Transferencia de Calor y Control Térmico

Isabel Pérez Grande
isabel.perez.grande@upm.es
David González Bárcena
david.gonzalez@upm.es

1

1

Passive Thermal Control: Coatings and surface finishes

2

2

Index

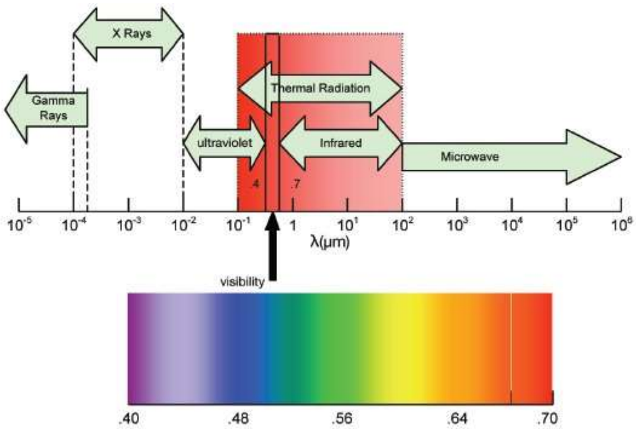
- Thermal Radiation
  - Spectrality (Blackbody radiation)
  - Directionality
  - Radiative properties
- Solar radiation
- Space environment
- Thermo-optical properties
- Thermo-optical coatings. Types
- Thermo-optical coatings. Degradation

3

3

- Thermal Radiation

Electromagnetic radiation emitted from all matter that is a non-zero temperature in the wavelength range from 0.1 μm to 100 μm.



4

- The mechanism of radiation emission is related to energy released due to the **energy transitions** of molecules, atoms, and electrons of a substance. The amount of thermal radiation emitted at each frequency depends on the internal energy and therefore, **the temperature**.

- Thermal radiation does not require a material medium for its propagation. It takes place in the form of discrete photons or quanta (*Quantum Theory*, Max Plank) with an energy of:

$$E = h\nu \, ; \qquad h = 6.6256 \cdot 10^{-34}\ \mathrm{J \cdot s}$$

- In vacuum, it propagates at speed of light c_0 = 2.9979x10^8 m/s.

- It is characterized by its frequency (depends only on the source) and its wavelength, dependent of the medium through which the wave travels:

$$\lambda = c/\nu$$

Thermal radiation depends on the wavelength and the direction.

5

❑ Blackbody radiation

- Perfect emitter and absorber of radiation.
- Radiation do not depend on direction (diffuse).
- In vacuum, radiation depends only on temperature.

Stefan–Boltzmann law

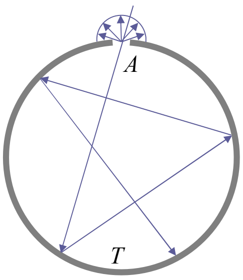
* Determined experimentally by Joseph Stefan and theoretically verified in by Ludwig Boltzmann.

Radiation energy emitted by a blackbody per unit time and per unit surface area.

$E_b(T) = \sigma T^4$ (Total Blackbody emissive power)

$\sigma = 5.67 \cdot 10^{-8}\ \mathrm{W/m^2K^4}$ (Stefan-Boltzmann constant)

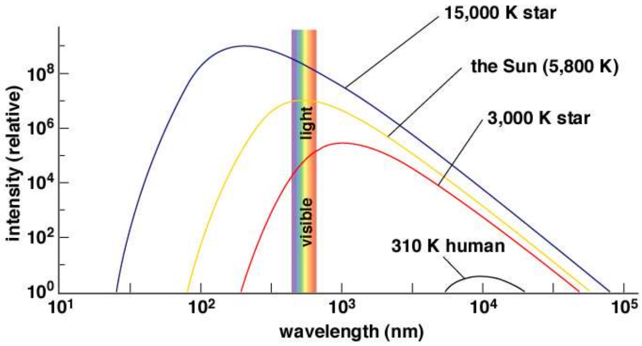
Blackbody ≠ Black surface (0.4 to 0.76 μm)



6

Spectral emissivity of a blackbody (Planck's law)

- Continuous function of wavelength.
- At any wavelength, the amount of emitted radiation increases with increasing temperature.
- As temperature increases, the curves shift to the left to the shorter wavelength region.



A black body is a theoretical object that completely absorbs all of the light that it receives and reflects none. A black body also is a perfect emitter of light over all wavelengths, but there is one wavelength at which its emission of radiation has its maximum intensity.

Spectral emissive power of a blackbody (Planck's law)

Amount of radiation energy emitted by a blackbody at an absolute temperature, T, per unit time, per unit surface area, and per unit wavelength about the wavelength, λ.

$$E_b(\lambda,T)=\frac{C_1}{\lambda^5\left(\exp\left(\frac{C_2}{\lambda T}\right)-1\right)}$$

$$\begin{cases} C_1 = 2\pi hc^2 = 3.742\cdot 10^8 \ \mathrm{W\cdot \mu m^4/m^2} \\ C_2 = hc/k = 1.439\cdot 10^4 \ \mathrm{\mu m\cdot K} \end{cases}$$

$k = 1.38065\cdot 10^{-23}$ J/K (Boltzmann's constant)

$$E_b(T)=\int_0^\infty E_{b,\lambda}(\lambda,T)\,\mathrm{d}\lambda = \sigma T^4$$

Stefan-Boltzmann law

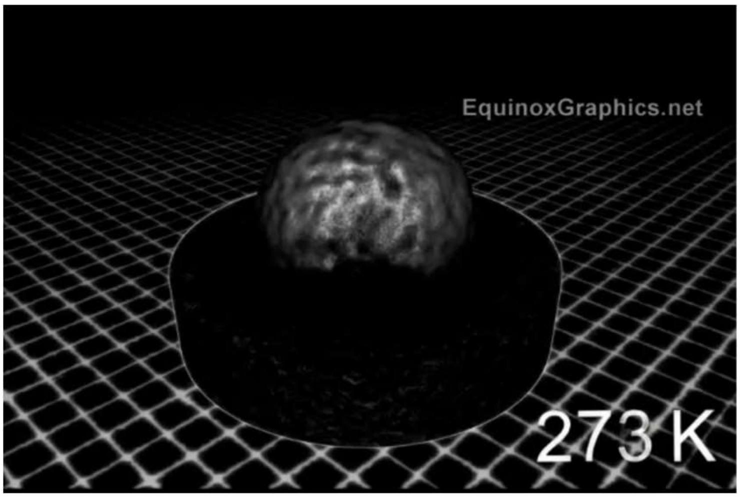
Blackbody radiation function

$$f_\lambda(T)=\frac{1}{\sigma T^4}\int_0^\lambda E_{b,\lambda}(\lambda,T)\,\mathrm{d}\lambda$$

Wien's displacement law

$$\lambda_{\text{max power}} T = 2898\ \mathrm{\mu m\cdot K}$$

https://www.youtube.com/watch?v=cPQeaAkAM_A



9

9

Exercise 1

The temperature of the filament of an incandescent lightbulb is 2500 K. Assuming the filament to be a blackbody, determine:

a) The fraction of the radiant energy emitted by the Sun that falls in the visible range (0.4 µm to 0.76 µm).

b) The fraction of the radiant energy emitted by the filament that falls in the visible range.

c) The wavelength at which the emission of radiation from the Sun and the filament peaks.

d) For a filament of 40 µm diameter and 0.5 m length, the total amount of radiation energy emitted in 5 min.

λT, µm · K	f_λ	λT, µm · K	f_λ
200	0.000000	6200	0.754140
400	0.000000	6400	0.769234
600	0.000000	6600	0.783199
800	0.000016	6800	0.796129
1000	0.000321	7000	0.808109
1200	0.002134	7200	0.819217
1400	0.007790	7400	0.829527
1600	0.019718	7600	0.839102
1800	0.039341	7800	0.848005
2000	0.066728	8000	0.856288
2200	0.100888	8500	0.874608
2400	0.140256	9000	0.890029
2600	0.183120	9500	0.903085
2800	0.227897	10,000	0.914199
3000	0.273232	10,500	0.923710
3200	0.318102	11,000	0.931890
3400	0.361735	11,500	0.939959
3600	0.403607	12,000	0.945098
3800	0.443382	13,000	0.955139
4000	0.480877	14,000	0.962898
4200	0.516014	15,000	0.969981
4400	0.548796	16,000	0.973814
4600	0.579280	18,000	0.980860
4800	0.607559	20,000	0.985602
5000	0.633747	25,000	0.992215
5200	0.658970	30,000	0.995340
5400	0.680360	40,000	0.997967
5600	0.701046	50,000	0.998953
5800	0.720158	75,000	0.999713
6000	0.737818	100,000	0.999905

10

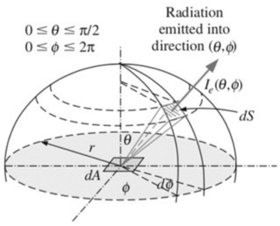
10

❑ Thermal radiation directionality

Directional distribution of emitted (or incident) radiation is usually not uniform.

Emitted radiation intensity, I_e

The rate at which radiation energy $\mathrm{d}Q_e$ is emitted at the wavelength λ in the (θ, Φ) direction per unit area normal to this direction, per unit solid angle about this direction.



Cengel, Y.A., Heat Transfer. A practical approach.

$$I_{\lambda,e}(\lambda,\theta,\phi,T) = \frac{\delta\dot{Q}_e}{\mathrm{d}A\cos\theta\,\mathrm{d}\omega\,\mathrm{d}\lambda} \qquad [\mathrm{W/(m^2\cdot sr\cdot \mu m)}]$$

- **Spectral hemispherical emissive power, E_λ**

$$E_\lambda(\lambda,T) = \int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,e}(\lambda,\theta,\phi,T)\cos\theta\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi$$

Diffuse $\quad E_\lambda(\lambda,T) = \pi\, I_{\lambda,e}(\lambda,T)$

- **Total emissive power, *E***

$$E(T) = \int_0^{\infty}\int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,e}(\lambda,\theta,\phi,T)\cos\theta\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi\,\mathrm{d}\lambda$$

Blackbody $\quad E_b(T) = \sigma T^4$

11

11

❑ Radiative properties

Emissivity

The ratio of the radiation emitted by the surface at a given temperature to the radiation emitted by a blackbody at the same temperature.

$0 < \varepsilon < 1$ (Blackbody)

- **Spectral directional emissivity**

$$\varepsilon_{\lambda,\theta}(\lambda,\theta,\phi,T) = \frac{I_{\lambda,e}(\lambda,\theta,\phi,T)}{I_{b\lambda,e}(\lambda,T)}$$

Diffuse $\quad \varepsilon_{\lambda,\theta}(\lambda,\theta,\phi,T) = \varepsilon_\lambda(\lambda,T)$

- **Spectral hemispherical emissivity**

$$\varepsilon_\lambda(\lambda,T) = \frac{E_\lambda(\lambda,T)}{E_{b\lambda}(\lambda,T)}$$

Greybody $\quad \varepsilon_\lambda(\lambda,T) = cte$

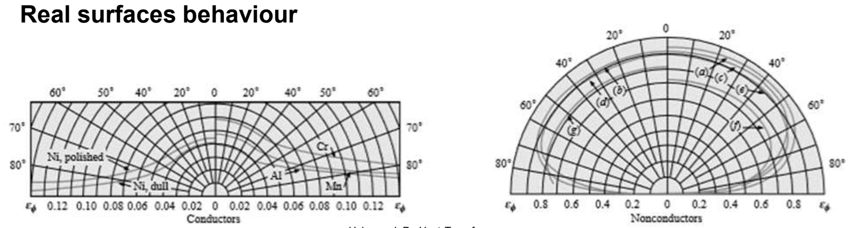
- **Total hemispherical emissivity**

$$\varepsilon(T) = \frac{E(T)}{E_b(T)} = \frac{\int_0^\infty \varepsilon_\lambda(\lambda,T)E_{b,\lambda}(\lambda,T)\mathrm{d}\lambda}{\sigma T^4}$$

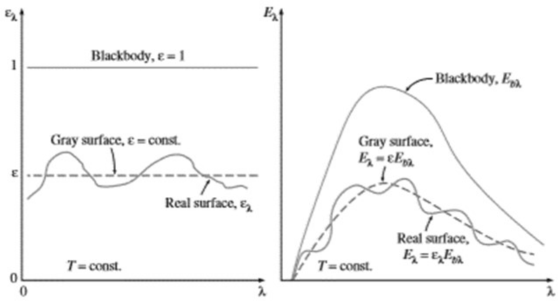
12

12

Real surfaces behaviour



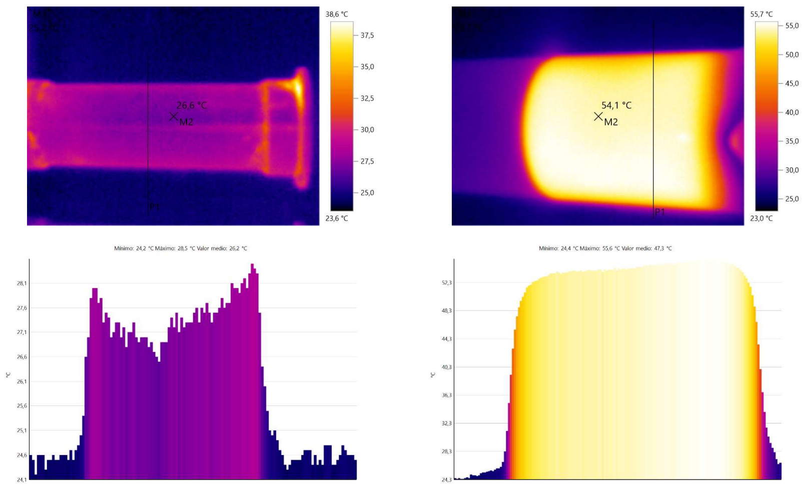
Holman, J. P., Heat Transfer



Cengel, Y.A., Heat Transfer. A practical approach.

13

13



14

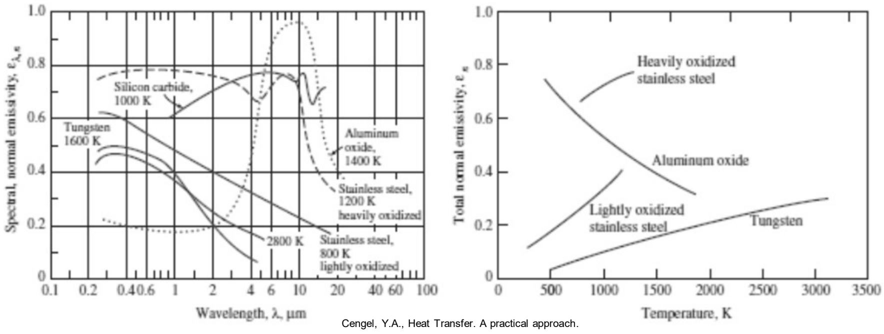
14

Exercise 2

The spectral emissivity function of the tungsten filament (E1) is approximated as:

$$\begin{cases} \varepsilon_1 = 0.4, & 0 \le \lambda < 0.76\ \mu\text{m} \\ \varepsilon_2 = 0.3, & 0.76\ \mu\text{m} \le \lambda < 2.0\ \mu\text{m} \\ \varepsilon_3 = 0.1, & 2.0\ \mu\text{m} \le \lambda < \infty \end{cases}$$

Determine the average emissivity of the surface and the total amount of radiation energy emitted in 5 min.



Cengel, Y.A., Heat Transfer. A practical approach.

15

Incident radiation intensity, *Ii*

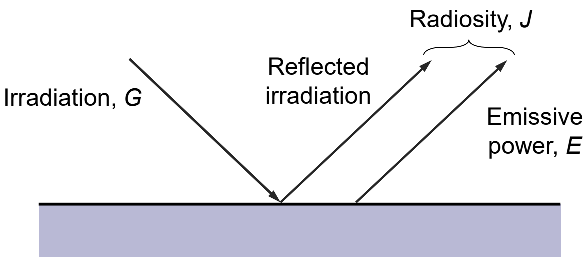
The rate at which radiation energy dQ_i *is incident from the (θ,Φ) direction per unit area of the receiving surface normal to this direction and per unit solid angle about this direction.*

- **Spectral irradiation, G**

$$G_\lambda(\lambda) = \int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,i}(\lambda,\theta,\phi)\cos\theta\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi$$

- **Irradiation, G**

$$G = \int_0^{\infty} G_\lambda(\lambda)\ \mathrm{d}\lambda$$



16

16

Absorptance

$$\alpha(\lambda,\theta,\phi,T)=\frac{I_{\lambda,i,abs}(\lambda,\theta,\phi,T)}{I_{\lambda,i}(\lambda,\theta,\phi)}$$

(Spectral directional)

$$\alpha(\lambda,T)=\frac{G_{\lambda,abs}(\lambda,T)}{G_{\lambda}(\lambda)}$$

(Spectral hemispherical)

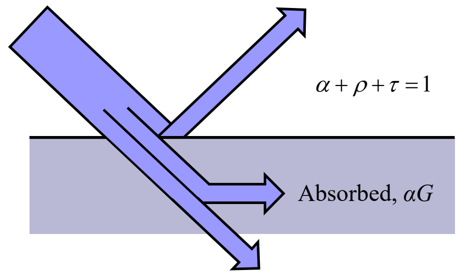
$$\alpha(T)=\frac{\int_0^{\infty}\alpha(\lambda,T)G_{\lambda}(\lambda)\mathrm{d}\lambda}{\int_0^{\infty}G_{\lambda}(\lambda)\mathrm{d}\lambda}$$

Reflectance

$$\rho(\lambda,\theta,\phi,T)=\frac{I_{\lambda,i,ref}(\lambda,\theta,\phi,T)}{I_{\lambda,i}(\lambda,\theta,\phi)}$$

Transmitance

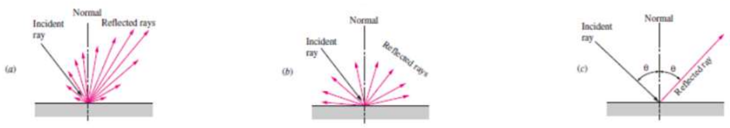
$$\tau(\lambda,\theta,\phi,T)=\frac{I_{\lambda,i,tr}(\lambda,\theta,\phi,T)}{I_{\lambda,i}(\lambda,\theta,\phi)}$$



$$\alpha+\rho+\tau=1$$

17

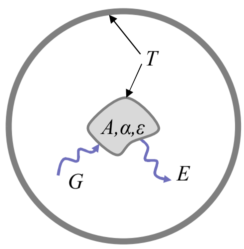
17



Cengel, Y.A., Heat Transfer. A practical approach.

Kirchhoff's Law

The total hemispherical emissivity of a surface at temperature T is equal to its total hemispherical absorptivity for radiation coming from a blackbody at the same temperature.



$$G_{abs}=\alpha G=\alpha\sigma T^4$$
$$E_{emit}=\varepsilon\sigma T^4$$

$$A_s\alpha\sigma T^4=A_s\varepsilon\sigma T^4$$

(spectral directional form)

$$\alpha(\lambda,\theta,\phi,T)=\varepsilon(\lambda,\theta,\phi,T)\xrightarrow{\text{Diffuse}}\alpha(\lambda,T)=\varepsilon(\lambda,T)\xrightarrow{\text{Grey}}\alpha(T)=\varepsilon(T)$$

* Special care when there is considerable difference between the surface temperature and the temperature of the source of incident radiation.

16

18

- Solar Radiation

Solar Irradiance

The rate at which solar energy is incident on a surface normal to the sun's rays at the outer edge of the atmosphere when the earth is at its mean distance from the Sun.

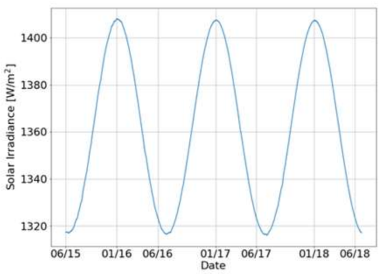
$$T_{Sun} = 5778 \text{ K} \qquad \xrightarrow{\textit{Inverse-square Law}}$$
$$E_{emit} = \sigma T_{Sun}^4$$

19

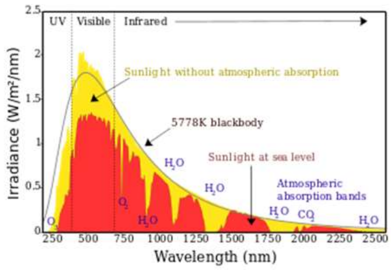
- Solar Radiation

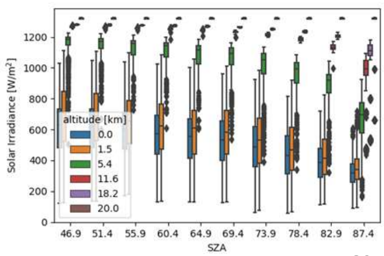
Solar Irradiance

The rate at which solar energy is incident on a surface normal to the sun's rays at the outer edge of the atmosphere when the earth is at its mean distance from the Sun.

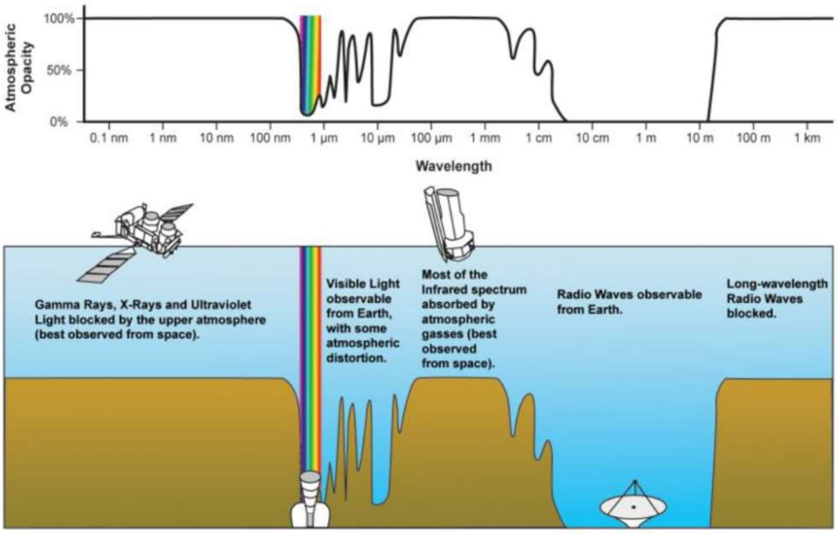


$$T_{Sun} = 5778 \text{ K} \qquad \xrightarrow{\textit{Inverse-square Law}} \qquad G_S = 1373 \text{ W/m}^2$$
$$E_{emit} = \sigma T_{Sun}^4$$



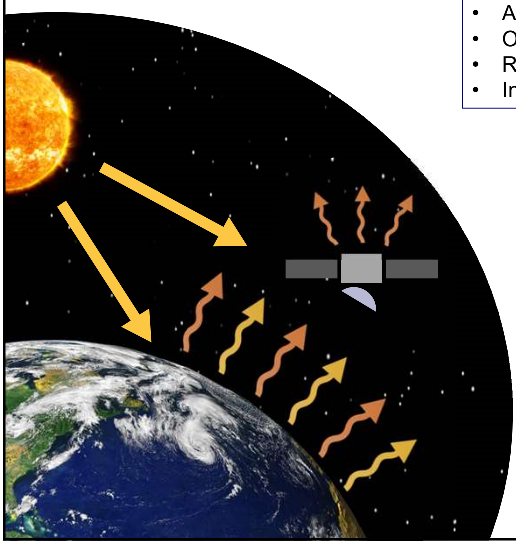


20



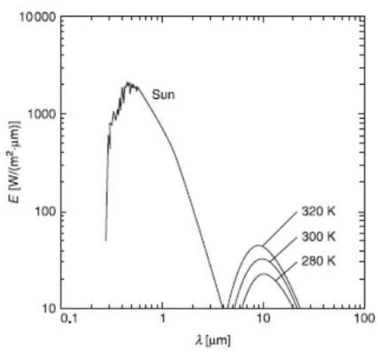
21

- Space environment



- Direct Solar Irradiance
- Albedo
- Outgoing Longwave Radiation
- Radiative cooling to outer Space
- Internal Heat Generation

Meseguer, J., Pérez-Grande, I., Sanz-Andrés, A. "Spacecraft thermal control",



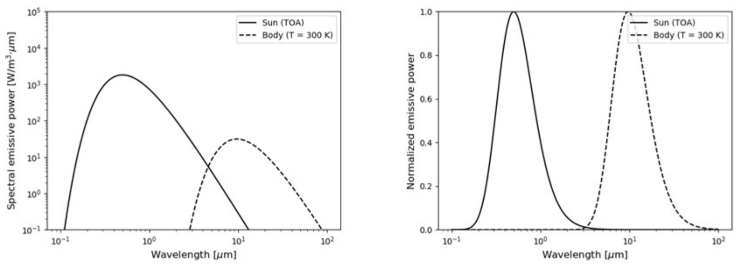
22

22

23

23

- Thermo-optical properties



Two ranges of interest:

- Wavelength from 0.1 to 2 μm → Solar radiation.
- Wavelength from 2 to 100 μm → IR radiation.

Kirchhoff's law (IR)

- $\alpha(\lambda, T) = \varepsilon(\lambda, T)$

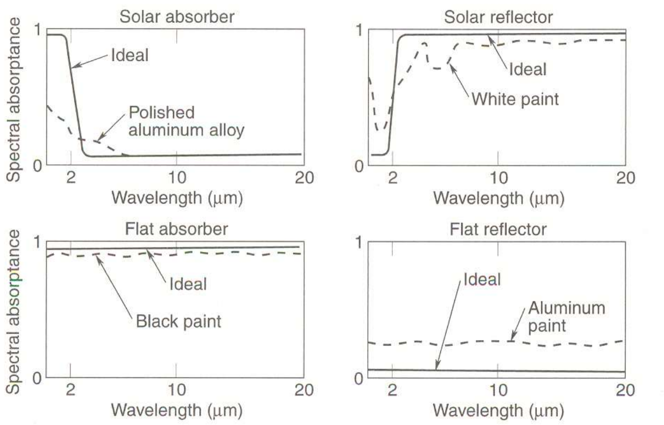
Solar absorptance, α_s

Total hemispherical infrared emissivity, ε

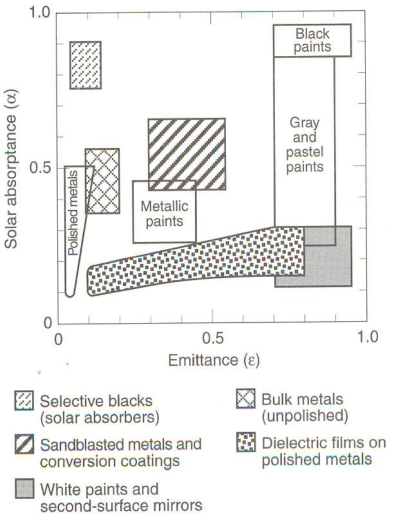
24

24

- Thermo-optical coatings types

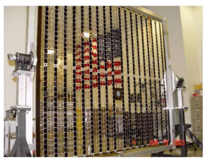


Gilmore, D.G., "Spacecraft thermal control handbook"



Gilmore, D.G., "Spacecraft thermal control handbook"

- Black paints ↑ α_s ↑ ε
- White paints ↓ α_s ↑ ε
- Second Surface Mirrors (SSM) ↓ α_s ↑ ε
- Polished metals ↓ α_s ↓ ε
- Solar absorbers ↑ α_s ↓ ε

External coatings

- Insulation blankets (Black kapton, aluminized kapton and beta cloth)
- Radiator coatings (SSM or white paints)
- Paints (based in absorptance and other criteria)

Internal coatings

- High emittance coatings (Black paints)
- Low emittance coatings (Bare or polished surfaces of aluminium, kapton tape with vapour-deposited aluminium or gold coatings and bare stainless steel).

Surface Finish	α (Beginning of Life)	ε
Optical Solar Reflectors		
8 mil Quartz Mirrors	0.05 to 0.08	0.80
2 mil Silvered Teflon	0.05 to 0.09	0.66
5 mil Silvered Teflon	0.05 to 0.09	0.78
2 mil Aluminized Teflon	0.10 to 0.16	0.66
5 mil Aluminized Teflon	0.10 to 0.16	0.78
White Paints		
S13G-LO	0.20 to 0.25	0.85
Z93	0.17 to 0.20	0.92
ZOT	0.18 to 0.20	0.91
Chemglaze A276	0.22 to 0.28	0.88
Black Paints		
Chemglaze Z306	0.92 to 0.98	0.89
3M Black Velvet	~0.97	0.84
Aluminized Kapton		
1/2 mil	0.34	0.55
1 mil	0.38	0.67
2 mil	0.41	0.75
5 mil	0.46	0.86
Metallic		
Vapor Deposited Aluminum (VDA)	0.08 to 0.17	0.04
Bare Aluminum	0.09 to 0.17	0.03 to 0.10
Vaporized Deposited Gold	0.19 to 0.30	0.03
Anodized Aluminum	0.25 to 0.86*	0.04 to 0.88*
Miscellaneous		
1/4 mil Aluminized Mylar, Mylar Side	(Material degrades in sunlight)	0.34
Beta Cloth	0.32	0.86
Astro Quartz	~0.22	0.80
MAXORB	0.9	0.1

* Anodizing and similar surface treatments must be carefully controlled in order to produce repeatable optical properties.

Gilmore, D.G., "Spacecraft thermal control handbook"

27

27

Specialty finishes

- Very high absorptance and very low emittance (MAXORB and TiNOX).
- Very low absorptance (overcoated silver).
- Low absorptance and low emittance (aluminium paints or silicon-oxide-coated aluminium).
- Controlled anodize or alodine processes.

Surface Finish	α (Beginning of Life)	ε
Optical Solar Reflectors		
8 mil Quartz Mirrors	0.05 to 0.08	0.80
2 mil Silvered Teflon	0.05 to 0.09	0.66
5 mil Silvered Teflon	0.05 to 0.09	0.78
2 mil Aluminized Teflon	0.10 to 0.16	0.66
5 mil Aluminized Teflon	0.10 to 0.16	0.78
White Paints		
S13G-LO	0.20 to 0.25	0.85
Z93	0.17 to 0.20	0.92
ZOT	0.18 to 0.20	0.91
Chemglaze A276	0.22 to 0.28	0.88
Black Paints		
Chemglaze Z306	0.92 to 0.98	0.89
3M Black Velvet	~0.97	0.84
Aluminized Kapton		
1/2 mil	0.34	0.55
1 mil	0.38	0.67
2 mil	0.41	0.75
5 mil	0.46	0.86
Metallic		
Vapor Deposited Aluminum (VDA)	0.08 to 0.17	0.04
Bare Aluminum	0.09 to 0.17	0.03 to 0.10
Vaporized Deposited Gold	0.19 to 0.30	0.03
Anodized Aluminum	0.25 to 0.86*	0.04 to 0.88*
Miscellaneous		
1/4 mil Aluminized Mylar, Mylar Side	(Material degrades in sunlight)	0.34
Beta Cloth	0.32	0.86
Astro Quartz	~0.22	0.80
MAXORB	0.9	0.1

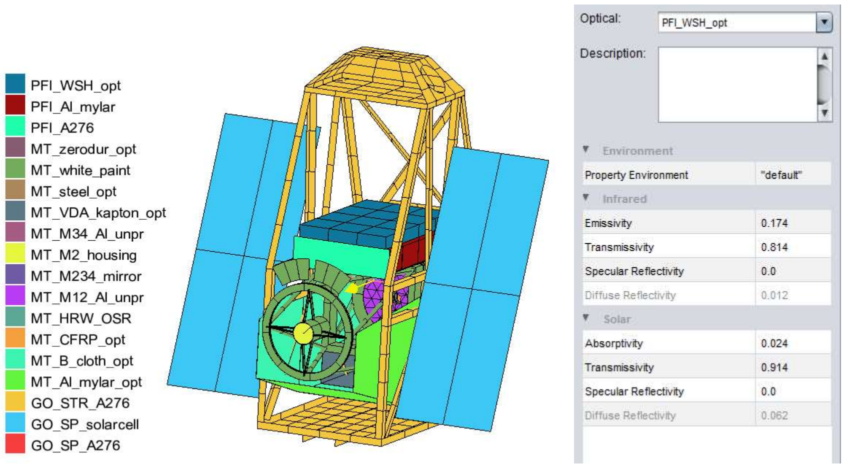
* Anodizing and similar surface treatments must be carefully controlled in order to produce repeatable optical properties.

Gilmore, D.G., "Spacecraft thermal control handbook"

28

28

Thermal model implementation



29

29

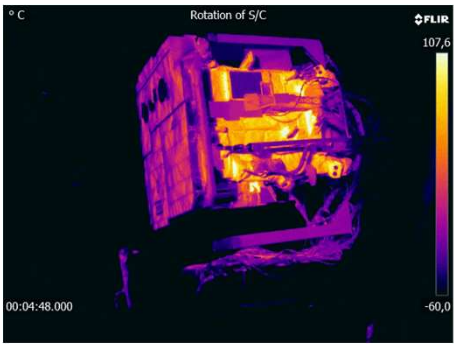
Measurements

- **Emissivity**: Incoming radiation from an opaque body kept at temperature T under cryogenic vacuum (avoid reflections) and dividing the result by the corresponding Planck's equation value (emissometer)
  - For total hemispherical emissivity, a simple energy balance may be used with an electrically-heated sample in a cryogenic vacuum.
- **Reflectance**: Dividing the increase in irradiation detected from an opaque body (discounting emission and transmission) by a sinusoidal variation of the intended irradiation shining on the object (to discount other reflections)
  - If an infrared source is used, Kirchhoff's law implies $\varepsilon = 1 - \rho$.
- **Absorptance**: Measuring reflectance in opaque bodies or in terms of the exiting radiation in transparent media.
  - On photovoltaic cells (with an efficiency of $\eta = (VI)_{max}/(G_s A)$) the thermal absorption is $\alpha_{th} = \alpha - \eta F_p$ where F_p is the packaging factor.
- **Transmittance**: In terms of the extinction coefficient and the reflectance.

30

30

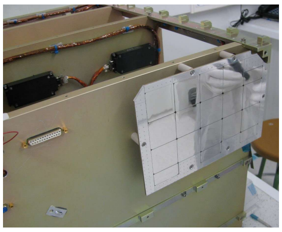
Solar Orbiter

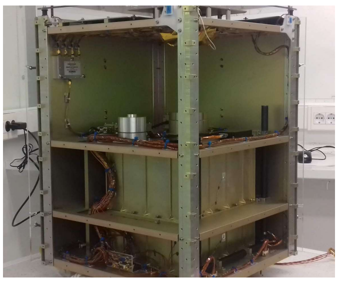


31

31

UPMSat-2

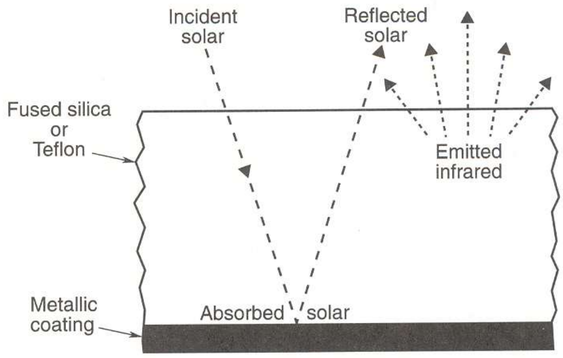




32

32

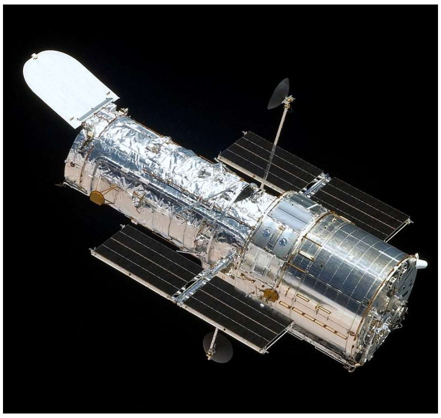
- Second-Surface Mirrors: SSM, OSR
  - Quartz second-surface mirrors: Optical Solar Reflectors (OSRs).
  - Teflon second-surface mirrors: Flexible OSRs.



Gilmore, D.G., "Spacecraft thermal control handbook"

33

33



34

34

- Thermo-optical coating degradation

Causes

- Contamination
- UV Radiation
- Atomic Oxygen
- Charged particles
- Micrometeoroids and debris

Effects

- Increase in solar absorptance
- No effect on IR emissivity

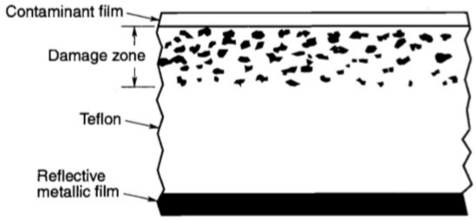


Fig. 4.8. Metalized Teflon degradation model.

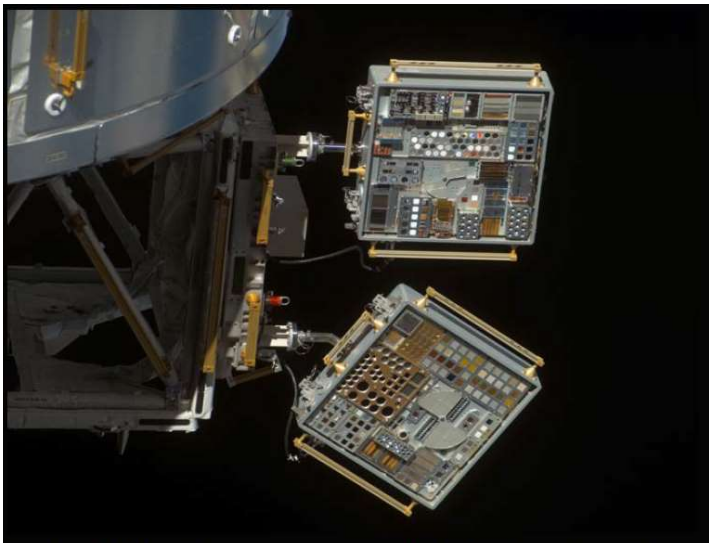
Gilmore, D.G., "Spacecraft thermal control handbook"

Consequences

- Spacecraft radiator have to be sized (oversized) to account for the substantial increase in absorbed solar energy (Effective performance at different temperatures).

35

35



Close-up view of the Materials International Space Station Experiment (MISSE) 6A and 6B Passive Experiment Containers (PECs) on the European Laboratory/Columbus. Photo was taken during a flyaround of STS-123 Space Shuttle Endeavor.

36

36

- **Contamination**
  - Outgassing products (ECSS-Q-ST-70-02C).
  - Thruster-generated contaminants.
  - Released particles with the spacecraft.

Table 4.2. Outgassing Data for Thermal-Control Surface Materials

Material	TML (%)	CVCM (%)
OSR	0.00	0.00
FEP Teflon	0.77	0.35
Kapton	0.78	0.03
Glass fabric/Kapton	0.42	0.05
Black Kapton	0.50	0.02
Glass fabric/Black Kapton	0.53	0.06
White polyurethane paint	0.99	0.08
Black polyurethane paint	1.91	0.28
White silicone paint	0.54	0.10
Black silicone paint	0.43	0.04
White inorganic paint	>1.00	0.00

* Percent total mass loss (percent TML) and percent collected volatile condensable materials (percent CVCM)

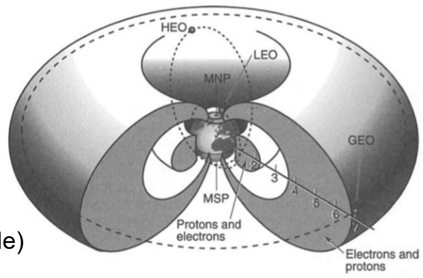
Gilmore, D.G., "Spacecraft thermal control handbook"

37

37

- **UV Radiation (vacuum UV radiation < 200 nm)**
  - Enhance the outgassing.
  - Corruption of thermal coatings.

- **High-energy particles**
  - Trapped radiation
  - Quite Sun radiation
  - Solar flare radiation (11 years cycle)
  - Low-energy plasma



Gilmore, D.G., "Spacecraft thermal control handbook"

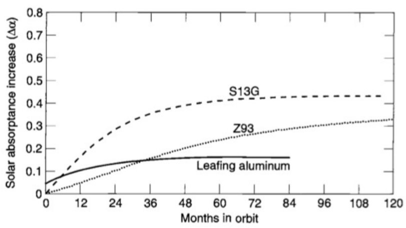


Fig. 4.10. Paint degradation.

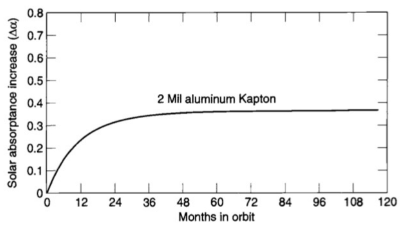


Fig. 4.11. Kapton absorptance degradation.

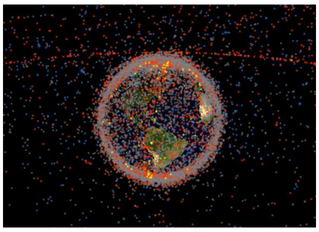
Gilmore, D.G., "Spacecraft thermal control handbook"

38

38

- **Atomic Oxygen**
  - Low orbit environments.
  - Affects polymer materials (Kapton).
  - Negligible in metals.

- **Micrometeoroids and debris**
  - Hundreds of impacts (< 5 mm).
  - Negligible or limited effects.



http://stuffin.space/

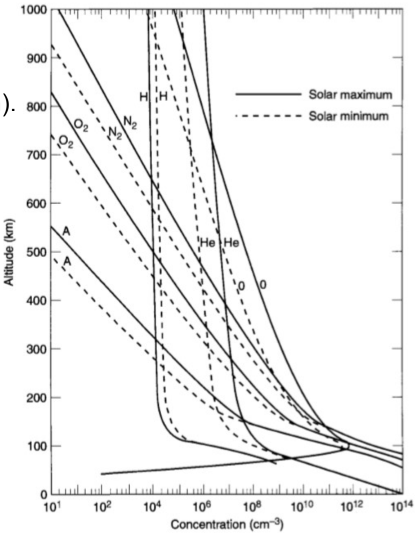
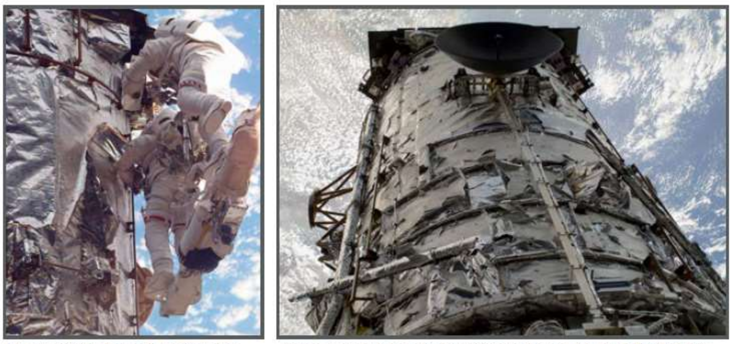


Fig. 4.5. AO concentration.

Gilmore, D.G., "Spacecraft thermal control handbook"



Large radiation-induced cracks in the outer layer of multilayer insulation after 6.8 years of space exposure (Townsend et al., 1999).

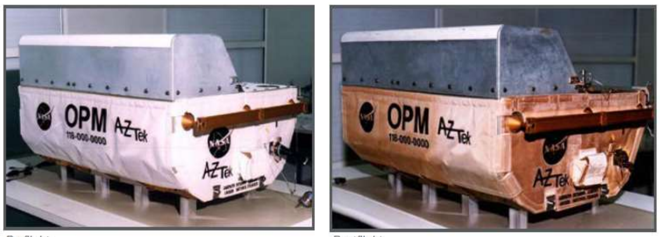
Severe degradation to the aluminized-Teflon® outer layer of multilayer insulation after 19 years of space exposure (Yang and de Groh, 2010).

Figure 2. Space-exposure damage to Hubble Space Telescope multilayer insulation.

Preflight

Postflight

Figure 1. Preflight and postflight Long Duration Exposure Facility M0001 Heavy Ions in Space experiment, indicating atomic oxygen erosion and ultraviolet degradation.



Preflight

Postflight

Figure 4. Preflight and postflight images of the Optical Properties Monitor shown with ultraviolet-darkened insulation after nine months of exposure on the Mir Space Station.

41

41

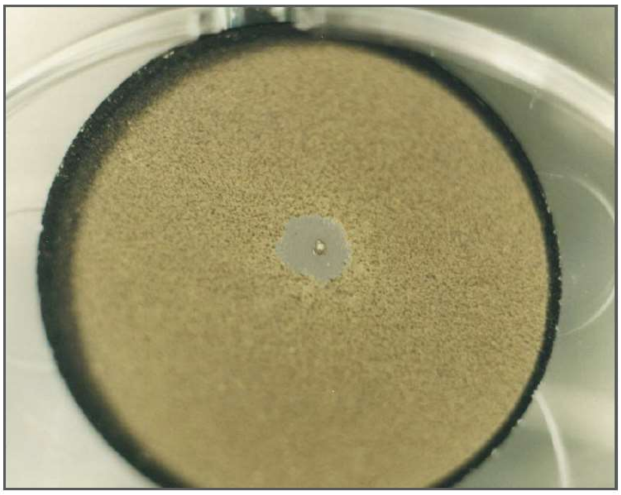


Figure 7. A micrometeoroid or orbital debris impact results in a 0.6-mm diameter crater and approximately 3-mm diameter spall (loss of the coating). 2.54 cm diameter Tiodize coating on titanium flown on the Long Duration Exposure Facility A0171 experiment.

42

42

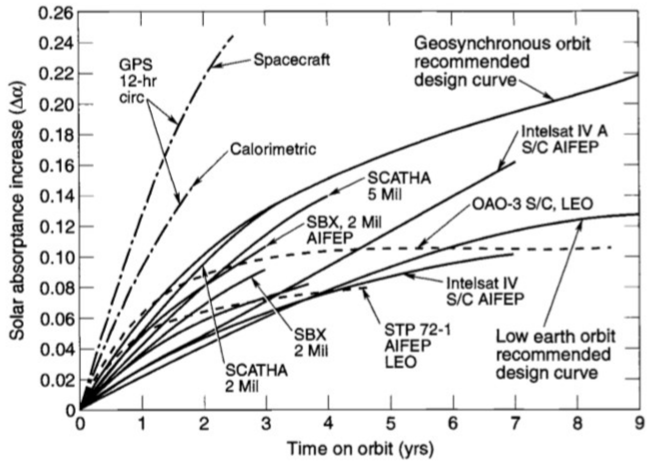


Fig. 4.9. Metalized Teflon degradation.

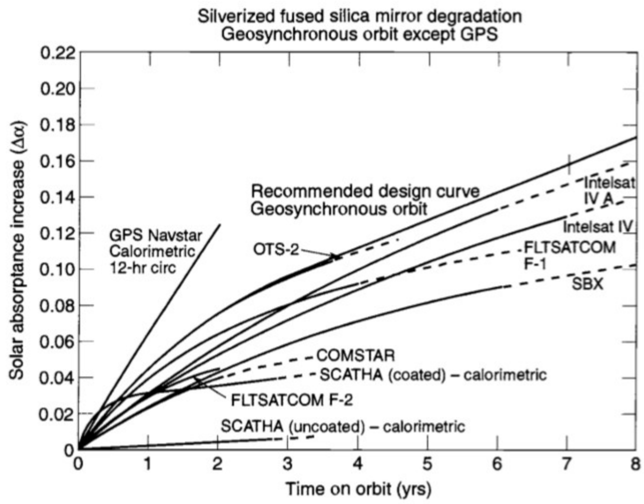


Fig. 4.7. Degradation of quartz mirrors in geosynchronous orbit.

Exercise 3

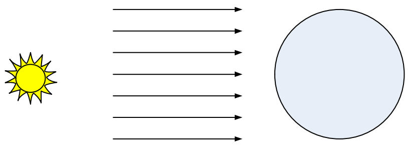
A sphere of radius R with thermo-optical properties α_s and ε and an area A in the space at 1 AU is only exposed to solar radiation.

a) Present the thermal balance.

b) Assuming a steady-state, check the influence of different optical coatings for a sphere radius $R = 0.5$ m.

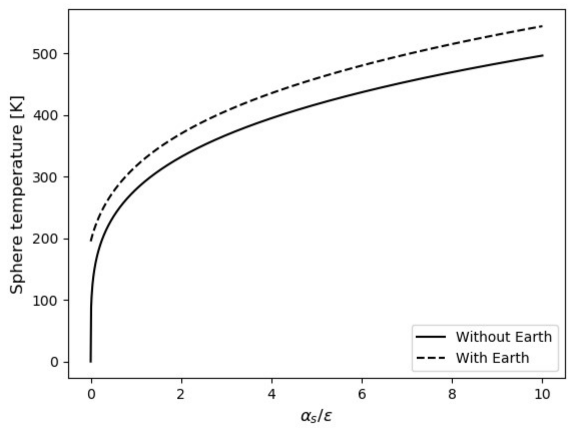
c) Consider the effect of the Earth (circular orbit at an altitude of 300 km) and show the temperature as a function of the ratio α_s/ε.

Data: $R_E = 6378$ km; $\alpha_E = 0.7$; $\varepsilon_E = 0.6$; $T_E = 288$ K



45

45



46

46

Exercise 4

Dimension the thermal control system of the previous sphere (α_s, ε and heater power P_H) considering an internal heat source of P_c = 200 W being the temperature requirements T_{min} = 240 K and T_{max} = 300 K.

** Firstly, dimensioning the Hot Case (α_s, ε) guaranteeing the survival for the BoL and EoL. Then, dimensioning the Cold Case (P_H).*

a) Consider the hot (illumination) and cold (eclipse) steady-state cases.

b) Consider the effect of covering the sphere by a one-node shield of R = 0.55 m with the same thermo-optical properties.

c) Compare the results with a two-nodes shield (MLI) with Beta Cloth outside, VDA-Kapton inside and an equivalent emissivity of 0.01.

REFERENCES

- Meseguer, J., Pérez-Grande, I., Sanz-Andrés, A. "Spacecraft thermal control", Woodhead Publishing, 2012.
- Gilmore, D.G., “Spacecraft thermal control handbook”, The Aerospace Corporation Press, 2002.
- Holman, J. P., “Heat Transfer (8ª ed.)”, McGraw-Hill, 1997.
- Cengel, Y.A., “Heat Transfer. A practical approach”.