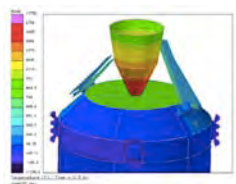
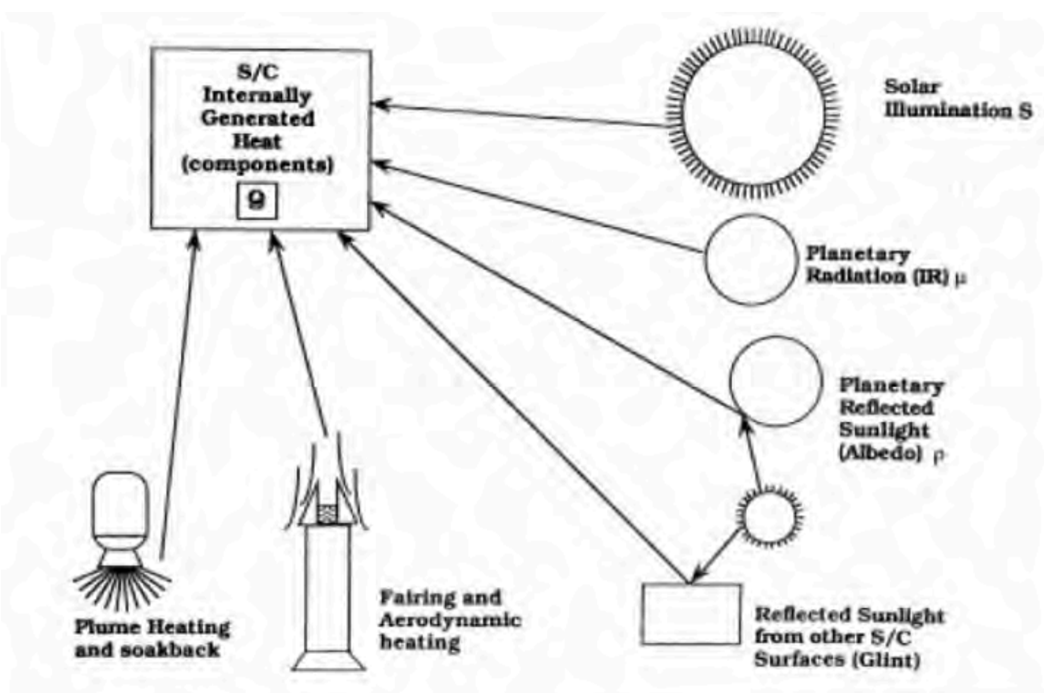
Thermal Control Systems

Space System Design, MAE 342, Princeton University
Robert Stengel

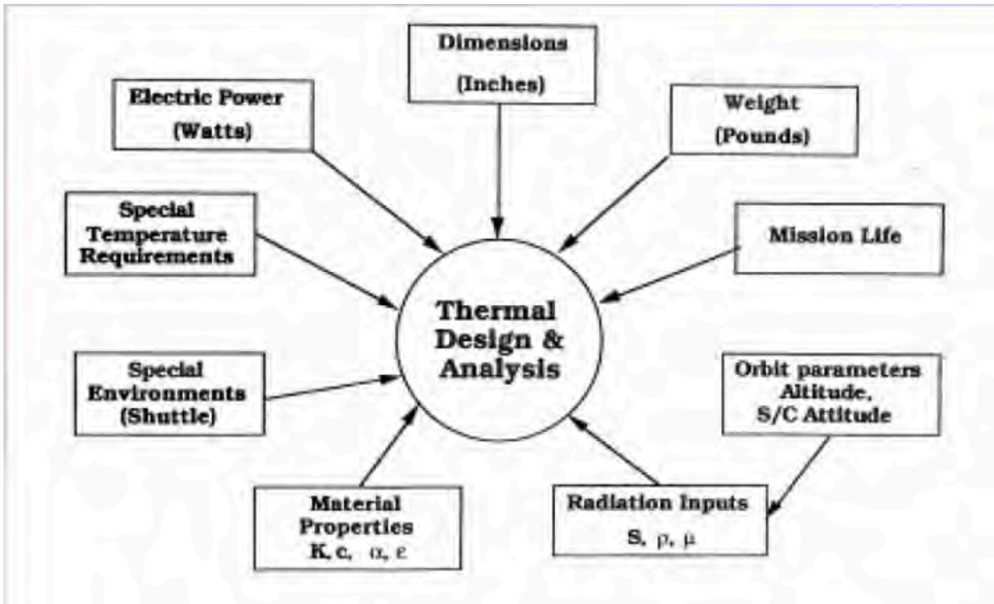
- **Thermal design overview**
- **Conduction, convection, and radiation**
- **Types of thermal control**
- **Thermal analysis**
- **Thermal testing**



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

Typical Spacecraft Design Temperatures

Component/ System	Operating Temperature (C)	Survival Temperature (C)
Digital electronics	0 to 50	-20 to 70
Analog electronics	0 to 40	-20 to 70
Batteries	10 to 20	0 to 35
IR detectors	-269 to –173	-269 to 35
Solid-state particle detectors	-35 to 0	-35 to 35
Momentum wheels	0 to 50	-20 to 70
Solar panels	-100 to 125	-100 to 125

J. C. Keesee

Conduction and Convection

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

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

h: Heat transfer coefficient, W/m^2-K

ΔT: Temperature difference, K

Heat transfer from conduction within material

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

Heat transfer resulting from fluid flow

$$q = h_{conv}\Delta T: \; h_{conv} = \text{Convection coefficient}$$

Thermal Radiation

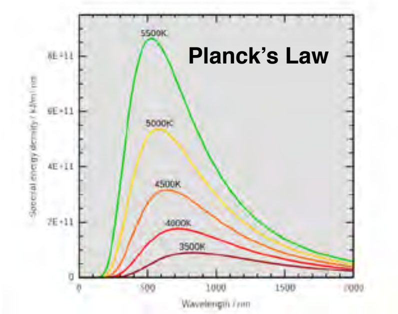
Electromagnetic radiation to/from/across space
Integrated over all wavelengths

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

$$\sigma_{SB} = \text{Stefan-Boltzmann coefficient}$$

$$= 5.67\times10^{-8}\ \text{W}/\left(\text{m}^{2}\text{-K}^{4}\right)$$

$$\varepsilon,\alpha = \text{ Emissivity/absorptivity, } \leq 1$$



For a given material

$$\varepsilon = \alpha \text{ at a given wavelength (Kirchoff's Law)}$$

$$\varepsilon \neq \alpha \text{ if peak emission and absorption wavelengths are different}$$

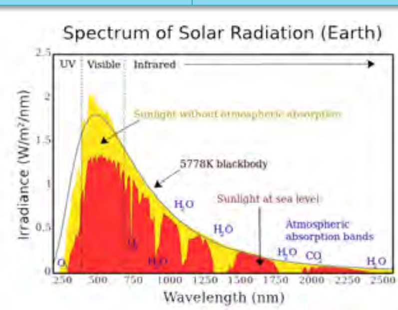
Solar Illumination

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

$$P_{Sun} = 3.856\times10^{26}\,\text{W}$$

$$J_{Sun} = P_{Sun}/4\pi r_{Sun}^{\ 2} = 3.856\times10^{26}/\left[6.957\times10^{8}\ (\text{m})\right]^{2}$$

$$= 7.355\times10^{8}\ \text{W/m}^{2}\ @\ \text{solar surface}$$



Thermal Radiation Absorbed and Emitted by Earth

Average Solar Radiation Absorbed by Earth

$$Q_{in} = \pi R_E^{\ 2}\left(1-\rho\right) J_{S_{Earth}}$$

$$\rho = 0.35,\quad \text{Albedo, \%/100}$$

Average Earth-Emitted Radiation

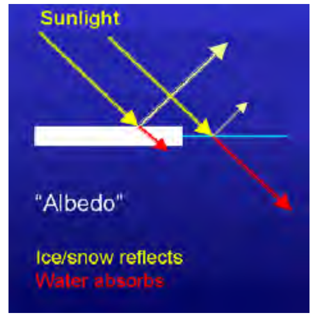
$$Q_{out} = 4\pi R_E^{\ 2}\sigma T_E^{\ 4}$$

$$T_E:\quad \text{Earth average temperature}$$

Earth's Radiative Equilibrium Temperature

$$Q_{out} = Q_{in}$$

$$T_E = 250\ \text{K}$$



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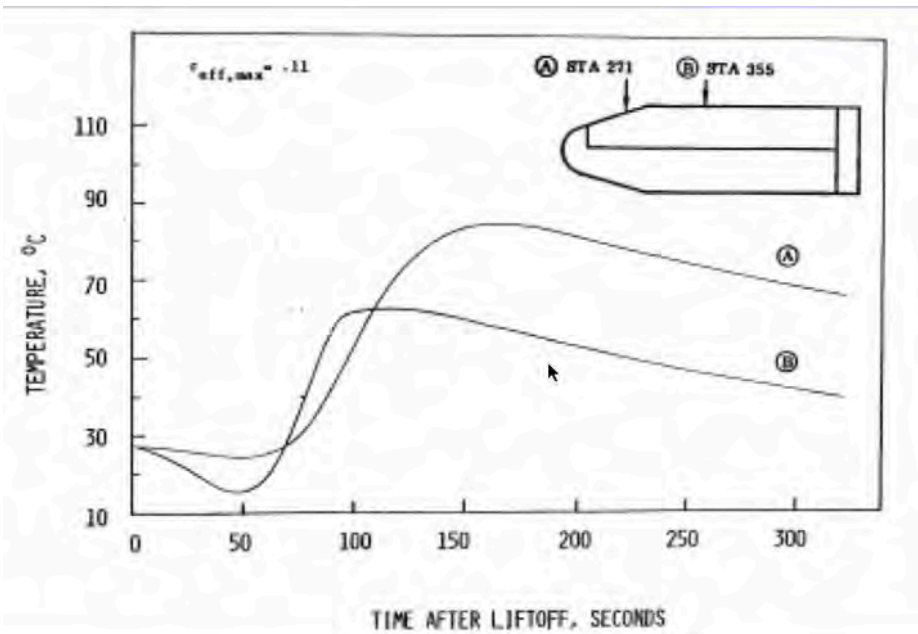
Fairing Inner Surface Maximum Temperatures



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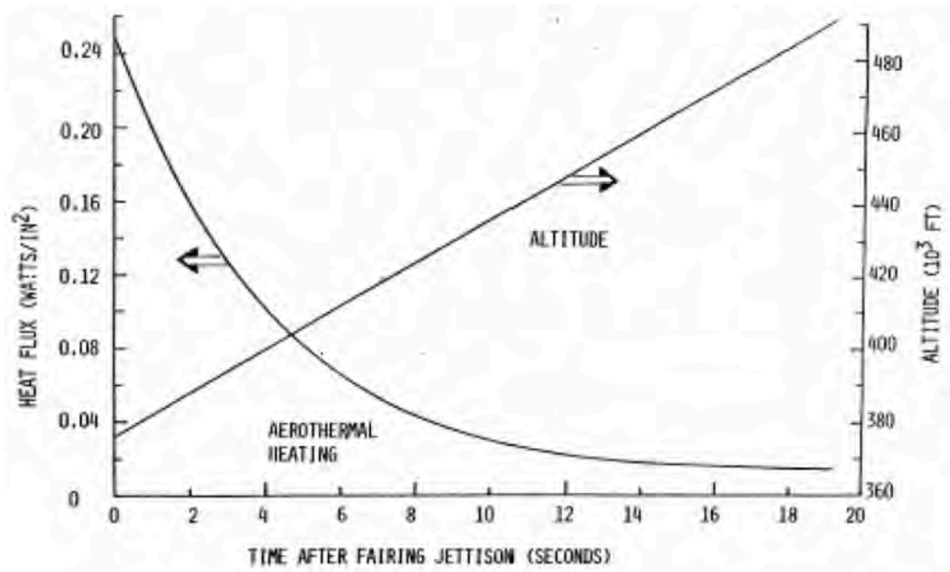
Aerothermal Heating after Fairing Jettison



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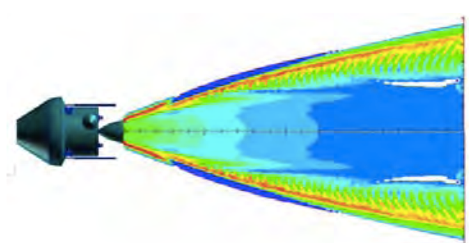
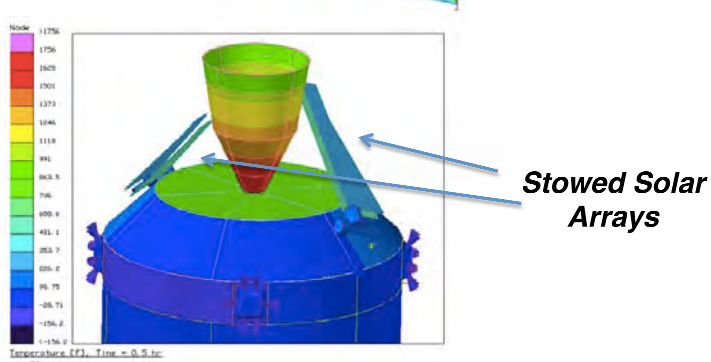
Radiative Heating from Rocket Plume and Engine Nozzle





Need for Thermal Control

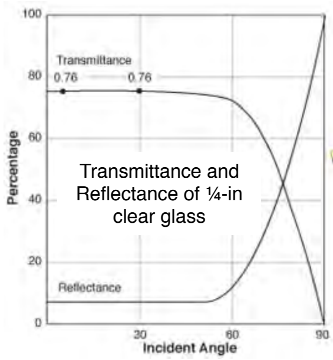
- **Maintain proper operating temperatures for**
  - Electronics
  - Sensors & actuators
  - Propulsion & propellant systems
  - Payload instruments
  - Mechanical devices

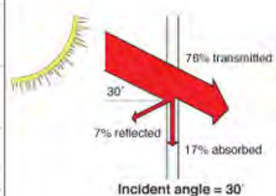
Thermal Control Types

- **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

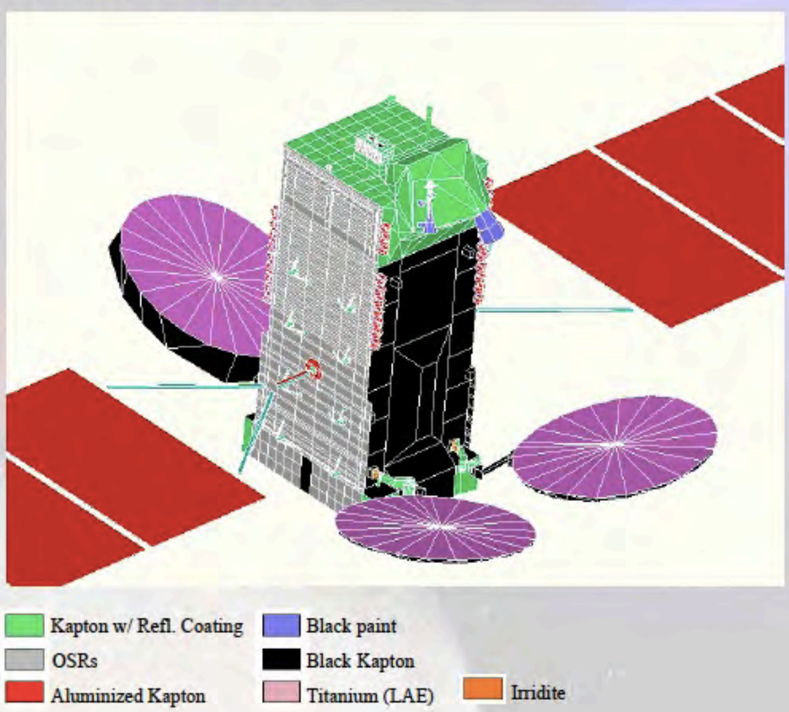
- Incident energy distribution
  - Absorptivity (α)
  - Reflectivity (ρ)
    - Specular (mirror-like)
    - Diffuse
  - Transmittance through coating (τ)





$$\boxed{(\alpha+\rho+\tau)=1}$$

Design Application – Typical A2100Thermal Coatings



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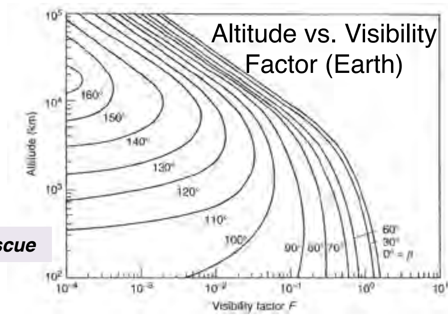
Spacecraft Thermal Balance

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



Fortescue

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

surf : "Wetted" surface area of spacecraft
pr : Planetary radiation
alb : Albedo
sol : Solar

Emissivity and Absorptivity of Surfaces

Surface	Absorptance (α)	Emittance (ε)	α/ε
Polished beryllium	0.44	0.01	44.00
Goldized kapton (gold outside)	0.25	0.02	12.5
Gold	0.25	0.04	6.25
Aluminium tape	0.21	0.04	5.25
Polished aluminium	0.24	0.08	3.00
Aluminized kapton (aluminium outside)	0.14	0.05	2.80
Polished titanium	0.60	0.60	1.00
Black paint (epoxy)	0.95	0.85	1.12
Black paint (polyurethane)	0.95	0.90	1.06
—electrically conducting	0.95	0.80–0.85	1.12–1.19
Silver paint (electrically conducting)	0.37	0.44	0.84
White paint (silicone)	0.26	0.83	0.31
—after 1000 hours UV radiation	0.29	0.83	0.35
White paint (silicate)	0.12	0.90	0.13
—after 1000 hours UV radiation	0.14	0.90	0.16
Solar cells, GaAs (typical values)	0.88	0.80	1.10
Solar cells, silicon (typical values)	0.75	0.82	0.91
Aluminized kapton (kapton outside)	0.40	0.63	0.63
Aluminized FEP	0.16	0.47	0.34
Silver coated FEP (SSM)	0.08	0.78	0.10
OSR	0.07	0.74	0.09

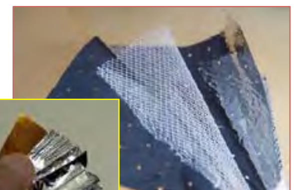
Notes: SSM, Second Surface Mirror. OSR, Optical Solar Reflector.

Fortescue

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 (2^{nd}-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

Material	Density, ρ, lb/in^3	Conductivity, k, W/in-°C	k/ρ
Aluminum	0.098	4.8	49
AlBeMet (metal matrix composite)	0.075	5.3	71
Beryllium	0.067	3.8	57
Copper	0.323	9	28

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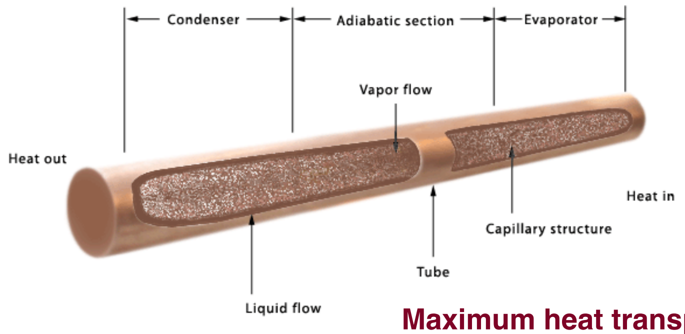
Convective Heat Pipe



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

Maximum heat transport rate in zero "g"

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

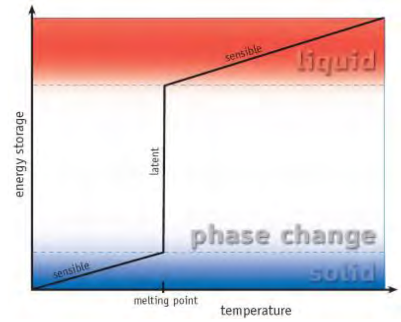
A_{wick} : cross-sectional area	H_v : latent heat of vaporization
l_{eff} : effective length	η : liquid-phase dynamic viscosity
ϕ : wick permeability	σ : surface tension
ρ : liquid-phase density	r_o : effective pore radius of wick

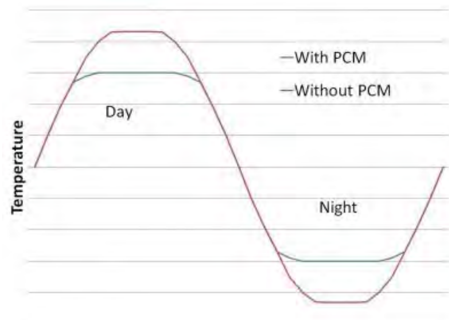
Constant Conductance Heat Pipes

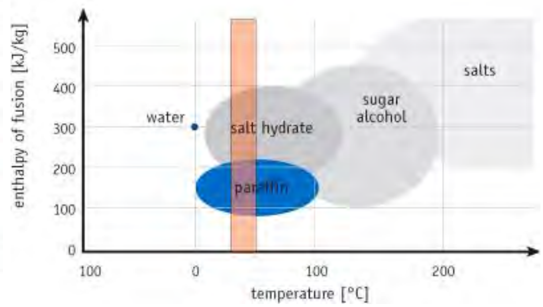
Heat pipes carry excess heat to radiators

Solid-Liquid Phase Change Material

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

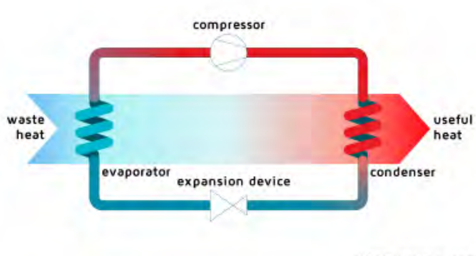


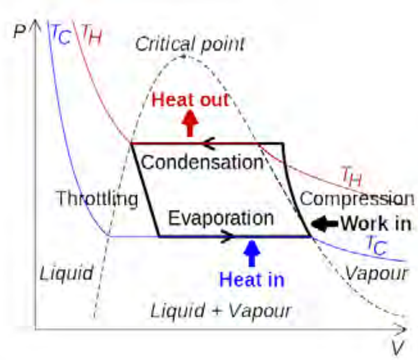




Active Heat Pumps

- **~ 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

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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

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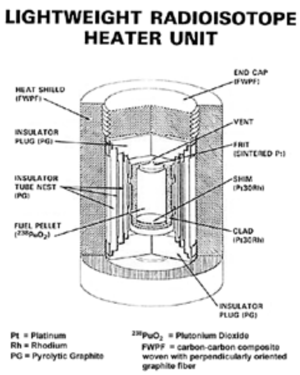
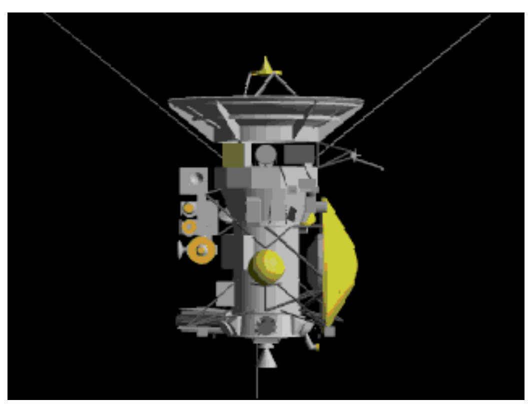
Radioisotope Heating Units

- **Typically a few grams of *PU_{238}* or another radioisotope**
- **Simplify thermal control, as they give known amount of heat continuously for decades**
- **Cassini-Huygens contained 82 *RHUs* plus 3 *RTGs***



Radiative Fins on Cassini-Huygens Radioisotope Thermoelectric Generator



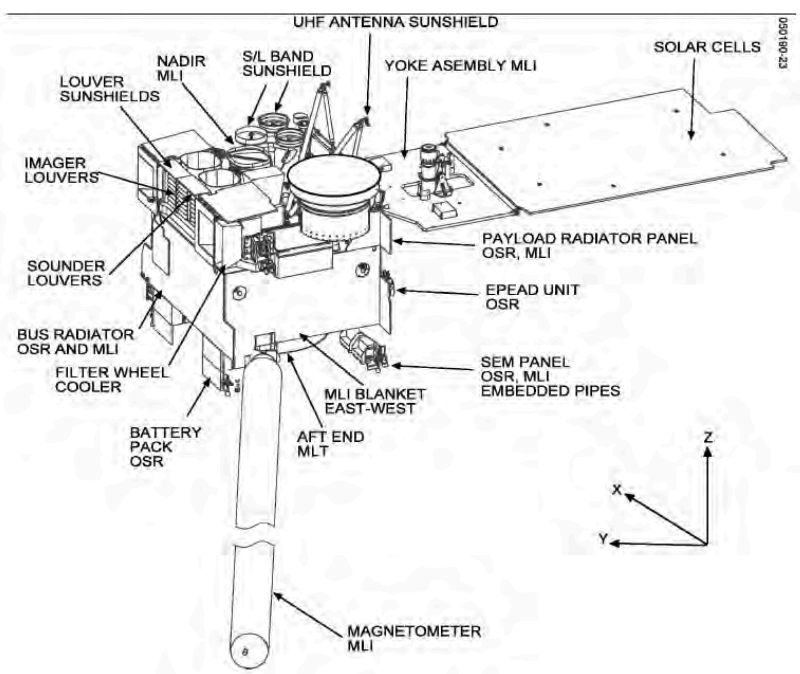
Thermal Louvers

Louvers vary emissivity of a radiator in response to temperature

RosettaThermal Louvers

Messenger Thermal Louvers

GOES Thermal Control Sub-System

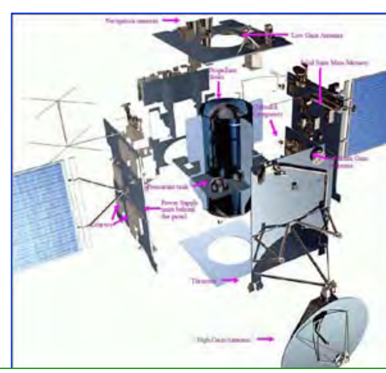


Thermal Analysis

- **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

$$Q_c = \frac{\lambda A}{l}\Delta T: \quad \begin{array}{l} \lambda = \text{ Conductivity coefficient} \\ A = \text{Cross-sectional area} \\ l = \text{ Conductive path length} \end{array}$$

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*

$$Q_{c_{ij}} = h_{c_{ij}}\left(T_i - T_j\right); \quad i = 1,n; \quad j = 1,n$$

Radiative Heat Exchange

Radiative heat transfer from *i^th^* to *j^th^* node

$$Q_{r_{ij}} = A_i F_{ij} \varepsilon_{ij} \sigma h_{ij} \left(T_i^{\,4} - T_j^{\,4} \right); \quad i = 1,n; \quad j = 1,n$$

A_i : Area of surface i

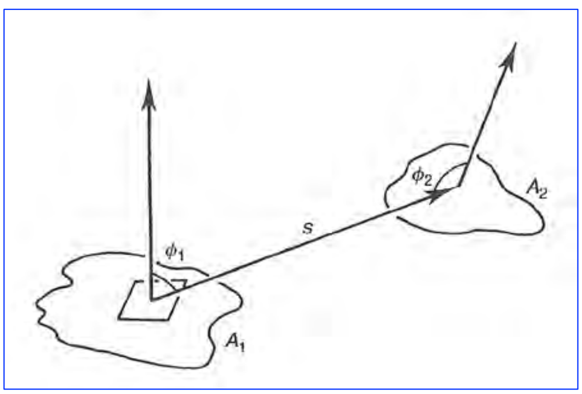
F_{ij} : Radiative view factor of surface j as seen from surface i

ε_{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

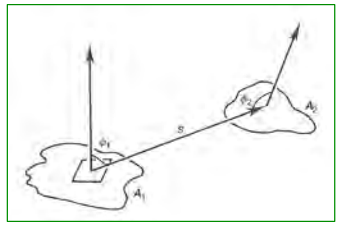


$I_1 = I_0 \cos\phi_1$: I_0 = Radiation intensity normal to A_1

Differential radiation from *δA_1* falling on *δA_2*

$$\delta Q_{r_{12}} = \frac{I_0 \left(\delta A_1 \cos\phi_1 \right)\left(\delta A_2 \cos\phi_2 \right)}{s^2}$$

View Factor for Two Surfaces



Total radiation from A_1 falling on A_2

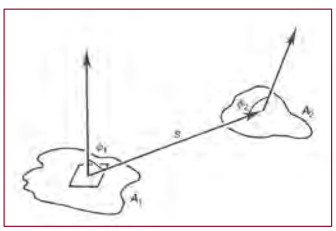
$$Q_{r_{12}} = I_0 \int_{A_1} \int_{A_2} \frac{\cos\phi_1 \cos\phi_2}{s^2} dA_1 \, dA_2$$

Total radiation from A_1

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

View factor from A_1 to A_2

$$F_{12} = \frac{Q_{r_{12}}}{Q_{r_{total}}} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos\phi_1 \cos\phi_2}{\pi s^2} dA_1 \, dA_2$$



View Factor for Two Surfaces

View factor × area for general nodes

$$A_i F_{ij} = \int_{A_i} \int_{A_j} \frac{\cos\phi_i \cos\phi_j}{\pi s_{ij}^2} dA_1 \, dA_2$$

Consequently

$$A_i F_{ij} = A_j F_{ji}$$

Effective Emittance Between Surfaces

If surfaces are effectively "black"

$$\boxed{\varepsilon_{ij} = 1}$$

Specular emittance is complex

For two, parallel, diffuse surfaces

$$\boxed{\varepsilon_{ij} = \frac{\varepsilon_i \varepsilon_j}{\varepsilon_i + \varepsilon_j - \varepsilon_i \varepsilon_j}}$$

Calculation of Nodal Temperatures

Heat balance for *i*th of *n* nodes

$$\boxed{Q_{net_i} = Q_{ext_i} + Q_{int_i} - \varepsilon_i \sigma A_{space_i} T_i^4 - \sum_{j=1}^{n} \left[h_{c_{ij}} \left(T_i - T_j \right) + \sigma A_i F_{ij} \varepsilon_{ij} \left(T_i^4 - T_j^4 \right) \right]}$$

$$\boxed{Q_{ext_i} \triangleq A_{pr} J_{pr} \varepsilon_i + \alpha J_{sol} \left(A_{sol} + aFA_{alb} \right)}$$

Time variation of *i*th nodal temperature is solution to *n* nonlinear ODEs

$$m_i C_i \frac{dT_i(t)}{dt} = Q_{net_i}(t)$$

m_i : Mass of node i

C_i : Specific heat of node i

Calculation of Nodal Temperatures

Linearize the ODEs

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

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

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

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

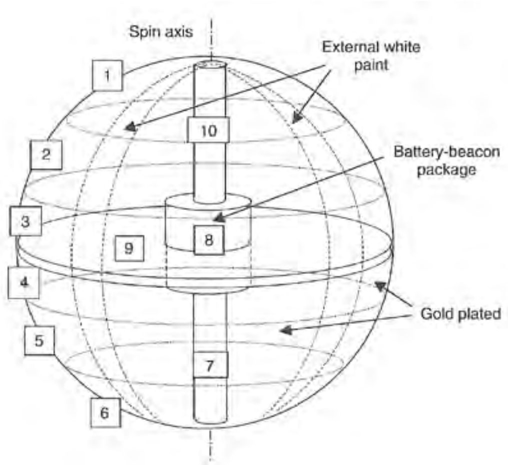
(Vector-matrix form)

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

Thermal Design Example

(Sec. 11.5, Fortescue)

Spherical Upper-Atmosphere Satellite



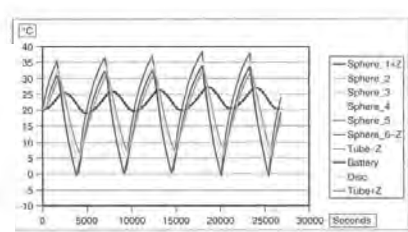


Figure 11.6 Temperature evolution, side-to-Sun, maximum eclipse

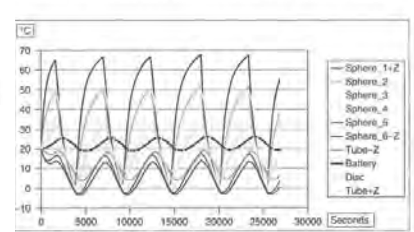


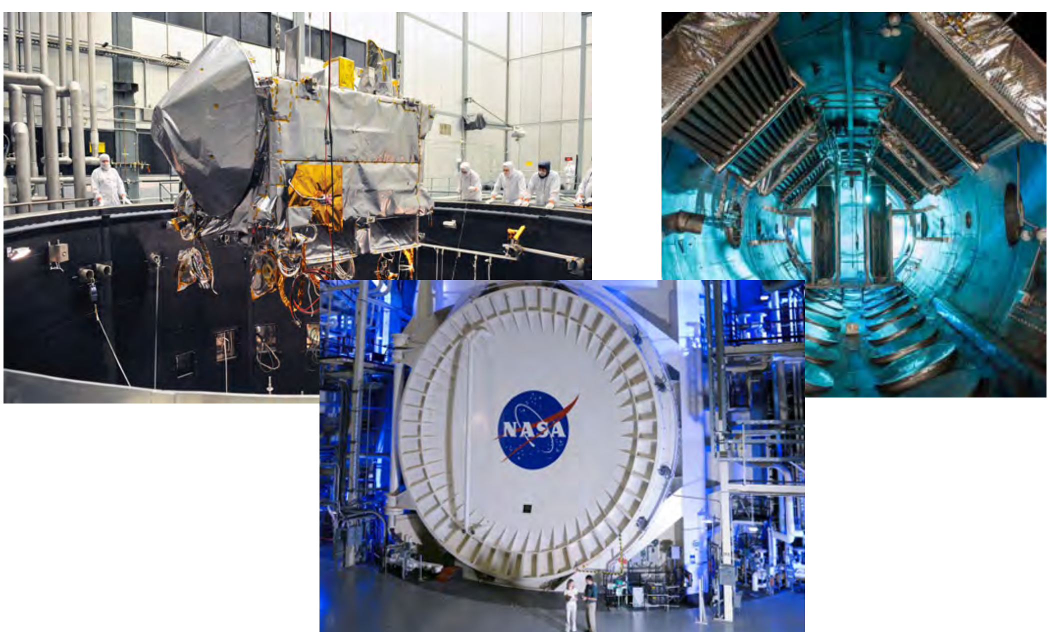
Figure 11.7 Temperature evolution, top-to-Sun, maximum eclipse

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

Thermal-Vacuum Testing

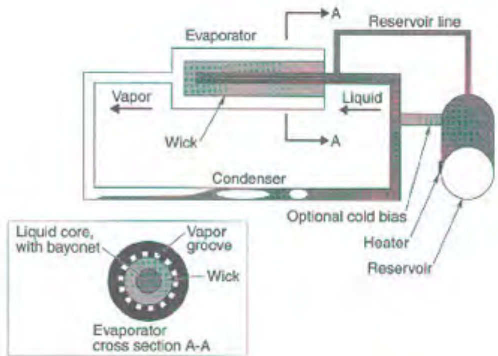


Next Time: Communications

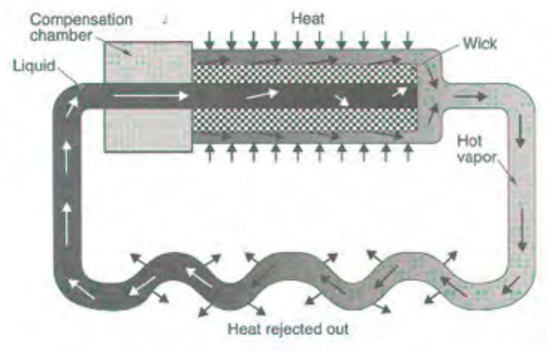
Supplemental Material

Heat Pumps

Capillary Pumped Loop



Looped Heat Pipe



Prager et al, 2002