SESA2024
Astronautics

Chapter 10:
Thermal Control

Contents

Thermal Control

Function

Equipment reliability

Reliable, long-term performance of most spacecraft components require them to operate within thermal tolerances

Approximate operating thermal environment	
Batteries	0° C → $+25^\circ$ C
Fuel (e.g. hydrazine)	$+10^\circ$ C → $+50^\circ$ C
Microprocessors	-5° C → $+40^\circ$ C
Mechanical bearings (e.g. reaction wheels)	0° C → $+45^\circ$ C
Solar arrays	-150° C → $+50^\circ$C

Thermal Control

Payload Requirements

- Radiation of dissipated power
- Sensor cooling (e.g. an IR observatory)
- Very small thermal gradients / thermal shock (e.g. extreme pointing requirement of the Hubble Space telescope)

Thermal Control

Heat Transfer Mechanisms

- **Conduction:** molecular excitation without appreciable displacement
- **Convection:** heat transport by fluid mixing (needs to be 'forced' in a μg environment)
- **Radiation:** electromagnetic wave (IR) emission arising from body temperature (requires no medium)

In LEO mean free path λ_p of particles is large in comparison with spacecraft dimensions:

e.g. λ_p ~ 250 m for h = 200 km

~ 15 km for h = 400 km (depending on solar activity)

Thermal Control

Heat Transfer Mechanisms

Conduction and convection are ineffective

(which is just as well, as kinetic temperature of upper atmosphere ~1000 K)

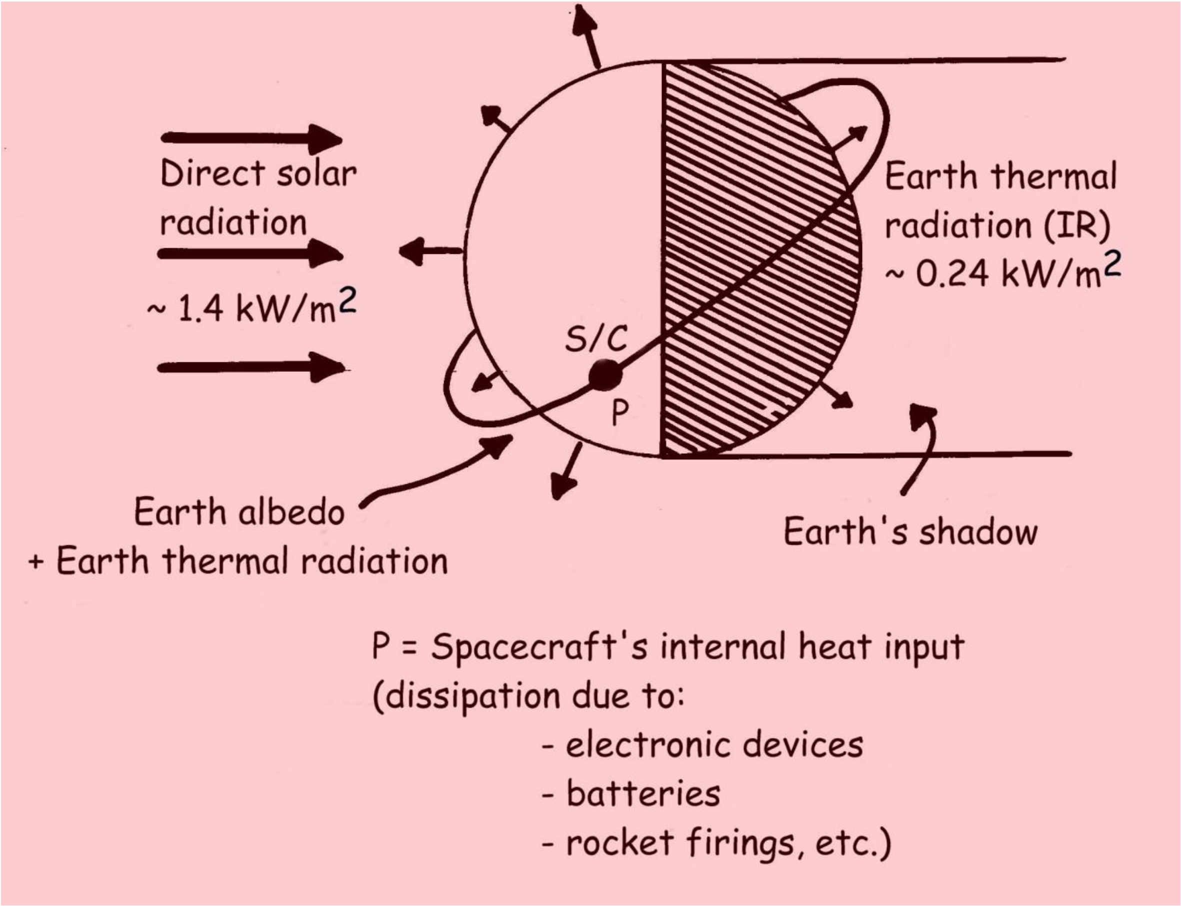
Thermal Radiation Environment

- **Radiation** serves as the dominant heat transfer mechanism between the spacecraft and its environment

Thermal Control

Thermal Radiation Environment

- **Heat inputs:**



Thermal Control

Thermal Radiation Environment

- **Heat outputs:**
  - Thermal radiation emission (IR) from spacecraft surfaces
- **Thermal balance:**
  - Environmental inputs + internally dissipated heat must balance radiation loss from spacecraft surfaces

$\Rightarrow$ Spacecraft equilibrium temperature

Material Properties and Radiation

Absorption of radiation

- Consider incident radiation at a wavelength λ (μm) with intensity $q_i(\lambda)$ (W m^{-2} μm^{-1})

$$q_a(\lambda) + q_r(\lambda) + q_t(\lambda) = q_i(\lambda)$$

- **Definitions:**
  - Spectral absorptance

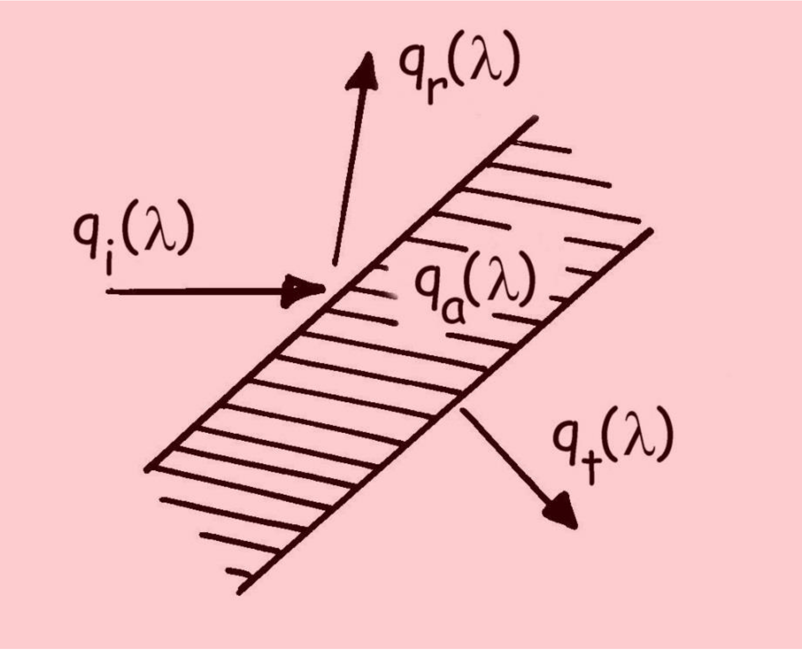
$$\alpha_\lambda \equiv q_a(\lambda)/q_i(\lambda)$$

  - Spectral reflectance

$$\rho_\lambda \equiv q_r(\lambda)/q_i(\lambda)$$

  - Spectral transmittance

$$\tau_\lambda \equiv q_t(\lambda)/q_i(\lambda)$$



Material Properties and Radiation

Absorption of radiation

Therefore $\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1$

Generally (for wavelengths of interest) spacecraft surfaces are opaque, so that

$$\alpha_\lambda + \rho_\lambda = 1 \qquad \tau_\lambda = 0 \qquad (10.1)$$

- **Definition:**
  - **A Blackbody (BB) is**
    - One that absorbs all radiation incident upon it
    - One that emits at any particular temperature the maximum possible amount of thermal radiation

      (a useful theoretical concept)

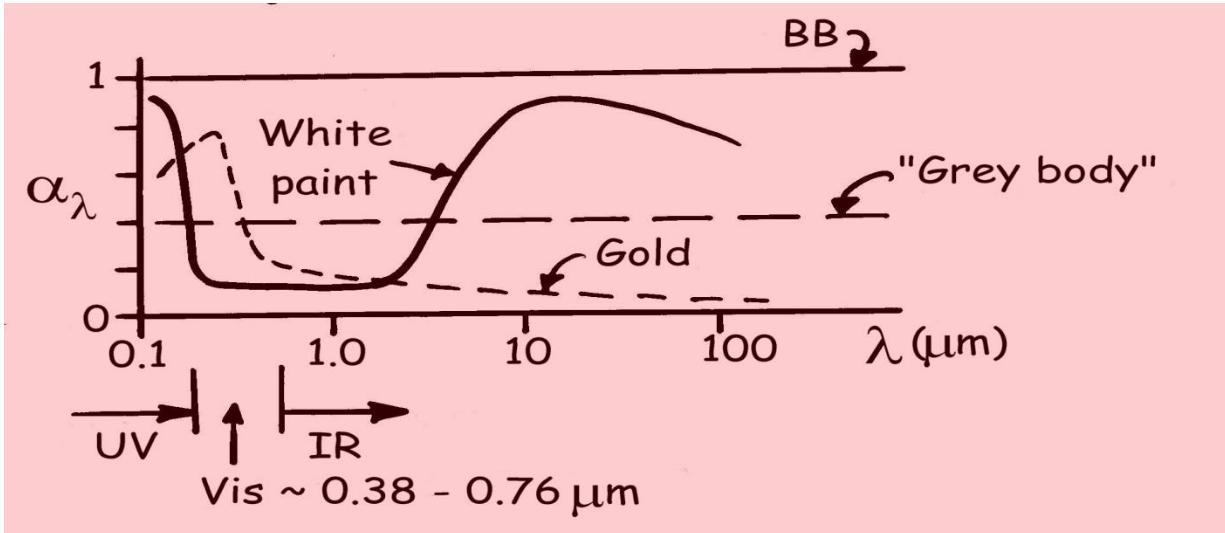
Material Properties and Radiation

Absorption of radiation

- **Therefore** for a BB, $\rho_\lambda = 0$

$$\Rightarrow \quad \alpha_\lambda = 1, \text{ for all } \lambda$$

- For real materials α_λ and ρ_λ are dependent upon λ – hence the colour of materials:



Material Properties and Radiation

Absorption of radiation

- **Total absorption:**

The total absorption of radiation by the material is

$$\overline{Q}_a = \int_0^{\infty} q_i(\lambda)\alpha_\lambda(\lambda)d\lambda \qquad (\mathrm{W\ m^{-2}})$$

Hence we define the absorptance α of the material, with respect to a specific radiation source, as

$$\alpha = \frac{\int_0^{\infty} q_i(\lambda)\alpha_\lambda(\lambda)d\lambda}{\int_0^{\infty} q_i(\lambda)d\lambda} \qquad (10.2)$$

Material Properties and Radiation

Absorption of radiation

- **Note that:** the value of α depends on both the material and the source of radiation (e.g. the response of white paint varies with respect to the radiation source)

- Hence, under solar illumination $q_S(\lambda)$ (W m^{-2} µm^{-1}), the solar absorptance is

$$\alpha_S = \frac{\int_0^\infty q_S(\lambda)\alpha_\lambda(\lambda)d\lambda}{\int_0^\infty q_S(\lambda)d\lambda} \qquad (10.3)$$

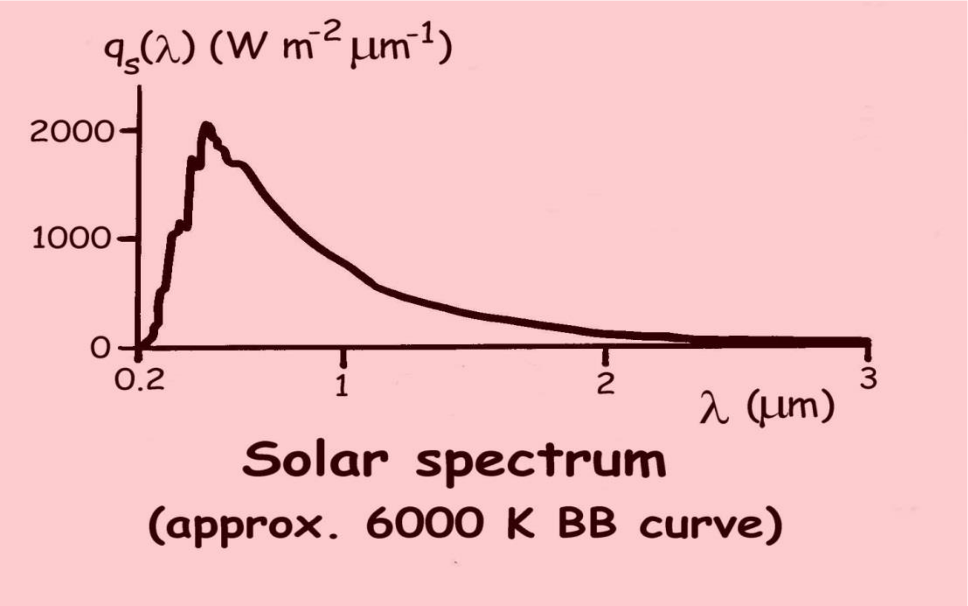
- But to a good degree of approximation, we can write ...

Material Properties and Radiation

Absorption of radiation

$$\alpha_S = \frac{\int_{0.2}^{3.0} q_S \alpha_\lambda d\lambda}{\int_{0.2}^{3.0} q_S d\lambda}$$

since ~ 97% of the total energy falls within this 'window'.



Material Properties and Radiation

Emission of radiation

- **Blackbody emission**
  - For a perfect BB radiating surface, the rate of emission is solely dependent upon the temperature of the surface as formulated by Plank:

$$q_\lambda = \frac{2\pi h c^2}{\lambda^5\left[\exp\left(\frac{ch}{k\lambda T}\right)-1\right]} \quad (\mathrm{W\ m^{-2}\ \mu m^{-1}})$$

where

Plank's constant, $h = 6.625\times10^{-34}$ W s^2

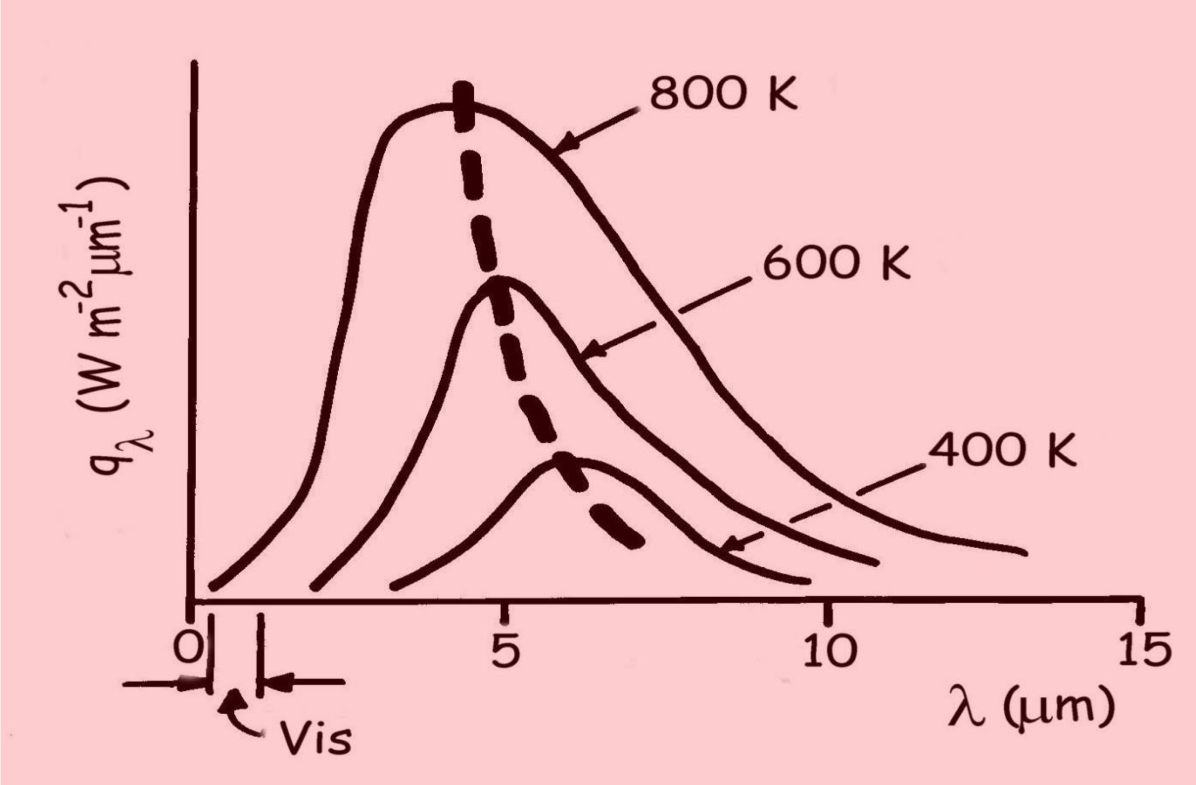
Boltzmann's constant, $k = 1.380\times10^{-23}$ W s K^{-1}

Speed of light, $c = 3\times10^{8}$ m s^{-1}

Material Properties and Radiation

Emission of radiation

- **The IR BB emission spectra** can be obtained by plotting Plank's Law:



Material Properties and Radiation

Emission of radiation

- **Wien's Displacement Law** describes the relationship between temperature T and the wavelength $\lambda_{\max}$ corresponding to max q_λ ,

$$\lambda_{\max} T = 2.898 \times 10^3 \quad (\mu\text{m K})$$

e.g. Earth spectrum peaks at $\lambda \approx 10\ \mu\text{m} \quad \Rightarrow \quad T_{Earth} \sim 290\ \text{K}$

Material Properties and Radiation

Emission of radiation

- **Total emission** from a blackbody is given by

$$q_{BB} = \int_0^\infty q_\lambda \, d\lambda$$

which leads to the Stefan-Boltzmann equation:

$$q_{BB} = \sigma T^4 \quad (\text{W m}^{-2}) \qquad (10.4)$$

where the Stefan-Boltzmann constant is

$$\sigma = 5.669 \times 10^{-8} \ \text{W m}^{-2}\,\text{K}^{-4}$$

Material Properties and Radiation

Emission of radiation

- **Definition:**
  - The emittance ε of a real material surface is defined by

$$\varepsilon \equiv q(T)/q_{BB}(T) < 1 \qquad (10.5)$$

where $q(T)$ (W m^{-2}) is the measured amount of thermal radiation from the real surface at temperature T (K), and $q_{BB}(T)$ is the corresponding amount for an otherwise identical BB surface at the same temperature.

  - The combination of (10.4) and (10.5) gives the thermal emission from a real surface

$$q(T) = \varepsilon\sigma T^4 \qquad (\mathrm{W\ m^{-2}}) \qquad (10.6)$$

Spacecraft Thermal Balance

Recall

The environmental inputs + the spacecraft internally dissipated power must balance the radiation loss from the spacecraft surfaces

$\Rightarrow$ Spacecraft equilibrium temperature

Heat Inputs:

Direct solar radiation

$$Q_S = q_S \, \alpha_S \, A_S^{proj} \quad \text{(W)}$$

where

$q_S = 1350 \;\; \text{W/m}^2$

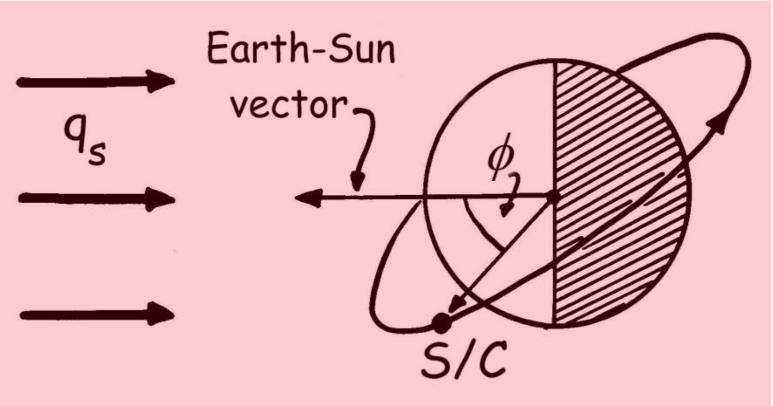
$\alpha_S = \text{solar absorptance}$

$A_S^{proj} = \text{projected area of spacecraft relative to Sun}$

Spacecraft Thermal Balance

Earth Albedo

This is the fraction of incident solar radiation reflected from the planet's surface and atmosphere, typically about 34%



$$Q_a = a\ q_S\ \alpha_S\ A_E^{proj} \cos\phi\ \ \beta\ \ F \quad \text{(W)}$$

Assumption!

where

$a = 0.34 =$ Earth albedo

$A_E^{proj} =$ projected area of spacecraft relative to Earth

$\phi =$ geocentric angle between spacecraft and Sun

$\beta = 1 \quad \text{for } -90^o < \phi < 90^o, \quad \beta = 0$ otherwise

$F = \left(R_E / R_{orb}\right)^2$

Assumption!

Spacecraft Thermal Balance

Earth Thermal Emission

$$Q_E = q_E \, \varepsilon \, A_E^{proj} \, F \qquad \text{(W)}$$

where

$$q_E = 240 \;\; \text{W/m}^2$$

Note: the use of ε for absorptance of IR!
Kirchoff's Law says that $\alpha = \varepsilon$ when the absorbing body (the S/C) is at the same temperature (~ 290 K) as the radiating source (the Earth)

Internal Dissipation

$$Q_{dis} = P \qquad \text{(W)}$$

Spacecraft Thermal Balance

Heat Outputs

Spacecraft Thermal Emission

$$Q_{S/C} = \varepsilon \, \sigma \, T^4 A_{surf} \qquad \text{(W)}$$

where

$$A_{surf} = \text{total S/C surface area}$$

For equilibrium:

$$\underbrace{Q_S + Q_a + Q_E + Q_{dis}}_{\text{S/C heat inputs}} = \underbrace{Q_{S/C}}_{\text{S/C heat outputs}} \qquad (10.7)$$

Spacecraft Thermal Balance

Thermal Balance Equation

$$q_S \alpha_S A_S^{proj} + a q_S \alpha_S A_E^{proj} \cos\phi \, \beta \left(\frac{R_E}{R_{orb}} \right)^2 + q_E \varepsilon \, A_E^{proj} \left(\frac{R_E}{R_{orb}} \right)^2 + P = \varepsilon \, \sigma \, T^4 A_{surf} \tag{10.8}$$

Effective values of α_S and ε

- In general α_S and ε are not uniform for each spacecraft surface → use "effective" values of α_S and ε weighted by area …

e.g. if a surface has absorptance $\alpha_S^{(1)}$ over 90% (by area) and $\alpha_S^{(2)}$ over 10% then

$$\alpha_S^{eff} = 0.9 \, \alpha_S^{(1)} + 0.1 \, \alpha_S^{(2)}$$

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Thermal Control (passive)

Thermal Control by Choice of Spacecraft Surface

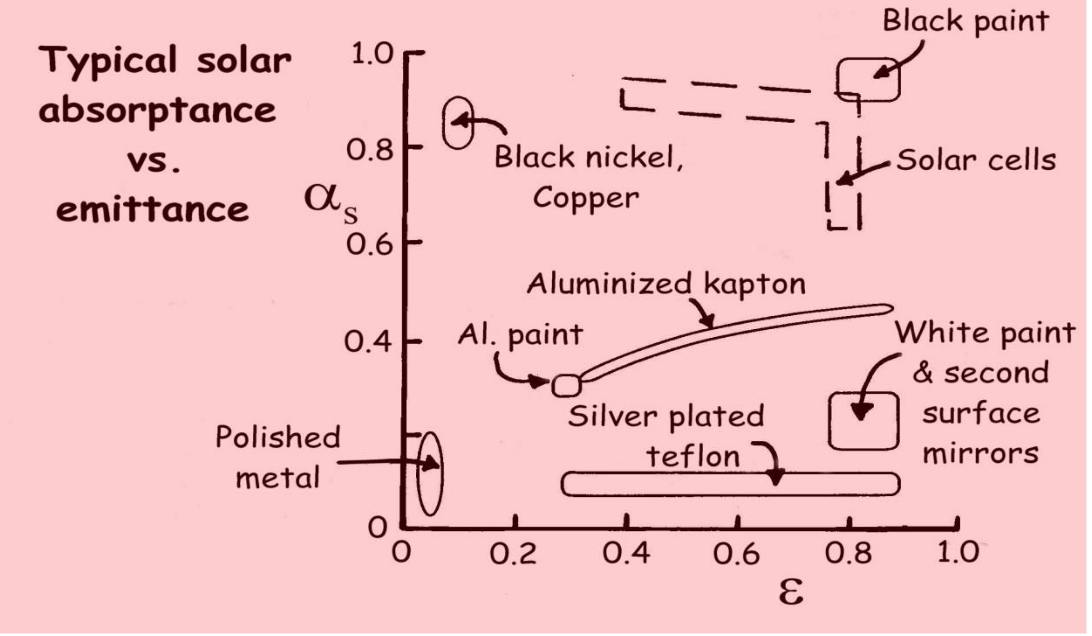
Rearranging the thermal balance equation, we have:

$$\sigma T^4 = q_S \frac{\alpha_S}{\varepsilon}\left\{\frac{A_S^{proj}}{A_{surf}} + a\frac{A_E^{proj}}{A_{surf}}\cos\phi\beta F\right\} + q_E \frac{A_E^{proj}}{A_{surf}} F + \frac{P}{\varepsilon A_{surf}}$$

Then provided that

$q_E, P \ll q_S$ then

$$T = f\left(\frac{\alpha_S}{\varepsilon}\right) \quad (10.9)$$



Thermal Control (passive)

Thermal Control by Choice of Spacecraft Surface

- **Hence,** if we require to reduce *T* then decrease α_S / ε
  - e.g. Use white paint or SSMs (transparent plastic sheet with aluminized rear surface)
- **To increase** *T*, increase α_S / ε
  - e.g. Use copper or black nickel
- **Note that** orbital environment (UV and AO) will degrade thermal surfaces such that (generally) *T* will increase over the spacecraft's mission lifetime

Thermal Control (passive)

Guidelines for Passive Thermal Design of Spacecraft

Lessons from nature …

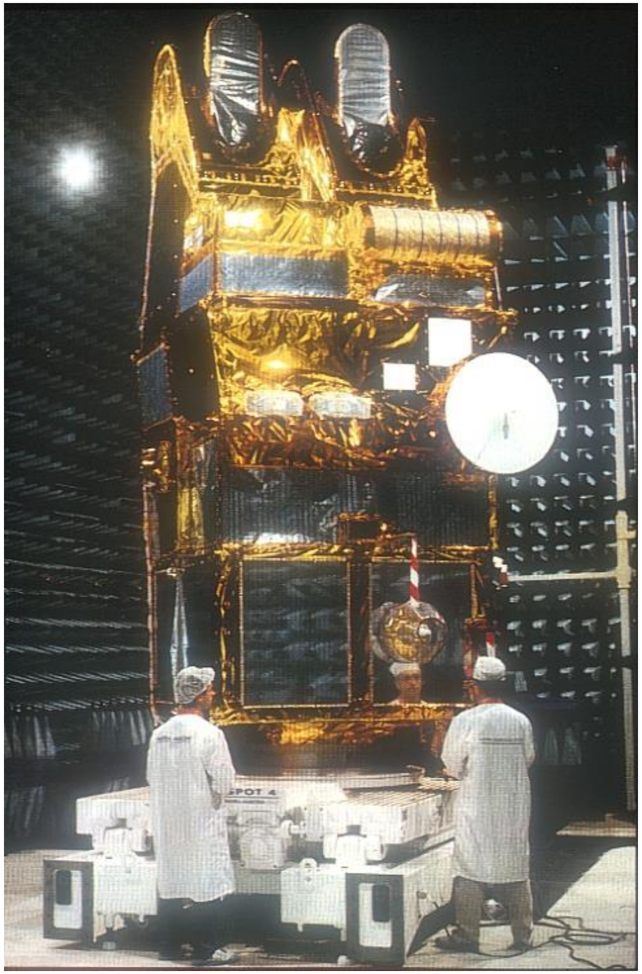
Thermal Control (passive)

Guidelines for Passive Thermal Design of Spacecraft

- **Objective:** create a balance of heat input from environment + onboard dissipation

  = thermal emission to the environment

- Insulate any non-radiating surfaces with multi-layer insulation (MLI)
- Size radiating surfaces large enough to keep equipment within upper temperature limits during hot phases
- Size heaters large enough to maintain lower temperature limits during cold phases



Impact on Spacecraft

Principal Trade-off

Passive thermal control vs. Active thermal control

- **Passive** (e.g. surface coatings)**:**
  - –No power requirement
  - –No moving parts (mechanisms)
  - –Simple, reliable
  - –Low cost
- **Active** (e.g. fluid loop)**:**
  - –Power requirement
  - –Mechanisms (reliability)
  - –Greater mass
  - –High(er) cost

Impact on Spacecraft

- **Active methods** are generally more flexible and adaptive to varying thermal environments, and higher heat transfer rates

- **But** … the industry will try to use passive methods whenever possible

- **The thermal control engineer** is involved in the design of nearly all other onboard systems.

Chapter 10 Summary

Key points:

Thermal Control

- Function and specific requirements of the subsystem
- Mechanisms of heat transfer
- Heat inputs and outputs leading to the thermal balance

Material Properties and Radiation

- Incident radiation and what happens to the radiation when it hits a body
- Definition of a blackbody
- Definition of absorption of a body under solar illumination
- Blackbody emission
- Definition of the thermal emission of a real surface

Spacecraft Thermal Balance

- Numerical definition of the heat inputs and outputs of the spacecraft thermal balance equation
- Assumptions of the equation and the use of effective values

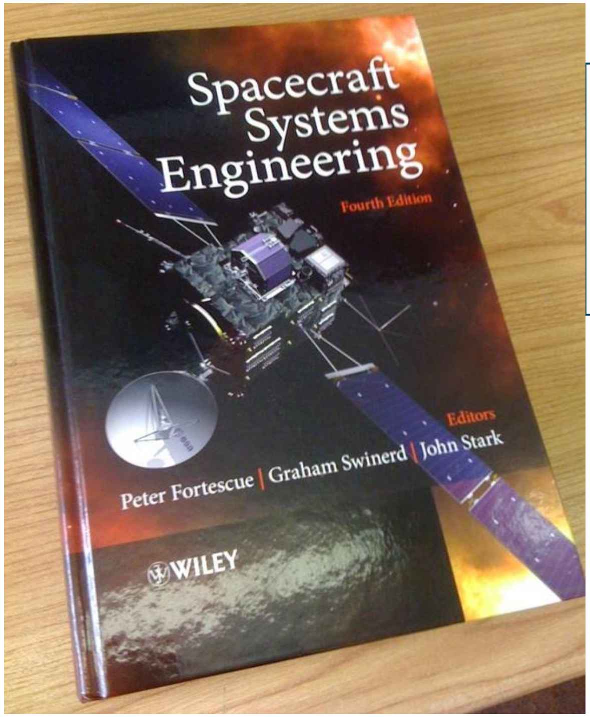
Thermal Control (Passive)

- Modification of the thermal balance equation and the assumption that allows the spacecraft temperature to be passively controlled
- Guidelines for passive thermal design of spacecraft

Impacts on the Spacecraft

- Outline of the key impacts of the thermal control subsystems on the design of the spacecraft

Chapter 10 Summary



Read Chapter 11 of Fortescue, Stark & Swinerd