Assessment of Space Solar Power Technologies for Next Decadal Planetary Science Missions

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Study Objectives
Solar Cell/Array Technology Assessment

• Review the space solar power system needs of future planetary science missions

• Assess the capabilities and limitations of state of practice space solar cell/array systems to meet the needs of future planetary science missions.

• Assess the status of advanced solar cell/array technologies currently under development at NASA, DOD, DOE and Industry and assess their potential capabilities and limitations to meet the needs of future planetary science missions.

• Assess the adequacy of on-going technology development programs at NASA, DoD, DOE and Industry to advance space solar power system technologies that can meet the needs of future planetary science missions.

• Identify technology gaps and technology programs to meet the needs of future planetary science missions.
Review Team
Solar Cell/Array Technology Assessment

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PV Technology Challenges for Outer Planet Missions

- Low Solar Intensities (< 40 W/m²)
- Low Temperatures (< -140 C)
- High Radiation (6e15 1MeV e-/cm²)
- Low Mass (~ 3X lower than SOP)
- Low Stowage Volume (~ 3X lower than SOP)
- Long Operational Life (> 15 years)
- High Reliability
Over 3 orders of magnitude reduction in solar irradiance from Earth to Pluto
### PV Capability Needs for Next Decadal Outer Planet Missions

<table>
<thead>
<tr>
<th>Mission Type</th>
<th>Mission</th>
<th>Performance Capability Needs*</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbiters/Flyby</td>
<td>Jupiter</td>
<td>• LILT Capability (&gt; 38% at 10 AU &amp; &lt; -140 C)</td>
<td>Enhancing &amp; Enabling</td>
</tr>
<tr>
<td></td>
<td>Saturn</td>
<td>• Radiation Tolerance (6 \times 10^15 \text{ 1MeV } \text{e}/\text{cm}^2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Europa</td>
<td>• High Voltage (&gt;100V)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Titan</td>
<td>• High Power (&gt;50 kW@ 1AU)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Enceladus</td>
<td>• Low Mass (3X lower than SOP/&gt;250 W/kg)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Long Life (&gt; 15 years)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High Reliability</td>
<td></td>
</tr>
</tbody>
</table>
Solar Cell Efficiency Improvements

- **Si n/p cells**: 1970

- **Dual Use Science 29% demonstrated**: 1970
- **4-J Theoretical limit**: 1970

**Goals**

- **Hi Eff Si**: Goal: 115-130 W/kg
  - 475W/m2
  - < $500/W
- **Thin-film cells**: Goal: 200-450 W/kg
  - < $100/W

- **Thin-film submodules**: ~ 1 sq ft
Overview of SOP Triple-Junction Solar Cells

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Azur Space</th>
<th>SolAero Technologies</th>
<th>Spectrolab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer’s designation</td>
<td>3G30C</td>
<td>ZTJ</td>
<td>XTJ-prime</td>
</tr>
<tr>
<td>Efficiency at 28 deg C, AM0¹</td>
<td>29.8%</td>
<td>29.5%</td>
<td>30.7%</td>
</tr>
<tr>
<td>Voltage at maximum power, 28 deg C, AM0 (V)</td>
<td>2.41</td>
<td>2.41</td>
<td>2.39</td>
</tr>
<tr>
<td>Typical areal mass density (mg/cm²)</td>
<td>86</td>
<td>84</td>
<td>84</td>
</tr>
<tr>
<td>Temperature coefficient at 28 deg C, un-irradiated</td>
<td>-0.23%</td>
<td>-0.22%</td>
<td>-0.22%</td>
</tr>
<tr>
<td>Typical cell thickness (µm)</td>
<td>150</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>Normalized maximum power degradation at</td>
<td>Not reported</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>1E15 1 MeV e/cm² per AlAA-S111</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalized maximum power degradation at</td>
<td>0.9</td>
<td>Not reported</td>
<td>0.87</td>
</tr>
<tr>
<td>1E15 1 MeV e/cm² per ECSS-ET-20-08C³</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar absorptance</td>
<td>0.91</td>
<td>0.92</td>
<td>0.88</td>
</tr>
</tbody>
</table>


¹Reported efficiencies assume a solar intensity of 135.3 mW/cm².

²Values represent Ge wafer thickness. Azur Space and Spectrolab have offered cell thickness down to 80 mm; 140-150 mm has been the standard in flight production.

³The ECSS test standard includes photon and temperature annealing subsequent to irradiation.

- Current cells provide ≈30% efficiency at beginning-of-life, AM0
- Minor variations in voltage, current, radiation degradation and thermal properties between different manufacturers (Temperature annealing not practicable for cells under LILT conditions.)
Overview of State-of-Practice Solar Arrays

- **Body mounted array** – installed directly on body of spacecraft or platform
  - No sun-tracking mechanisms
- **Deployable rigid array** – rigid panels stowed for launch and unfolded on orbit
  - Panel structure is typically honeycomb sandwich with composite face-sheets
  - Sun-tracking in one or two axes
- **Deployable flexible array** – flexible blanket deployed by an extensible structure
  - Flexible fold-out array: blanket is folded when stowed
  - Flexible roll-out array: blanket is rolled on a mandrel when stowed
- **Combination of body mounted and deployable**, ex. SMAP, MER Rovers
- **Specialized versions of all three types include**
  - Electrostatically clean arrays – prevent accumulation of electric charge on array surfaces
  - High temperature arrays – survive high irradiance for missions close to the sun

### Summary of Current Array State-of-Practice

<table>
<thead>
<tr>
<th>Array technology</th>
<th>Maximum power at 1 AU (current state-of-practice), approximate*</th>
<th>Specific power at 1 AU, BOL (W/kg)**</th>
<th>Areal power density (W/m²)**</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body-mounted array</td>
<td>2 kW</td>
<td>N/A</td>
<td>314</td>
<td>9</td>
</tr>
<tr>
<td>Deployable rigid array</td>
<td>25 kW</td>
<td>80</td>
<td>330</td>
<td>9</td>
</tr>
<tr>
<td>Flexible fold-out array</td>
<td>120 kW</td>
<td>150</td>
<td>338</td>
<td>9</td>
</tr>
<tr>
<td>Flexible roll-out array</td>
<td>25 kW</td>
<td>150</td>
<td>338</td>
<td>7</td>
</tr>
</tbody>
</table>

*Based on demonstrated capability
**Assuming all arrays have SoP triple junction cells
# Future PSD Mission Needs vs SOP Capabilities

<table>
<thead>
<tr>
<th>Type of PSD Missions</th>
<th>Future Mission Needs</th>
<th>SOP Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mission General Needs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All Missions</td>
<td>High Efficiency Solar Cells (~38%)</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>Low Mass Arrays (&gt; 250 W/kg)</td>
<td>150 W/kg</td>
</tr>
<tr>
<td><strong>Mission Specific Needs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer Planet Missions</td>
<td>LILT Capability up to 10 AU</td>
<td>LILT capability up to 5.5 AU</td>
</tr>
<tr>
<td>Solar Electric Propulsion</td>
<td>High Voltage, High Power Arrays (300V, 100 kW)</td>
<td>100 V &amp; &lt; 30 kW</td>
</tr>
<tr>
<td>Missions</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Future planetary science missions require PV power systems that are mass and volume efficient have long life and operate under extreme environments.
- SOP PV systems are heavy and have limited operational capabilities at extreme environments.
# Advanced Cell Technology Table

<table>
<thead>
<tr>
<th>Cell technology</th>
<th>Potential Capability</th>
<th>Status</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverted metamorphic</td>
<td>36-37%</td>
<td>34-35% demonstrated in lab cells</td>
<td>Achieving cost parity</td>
</tr>
<tr>
<td>Dilute nitride</td>
<td>36-37%</td>
<td>30-31% demonstrated in lab cells</td>
<td>Volume manufacturability</td>
</tr>
<tr>
<td>Upright metamorphic</td>
<td>36-37%</td>
<td>29-30% demonstrated in lab cells</td>
<td>Material quality in high bandgap subcells</td>
</tr>
<tr>
<td>Semiconductor Wafer bonding</td>
<td>36-37%</td>
<td>34-35% demonstrated in lab cells</td>
<td>Achieving cost parity</td>
</tr>
<tr>
<td>Near-IR absorbers</td>
<td>36-37%</td>
<td>26-27% demonstrated in lab cells</td>
<td>Performance improvement over SoP</td>
</tr>
</tbody>
</table>
# Developing Solar Array Technology

**Flexible arrays**

<table>
<thead>
<tr>
<th>Solar Array</th>
<th>Manufacturer</th>
<th>Type</th>
<th>Key features</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2100 spacecraft</td>
<td>Lockheed Martin</td>
<td>Flexible fold-out</td>
<td>Based on heritage ISS solar arrays</td>
<td>In development for flight programs</td>
</tr>
<tr>
<td>Composite Beam Roll-Up Solar Array (COBRA)</td>
<td>SolAero</td>
<td>Flexible roll-out, circular</td>
<td>Extends diameter beyond Ultraflex design. Intended to reach &gt;100 kW capability.</td>
<td>Demonstrated deployment &gt;10 m diameter in ground test.</td>
</tr>
<tr>
<td>Mega-Rosa</td>
<td>Deployable Space Systems (DSS)</td>
<td>Flexible roll-out</td>
<td>Deployment of multiple ROSAs from a central spine. Intended to reach &gt;100 kW capability.</td>
<td>Deployment mechanism concept demonstrated in ground test.</td>
</tr>
</tbody>
</table>

- Flexible array development is continuing, focused on lower mass and higher power
- Goals are 500 W/kg specific power and 80 kW/m³ stowage at BOL, 1 AU
Specific Power vs Distance from Sun

- SoP arrays provide higher specific power than MMRTGs at Jupiter
- Advanced arrays are could reach the specific power of MMRTGs at Saturn
Key Findings

• Solar power systems have been used to power a wide range of planetary science missions
  – 0.3 AU to 5.5 AU
  – Mars surface, Jupiter, Mercury, Asteroid
• Future planetary science missions have unique solar power system needs
  – High Power Solar Arrays (>100 kW) for solar electric propulsion missions (outer planet & asteroid)
  – High Efficiency Solar Cells (> 37%) for small spacecraft planetary missions
  – High Specific Power (> 4 W/kg at 10 AU) & LILT capable (4-10 AU) Solar Arrays for outer planetary missions
• SOP PV systems have limited operational capabilities at extreme environments.
  – Low solar intensities and low temperature environments of outer planets
  – High temperature, high/low solar intensity and corrosive environments of Venus
  – Dusty Mars environments
• Advanced solar cells and arrays are under development at several companies and universities with support from DOD and private funding
  – Cell Technologies (32-36%): 4-5 J cells, Inverted metamorphic, Dilute nitride, Upright metamorphic, Wafer bonding
  – Array Technologies (150-300 W/kg): Flexible fold-out, Flexible roll-out and Concentrator
• No NASA significant investments in the area of advanced space solar cells and arrays
  – Some limited investments are in the area high power arrays and LILT solar cells.
General Recommendations

• Targeted investments should be made in the specific solar cell and array technologies needed to withstand the unique planetary environments.

• Partnerships with HEOMD and STMD and/or other government agencies such as DoE and DoD (AFRL, Aerospace Corporation, NRL, and ARL) should be established and maintained to leverage/tailor the development of advanced cell and array technologies to meet future planetary science mission needs.

• Existing infrastructure for PV technology development, testing and qualification at various NASA Centers should be upgraded to support future planetary science missions, as needed.
Specific Recommendations

• Develop high power (>100 kW) and low mass (200–250 W/kg) solar arrays for future solar electric propulsion missions operable up to 10 AU (for outer planet missions).

• Develop higher efficiency LILT solar cells and low mass, radiation resistant arrays for orbital missions to Jupiter, Saturn, and Ocean Worlds (Europa, Titan, etc.).

• Develop LIHT cells and arrays tolerant of the sulfurous environment required for Venus aerial and surface missions.

• Develop solar cells tuned to the Mars solar spectrum and solar arrays with dust mitigation capability for future Mars surface missions.

• Leverage the DoD investment in higher efficiency solar cells (~38%) and array technologies to enhance next decadal planetary space science missions.
Solar Powered PSD Missions

Juno

Ongoing

SEP stage for Uranus/Neptune missions

Near Future

Mission Concepts

Titan Saturn System Mission Concept (2011)
Acknowledgements

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Backup
### Solar Arrays on NASA Planetary Science Missions

**Launches since FY2000**

<table>
<thead>
<tr>
<th>Mission class</th>
<th>Mission</th>
<th>Destination</th>
<th>Launch date</th>
<th>Solar cell technology</th>
<th>Solar array technology</th>
<th>Power capability at 1 AU (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer planets</td>
<td>Juno</td>
<td>Jupiter</td>
<td>5-Aug-11</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>14000</td>
</tr>
<tr>
<td>Inner planets</td>
<td>Messenger</td>
<td>Mercury</td>
<td>3-Aug-04</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>LCROSS</td>
<td>Moon</td>
<td>18-Jun-09</td>
<td>Triple junction</td>
<td>Body-mounted</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>Lunar Reconnaissance Orbiter</td>
<td>Moon</td>
<td>18-Jun-09</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>1850</td>
</tr>
<tr>
<td></td>
<td>Grail</td>
<td>Moon</td>
<td>10-Sep-11</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>763</td>
</tr>
<tr>
<td></td>
<td>LADEE</td>
<td>Moon</td>
<td>6-Sep-13</td>
<td>Triple junction</td>
<td>Body-mounted</td>
<td>295</td>
</tr>
<tr>
<td>Mars</td>
<td>Mars Odyssey</td>
<td>Mars</td>
<td>7-Apr-01</td>
<td>GaAs/Ge</td>
<td>Deployable rigid</td>
<td>2092</td>
</tr>
<tr>
<td></td>
<td>Mars Exploration Rover (2)</td>
<td>Mars surface</td>
<td>10-Jun-03/7-Jul-03</td>
<td>Triple junction</td>
<td>Body-mounted</td>
<td>390</td>
</tr>
<tr>
<td></td>
<td>Mars Reconnaissance Orbiter</td>
<td>Mars</td>
<td>12-Aug-05</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>6000</td>
</tr>
<tr>
<td></td>
<td>Phoenix</td>
<td>Mars surface</td>
<td>4-Aug-07</td>
<td>Triple junction</td>
<td>Ultraflex</td>
<td>1255</td>
</tr>
<tr>
<td></td>
<td>MAVEN</td>
<td>Mars</td>
<td>18-Nov-13</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>3165</td>
</tr>
<tr>
<td>Asteroids/comets</td>
<td>Deep impact/EPOXI</td>
<td>Tempel-1/Hartley-2</td>
<td>12-Jan-05</td>
<td></td>
<td>Body-mounted</td>
<td>620</td>
</tr>
<tr>
<td></td>
<td>Dawn (with solar electric propulsion)</td>
<td>Vesta/Ceres</td>
<td>27-Sep-07</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>10300</td>
</tr>
<tr>
<td></td>
<td>OSIRIX-REx</td>
<td>Bennu</td>
<td>8-Sep-16</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>3000</td>
</tr>
</tbody>
</table>

- Vast majority of missions since FY2000 utilized triple junction solar cells on deployable, rigid arrays
Advanced Solar Cell Technology
Overview

Bandgap optimization for high AM0 efficiency
• Inverted metamorphic
• Dilute nitride
• Upright metamorphic
• Wafer bonding
• Near-IR absorbers

Improved operation in special environments
• Low irradiance low temperature
• High temperature
• Surface spectra
• Corrosive atmosphere
• Lightweight flexible
• High radiation
# PV Technology Needs of Next Decadal Solar Electric Propulsion Missions

<table>
<thead>
<tr>
<th>Solar Cell &amp; Array Characteristics</th>
<th>Past</th>
<th>Present</th>
<th>Next Decadal Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>High voltage</td>
<td></td>
<td></td>
<td>300V</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>2.5</td>
<td>10-20</td>
<td>50-200</td>
</tr>
<tr>
<td>Specific Power (W/kg)</td>
<td>50-70</td>
<td>80-110</td>
<td>&gt;150</td>
</tr>
<tr>
<td>Stowage Volume (kW/m³)</td>
<td>~3-10</td>
<td>&gt;30</td>
<td>&gt;40</td>
</tr>
<tr>
<td>LILT Performance</td>
<td>Uncertain behavior under LILT conditions</td>
<td>Uncertain behavior under LILT conditions</td>
<td>LILT Capability needed (&gt; 2.5 AU)</td>
</tr>
<tr>
<td>Cost $M/ kW</td>
<td>1-2</td>
<td>1.0</td>
<td>0.3-0.5</td>
</tr>
<tr>
<td>Other factors:</td>
<td>Complex deployment system</td>
<td>Simpler and reliable deployment system</td>
<td>Simplest and most reliable deployment system</td>
</tr>
</tbody>
</table>
Solar Powered PSD Missions

- Mars Odyssey
- Mars Reconnaissance Orbiter
- Mars Pathfinder
- Messenger
- Maven
- Grail
- Mars Pathfinder
- Stardust-NExT
- OSIRIS-REx
- Juno
- Deep Impact
- Dawn
- Genesis
- Meridiani Planum
Improved Operation in Special Environments
Low Irradiance Low Temperature (LILT) Conditions

LILT = low irradiance low temperature (e.g. Jupiter 5.5AU -140°C, Saturn 9.5AU -165°C)
LIRT = low irradiance room temperature, current practice for screening and binning
SoP cells intended for LILT applications

• Device modifications needed to eliminate mechanisms that limit LILT performance,
  using 1 AU-optimized SoP or advanced cells as starting point
• Also, screening yield improvements for qualitative cell-build cost reductions
• TRL = 4 for SoP-based, 2 for advanced cells
• Remaining challenge = statistical significance, advanced cells
Summary of Findings

• Several types of advanced solar cells are under development at several companies and universities with support from DOD and private funding
  • 4-5 J cells, Inverted metamorphic, Dilute nitride, Upright metamorphic, Wafer bonding
• Significant improvement in solar cell performance is envisioned
  • Near-term: > 33% efficient
  • Mid– to Far-Term: > 37% efficient

• Several types of advanced solar arrays are under development with support from DOD and private funding
  • Flexible fold-out, Flexible roll-out, Concentrator

• Major advances in Solar Array Performance are envisioned
  • Near-term: 150-200 W/kg
  • Mid- to Far-term: 200-250 W/kg

• The biggest technology investments are mostly from DOD
  • Currently there is limited NASA funding in high power arrays and LILT solar cells
• NASA needs to work with DOD to advance and tailor advanced PV technologies for future planetary science missions
## Developing Solar Array Technology

**Concentrator arrays**

<table>
<thead>
<tr>
<th>Reflective Concentrators</th>
<th>Refractive Concentrators</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cell Saver Solar Array</strong></td>
<td><strong>SOLAROSA</strong></td>
</tr>
<tr>
<td>Manufacturer: Orbital ATK</td>
<td>Manufacturer: DSS</td>
</tr>
<tr>
<td>Description: reflective ~2X concentrator</td>
<td>Description: Stretched lens on flexible blanket</td>
</tr>
<tr>
<td>Key features: Focused on cost reduction</td>
<td>Key features: Incorporates Fresnel lens into ROSA</td>
</tr>
<tr>
<td>Status: Flight experiment in orbit</td>
<td></td>
</tr>
</tbody>
</table>

**Flexible Array Concentrator Technology (FACT)**

Manufacturer: DSS

Description: Incorporates reflective concentrator into ROSA

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- Research and development has been performed on multiple technologies that utilize concentrated sunlight.