Assessment of Power Conversion and Energy Storage Technologies for Future Space Science Missions

S. Surampudi, D. Rapp, J. Cutts and S. Khanna
Jet Propulsion Laboratory

Space Power Workshop
April 21, 2005
Outline

• Background
• Radioisotope Power Source Technology
• Solar Cell and Array Technology
• Energy Storage Technology
• Summary
Power Technology Study Objectives

• NASA-Code S requested JPL to assess and identify advanced power source and energy storage technologies needed to enable and enhance the capabilities of future NASA Space Science missions (beyond 2010)
  – Radioisotope Power Source Technologies
  – Solar Cells/Arrays
  – Energy Storage Technologies

• Recommend technology programs that are critical for future NASA Space Science missions and prepare technology road maps and investment strategies.

The assessment studies have been co-sponsored by the Director for Technology, Office of Space Science, the Solar System Exploration Division and the Mars Exploration Program.
Space Science Missions

Solar System

Mars Exploration

Sun Earth Connection

Origins
Solar System Exploration Mission Concepts - Far Term

- Venus Sample Return
- Europa Surface and Subsurface
- Comet Nucleus Sample Return
- Neptune/Triton Orbiter
- Giant Planet Deep Probes
- Titan Organic Explorer
Mars Exploration Mission Concepts- Far Term
# Power Technology Assessment Status

<table>
<thead>
<tr>
<th>Power Technology</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Cell and Array Technology</td>
<td><strong>Completed</strong> - Report published in December 2003 Report #JPL D-24454, Rev. A</td>
</tr>
<tr>
<td>Energy Storage Technologies</td>
<td><strong>Completed</strong> – Report published in March 2005</td>
</tr>
</tbody>
</table>
Assessment of Advanced Radioisotope Power System Conversion Technologies
Advanced Radioisotope Power System Conversion Technologies Review Team

- Rao Surampudi, JPL, Chairperson.
- Lisa Herrera, DOE
- Bob Carpenter, OSC (DOE support contractor)
- Robert Wiley, BA&H (DOE support contractor)
- Lee Mason, GRC
- Mohamed El-Genk, UNM
- Jack Mondt, JPL
- Donald Rapp, JPL
- Bill Nesmith, JPL
Past NASA Missions Using RPS – Including Moon and Mars

- Apollo
- Viking
- Voyager
- Galileo
- Ulysses
- Cassini

Since 1961, 40 RTGs have been used on 22 US space systems.
Potential Future RPS-Powered Missions

Near-term (2006 to 2015)
- Pluto-Kuiper Belt Explorer (launch ~2006)
- Mars Science Laboratory (launch by 2009)
- 2nd New Frontiers Mission (launch by 2010)
- Mars Scout Missions (launches 2011 & 2015)
- Solar Probe (launch ≥2012)

Vision Missions (≥2015)
- Medium Size (New Frontiers)
  - Trojan/Centaur Reconnaissance Flyby
  - Asteroid Rover/Sample Return
  - Io Observer
  - Ganymede Observer
- Flagship Class
  - Europa Lander
  - Titan Explorer
  - Neptune-Triton Explorer
  - Uranus Orbiter with Probes
  - Saturn Ring Observer
  - Venus Sample Return
  - Mercury Sample Return
  - Comet Cryogenic Sample Return
  - Interstellar Probe
Summary of Future Mission Needs For Radioisotope Power Systems

- Need 100 Watt Class RTG Modules
  - Future missions are smaller in size and require lower power
- Low Mass
  - High Specific Power 8-10 W/kg (2 X SOA SiGe RTGs)
- High Efficiency 13-25 % (2-4 X SOA SiGe RTG’s)
  - Uses Less Radioisotope Material
- Long Life
  - 14 Years - Enable Deep Space Missions
- Low EMI & Vibration
  - Enable use of High Precision Cameras and Magnetometers
- Function in CO₂ and other planetary Atmospheres
  - Enable Long Duration Mars and other planetary surface missions (> 2 earth years)
SOA Radioactive Power Source
Characteristics of SOA GPHS- RTG

Performance Characteristics

- Power: 285 W (BOL)
- Mass: 56 kg
- Efficiency: 6.5%
- Specific Power: 5.1 W/kg
- Life: > 20 years demonstrated
- Hot Side Temp.: 1273 K
- Cold Side Temp.: 573 K

Advantages

- Long operational life
- High reliability

Limitations

- Low Specific Power
- Low Efficiency (Requires more Pu)
Advanced RPS Technologies

- Alkali Metal Thermal to Electric (AMTEC)
- Advanced Thermoelectric (TE)
- Advanced Stirling Engine Converter (SEC)
- * Thermal Acoustics (TA)
- * Thermionics (TI)
- * Thermophotovoltaics (TPV)

* Early stages of Development
Performance Characteristics of Advanced Radioisotope Power Sources

<table>
<thead>
<tr>
<th>Characteristics*</th>
<th>Si-Ge RTG</th>
<th>STEC</th>
<th>AMTEC</th>
<th>SEC(1.0)</th>
<th>SEC(1.1)</th>
<th>SEC(2.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Temperature (K)</td>
<td>1273</td>
<td>1200</td>
<td>1150</td>
<td>920</td>
<td>920</td>
<td>920</td>
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<tr>
<td>Cold Temp(K)</td>
<td>573</td>
<td>500</td>
<td>600</td>
<td>350</td>
<td>350</td>
<td>350</td>
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<tr>
<td>Efficiency (%)</td>
<td>6.5</td>
<td>15</td>
<td>16.2</td>
<td>23</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Specific Power (W/kg)</td>
<td>4.5</td>
<td>10.2</td>
<td>8.8</td>
<td>4.1</td>
<td>6.0</td>
<td>7.5</td>
</tr>
<tr>
<td>System Mass (100 W)</td>
<td>31.2</td>
<td>14</td>
<td>13.6</td>
<td>27</td>
<td>20</td>
<td>16</td>
</tr>
</tbody>
</table>

STC, AMTEC and SEC can be designed to function in both deep space vacuum and planetary environments.
Recommendations

NASA to initiate a program to develop Advanced-Stirling, AMTEC and Segmented -TE converter technologies for missions beyond > 2010.

- Establish performance gates and monitor technology progress by the same independent review board
- Down select after two to three years the most promising technologies that meet the requirements for the greatest number of future NASA ESS, SEC and MEP missions.
- Develop selected converter technologies to TRL 5
- Develop advanced radioisotope power system from TRL 5 to TRL 6 with funds from flight project to meet its specific requirements.
Solar Cell and Array Technology Assessment
Solar Cell and Array Technology Assessment Review Team

NASA-JPL
- Rao Surampudi – Chairman
- Donald Rapp
- Paul Stella/ Nick Mardesich
- Bill Nesmith

NASA GRC
- Sheila G. Bailey
- Henry B. Curtis
- Mike Piszczor,

NASA-GSFC
- Ed Gaddy,

DOD/DOE
- Dean Marvin, Aerospace Corp.
- Larry Kazmerzki, DOE-NREL
Applications of Photovoltaic Power Systems

Used on several space science missions launched to date:

- Near sun: Venus, Mercury…
- Outbound: Mars, Asteroids…
- Earth: Earth observing
- SEP: Deep Space 1…
- Surface: MERs, Pathfinder
Solar Array Environments for Code-S Missions

Military, Com, NASA Code Y

NASA Code S

- High solar intensity
- High temperature
- Electrons, protons, Atomic oxygen, Charging effects (fields/particles missions)
- Low-intensity
- Low temperatures
- Jupiter radiation belt
- Dust contamination
Unique Capabilities Needed for SSE Missions
SEP to Comets and Asteroids

High array specific power reduces total spacecraft wet mass

**Unique Capabilities Needed:**

**Arrays with:**

- High power scalable to ~ 80 kW
- High Voltage
- High Specific Power (> 400 W/kg)
- Low Cost – $0.5M/kW
- LILT Performance to 5 AU

**Current State of Practice**

- Power ~ 7 kW
- Voltage ~ 100 V
- Specific Power ~ 100 W/kg
- Cost ~ $2M/kW
- LILT to 2 AU
Solar Array Needs for Mars Exploration

Mars Surface Missions

SOLAR ARRAY POWER DENSITY

- Solar array area on rovers is very limited
- High power density (W/m²) is critical need
  - Currently 130 W/m² in 2003
  - Need 220 W/m² by 2010

EXTENDED OPERATING LIFE

- Need extended operating lifetime capability of solar arrays in dusty environment
  - Currently 90-100 sols
  - Need is > 670 sols (1 Martian year)
Solar Array Needs for SEC Near-Sun Missions
High Temperature Arrays

SEC Theme Plans Near Solar Missions

<table>
<thead>
<tr>
<th>Mission</th>
<th>Priority</th>
<th>Suns</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current SOA</td>
<td>---</td>
<td>10</td>
<td>2003</td>
</tr>
<tr>
<td>Sentinels</td>
<td>enhancing</td>
<td>1 - 11</td>
<td>2008</td>
</tr>
<tr>
<td>Telemachus</td>
<td>enhancing</td>
<td>.03 - 25</td>
<td>2010</td>
</tr>
<tr>
<td>Telemachus</td>
<td>enabling</td>
<td>1 - 25</td>
<td>2010</td>
</tr>
<tr>
<td>PASO</td>
<td>enabling</td>
<td>1 - 35</td>
<td>2015</td>
</tr>
</tbody>
</table>

**Need:**
- Operate at 0.2 AU or less
- Operate at 400 to 450 °C
- Additional benefit for LILT tolerance

**Current SOA:**
- Partly fill array with reflectors, tilt from sun
- Operate at 120°C at 0.3 au
- Vulnerable to loss of attitude control
- Reduced power level

Array reaches ~ 450°C at 0.2 AU
Solar Array Needs for Earth Orbital Missions

SEC Magnetospheric Missions:
• Electrostatically Clean Arrays

All Earth Orbital Missions (Codes S, Y,...)
• High Specific Power Arrays
Unique Solar Array Needs for Space Science Missions

• **Solar System Exploration Program**
  – Driving Missions: Comet and Asteroid and Outer Planetary Missions using Solar Electric Propulsion
  – Unique Needs
    • High power and low cost solar arrays
    • High specific power (watts/kg) arrays
    • Solar arrays that can operate in Low Intensity & Low Temperature (LILT) conditions

• **Mars Exploration Program**:
  – Driving Missions: Mars Surface Missions
  – Unique Needs
    • Arrays with high power per unit area (watts/m²)
    • Long-life arrays in the dusty environment

• **Sun-Earth Connection Program**
  – Driving Missions: Near-Solar Missions (Telemachus, PASO, Sentinels),
  – Unique Needs
    • Arrays that can operate at solar fluxes
    • Arrays that can function at high and low solar fluxes

• **Earth Orbital Missions**
  – High Specific Power Arrays
  – Electrostatically Clean Arrays

**Space Science Missions have Unique Solar Array Needs**
SOA Solar Cells & Arrays-Overview

• Solar Cells
  – High efficiency Silicon and Multi Junction Solar Cells are presently being used in many space missions

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Efficiency Si Cells</td>
<td>16 %</td>
</tr>
<tr>
<td>Multi Junction Solar Cells</td>
<td>26.5%</td>
</tr>
</tbody>
</table>

• Solar Arrays
  – Body mounted, rigid panel and flexible deployable arrays are currently being used in many spacecraft.
  – These arrays are mostly suitable for low–medium power (0.5-5 kW) applications

<table>
<thead>
<tr>
<th>Array Type</th>
<th>Specific Power (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Panel Array</td>
<td>30-40 (3 J)</td>
</tr>
<tr>
<td>Flexible Fold Out Arrays</td>
<td>30-50 (Si)</td>
</tr>
<tr>
<td>Concentrator Arrays</td>
<td>30-60</td>
</tr>
</tbody>
</table>

Performance of SOP Solar Cells and Arrays is Inadequate for Future Code-S Missions
Status of Advanced Solar Cells & Arrays

• Solar Cells
  – Majority of the advanced solar cell technology programs are focused on improving cell efficiency and lowering the cost of the cells
  – Improved Triple Junction solar cells (28%) are in testing and qualification stage
  – Four Junction solar cells with a projected 35% efficiency are under development
  – Thin film cells are being scaled up to large sizes with >10% efficiency
  – Limited work on Mars Cells, LILT cells & high Temperature Cells

• Solar Arrays
  – Several low mass arrays with a projected specific power goal of 100-150 W/kg are in various stages of development (TRL 2-4)
    • These include: Ultraflex; Square Rigger; Inflatable boom deployed arrays; Advanced concentrator array
Advanced Solar Cell Technologies Under Development

**Multi Junction Crystalline Cell**
Status: 30%
Goal: 39%

**Thin Film Triple a-Si Cell**
10-12%, on SS substrate
7.5 on polyimide

**Si-C Cells:**
Feasibility explored
GaInP Cells: ~ 5% at 450 C,
Goal 11% at 450 C

**Quantum Dot Solar Cells**
Status: Materials development
Goal: > 40%

**Thin Film Cu(In,Ga)S₂ Cell**
Status: (9-10%)
Goal: 20%

**AM0 Solar Spectrum**
Pin = 1367 W/m²

**Low Eg Material (1.05 eV)**

**GaAs (1.42 eV)**

**Ge (0.67 eV)**

Substrate
A Glimpse Into Future Array Designs

**UltraFlex**

**Product Performance Targets:**
- Specific Power*: 150-300 W/kg
- Stowage volume*: 30-70 kW/m^3
- Status: 100 W/kg

**CellSaver**

**Product Performance Targets:**
- Specific Power*: 100-120 W/kg
- Stowage volume*: 10-15 kW/m^3
- Status: 60 W/kg

**SquareRigger**

**Product Performance Targets:**
- Specific Power*: 100-300 W/kg
- Stowage volume*: 25-45 kW/m^3
- Status: Critical components fabricated

**FTFPV Solar Array**

**Product Performance Targets:**
- Specific power: 200-450 W/kg (10-15% FTFPV)
- Stowage volume: ~25 kW/m^3
- Status: Module development & testing, in progress
Summary of Recommendations

Recommendations:

• Develop advanced cells (high efficiency cells, LILT cells, Mars Cells, high temperature cells).
  – Driving Missions: Outer Planet & Comet/Asteroid SEP Missions, Mars Surface Missions, SEC Near Sun missions, Earth & Mars Orbital Missions
  – Partner with AFRL to develop high efficiency solar cells and thin film cells

• Develop advanced arrays (high power & low mass arrays, long life Mars arrays, high temperature arrays).
  – Driving Missions: Outer Planet & Comet/Asteroid SEP missions, Mars Surface Missions, SEC Near Sun missions, Earth & Mars Orbital Missions

• Need to space qualify high power arrays (80 kW) for Solar Electric Propulsion missions (beyond NMP ST-8, 7 kW).
## Performance Parameter Targets - Cells

<table>
<thead>
<tr>
<th>Mission Type</th>
<th>2003</th>
<th>2006</th>
<th>2010</th>
<th>2015</th>
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<tbody>
<tr>
<td><strong>SSE SEP Missions</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>High Efficiency Cells</td>
<td>27</td>
<td>30</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Efficiency at 1 AU</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LILT-Resistant Cells</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>45</td>
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<tr>
<td>Efficiency at 3-5 AU</td>
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<tr>
<td>Thin-Film Cells</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
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<tr>
<td>Efficiency (large scale)</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Mars Surface Missions</strong></td>
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<tr>
<td>Mars Optimized Cells</td>
<td>24</td>
<td>29</td>
<td>34</td>
<td>38</td>
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<tr>
<td>Efficiency On Mars</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>SEC Near-Sun Missions</strong></td>
<td></td>
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<tr>
<td>High Solar Flux Cells</td>
<td>8</td>
<td>11</td>
<td>25</td>
<td>35</td>
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<tr>
<td>Solar Flux (suns)</td>
<td></td>
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</table>
### Performance Parameter Targets - Arrays

<table>
<thead>
<tr>
<th>Missions</th>
<th>Capabilities</th>
<th>Parameter</th>
<th>2003</th>
<th>2006</th>
<th>2010</th>
<th>2015</th>
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<tr>
<td>SSE SEP Missions</td>
<td>High Power, Low Mass, Lower Cost Arrays</td>
<td>Array Power (kW) at 1 AU</td>
<td>3</td>
<td>7</td>
<td>40</td>
<td>&gt;40</td>
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<tr>
<td></td>
<td></td>
<td>Specific Power @ 1 AU (W/kg)</td>
<td>60</td>
<td>175</td>
<td>225</td>
<td>300</td>
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<tr>
<td></td>
<td></td>
<td>Array Cost ($M/kW)</td>
<td>1</td>
<td>0.9</td>
<td>0.7</td>
<td>0.4</td>
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<tr>
<td>Mars Surface Missions</td>
<td>Arrays with Mars Cells</td>
<td>Power Density (W/m^2)</td>
<td>130</td>
<td>160</td>
<td>175</td>
<td>190</td>
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<tr>
<td></td>
<td>Array Dust Mitigation</td>
<td>Operating Life (Sols)</td>
<td>100</td>
<td>200</td>
<td>670</td>
<td>1000</td>
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<tr>
<td>SEC Near-Sun Missions</td>
<td>High Solar Flux Arrays</td>
<td>Solar Flux (suns)</td>
<td>8</td>
<td>11</td>
<td>25</td>
<td>35</td>
</tr>
</tbody>
</table>
Assessment of Energy Storage Technologies
Energy Storage Review Team

NASA/JPL
- Jack Mondt, Chair
- Subbarao Surampudi
- Gerald Halpert, Sec'y
- Donald Rapp

NASA/GRC
- Michelle Manzo
- Ken Burke
- Fred Wolff

NASA/GSFC
- Gopalakrishna Rao

NASA/JSC
- Bob Bragg

DOD/DOE
- Ed Plichta, Army CECOM
- Steve Vukson, AF AFRL
- Valerie Browning, DARPA
- George Methlie, CIA
- Robert Sutton, DOE/Argonne

• Consultants
- Richard Marsh, AF Ret.
- Robert Savinall, Case Western Res. Univ.
Energy Storage Systems: Past Applications

- Mars Path Finder
- Cassini Probe
- Stardust
- Hubble
- Spirit & Opportunity
- MGS

Energy storage systems have been used in 99% of the robotic space missions launched since 1960.
Energy Storage Needs of Code S Missions

Military, Com, NASA Code Y

NASA Code S

- High temperature
- Long Cycle Life
- Low Mass/Volume

- Low Temperature Perf.
- Radiation Tolerance
- Long Life
- Low Mass
- Low Volume
## Energy Storage Technology Needs of Next Decadal SSE Missions

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer planetary landers/probes (Battery powered)</td>
<td>• JIMO Lander</td>
<td>• Low temp operation (&lt; -100°C)</td>
<td>Primary</td>
<td>Enabling</td>
</tr>
<tr>
<td></td>
<td>• Europa Lander</td>
<td>• Long life (&gt; 10 years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Neptune probes</td>
<td>• Radiation resistance (5-20 Mrads)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Giant planet atmospheric deep probes</td>
<td>• Low mass &amp; volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer planetary landers/probes (RPS powered)</td>
<td>• JIMO Lander</td>
<td>• Long life (&gt; 10 years)</td>
<td>Rechargeable</td>
<td>Enabling/Enhancing</td>
</tr>
<tr>
<td></td>
<td>• Europa Lander</td>
<td>• Radiation resistance (5-20 Mrads)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Neptune probes</td>
<td>• Low mass &amp; volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner planetary landers</td>
<td>• Venus sample return</td>
<td>• High temp. Operation (475°C)</td>
<td>Primary</td>
<td>Enabling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Low mass &amp; volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer planetary orbiters/fly-by RPS powered</td>
<td>• JIMO</td>
<td>• Long life (&gt; 20 years)</td>
<td>Rechargeable</td>
<td>Enhancing</td>
</tr>
<tr>
<td></td>
<td>• Neptune/Triton</td>
<td>• Radiation resistance (5-20 M Rads)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Ultra low temperature, long life & radiation resistant primary batteries for outer planetary probes
- Long life & radiation tolerant rechargeable batteries for outer planetary orbiter/fly-by missions
- High temperature primary batteries for inner planetary probes
## Energy Storage Technology Needs of Next Decadal Mars Missions

<table>
<thead>
<tr>
<th>Mission Type</th>
<th>Mission</th>
<th>Needs*</th>
<th>Energy Storage Type</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbiters</td>
<td>Mars Telecom</td>
<td>• Long cycle life (30K @ 30% DoD)</td>
<td>Rechargeable</td>
<td>Enhancing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Low mass &amp; volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Powered Landers &amp; Rovers</td>
<td>• MER follow-ons</td>
<td>• Low mass (&gt;120 Wh/kg)</td>
<td>Rechargeable</td>
<td>Enabling/Enhancing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Low temp. Operation (-60°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Mars Sample Return</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RPS Powered Rovers</td>
<td>MSL follow on</td>
<td>• Long life</td>
<td>Rechargeable</td>
<td>Enhancing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Radiation tolerance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor Networks</td>
<td>Scouts</td>
<td>• Low temp. (-80°C) operational capability</td>
<td>Primary</td>
<td>Enabling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Low mass and volume</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Long cycle life & high specific energy rechargeable batteries for Mars orbiters
- High specific energy and low temperature, rechargeable batteries for solar powered landers/rovers
- Low temperature primary batteries for Mars surface probes/sensor networks
# Decadal Energy Storage Technology Needs of SEC Missions

<table>
<thead>
<tr>
<th>Program</th>
<th>Mission Type</th>
<th>Missions</th>
<th>Capability Need</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEC Program</td>
<td>Missions to Inner Planets &amp; Sun</td>
<td>PASO, Sentinel, Solar</td>
<td>High Temperature Primary Batteries</td>
</tr>
<tr>
<td></td>
<td>Outer Planetary Missions</td>
<td>Neptune Orbiter</td>
<td>Long Life, Low Mass, Radiation Resistance Rechargeable Batteries</td>
</tr>
</tbody>
</table>

- Long life & radiation tolerant rechargeable batteries outer planetary orbiter /fly-by missions
- High temperature primary batteries for inner planetary missions
Summary of Energy Storage Technology Needs of NASA Code S Missions

1. Low temperature primary (<-100°C) and rechargeable (<-60°C) batteries for planetary probes and Mars surface missions

2. High temperature batteries (> 475 °C) for inner planetary missions

3. Long calendar life (>15 years), high specific energy (>120 Wh/kg) & radiation tolerant rechargeable batteries for outer planetary missions

4. Long cycle life (>30,000 cycles) and high specific energy (>120 Wh/kg) rechargeable batteries for Mars and earth orbital SEC, SEU & origins missions

5. High specific energy primary batteries (>500 Wh/kg) for comet/asteroid probes
SOP Aerospace Batteries

Primary Batteries

- Li-SO$_2$ MER Battery
- Li-SOCl$_2$ Pathfinder Lander Battery

Rechargeable Batteries

- Ag-Zn Battery
- Standard Ni-Cd Solar Max Battery
- CPV Ni-H$_2$ Battery
- Odyssey 2
- Li-Ion Battery
- MER Rover
## Characteristics of SOP Primary Batteries

<table>
<thead>
<tr>
<th>Type</th>
<th>Application</th>
<th>Mission</th>
<th>Specific Energy, Wh/kg (b)</th>
<th>Energy Density, Wh/l (b)</th>
<th>Operating Temp. Range, °C</th>
<th>Mission Life (yrs)</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-SO₂</td>
<td>Cell</td>
<td>Galileo Probe, Genesis SRC, MER Lander, Stardust SRC</td>
<td>238</td>
<td>375</td>
<td>-40 to 70</td>
<td>&lt;10</td>
<td>Voltage Delay</td>
</tr>
<tr>
<td></td>
<td>Battery</td>
<td>Li-SO₂ Battery Cell</td>
<td>90-150</td>
<td>130-180</td>
<td>-20 to 60</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Li-SOCl₂</td>
<td>Cell</td>
<td>Sojourner, Deep Impact, DS-2, Centaur Launch batteries</td>
<td>390</td>
<td>878</td>
<td>-30 to -60</td>
<td>&gt;5</td>
<td>Severe voltage delay</td>
</tr>
<tr>
<td></td>
<td>Battery</td>
<td>Li-SOCl₂ Battery Cell</td>
<td>200-250</td>
<td>380-500</td>
<td>-20 to 30</td>
<td>&lt; 5</td>
<td></td>
</tr>
<tr>
<td>Li-CFx</td>
<td>Cell</td>
<td>Li-CFx Cell</td>
<td>614</td>
<td>1051</td>
<td>-20 to 60</td>
<td></td>
<td>Poor power capability</td>
</tr>
</tbody>
</table>

### Limitations
- Moderate specific energy (100-250 Wh/kg)
- Limited operating temp range (-40 C to 70°C)
- Radiation tolerance poorly understood
- Voltage delay
## Characteristics SOP Rechargeable Batteries

<table>
<thead>
<tr>
<th>Technology</th>
<th>Mission</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</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag-Zn</td>
<td>Pathfinder Lander</td>
<td>100</td>
<td>191</td>
<td>-20 to 25</td>
<td>2</td>
<td>100</td>
<td>Electrolyte Leakage Limited Life</td>
</tr>
<tr>
<td>Ni-Cd</td>
<td>Landsat, TOPEX</td>
<td>34</td>
<td>53</td>
<td>-10 to 25</td>
<td>3</td>
<td>25-40K</td>
<td>Heavy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Poor Low Temp. Perf.</td>
</tr>
<tr>
<td>Super Ni-Cd</td>
<td>Sampex Battery, Image</td>
<td>28-33</td>
<td>70</td>
<td>-10 to 30</td>
<td>5</td>
<td>58K</td>
<td>Heavy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Poor Low Temp. Perf.</td>
</tr>
<tr>
<td>IPV Ni-H₂</td>
<td>Space Station, HST, Landsat 7</td>
<td>8-24</td>
<td>10</td>
<td>-10 to 30</td>
<td>6.5</td>
<td>&gt;60K</td>
<td>Heavy, Bulky</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Poor Low Temp. Perf.</td>
</tr>
<tr>
<td>CPV Ni-H₂</td>
<td>Odyssey, Mars 98 MGS, EOS Terra Stardust, MRO</td>
<td>30-35</td>
<td>20-40</td>
<td>-5 to 10</td>
<td>10 to 14</td>
<td>50 K</td>
<td>Heavy, Bulky</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Poor Low Temp. Perf.</td>
</tr>
<tr>
<td>SPV Ni-H₂</td>
<td>Clementine, Iridium</td>
<td>53-54</td>
<td>70-78</td>
<td>-10 to 30</td>
<td>10</td>
<td>&lt;30 K</td>
<td>Heavy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Poor Low Temp. Perf.</td>
</tr>
<tr>
<td>Li-Ion</td>
<td>MER-Rover</td>
<td>90</td>
<td>250</td>
<td>-20 to 30</td>
<td>1</td>
<td>&gt;500</td>
<td>Limited Life</td>
</tr>
</tbody>
</table>

### Limitations of Ni-Cd & Ni-H₂ batteries:
- Heavy and bulky
- Limited operating temp range (-10°C to 30°C)
- Radiation tolerance poorly understood.
Adv. Energy Storage Technologies
Under Development

The Lithium Polymer Battery Concept

Li solid state Batteries

Flywheel System Schematic

PEM Fuel Cells

Regenerative Fuel Cells
Characteristics of Advanced Rechargeable Batteries

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>SOP Ni-H₂</th>
<th>Li-Ion with liquid electrolyte</th>
<th>Li-Solid Polymer Electrolyte*</th>
<th>Li-Solid Inorganic Electrolyte*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology Readiness Level</td>
<td>10</td>
<td>5-9</td>
<td>3</td>
<td>1-2</td>
</tr>
<tr>
<td>Specific energy (Wh/kg)</td>
<td>30-40</td>
<td>100-150</td>
<td>&gt;200</td>
<td>&gt;200</td>
</tr>
<tr>
<td>Energy density (Wh/l)</td>
<td>40-50</td>
<td>200-300</td>
<td>300-450</td>
<td>&gt;300</td>
</tr>
<tr>
<td>Cycle life</td>
<td>60,000</td>
<td>1500</td>
<td>1500</td>
<td>&gt;10,000</td>
</tr>
<tr>
<td></td>
<td>(at 30% DOD)</td>
<td>(at 100% DOD)</td>
<td>(at 100% DOD)</td>
<td>at 100% DOD</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-5-30 C</td>
<td>-60 to 80 C</td>
<td>0-80 C</td>
<td>0-80 C</td>
</tr>
<tr>
<td>Self discharge rate</td>
<td></td>
<td>1% / month</td>
<td>0.25% / month</td>
<td>0.1% month</td>
</tr>
<tr>
<td>Shape factor /packing eff</td>
<td>Poor</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
</tbody>
</table>
Characteristics of Fuel Cells

- Gemini 1962-1968
- Apollo 1966-1978
- Shuttle, 1981-current
- Future Programs

Specific Power, W/kg

- Early PEM Fuel Cell
- Alkaline Fuel Cell
- Gen II Alkaline Fuel Cell
- Advanced PEM Fuel Cell (Proposed)
Recommendations

• Develop advanced primary and rechargeable battery technologies to enable future space science missions
  – High specific energy and long-life rechargeable batteries for Mars and earth orbital missions (long cycle life) and outer planetary missions
  – Low temperature rechargeable Li-Ion batteries ( -80 C) to enable/enhance the capabilities of solar powered in-situ exploration missions
  – Low temperature lithium primary batteries ( < -100 C ) to enable/enhance the capabilities of planetary probes and in-situ exploration missions.

• Conduct a study to evaluate competing high temperature rechargeable and primary battery technologies to determine their value in enabling high-performance future missions (surface and atmospheric) to Venus

• Establish a test and validation program to demonstrate the electrical performance, life capabilities, and identify problems of advanced energy storage technologies.

• Work with AFRL and other DoD agencies to transition advanced energy storage technologies to industry for technology maturation and mission insertion.
# Long Life Rechargeable Battery Performance Targets

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Ni-H2 Present State of Practice</th>
<th>Lithium Technology Present State of Practice</th>
<th>Goal 5 years</th>
<th>Goal 10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Energy (Wh/kg)</td>
<td>30</td>
<td>100</td>
<td>120</td>
<td>200</td>
</tr>
<tr>
<td>Energy Density (Wh/liter)</td>
<td>10</td>
<td>200</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>Cycle Life at 30% DOD *</td>
<td>50,000</td>
<td>10-15,000</td>
<td>30,000</td>
<td>50,000</td>
</tr>
<tr>
<td>Calendar Life (years)</td>
<td>15</td>
<td>3</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

* DOD = Depth-of-discharge
# Low Temperature Rechargeable Battery Performance Targets

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Lithium Ion Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific energy at 0°C (Wh/kg)</td>
<td>Present State-of-Practice</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Life Time (yrs)</td>
<td>5 yrs</td>
</tr>
<tr>
<td>Cycle Life (# of cycles) (80%DOD)</td>
<td>&gt; 500</td>
</tr>
<tr>
<td>Low Temperature Performance</td>
<td></td>
</tr>
<tr>
<td>Specific Energy at –20°C</td>
<td>70</td>
</tr>
<tr>
<td>Specific Energy at –40°C</td>
<td>40</td>
</tr>
<tr>
<td>Specific Energy at –60°C</td>
<td>0</td>
</tr>
<tr>
<td>Specific Energy at –80°C</td>
<td>0</td>
</tr>
<tr>
<td>Discharge rate (hours)</td>
<td>&gt;10</td>
</tr>
</tbody>
</table>
## Low Temperature Primary Battery Performance Targets

<table>
<thead>
<tr>
<th>Primary Energy Storage Characteristics</th>
<th>Present State of Practice</th>
<th>Goal (5 years)</th>
<th>Goal (10 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Energy at 0°C (Wh/kg)</td>
<td>250</td>
<td>400</td>
<td>600</td>
</tr>
<tr>
<td>Specific Energy at –40°C (Wh/kg)</td>
<td>100</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>Specific energy at –80°C (Wh/kg)</td>
<td>50</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Discharge rate (hrs)</td>
<td>&gt; 20</td>
<td>&gt; 20</td>
<td>&gt; 20</td>
</tr>
</tbody>
</table>
Acknowledgments

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