Spacecraft Power Systems

AOE 4065

Space Design

Refs: SMAD Chap 11.4, G&F Chap 10,
F&S Chap 11, P&M Chap 6

Electrical Power Subsystem (EPS) Functions

- Supply electrical power to spacecraft loads
- Control and distribute electrical power
- Meet average and peak electrical loads
- Provide power conditioning and conversion
- Provide command and telemetry capability
- Protect spacecraft against EPS failure
- Suppress transient bus voltage spikes
- Provide energy storage for eclipse and peak demands
- Provide specialized power for specific functions such as firing ordinance for mechanism deployment

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Power Subsystem Functions

Power Source → Source Control → Power Management and Distribution → Power Processors → Load

Power Management and Distribution ↔ Energy Storage Control ↔ Energy Storage

Power Source
- Solar photovoltaic
- Radio-isotope thermoelectric generator
- Nuclear reactor
- Solar dynamic
- Fuel cells
- Primary batteries

Source Control
- Shunt regulator
- Series regulator
- Shorting switch array

Power Conditioning
- DC-DC converters
- DC-AC inverters
- Regulators

Energy Storage Control
- Charger
- Regulator

Energy Storage
- Batteries
- Flywheels

Power Subsystem Design

- Identify requirements
  - mission lifetime
  - spacecraft electrical power profile, especially average power
- Select and size power source
  - usually solar arrays for Earth-orbiting s/c
  - EOL requirement, type of solar cell, configuration, all drive size
- Select and size energy storage
  - eclipse and load-leveling requirement
  - battery type
- Identify power regulation and control
  - peak-power tracker or direct-energy-transfer
  - thermal control
  - bus-voltage quality, conversion

Power Subsystem Requirements

- Average electrical power - sizes power source (solar array size)
- Peak electrical power - sizes energy storage (battery capacity)
- Mission life - degradation affects sizing of batteries and solar arrays
- Orbit - defines achievable solar energy, eclipse periods, radiation environment
- Spacecraft configuration - spinner implies body-mounted solar cells; 3-axis implies solar panels

Power Sources (SMAD)

Design Parameter	Solar Photovoltaic	Solar Thermal Dynamic	Radioisotope	Nuclear Reactor	Fuel Cell
Power range (kW)	0.2 - 300	5 - 300	0.2 - 10	5 - 300	0.2 - 50
Power density (W/kg)	25 - 200	9 - 15	5 - 20	2 - 40	275
Cost ($/W)	800 - 3000	1000 - 2000	16K – 200K	400K – 700K	N/A
Maneuverability	Low	Medium	High	High	High
Drag (LEO)	High	High	Low	Medium	Low
Degradation	Medium	Medium	Low	Low	Low
Storage for eclipse	Yes	Yes	No	No	No
Sensitivity to θ_o	Medium	High	None	None	None
Sensitivity to s/c shadowing	Low	High	None	None	None
Obstruction of s/c viewing	High	High	None	Medium	None
Fuel availability	Unlimited	Unlimited	Very low	Very low	Medium
Safety analysis	Minimal	Minimal	Routine	Extensive	Routine
IR signature	Low	Medium	Medium	High	Medium
Applications	Earth orbit	Interplanetary and Earth orbit	Interplanetary	Interplanetary	Interplanetary

Solar Energy

- The solar constant, $G_s = 1358\ W/m^2$, is the total solar energy incident on a unit area perpendicular to the sun's rays at the mean Earth-Sun distance outside the Earth's atmosphere
- It varies between about 1310 and 1400 on an annual cycle, with max at perihelion and min at aphelion

Power vs Energy: Power (Watts) is time-rate-of-change of Energy (Watt-hours)

Orbital Considerations

- Fraction of time in sunlight = $(\pi+2\alpha)/(2\pi)$

  where

  $\alpha = \sin^{-1}(R_e \tan\beta / (a \cos\theta_o))$

  $\beta = \cos^{-1}(R_e/a)$

  θ_o = angle between orbit plane and sun direction

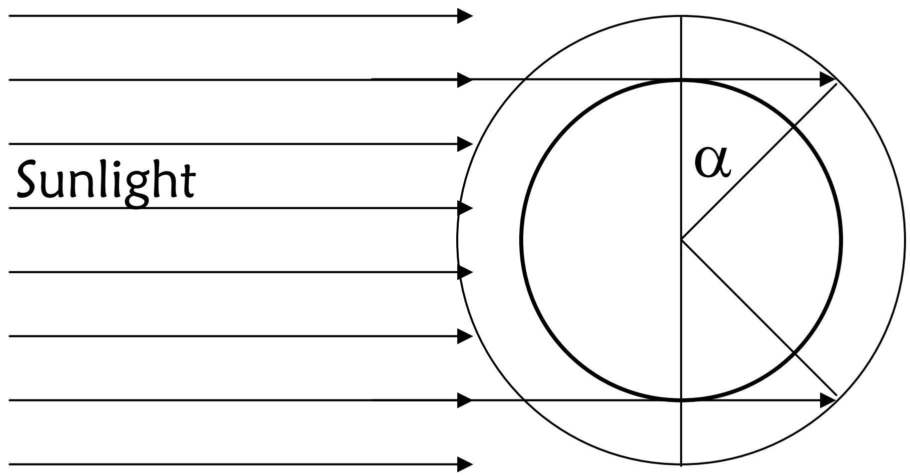
  $a = R_e + H$

- Solar array must collect enough energy during sunlight to power spacecraft during entire orbit

- Solar array power during daylight

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

- P = power, T = time, X = path efficiency



Efficiency and Degradation

- Production efficiency, η, of solar cells ranges from 14-22%
  - silicon: 14% gallium arsenide: 19%
    indium phosphide: 18% multijunction GaAs: 22%
- Path efficiency is from solar array through batteries to loads
  - direct energy transfer: $X_e = 0.65$, $X_d = 0.85$
  - peak-power tracking: $X_e = 0.60$, $X_d = 0.80$
- Inherent degradation
  - design & assembly losses, temperature-related losses, shadowing due to appendages: $I_d \approx 0.77$ (0.49-0.88)
- Cosine loss, factor of $\cos\theta$
  - incidence angle between array normal and Sun vector
  - typically use worst-case Sun angle
- Life degradation
  - thermal cycling, micrometeoroids, plume impingement, material outgassing, radiation: degradation/year = 2-4%/year
  - $L_d = (1\text{-degradation/year})^{\text{satellite life}}$

P_{BOL} and P_{EOL}

- BOL = Beginning of life
- EOL = End of Life

P_o	$= \eta \times 1358\ W/m^2$	output power/unit area
P_{BOL}	$= P_o\, I_d \cos\theta$	BOL power/unit area
P_{EOL}	$= L_d\, P_{BOL}$	EOL power/unit area

- Solar array size to meet power requirement

$$A_{sa} = P_{sa}/P_{EOL}$$

- Mass of solar array ranges from 14 to 47 W/kg

$$M_{sa} = 0.04\, P_{sa}$$ (for 25 W/kg)

- Keep in mind that this formula is an approximation, especially since the angle θ changes continuously

Example Solar Array Sizing

1500 W load

1000 km orbit

5 year lifetime

Assume DET

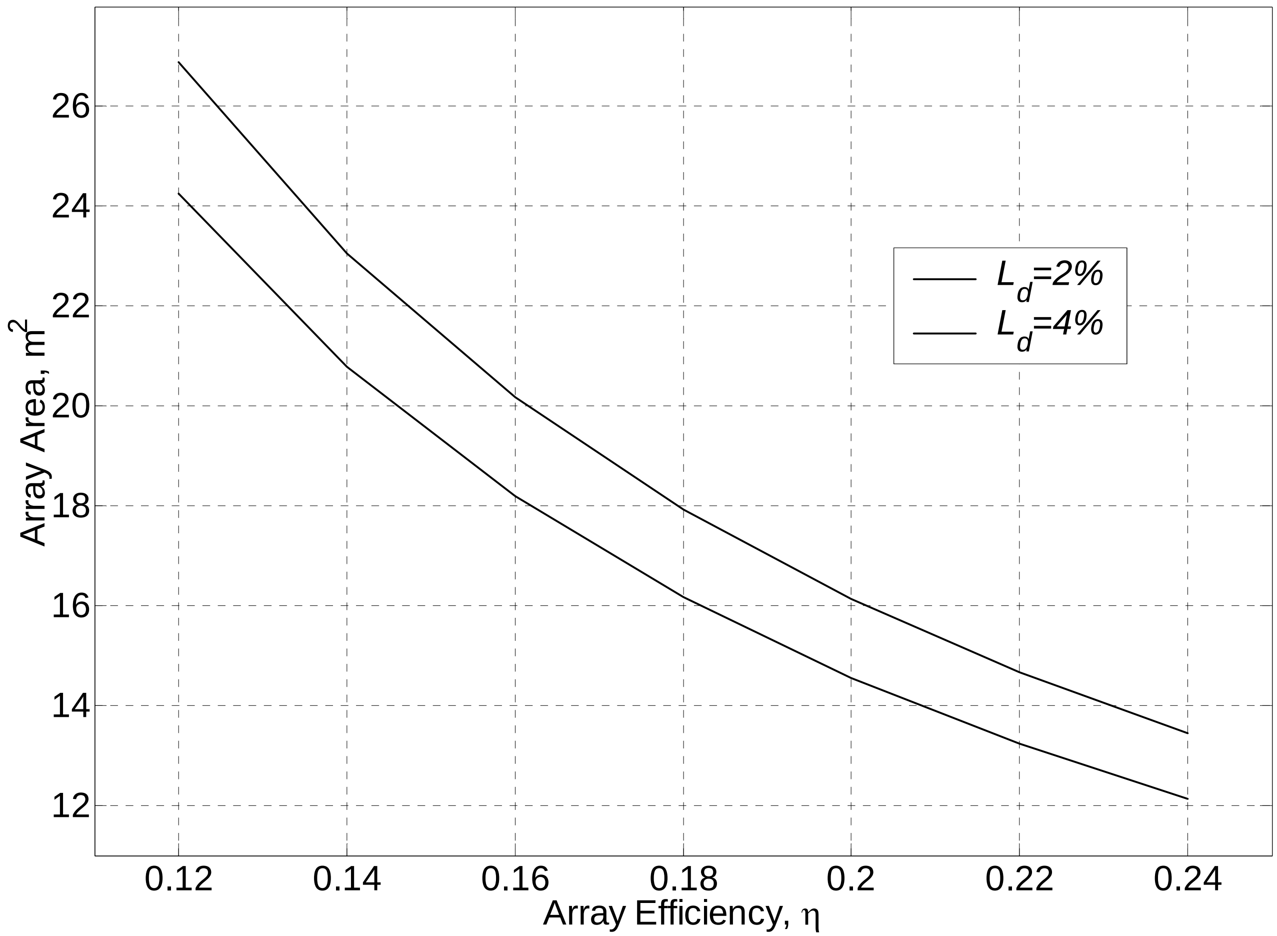
105 min period

35 min eclipse

P_{sa} = 1946 W

θ_o = 45°

Vary L_d and η



Solar Array String Length

- $P_{sa} = N \times P_{cell}$
  where N is number of cells in array, and P_{cell} is power produced by a single cell.
  Determines N.
- $I_{sa} = N_{||} \times I_{cell}$
  where $N_{||}$ is number of cells in parallel, and I_{cell} is current output of a single cell.
  $N_{||}$ is used to minimize shading effects.
- $V_{sa} = N_{\text{series}} \times V_{cell}$
  where N_{series} is number of cells in series, and V_{cell} is voltage output of a single cell.
  N_{series} is used to achieve desired bus voltage.

Example:

$$P_{sa} = 1946\ W,\ 28\ V\ bus$$

$$V_{cell} = 0.5\ V,\ I_{cell} = 150\ mA \Rightarrow P_{cell} = 75\ mW$$

$$\Rightarrow N = 29{,}947 \approx 30{,}000\ cells$$

$$N_{\text{series}} = 56$$

Energy Storage Sizing

- Batteries*, flywheels, fuel cells, …
- Battery = individual cells in series
- Batteries can be connected in series to increase voltage
- … or in parallel to increase current
- Bus voltage determines number of cells
- Energy stored described by ampere-hour or watt-hour capacity
- Sized to provide power during eclipse or during peak loading

*Electrochemical batteries are most commonly used.

Energy Storage Issues

- Physical:
  - Size, mass, configuration, orientation, location, static and dynamic load environment
- Electrical:
  - Voltage, current, cycles, depth of discharge
- Programmatic:
  - Cost, shelf life, cycle life, mission, reliability, maintainability, produceability, …

Energy Storage Terms

- Specific Energy Density - W hr/kg, a performance measure for batteries
- Primary Batteries - nonrechargeable batteries
  - short missions with medium to high power load
  - long-term, low-power tasks
  - SED typically 90 - 400 W hr/kg
- Secondary Batteries - rechargeable batteries
  - provide power during eclipse or peak loading
  - SED typically 25 - 200 W hr/kg
- Depth-of-Discharge - % of capacity used during a single discharge cycle
  - higher DOD leads to shorter cycle life
  - 10-20% for NiCd batteries
  - 40-60% for NiH_2 batteries
- Charge Rate - rate at which battery can accept charge
  - higher charge rate leads to shorter cycle life

Energy Storage Subsystem Sizing

- Requirements
  - Mission lifetime
  - Orbital parameters: eclipse frequency and duration
  - Power profile: voltage, current, depth of discharge, # cycles
  - Battery limitations
- Battery type and properties
- Battery capacity:

$$C_r = P_e\, T_e \,/\, (\mathrm{DOD}\; N\; \eta)$$

A Power MicroProject

Size a power system to support a 1500 W load in a 1000 km circular orbit with a 10 year lifetime

Given:

Bus voltage: 28 V DC

Silicon solar cells: η = 14 %

Power density: 25 W/kg

Direct energy transfer

Energy density: 30 W hr/kg

Maximum DOD: 30 %

Inherent degradation: 80 %

Annual degradation: 3 %

Worst case sun angle: 23°

Angle between orbit plane & sun direction: 0

Determine:

Solar array power output

Size and mass of solar array

Mass of batteries

Report:

Technical report with Introduction, Development, Sample calculations, Conclusions, Discussion of alternatives /technologies that were not included, References