Fundamentals of Space Systems and Space Subsystems

Instructor:

V. L. Pisacane, PhD

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Fundamentals of Space Systems and Space Subsystems

SPACECRAFT POWER

by

V. L. Pisacane, PhD
TOPICS

- Introduction
- Nuclear Reactors
- Radioisotope Generators
- Fuel Cells
- Solar Thermal Dynamic
- Auxiliary Power Units
- Primary Batteries
- Secondary Batteries
- Solar-Orbital Geometry
- Solar Cell Basics
- Solar Arrays
- Power System Control
- Design Principles
- Sample Power System Configurations
INTRODUCTION
Function and Components of Spacecraft Power System

- Power System Functions
  - Supply electrical power to spacecraft loads
  - Distribute and regulate electrical power
  - Satisfy average and peak power demands
  - Condition and convert voltages
  - Provide command and telemetry capability for power system
  - Provide energy storage for eclipse and peak demands
  - Provide power for specific functions. E.g., firing ordinance for mechanism deployment
## INTRODUCTION

Characteristics of Potential Power Sources

<table>
<thead>
<tr>
<th>Technology</th>
<th>Solar Restrictions</th>
<th>Power kW</th>
<th>Secondary Power</th>
<th>Duration</th>
<th>Flight Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Reactor</td>
<td>None</td>
<td>≤ 10</td>
<td>-</td>
<td>&gt; 20 y</td>
<td>Limited</td>
</tr>
<tr>
<td>Radioisotope</td>
<td>None</td>
<td>≤ 1</td>
<td>-</td>
<td>&gt; 20 y</td>
<td>Interplanetary</td>
</tr>
<tr>
<td>Fuel Cells</td>
<td>None</td>
<td>≤ 200</td>
<td>-</td>
<td>Weeks</td>
<td>Crewed Missions</td>
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<tr>
<td>Solar Thermal Dynamic</td>
<td>&lt; 2 AU</td>
<td>≤ 20</td>
<td>Batteries</td>
<td>&lt; 20 y</td>
<td>Not employed</td>
</tr>
<tr>
<td>Auxiliary Power Units</td>
<td>None</td>
<td>&gt; 10</td>
<td>-</td>
<td>hours</td>
<td>Shuttle Hydraulics</td>
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<tr>
<td>Primary Batteries</td>
<td>None</td>
<td>≤ 1</td>
<td>-</td>
<td>&lt; Months</td>
<td>Limited</td>
</tr>
<tr>
<td>Secondary Batteries</td>
<td>&lt; 2 AU</td>
<td>≤ 20</td>
<td>-</td>
<td>&lt; 20 y</td>
<td>Needs Primary Power</td>
</tr>
<tr>
<td>Solar Photovoltaic</td>
<td>&lt; 2 AU</td>
<td>≤ 20</td>
<td>Batteries</td>
<td>&lt; 20 y</td>
<td>Primary</td>
</tr>
</tbody>
</table>
INTRODUCTION
Range of Applications

LOAD POWER (kW)

100
10
1
0.1

HOURS

1 DAY
10 DAYS
MONTHS
YEARS

NUCLEAR THERMIONICS
SOLAR DYNAMIC AND PHOTOVOLTAIC
NUCLEAR THERMIONIC OR SOLAR DYNAMIC
PHOTOVOLTAIC OR IOSTOTPE - THERMEOELECTRIC

CHEMICAL DYNAMIC (APUs)
PRIMARY BATTERIES
FUEL CELL

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NUCLEAR REACTORS
Introductions

- Nuclear reactors can in principle be either fission or fusion reactors

- Fission Reactors
  - Nuclear fission is the reaction in which an atomic nucleus splits, or fissions, into fragments, usually two fragments of comparable mass, with the release of large amounts of energy in the form of heat and radiation
  - Commercial terrestrial reactors and space reactors have been fission based

- Fusion reactor
  - Nuclear fusion is the reaction in which two or more nuclei combine together to form a new element with higher atomic number (more protons in the nucleus) with the release of large amounts of energy in the form of heat and radiation
  - Not currently realizable but has several advantages including higher power output

- Conversion of heat to electricity
  - Thermoelectric or Seebeck effect
    - A static device of 2 dissimilar conductors with ends at different temperatures with one set of ends connected will produce a voltage at the other end
  - Thermionic conversion
    - A static device that converts heats into electricity by boiling electrons from a hot emitter across a small inter-electrode gap to a cooler collector
Thermoelectric Converter
Efficiency ≈ 2-10 percent

Thermionic Converter
Efficiency ≈ 5-15 percent

The Role of Nuclear Power and Nuclear Propulsion in the Peaceful Exploration of Space, IAEA, 2005

http://www.propagation.gatech.edu/ECE6390/project/Fall2010/Projects/group8/power.html
<table>
<thead>
<tr>
<th></th>
<th>USA SNAP-10A</th>
<th>USSR Romashka</th>
<th>USSR BUK</th>
<th>USSR TOPAZ-I</th>
<th>USSR TOPAZ-II</th>
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</thead>
<tbody>
<tr>
<td>Number</td>
<td>1</td>
<td>1</td>
<td>31</td>
<td>2</td>
<td>0</td>
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<tr>
<td>Power, kW$_t$</td>
<td>43</td>
<td>28.2</td>
<td>100</td>
<td>150</td>
<td>135</td>
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<td>Power, kW$_e$</td>
<td>0.58</td>
<td>0.47</td>
<td>3</td>
<td>5</td>
<td>5.5</td>
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<tr>
<td>Fuel</td>
<td>U-ZrH$_x$</td>
<td>UC$_2$</td>
<td>U-Mo</td>
<td>UO$_2$</td>
<td>UO$_2$</td>
</tr>
<tr>
<td>Converter</td>
<td>TE</td>
<td>TE</td>
<td>TE</td>
<td>TI</td>
<td>TI</td>
</tr>
<tr>
<td>Mass Fuel, kg</td>
<td>4.3</td>
<td>30</td>
<td>11.5</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Total Mass, kg</td>
<td>435</td>
<td>450</td>
<td>930</td>
<td>980</td>
<td>1061</td>
</tr>
<tr>
<td>Specific Power, W$_e$/kg</td>
<td>1.3</td>
<td>1.0</td>
<td>3.2</td>
<td>5.1</td>
<td>5.2</td>
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<tr>
<td>Coolant</td>
<td>NaK</td>
<td>Conduction</td>
<td>NaK</td>
<td>NaK</td>
<td>NaK</td>
</tr>
</tbody>
</table>

SNAP = System for Nuclear Auxiliary Power
TE = Thermoelectric
TI = Thermionic
TOPAZ II also known as the Yenisey

U-ZrH$_x$ = Uranium-zirconium hydride
UC$_2$ = Uranium carbide
U-Mo = Uranium-Molybdenum
UO$_2$ = Uranium dioxide
TOPAZ II

The Role of Nuclear Power and Nuclear Propulsion in the Peaceful Exploration of Space, IAEA, 2005

SNAP-10A

Selected Space Nuclear Reactors

1. Cesium vapor supply system
2. Thermionic reactor converter
3. Liquid metal circuit pipeline
4. Reactor shielding
5. Liquid metal circuit expansion tank
6. Radiator
7. Frame structure

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Spacecraft Power - 9
## RADIOISOTOPE GENERATORS
### History of Radioisotope Generator Development

<table>
<thead>
<tr>
<th></th>
<th>GPHS-RTG</th>
<th>MM-RTG</th>
<th>ASRG</th>
<th>ARTG</th>
<th>TPV</th>
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</thead>
<tbody>
<tr>
<td><strong>Availability</strong></td>
<td>Past</td>
<td>Present</td>
<td>In Development</td>
<td>Future</td>
<td>Future</td>
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<td><strong>Electrical Power, BOL ( W_e )</strong></td>
<td>285</td>
<td>125</td>
<td>(~140-150)</td>
<td>(~280-420)</td>
<td>(~38-50)</td>
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<tr>
<td><strong>Heat Power, BOL ( W_t )</strong></td>
<td>4500</td>
<td>2000</td>
<td>(~500)</td>
<td>(~3000)</td>
<td>(~250)</td>
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<tr>
<td><strong>Efficiency, %</strong></td>
<td>6.3</td>
<td>6.3</td>
<td>(~28-30)</td>
<td>~</td>
<td>~</td>
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<tr>
<td><strong>Mass, kg</strong></td>
<td>56</td>
<td>44.2</td>
<td>(~19-21)</td>
<td>(~40)</td>
<td>~7</td>
</tr>
<tr>
<td><strong>Specific Power, ( W_e/kg )</strong></td>
<td>5.1</td>
<td>2.8</td>
<td>(~7-8)</td>
<td>(~7-10)</td>
<td>~6-7</td>
</tr>
<tr>
<td>(^{238}\text{Pu Mass, kg})</td>
<td>7.6</td>
<td>3.5</td>
<td>(~3.2)</td>
<td>(~19.3)</td>
<td>~1.6</td>
</tr>
<tr>
<td><strong>Number GPHS Modules</strong></td>
<td>18</td>
<td>8</td>
<td>2</td>
<td>12</td>
<td>1</td>
</tr>
</tbody>
</table>

**Definitions**

- **ARTG** = Advanced Radioisotope Thermal Generator
- **ASRG** = Advanced Stirling Radioisotope Generator
- **BOL** = Beginning Of Mission
- **GPHS** = General Purpose Heat Source
- **MM** = Multi-Mission
- **RTG** = Radioisotope Thermoelectric Generator
- **TPV** = ThermoPhotoVoltaic
RADIOISOTOPE GENERATORS
Schematics GPHS RTG and MMRTG

Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)
Mass = 43 kg, Diam = 64 cm, Length = 66 cm

General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS RTG)
Mass = 56 kg, Diam = 42.2 cm, Length = 114 cm
## RADIOISOTOPE GENERATORS
### History of US RTGs in Space

<table>
<thead>
<tr>
<th>Year</th>
<th>Program</th>
<th>Mission</th>
<th>RTG Type</th>
<th>No of S/C</th>
<th>No of RTGs</th>
<th>RTG Power, W&lt;sub&gt;e&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961-64</td>
<td>Transit</td>
<td>Navigation</td>
<td>SNAP</td>
<td>5</td>
<td>5</td>
<td>2.7-25</td>
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<td>1969</td>
<td>Nimbus</td>
<td>Meteorology</td>
<td>SNAP</td>
<td>1</td>
<td>2</td>
<td>40</td>
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<td>1969-72</td>
<td>Apollo</td>
<td>Lunar Exploration</td>
<td>SNAP</td>
<td>6</td>
<td>6</td>
<td>70</td>
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<td>1972</td>
<td>Transit</td>
<td>Navigation</td>
<td>SNAP</td>
<td>1</td>
<td>1</td>
<td>30</td>
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<td>1972-73</td>
<td>Pioneer</td>
<td>Interplanetary Science</td>
<td>SNAP</td>
<td>2</td>
<td>8</td>
<td>60</td>
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<tr>
<td>1975</td>
<td>Viking</td>
<td>Mars Science</td>
<td>SNAP</td>
<td>2</td>
<td>4</td>
<td>60</td>
</tr>
<tr>
<td>1976</td>
<td>LES</td>
<td>Communications</td>
<td>MHW-RTG</td>
<td>2</td>
<td>4</td>
<td>160</td>
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<tr>
<td>1977</td>
<td>Voyager</td>
<td>Interplanetary Science</td>
<td>MHW-RTG</td>
<td>2</td>
<td>6</td>
<td>160</td>
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<tr>
<td>1989</td>
<td>Galileo</td>
<td>Jupiter Flyby</td>
<td>GPHS-RTG</td>
<td>1</td>
<td>2</td>
<td>285</td>
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<tr>
<td>1990</td>
<td>Ulysses</td>
<td>Solar Polar Science</td>
<td>GPHS-RTG</td>
<td>1</td>
<td>1</td>
<td>285</td>
</tr>
<tr>
<td>1997</td>
<td>Cassini</td>
<td>Saturn/Titan Science</td>
<td>GPHS-RTG</td>
<td>1</td>
<td>3</td>
<td>285</td>
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<tr>
<td>2006</td>
<td>New Horizons</td>
<td>Pluto/Kyper Science</td>
<td>GPHS-RTG</td>
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<td>1</td>
<td>285</td>
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<td>2011</td>
<td>MSL</td>
<td>Mars Science</td>
<td>MM-RTG</td>
<td>1</td>
<td>1</td>
<td>285</td>
</tr>
</tbody>
</table>

**GPHS** = General Purpose Heat Source  
**LES** = Lincoln Experimental satellite  
**MM-RTG** = MultiMission  
**MSL** = Mars Science Laboratory  
**RTG** = Radioisotope Thermoelectric Generator  
**SNAP** = System for Nuclear Auxiliary Power
RADIOISOTOPE GENERATORS
RTG Degradation in Space and Potential Isotopes

Degradation of RTGs in space

Potential Isotopes for RTGs

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-Life</th>
<th>Specific Power $W_t , g^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stronium-90</td>
<td>29.0 y</td>
<td>0.93</td>
</tr>
<tr>
<td>Cesium-137</td>
<td>30.1 y</td>
<td>0.42</td>
</tr>
<tr>
<td>Cerium-144</td>
<td>284.4 d</td>
<td>25.6</td>
</tr>
<tr>
<td>Polonium-210</td>
<td>136.4 d</td>
<td>141.0</td>
</tr>
<tr>
<td>Plutonium-238</td>
<td>87.7 y</td>
<td>0.56</td>
</tr>
<tr>
<td>Americium-241</td>
<td>432 y</td>
<td>0.11</td>
</tr>
<tr>
<td>Curium-244</td>
<td>18.1 y</td>
<td>2.84</td>
</tr>
</tbody>
</table>

Notice both high half life and specific power of Plutonium-238
Variations in power due to changing aspect with respect to Sun affecting thermoelectric conversion

- ALICE = Ultraviolet imaging spectrometer
- LORRI = Long Range Reconnaissance Imager
- PEPSSI = energetic particle spectrometer
- RALPH = Visible and infrared imager and spectrometer
- REX = Radio Science Experiment
- RTG = Radioisotope Thermoelectric Generator
- SDC = Student Dust Counter
- SWAP = Solar Wind Around Pluto
ASRG Characteristics
- Mass: 32 kg
- Power BOL: ~130-140 kW<sub>e</sub>
- Power degradation ~ 0.8% per year
- Lifetime: 3 y storage + 14 y operations
- Conversion Efficiency: > 27%
- Dimensions: 50 x 50 x 80 cm
- Specific Power: 8.0 W<sub>e</sub>/kg

Stirling Cycle Converter
- The four step cycle is shown below
FUEL CELLS
Introduction

- Fuel cell is similar to a battery but the fuel and oxidizer are stored externally.
- Used primarily on manned missions: Gemini, Apollo, MIR, Shuttle.
- No fuel cells on the ISS.
- Most used ingredients are Hydrogen fuel and Oxygen oxidizer with byproduct of potable water.
- Used to generate high power for limited periods of time.
- Limited by need to store fuel and oxidizer.
- Highly efficient ~ 40-60%.
- High specific power ~ 275 $W_e$ kg$^{-1}$.
- Regenerative fuel cells, produce $H_2$ and $O_2$ from electrolysis of byproduct of $H_2O$. 

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**FUEL CELL**

**Fuel Cell**

---

**Regenerative Fuel Cell**
FUEL CELLS
Shuttle Fuel Cells

- NASA alkaline fuel cell provides electrical power for on-board systems as well as drinking water
- Each of 3 fuel cells is re-startable and reusable up to 2,000 h on line
- Dimensions: 36 cm X 38 X 100 cm
- Mass: 116 kg
- Power: 12 kW_e peak and 7 kW_e continuous
- Specific Energy: 104 W_e kg^{-1}
- Flow rates: O_2 is 2 kg h^{-1} and H_2 is 0.2 kg h^{-1}
- Alkaline fuel cells use an electrolyte of an aqueous (water-based) solution of potassium hydroxide (KOH) retained in a porous stabilized matrix
- Operating temperature is 93 °C

From: http://www.fctec.com/fctec_types_afc.asp

Principles of Alkaline Fuel Cell
A solar dynamic electrical power system was a candidate for Space Station Freedom that had a power requirement of 300 kW$_e$

A possible configuration is illustrated in the figure.

The Sun’s energy is focused by a parabolic concentrator on a receiver that boils a fluid to produce a vapor or heats a gas that drives a turbine that drives an electrical generator to produce electrical power.

No solar dynamic power systems have been flown.

Courtesy of NASA Glenn Research Center
AUXILIARY POWER UNITS (APU)
Introduction

- The Shuttle auxiliary power is hydrazine-fueled and turbine-driven
- Generates mechanical shaft power to drive a hydraulic pump that produces pressure for the orbiter's hydraulic systems
- There are three separate APUs, three hydraulic pumps, and three hydraulic systems
- Provide hydraulics to operate, flight control surfaces, engine gimbals, brakes, and deploy landing gear and retract umbilicals
- Each APU consists of a fuel tank, a fuel feed system, a system controller, an exhaust duct, lube oil cooling system, and fuel/lube oil vents and drains and exhaust ducts

Each APU delivers 10 kW

Image courtesy of NASA
PRIMARY BATTERIES
Introduction

- Primary batteries have nonreversible electrochemistry
- Primary batteries have high energy per unit mass compared to secondary batteries

Applications
  - Supply short burst of power
    - During launch until deployment of solar array
    - Fire pyrotechnic devices, extend booms, etc
  - Low power short duration missions
    - Typically a few weeks to a few months

Examples
  - Lithium-Sulfur Dioxide (Li-SO2) Batteries
    - Galileo Probe,
    - Genesis
    - Mars Exploration Rover (MER
    - Stardust
  - Lithium-Thionyl Chloride (Li-SOCl2) Batteries
    - Deep Space 2 Mars dual probes
    - Mars Pathfinder Sojourner Rover as backup

Typical voltage characteristic

From: MR Patel Spacecraft Power systems
# PRIMARY BATTERIES

## Sample Battery Characteristics and Performance

<table>
<thead>
<tr>
<th>Type</th>
<th>Cell Parameters and Battery Parameters by Mission Application</th>
<th>Nominal Voltage</th>
<th>Specific Energy, Wh/kg</th>
<th>Energy Density, Wh/l</th>
<th>Specific Power, W/kg</th>
<th>Operating Temp. Range, °C</th>
<th>Capacity Loss % Per Year</th>
<th>Mission Life (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag-Zn</td>
<td>Cell</td>
<td>1.81</td>
<td>200</td>
<td>550</td>
<td>1100</td>
<td>0 to +55</td>
<td>60</td>
<td>1</td>
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<tr>
<td></td>
<td>Typical Launch Vehicle</td>
<td>28</td>
<td>119</td>
<td>280</td>
<td>120</td>
<td>5 to +40</td>
<td>60</td>
<td>1</td>
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<tr>
<td>Li-SO₂</td>
<td>Cell</td>
<td>2.9</td>
<td>238</td>
<td>375</td>
<td>680</td>
<td>-40 to +70</td>
<td>&lt;1</td>
<td>9</td>
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<td></td>
<td>Galileo Probe Battery</td>
<td>38</td>
<td>91</td>
<td>145</td>
<td>260</td>
<td>-15 to +60</td>
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<td>Genesis Battery</td>
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<td>400</td>
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<td>MER</td>
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<td>Stardust</td>
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<td>192</td>
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<td>519</td>
<td>-26 to +50</td>
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<td>Li-SOCl₂</td>
<td>Cell</td>
<td>3.2</td>
<td>390</td>
<td>875</td>
<td>140</td>
<td>-30 to - 60</td>
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<td></td>
<td>Sojourner</td>
<td>9</td>
<td>245</td>
<td>515</td>
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<td>-20 to 30</td>
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<td>Deep Impact</td>
<td>33</td>
<td>221</td>
<td>380</td>
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<td>&lt;2.5</td>
<td>4</td>
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<td>DS-2</td>
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<td>128</td>
<td>340</td>
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<td>-80 to +30</td>
<td>&lt;2.5</td>
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<td>200</td>
<td>515</td>
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<td>-20 to +30</td>
<td>&lt;2.5</td>
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<td>Li-BCX</td>
<td>Cell</td>
<td>3.4</td>
<td>414</td>
<td>930</td>
<td>150</td>
<td>-40 to +70</td>
<td>&lt;2</td>
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<td>Astronaut Equipment</td>
<td>6</td>
<td>185</td>
<td>210</td>
<td>115</td>
<td>-40 to +72</td>
<td>&lt;2</td>
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<tr>
<td>Li-CFx</td>
<td>Cell</td>
<td>2.6</td>
<td>614</td>
<td>1050</td>
<td>15</td>
<td>-20 to 60</td>
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<td>Range Safety battery</td>
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<td>167</td>
<td>150</td>
<td>15</td>
<td>-20 to 60</td>
<td>&lt;1</td>
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</table>

Ag Zn=Silver Zinc, Li-SO₂=Lithium Sulfur Dioxide, Li-SOCl₂=Lithium Thionyl Chloride, Li-BCX=Lithium Bromide Complex, Li-CFx=Lithium Carbon Monofluoride

From: R Surampudi, R Bugga, MC Smart, SR Narayanan HA Frank and G Halpert, Overview of Energy Storage Technologies for Space Applications, Jet Propulsion Laboratory, Pasadena, CA 91109

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SECONDARY BATTERIES
Introduction

- Secondary batteries have reversible electrochemistry
- Lower energy density than primary batteries
- Ni-Cd and Ni-H$_2$ suitable for LEO with life > 5 years at 30,000 cycles
- Li-Ion more suitable for GEO with 90 days per year eclipses
- Example SAFT VES 180 – Very high specific energy space cell
  - Lithium ion battery
  - 11 y 60,000 cycles LEO orbit at 20% DOD
  - 18 y 2,000 cycles GEO orbit at 80% DOD
  - Specific energy 175 Wh/kg
  - Nominal voltage 3.6 V
  - Operating temp 0-40°C
# SECONDARY BATTERIES

Sample Battery Characteristics and Performance

<table>
<thead>
<tr>
<th>Technology</th>
<th>Use</th>
<th>No of Batteries &amp; Cells</th>
<th>Ah Rated/actual</th>
<th>Operating Voltage</th>
<th>Specific Energy, Wh/kg</th>
<th>Energy Density, Wh/l</th>
<th>Operating Temp. Range, °C</th>
<th>Design life, Years</th>
<th>Cycle life to Date</th>
<th>Manufacturer</th>
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<td>Ag-Zn</td>
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<td>1.5</td>
<td>130</td>
<td>248</td>
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<td>BST</td>
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<td>Pathfinder Lander</td>
<td>1/18</td>
<td>40/58</td>
<td>27</td>
<td>85</td>
<td>190</td>
<td>-20 to 25</td>
<td>2</td>
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<td>Yardney</td>
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<td>Ni-Cd</td>
<td>Standard 50 Ah</td>
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<td>1.25</td>
<td>31</td>
<td>111</td>
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<td>3</td>
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<td>Gates</td>
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<td>Landsat</td>
<td>3/22</td>
<td>50 / 60</td>
<td>22-36</td>
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<td>61</td>
<td>-20 to 26</td>
<td>3</td>
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<td>MDAC</td>
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<td>TOPEX</td>
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<td>50 / 60</td>
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<td>Super Ni-Cd</td>
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<td>21/24</td>
<td>28</td>
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<td>71</td>
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<td>Landsat 7</td>
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<td>77</td>
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<td>EPI</td>
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<td>MIDEX MAP</td>
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<td>16/17.5</td>
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<td>15/18</td>
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<td>60/70</td>
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<td>3 - 5</td>
<td>50K</td>
<td>JCI/ EPI</td>
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<td>4.0</td>
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<td>Yardney</td>
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<td>MER-Rover</td>
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<td>16-20</td>
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<td>90</td>
<td>250</td>
<td>-20 to 30</td>
<td>3</td>
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<td>Yardney</td>
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</table>

Ag-Zn=Silver Zinc, Ni-Cd=Nickel Cadmium, IPV=Individual Pressure Vessel, CPV=Common Pressure Vessel, SPV=Single Pressure Vessel, Ni-H2=Nickel Hydrogen, Li-ion=Lithium Ion

From: R Surampudi, R Bugga, MC Smart, SR Narayanan HA Frank and G Halpert, Overview of Energy Storage Technologies for Space Applications, Jet Propulsion Laboratory, Pasadena, CA 91109

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SECONDARY BATTERIES
Sample Battery Characteristics and Performance

From MR Patel, Spacecraft Power Systems, CRC Press 2005

Ag Zn=Silver Zinc,
Li-BCX=Lithium Bromide Complex
Li-CFx=Lithium Carbon Monofluoride
Li-ion=Lithium ion
LiMnO2=Lithium Manganese Dioxide
Li-SO2=Lithium Sulfur Dioxide
Li-SOCl2=Lithium Thionyl Chloride
NiH2=Nickel Hydrogen
NiMH=Nickel Metal Hydride

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SECONDARY BATTERIES
Battery Parameters 1/2

- Battery capacity specified in watt-hours (W-h) or amp-hours (A-h)

\[ C_{W-h} = C_{A-h} \times V_{operating} \]

- Battery discharge and charge rates are expressed as fraction of total capacity
  - Charge/Discharge rates expressed as C/n where n is the number of hours to charge or discharge the battery
  - Example: Battery with capacity of 100 A-h is charged at C/2 if charging current is 50 A
  - Charge rates
    - Very Fast \( n < 1 \)
    - Quick \( n \approx 3 \)
    - Standard \( n \approx 10 \)
    - Minimum \( n \approx 20 \)
    - Trickle \( n = 50 \)

  - Greater the charge and discharge rates the shorter the battery life

- Charge efficiency is defined as

\[ \eta_{energy} = \frac{\text{EnergyOutput}}{\text{EnergyInput}} \]

- Cycle life is the number of Charge/Discharge (C/D) cycles the battery can deliver and still meet the minimum required voltage (cut-off voltage)
SECONDARY BATTERIES
Battery Parameters 2/2

- Depth of discharge is defined as
  \[
  \text{DOD} = \frac{C_{A-h \text{ (extracted from fullycharged battery)}}}{C_{A-h \text{ (rated capacity)}}} = \frac{C_{W-h \text{ (extracted from fullycharged battery)}}}{C_{W-h \text{ (rated capacity)}}}
  \]
  - Greater the depth of discharge the shorter the cycle life
- Specific Energy = energy stored per unit of battery mass, W-h-kg\(^{-1}\)
- Energy Density = energy stored per unit of battery volume, W-h-l\(^{-1}\) (per liter)
- State of Charge is defined as
  \[
  \text{SOC} = \frac{C_{A-h \text{ (remaining capacity)}}}{C_{A-h \text{ (rated capacity)}}} = \frac{C_{W-h \text{ (remaining capacity)}}}{C_{W-h \text{ (rated capacity)}}} = 1 - \text{DOD}
  \]
- Required battery capacity is
  \[
  C_{W-h} = \frac{P_r T_r}{(\text{DOD}) N \eta}
  \]
  where
  \[
  C_{W-h} = \text{battery capacity}
  P_r = \text{power required to be drawn from battery}
  T_r = \text{time power is needed}
  \text{DOD} = \text{depth of discharge}
  N = \text{number of batteries}
  \eta = \text{transmission efficiency to load}
  \]
SECONDARY BATTERIES
Operating Characteristics

Charge /Discharge cycle NiH$_2$ battery in LEO

Memory effect in NiCd battery at point M

Battery life as function of DOD and Temperature

Charge efficiency versus state-of-charge NiH$_2$ battery

Figures from MR Patel, Spacecraft Power Systems, CRC Press 2005
SECONDARY BATTERIES
Sample Batteries

From: NASA Glenn research Center
# SECONDARY BATTERIES

## Sample Battery Configurations

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Launched</th>
<th>Battery Characteristics</th>
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</thead>
<tbody>
<tr>
<td>LANDSAT-7</td>
<td>April 1999</td>
<td>2 Batteries (17 Cells/Battery, 50 Ah Ni/H(_2))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LEO, 5 years (less than 30,000 cycles)</td>
</tr>
<tr>
<td></td>
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<td>DOD 17%, 0 to 10°C</td>
</tr>
<tr>
<td>EOS Terra</td>
<td>December 1999</td>
<td>2 Batteries (54 cells/battery, 50 Ah NiH(_2))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LEO, 5 years, &lt; 30,000 cycles</td>
</tr>
<tr>
<td></td>
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<td>DOD 30% -5 to 10°C</td>
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<tr>
<td>TDRS-H</td>
<td>June 2000</td>
<td>1 Battery (3 8-Cell Packs and 1 5-Cell Pack/Battery, 110 Ah Ni/H(_2))</td>
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<tr>
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<td>GEO, 15 years, DOD 73% assuming 3 failed cells, 5°C</td>
</tr>
<tr>
<td>EOS PM-1 Aqua</td>
<td>May 2002</td>
<td>1 Battery (24 Cells/Battery, 160 Ah Ni/H(_2))</td>
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<tr>
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<td>LEO, 6 years, &lt;35,000 cycles</td>
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<tr>
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<td></td>
<td>DOD 30%, 0 to 10°C</td>
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<tr>
<td>POES L,M</td>
<td>September 2000-June 2002</td>
<td>3 Batteries per spacecraft (17 Cells/Battery, 40 Ah Ni/Cd)</td>
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<td>LEO/Polar, 2 years (Design), 3 years (Goal), DOD 0.21%, 5°C</td>
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<tr>
<td>HST</td>
<td>2003 Battery Change-out</td>
<td>6 Batteries (22 Cells/Battery, 80 Ah Ni/H(_2))</td>
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<td>Servicing Mission 4</td>
<td>LEO, 5 years (less than 32,000 cycles), DOD &lt; less 10%, -5 to 5°C</td>
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</tbody>
</table>

From: DL Britton and TB Miller, Battery Fundamentals and Operations, NASA Glenn Research Center, April 2000
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