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Class Agenda

- Spacecraft thermal environment
- Thermal control components
- Thermal design and development process
- Thermal control challenges
- Heat balance estimation
- Mass, power, telemetry estimates

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Thermal Control Subsystem

- Maintain all spacecraft and payload components and subsystems within their required temperature limits for each mission phase
- Operational limits – component must remain within while operating
- Survival limits – component must remain within at all times, even when not powered
- Gradient requirement – make sure different parts of spacecraft are not hotter/colder than others

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Thermal Control Requirements

Component	Operational Temp. Range (°C)	Survival Temp. Range (°C)
Batteries	0 to15	-10 to 25
Power Box Baseplate	-10 to 50	-20 to 60
Reaction Wheels	-10 to 40	-20 to 50
Gyros/IMUs	0 to 40	-10 to 50
Start Trackers	0 to 30	-10 to 40
C&DH Box Baseplate	-20 to 60	-40 to 75
Hydrazine Tanks and Lines	15 to 40	5 to 50
Antenna Gimbals	-40 to 80	-50 to 90
Antennas	-100 to 100	-120 to 120
Solar Panels	-150 to 110	-200 to 130

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Thermal Control Subsystem

- Two categories
  - Passive thermal control – materials, coatings, or surface finishes to maintain temperature limits
  - Active thermal control – generally more complex and expensive, maintains temperature by some active means (heaters, thermo-electric motors)
- Low-cost thermal control is designed to keep spacecraft at cool end of allowable temperatures (components last longer)

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Thermal Control System Design Process

Step	Inputs	Outputs	Key Issues
1. Identify thermal requirements and constraints	Component thermal requirements	System level thermal requirements Specialized requirements for specific equipment	Identify payload thermal requirements Identify major elements that may present thermal challenges
2. Determine thermal environment	Orbit/attitude history Spacecraft size and shape Internal heat sources	Total energy input to spacecraft Profile of energy input vs. time	Max & min distances to Sun Max & min distances to Earth or other central body Chemical or nuclear internal heat sources

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Thermal Control System Design Process

Step	Inputs	Outputs	Key Issues
3. Identify thermal challenges or problem areas	Thermal requirements Heat sources Equipment placement and attitude history	List of specific thermal problem areas or problem times or events (hot, cold, or stability)	Identify major elements that generate large amounts of heat, need cryo operating temperatures, etc.
4. Identify applicable thermal control techniques	Thermal requirements and energy profile from above Additional constraints	Preliminary list of thermal control mechanisms for mission duration and principal spacecraft components, areas, or times	Prefer passive over active systems Component placement often key Pay particular attention to problem areas or severe thermal constraints

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Thermal Control System Design Process

Step	Inputs	Outputs	Key Issues
5. Determine radiator and heater requirements	List of thermal environments & events Thermal control approach Component temperature requirements	Radiator sizes and temperatures to manage hot case with margin Heater power for cold case thermal control	Take into account: degradation of thermal surfaces over mission life, longest eclipse furthest from warm central body
6. Estimate TCS mass and power	List of TCS methods and components	TCS mass TCS power	Typically 2% to 10% of dry mass May impact mass & power of other subsystems
7. Document and iterate			Thermal robustness can be key to system design

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Spacecraft Thermal Environment

- Thermal control is process of energy management in which thermal environment plays a major role
- Different environments
  - Ground testing
  - Transportation
  - Launch
  - Orbit transfer
  - Operational orbits with nominal and safehold attitudes

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Spacecraft Thermal Environment

- Overall thermal control is achieved by balancing heat emitted by spacecraft as IR radiation against heat dissipated by internal components plus heat absorbed from environment
- No convection in space
- Thermal design analysis must consider worst case hot and cold combinations of waste heat generated by spacecraft components in various operating modes and variable environmental heat loads on spacecraft

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Direct Solar

- Sunlight is major source of environmental heating on most spacecraft
- Sun – stable source
- Earth's elliptical orbit does change intensity
- Summer solstice – Earth farthest from sun, 1322 W/m^2
- Winter solstice – 1414 W/m^2
- Energy distribution
  - 7% ultraviolet
  - 46% visible
  - 47% near IR

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Albedo

- Sunlight reflected off a planet or moon
- Usually expressed as fraction of incident sunlight that is reflected back to space
- Reflectivity is higher over land than ocean
- Tends to increase with latitude
- See Table 11-45A for further information

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Earth IR

- All incident sunlight not reflected as albedo is absorbed by Earth and eventually re-emitted as IR energy or blackbody radiation
- Varies with local temperature and cloud cover
- Warmer surfaces emit more radiation than colder ones
- Generally tropics are highest
- Usually spacecraft is warmer than effective Earth temperature – net transfer from spacecraft
- Usually ignore Earth when calculating heat rejection from spacecraft to space
- Free molecular heating – bombardment by individual molecules in outer reaches of atmosphere

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Environment of Interplanetary Missions

- Expose spacecraft to a range of thermal environments much more severe than those encountered in Earth orbit
- During cruise – heating by sun – falls of as square of distance from Sun
- At planet – exposed to IR and albedo loads
- See Table 11-45B for information on planets and moon

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Surface Finishes

- Wavelength-dependent thermal control coatings are used for various purposes
  - Several are space qualified
- Two primary surface properties
  - IR emissivity, ε
  - Solar absorptivity, α
  - See Table 11-46 for properties

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Surface Finishes

- Average temperature for a sphere

$$\sigma T^4 = \left(\frac{\alpha}{\varepsilon}\right) \times H_1 S \times \left(\frac{A_p}{A}\right)$$

- σ = Stefan Boltzmann's constant, 5.67051×10^{-8} W/m^2K^4
- A_p = projected area
- A = total area
- S = 1367 W/m^2
- Sphere = $A_p/A = 0.25$

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Insulation

- Multilayer insulation (MLI) – used to either prevent excess heat loss from a component or excessive heating from environmental fluxes or rocket plumes; composed of multiple layers of low-emittance films with low conductivity between layers
- Most spacecraft are covered with MLI blankets with cutouts provided for radiator areas
- Single-layer insulation – used in place of MLI where a lesser degree of thermal isolation is required
- Atmospheric conditions require foam, batt, and aerogels

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MLI Effect

$$Q = \frac{\varepsilon\sigma A(T_x^{\,4} - T_y^{\,4})}{N}$$

- Q = heat leak (W)
- ε_{eff} = effective emissivity
- σ = Stefan Boltzmann's constant, 5.67051 x 10^{-8} W/m^{2}K^4
- A = surface area (m^2)
- T_x = higher temperature (K)
- T_y = lower temperature (K)
- N = number of MLI layers

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Radiators

- Reject waste heat into space
  - Reject heat by IR radiation from their surfaces
- Radiating power is dependent on emissivity of surface and its temperature
- Must reject both satellite waste heat plus any radiant heat load from environment or other spacecraft surfaces that are absorbed by radiator
- Most radiators have surface finishes with high IR emissivity (>0.8) and low absorptivity (<0.2)
- Reject between 100 to 350 W of spacecraft internally generated electronics waste heat per square meter

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Heat Leaving Radiator

$$Q = \varepsilon \sigma A T^4$$

- Q = heat leak (W)
- ε = emissivity
- σ = Stefan Boltzmann's constant, 5.67051 x 10^{-8} W/m^2K^4
- A = surface area (m^2)
- T = absolute temperature (K)

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Heaters

- Sometimes required to protect components from cold-case environmental conditions or to make up for heat that is not dissipated when an electronic box is turned off
- May be used with thermostats to provide precise temperature control of a particular component
- Also used to warm components to their minimum operating temperature before they are turned on
- Patch heater – consists of electrical resistance element sandwiched between two sheets of flexible electrically insulating material
- Cartridge heater – wound resistor enclosed in a cylindrical metallic case

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Louvers

- Most commonly place over external radiators
- Used to modulate radiant heat transfer between internal spacecraft surfaces or from internal surfaces directly to space through openings in spacecraft wall
- Most common “venetian-blind”

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Heat Pipe

- Uses closed two-phase fluid-flow cycle to transport large quantities of heat from one location to another without the use of electrical power
- Can be used to create isothermal surfaces or to spread out heat from localized source uniformly over a large area
- Basic elements – working fluid, wick structure, and envelope

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Thermal Design and Development Process

- Establishing a preliminary thermal design for spacecraft is usually a two-part process
- 1st – select a thermal design for the body – serves as a thermal sink
- 2nd – select thermal designs for various components located both within and outside spacecraft body
- Begin with passive design (keep simple as possible)
- Need to minimize mass, cost and test complexity while maximizing reliability

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Thermal Design and Development Process

- Same basic approach used on most spacecraft
  - Insulate spacecraft from space environment with MLI blankets and provide radiator areas with low solar absorptance and high infrared emittance to reject waste heat
  - High power components are usually mounted on walls of spacecraft – provides direct conduction path to radiating surfaces on outside
- Two models developed
  - Geometric math model – calculating radiation interchange factors
  - Thermal math model – predicting temperatures

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Thermal Control Challenges

- Batteries
  - Require cooler operating temperatures and small temperature ranges than electrical components
- External mechanisms
  - Located outside of spacecraft where thermal environments are much more extreme
- Optical elements
  - Don't like large cold temperature excursions
- Lasers
  - Are large heat sources – requires stable temperature control

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Thermal Control Challenges

- IR detectors operate at very cold temperatures
- Techniques for cooling
  - Passive radiators
  - Stored cryogens
  - Refrigerator system

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Heat Balance Estimation

- Successful thermal design must include adequate radiator area to accommodate maximum operational power during hottest operational environment without exceeding allowable temperatures
- Might need heaters
- “Survival” heaters are common

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Operating Environments

- Low Earth Orbit (LEO)
  - Between 400 to 800 km
  - At low inclinations, eclipse periods are fairly consistent
  - Sun-synchronous missions have fairly constant eclipse periods and a smaller range of Sun angle to contend with, have “cold-side” of spacecraft that is never in direct sunlight
  - High inclinations – may have weeks or months with no eclipses

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Operating Environments

- Geostationary (GEO)
  - ± 23.5° angular north-south motion of Sun during year results in some solar input on north and south facing sides of spacecraft
  - Equinox is normally cold scenario for mission – eclipse season of about 3 weeks with daily eclipses up to 72 minutes
- High Earth Orbit
  - Thermal environments vary due to eccentricity of orbit
  - @ perigee – albedo and IR are greatest, @ apogee – only direct solar is signficant

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Operating Environments

- Interplanetary missions
  - Have considerable variation in solar flux
    - Varies inversely with square of distance from Sun
  - Ex. – Cassini @ Venus 2700 W/m^2, @ Saturn 15 W/m^2
  - Outer planets use radioactive power sources – waste heat must be distributed around satellite by thermal subsystem
  - Each planet has its own albedo and infrared radiation characteristics (see Table 11-45B)

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Radiator Requirements

- Heat balance on radiators is dominant factor in thermal design
- Generalized heat balance equation

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

$$Q_{external} + Q_{\text{int}ernal} = Q_{radiator} + Q_{MLI}$$

- $Q_{external}$ = environmental heat absorbed
- $Q_{internal}$ = power dissipation
- $Q_{radiator}$ = heat rejected by spacecraft primary radiator surfaces
- Q_{MLI} = heat lost from blankets and elsewhere on spacecraft

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Mass, Power, and Telemetry Estimates

Component	Mass	Power	Comments
MLI	0.73 kg/m^2	0	Base on 15 layers
Heaters Thermostats Thermistors Adhesives/Paints	Various	Various	Based on heater power requirements
Heat Pipes	0.15 kg/m	10 W for VCHP	Mass per unit length Add 1-3 kg each of VCHP reservoirs Control power for VCHPs only
LHP Evaporator	2-5 kg	10-30 W	Control power
Radiator Panels	3.3 kg/m^2	0	Honeycomb radiator Add heat pipe mass if embedded
Electronic Controllers	0.2 kg	1-3 W	Each

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