Spacecraft Thermal Control

**OBJECTIVE:** Maintain the temperature of all spacecraft components within appropriate limits over the mission lifetime, subject to a given range of environmental conditions and operating modes.

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Thermal Control

Two classes

- Passive (preferred when possible)
  - Sunshades
  - Cooling fins
  - Specialty paints and coatings
  - Insulating blankets
  - Heat pipes
  - Geometry

- Active (when passive control is insufficient or unsuitable)
  - Pumped fluid loops
  - Adjustable louvers or shutters
  - Radiators
  - Operational work arounds
Heat Transfer Mechanisms

- Radiation
  - Direct solar radiative
  - Solar radiation reflected from nearby planets
  - Thermal energy radiated from nearby planets
  - Radiation from the spacecraft to deep space

- Conduction
  - Primarily controls the flow of energy between different parts of the spacecraft itself

- Convection
  - Relatively unimportant in space vehicle design
Spacecraft Thermal Environment (1/2)

- Design concerns in planetary orbit
  - Variation of eclipse time as orbit precesses
  - Variation of solar intensity with the seasons
  - Reflected solar energy from the planet
  - Orbital altitude
  - Albedo
  - Orbit inclination

- Concerns in interplanetary flight
  - Variation of sun’s intensity with distance
  - Effect of destination planet
Operational activities
- Free molecular flow
- On/off switching of onboard equipment
- Thruster firings (chemical propellant)
  - Propellant tank and/or line cooling
  - Local heating near thruster
- Expenditure of propellant
  - Reduces spacecraft thermal mass
  - Changes transient thermal response

Effects of time in space
- Surface characteristics change from exposure
  - Ultraviolet light
  - Atomic oxygen (oxygen atom)
  - Micrometeoroid and orbital debris impact (MMOD)
- Affects absorptivity and emissivity
- Anomalous events; i.e., must include margin in the design
Methods of Thermal Control (1/6)

- Passive thermal control
  - Geometry
    - Design with thermal control in mind
  - Insulation blankets
    - Multi-layer design (usually)
      - Aluminized Mylar layered with sheets of nylon or Dacron mesh
      - External coatings (fiberglass, Dacron, etc)
  - Sun shields
    - As simple as polished or gold plated aluminum
    - Silvered Teflon
      - Acts as a second surface mirror
      - Silver coating provides good visible light reflectivity
      - Teflon provides high infrared emissivity
    - Glass mirror is thermally more efficient, but heavy
Methods of Thermal Control (2/6)

- **Cooling fins**
  - Dissipate large amounts of heat, or
  - Dissipate smaller amounts of heat at low temperatures
  - Large numbers of fins:
    - May be difficult to obtain adequate view factor
    - Larger fins have limited effectiveness

- **Heat pipe (two-phase flow)**
  - Tube with a wick and partially filled with fluid (anhydrous ammonia)
  - Tube conducts heat from a hot spot to a cold spot
    - Fluid evaporates at hot end (gas)
    - Condenses at cold end (liquid)
    - Capillary action of the wick draws fluid back to hot end
  - Conducts heat as long as temperature differential exists

- **Issues**
  - Wick can dry out at the hot end
  - Wick can freeze at the cold end
  - 0 g function difficult to simulate
  - 50% margin customary
Active Thermal Control

- Heaters
  - Simple
  - Control from the ground, autonomously, or both
- Mechanically pumped two-phase heat pump
- Liquid loops
  - Can be massive for space apps
  - Water is preferred for internal, pressurized modules
  - Characteristics of liquid for external loops
    - Specific heat \( \rightarrow \) high
    - Dynamic viscosity \( \rightarrow \) low
    - Boiling point \( \rightarrow \) high
    - Must not freeze
- Shuttle: Freon-21
- ISS: ammonia
Methods of Thermal Control (4/6)

- Heat pumps
  - Increase temperature of a radiator
  - Why do that?
  - Heat radiated from a surface is proportional to the fourth power of its temperature
  - Small increase in radiator temperature ➔ rate of heat dissipation

- Penalty
  - Mass increase
  - Power increase
  - ∴ if possible, increase radiator size

- Applications
  - Cool communication components: increase S/N
  - Refrigeration for food or biological samples
Methods of Thermal Control (5/6)

Refrigeration

- +4°C to -20°C (Food storage)
  - Thermoelectric cooling (Peltier effect)
  - Two-phase heat pump (Rankine cycle)
    - Domestic refrigerator
    - Problems with 0g
- -80°C (Long duration storage of bio samples)
  - Single phase gas cycle
  - Brayton cycle
    - ISS and Hubble Space Telescope
- -193°C (Earth observation)
  - GEO: carefully designed radiators
  - LEO: mechanical coolers (Stirling cycle)
- < -269°C
  - Of interest to astronomers
Methods of Thermal Control (6/6)

- Shutters and louvers

Voyager

(Spacecraft shown without thermal blankets for clarity)
Heat Transfer Mechanisms (1/2)

- **Conduction**
  - Usually the primary heat transfer mechanism *within* a spacecraft
  - Lack of convection: must provide adequate conduction paths
    - Material selection important
    - Un-welded joints: poor thermal conductors
      - Conduction pads
      - Thermal grease
      - Metal loaded epoxy
  - **High thermal conductivity** $\rightarrow$ high electrical conductivity
    - Situations requiring high thermal conductivity and electrical *isolation* can be challenging
    - Beryllium oxide (BeO)
      - High thermal conductivity
      - Excellent insulator
      - Dust is highly toxic

- **Fourier’s Law**

\[
Q = -\kappa A \left( \frac{dT}{dx} \right)
\]

Where:

- \( Q \) = power (BTUs)
- \( A \) = area
- \( \kappa \) = thermal conductivity
- \( T \) = temperature, °K
- \( x \) = linear distance over conduction path
Radiative Heating
- Transport of energy by electromagnetic waves
- Typically, the *only* practical means of heat transfer between a spacecraft and its environment
- Heat flux from a surface varies as the fourth power of its temperature
- May create configuration issues
- Frequencies of interest for thermal transport:
  - 200nm < frequency < 200µm
  - Between middle ultraviolet and far infrared
Emissivity ($\varepsilon$) and Absorptivity ($\alpha$)

- **Stefan-Boltzman law**

  $$Q = \varepsilon \sigma AT^4$$

  - $T$ = surface temperature
  - $A$ = surface area
  - $\varepsilon$ = emissivity ($1$ for a BB)
  - $\sigma = 5.67 \times 10^{-3} \text{ (w/m}^2\text{)K}^4$

- **Blackbody**
  - Idealization: neither reflects nor transmits incident energy
  - Perfect absorber at all wavelengths and angles; $\alpha = 1$
  - Emits the maximum possible energy at all wavelengths and angles for a given temperature ($\varepsilon = 1$)
  - Radiative energy is a function of temperature only
  - Need to know absorptivity and emissivity of real substances for design trades
\( \varepsilon \) and \( \alpha \) of Real Surfaces

- Black Nickel, Chromium, Copper
- Polished Metal
- Aluminum Paint
- Aluminized Kapton
- Silvered Teflon
- Black Paint
- White Paint
Radiative Heat Transfer Between Surfaces

- Need to be able to compute radiative heat transfer between parts of the spacecraft and its surroundings
- Every surface radiates to and receives radiation from all other surfaces within its hemispherical field of view
- Typically, requires a numerical solution
Lumped Mass Approximation
- Simplest analytical thermal model
- Each node represents a thermal mass
- Each node is connected to other nodes by thermal resistances
- Must identify heat sources and sinks (internal and external)
  - Electronics packages
  - Heaters
  - Cooling devices
  - Radiators

Nodes
- Major pieces of structure

Thermal resistances
- Model the conductive and radiative links (including joints)
- Emissivity and absorptivity of the surfaces
Spacecraft Energy Balance

\[ Q_{ss} = \sigma_s A_s F_{s,s}(T^4_s - T^4_{\text{space}}) \]

\[ Q_{se} = \sigma_s A_s F_{s,e}(T^4_s - T^4_e) \]

\[ Q_{er} = a\alpha_s F_{s,se} A_s I_{\text{sun}} \]

\[ Q_{\text{sun}} = \alpha_s A \ I_{\text{sun}} \]

Direct Sunlight

Reflected Sunlight

Radiated To Earth

EARTH
Spacecraft Energy Balance

\[ Q_{\text{sun}} + Q_{\text{er}} + Q_i = Q_{\text{ss}} + Q_{\text{se}} \]

\[ Q_{\text{sun}} = \alpha_s A \quad I_{\text{sun}} = \text{solar input to spacecraft} \]
\[ Q_{\text{er}} = a \alpha_s F_{s,se} A_A^T I_{\text{sun}} = \text{earth reflected solar input} \]
\[ a = \text{earth albedo (0.07-0.85)} \]
\[ \alpha_s = \text{spacecraft surface absorptivity} \]
\[ \varepsilon_s = \text{spacecraft surface emissivity} \]
\[ Q_i = \text{internally generated power} \]
\[ Q_{\text{se}} = \sigma_s A_s F_{s,e} (T^4_s - T^4_e) = \text{net power radiated to earth} \]
\[ Q_{\text{ss}} = \sigma_s A_s F_{s,s} (T^4_s - T^4_{\text{space}}) = \text{net power radiated to space} \]

Factors:
- \( F_{s,s} = \text{fraction of radiant energy leaving SC that is intercepted by space} \)
- \( F_{s,e} = \text{fraction of radiant energy leaving SC that is intercepted by earth} \)
Simplifying assumptions
- $T_{\text{space}} \approx 0$ and
- $F_{s,s} + F_{s,e} = 1$

The energy balance equation becomes

$$\varepsilon_s \sigma A_s T_s^4 = \varepsilon_s \sigma A_s F_{s,e} T_e^4 + Q_{\text{sun}} + Q_{\text{er}} + Q_i$$

This equation can be used to estimate the “average” spacecraft temperature.
Thermal Analysis Tools

- SINDA (early version called CINDA)
  - Finite difference analysis
  - Create a nodal mesh, or grid
  - Apply desired boundary conditions

- FLUINT
  - Developed for internal one dimensional flows such as pumped fluid loops
  - Restricted to low-speed, incompressible flow of one viscous fluid

- SINDA versions that contain FLUINT are available
Accuracy

- Thermal analysis is typically not as accurate as other disciplines.
- During early design phases, the thermal system should be able to handle a heat load at least 50% > than analytically predicted.
- Over the course of the project – as more is learned – the final margin may be as low as 20%.
- Large margins may mean that the system is over-designed.
- But, the consequences of under-design can be catastrophic.
MISSION PROFILE
- Launch
- Maneuvers
- Orbits
- Cruise Periods

LOCATIONS & ORIENTATIONS
(Distance & Direction to Heat Source)
- Sun
- Planet Reflection
- Planet IR

ELECTRICAL POWER
- Components
- Duty Cycles

SELECT SIMPLIFIED GEOMETRY

SELECT SURFACE FINISH PROPERTIES, (α & ε)

COMPUTE ALL AVERAGE INCIDENT HEAT FLUXES

COMPUTE RADIANT DISSIPATION CAPABILITY

COMPUTE ABSORBED HEAT FLUXES

COMPUTE TEMPERATURES FOR HEAT BALANCE

COMPARE COMPUTED TEMPERATURES WITH REQUIREMENTS

DESIGN

CHANGE AREAS AND FINISHES

INFORMATION

ANALYSIS