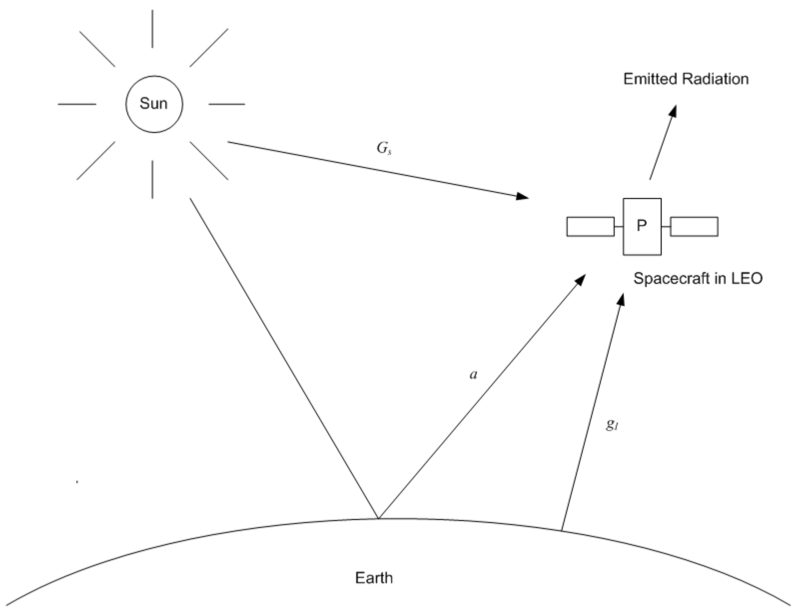
6 Thermal

6.1 Thermal Equilibrium Temperatures

In order to make a design for a thermal control system to meet the temperature requirements one need to identify the heat sources affecting the system. The heat sources for a spacecraft orbiting planet Earth is the Sun, the Earth and also the heat produced by the system itself denoted P below:



The estimated equilibrium temperature for a body in space is obtained by the energy balance equation which is a derivative from the conservation of energy:

$$Absorbed energy + Dissipated energy - Emitted energy = 0$$

$$q_{absorbed} + q_{dissipated} - q_{emmited} = 0$$

Case:
Let us consider an add-on spacecraft module with the structure shown below consisting of 5 surfaces

And let us also define a **hot** scenario for the module situated on a S/C orbiting Earth at an altitude of 500 km to be:

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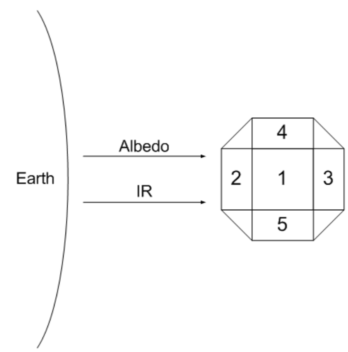
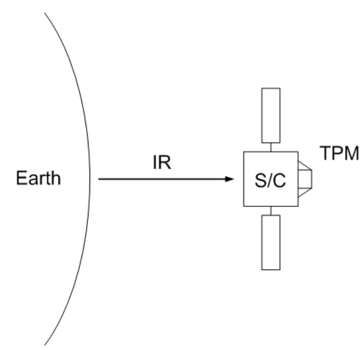


with the normal vector of surface 1 parallel to the incoming solar radiation and also a contribution of albedo and IR radiation from planet Earth. Further, a **cold** scenario can be defined as illustrated below



without any influence of direct sunlight or albedo.

- Solar constant at 1 A.U is 1418 W/m2
- Earth IR emission at 500 km altitude is 222 W/m2
- Earth albedo 0.35
- Internally generated heat dissipation is 40 W (hot case only)
- Consider white painted surfaces
- Side x=0.2 m

Answer the following questions:

1. What will be the uniformly distributed equilibrium temperatures for the system containing surface 1 to 5 in the hot- and cold scenarios respectively, only considering radiation as heat transfer?

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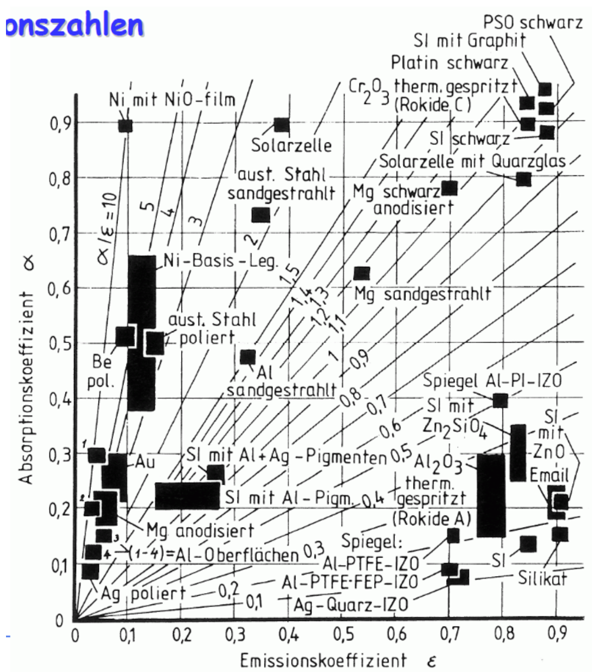
2. Consider gold coating on all the surfaces and calculate the new hot case equilibrium temperature for the system

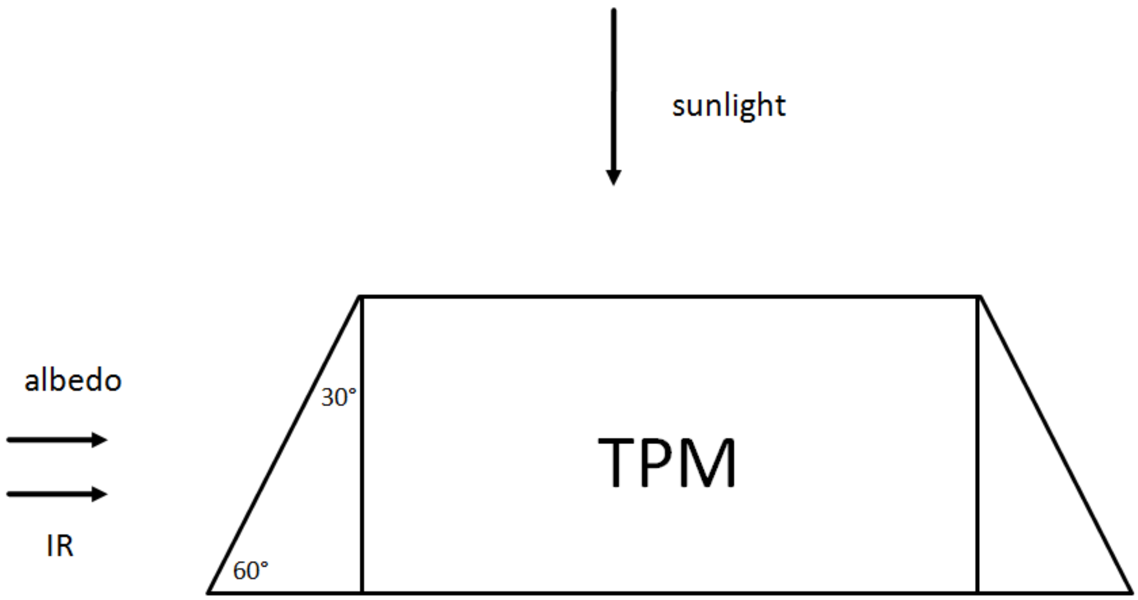
3. Assume a heat flow from the S/C body to the module (in the cold case) that corresponds to an internally generated heat dissipation of 10 W and calculate the new cold case equilibrium temperature.

4. Assume that the internally generated heat can be transferred to a space radiator onboard the hosting S/C. What is the required area of the space radiator when its working temperature is 30°C and it is white painted?

5. Calculate the new hot case equilibrium temperature for the module when the space radiator is assumed to take care of the internally generated heat.



1.
For the hot case we start with the detemination of the view factors. The view factor is a number between 0 and 1 which relates the area and the angle between the area normal vector and the view. The view factor has to be determined for every side of the system facing outside. From the drawing we can determine the following angles:



View Factor	Notation	Function	Absolute No.
Sun - 1	$F_{S,1}$	$\sin 90°$	1
Sun - 2 to 5	$F_{S,2-5}$	$\sin 30°$	0.5
Albedo - 2	$F_{a,2}$	$\sin 60°$	0.866
IR - 2	$F_{IR,2}$	$\sin 60°$	0.866

For the energy balance we use the following equation **(hot case)**:

$$Q_{int} + \sum_{i=1}^{5} q_s \cdot F_{S,i} \cdot A_i + q_a \cdot F_{a,i} \cdot A_i + q_{IR} \cdot F_{IR,i} \cdot A_i - \sigma \cdot e_{IR} \cdot A_{Tot} \cdot T^4 = 0$$

Here the q terms denote the specific heat flow either from the sun (s) the earth albedo (a) or the earth infrared radiation (IR). This term is multiplied with the area which is relevant for the heat exchange, which is the real area multiplied with the view factor ($F \cdot A$). The σ variable denotes the Boltzmann constant where T is the spacecraft temperature. α and are the absorption and emission coeeficients of the surfaces.
The specific heat flows for the three radiation types can be found using the following equations:

$$q_s = G_s \cdot \alpha_s$$

$$q_a = G_s \cdot \alpha_s \cdot a \cdot Ka \cdot \sin^2 \rho$$

$$q_{IR} = G_{IR} \cdot \epsilon_I R$$

$$q_{out} = \sigma \cdot \epsilon_{IR} \, T^4$$

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Note that the emited heat flow is emited over the complete area facing outside!
Now we are rearranging the energy equation to obtain the system temperature:

$$T_{Hot} = \left[\frac{Q_{int} + \sum_{i=1}^{5} q_s \cdot F_{S,i} \cdot A_i + q_a \cdot F_{a,i} \cdot A_i + q_{IR} \cdot F_{IR,i} \cdot A_i}{\sigma \cdot \epsilon_{IR} \cdot A_{Tot}}\right]^{0.25}$$

Q_{int} must be in Watts and $A_{Tot} = 5A$. The variable a denotes the earth albedo factor. The Ka factor is a correction factor for the albedo.It is defined as the ratio between the sunlit aurface of the earth to the total visible surface. For the hot case we assume it to be 1. ρ is the angular size of the earth which is a function of the orbit height. We will now compute the three incoming heat flows:

$$G_S \cdot \alpha_s \cdot (F_{S,1} + 4 \cdot F_{S,2-5}) \cdot A = 1418 \cdot 0.5 \cdot (1 + 4 \cdot 0.5) \cdot 0.04 = 85.1W$$

$$G_S \cdot a \cdot \alpha_s \cdot F_{a,2} \cdot A \cdot Ka \cdot \sin^2 \rho = 1418 \cdot 0.35 \cdot 0.5 \cdot 0.866 \cdot 0.04 \cdot 1 \cdot 0.859 = 7.4W$$

$$G_{IR} \cdot \epsilon_{IR} \cdot F_{IR,2} \cdot A = 222 \cdot 0.8 \cdot 0.866 \cdot 0.04 = 6.2W$$

This gives us:

$$T_{Hot} = \left[\frac{40W + 85.1W + 7.4W + 6.2W}{5.67 \cdot 10^{-8} \cdot 0.8 \cdot 5 \cdot 0.04}\right]^{0.25} = 350°K = 77°C$$

For the cold case all the incoming heat fluxes except the earth IR are not available and there will be no internal dissipation. The equation then is simplified to:

$$T_{cold} = \left[\frac{6.2W}{5.67 \cdot 10^{-8} \cdot 0.8 \cdot 5 \cdot 0.04}\right]^{0.25} = 161K$$

2.
Now we will change the coating material of the system to a gold painting ($\alpha = 0.3$ und ß$epsilon = 0.025$). For the hot case the calculation will then be:

$$T_{Hot} = \left[\frac{40W + 51W + 3.2W + 0.2W}{5.67 \cdot 10^{-8} \cdot 0.025 \cdot 5 \cdot 0.04}\right]^{0.25} = 760°K = 486°C$$

3.
Now we are considering an heat flow from the spacecraft to our subsystem. The heat flow can be regarded as in internal heat dissipation of 10 W. We will use the same equation as in step 1 but we will ngelect the incoming heat via the earth IR.

$$T_{cold} = \left[\frac{10W + 6.2W}{\sigma \cdot \epsilon_{IR} \cdot A_{Tot}}\right]^{0.25} = 205K$$

We will use the same equation for the gold painting

$$T_{cold} = \left[\frac{10W + 6.2W}{\sigma \cdot \epsilon_{IR} \cdot A_{Tot}}\right]^{0.25} = 488K$$

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You can see that the correct painting will help you to lift your temperature up. The cold case with 488 K is too high but you can see how large the influence of the painting is for a spacecraft's thermal condition.

4.

Now we are using an radiator that helps us to get rid of the heat in our system. When we try to find the area needed to radiate the internal dissipated 40W from the subsystem we use the following equation:

$$Q_{int} = \sigma \cdot \epsilon_{IR} \cdot A_{Tot} \cdot T_r^4$$

$$A_r = \frac{Q_{int}}{\sigma \cdot \epsilon_{IR} \cdot T_r^4} = 0.1m^2$$

5.

If we now assume that our radiator can be implemented and the internally dissipated heat is taken care of we can compute the new hot case temperature:

$$T_{Hot} = \left[\frac{85.1W + 7.4W + 6.2W}{5.67 \cdot 10^{-8} \cdot 0.8 \cdot 5 \cdot 0.04}\right]^{0.25} = 49°C$$

For the gold painting we get

$$T_{Hot} = \left[\frac{51W + 3.2W + 0.2W}{5.67 \cdot 10^{-8} \cdot 0.025 \cdot 5 \cdot 0.04}\right]^{0.25} = 389°C$$

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