Astronautics (SESA2024)

Section 10: Thermal Control – suggested solutions.

1. Thermal control is first necessary to ensure the long-term and reliable performance of the spacecraft components. Every component on the spacecraft is designed to operate within temperature limits, the most important of these include batteries, propellant and mechanical devices. Any deviation from these design limits may result in component failures. There may also be specific thermal requirements for the payload which includes tight temperature constraints, thermal gradients or thermal stability.

2. The general definition of spectral absorptance is:

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

Where q_i is the intensity of the incident radiation at a wavelength of λ (in units $\mathrm{Wm^{-2}\,\mu m^{-1}}$) and q_a is the magnitude of the incident radiation that is absorbed by the material. Therefore α is a ratio parameter of the quantity of radiation absorbed, proportional to the incident radiation, with a value between 0 and 1 which varies as a function of λ.
The ideal theoretical body called a 'blackboard' has an absorptance value of 1 for all wavelengths. It is a perfect absorber.

3. The emittance of a real material surface is defined by:

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

where $q(T)$ ($\mathrm{W\,m^{-2}}$) 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 blackbody surface at the same temperature. So the emittance ratios the real material output to that of a blackbody, and again it has a value between 0 and 1.
When substituting in the equation of the emittance for a blackbody, the emittance for the real material surface becomes:

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

4. The main inputs are: the direct solar radiation, the Earth albedo (Suns radiation reflected off the Earth), the direct radiation from the Earth and the spacecraft's internal heat dissipation.
The main output is: the thermal radiation emission from all the spacecraft surfaces.

5. The spacecraft thermal balance equation, which is:

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

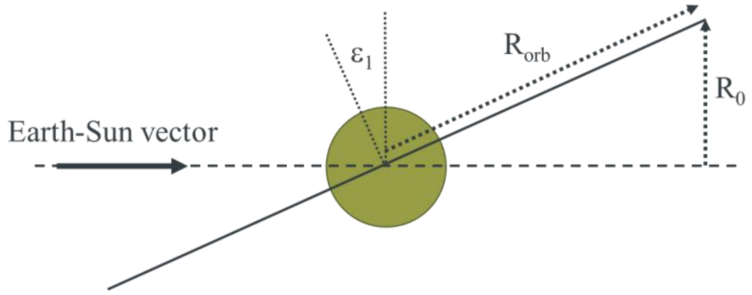
can be rearranged by dividing through by ε and the spacecraft surface area (A_{surf}), giving:

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

Provided that the Sun's input is much greater than both the input from the Earth and the on-board heat dissipation, then the balance temperature of the spacecraft becomes a function of the ratio of the absorptance and emittance.

6. Active thermal control would become necessary if passive methods were not sufficient to be able keep the on-board components within their thermal tolerance range. This most notably might be the case if there were very specific payload thermal requirements (such as the cooling of payload sensors), or if the spacecraft was subjected to particular harsh and/or highly variable environmental conditions.
The choice to use active methods generally implies that there is a power requirement associated with it along with the inclusion of mechanical components (hence possible reliability issues). This typically results in greater subsystem mass and a higher cost.

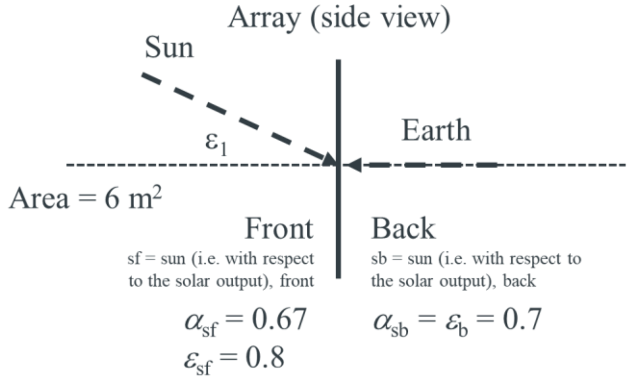
7. To determine if an eclipse will occur construct an image of the geometry of the system…



If $R_0 >$ Earth's radius, then no eclipse will occur.

$R_{orb} \sin \varepsilon_1 = R_0$ so $R_0 = 7177$ km, therefore no eclipse.

Array Temperatures
Local noon position



Sun's input

$Q_s = q_s\ \alpha_{sf}\ A_s^{proj}$
$= (1400)\ (0.67)\ (6 \cos (23.5))$
$= 5161$ W

Earth's Albedo

$Q_a = a\ q_s\ \alpha_{sB}\ A_E^{proj} \cos (\phi)\ (R_E/R_{orb})^2$
$= (0.34)\ (1400)\ (0.7)\ (6) \cos (23.5)\ (0.1256)$
$= 230$ W

Earth's input

$Q_E = q_E\ \alpha_B\ A_E^{proj}\ (R_E/R_{orb})^2$
$= (240)\ (0.7)\ (6)\ (0.1256)$
$= 127$ W

Output

$Q_{array} = \varepsilon_{eff}\ \sigma\ T^4\ A_{surf}$
$= ((0.8 + 0.7)/2)\ (5.67 \times 10^{-8})\ T^4\ (12)$
$= 5.103 \times 10^{-7}\ T^4$

$T^4 = (5161 + 230 + 127) / (5.103 \times 10^{-7})$
$T = 322\ K = \sim 49^oC$

Local midnight

(Think how the movement of the array to the midnight position will change the position of the Sun and Earth relative to the array as shown in the previous figure.)

Sun's input

$Q_s = 5161$ W

Earth's Albedo

$Q_a = \sim 0$ W

Earth's input

$Q_E = q_E\ \alpha_B\ A_E^{proj}\ (R_E/R_{orb})^2$
$= (240)\ (0.8)\ (6)\ (0.1256)$
$= 145$ W

Output

$Q_{array} = 5.103 \times 10^{-7}\ T^4$

$T^4 = (5161 + 145) / (5.103 \times 10^{-7})$
$T = 319\ K = \sim 46^oC$

Local dawn/dusk

(Think again how the movement of the array to the terminator position will change the position of the Sun and Earth relative to the array as shown in the previous figure.)

Sun's input

$Q_s = 5161$ W

Earth's Albedo

$Q_a = \sim 0$ W

Earth's input

$Q_E = \sim 0$ W

Output

$Q_{array} = 5.103 \times 10^{-7}\, T^4$

$T^4 = (5161) / (5.103 \times 10^{-7})$
$T = 317\ K = \sim 44^oC$

Approximate temperature profile: