MAE 468/568
Elements of Spacecraft Design

Ch. 6 – Power

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Class Agenda

- Power sources
- Energy storage
- Power distribution
- Power regulation and control
- Radioisotope Thermoelectric Generator (RTG)

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UAH Electrical Power Subsystem

- Provides, stores, distributes, and controls spacecraft electrical power
- Important sizing requirements
  - Demands for average and peak electrical power
  - Orbital profile (inclination and altitude)
- Power loads
  - Beginning-of-life (BOL)
  - End-of-life (EOL)

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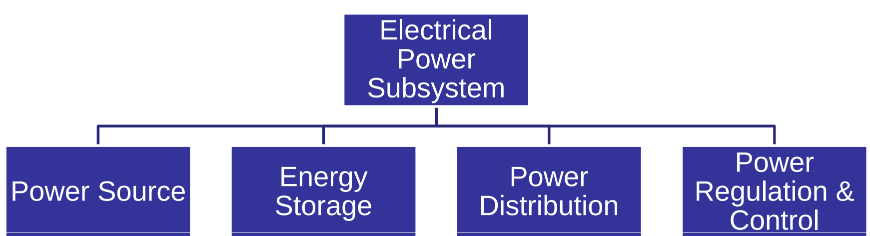
UAH Electrical Power Subsystem



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EPS Functions

- Supply continuous source of electrical power to spacecraft loads during mission life
- Control and distribute electrical power to spacecraft
- Support power requirements for average and peak electrical load
- Provide converters for ac and regulated dc power buses
- Provide command and telemetry capability for EPS health and status
- Protect spacecraft payload against failures within the EPS
- Suppress transient bus voltages and protect against bus faults
- Provide ability to fire ordnance

EPS Preliminary Design Process

1. Identify requirements
   - Mission type, mission life, spacecraft electrical profile
2. Select and size power source
   - Average load requirements, EOL power requirement, solar array type
3. Select and size energy storage
   - Eclipse and load-leveling energy storage requirement
4. Identify power regulation and control
   - Thermal control requirements

System Parameter Effects on EPS

Parameter	Effects on Design
Average Electrical Power Requirement	Sizes the power-generation system and possibly the energy storage system given the eclipse period and depth of discharge
Peak Electrical Power Required	Sizes the energy storage system and the power processing and distribution equipment
Mission Life	Longer mission life (>7 yr) implies extra redundancy design, independent battery charging, larger capacity batteries, and larger arrays
Orbital Parameters	Defines incident solar energy, eclipse/Sun periods, and radiation environment
Spacecraft Configuration	Spinner typically implies body-mounted solar cells; 3-axis stabilized typically implies body-fixed and deployable solar panels

Power Sources

- Primary batteries – power source for launch vehicles; used for hours
- Four types
  - Photovoltaic solar cells – most common power source; converts incident solar radiation directly to electrical energy
  - Static power – use heat source for direct thermal-to-electric conversion (Pu-238 or U-235)
  - Dynamic power – use heat source to produce electrical power using Brayton, Stirling, or Rankine cycles
  - Fuel cell – used on manned space missions

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Solar Array Design Process

- Step 1 – Determine requirements and constraints for power subsystem solar array design
- Use EOL for solar array design
- Might have issues with BOL power

$$P_t = 1.1568 P_{PL} + 55.497 \quad \text{(Comsats)}$$

$$P_t = 602.18 \ln(P_{PL}) - 2761.4 \quad \text{(Metsats)}$$

$$P_t = 332.93 \ln(P_{PL}) - 1046.6 \quad \text{(Planetary)}$$

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Solar Array Design Process

- Factors of mass, area, cost, and risk must be assessed
- Silicon – cost least, requires larger area arrays
- GaAs – more costly, but less mass
- Solar array illumination intensity depends on Sun incidence angles, eclipse periods, solar distance, and concentration of solar energy

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Solar Array Design Process

- Step 2 – Calculate amount of power that must be produced by the solar arrays (during daylight)

$$P_{sa} = \frac{\left(\frac{P_e T_e}{X_e} + \frac{P_d T_d}{X_d} \right)}{T_d}$$

- Direct energy transfer
  - $X_e = 0.65$, $X_d = 0.85$
- Peak power tracking
  - $X_e = 0.60$, $X_d = 0.8$

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Solar Array Design Process

- Step 3 – Select type of solar cell and estimate power output, P_O, with the Sun normal to the surface of the cells

- Silicon – $202 * H_1$ W/m^2
- GaAs – $253 * H_1$ W/m^2
- Multijunction – $301 * H_1$ W/m^2

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Solar Array Design Process

- Effect of distance on solar intensity is an inverse square law, where R is distance from sun in millions of kilometers

$$H_1 = \left(\frac{149.6}{R}\right)^2$$

Planet	Mean distance (km X 10^6)
Mercury	57.9
Venus	108.2
Earth	149.6
Mars	228.0
Jupiter	778.4
Saturn	1433.3
Uranus	2882.8
Neptune	4516.8
Pluto	5890

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Solar Array Design Process

- Step 4 – Determine beginning-of-life (BOL) power production capacity, P_{BOL}, per unit area of the array

$$P_{BOL} = P_O I_d \cos\theta$$

- $I_d = 0.77$
- θ = sun incidence angle

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Solar Array Design Process

- Step 5 – Determine end-of-life (EOL) power production capability, P_{EOL}, for the solar array

$$P_{EOL} = P_{BOL} L_d$$

$$L_d (1 - degredation / yr)^{satellitelife}$$

- Degradation
  - Si: 3.75% per yr
  - GaAs: 2.75% per yr
  - Multijunction: 0.5% per yr

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Solar Array Design Process

- Step 6 – Estimate solar array area, A_{sa}, required to produce the necessary power, P_{sa}, based on P_{EOL}

$$A_{sa} = \frac{P_{sa}}{P_{EOL}}$$

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Solar Array Design Process

- Step 7 – Estimate mass of solar array

- Body fixed – 3.4 kg/m^2
- Rigid fold-out – 4.0 kg/m^2
- Flex roll-out – 3.6 kg/m^2
- Flex fold-out – 1.9 kg/m^2

- Step 8 – Document assumptions

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Energy Storage

- Integral part of a spacecraft's electrical power subsystem
- Provides primary power for short missions (<1 week)
- Provides backup power for longer missions (>1 week)
- Needed for peak-power and eclipse periods

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Issues in Energy Storage During Preliminary Design

- Physical
  - Size
  - Mass
  - Configuration
  - Operation position
  - Static and dynamic environment
- Electrical
  - Voltage
  - Current loading
  - Duty cycles
  - Number of duty cycles
  - Activation time and storage time
  - Limits on depth-of-discharge
- Programmatic
  - Cost
  - Shelf and cycle life
  - Mission
  - Reliability
  - Maintainability
  - Produceability

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Batteries

- Primary
  - Convert chemical energy into electrical energy but cannot reverse this conversion – they can not be recharged
  - Apply to short missions (less than one day) or long term tasks which use very little power
- Secondary
  - Convert chemical energy into electrical energy during discharge and electrical energy into chemical energy during charge
  - Can repeat process thousands of cycles
  - Provides power during eclipse periods

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Secondary Batteries

Secondary Battery Couple	Specific Energy Density (W-hr/kg)	Status
Nickel-Cadmium	25-30	Space qualified, extensive database
Nickel-Hydrogen (individual pressure vessel design)	35-43	Space qualified, good database
Nickel-Hydrogen (common pressure vessel design)	40-56	Space qualified for GEO and planetary
Nickel-Hydrogen (single pressure vessel design)	43-57	Space qualified
Lithium-ion	70-110	Under development
Sodium-Sulfur	140-210	Under development

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Depth-of-Discharge (DOD)

- Percent of total battery capacity removed during a discharge period
- Higher percentages imply shorter cycle life
- NiH_2 = 40-60%
- NiCd = 10-20%

$$C_r = \frac{P_e T_e}{(DOD)Nn}$$

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Power Distribution

- Consists of cabling, fault protection, and switching gear to turn power on and off to the spacecraft loads
- Designs depend on
  - Source characteristics
  - Load requirements
  - Subsystem functions
- Selection based on keeping power losses and mass at a minimum while attending to survivability, cost, reliability, and power quality

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Power Regulation and Control

- Energy source determines how we regulate a spacecraft's power
- Photovoltaics are controlled to prevent batter overcharging and undesired spacecraft heating
- Two methods
  - Peak-power tracker – extracts the exact power a spacecraft requires up to the array's peak power
  - Direct-energy-transfer – dissipates power not used by the loads

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RTGs

- Offer a spacecraft power source
  - Independent of sun
  - Missions where independence in mandatory
- Development of RTGs assigned to Atomic Energy Commission
- 1st RTG – SNAP-3 – 1961
- Early power density – 1W/kg
- Galileo reached – 5.4 W/kg
- RTGs convert energy released during decay of an isotope – Pu 238 – into electricity using thermoelectric effect

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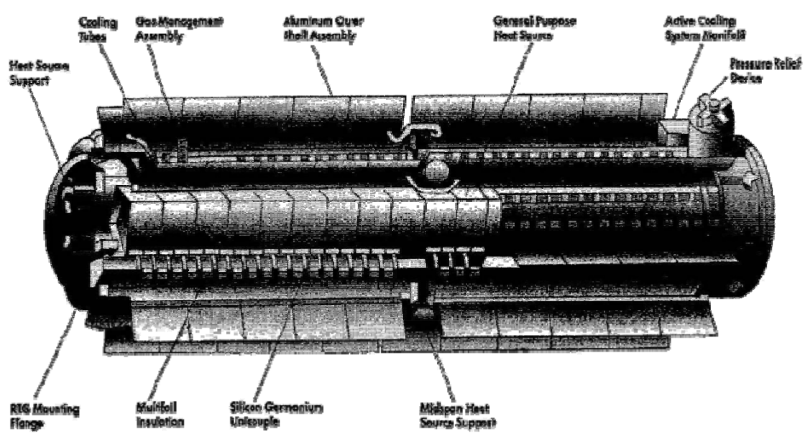
RTGs



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RTGs

- Heat source blocks in central core contain isotope capsules, each encased in an individual reentry heat shield
- Each of heat source blocks are in thermal contact with hot junction of thermoelectric units
- Power collected from thermoelectric units in a series-parallel arrangement and brought out of unit through connector
- Waste heat generated, about 90%, is radiated to space by fins

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RTGs

- Disadvantages
  – Cost of units, particularly cost of isotope
  – Cost of labor involved in demonstrating compliance with safety requirements
  – Cost of safety provisions for ground crew
  – Power decreases with time because of radiation damage to units as well as nuclear decay
  – Neither power output nor heat output can be turned off
  – Emitted radiation is detrimental to electronics and instruments – extended boom is required
- RTGs not used when solar arrays will suffice

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