Heat Sources
Thermal Design Task

Distribution and uniformity of proper temperatures

Thermal Design Environments

- Pre-launch (shipping, on pad)
- Launch and transfer orbit
- Mission characteristics
  - On orbit
    - Diurnal variations
    - Seasonal variations
    - Mission life variations
    - Surface property degradation
  - On planetary surface
- Sun exposure
- Shadow
Thermal Design Constraints

- Equipment utilization philosophy
- Design margin philosophy
- Failure mode philosophy
- Power system margin
- Mass budget
- Temperature specifications
- Sun/shadow duty cycle
- Equipment redundancy

Typical Temperature Requirements

- Maximum & minimum operational/non-operational temperatures
- Maximum diurnal swing
- Maximum gradients
- Survival/safe state temperature
- Allowable rate of change
- Control requirements of sub-systems
Conduction and Convection

\[ q = h \Delta T : \text{Heat flux density, } \text{W/m}^2 \]

[thermal power/unit area = (thermal energy change/unit time)/unit area]

- \( h \): Heat transfer coefficient, \( \text{W/m}^2 \cdot \text{K} \)
- \( \Delta T \): Temperature difference, \( \text{K} \)

Heat transfer from conduction within material

\[ q = \frac{\lambda}{l} \Delta T : \quad \lambda = \text{Conductivity coefficient} \]
\[ l = \text{Conductive path length} \]

Heat transfer resulting from fluid flow

\[ q = h_{\text{conv}} \Delta T : \quad h_{\text{conv}} = \text{Convection coefficient} \]
Thermal Radiation

Electromagnetic radiation to/from/ across space
Integrated over all wavelengths

\[ q = \sigma_{SB} \left( \varepsilon_{hot} T_{hot}^4 - \alpha_{cold} T_{cold}^4 \right) \]

\( \sigma_{SB} \) = Stefan-Boltzmann coefficient
\[ = 5.67 \times 10^{-8} \text{ W/} (\text{m}^2 \cdot \text{K}^4) \]
\( \varepsilon, \alpha \) = Emissivity/absorptivity, \( \leq 1 \)

For a given material

\[ \varepsilon = \alpha \] at a given wavelength (Kirchoff’s Law)
\( \varepsilon \neq \alpha \) if peak emission and absorption wavelengths are different

Solar Illumination

<table>
<thead>
<tr>
<th>Distance, AU</th>
<th>Planet</th>
<th>Average Solar Intensity, ( J_S ), W/m²</th>
<th>Planet Albedo, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.39</td>
<td>Mercury</td>
<td>9145</td>
<td>6-10</td>
</tr>
<tr>
<td>0.72</td>
<td>Venus</td>
<td>2697</td>
<td>60-76</td>
</tr>
<tr>
<td>1</td>
<td>Earth</td>
<td>1349</td>
<td>31-39</td>
</tr>
<tr>
<td>1.52</td>
<td>Mars</td>
<td>605</td>
<td>15</td>
</tr>
<tr>
<td>5.2</td>
<td>Jupiter</td>
<td>51</td>
<td>41-52</td>
</tr>
<tr>
<td>9.54</td>
<td>Saturn</td>
<td>16</td>
<td>42-76</td>
</tr>
<tr>
<td>19.19</td>
<td>Uranus</td>
<td>4</td>
<td>45-66</td>
</tr>
<tr>
<td>30.07</td>
<td>Neptune</td>
<td>2</td>
<td>35-62</td>
</tr>
<tr>
<td>39.46</td>
<td>Pluto</td>
<td>1</td>
<td>16-40</td>
</tr>
</tbody>
</table>

\[ P_{Sun} = 3.856 \times 10^{26} \text{ W} \]
\[ J_{Sun} = P_{Sun} / 4 \pi r_{Sun}^2 = 3.856 \times 10^{26} / \left( 6.957 \times 10^8 \text{ m} \right)^2 \]
\[ = 7.355 \times 10^4 \text{ W/m}^2 \text{ @ solar surface} \]
Thermal Radiation Absorbed and Emitted by Earth

Average Solar Radiation Absorbed by Earth

\[ Q_{in} = \pi R_E^2 (1 - \rho) J_{Earth} \]
\[ \rho = 0.35, \text{ Albedo, } \%/100 \]

Average Earth-Emitted Radiation

\[ Q_{out} = 4\pi R_E^2 \sigma T_E^4 \]
\[ T_E : \text{ Earth average temperature} \]

Earth’s Radiative Equilibrium Temperature

\[ Q_{out} = Q_{in} \]
\[ T_E = 250 \text{ K} \]

Fairing Inner Surface Maximum Temperatures
Aerothermal Heating after Fairing Jettison

Radiative Heating from Rocket Plume and Engine Nozzle

Stowed Solar Arrays
Need for Thermal Control

- Maintain proper operating temperatures for
  - Electronics
  - Sensors & actuators
  - Propulsion & propellant systems
  - Payload instruments
  - Mechanical devices

Thermal Control Types

- Passive
  - Coatings and paints
  - Thermal isolation
  - Heat sinks
  - Convective heat pipes
  - Phase Change Materials

- Active
  - Circulating heat pumps
  - Heaters
  - Thermoelectric devices
  - Thermal louvers
Coatings and Paint

- Incident energy distribution
  - Absorptivity ($\alpha$)
  - Reflectivity ($\rho$)
    - Specular (mirror-like)
    - Diffuse
  - Transmittance through coating ($\tau$)

\[(\alpha + \rho + \tau) = 1\]
Spacecraft Thermal Balance

\[ T_{av}^4 = \frac{1}{\sigma A_{surf}} \left[ A_{pr} J_{pr} + [\alpha J_{sol} (A_{sol} + aF_{alb})] + Q \right] / \epsilon \]

\( A_i \): Projected spacecraft area for \( i \)th effect, \( \text{m}^2 \)
\( J_i \): Radiation intensity for \( i \)th effect, \( \text{W/m}^2 \)
\( Q \): Internally dissipated power, \( \text{W} \)
\( a \): Planet’s albedo, \%/100
\( F \): Albedo visibility factor, \%/100
\( \beta \): Angle between local vertical and Sun’s rays

Altitude vs. Visibility Factor (Earth)

\( \frac{\text{surf}}{A_{surf}} \): "Wetted" surface area of spacecraft
\( pr \): Planetary radiation
\( alb \): Albedo
\( sol \): Solar

Emissivity and Absorptivity of Surfaces

<table>
<thead>
<tr>
<th>Surface</th>
<th>Absorptance (( \alpha ))</th>
<th>Emissance (( \epsilon ))</th>
<th>( \omega/\epsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished beryllium</td>
<td>0.44</td>
<td>0.01</td>
<td>44.00</td>
</tr>
<tr>
<td>Goldized kapton (gold outside)</td>
<td>0.25</td>
<td>0.02</td>
<td>12.3</td>
</tr>
<tr>
<td>Gold</td>
<td>0.25</td>
<td>0.04</td>
<td>6.25</td>
</tr>
<tr>
<td>Aluminium tape</td>
<td>0.21</td>
<td>0.04</td>
<td>5.23</td>
</tr>
<tr>
<td>Polished aluminium</td>
<td>0.24</td>
<td>0.08</td>
<td>3.00</td>
</tr>
<tr>
<td>Aluminized kapton (aluminium outside)</td>
<td>0.14</td>
<td>0.05</td>
<td>2.80</td>
</tr>
<tr>
<td>Polished titanium</td>
<td>0.60</td>
<td>0.60</td>
<td>1.00</td>
</tr>
<tr>
<td>Black paint (epoxy)</td>
<td>0.05</td>
<td>0.85</td>
<td>1.12</td>
</tr>
<tr>
<td>Black paint (polyurethane)</td>
<td>0.95</td>
<td>0.90</td>
<td>1.06</td>
</tr>
<tr>
<td>—electrically conducting</td>
<td>0.95</td>
<td>0.80–0.85</td>
<td>1.12–1.19</td>
</tr>
<tr>
<td>Silver paint (electrically conducting)</td>
<td>0.37</td>
<td>0.44</td>
<td>0.84</td>
</tr>
<tr>
<td>White paint (silicone)</td>
<td>0.26</td>
<td>0.83</td>
<td>0.31</td>
</tr>
<tr>
<td>—after 1000 hours UV radiation</td>
<td>0.29</td>
<td>0.83</td>
<td>0.35</td>
</tr>
<tr>
<td>White paint (silicate)</td>
<td>0.12</td>
<td>0.90</td>
<td>0.13</td>
</tr>
<tr>
<td>—after 1000 hours UV radiation</td>
<td>0.14</td>
<td>0.90</td>
<td>0.16</td>
</tr>
<tr>
<td>Solar cells, GaAs (typical values)</td>
<td>0.88</td>
<td>0.80</td>
<td>1.10</td>
</tr>
<tr>
<td>Solar cells, silicon (typical values)</td>
<td>0.75</td>
<td>0.82</td>
<td>0.91</td>
</tr>
<tr>
<td>Aluminized kapton (kapton outside)</td>
<td>0.40</td>
<td>0.63</td>
<td>0.63</td>
</tr>
<tr>
<td>Aluminized FEP</td>
<td>0.16</td>
<td>0.47</td>
<td>0.34</td>
</tr>
<tr>
<td>Silver coated FEP (SSM)</td>
<td>0.08</td>
<td>0.78</td>
<td>0.10</td>
</tr>
<tr>
<td>OSR</td>
<td>0.07</td>
<td>0.74</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Absorptivity increases over time due to UV degradation and contamination.
Thermal Isolation

- Choose materials to reduce conduction
- Choose surface to reduce radiation
- Multi-Layer Insulation (MLI), e.g.,
  - Facing space: conductive black Kapton, or brown Kapton over aluminum or silver (2nd surface mirror)
  - Inner layers: double-sided aluminized Mylar, polyester mesh
  - Facing spacecraft: double-sided aluminized Kapton
- MLI attached to spacecraft with Velcro and tape, grounded to spacecraft

Heat “Sinks”

- Materials with high thermal conductivity and low density adjacent to high heat sources
- Connected to cooling elements, e.g., fins, pins, heat pipes (or “slugs”) for heat transfer

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, ρ, lb/in³</th>
<th>Conductivity, k, W/in·°C</th>
<th>k/ρ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.098</td>
<td>4.8</td>
<td>49</td>
</tr>
<tr>
<td>AlBeMet (metal matrix composite)</td>
<td>0.075</td>
<td>5.3</td>
<td>71</td>
</tr>
<tr>
<td>Beryllium</td>
<td>0.067</td>
<td>3.8</td>
<td>57</td>
</tr>
<tr>
<td>Copper</td>
<td>0.323</td>
<td>9</td>
<td>28</td>
</tr>
</tbody>
</table>

Wong
Convective Heat Pipe

- Liquid-vapor transition
- Natural capillary circulation within a wick

Maximum heat transport rate in zero “g”

\[
Q_{\text{max}} = \frac{A_{\text{wick}} \phi \rho H_v}{l_{\text{eff}}} \left( \frac{2\sigma}{r_o} \right) \eta
\]

- \(A_{\text{wick}}\): cross-sectional area
- \(l_{\text{eff}}\): effective length
- \(\phi\): wick permeability
- \(\rho\): liquid-phase density
- \(H_v\): latent heat of vaporization
- \(\eta\): liquid-phase dynamic viscosity
- \(\sigma\): surface tension
- \(r_o\): effective pore radius of wick

Constant Conductance Heat Pipes

Heat pipes carry excess heat to radiators
Solid-Liquid Phase Change Material

- Increased thermal capacity required for periodic loads
- Latent heat released during solid-liquid change

Active Heat Pumps

- ~ Air conditioning, residential heating and cooling
- Use of compressor, pumping, refrigerant, and expansion
Heater Locations on a Communications Satellite

- North-South transponder panels
- Batteries
- Reflector gimbals and hinges
- Solar array deployment system
- GN&C system
  - Earth sensor assembly
  - Sun sensor detector
  - Sun sensor electronics
  - Inertial measurement unit
- Propulsion system
  - Hydrazine/oxidizer tanks
  - Propulsion lines
  - Thruster valves
  - Liquid apogee engine injector

Heater Hardware

- Heater Element
  - Cupro-nickel or Inconel dissipating element
- Mechanical Thermostat
  - On-off control for deployment mechanism damper heaters
- On-Board Computer (OBC)
  - Maintains on-off control
  - Maintains allowable temperatures
- Control Thermistor
  - Input to OBC
- Field Effect Transistor Electrical Switch
  - High-voltage switching
Radioisotope Heating Units

• Typically a few grams of $^{238}_{\text{PU}}$ or another radioisotope
• Simplify thermal control, as they give known amount of heat continuously for decades
• Cassini-Huygens contained 82 RHUs plus 3 RTGs
Thermal Louvers
Louvers vary emissivity of a radiator in response to temperature

GOES Thermal Control Sub-System
Thermal Analysis

• Thermal Mathematical Model (TMM)
  – Closed-form idealizations
  – Finite element/difference software
  – Steady state (thermal equilibrium)
  – Transient response
  – Cycling

• Thermal network models
  – Nodes
    • Elements that can be characterized by a single temperature
    • Energy storage devices
  – Conductors
    • Energy transport
  – Energy sinks

Thermal Mathematical Model

• Conduction, Convection, and Radiation
• Identification of *Isothermal Nodes*:
  – Temperature
  – Thermal capacity
  – Heat dissipation
  – Conductive interfaces
  – Radiative interfaces
    • Surrounding nodes
    • Free space
Conductive Heat Exchange

Conductive heat flow rate

\[ Q_c = \frac{\lambda A}{l} \Delta T : \quad \lambda = \text{Conductivity coefficient} \]
\[ A = \text{Cross-sectional area} \]
\[ l = \text{Conductive path length} \]

Temperature difference between path ends

\[ \Delta T = Q_c \frac{1}{h_c} : \quad h_c = \text{Thermal conductance} \]

Temperature difference, many serial paths

\[ \Delta T = Q_c \left( \frac{1}{h_1} + \frac{1}{h_2} + \frac{1}{h_3} + \cdots \right) = Q_c \frac{1}{h_c} \]
\[ h_c = \frac{h_1 h_2 h_3 \cdots}{h_1 + h_2 + h_3 + \cdots} = \text{Effective heat conductance} \]

Conductive Heat Exchange

Temperature difference, many serial paths

\[ \Delta T = Q_c \left( \frac{1}{h_1} + \frac{1}{h_2} + \frac{1}{h_3} + \cdots \right) = Q_c \frac{1}{h_c} \]

Effective heat conductance

\[ h_c = \frac{h_1 h_2 h_3 \cdots}{h_1 + h_2 + h_3 + \cdots} \]

Conductive heat transfer from \(i^{th}\) to \(j^{th}\) node

\[ Q_{c_{ij}} = h_{c_{ij}} (T_i - T_j); \quad i = 1, n; \quad j = 1, n \]
Radiative Heat Exchange

Radiative heat transfer from \( i^{th} \) to \( j^{th} \) node

\[
Q_{ij} = A_i F_{ij} \varepsilon_{ij} \sigma (T_i^4 - T_j^4); \quad i = 1,n; \quad j = 1,n
\]

- \( A_i \): Area of surface \( i \)
- \( F_{ij} \): Radiative view factor of surface \( j \) as seen from surface \( i \)
- \( \varepsilon_{ij} \): Effective emittance of \( i \) on \( j \)

For the \( i^{th} \) interior node

\[
\sum_{j=1}^{k} F_{ij}; \quad k = \# \text{ of surrounding surfaces}
\]

View Factor for Two Surfaces

\[
I_1 = I_0 \cos \phi_1: \quad I_0 = \text{Radiation intensity normal to } A_1
\]

Differential radiation from \( \delta A_1 \) falling on \( \delta A_2 \)

\[
\delta Q_{n2} = \frac{I_0 (\delta A_1 \cos \phi_1)(\delta A_2 \cos \phi_2)}{s^2}
\]
View Factor for Two Surfaces

Total radiation from $A_1$ falling on $A_2$

$$Q_{n_2} = I_0 \int \frac{\cos \phi_1 \cos \phi_2}{s^2} dA_1 dA_2$$

Total radiation from $A_1$

$$Q_{\text{total}} = 2\pi A_1 I_0 \int_0^{\pi/2} \cos \phi \sin \phi d\phi = \pi A_1 I_0$$

View factor from $A_1$ to $A_2$

$$F_{12} = \frac{Q_{n_2}}{Q_{\text{total}}} = \frac{1}{A_1 A_2} \int \int \frac{\cos \phi_1 \cos \phi_2}{\pi s^2} dA_1 dA_2$$

View Factor for Two Surfaces

View factor x area for general nodes

$$A_i F_{ij} = \int \int \frac{\cos \phi_i \cos \phi_j}{\pi s_{ij}^2} dA_i dA_j$$

Consequently

$$A_i F_{ij} = A_j F_{ji}$$
Effective Emittance Between Surfaces

If surfaces are effectively “black”

\[ \varepsilon_{ij} = 1 \]

Specular emittance is complex

For two, parallel, diffuse surfaces

\[ \varepsilon_{ij} = \frac{\varepsilon_i \varepsilon_j}{\varepsilon_i + \varepsilon_j - \varepsilon_i \varepsilon_j} \]

Calculation of Nodal Temperatures

Heat balance for \( i^{th} \) of \( n \) nodes

\[
Q_{\text{net}_i} = Q_{\text{ext}_i} + Q_{\text{int}_i} - \varepsilon_i \sigma A_{\text{space}_i} T_i^4 - \sum_{j=1}^{n} \left[ h_{c_{ij}} (T_i - T_j) + \sigma A_{ij} \varepsilon_{ij} \left( T_i^4 - T_j^4 \right) \right] + A_i F_{ij} (T_i^4 - T_j^4) + A_{pr} J_{pr} \varepsilon_i + \alpha J_{sol} (A_{sol} + aFA_{alb})
\]

Time variation of \( i^{th} \) nodal temperature is solution to \( n \) nonlinear ODEs

\[
m_i C_i \frac{dT_i(t)}{dt} = Q_{\text{net}_i}(t)
\]

\( m_i \) : Mass of node \( i \)

\( C_i \) : Specific heat of node \( i \)
Calculation of Nodal Temperatures

**Linearize the ODEs**

\[
m_i C_i \frac{dT_i(t)}{dt} = m_i C_i \frac{dT_{i_{nom}}(t) + \Delta T_i(t)}{dt} = m_i C_i \frac{d[T_{i_{nom}}(t)]}{dt} + m_i C_i \frac{d[\Delta T_i(t)\ ]}{dt}
\]

\[= Q_{net_i}(T_i(t)) = Q_{net_i}[T_{i_{nom}}(t) + \Delta T_i(t)] \approx Q_{net_i}[T_{i_{nom}}(t)] + \frac{dQ_{net_i}}{dT_i}[T_{i_{nom}}(t)] \Delta T_i(t) \]

**Perturbation responses and quasi-steady-state can be found using**

\[
m_i C_i \frac{d[\Delta T_i(t)\ ]}{dt} = \frac{dQ_{net_i}}{dT_i}[T_{i_{nom}}(t)] \Delta T_i(t)
\]

*(Vector-matrix form)*

\[
[mC] \Delta \dot{x}(t) = F \Delta x(t); \quad \Delta \dot{x}(t) = [mC]^{-1} F \Delta x(t)
\]

**Thermal Design Example**

*(Sec. 11.5, Fortescue)*

*Spherical Upper-Atmosphere Satellite*
Thermal Testing

- Levels of thermal test
  - Black box components
  - Sub-system module
  - Complete spacecraft

- Types of Test
  - Functional
  - Thermal cycling
  - Thermal balance
  - Deployment
  - Life

- Test objectives
  - Verify the thermal design in simulated environment
  - Validate the thermal model
  - Workmanship screening

Wong
Next Time:
Communications

Supplemental Material
Heat Pumps

**Capillary Pumped Loop**

![Diagram of Capillary Pumped Loop]

**Looped Heat Pipe**

![Diagram of Looped Heat Pipe]

*Prager et al, 2002*