Elements of the System
- Solar Cell Arrays
- Batteries
- Radioisotope
- Thermoelectric Generators
- Primary Power
- Secondary Power
- Management, Distribution, and Control
- Power Budget

Preliminary Design Process for Power System

<table>
<thead>
<tr>
<th>Step</th>
<th>Information Required</th>
<th>Derived Requirements</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Identify Requirements</td>
<td>Top-level requirements, mission type (LEO, GEO), spacecraft configuration, mission life, payload definition</td>
<td>Design requirements, spacecraft electrical power profile (average and peak)</td>
<td>Secs. 10.1, 10.2</td>
</tr>
<tr>
<td>2. Select and Size Power Source</td>
<td>Mission type, spacecraft configuration, average load requirements for electrical power</td>
<td>EOL power requirement, type of solar cell, mass and area of solar array, solar array configuration (2-axis tracking panel, body-mounted)</td>
<td>Sec. 10.1, 10.2 Table 10-9 Sec. 11.4.1 Table 11-34</td>
</tr>
<tr>
<td>3. Select and Size Energy Storage</td>
<td>Mission orbital parameters, average and peak load requirements for electrical power</td>
<td>Eclipse and load-leveling energy storage requirement (battery capacity requirement), battery mass and volume, battery type</td>
<td>Sec. 11.4.2 Tables 11-3, 11-4, 11-38, 11-39, 11-40 Fig. 11-11</td>
</tr>
<tr>
<td>4. Identify Power Regulation and Control</td>
<td>Power-source selection, mission life, requirements for regulating mission load, and thermal-control requirements</td>
<td>Peak-power tracker or direct-energy-transfer system, thermal-control requirements, bus-voltage quality, power control algorithms</td>
<td>Sec. 11.4.4</td>
</tr>
</tbody>
</table>

McDermott; Larson & Wertz, 1999
Effects of System Level Parameters

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

McDermott; Larson & Wertz, 1999

Typical Electrical Power Requirements

- Generate electrical power for s/c systems
- Store power for “fill-in” when shadowed from Sun
- Distribute power to loads
- Condition power (e.g., voltage regulation)
- Protect power bus from faults
- Provide clean, reliable, uninterrupted power
Power System Analysis

• Power budget
  – Payload, bus, and charge loads
  – Error margins

• Energy balance
  – Dynamic simulation over multiple duty cycles

• Stability Analysis
  – Small-signal AC stability
  – Bus impedance
  – Bus ripple
  – Transient response

Power System Sizing

• Power system must
  – Support the spacecraft through entire mission
  – Recharge batteries after longest eclipse
  – Accommodate electric propulsion/attitude control
  – Accommodate failures to assure reliability
  – Account for margins and contingencies

• Factors affecting size
  include
  – Satellite orbit
  – Seasonal variation
  – Life degradation
  – Total eclipse load
  – Number of discharges
Power Management and Distribution

- Solar array control
- Battery charge control
- Battery discharge control
- Power distribution and protection
- Bus voltage regulation and conditioning
- Power switching
- Power telemetry
- Requirements driven by power system architecture, bus voltage, and power levels

GOES-P Electric Power Sub-System
Power System Tradeoffs

Selection of Power System Type
Functional Blocks of Electrical Power System

- Energy generation
- Energy storage
- Power management and distribution

Functional Blocks of Solar Cell/Battery Electrical Power System
Power System Architectures

- **Unregulated (battery-dominated) bus**
  - Bus voltage determined by battery voltage

- **Sunlight regulated bus**
  - Bus voltage regulated during sunlit period
  - Bus voltage determined by battery voltage during eclipse

- **Fully regulated bus**
  - Bus voltage regulated in sunlight and eclipse
  - Power converter boosts variable battery voltage to bus voltage

Solar Cells and Arrays
Solar Cells

- Silver, palladium, titanium, silicon “sandwich”
- [p-n junction]
- Photons hit panel
- Electrons are excited, generating heat or traveling through material, e.g., boron or phosphorus, generating a current

Theoretical Single-Junction Solar Cell Efficiency

- **Bandgap**: Energy Range in which no electron states can exist
- Photon energy must exceed bandgap for current to flow across p-n junction

*Rauschenbach; Fortescue, 2011*
Multi-Junction Solar Cells

Material-dependent relationship between wavelength and bandgap

Current-Voltage-Power Characteristics of Typical Solar Cells

- Silicon (Efficiency 15%)
- Gallium Arsenide (GaAs)
  - Dual Junction (~22%)
  - Triple Junction (~28%)
  - Quad Junction (>30%)
Solar Arrays

- Generate power during sunlit periods for
  - Payload
  - Operation of power bus
  - Charging batteries
- Typical power output: 2kW – 15kW

MAVEN Solar Array Deployment
https://www.youtube.com/watch?v=oxxUuo4tgWs
Solar Array Design

- Each solar cell produces
  - $< 2 \text{ W}$
  - $0.7 - 3 \text{ V}$
- Series arrangement to produce voltage
- Parallel arrangement to produce current

Solar Cells Don’t Function During Eclipse

1,000-km, 32° inclination example

Larson & Wertz, 1999
Eclipse Duration

Orbit-Angle Segment of Eclipse

\[ \Phi = 2 \cos^{-1} \left( \frac{\cos \rho}{\cos \beta_S} \right) \]
\[ = 2 \cos^{-1} \left( \frac{\cos \rho}{\sin \beta_S'} \right), \text{ rad} \]

Duration of Eclipse

\[ T_{\text{eclipse}} = \frac{\Phi}{2\pi} P_{\text{orbit}}, \text{ min} \]

Secondary power required during the eclipse

\[ \rho = \text{Spherical angle of Earth disk, rad} \]
\[ \beta = \text{Spherical angle of Sun above the orbit plane, rad} \]
\[ \Phi = \text{Spherical angle of eclipse, rad} \]
\[ T_{\text{eclipse}} = \text{Duration of eclipse, min} \]

Batteries

- Nickel Cadmium (NiCd)
  - Heavier, older tech
  - Lower volume
- Nickel Hydrogen (NiH2)
  - High # of charging cycles
  - Pressurized vessels
- Lithium Ion (Li Ion)
  - State of the art
  - 1/2 the mass, 1/3 the volume of NiH2
  - Extra care required in charging

**Batteries**

- **Nickel Cadmium (NiCd)**
  - Heavier, older tech
  - Lower volume
- **Nickel Hydrogen (NiH2)**
  - High # of charging cycles
  - Pressurized vessels

**Lithium-Ion Battery Modules**

Choy Patent

Hall Patent

[Links to Choy and Hall patents]
**Battery Comparison**

![Battery Comparison Diagram]


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**Performance of Spacecraft Batteries**

**Table 10.6** Performance of battery technologies for space use [23]

<table>
<thead>
<tr>
<th>Type</th>
<th>Specific energy (W h/kg)</th>
<th>Mission examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni-Cd</td>
<td>28–34</td>
<td>Sampex</td>
</tr>
<tr>
<td>Ni-H₂</td>
<td>30–54</td>
<td>Odyssey</td>
</tr>
<tr>
<td>Ag-Zn</td>
<td>100</td>
<td>Pathfinder</td>
</tr>
<tr>
<td>Li-Ion</td>
<td>90</td>
<td>MER Rover</td>
</tr>
<tr>
<td>Li-SO₂</td>
<td>90–150</td>
<td>Galileo</td>
</tr>
<tr>
<td>Li-SOCl₂</td>
<td>200–250</td>
<td>Sojourner</td>
</tr>
</tbody>
</table>

Three Spacecraft Examples

Table 10.7  Hubble space telescope (HST), Intelsat VII and Eurostar 3000 battery summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HST</th>
<th>Intelsat VII</th>
<th>Eurostar 3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>Ni-H$_2$</td>
<td>Ni-H$_2$</td>
<td>Li-ion</td>
</tr>
<tr>
<td>Specific energy (W h/kg)</td>
<td>57.14</td>
<td>61.26</td>
<td>175</td>
</tr>
<tr>
<td>Capacity (A-h)</td>
<td>96</td>
<td>91.5</td>
<td>50</td>
</tr>
<tr>
<td>Cell dimensions:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter (cm)</td>
<td>9.03</td>
<td>8.89</td>
<td>5.3</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>23.62</td>
<td>23.67</td>
<td>25.0</td>
</tr>
<tr>
<td>Cell mass (kg)</td>
<td>2.1</td>
<td>1.867</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Definitions

- **Capacity**: fully charged amount of energy
- **State of Charge (SOC)**: How much charge remains in battery
- **Depth of Discharge**: How much charge is taken out of battery
- **Charge Rate**: Rate (current) at which charge (Ah) is put into battery
- **Charge Efficiency**: How much charge energy is stored
- **Charge/Discharge Ratio**: Charge required to restore beginning SOC following discharge
- **Self Discharge**: Low-level leakage
- **Trickle Charge**: Continuing charge to counter self-discharge
- **Balancing**: Equalizing the SOC of each cell in a battery
Fuel Cell

Produces electricity from hydrogen and oxygen
Water is a by-product

Proton Exchange Membrane Fuel Cell

Gemini Fuel Cell
47 x 37.5 x 63.5cm
Reformed Methanol Fuel Cell

- Methanol: source of hydrogen
  - Partial oxidation (hydrogen-rich gas)
  - Autothermal reforming (steam treatment)
  - Water-gas-shift (“water gas”)
  - Preferential oxidation (removal of CO, which “poisons” the fuel cell catalyst)

Thermoelectric Power Generation
Radioactive Isotope Thermoelectric Generator (Cassini Spacecraft)

Radioactive Isotope Thermoelectric Generator

<table>
<thead>
<tr>
<th>Name</th>
<th>Used on (# of RTGs)</th>
<th>Electrical Output (W)</th>
<th>Heat Output (W)</th>
<th>Radioisotope 38Pu (kg)</th>
<th>Max fuel used (kg)</th>
<th>Mass (kg)</th>
<th>Power/Mass (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMRTG</td>
<td>MSL/Curiosity rover</td>
<td>~110</td>
<td>~2000</td>
<td>238Pu</td>
<td>~4</td>
<td>~65</td>
<td>~2.4</td>
</tr>
<tr>
<td>GPHS-RTG</td>
<td>Cassini (3), New Horizons (1), Galileo (2), Ulysses (1), LES-8/6, Voyager 1 (3), Voyager 2 (3)</td>
<td>300</td>
<td>4400</td>
<td>238Pu</td>
<td>7.8</td>
<td>55.9-57.8</td>
<td>5.2-6.4</td>
</tr>
<tr>
<td>MHK-RTG</td>
<td>Transit 8/4 (1)</td>
<td>160</td>
<td>2400</td>
<td>238Pu</td>
<td>~4.5</td>
<td>37.7</td>
<td>4.2</td>
</tr>
<tr>
<td>SNAP-3A</td>
<td>Transit ST/12 (1)</td>
<td>2.7</td>
<td>52.5</td>
<td>238Pu</td>
<td>?</td>
<td>2.1</td>
<td>1.3</td>
</tr>
<tr>
<td>SNAP-4A</td>
<td>Nimbus-3 (2), Pioneer 10 (4), Pioneer 11 (4)</td>
<td>25</td>
<td>525</td>
<td>238Pu</td>
<td>~1</td>
<td>12.3</td>
<td>2</td>
</tr>
<tr>
<td>SNAP-19</td>
<td>Viking 1 (2), Viking 2 (2)</td>
<td>42.7</td>
<td>525</td>
<td>238Pu</td>
<td>~1</td>
<td>15.2</td>
<td>2.8</td>
</tr>
<tr>
<td>SNAP-27</td>
<td>Apollo 12–17 ASEP (1)</td>
<td>73</td>
<td>1,480</td>
<td>238Pu</td>
<td>~1</td>
<td>20</td>
<td>3.6</td>
</tr>
<tr>
<td>Buk (BES-5)</td>
<td>US-4a (1)</td>
<td>3000</td>
<td>100,000</td>
<td>235U</td>
<td>~30</td>
<td>~1000</td>
<td>3</td>
</tr>
<tr>
<td>SNAP-10A</td>
<td>SNAP-10A (1)</td>
<td>600</td>
<td>30,000</td>
<td>Enriched uranium</td>
<td>~431</td>
<td>~1.4</td>
<td></td>
</tr>
</tbody>
</table>
New Horizons Electrical Power System

Stirling Cycle Radioactive Isotope Thermoelectric Generator
Next Time:
Thermal Control Systems

Supplemental Material
Power Management and Distribution

Conversion
- DC/DC converters
- Other

Management (regulation)
- Unregulated
- Regulated
  - Power control
  - Charge control
  - Discharge control
  - Combination

Distribution
- Wiring
- Switches
- ‘Fuses’

Power System Layout

Solar array
SPA (1)
SPA (2)
SPA (3)
SPA (4)

Power transfer device
Short regulator

PCDU

Main bus

Hastelloy

Charge

SUN STATE

MCU

BDR control

BDR switches

Overload detect

Battery pack

Data/control line

Power line

Fortescue
Current-Voltage Characteristic of a Typical Solar Cell

Fortescue