Spacecraft Power Systems

The Generation and Storage of Electrical Power

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Power Systems

- Batteries → Solar Cells + Batteries → Fuel Cells → RTG → Nuclear Reactors → ?

- Functions of the Power System
  - Controls the generation, storage, and efficient use of power
  - Provides protection against cascading failures
  - Provides redundant paths or components in case of failure
Power System Design Drivers (½)

- Customer/User requirements
- Mission, ConOps
- Spacecraft configuration
  - Mass constraints
  - Dimensional constraints
  - Launch Vehicle constraints
  - Thermal constraints
- Expected lifetime
Power System Design Drivers (2/2)

- Attitude control system
  - Pointing requirements
  - Viewing requirements

- Orbit or trajectory
  - With respect to the sun

- Payload requirements
  - Voltage, current
  - Duty cycle, peak load
  - Fault protection

- Mission constraints
  - Maneuver rates
  - G-loads create inertial loads
Power System Functional Block Diagram

- Batteries
- Solar
- RTG
- Fuel Cells
- Nuclear
- R Dynamic
- Solar Dynamic

- Shunt Regulator
- Series Regulator
- Shorting Switch Array

- DC-DC conversion
- DC-AC conversion
- Voltage regulator

- Battery charge control
- Voltage regulator
Design Practice (1/2)

- **Direct Current Switching**
  - Switches or relays: positive line to an element with a direct connection to “ground” on negative side
  - Therefore, element is inert until commanded

- **Arc Suppression**
  - Locate as close to the source of the arc as possible
  - Current-carrying elements should not be exposed to the ambient plasma
    - Conductive cables, connectors, solar array edges

- **Modularity**
  - Simplifies testing
  - Easier element replacement
  - Reduces “collateral” damage
Design Practice (2/2)

- **Grounding**
  - Cause of some debate among EEs
  - Common ground preferable to individual component grounding
    - Easier to maintain a common potential
    - Less likely to disturb sensitive components
    - Can be difficult to do in large spacecraft
  - Sometimes it is necessary to completely isolate an element from other spacecraft noise

- **Continuity**
  - Avoid buildup of static potential; i.e., any voltage difference
  - Any shielding must have continuity and a common ground

- **Complexity**
  - KISS
Battery Design Considerations

- Physical
  - Size, mass, environmental requirements

- Electrical
  - Voltage
  - Current loading
  - Duty cycles
  - Limits on depth-of-discharge
  - Fault recovery

- Programmatic
  - Cost, reliability, maintainability, safety
Batteries: Definition of Terms (1/2)

- **Charge Capacity, $C_{chg}$**
  - Total electric charge stored in a battery; measured in amp-hours (e.g., 40A for 1 hour = 40Ah)

- **Average Discharge Voltage, $V_{avg}$**
  - (Number of cells in series) * (Cell discharge voltage)

- **Energy Capacity, $E_{bat}$**
  - Total energy stored in a battery; 
    $[C_{chg} \times V_{avg}]$ (Joules or watt-hours)

- **Depth of Discharge, DOD**
  - Percent of battery capacity used in discharge cycle
  - 75% DOD means 25% remaining
  - Try to limit DOD to promote longer cycle life
Batteries: Definition of Terms (2/2)

- **Charge Rate**, $R_{\text{chg}}$
  - Rate at which the battery can accept charge (amps/unit time)

- **Energy Density**, $e_{\text{bat}}$
  - Energy per unit mass stored in battery
  - Joules/kg or Watt-hours/kg

- Two categories of batteries
  - Primary
  - Secondary
Primary Batteries

- Long storage capability (missile in a silo)
- Dry (without electrolyte) until needed
  - Activate by introducing electrolyte into dry battery
  - Electrolyte may be solid at room temperature
    Activate heater to melt electrolyte. (Thermal battery)
- Typically have a fairly large energy density
- Used for early major mission events
  - Short duration
  - May be isolated from major power bus
  - Usually non-rechargeable
  - Mass penalty
Secondary Batteries (1/2)

- Lower energy density, but rechargeable
- Requires DOD management
  - LEO – eclipse is about 40% of the orbit
  - 12 – 16 discharge cycles per day
  - Leads to battery degradation and lifetime reduction
- Maximum allowable DOD:

\[
DOD = \frac{\text{Energy required during eclipse}}{\text{Stored battery energy}} = \frac{P_L t_d}{C_{\text{chg}} V_{\text{avg}}} = \frac{P_L t_d}{E_{\text{bat}}}
\]

- \(P_L\) = load power
- \(t_d\) = discharge time
- \(C_{\text{chg}}\) = charge capacity
- \(V_{\text{avg}}\) = average discharge voltage
- \(E_{\text{bat}}\) = total battery energy capacity
# Secondary Batteries (2/2)

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Energy Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver-zinc (Ag-Zn)</td>
<td>120 – 130 (W-hr)/kg</td>
</tr>
<tr>
<td>Silver-cadmium (Ag-Cd)</td>
<td>60 – 70 (W-hr)/kg</td>
</tr>
<tr>
<td>Nickel-cadmium (Ni-Cd)</td>
<td>20 – 30 (W-hr)/kg</td>
</tr>
<tr>
<td>Nickel-hydrogen (Ni-H₂)</td>
<td>60 – 70 (W-hr)/kg</td>
</tr>
<tr>
<td>Nickel-metal hydride (Ni-MH)</td>
<td>120 – 130 (W-hr)/kg</td>
</tr>
<tr>
<td>Lithium Thionyl Chloride (Li-SOCl₂)</td>
<td>650 (W-hr)/kg</td>
</tr>
<tr>
<td>Lithium Vanadium Pentoxide (Li-V₂O₅)</td>
<td>250 (W-hr)/kg</td>
</tr>
<tr>
<td>Lithium Sulfur Dioxide (Li-SO₂)</td>
<td>50 – 80 (W-hr)/kg</td>
</tr>
</tbody>
</table>
DOD Management

- Typically, a LEO spacecraft spends 40% of its time discharging and 60% charging.
- DOD during eclipse is limited by the rate at which its batteries can be restored in sunlight by solar arrays.
- All expended energy must be restored or net drain.
- Driver is the charge rate, $R_{chg}$
  - DOD limited to 7-8% per orbit
  - Battery temperature can affect charge rate.
- Battery generally must be charged at a voltage $> V_{avg}$ (~20% higher) to restore full charge.
- This is a driver in the solar array design.

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Solar Arrays

- Photoelectric Effect
  - Electrons are emitted from matter as a result of absorption of short wavelength electromagnetic radiation such as visible light.

- Originally limited to spacecraft skin acreage
- Deployable panels more flexible, but more complex

- Solar Cell Characteristics
  - 1st order: $V$ decreases as $T$ increases (and vice versa)
  - 2nd order: $I$ increases as $T$ increases, BUT
    - Only about 10% relative to the voltage drop
  - Therefore, overall power output is reduced as temperature increases. $P = I \times V$

- May need radiators to remove excess heat
Solar Cell Capability

- Delivered electrical power:
  \[ P_e = \Phi e A(1 - I) \]
  \( \Phi = \) solar flux (W/m\(^2\))
  \( e = \) cell efficiency (≈15% for silicon)
  \( A = \) area
  \( I = \) parasitic losses (≈10%)

- **Nominal solar flux density at earth:** 1353 W/m\(^2\) at 1 AU
  \[ \Phi = W(a/d)^2 \cos(\theta) \]
  \( W = \) Nominal solar flux
  \( a = \) Mean earth-sun distance
  \( d = \) actual earth-sun distance
  \( \theta = \) panel inclination

- **Cell efficiency (t)**
  \[ e_{EOL} = e_{BOL} e^{-0.043T} \]
  \( T = \) time in orbit years
Maximum Power Point (MPP)

- Desirable to operate at the MPP if possible
- Minimize mass and maximize efficiency

Maximum area rectangle under the IV curve

- $I$
- $V$

MPP
Sun Tracking

- Ideal situation: sun normal to the array
- Cosine rule applies – up to a point

![Diagram showing sun tracking and cosine function up to 45-60°, then falling off rapidly]
Beta and Alpha

- **Beta, \( \beta \)**
  - Angle between a line from the sun to the center of the earth, and spacecraft orbit

- **Alpha, \( \alpha \)**
  - *Apparent* rotation of sun angle from spacecraft pov during its orbit. \( \alpha = 0-360^\circ \)
Solar-to-Electric

- Efficiency of solar cells
  - Gallium arsenide solar cells (Ga-As)
    - More efficient (20%) and radiation tolerant
    - More expensive
  - Crystalline Silicon Cells
    - 11-16%, 18-20%, >20%?
  - Multi-junction (multi-layer cells)
    - Top layer converts light in the visible range
    - Bottom layer(s) optimized for infrared
    - Up to 30% efficiency
    - Not surprisingly, very expensive
Radioisotope Thermoelectric Generator (RTG)

- Converts heat energy generated by radioisotope decay into DC energy via thermoelectric effect
  - Plutonium 238, $^{238}\text{Pu}$
  - Strontium 90, $^{90}\text{Sr}$
- Complicated ground handling
- RTG radiation
  - Alpha rays
  - Detrimental to spacecraft electronics
  - Clothing (or paper) will stop alpha rays
  - Don’t inhale $^{238}\text{Pu}$ dust
  - $^{238}\text{Pu}$ pellets are a ceramic form – no dust if exposed
- Expensive but effective and reliable
Fuel Cells

- Direct conversion of chemical energy into electricity
- More efficient than batteries
- Oxidizer and fuel fed into a cell
- Electricity generated from oxidation reaction in the cell
- Space applications use oxygen/hydrogen
- By product: water
- \( \sim 35\% \) efficiency
Power Conditioning & Control

- Voltage from power source, especially solar arrays, may fluctuate
- Power conditioning functions
  - Control solar array output
  - Control battery charge/discharge cycle
  - Regulate voltage supplied to spacecraft systems
Additional Power Sources

- Nuclear Reactors
- Dynamic Isotope Systems
- Alkali Metal Thermal-to-Electric Conversion (AMTEC)
- Solar Dynamic
Backup
Dissipative Systems

- Simpler
- Not in series with array output

- Solar Array
- Shunt
- Battery Charge Controller
- Spacecraft Loads
- Battery

Dissipates current in excess of instantaneous load requirement
Non-dissipative Systems (PPT)

- In series regulation of solar power

- Usually reserved for large spacecraft