- $A_s = 0.0707\ \text{m}^2$; $A_{rad} = 0.2827\ \text{m}^2$
- Free space with sun

$$I_s \alpha A_s + P_{\text{int}} = \varepsilon \sigma A_{rad} T^4 \Rightarrow T = \left(\frac{I_s \alpha A_s + P_{\text{int}}}{\varepsilon \sigma A_{rad}} \right)^{1/4} = 362°K$$

AERCam/SPRINT (LEO Cargo Bay)

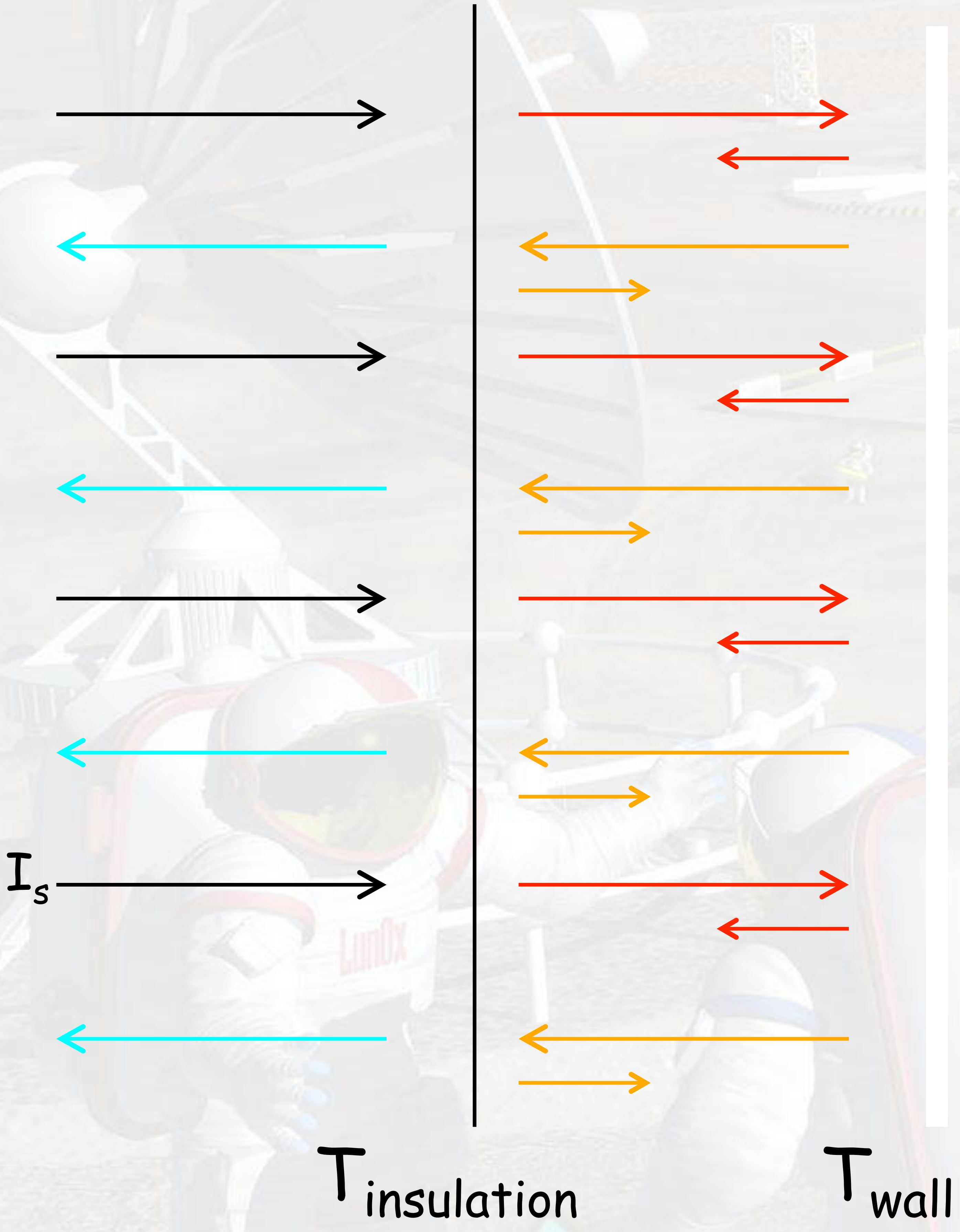
- T_{env}=280°K
- LEO cargo bay, no sun

$$P_{\text{int}} = \varepsilon\sigma A_{rad}\left(T^4 - T_{env}^4\right) \Rightarrow T = \left(\frac{200W}{0.8\left(5.67\times10^{-8}\dfrac{W}{m^{2}{}^\circ K^4}\right)\left(0.2827\,m^2\right)} + (280^\circ K)^4\right)^{1\!/\!4} = 384^\circ K$$

- LEO cargo bay with sun

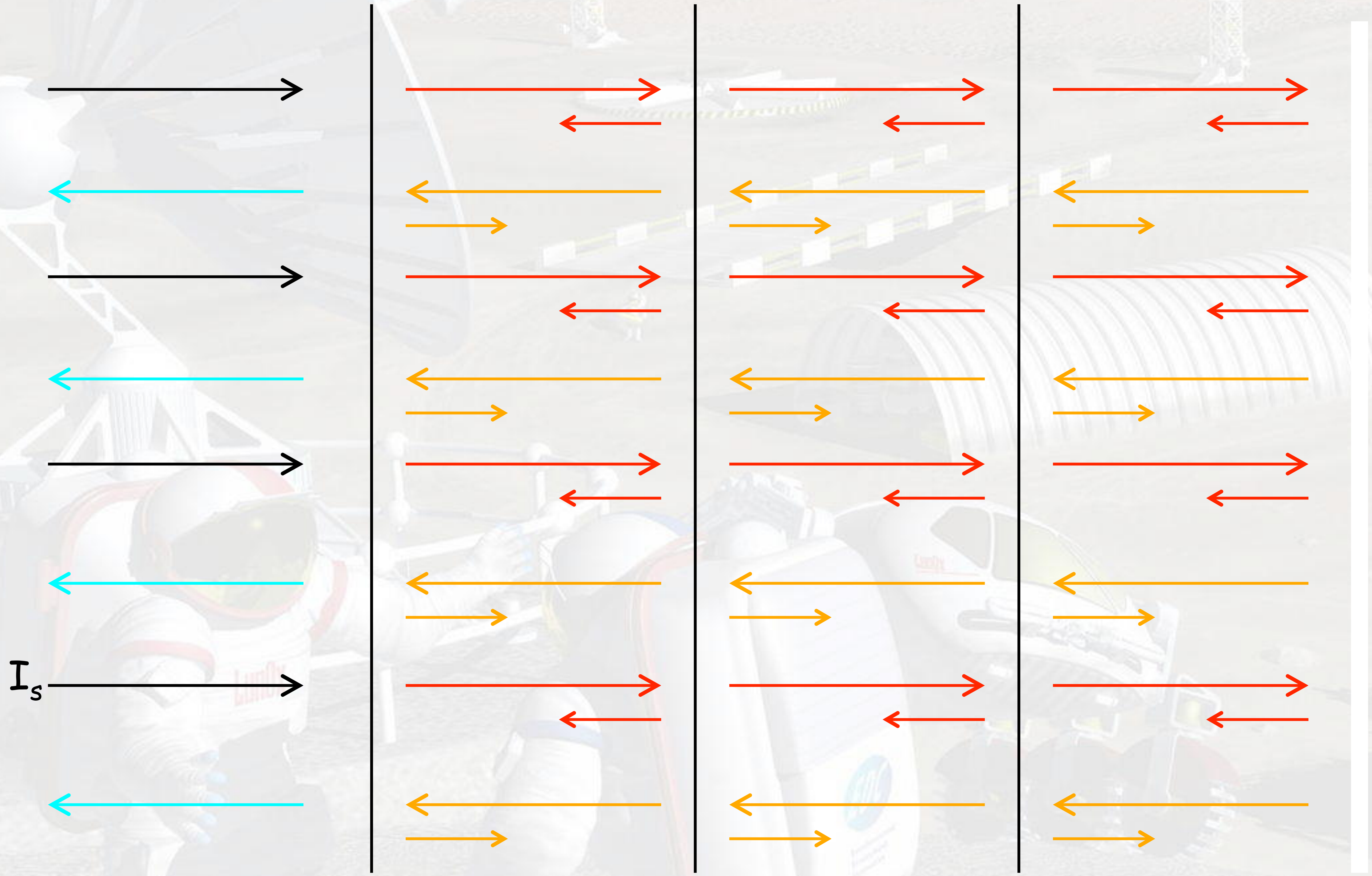
$$I_s\alpha\, A_s + P_{\text{int}} = \varepsilon\sigma A_{rad}\left(T^4 - T_{env}^4\right) \Rightarrow T = \left(\frac{I_s\alpha\, A_s + P_{\text{int}}}{\varepsilon\sigma A_{rad}} + T_{env}^4\right)^{1\!/\!4} = 391^\circ K$$

Radiative Insulation



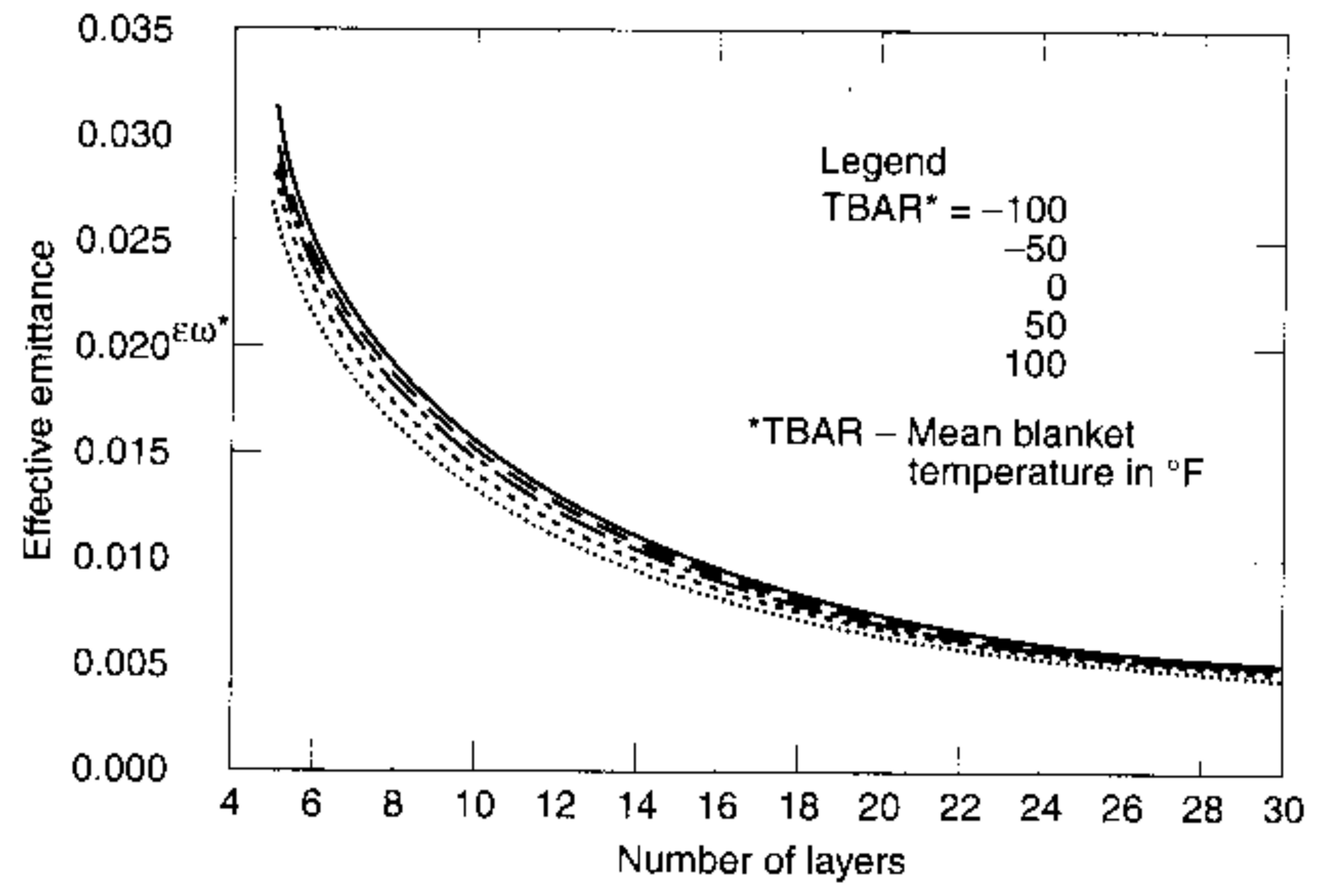
- Thin sheet (mylar/kapton with surface coatings) used to isolate panel from solar flux
- Panel reaches equilibrium with radiation from sheet and from itself reflected from sheet
- Sheet reaches equilibrium with radiation from sun and panel, and from itself reflected off panel

Multi-Layer Insulation (MLI)



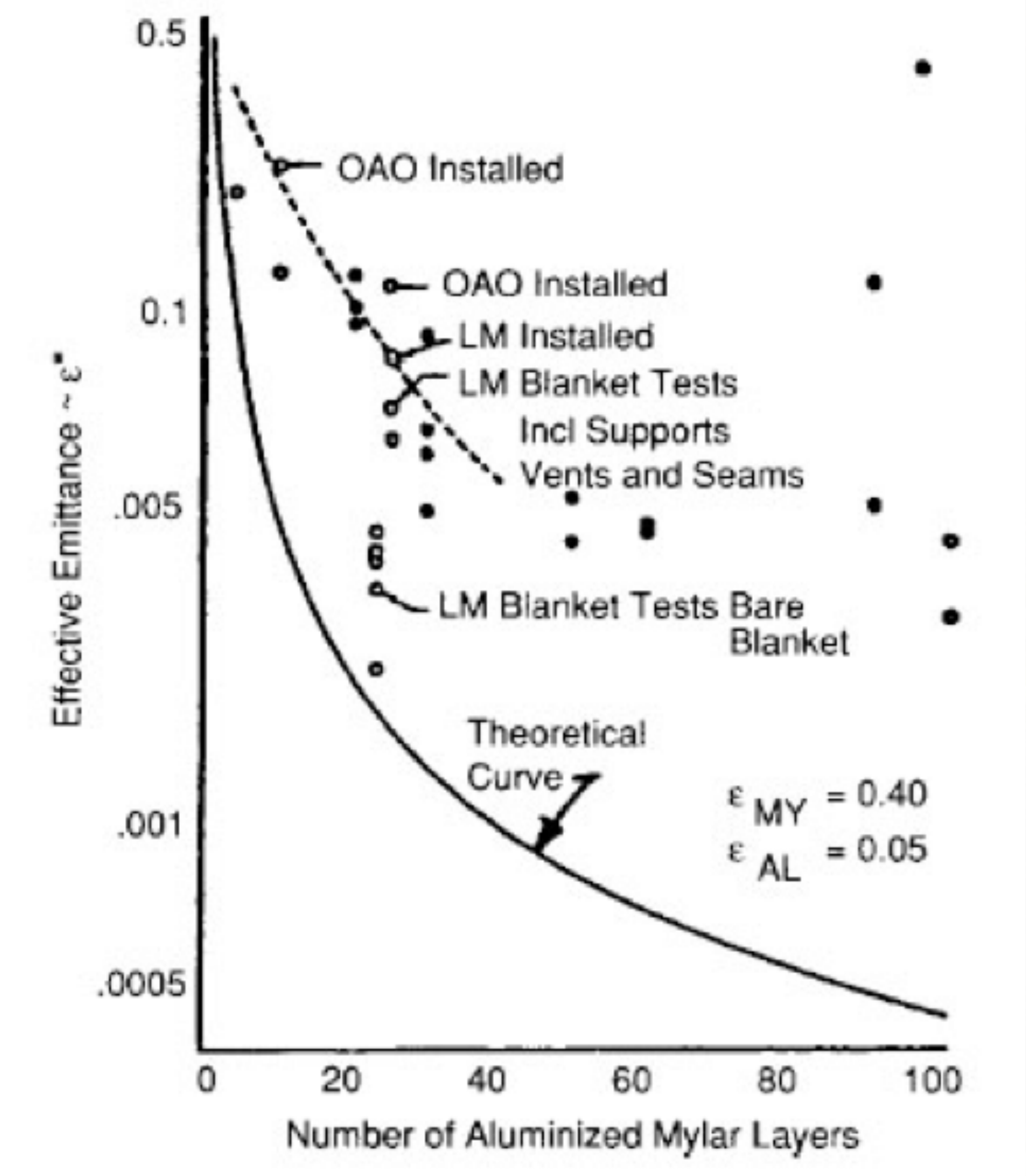
- Multiple insulation layers to cut down on radiative transfer
- Gets computationally intensive quickly
- Highly effective means of insulation
- Biggest problem is existence of conductive leak paths (physical connections to insulated components)

Emissivity Variation with MLI Layers



Ref: D. G. Gilmore, ed., *Spacecraft Thermal Control Handbook* AIAA, 2002

Finer Detail on Effective Emissivity



Estimating Function for MLI

$$\epsilon_{eff} = \left(\frac{2n}{\epsilon_{mylar}} - n - 1 + \frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} \right)$$

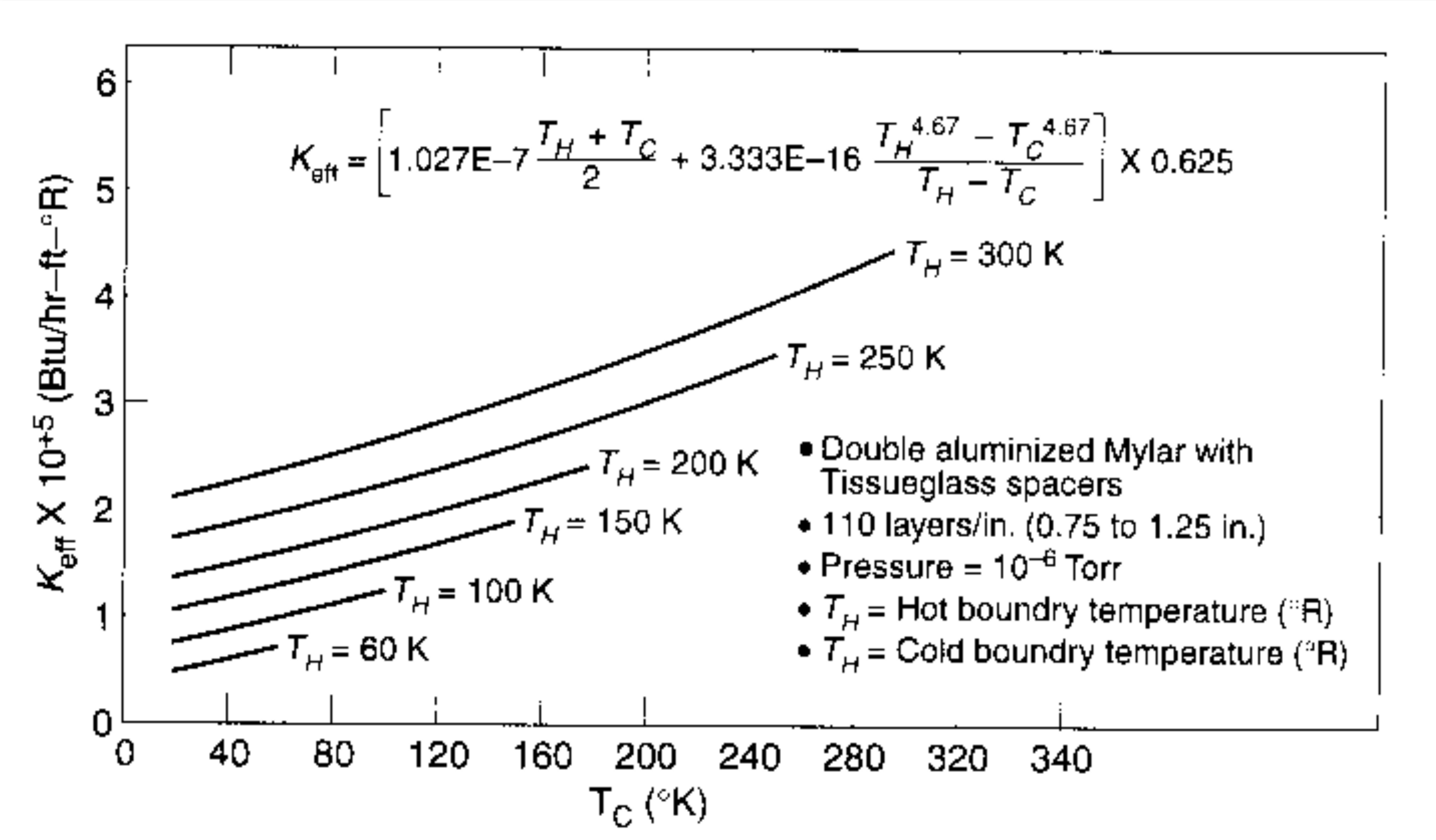
$\epsilon_{mylar} = 0.03$

$n =$ number of MLI layers

$\epsilon_1 =$ emissivity of coating on side 1

$\epsilon_2 =$ emissivity of coating on side 2

MLI Thermal Conductivity



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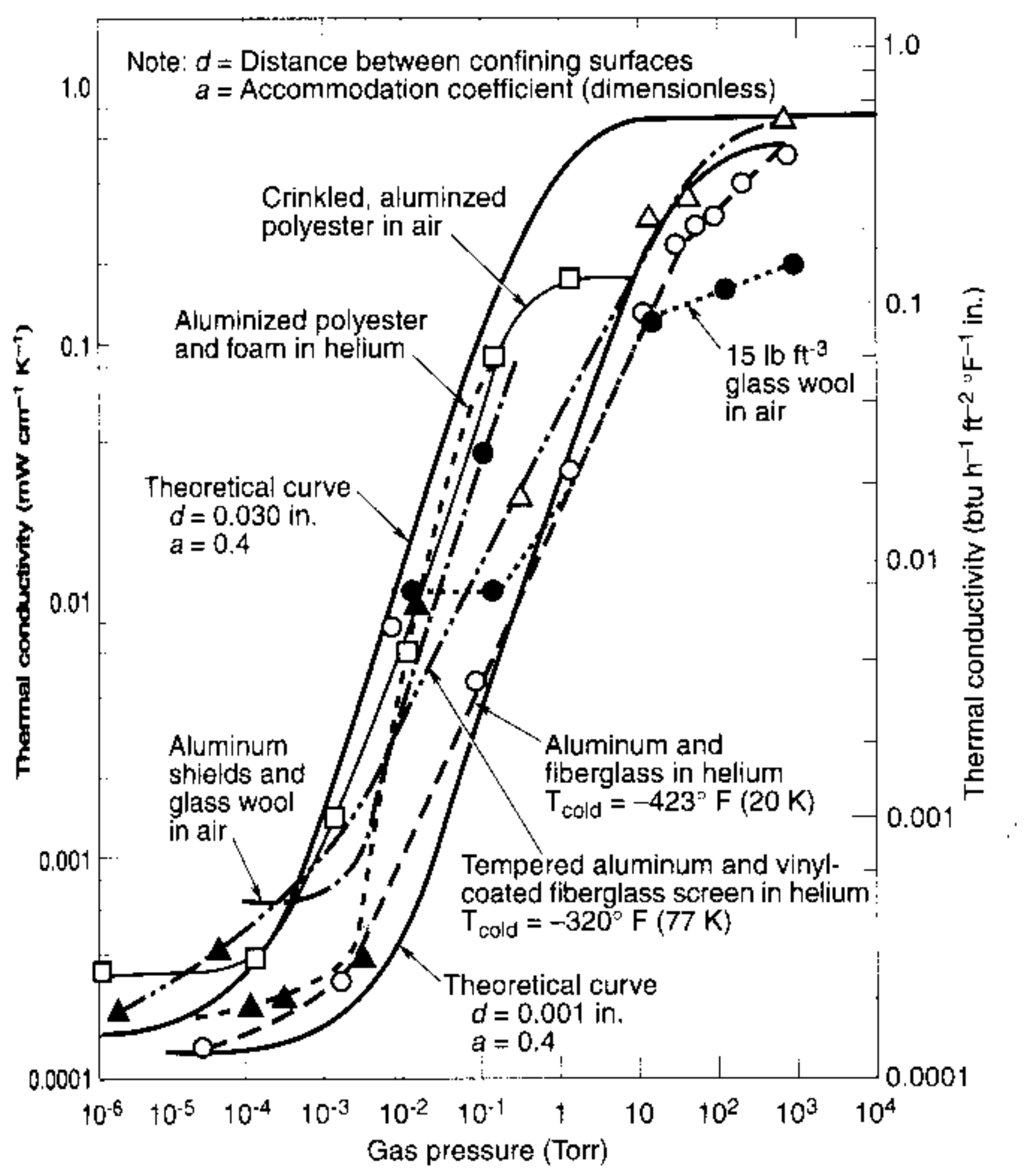
Effect of Ambient Pressure on MLI



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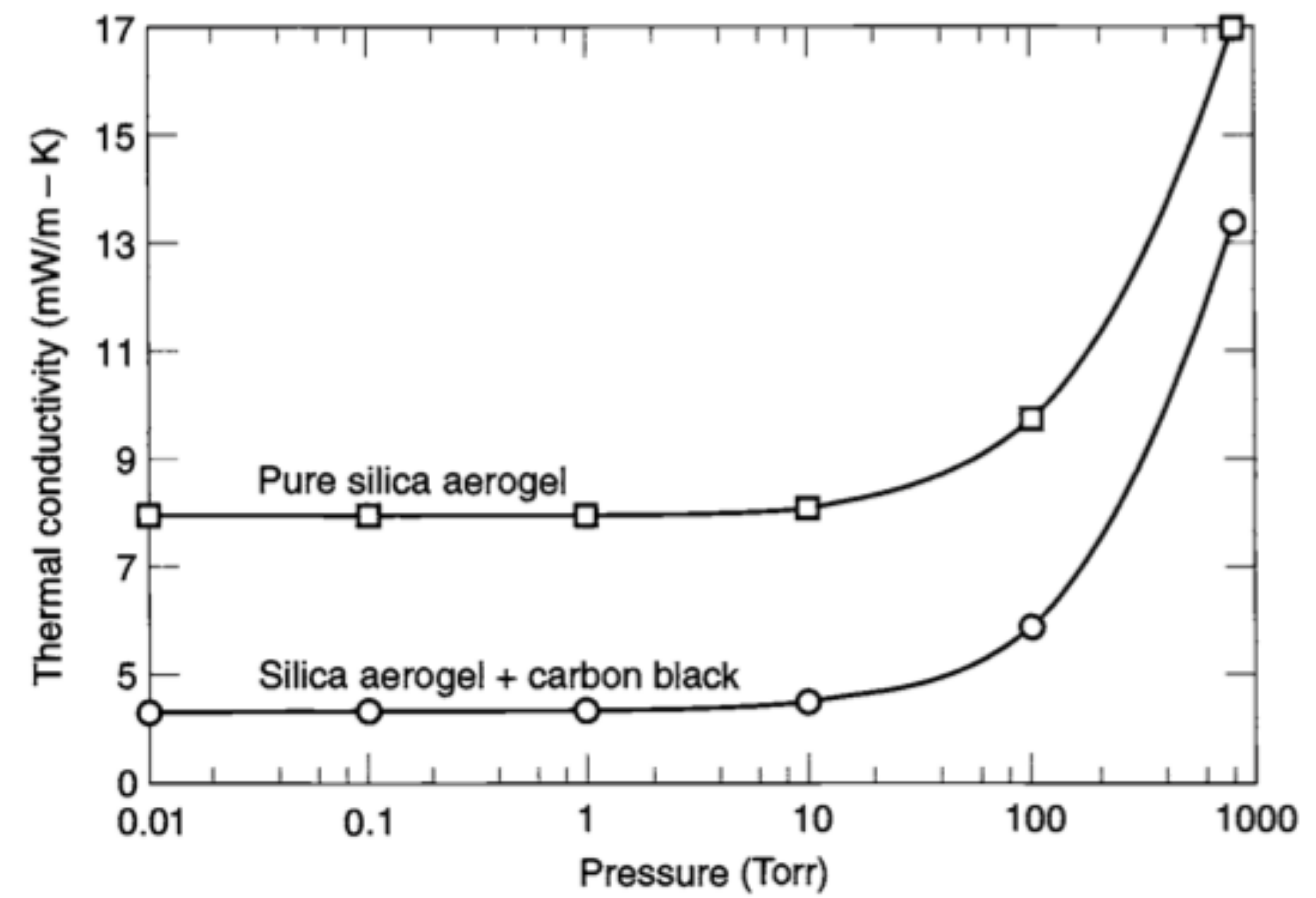
Silica Aerogel Insulation



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1D Conduction

- Basic law of one-dimensional heat conduction (Fourier 1822)

$$Q = -KA\frac{dT}{dx}$$

where

K=thermal conductivity (W/m°K)

A=area

dT/dx=thermal gradient

3D Conduction

General differential equation for heat flow in a solid

$$\nabla^2 T(r,t) + \frac{g(r,t)}{K} = \frac{\rho c}{K}\frac{\partial T(r,t)}{\partial t}$$

where

g(r,t)=internally generated heat

ρ=density (kg/m^3)

c=specific heat (J/kg°K)

K/ρc=thermal diffusivity

Simple Analytical Conduction Model

- Heat flowing from (i-1) into (i)

…	T_{i-1}	T_i	T_{i+1}	…

$$Q_{in} = -KA\frac{T_i - T_{i-1}}{\Delta x}$$

- Heat flowing from (i) into (i+1)

$$Q_{out} = -KA\frac{T_{i+1} - T_i}{\Delta x}$$

- Heat remaining in cell

$$Q_{out} - Q_{in} = \frac{\rho c}{K}\frac{T_i(j+1) - T_i(j)}{\Delta t}$$

Finite Difference Formulation

- Time-marching solution

$$T_i^{n+1} = T_i^n + d(T_{i+1}^n - 2T_i^n + T_{i-1}^n)$$

where

$$d = \frac{\alpha \Delta t}{\Delta x^2} \qquad \alpha = \frac{k}{\rho C_v} = \text{thermal diffusivity}$$

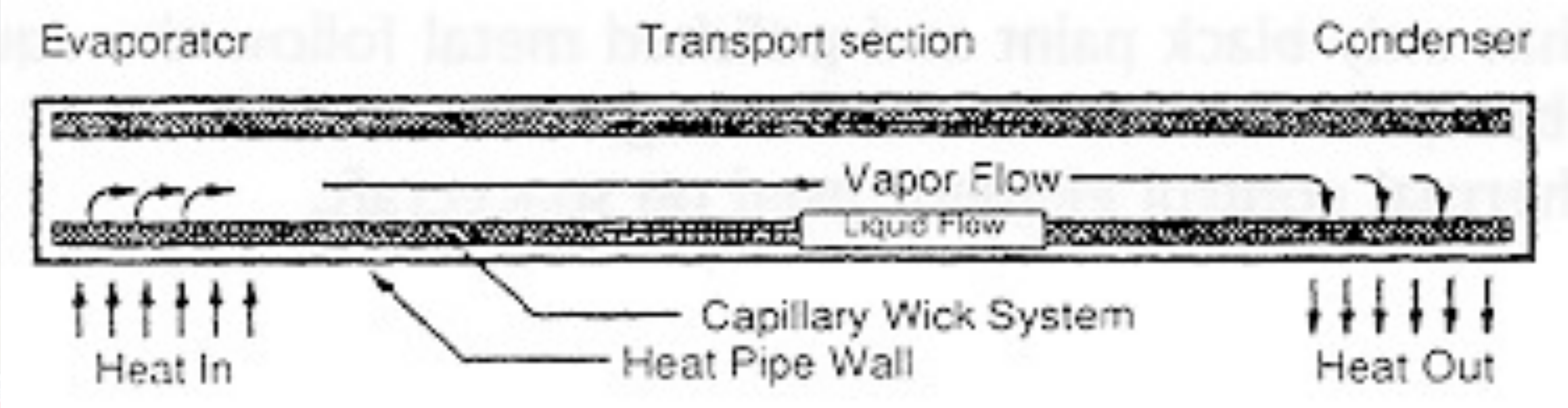
- For solution stability,

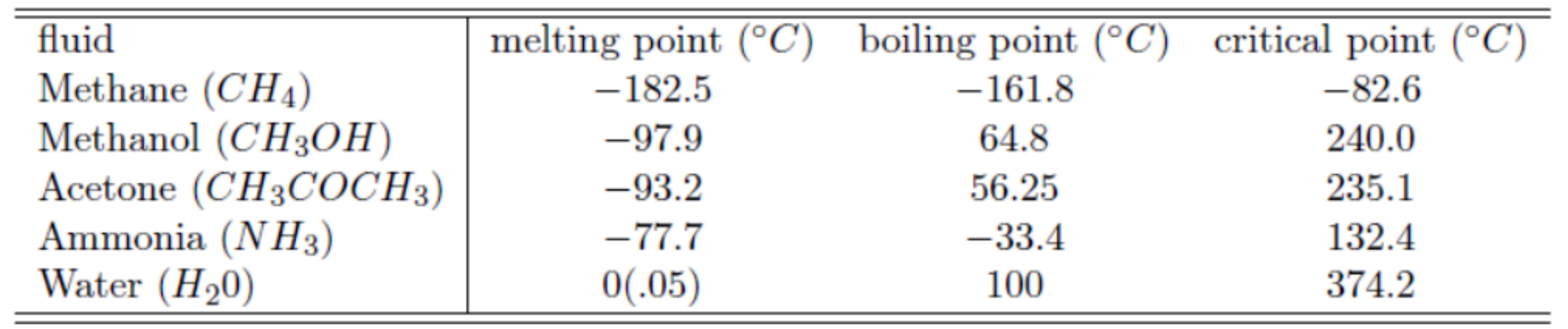
$$\Delta t < \frac{\Delta x^2}{2\alpha}$$

Thermal Control Elements

- Passive systems
  - Coatings
  - Heat shunts
  - Multilayer insulation
  - Heat pipes
- Active systems
  - Heaters
  - Louvers
  - Pumped fluid loops

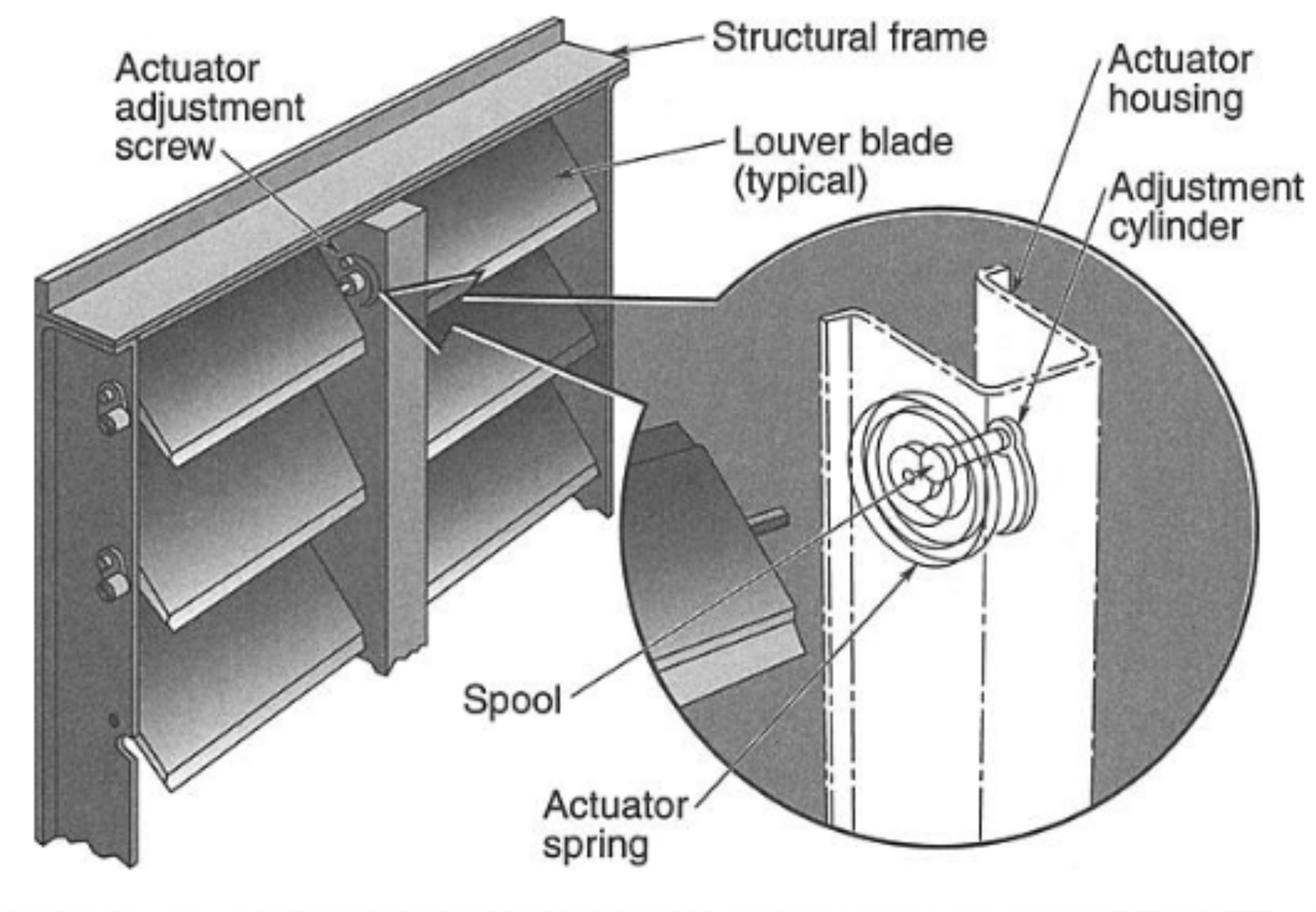
Heat Pipe Schematic





fluid	melting point (°C)	boiling point (°C)	critical point (°C)
Methane (CH_4)	−182.5	−161.8	−82.6
Methanol (CH_3OH)	−97.9	64.8	240.0
Acetone (CH_3COCH_3)	−93.2	56.25	235.1
Ammonia (NH_3)	−77.7	−33.4	132.4
Water (H_20)	0(.05)	100	374.2

Thermal Louvers



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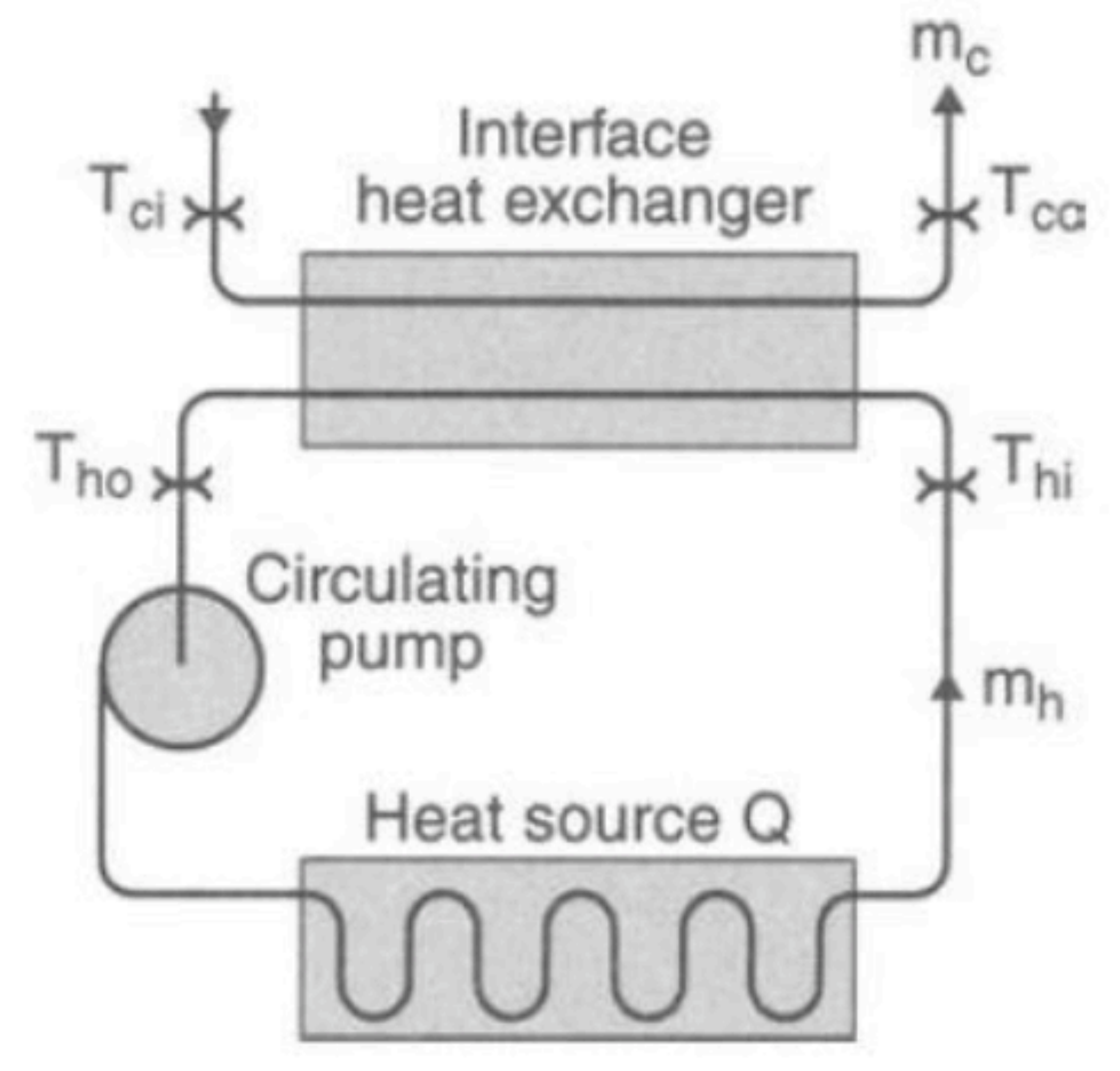
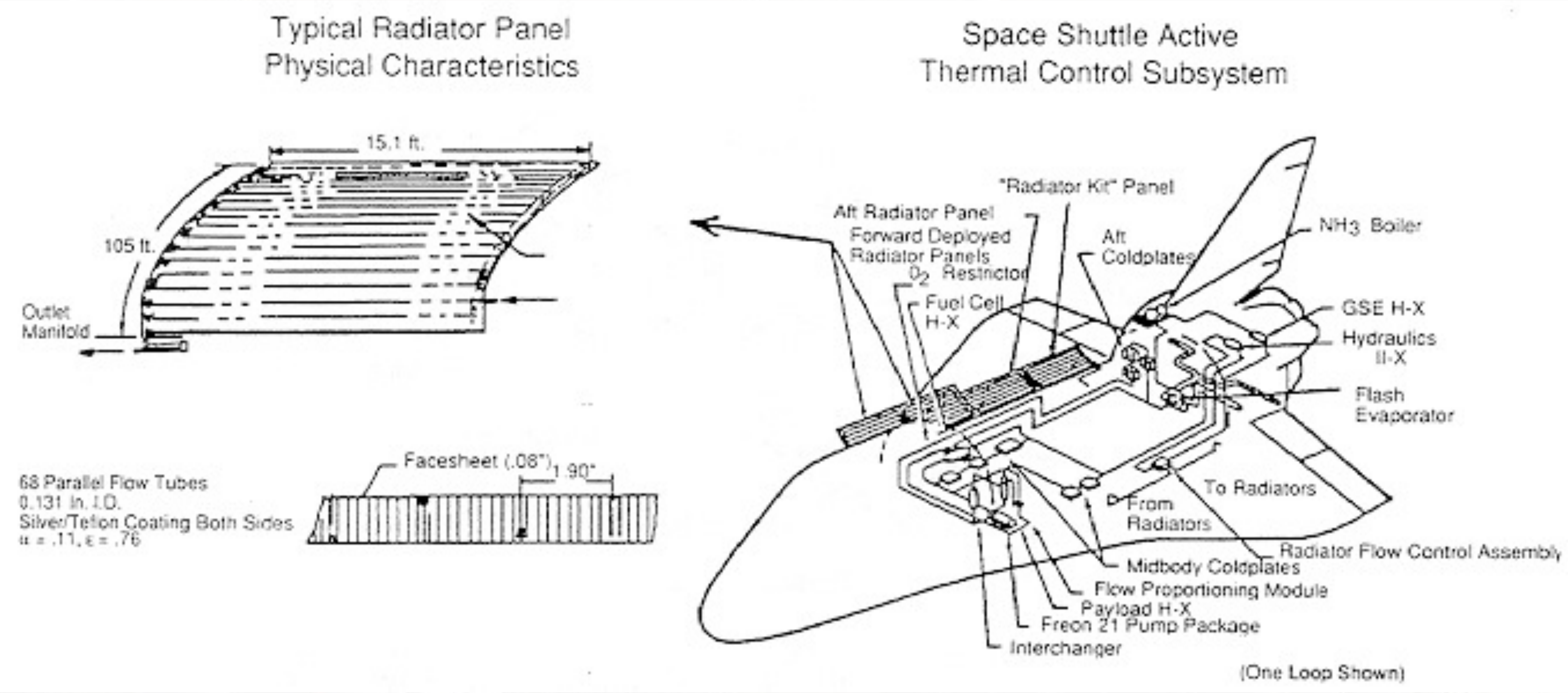
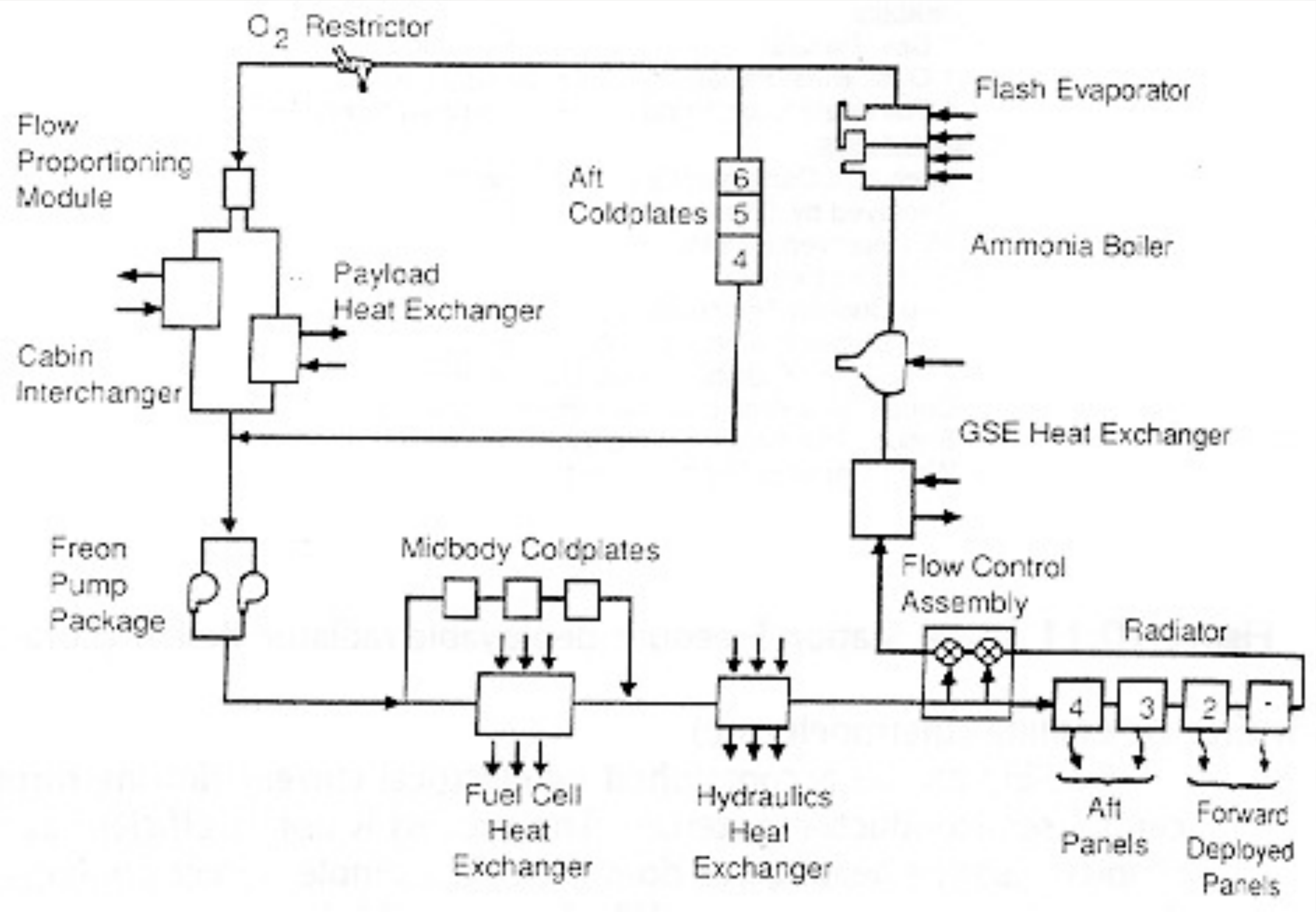
Pumped Fluid Loops



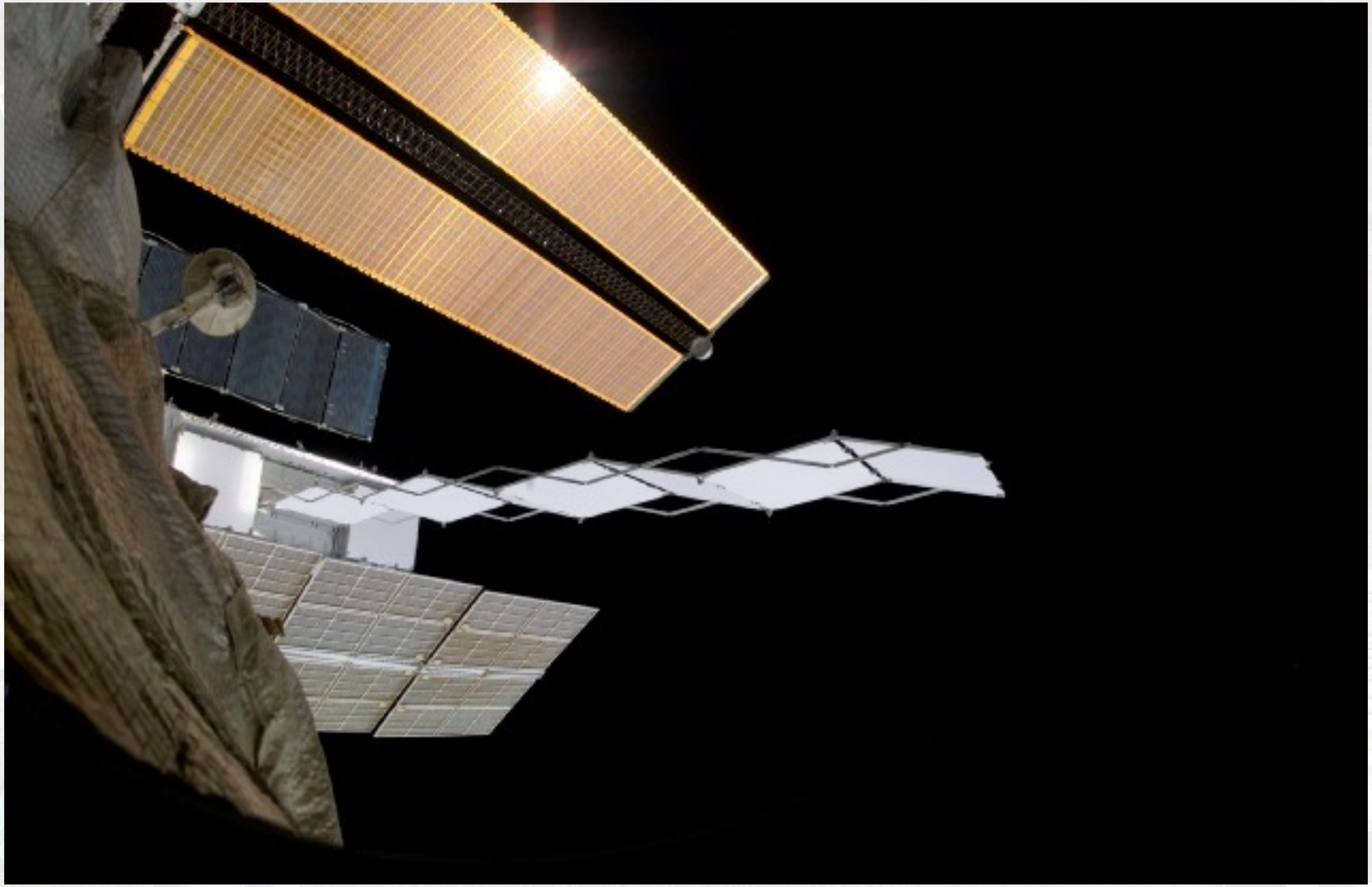
Shuttle Thermal Control Components



Shuttle Thermal Control System Schematic

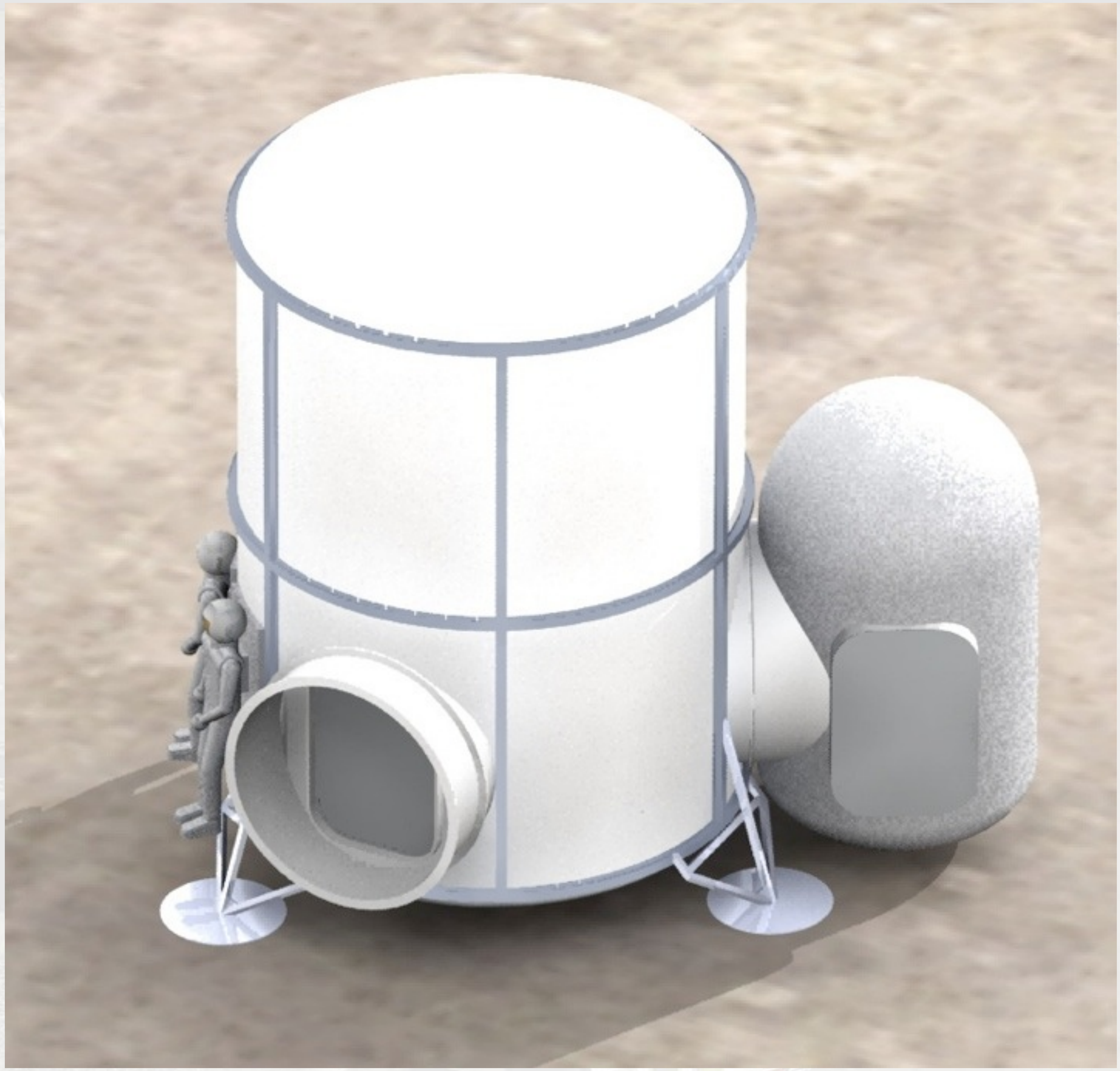


ISS Radiator Assembly



Case Study: ECLIPSE Thermal Analysis

- Developed by UMd SSL for NASA ESMD
- Minimum functional habitat element for lunar outpost
- Radiator area - upper dome and six upper cylindrical panels



ECLIPSE Heat Sources

- Solar heat load (modeling habitat as right circular cylinder)

$$A_{illuminated} = \ell d \sin\beta + \frac{1}{4}\pi d^2 \cos\beta$$

$$Q_{solar} = A_{illuminated}\alpha I_s$$

- Electrical power load = 4191 W
- Metabolic work load (4 crew) = 464 W

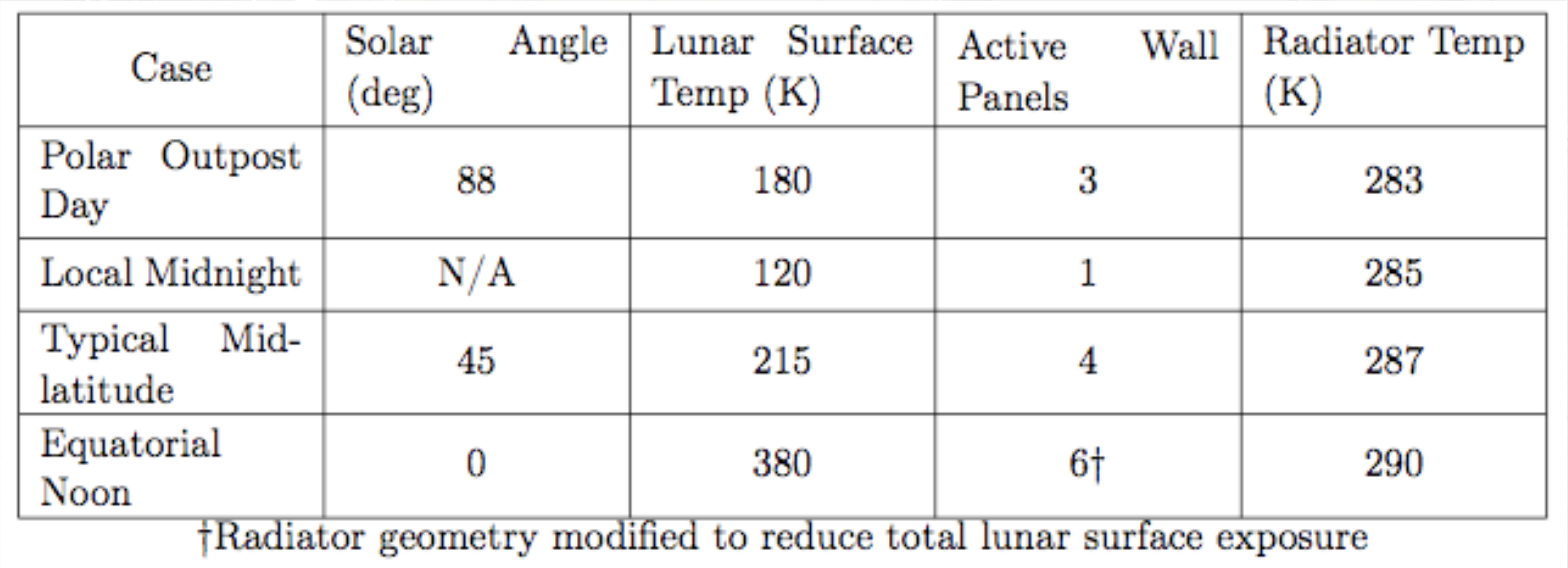
Thermal Modeling for Lunar Surface

- Assume upper dome radiates only to deep space
- Assume side panels radiate half to deep space and half to lunar surface
- Assume (conservatively) that lunar surface radiates as a black body

$$Q_{internal} + Q_{solar} = \epsilon\sigma \left[A_{dome} T_{rad}^4 + n_{rad} A_{panel} \left(T_{rad}^4 - \frac{1}{2} T_{moon}^4 \right) \right]$$

$$T_{rad} = \left[\frac{1}{A_{dome} + n_{rad} A_{panel}} \left(\frac{Q_{internal} + Q_{solar}}{\epsilon\sigma} + \frac{1}{2} n_{rad} A_{wall} T_{moon}^4 \right) \right]^{\frac{1}{4}}$$

ECLIPSE Thermal Results



Case	Solar Angle (deg)	Lunar Surface Temp (K)	Active Wall Panels	Radiator Temp (K)
Polar Outpost Day	88	180	3	283
Local Midnight	N/A	120	1	285
Typical Mid-latitude	45	215	4	287
Equatorial Noon	0	380	6†	290

†Radiator geometry modified to reduce total lunar surface exposure