Solar Power Technologies for Future Planetary Science Missions

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Solar Power Technologies for Future Planetary Science Missions

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Assessment Team

Jet Propulsion Laboratory, Caltech
Rao Surampudi (Chair)
Julian Blosiu
Paul Stella
John Elliott
Julie Castillo

Goddard Space Flight Center
Thomas Yi
John Lyons

Glenn Research Center
Mike Piszczor
Jeremiah McNatt

Langley Research Center
Chuck Taylor

Johns Hopkins University Applied Physics Laboratory
Ed Gaddy

Aerospace Corporation
Simon Liu

U.S. Army
Ed Plichta

NASA HQ
Christopher Iannello

Advisory Committee and Editors

Patricia M. Beauchamp
James A. Cutts

Foreword

Future planetary exploration priorities envisioned by the National Research Council's (NRC's) *Vision and Voyages for Planetary Science in the Decade 2013–2022*,[1] developed at the request of the NASA Planetary Science Division (PSD), seek to reach targets of broad scientific interest across the solar system. Power systems are required for all of these mission concepts, but which power system is optimal for a particular potential mission depends on the mission's scientific and operational needs and, in some cases, constraints imposed by NASA. Radioisotope Power Systems (RPS) are extremely important options for many planetary mission types, particularly to the outer reaches of the solar system and beyond, and the current capabilities and future technological pathways for RPS have been extensively discussed and previously documented.[2,3] However, solar power is used for the majority of planetary spacecraft and, as a complement to recent RPS studies, this report assesses the capabilities and limitations of state-of-practice solar power systems and the status of advanced solar power technologies, and it documents innovations needed for upcoming mission concept scenarios. Although solar power has been used on most planetary missions to date, it has limitations as missions seek to operate further away from the Sun or in Sun-shadowed regions. Thanks in part to the commercial sector, there have been substantial advances in solar cell and solar array technologies that have enabled some outer planet missions, such as Juno, to be accomplished with solar power, which were long thought to be out of the reach of such technologies. Now we see that even some mission concepts to Saturn are possible with current solar power technology. A companion report assesses energy storage technologies for planetary missions because, in some cases, missions may need primary batteries for power.

Patricia M. Beauchamp
Chief Technologist,
Engineering and Science Directorate
Jet Propulsion Laboratory,
California Institute of Technology
Pasadena, CA 91109

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[1] National Research Council, "Vision and Voyages for Planetary Science in the Decade 2013-2022," The National Academies Press, Washington, DC (2011). https://solarsystem.nasa.gov/docs/131171.pdf

[2] John Hopkins University, Applied Physics Laboratory. 2015. Nuclear Power Assessment Study, TSSD-23122. http://solarsystem.nasa.gov/rps/npas.cfm

[3] Jet Propulsion Laboratory, California Institute of Technology. June 2017. Next-Generation Radioisotope Thermoelectric Generator Study Final Report, JPL D-99657.

Acknowledgments

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Special gratitude is extended to Joel Schwartz, Andreea Boca, and the many individuals who contributed their knowledge and time in preparation of this report. Special thanks to Mary Young for the technical publications support during the report preparation and to Richard Barkus for development of the cover. The authors would also like to acknowledge the valuable technical information provided by solar cell and array manufacturers and aerospace companies (Spectrolab, SolAero, mPower, Microlink, Alta Devices, Orbital-ATK, Deployable Space Systems, Inc., Lockheed Martin Astronautics, Boeing Defense, Space, and Security, and Sierra Nevada Corporation), as well as by the Department of Defense and National Laboratories (Army Research Laboratory, Air Force Research Laboratory, Aerospace Corporation, Navy Research Laboratory, and Applied Physics Laboratory).

Other Reports in this Series (which can be found on https://solarsystem.nasa.gov)

Power Technology

- Advanced Radioisotope Power Systems Report, Report No. JPL D-20757, March 2001.
- Solar Cell and Array Technology for Future Space Missions, Report No. JPL D-24454, Rev. A, December 2003.
- Energy Storage Technology for Future Space Science Missions, Report No. JPL D-30268, Rev. A, November 2004.
- Energy Storage Technologies for Future Planetary Science Missions, Report No. JPL D-101146, December 2017.

Planetary Protection Technology

- Planetary Protection and Contamination Control Technologies for Future Space Science Missions, Report No. JPL D-31974, June 2005.
- Assessment of Planetary Protection and Contamination Control Technologies for Future Science Mission, Report No. JPL D-72356, January 2012.

Extreme Environments

- Extreme Environment Technologies for Future Space Science Missions, Report No. JPL D-32832, September 2007.

Guidance Navigation and Control

- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part I. Onboard and Ground Navigation and Mission Design, Report No. JPL D-75394, October 2012.
- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part II. Onboard Guidance, Navigation, and Control, Report No. JPL D-75431, January 2013.
- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part III. Surface Guidance, Navigation, and Control, Report No. JPL D-78106, April 2013.

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Executive Summary

Background

In order to plan effectively for the future, NASA's Planetary Science Division requested an assessment of the space solar power technologies required to enable/enhance the capabilities of future planetary science mission concepts (>2025). The study report is organized into five major sections: 1) study overview, 2) potential solar power system needs of future planetary science missions, 3) capabilities and limitations of state-of-practice (SOP) space solar power systems, 4) status of advanced solar cell and array technologies, and 5) findings and recommendations.

Study Overview

The specific objectives of the study include: a) review the solar power system needs of potential future planetary science missions, b) assess the capabilities and limitations of state of practice space solar cell/array systems, c) assess the status of advanced solar cell/array technologies currently under development and assess their potential capabilities and limitations, and d) identify and recommend candidate solar cell and array technologies required for future planetary science mission concepts.

JPL assembled a technical assessment team to perform this study. The team consisted of subject matter experts in the areas of mission planning, spacecraft power systems engineering, and space solar power systems and technologies. The assessment team members were selected from NASA (HQ, JPL-Caltech, GRC, LaRC, and GSFC), Aerospace Corporation, Johns Hopkins University Applied Physics Laboratory (JHU-APL), and Department of Defense (DoD). The team met with engineers and technologists from U.S. solar cell and array manufacturers, aerospace organizations, and NASA mission centers to obtain information on the capabilities and limitations of the SOP technologies. In addition, the team also met with several solar cell and array scientists and technologists from universities, industry, NASA, DoD, and aerospace organizations to obtain information on advanced solar cell and array technologies currently under development. The assessment team held four meetings to: a) obtain information about potential next decadal planetary science mission concepts and their power system needs, b) determine the capabilities of SOP space solar power systems, c) assess the status and potential capabilities of advanced photovoltaic (PV) power systems under development at various national laboratories, industry, and universities, and d) summarize the findings and compile the recommendations.

Future Mission Concept Needs

Potential planetary science missions targeted for time period to be covered by the next decadal survey (2023–2032) are grouped into four categories: a) outer planets b) inner planets, c) Mars, and d) small bodies. The assessment team met with mission formulation study leads and power system engineers from JPL, GSFC, Marshall Space Flight Center (MSFC), and JHU-APL to identify potential planetary science missions that could be considered for implementation in the next 10–15 years and determine the PV power system needs for solar powered mission concepts. The major findings of the review team on the PV power system needs of these four groups of solar powered planetary science missions are given below.

a) Outer Planet Missions

Radioisotope power systems are generally attractive for outer planet mission concepts because RPS can be used in environments with limited or no sunlight. However, in some cases, solar power systems are preferred compared to RPS due to performance, mass, or cost considerations. NASA's

Juno mission is currently demonstrating the technical feasibility of using solar power at Jupiter distance and the Europa Clipper mission has also baselined solar power.

Many planetary scientists are presently advocating two broad groups of outer planet missions for future development: a) those to the Ice Giants—Neptune and Uranus, and b) those to Ocean Worlds which include a number of moons of the outer planets with subsurface oceans of liquid water. Potential Ocean World mission destinations include Enceladus, Europa, Titan, Ganymede, and Callisto.

The major technical challenges for solar-powered outer planet missions are operation in extreme low solar irradiance and low temperature environments. The solar irradiance at Jupiter (5.1 AU) is 3.7% of that at 1 AU. At Saturn (9.5 AU) it is 1.1%, at Uranus (19.2 AU) it is 0.28%, and at Neptune (30 AU) it is 0.1%. In view of these low solar intensities, missions would need solar arrays with high power capability (>30 kW) at 1 AU to produce the required power (>500 W) at such large distances (at >5 AU). In addition, Jupiter mission concepts require solar power systems that can operate in high radiation environments. Other important requirements include long-life capability and high reliability. Additionally, mission concepts using solar electric propulsion (SEP) would require high-power solar arrays (>50 kW at 1 AU).

The major findings of the review team on the solar power systems required for outer planet mission concepts to be considered in the next decadal survey are given below:

1. Ocean World missions require high efficiency (>38%), high voltage (>100 V) and high power (>20 kW at 1 AU) solar power systems that can operate efficiently in low irradiance, low temperature (LILT) environments. These missions would also require solar power systems with low mass and volume. Missions to Jupiter and its moons require solar power systems that can operate efficiently in high radiation environments.
2. The use of solar power systems for missions beyond Saturn (Ice Giants missions) is highly challenging, and would require significant advances in solar cells and array technologies to reduce mass and volume and improve operational efficiency and life capabilities.

b) Inner Planet Missions

Inner planet missions to Venus and Mercury present quite different challenges for solar power systems, because the power systems would need to operate in very close proximity to the Sun. The Venus mission concepts under consideration for the next decade include: a) orbital missions, b) variable altitude aerial platforms, and c) long-duration surface probes. The technical challenges of the inner planet missions vary depending on the type of spacecraft (flyby, orbital, aerial, and surface) and destination (Venus, Mercury). No missions to Mercury are presently under consideration for the next decade or two.

Venus exploration mission concepts pose several challenges for solar power systems and they depend significantly on the type of mission (orbital/surface/aerial). The temperature and pressure on Venus ranges from 460°C and 90 bars at the surface, to a benign 0°C and 1 bar at an altitude of 55 km. In addition, very little sunlight reaches the Venus surface. There is very little atmospheric motion near the surface. However, at 55 km altitude, the winds are strong enough to enable aerial mission concepts, such as those with balloons.

The major findings of the review team on the solar systems required for next decadal Venus mission concepts are given below:

1. Venus orbital missions can be implemented with existing solar power systems, as these environmental conditions are relatively benign and are similar to those of Earth orbital missions. However, future missions concepts would benefit from the use of high-efficiency solar cells and low-mass solar arrays.
2. High-altitude aerial missions where solar fluxes are high and temperatures are benign would require few solar power innovations except protection from the sulfuric acid environment.
3. Low-altitude Venus aerial missions would require solar power systems capable of operating in low solar irradiance (50–300 W/m^2), high temperature (200–350°C), and corrosive environments.
4. Solar cells required for these missions need to be optimized to operate efficiently under the altered Venus surface solar spectrum.

Mercury orbital missions, such as NASA's MESSENGER and the European Space Agency's (ESA's) BepiColombo mission, required solar power systems that could operate in extremely high solar intensities (1000–14000 W/m^2) and high-temperature environments (~270°C).

c) Mars Mission Concepts

Although the NASA Mars mission roadmap is unclear after the 2020 launch of the next Mars rover, Mars science mission concepts under consideration for the next decade include: 1) multi-functional next-generation Mars orbiters, 2) potential Mars sample return missions (includes Mars ascent vehicles, landers, and sample-fetching rovers), 3) Mars helicopters and other forms of proposed aerial vehicles, and 4) human Mars precursor missions (large landers, rovers, demonstrations for in-situ resource utilization). The major solar power system challenges for Mars surface missions are: 1) efficient operation of solar arrays under the Mars solar spectrum, 2) the complexity of deploying and operating large photovoltaic arrays on rovers and landers, and 3) efficient operation of solar arrays in Mars dust environments.

The major findings of the review team on the solar power systems required for next decadal Mars mission concepts are given below:

1. Mars orbital missions do not present major challenges for solar power technologies and can be implemented with SOP systems. However, future missions would benefit from the use of high-efficiency solar cells and low-mass solar arrays.
2. Future Mars surface landers and rovers require solar cells capable of operating efficiently under Mars solar *spectral* conditions. Since the effective solar spectrum at the surface of Mars is depleted at short wavelengths, a cell designed to maximize the efficiency in the red-shifted spectrum on Mars would optimize solar power for Mars surface and aerial missions. Additionally, surface missions using solar arrays could benefit greatly and reduce operational costs by incorporating dust removal capabilities.
3. Mars aerial missions would require high efficiency solar cells and low-mass solar arrays since mass would be at a premium for helicopters and airplanes.

4. Future human precursor missions likely require low mass and high power arrays with autonomous deployment capability. These missions also would require solar arrays capable of operating efficiently in dusty martian environments.

d) Small Body Mission Concepts

Small bodies in our solar system include asteroids, comets, and dwarf planets, such as Ceres and Pluto. Science priorities and potential mission recommendations, provided through community white papers and the Small Body Assessment Group (SBAG), include the following: a) Near-Earth Objects: Mega-multi-flyby, Multi-rendezvous, and Sample Return, b) Main belt asteroids and Jupiter Trojans: Main Belt Sample Return, Multi-asteroid Rendezvous, and Jupiter Trojan rendezvous, c) Comets: Comet Surface Sample Return and Comet Nuclear Sample Return, d) Small Satellites: Phobos and Deimos Sample Return, e) Dwarf Planets: Flyby (rendezvous preferred), and f) Centaurs and Trans-Neptunian Objects: Flyby (rendezvous preferred). Of particular interest is solar electric propulsion, which is an attractive option for some, but not all small body mission concepts.

The major technical challenges of the solar power systems required for small body missions are: a) large solar arrays with low mass and low stowage volume (~2× lower than SOP), and b) long operational life (>10 years).

The major findings on the solar power systems required for next decadal small body mission concepts are given below:

1. Solar electric propulsion missions to small bodies would require high voltage (>100 V), high power solar arrays (20–100 kW at 1 AU), with low mass and low stowage volume;
2. Missions to small bodies beyond 3 AU are similar to outer planet missions and would require solar cells capable of operating in LILT environments.

State of Practice Solar Power Systems

This assessment team met with engineers and technologists from U.S. solar cell and solar array manufacturers and user organizations, such as NASA mission centers, and from aerospace industry to obtain information on the SOP solar cell array capabilities and their limitations. The major findings on the capabilities and limitations on SOP space solar power systems cell and arrays are:

Solar Cells: Through the 1980s, spacecraft used primarily silicon solar cells with efficiencies increasing from less than 10% to over 15%. During the 1990s, gallium arsenide (GaAs) solar cells began to replace silicon solar cells, and progressed from single junction to dual junction cells that were grown on germanium substrates (replacing the more expensive GaAs substrates). During the 2000s, triple junction solar cells became the standard for most space missions. Today's space solar cells offer efficiencies of ~30% at 1 AU along with resilience to radiation (electrons and protons). Future solar cells are expected to reach efficiencies of ~38% at 1 AU by the mid-2020s.

Solar Arrays: The types of solar arrays currently in use are: a) body-mounted arrays, b) deployable rigid arrays, and c) flexible fold out arrays. During the past 25 years, the specific power of solar arrays has improved from 30 W/kg to 100 W/kg. In the past decade, these advances have enabled several orbital and surface missions at Mars, as well as flyby and orbital missions to small bodies and inner planets.

Limitations: In spite of these advances, SOP solar power systems are not attractive for the following future planetary mission concepts:

1. Outer planetary missions beyond Saturn, because of limited performance capabilities at low solar irradiance and low-temperature environments;
2. Low-altitude Venus aerial and surface missions, due to their limited operational capabilities at high temperatures, high/low solar irradiance, and corrosive environments;
3. Long-duration Mars surface solar powered missions, because of dust accumulation on solar arrays;
4. High-power, solar electric propulsion missions to small bodies and outer planets, because such solar arrays would be heavy, bulky, and could not function in LILT environments.

Advanced Space Solar Power Technologies

The assessment team met with several solar cell and array scientists and technologists from universities, industry, NASA, DoD, and aerospace industry to obtain information on advanced solar cell and array technologies currently under development. The major findings of the review team on the status of advanced solar cell and array technologies are given below.

Solar Cells: High-efficiency solar cells are under development at several companies and universities with support from DoD and private funding. NASA supports cell development through the Small Business Innovation Research (SBIR) and other programs. The advanced solar cells architectures under development include a) inverted metamorphic multi-junction (IMM), b) dilute nitride, c) upright metamorphic, and d) semiconductor wafer bonding technologies (SBT). SBT refers to the mechanical connection of one semiconductor wafer on top of another. Significant improvements in solar cell performance are envisioned: a) near-term (1–2 years): >33% efficient, and b) mid- to far-term (5–10 years): >37% efficient.

The IMM solar cells under development have an efficiency of approaching 35% at beginning-of-life (BOL), 28°C, under the standard spectrum outside the Earth's atmosphere (Air Mass 0 [AM0]) conditions. Space qualification of these types of cells is currently in progress. Development of dilute nitride cells for space applications is also underway and efficiencies from 30–31% have been reported[4] under the same conditions. To date, upright metamorphic multi-junction (UMM) solar cells have an efficiency from 29–30% at AM0. SBT cells under development have an efficiency of 34–35% at AM0.

Limited work is currently in progress on the development of solar cells that can function: a) at low[5] solar irradiance and low temperatures (outer planet environments) and b) at high temperature, high/low solar irradiance and corrosive environments of Venus. No identified research projects are currently underway on the development of solar cells that can function effectively under Mars *spectral* conditions, although research has been done in this area in the past.[6] Research into martian dust removal has also been previously been studied but is not currently being pursued.[5]

[4] Suarez, Ferran, et al., "High Efficiency Multijunction Solar Cell Based on Diluted Nitrides", Presented at 33rd Space Power Workshop, Manhattan Beach CA (2015).
[5] Boca, Andreea, et al., "Advanced-Architecture High-Efficiency Solar Cells for Low Irradiance Low Temperature (LILT) Applications", Proceedings of 44th IEEE-PVSC (2017).
[6] Stella, Paul, et al., "Mars optimized solar cell technology (MOST)", Proceedings of 33rd IEEE-PVSC (2008).

Solar Arrays: Several types of advanced solar arrays are under development with support from DoD, commercial funding and NASA. Advanced solar arrays under development include: a) flexible fold-out, b) flexible roll-out, c) concentrator, and d) solar arrays for extreme environments. Major advances in solar array performance are envisioned: a) near-term: 150–200 W/kg, b) mid- to far-term: 200–250 W/kg. A summary of the status of development of these advanced solar arrays is given below.

Flexible Fold-out Arrays: UltraFlex is a flexible fold-out solar array from Orbital-ATK, Inc. MegaFlex, currently under development in the same company, is an extension of their current UltraFlex array to larger diameters and higher power. The MegaFlex deploys as a flexible fold-out array with a circular geometry, similar to the UltraFlex. Deployment of a 10-m diameter MegaFlex has been demonstrated in a ground test and is intended to reach diameters as large as ~30 m.

Flexible Roll-out Arrays: Roll-out solar arrays (ROSA) have been recently unfurled and successfully tested at the International Space Station (ISS). Mega-ROSA is a flexible roll-out solar array under development at Deployable Space Systems, Inc. (DSS). It represents an extension of the ROSA to higher power. The Mega-ROSA comprises a set of multiple ROSAs deployed from a central structural spine. The Mega-ROSA is intended to reach power capability exceeding 100 kW at 1 AU, BOL.

Concentrator Arrays: Concentrator arrays offer a potential approach for mitigating the losses associated with LILT conditions. Specifically, increasing the effective irradiance using concentrating optics would allow solar cells in the outer solar system to operate as if they were much closer to the Sun. Concentrator arrays that have undergone some development over the past decade include a) Cell Saver Solar Array, b) Flexible Array Concentrator Technology (FACT), and c) Stretched Lens Array (SLA). For outer planet mission concepts, one has to be careful that the amount of power generated in Earth- or Venus-assisted trajectories to the outer planets does not overheat the arrays and associated hardware. This is usually mitigated by feathering the arrays to reduce the solar irradiance within the inner solar system. Novel ideas for concentrators are emerging, including gossamer or very large collectors, and may have potential that could substantially alter the ability to use solar power in the distant reaches of the solar system.

Solar Arrays for Extreme Planetary Environments: Solar arrays that can survive and operate in high-temperature environments and are actively cooled by a pumped fluid loop have been developed for Solar Probe mission concepts, which fly close to the Sun. Some limited work in the early 2000s has also been carried out on the development of dust-tolerant solar arrays for Mars. Technical feasibility of the dust removal has been demonstrated[7] but further work is needed to demonstrate this at the system level. Limited work is currently in progress on the development of arrays for low-irradiance, high-temperature conditions on Venus.

Recommendations

The review team formulated the following overall and specific recommendations to NASA-PSD. These recommendations were formulated after reviewing the solar power system needs of future planetary science mission concepts and after examining the capabilities and limitations of SOP

[7] Calle, C. I., et al., "An Active Dust-Mitigation Technology for Mars Exploration," Proceedings of Concepts and Approaches for Mars Exploration (2012).

solar power systems, and the status of the advanced energy storage technologies currently under development.

Overall Recommendations

1. Targeted investments should be made in the specific solar cell and array technologies required for unique planetary environments.
2. Partnerships with the NASA Human Exploration and Operations Mission Directorate (HEOMD) and the Space Technology Mission Directorate (STMD) and/or other government agencies such as Department of Energy (DoE) and DoD (Air Force Research Laboratory [AFRL], Aerospace Corporation, Naval Research Laboratory [NRL], and Army Research Laboratory [ARL]) should be established and maintained to leverage/tailor the development of advanced cell and array technologies to meet future planetary science mission concept needs.
3. 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

Specific recommendations on solar cell and array technologies required for future planetary science mission concepts are that PSD should leverage the DoD investment in higher-efficiency solar cells (~38%) and array technologies to enhance options for future planetary space science missions and develop:

1. High power (>100 kW) and low mass (200–250 W/kg) solar arrays operable up to 10 AU (for outer planet missions);
2. Higher efficiency LILT solar cells and low mass, radiation resistant arrays for potential orbital missions to Jupiter, Saturn, and Ocean Worlds (Europa, Titan, etc.);
3. Low irradiance, high temperature (LIHT) cells and arrays tolerant of the sulfurous environment required for Venus aerial and surface mission concepts;
4. Solar cells tuned to the Mars solar spectrum and solar arrays with dust mitigation capability for future Mars surface mission concepts.

1 Study Overview

1.1 Introduction

Most of the planetary science missions conducted to date have used solar power systems, including some Mars missions, and all of the inner planet and small body missions. However, outer planet missions, such as Voyager, Cassini, and Galileo, have typically used radioisotope power systems. But, this is changing. For the first time, Juno, a mission to Jupiter, is powered by a solar power system and a planned NASA mission to Jupiter's moon Europa, the Europa Clipper, has baselined the use of solar power. Figure 1-1 illustrates the current status of solar power missions in the solar system.

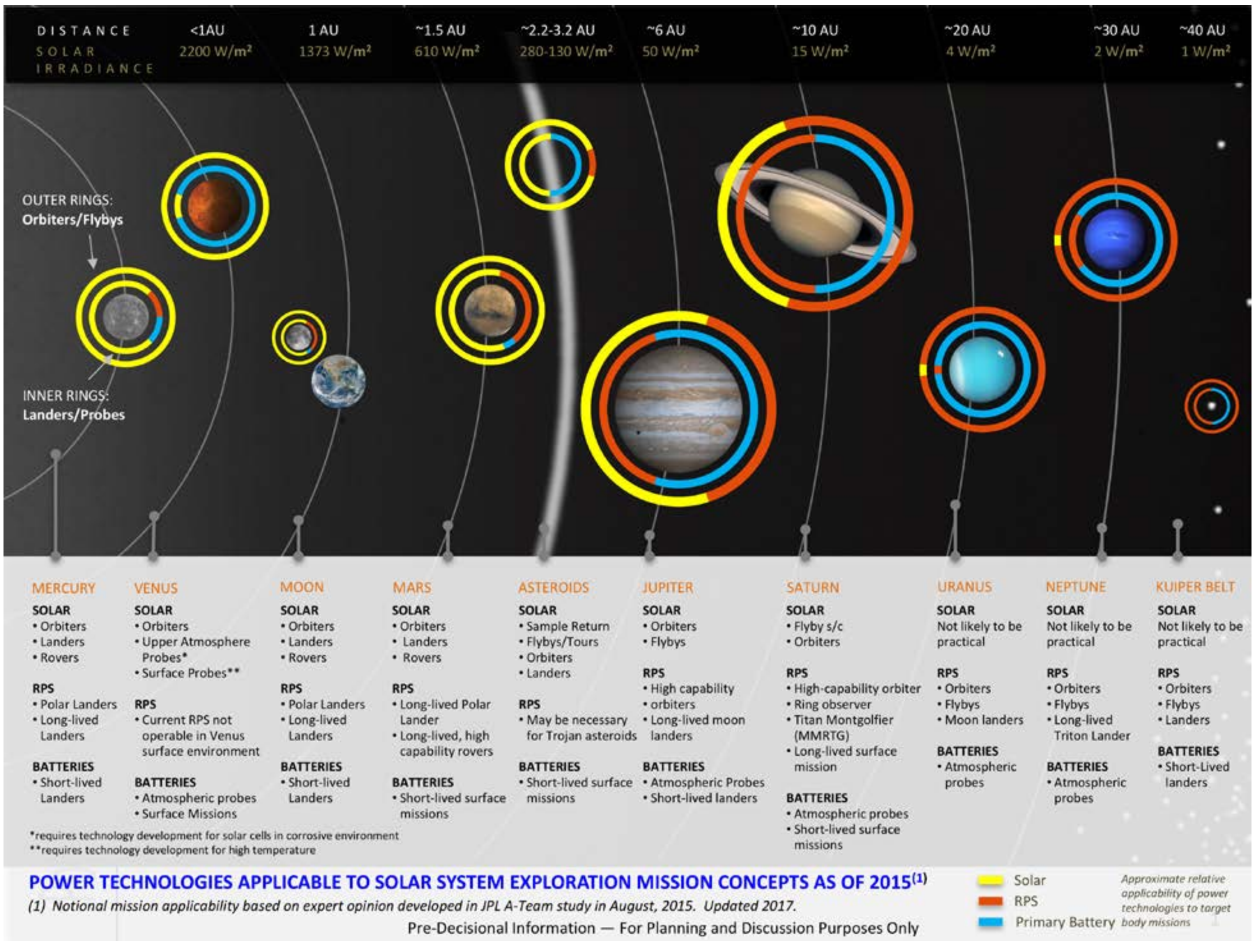

Figure 1-1. Approximate relative applicability of power technologies to target body mission concepts as of 2015, updated in 2017, showing solar power in yellow (outer rings for Orbiters and Flybys and inner rings for landers and probes)

In order to plan for the future, NASA's Planetary Science Division requested an assessment of the space solar power technologies required to enable/enhance the capabilities of future planetary science mission concepts (>2025). The study report is organized into five major sections: 1) overview, 2) potential solar power system needs of future planetary science missions, 3) capabilities and limitations of SOP space solar power systems, 4) status of advanced solar cell and array technologies, and 5) findings and recommendations.

1.2 Objectives

The purpose of this assessment was to identify candidate advanced space solar power technologies that would enable/enhance the capabilities of future Planetary Science mission concepts. The specific objectives were:

- Review the space solar power system needs of future planetary science mission concepts
- 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 in industry, and assess their potential capabilities and limitations to meet the needs of future planetary science missions.
- Identify and recommend candidate solar cell and array technologies required for future planetary science missions.

1.3 Approach

A technical assessment team was assembled to support this study. The team consisted of experts in the areas of mission planning, spacecraft systems engineering and space solar power subject matter experts. The team members were selected from NASA (HQ, JPL-Caltech, GRC, LaRC, GSFC), Aerospace Corporation, APL, and DoD.

Three multi-day meetings were held to: a) obtain information about potential next decadal planetary science missions and their power system needs, b) determine the capabilities of SOP space solar power systems, and c) assess the status and potential capabilities of advanced photovoltaic power systems under development at various national labs, industries, and universities. A fourth meeting was held to finalize the findings and recommendations.

To make the study tractable, the technology needs of a large number of potential future missions were distilled into four generic mission concept types. For each generic mission type, we analyzed the power needs, assessed the PV capabilities of SOP technologies, and identified the gaps between current capabilities and mission needs. The team also reviewed advanced PV technologies currently under development at various national laboratories, industries, and universities. The assessment team examined each PV technology to answer the following questions:

- How does it function?
- What is the present status of the technology?
- What is the future potential of the technology in terms of performance parameters such as specific power and efficiency under various conditions?
- What would be the impact of such improvements on future mission concepts?
- What technical challenges remain?

These results were analyzed to identify the most promising advanced solar power technologies with the greatest potential impact on enabling and enhancing future planetary science missions. The final results are documented in this report along with findings and recommendations.

1.4 Schedule

The assessment team conducted three multi-day meetings between March and September 2016. The first meeting was held at JPL, the second was held at NASA GSFC, and the third meeting was at NASA GRC. A fourth meeting was also held at JPL in October 2016. The final report was prepared as a draft in February 2017 for review by the assessment team and was revised to final form by November 2017.

1.5 Assessment Team

The Space Solar Power Technology Assessment Team members are:

1. Rao Surampudi, NASA JPL (Chair)
2. Julian Blosiu, NASA JPL
3. Paul Stella, NASA JPL
4. John Elliott, NASA JPL
5. Julie Castillo, NASA JPL
6. Thomas Yi, NASA GSFC
7. John Lyons, NASA GSFC
8. Ed Gaddy, JHU-APL
9. Mike Piszczor, NASA GRC
10. Jeremiah McNatt, NASA GRC
11. Ed Plichta, U.S. Army
12. Simon Liu, Aerospace Corporation
13. Chuck Taylor, NASA LaRC
14. Christopher Iannello, NASA HQ

1.6 Participants

This assessment required detailed technical information on: a) next decadal planetary science mission concepts and their projected solar power system needs, b) SOP solar power systems currently being used in various planetary space science missions and their capabilities, and c) advanced solar power technologies currently under development by other government agencies and their potential capabilities. The information was obtained from various NASA centers, aerospace companies, companies involved in the development and manufacturing of solar cells and arrays, and National Laboratories. The names of the organizations that supported this study are given below:

Solar Cell R&D/Manufacturers

1. Spectrolab
2. SolAero
3. mPower
4. Microlink
5. Alta Devices

Array R&D/Manufacturers

1. Orbital-ATK
2. DSS
3. Lockheed-Martin
4. Sierra Nevada Corporation
5. Boeing

NASA Centers

1. Glenn Research Center (GRC)
2. Jet Propulsion Laboratory-California Institute of Technology (JPL-Caltech)
3. Langley Research Center (LaRC)
4. Goddard Space Flight Center (GSFC)

DoD & National Laboratories

1. Army Research Laboratory (ARL)
2. Air Force Research Laboratory (AFRL)-Philips Laboratory
3. Aerospace Corporation
4. Navy Research Laboratory (NRL)
5. Applied Physics Laboratory (APL)

2 Space Solar Power Needs of Future Planetary Mission Concepts

2.1 Introduction

The NASA Planetary Science Division is considering a number of ambitious missions to various destinations in our solar system, including outer planets, inner planets, Mars and small bodies. The power systems required for these mission concepts have several unique needs compared to Earth-orbital missions, and the needs vary based on the destination and mission type. We invited mission formulation study leads and power system engineers from JPL, GSFC, MSFC, and APL to identify potential next decadal planetary science missions and their possible PV power system needs.

2.2 Outer Planetary Mission Concepts

The outer planet destinations consist of four planets: Jupiter, Saturn, Uranus, and Neptune, as well as their satellites (Figure 2-1). These planets combined have over a hundred moons orbiting them. In the past, Pluto was originally included in the outer planet category; however, it is now categorized as a dwarf planet. In the past, all outer planet missions have been powered by Radioisotope Thermoelectric Generators (RTGs). These include Pioneer 10, Pioneer 11, Voyager 1, Voyager 2, Galileo, Cassini, and Ulysses, and they were mostly flyby missions except for Galileo, which was the first Jupiter orbital mission (it also deployed an atmospheric probe to Jupiter), and Cassini, the first mission to orbit Saturn. RTGs were chosen to power these spacecraft after an assessment of their mission needs as compared to the often limited capabilities of earlier generation solar power systems.

Outer planet missions currently in operation include New Horizons [NH] (Pluto flyby) and Juno (Jupiter orbiter). Like the past outer planet missions, New Horizons is RTG-powered. Juno is the first solar-powered outer planet spacecraft. Juno, which has mission requirements less demanding than prior flagship missions to Jupiter, such as the RTG-powered Galileo, benefits from advanced solar cells that are 50% more efficient and radiation tolerant than silicon cells used in earlier space missions. The Europa Clipper will be the second NASA solar-powered outer planet mission and ESA is also developing a solar-powered orbiter bound for Jupiter (the Jupiter Icy Moons Explorer

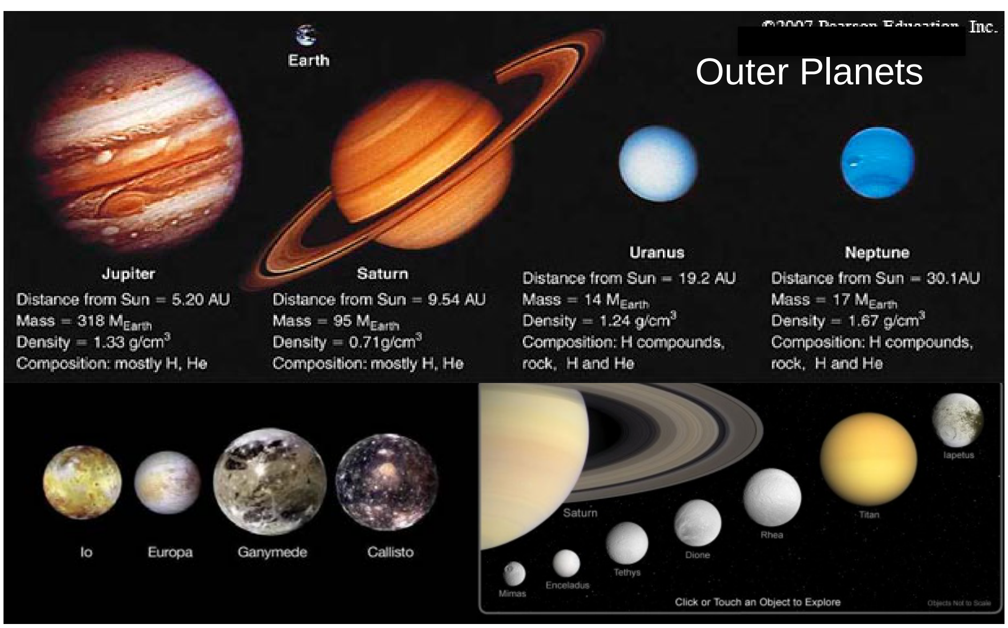

Figure 2-1. Outer Planet Mission Destinations.

[JUICE]). In addition, several New Frontiers outer planet mission concepts currently in the proposal stage are considering the use of solar power systems to destinations as far from the Sun as Saturn.

The most recent planetary science decadal survey, *Vision and Voyages,*[1] recommended the following outer planet mission concepts for development: a) Europa Multiple Flyby Mission, b) Uranus Orbiter, c) Enceladus Orbiter, d) Saturn Probe, and e) Io Observer. Among these, a Europa mission (Europa Clipper) was selected for development and is currently scheduled for launch in 2022/2023. The NRC has not yet initiated the next planetary decadal survey (2023–2032) and the outer planet missions recommended in the past decadal survey that were not able to be funded by NASA may again be considered for development in the next decade. Currently, scientists are predominately advocating two groups of outer planet mission concepts for future development: a) missions to Ocean Worlds and b) missions to the Ice Giants.

Ocean Worlds known to have subsurface oceans—determined from measurements by the Galileo and Cassini spacecraft—include Enceladus, Europa, Titan, Ganymede, and Callisto, although several other planetary bodies may also fall under this category. The overarching goals of the Ocean Worlds missions[8] are: a) identify Ocean Worlds in the solar system, b) characterize the oceans, c) characterize the habitability of each body, d) understand how life might exist at each Ocean World and search for life.

Orbital and probe missions to the Ice Giants, Neptune and Uranus, were considered as a high priority in *Vision and Voyages*.[1] In fact, the Giant Planets panel ranked Ice Giants as their #1 priority and recommended a Uranus orbiter/probe mission concept for development. Although this mission has undergone further study,[9] it has not been selected for development in this decade as yet, because of competing priorities and reduced funding. However, it may result in being one of the higher priority outer planetary missions for the next decade. Additionally, a Neptune System Orbiter with a probe could be another consideration for the next decade.

Radioisotope power systems are generally attractive for outer planet missions because they can be used in environments with limited or no sunlight. However, in some cases, solar power systems are more cost effective compared to radioisotope power systems, even when the total power system mass is higher. In addition, SEP is attractive for many outer planetary missions because it has the potential to significantly reduce risk and/or the cruise time required to reach the outer planets, and/or increase the payload mass. SEP to an outer planet might be in the form of an SEP stage containing solar arrays and electric propulsion elements that could be jettisoned, if desired, after use in the inner solar system.

The major technical challenges for solar-powered outer planet mission concepts are operation in extreme low solar intensities and low-temperature environments. The solar irradiance at Jupiter (5.1 AU) is 3.7% of that at 1 AU. At Saturn (9.5 AU) it is 1.1%, at Uranus (19.2 AU) it is 0.28%, and at Neptune (30 AU) it is 0.1%. In view of these low solar intensities, mission concepts need solar arrays with high power capability (>20 kW) at 1 AU to produce the required power (>500 W) at such large distances (at >5 AU). In addition, Jupiter missions would require solar power systems that can operate in high radiation environments. Other important requirements include long-life capability and high reliability. SEP missions also require high power solar arrays (>50 kW at 1 AU).

[8] http://www.lpi.usra.edu/opag/ROW/

[9] http://www.lpi.usra.edu/icegiants/mission_study/Full-Report.pdf

Higher-power solar arrays will benefit from high efficiency solar cells (>38%) to minimize the solar array size and mass. Such an advance would reduce the mass and area of the array by almost 20% without lowering power output. Additionally, reducing the solar array size improves the maneuverability of the spacecraft.

Solar power system needs of outer planet mission concepts are summarized in Table 2-1.

Table 2-1. Solar power system needs of the outer planet missions.

Mission Type	Mission	Performance Capability Needs
Orbiters/Flyby	Jupiter* Saturn Europa* Titan Enceladus	• LILT Capability (>38% at 10 AU and <−140°C) • Radiation Tolerance (6e15 1 MeV e-cm^2) • High Voltage (>100 V) • High Power (>50 kW at 1 AU) • Low Mass (3× lower than SOP) • Low Volume (3× lower than SOP) • Long Life (>15 years) • High Reliability

**Radiation tolerance is critical for Jupiter system, including Europa, missions.*

2.3 Inner Planet Mission Concepts

The inner planets include Mercury, Venus, Earth, and Mars. These rocky planets are nearer to the Sun and are much more closely spaced to each other than their outer planet counterparts. Here only Mercury and Venus are classified as inner planet destinations (Figure 2-2), while Mars missions are considered separately.

Past U.S. missions that explored Mercury are Mariner 10 and Mercury Surface Space Environment Geochemistry and Ranging (MESSENGER). NASA's Mariner 10 was the first U.S. spacecraft to fly by Mercury. MESSENGER was the first spacecraft to orbit Mercury. Both Mariner 10 and MESSENGER were solar powered. MESSENGER used a solar power system that was designed for operation at 0.31 AU. Two important features were incorporated in the design and operation of the MESSENGER solar power system. One feature involved the replacement of a significant fraction of the solar cells by optical solar reflectors (OSRs) to control the array temperature near the Sun; the

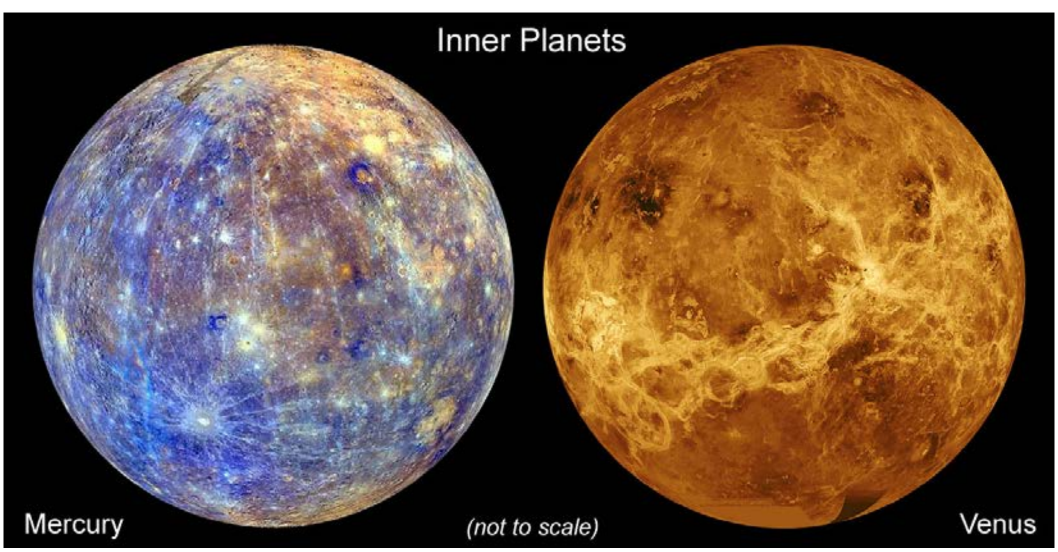

Figure 2-2. Inner Planet Mission Destinations.

Messenger design used about 2/3-cell coverage. The second feature was that the array was off-pointed from the Sun to avoid overheating.

All orbital and flyby missions to Venus have been solar powered and no current proposed mission to Venus envisages using RPS. The past planetary science decadal survey (2013–2022) recommended a Venus In-Situ Explorer (VISE) for development during 2013–2023. However, no Venus proposals were selected for development. Several proposals are currently being developed in response to the New Frontiers (NF)-4 mission call, with Step 2 selections expected late in 2017. NASA is also in discussions with Roscosmos, the Russian Space Agency, on a potential role in their Venera D mission, tentatively planned for 2025 launch.

The highest-priority science objectives (as defined by the Venus Exploration Analysis Group [VEXAG]) for the next decadal Venus exploration mission concepts are: 1) understand atmospheric formation, evolution, and climate history on Venus, 2) determine the evolution of the surface and interior of Venus, and 3) understand the nature of interior–surface–atmosphere interactions over time, including whether liquid water was ever present. Other potential Venus exploration missions under consideration include: a) orbital missions, b) constant and variable altitude aerial platforms, c) long-duration surface missions, and d) Venus sample return missions.

The technical challenges of Venus missions vary depending on the type of spacecraft (flyby, orbital, aerial, and surface) and destination. Venus orbital missions can be implemented with SOP solar power systems, as Venus orbital environmental conditions are relatively benign. Some potential Venus atmospheric and surface missions under consideration are given in Figure 2-3.

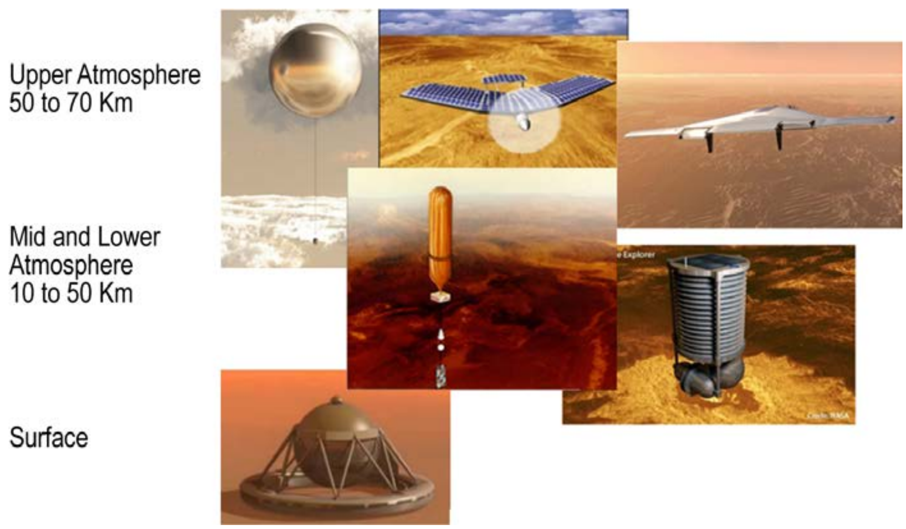

Figure 2-3. Potential Venus aerial and surface mission concepts under consideration.

Venus aerostats (balloons) operating at *high altitudes* (>50 km) can be implemented with SOP solar cells coated with materials for protection from the acidic environment. Venus airplanes and hybrid vehicles, such as the Venus Aerial Mid-Altitude Platforms (VAMP), require lightweight solar arrays resistant to the Venus corrosive environment. However, *medium- to low-altitude* Venus aerial missions impose several technical challenges. These include operation in low solar intensities (300–50 W/m^2), high temperature (200–350°C), and corrosive environments. Variation of pressure and temperature at various altitudes is given in Figure 2-4. Further, solar cells required for these mission concepts need to be optimized to operate efficiently under a filtered Venus solar spectrum (Figure 2-5).

The major technical challenges of Venus *surface* missions are operation in very low solar intensities (<5 W/m^2), high temperatures (>450°C) (Figure 2-4), and corrosive environments. The atmosphere is an amalgam of gases, composed primarily of carbon dioxide, with a 92 bar pressure and 460°C temperature at the surface. Short-duration Venus surface missions of a few hours were implemented using SOP primary batteries enclosed in an environmental chamber equipped with a complex thermal management subsystem. These past Venus surface missions did not consider the use of solar power systems because SOP solar cells could not function under the severe Venus surface environments, and also cannot function efficiently because Venus' solar spectrum is deficient in shorter wavelengths. However, long-duration Venus surface missions would require a rechargeable power system, which could be achieved with advanced solar cell and array technology. Solar power systems needs of the inner planet mission concepts are summarized in Table 2-2.

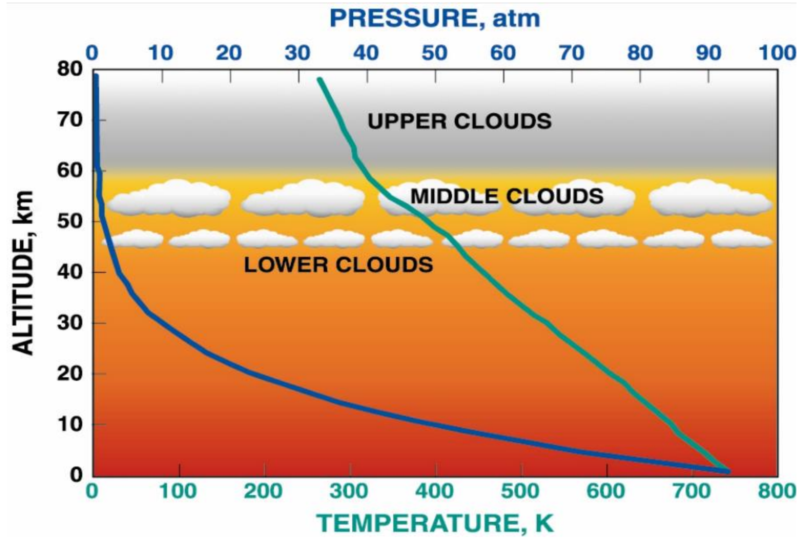

Figure 2-4. Variation of pressure and temperature at various altitudes at Venus.

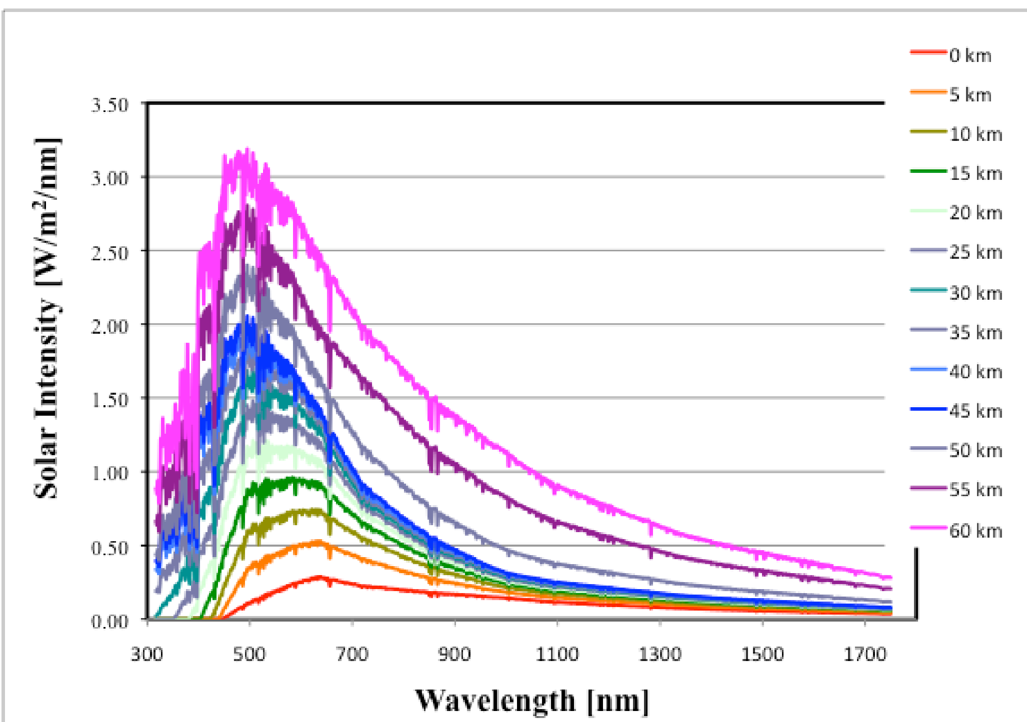

Figure 2-5. Simulated Solar Spectrum in Venus Atmosphere.

Table 2-2. Solar power systems needs of inner planet mission concepts.

Mission Type	Mission	Needs
Orbiters	Venus and Mercury	Low- Medium Temperature Operation High Solar Intensities at Mercury
Aerial (high- to mid-altitude)	Venus	Medium-High Temperature Operation (0–300°C) Venus Solar Spectrum Operation Operation in Corrosive Environments
Aerial (mid- to low-altitude)	Venus	Medium Temperature (0–300°C) operation. High Temperature (460°C) survival
Landers/Probes	Venus	High Temperature Operation (460°C) Low Solar Irradiance Operational Capability Venus Solar Spectrum Operation Operation in Corrosive Environments and Super-critical CO_2

2.4 Mars Mission Concepts

Since 1965, NASA (and now ESA and the Indian Space Research Organisation [ISRO]) have sent several robotic space missions to Mars to understand whether Mars was, is, or can be, a habitable world. The major goals of the NASA Mars Exploration Program are: 1) determine if Mars ever supported life, 2) understand the processes and history of climate on Mars, 3) understand the origin and evolution of Mars as a geological system, and 4) prepare for human exploration. Several types of spacecraft have been used for the exploration of Mars, including flybys, orbiters, landers, and rovers. All of the flyby and orbiting missions and several landers have been solar powered but radioisotope power systems were used to power some of the long-lived Mars landed missions (Viking 1–2 and Curiosity) and the upcoming Mars 2020 rover.

Mars exploration mission concepts being studied for the next decade include: 1) multi-functional next-generation Mars orbiters, 2) potential Mars Sample Return missions (includes Mars ascent vehicles, landers and sample fetching rovers), 3) a Phobos lander mission, 4) Mars helicopters and other forms of aerial vehicles, 5) subsurface explorers, and 6) human Mars precursor missions (large landers, rovers, in-situ resource utilization [ISRU] demonstrations missions). Some of the missions under consideration for the next decade and beyond are given in Figure 2-6.

It is envisioned that a Mars Sample Return (MSR) effort could be implemented with a series of three steps. The Mars 2020 rover mission will collect and cache surface samples for possible future return to Earth. It could be followed by an SEP-powered orbiter that would include a system designed to retrieve the samples from Mars orbit. The third element could be a fetch rover that would land, retrieve the cached samples, and inject them into Mars orbit, where the sample cache could be collected by the orbiter.

Mars subsurface missions are also under consideration for the next decade to provide information about the geology of the planet, the presence of water, and maybe even clues about whether Mars was ever a habitat for life. Mars aerial vehicles could enable the study of Mars from a perspective that has never been achieved before: aerial views from the martian sky where the spatial resolution is much better than can be achieved from orbit and the range of observation is much greater than is possible from the mast on a rover. NASA is also planning for human exploration of Mars in the mid- or late-2030s, and several robotic precursor missions to Mars are being considered, with a mixture of both scientific and human mission preparation objectives.

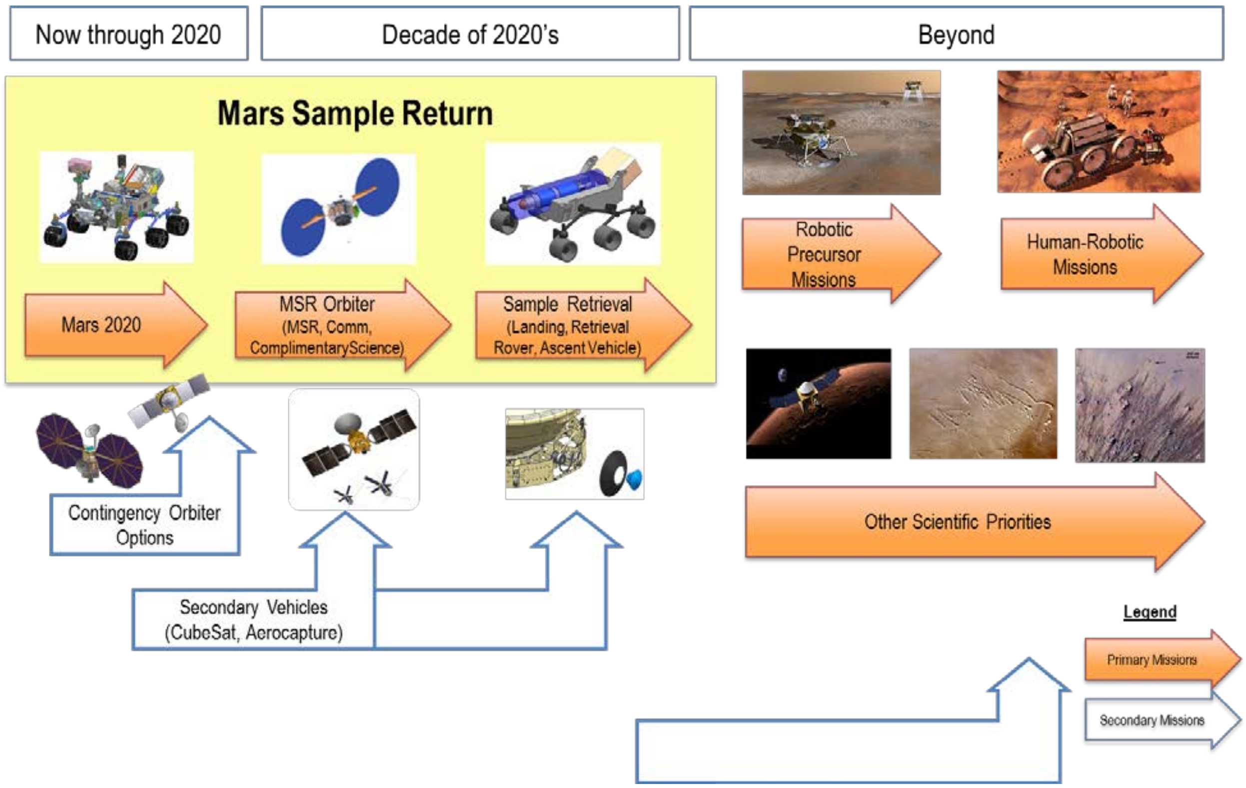

Figure 2-6. Notional future Mars missions under consideration for the next decade and beyond.

Among the potential future Mars mission concepts under consideration, the most challenging missions from the power system point of view are: 1) long-duration Mars landers and rovers required for potential Mars sample return missions, 2) Mars subsurface missions, 3) Mars aerial missions, 4) and Mars human precursor missions (large landers and rovers).

The major solar power system challenges for future Mars surface missions are: 1) efficient operation of solar arrays under Mars solar spectrum, 2) complexity of deploying and operating large photovoltaic arrays on rovers and landers, and 3) efficient operation of solar arrays in Mars dusty environments. In addition, human precursor missions require low mass and high-power arrays with autonomous deployment to demonstrate technical feasibility of human missions. Since the effective solar spectrum at the surface of Mars is depleted at short wavelengths, a cell designed to maximize efficiency in the red-shifted spectrum on Mars would be valuable for Mars surface applications. The other issue has to do with dust accumulation on the arrays. Dust accumulates on arrays and partially obscure them, thus reducing their power output. However, periodically, the observed martian dust devils and wind clean off the arrays and power levels are partially restored. For longer missions, overt dust removal techniques may be beneficial, since the naturally occurring dust removal processes may not be sufficiently reliable and repeatable, which would result in increased operational costs.

Solar cells maximized for martian surface operations are important to future aerial missions. With current technology for Mars helicopters, flight times are limited to a few minutes before the vehicle must land to recharge its batteries. With faster recharge times, flight repetition could be improved. For airplane concepts that do not descend to the surface, improvements in efficiency and specific power are needed for extended mission operations.

Solar power system needs of the future Mars missions are summarized in Table 2-3.

Table 2-3. Solar power system needs of the future Mars mission concepts.

Mission Type	Mission	Needs
Orbiters	Mars Orbiter	Low Mass (>3× lower than SOP) Low Volume (>3× lower than SOP) Long Life (15 years) High Reliability
Landers/Rovers	Robotic Precursor	Mars Solar Spectrum Operation High Efficiency Cells Low Mass (>3× lower than SOP) Low Volume (>3× lower than SOP) High Power Density (50% higher than SOP) Dust Removal Capability High Reliability
Aerial Vehicles	Helicopter	Low Mass (>4× lower than SOP) High Power Density (50% higher than SOP) Mars Solar Spectrum Operation Dust Tolerance

2.5 Small Body Mission Concepts

Small bodies in our solar system include asteroids, comets, and dwarf planets. Asteroids and comets are considered remnants from the giant cloud of gas and dust that condensed to create the Sun, planets, and moons some 4.5 billion years ago. Today, most asteroids orbit the Sun in a tightly packed belt located between Mars and Jupiter (Figure 2-7). Comets ablate and shed ice and dust as they approach the Sun in the course of their highly elliptical orbits. Dwarf planets are celestial bodies resembling a small planet, but lack certain technical criteria to be classified as planets. Dwarf planets, e.g., Ceres, Pluto, Eris, Haumea, Makemake, share their orbits around the Sun with other objects such as asteroids and comets. There have been multiple solar-powered missions to small bodies such as New Millennium Deep Space 1 (NM-DS-1), the first solar electric propulsion mission that passed by the near-Earth asteroid 9669 and comet Braille; Wide-field Infrared Survey Explorer (WISE), a solar-powered space-craft with an infrared-sensitive telescope; Stardust; and, Deep Impact. Stardust was a solar-

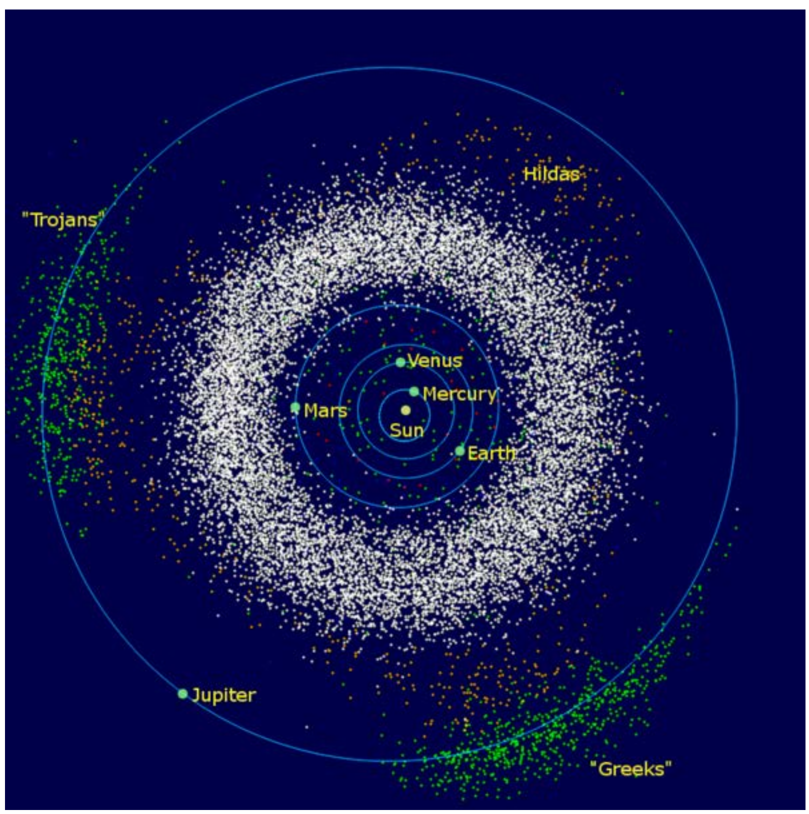

Figure 2-7. Asteroids orbit the Sun in a tightly packed belt located between Mars and Jupiter.

powered spacecraft that collected interstellar dust from the nucleus of comet Wild-2 during its closest encounter and returned it back to Earth for analysis. Deep Impact was a solar-powered mission that studied the composition of the comet Tempel 1.

Recent/ongoing comet and asteroid missions include: ESA's Rosetta, NASA's Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer (OSIRIS-REx), and Dawn. Rosetta was the first spacecraft to orbit a comet (67P/Churyumov-Gerasimenko) and carried a lander (Philae) developed by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt e.V. [DLR]) that was the first to land on the surface of a comet. Both the orbiter and the lander were solar powered. Rosetta was launched in 2004 and reached the comet almost ten years later in August 2014 after reaching distances as far as 5 AU. Flight system design required that the spacecraft enter a hibernation mode to conserve power when it was beyond 4.4 AU and Rosetta remained in that condition for 2.5 years. After surveying the comet and selecting a landing site, it deployed Philae to the surface in November 2014 but the vehicle bounced and landed on its side in a crevice. Power to the Philae lander solar arrays was occulted and it was only able to operate briefly until the mission ended.

Dawn is a NASA solar-powered spacecraft with solar electric propulsion requiring large solar arrays that targeted the giant asteroid Vesta and dwarf planet Ceres. Dawn entered Vesta orbit on July 16, 2011, and completed a 14-month survey mission before leaving for Ceres in late 2012. Dawn entered Ceres orbit on March 6, 2015, and may remain in orbit after the conclusion of its mission. OSIRIS-REx is also a solar-powered mission, but uses chemical propulsion. It was launched to a near-Earth asteroid called Bennu (formerly 1999 RQ36). OSIRIS-REx will orbit the asteroid beginning in August 2018 and is expected to return a sample to Earth in September 2023. NASA has also recently approved two new Discovery Program missions, Psyche and Lucy, to explore asteroids in early 2020s. Lucy is a solar-powered flyby mission with chemical propulsion and will visit six Trojan asteroids at close range from August 2027 through March 2033. Psyche is a planned solar powered, solar electric propulsion mission that would orbit the large metal asteroid of the same name.

Science priorities and mission concept recommendations for small bodies as provided by *Vision and Voyages*[1] and through community white papers and the SBAG are:

a) Near-Earth Objects: mega-multi-flyby, multi-rendezvous, sample return,
b) Main belt asteroids and Jupiter Trojans: main belt sample return, multi-asteroid rendezvous, Jupiter Trojan rendezvous,
c) Comets: comet surface sample return and comet nucleus sample return (flagship),
d) Small Satellites: Phobos and Deimos sample return,
e) Dwarf Planets: Haumea flyby (rendezvous preferred),
f) Centaurs and Trans-Neptunian Objects: flyby (rendezvous preferred).

SEP is an attractive option for some, but not for all small body missions. SEP missions require high voltage and high-power solar arrays (20–100 kW). The chemical propulsion missions also require solar power systems, but with low–medium power capability (<10 kW). The major technical challenges for solar electric propulsion missions are: 1) high voltage arrays (>100 V), 2) high power arrays (20–100 kW), 3) low mass, 4) low stowage volume, 5) radiation tolerance for some missions, 6) operational capability in LILT environments for some missions, and 7) high reliability.

Higher-power solar arrays would benefit from high efficiency solar cells (>38%) to minimize the solar array size and mass. The mass of the solar array is inversely proportional to the specific power of the array. For low values of the specific power, the array is very massive, and SEP is less mass-efficient than chemical propulsion. As the array specific power increases, a point is reached where SEP provides positive mass benefits to small body missions. For very large values of array specific power, the mass of the array becomes small compared to the balance of the spacecraft mass, and further increases in specific power produce only diminishing returns in mass saving. Reduced solar array size also improve the maneuverability of the spacecraft. Further, high-power solar arrays require low mass array structures with high reliability deployment capability. In addition, the missions to small bodies beyond 3 AU require solar cells capable of operating in low irradiance and low temperature environment. Table 2-4 summarizes the needs of the solar power systems required for small body missions.

Table 2-4. Solar power systems needs required for small body mission concepts.

Mission Type	Needs
Flyby/Orbiter	High Efficiency Solar Cells (>38%) High Voltage (>100–200V) High Power (>20 kW) Low Mass (>3× lower than SOP) Low Volume (>3× lower than SOP) Long Life (15 years) High Reliability
Surface Missions	Low Mass (>3× lower than SOP) Low Volume (>3× lower than SOP) High Power Density (50% higher than SOP) High Reliability

2.6 Summary

NASA is considering a number of exciting planetary science mission concepts for the decade of 2023–2032. The solar power system characteristics required for future potential planetary missions are given below:

- Outer planet missions could require high-power solar power systems that can function efficiently in low solar irradiance, low temperature, and high radiation environments
- Inner planet mid/low altitude aerial and surface missions could require solar power systems that can survive and function in high temperatures, low solar intensities, and corrosive environments.
- Mars surface missions would benefit from solar cells tuned to the Mars spectrum and require solar arrays with dust mitigation capability.
- High power SEP at small bodies and asteroids would require high voltage, low mass, and low volume solar array systems.

3 State-of-Practice Solar Cell and Array Technology

3.1 Introduction

Space solar power technology has advanced significantly since the first solar-powered satellite, Vanguard I, was launched in 1958. The first space solar array comprised six silicon solar cells that powered a 5 mW transmitter. Since that time both solar cell technology and array structure and deployment technology have undergone many changes leading to significant progress in power capability, mass and cost effectiveness. Spacecraft primarily used silicon solar cells through the 1980s, with cell efficiency increasing from less than 10% to over 15%. During the 1990s, GaAs solar cells began to replace silicon and progressed from single junction to dual junction cells grown on germanium substrates (replacing the more expensive GaAs substrates). During the 2000s, triple junction cells became the standard for most space missions. Today's space cells offer efficiencies of ~30% at 1 AU along with improved performance under electrons and protons radiation.

The earliest solar arrays comprised solar cells mounted on the body of a spacecraft, limiting the area available for solar cells and consequently available electrical power. Deployable structures were then developed enabling significantly larger arrays and hence higher power generation capability. Power output exceeding 20 kW is readily available on today's commercial satellites. To achieve even higher power, flexible blanket technology was developed so that a significantly larger area of solar cells could be stowed compactly for launch and unfolded or unrolled in space. The International Space Station (ISS) is the largest space solar power installation today, providing up to 120 kW using silicon solar cells on flexible blankets. Implementation of current triple junction cells on large flexible arrays could provide substantially higher capability.

A summary of the solar array technologies demonstrated on NASA planetary science missions is shown in Table 3-1. Each technology is discussed in the sections below.

Table 3-1. Solar Arrays on NASA Planetary Science Missions.

Mission Class	Mission	Destination	Launch Date	Solar Cell Technology	Solar Array Technology	Power Capability at 1 AU (W)
Outer planets	Juno	Jupiter	5-Aug-11	Triple junction	Deployable rigid	14000
Inner planetary systems	Messenger	Mercury	3-Aug-04	Triple junction	Deployable rigid	450
	LCROSS	Moon	18-Jun-09	Triple junction	Body-mounted	600
	Lunar Reconnaissance Orbiter	Moon	18-Jun-09	Triple junction	Deployable rigid	1850
	Grail	Moon	10-Sep-11	Triple junction	Deployable rigid	763
	LADEE	Moon	6-Sep-13	Triple junction	Body-mounted	295
Mars	Mars Global Surveyor	Mars	7-Nov-96	GaAs/Ge and Si	Deployable rigid	2100
	Mars Odyssey	Mars	7-Apr-01	GaAs/Ge	Deployable rigid	2092
	Mars Exploration Rover (2 rovers)	Mars surface	10-Jun-03 7-Jul-03	Triple junction	Deployable rigid	390
	Mars Reconnaissance Orbiter	Mars	12-Aug-05	Triple junction	Deployable rigid	6000
	Phoenix	Mars surface	4-Aug-07	Triple junction	UltraFlex	1255
	MAVEN	Mars	18-Nov-13	Triple junction	Deployable rigid	3165
Asteroids/ comets	Deep Impact/EPOXI	Tempel-1 Hartley-2	12-Jan-05	Triple junction	Body-mounted	620
	Dawn (with solar electric propulsion)	Vesta Ceres	27-Sep-07	Triple junction	Deployable rigid	10300
	OSIRIS-REx	Bennu	8-Sep-16	Triple junction	Deployable rigid	3000

LCROSS—Lunar Crater Observation & Sensing Satellite; LADEE—Lunar Atmosphere Dust & Environment Explorer; MAVEN—Mars Atmosphere & Volatile Evolution; EPOXI—Extrasolar Planet Observation & Characterization Investigation (EPOCh) + Deep Impact Extended Investigation (DIXI)

The following discussion of the technologies currently in use is divided into two sections, "State-of-Practice Space Solar Cells" and "State-of-Practice Space Solar Arrays" where SOP is defined as the technologies currently in space or in production for flight missions.

3.2 State-of-Practice Space Solar Cells

3.2.1 Device Technology

Current space solar arrays predominantly use triple junction III-V solar cells. These cells comprise three n/p junctions, grown using metal-organic vapor phase epitaxy (MOVPE) in a lattice-matched monolithic stack on a germanium substrate. The three junctions, or "subcells", include the III-V materials $GaInP_2$ and GaInAs, and a germanium substrate with an active junction. Each subcell is optimized to convert a different portion of the solar spectrum to electrical current, in particular, those photons with energy above the bandgap of the subcell material. The subcells are connected electrically in series by tunnel junctions, which are also part of the monolithic stack. Multi-junction cells provide higher efficiency than a single junction because higher energy photons can be converted to current at a higher potential than with a single junction device at a lower bandgap, minimizing thermal energy losses.

A simplified illustration of the SOP triple junction cell is shown in Figure 3-1, along with the solar irradiance spectrum. As shown in the figure, the highest bandgap material serves as the top junction and each successive subcell comprises a lower bandgap material. Hence, lower energy photons (i.e., light with longer wavelength) pass through the higher bandgap material and are converted to electrical current in the subcells below.

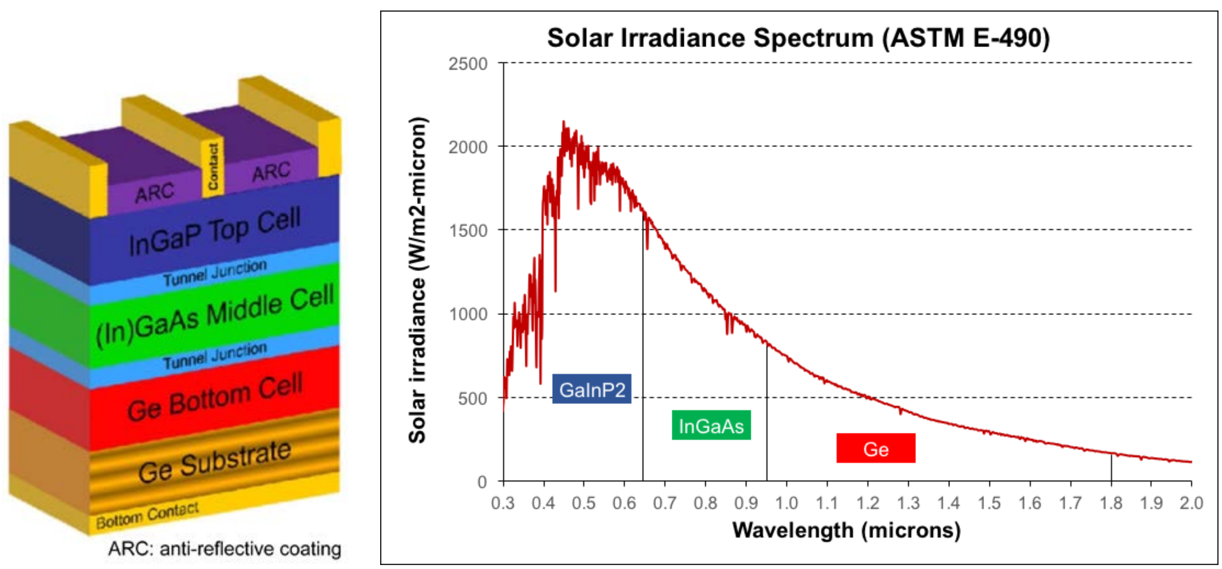

Figure 3-1. Illustration of a Triple-Junction Solar Cell and Solar Irradiance Spectrum. Three n/p junctions convert bands of successively longer wavelengths into electrical current.[10]

3.2.2 Current Production Solar Cells

A summary of space solar cells currently in production is provided in Table 3-2. The principal manufacturers include Azur Space (European), SolAero Technologies (formerly Emcore) and Spectrolab, Inc.; the latter two both are USA manufacturers. Each offer similar products based on

[10] https://www.greentechmedia.com/articles/read/arpa-e-award-caltechs-harry-atwater-aims-for-50-solar-efficiency

the $GaInP_2$/GaInAs/Ge structure. A range of different sizes is available, from ~20 cm^2 up to ~75 cm^2. The efficiencies listed in Table 3-2 refer to cell sizes in the 20–30 cm^2 range.

Azur Space also lists a silicon space solar cell on its website. The average efficiency at AM0, 28°C is 16.9% and the bare cell mass 32 mg/cm^2. These cells include a monolithically integrated Zener bypass diode. The cells are of the same type (referred to as "high efficiency silicon"), which were once common on space systems, and also previously produced by Sharp Corporation and Spectrolab.

SolAero Technologies also offers a 4-junction IMM solar cell. The average efficiency, as listed on its website, at AM0, 28°C is 33.0%. Although this cell is not fully qualified for general use, it provides higher performance capability and is a candidate for future missions. The IMM cell is discussed in detail below, under "Developing Cell Technologies".

The degradation due to radiation exposure is a critical parameter for many space missions. The summary data in Table 3-2 include two different values, representing two different test methods contained in published specifications for radiation testing. The two standards are published by the American Institute for Aeronautics and Astronautics (AIAA) and the European Cooperation for Space Standardization (ECSS), respectively. The ECSS standard (ECS-ET-20-08C) includes both photon and temperature annealing subsequent to irradiation and generally results in higher measured performance than the AIAA standard (AIAA-S111). The selection of the most accurate test method is an area of current research. For example, work is currently underway to compare the two methods and investigate which provides a more accurate measurement of actual in-orbit performance.

Table 3-2. Current Production Triple-Junction Space Solar Cells.

Characteristic	Value/Description		
Manufacturer	Azur Space	SolAero Technologies	Spectrolab
Manufacturer's designation	3G30C	ZTJ	XTJ-prime
Efficiency at 28°C, AM0[1]	29.8%	29.5%	30.7%
Voltage at maximum power, 28°C, AM0 (V)	2.41	2.41	2.39
Typical areal mass density (mg/cm^2)	86	84	84
Temperature coefficient at 28°C, un-irradiated (% Pmax/°C)	−0.23%	−0.22%	−0.22%
Typical cell thickness[2] (μm)	150	140	140
Normalized maximum power degradation at 1E15 1 MeV e/cm^2 per AIAA-S111	Not reported	0.85	0.85
Normalized maximum power degradation at 1E15 1 MeV e/cm^2 per ECSS-ET-20-08C[3]	0.90	Not reported	0.87
Solar absorptance	0.91	0.92	0.88

Source data: azurspace.com, solaerotech.com, spectrolab.com, September 7, 2016

[1] Reported efficiencies assuming a solar irradiance of 135.3 mW/cm^2.

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

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

3.2.3 Solar Cell Assemblies

Space solar cell assemblies comprise the solar cells described above with cover-glass, interconnects and, typically, a bypass diode installed. A simple illustration is shown in Figure 3-2.

The cover-glass is used for radiation shielding and improved thermal and optical characteristics. Ceria-doped borosilicate glass is used predominantly, although other materials such as fused silica have been used. Three common versions of ceria-doped borosilicate cover glass material, each

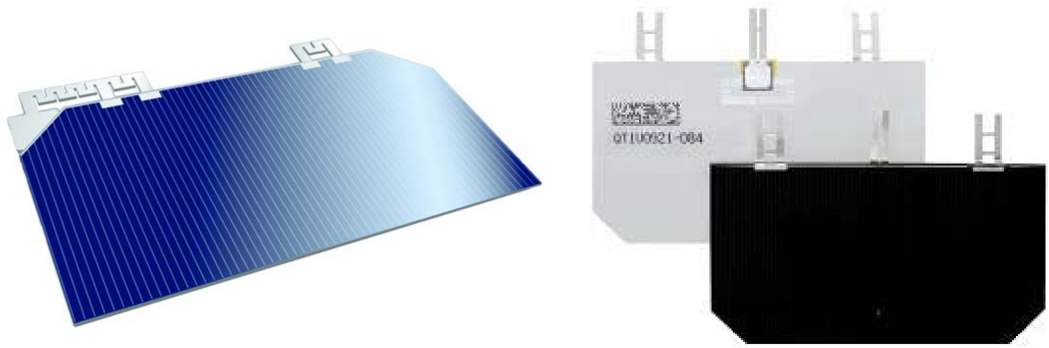

Figure 3-2. Solar Cell Assemblies. Two versions of a solar cell assembly are shown. At left is a SolAero cell incorporating a discrete bypass diode mounted in one corner.[11] At right is a Spectrolab cell with a discrete bypass diode mounted on the cell back side.[12]

manufactured by Qioptiq Space Technologies, include Qioptiq CMX, CMG, and CMO. CMG and CMO are formulated specifically for use with germanium-based cells. CMG is used most commonly while CMO offers improved optical transmission characteristics particularly at greater thickness (>200 μm). The cover-glass is attached to cells using optically transparent adhesive; the most common is Dow Corning 93-500 silicone.

Cover-glasses are normally coated to enhance optical properties. Common coatings include the following:

- Anti-reflective coating – one layer of magnesium fluoride (MgF_2) on front side
- Enhanced anti-reflective coating – multi-layer front side coating with slightly higher optical transmission that simple MgF_2
- Ultraviolet (UV) reflective coating – multi-layer anti-reflective front side coating with reflection band at wavelengths under ~350 nm under normal incidence; enables slightly lower operating temperature
- Static dissipative coating – typically a layer of indium-tin-oxide (ITO) under the anti-reflective coating; enables electrical charge flow to the cover-glass edge, which has a metallic coating for bleeding to ground
- Infrared reflective coating – multi-layer coating typically on the cover-glass back side that reflects wavelengths longer than the cell can use and also enables slightly lower operating temperatures. This coating is not presently in common use.

Solar cell interconnects are used for connecting solar cells electrically in series. Interconnect materials include both Kovar and molybdenum. Molybdenum is used for missions requiring magnetically clean arrays. In both cases the interconnect materials are clad or plated with silver. Interconnects generally require strain relief to provide survivability against excessive stress during thermal cycling (caused by different thermal expansion of panel components). Electrical connection is achieved by welding or soldering the interconnect to the cell n and p metallic contacts.

The bypass diodes shown in Figure 3-2 are connected electrically in parallel with the solar cell, but with opposite polarity orientation. The diode provides a current path around the cell in the event that the cell is in shadow, under-illuminated or damaged; in the absence of the bypass diode, current

[11] http://solaerotech.com
[12] http://spectrolab.com

would be forced through the cell by other cells in the series string. III-V cells are susceptible to permanent damage under such conditions from reverse bias breakdown. Bypass diodes can consist of discrete silicon chips connected to the cell with interconnects, as shown in Figure 3-2, or can be grown monolithically in the III-V material. Cells with monolithically integrated bypass diodes are offered by Azur Space and SolAero Technologies. These generally have slightly lower efficiencies than cells with discrete diodes but eliminate the need for interconnecting discrete diodes.

3.3 State-of-Practice Solar Arrays

An overview of the current state-of-practice for array level technologies is shown in Table 3-3. The values in the table are approximate and based on data in the public domain. Values for specific missions will depend on design details such as output voltage, wire harness design, geometrical layout and thermal environment.

In Table 3-3, maximum power is reported for arrays in orbit or, in the case of flexible roll-out technology, estimated from ground measurements. Values for specific power and areal power density are based on the assumption that all arrays utilize current production triple junction solar cells (this enables a consistent comparison of different architectures).

Table 3-3. Overview of Current Solar Array State-of-Practice.

Array Technology	Maximum power at 1 AU (current state-of-practice), approximate*	Specific power at 1 AU, BOL (W/kg)**	Areal power density at 1 AU, BOL (W/m^2)**	TRL
Body-mounted array	2 kW	N/A	314	9
Deployable rigid array	25 kW	80	330	9
Flexible fold-out array	120 kW	150	338	9
Flexible roll-out array	25 kW	150	338	7

* Based on demonstrated capability
** Assuming all arrays have SOP triple junction cells

A description of each technology is given below. Solar arrays can be classified using the following primary categories.

3.3.1 Body-Mounted Solar Arrays

Body-mounted arrays comprise solar panels installed directly on the body of a spacecraft or space platform. These arrays generally do not require deployment mechanisms and do not include Sun-tracking mechanisms. Orientation with respect to the Sun depends on the orientation of the space platform. The primary advantage of body-mounted arrays is simplicity because of the lack of deployment and tracking mechanisms. A second advantage, in the case of spinning spacecraft, is a lower operating temperature (and higher cell efficiency) compared with Sun-tracking arrays. The primary disadvantage is limited power capability due to limited size. In addition, spinning spacecraft do not illuminate all cells on the spacecraft, eliminating power from cells shadowed from the Sun by the spacecraft body. Hence, body-mounted arrays have generally been used on smaller platforms and missions with low power requirements (less than 2 kW). These include spinning satellites and, more recently, CubeSats. Figure 3-3 provides examples of each, incorporating low power body-mounted arrays.

Figure 3-3. Body-mounted arrays. From left to right: GOES 7 (NASA/NOAA) spinning satellite (illustration), CP8 IPEX (Cal Poly Intelligent Payload Experiment, app. 10 cm × 10 cm × 10 cm), RACE (Radiometer Atmospheric CubeSat Experiment).

3.3.2 Deployable Rigid Solar Arrays

The vast majority of space solar arrays currently deployed in space use rigid panels with strings of solar cells installed on a single side. The panels are stowed against the spacecraft or space platform during launch and subsequently unfolded upon deployment. Power levels (at 1 AU) vary over a wide range, from tens of watts to tens of kilowatts, depending on the mission. Figure 3-4 provides three examples: the Mars Exploration Rover, with 1.2 m^2 of array area; the Dawn spacecraft, with two deployable wings; and the Juno spacecraft, with three wings and a total array area of ~43 m^2.

Rigid arrays generally use a structure comprising honeycomb sandwich panels with composite face-sheets, such as graphite/epoxy, and aluminum honeycomb core. Solar cell strings are bonded on one side and wiring is installed on both front and back sides. Multiple panels are connected by hinges which deploy after release in orbit. Deployments are coordinated with damping or other hinge sequencing mechanisms. Single- or dual-axis tracking can be provided to maintain optimum pointing towards the Sun. In this case, power can be transferred across the rotating mechanism to the spacecraft or space platform.

Beginning-of-life specific power using current state-of-practice solar cells at 1 AU is typically up to ~80 W/kg. Areal power density is typically ~330 W/m^2. These values vary due to design details that may include the specific thermal environment, end-of-life (EOL) conditions for which the cell strings are optimized, wire harness design and specific solar cell type. Power output degradation throughout mission life depends on multiple factors, such as radiation environment, shielding design (e.g., cover-glass thickness), contamination environment and mission duration.

Numerous missions utilizing the rigid deployable architecture have incorporated designs to address specific mission requirements. Design elements that are particularly relevant to future missions include the following:

Figure 3-4. Deployable Rigid Arrays. From left to right: Mars Exploration Rover with 1.2 m^2 array, Dawn spacecraft (mission to Vesta and Ceres) with 36 m^2 array (illustration), Juno spacecraft (mission to Jupiter) with ~43 m^2 array (illustration).

Electrostatically clean arrays. Electrostatically clean arrays are designed to prevent accumulation of electric charge on solar array surfaces, either to control electric fields or prevent electrostatic discharge (ESD). ITO coatings can be used on solar cell cover-glass to bleed charge from the dielectric surface. Conductive tape can also be used to shield dielectric surfaces, such as adhesives, from space plasma.

High temperature arrays. Arrays operating at less than 1 AU are subject to high temperatures which reduce solar cell efficiency and can jeopardize survival of the hardware. For example, the MESSENGER mission operated at 0.31 AU and incorporated rows of mirrors between rows of solar cells to reflect light and reduce the operating temperature (similar to the Magellan Venus orbiter launched in 1989). The approach also included deliberate off-pointing of the array from the Sun. Even so, the nominal operating temperature was ~130°C, compared with 40 to 70°C that is typical at 1 AU.

The Solar Probe Plus mission (renamed Parker Solar Probe) is scheduled for launch in 2018 and will approach the Sun at less than 0.046 AU. Hence, the thermal environment is even more severe and an active cooling system is used to control the array temperature.

3.3.3 Deployable Flexible Solar Arrays

Deployable flexible arrays replace the rigid panel substrate described above with a flexible blanket, such as a mesh or polyimide sheet. As a result, the system mass can be reduced and a large array can be stowed in a smaller volume for launch. The specific power typically ranges from 100 to 175 W/kg for larger arrays, depending on the solar cell mass and deployment structure. The areal power density is slightly higher than for rigid panels (~338 W/m^2) using current state-of-the-art cells, due to slightly lower operating temperatures. Flexible arrays are capable of providing higher deployed strength and stiffness than traditional rigid arrays, by incorporating a highly stiff deployment boom or frame structure (see discussion of Cygnus array, below). Deployment mechanisms are generally more complex than for rigid panels. Current deployment architectures are described as follows:

Flexible fold-out arrays. Recent flexible fold-out arrays include the following:

- ISS arrays (manufactured by Lockheed-Martin)
- Terra (EOS AM-1) array, manufactured by Northrup-Grumman for the Terra Earth-observation spacecraft, based on the Advanced Photovoltaic Solar Array (APSA) developed with NASA
- UltraFlex array (manufactured by Orbital-ATK). The UltraFlex was used on the Mars Phoenix Lander and the Cygnus cargo resupply vehicle. The Cygnus completed four missions to the ISS using the UltraFlex, in December 2015, March 2016, October 2016 and April 2017. Several additional missions are planned. Each Cygnus wing has a diameter of 3.7 m and is designed to withstand 5 g's acceleration, highlighting one of the advantages available with a flexible fold-out architecture.[13] The UltraFlex is also providing power for the Mars InSight Lander, scheduled for launch in 2018.

Figure 3-5 shows each type of flexible fold-out array. As shown in the figure, the APSA (on the left) and ISS (in the middle) arrays comprise rectangular, flexible blankets (or semi flexible in the case of Terra), which are packed together for launch and are deployed with a boom (or booms), unfolding the blanket, similar to rigid panel arrays. The UltraFlex deploys in a circular manner, resulting in a

[13] http://www.orbitalatk.com/space-systems/space-components/solar-arrays/docs/FS007_15_OA_7463%20UltraFlex.pdf

disc-shaped structure (shown on the right in Figure 3-5). Fold-out arrays generally require motorized deployment. Current developments include a flexible fold-out array using state-of-practice solar cells, developed by Lockheed-Martin, available for commercial spacecraft,[14] and larger versions of the UltraFlex, such as the MegaFlex, developed by Orbital-ATK. The MegaFlex is discussed in more detail below under "Developing Array Technologies".

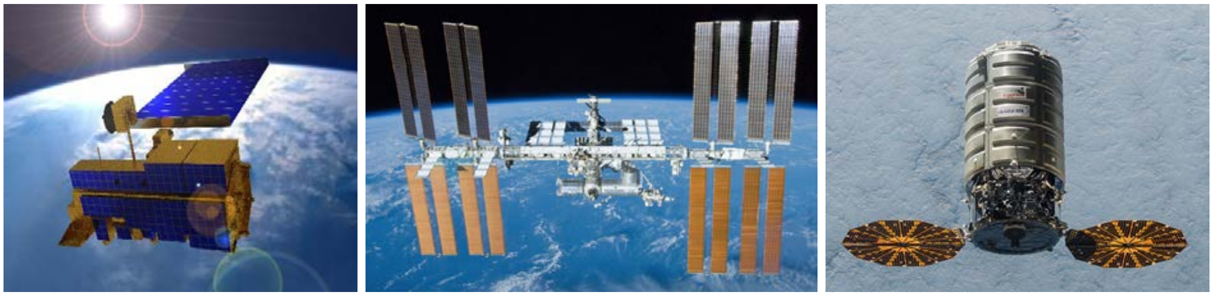

Figure 3-5. Flexible Fold-Out Arrays. *Left*: Illustration of Terra spacecraft with APSA based array.[15] *Middle*: International Space Station with eight flexible arrays and ~2500 m^2 total area.[16] *Right*: Cygnus resupply vehicle with UltraFlex array.[17]

Flexible roll-out arrays. Flexible roll-out arrays comprise a photovoltaic blanket that is rolled around a cylinder for launch and unrolled by a deployment boom(s) in orbit. Roll-out arrays were used on the Flexible Rolled-Up Solar Array (FRUSA) in 1973 and the Hubble Space Telescope in 1990, the latter subsequently replaced during a servicing mission in 1993.

More recently, the ROSA was developed by DSS using roll-out composite booms and a successful flight demonstration occurred on the ISS in July 2017.[19] The booms unroll without the assistance of a motor. Work on qualification of the ROSA for use on commercial satellites was reported by DSS and Loral Space Systems in 2015 and Figure 3-6 shows the ROSA under development. Further developments on the ROSA, including the MegaROSA, intended for higher power (>100 kW) capability, are described below under "Developing Array Technologies".

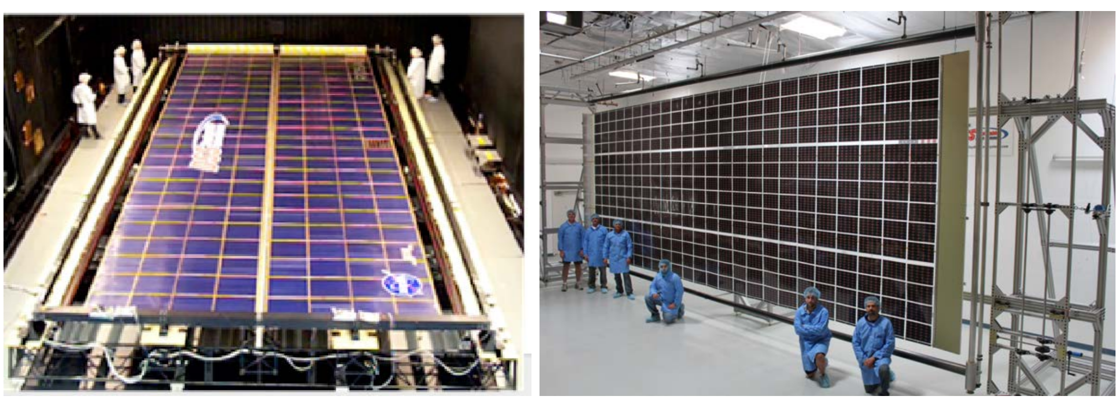

Figure 3-6. Flexible Roll-Out Array. The ROSA comprises a flexible photovoltaic blanket unrolled using composite booms.[18]

[14] http://www.lockheedmartin.com/us/news/press-releases/2014/september/0908-ss-a2100.html
[15] https://terra.nasa.gov/
[16] https://www.nasa.gov/mission_pages/station/main/index.html
[17] https://en.wikipedia.org/wiki/Cygnus_(spacecraft)
[18] http://www.dss-space.com/products_solar_array.html#flexible_blanket_arrays
[19] https://www.nasa.gov/feature/roll-out-solar-array-technology-benefits-for-nasa-commercial-sector

3.3.4 Concentrator Solar Arrays

Although concentrator arrays are not currently in use or in production for flight systems, concentrator technology previously developed for flight and technologies currently under development have potential importance for planetary exploration. Concentrator arrays refer to arrays in which sunlight from a given area is directed onto a smaller area of solar cells. Concentration of sunlight on solar cells alleviates the performance losses associated with LILT operation at the outer planets, since concentration increases the effective solar irradiance on the cells. At the same time, care in the design must be made to avoid high concentrated illumination intensities and temperatures when near the Earth. Hence, a brief overview of concentrator technology is provided here and new developments are discussed under "Developing Array Technologies".

Concentrator arrays can be either body-mounted, deployable rigid or deployable flexible arrays and the basic structure can be described by those three categories described earlier. The optics needed for concentration include the following:

Refractive optics. Refractive optics were used on the Deep Space 1 array, referred to as SCARLET (solar concentrating array with refractive linear element technology) and launched in 1998. The solar array was manufactured by Orbital-ATK. The array comprised rigid panels with Fresnel lenses having a line focus and ~8× concentration factor. The lenses were constructed from silicone on the back side of ceria-doped glass. Other approaches to refractive optics include point focus lenses and lenses constructed with alternate materials.

Reflective optics. Reflective optics designed for space include planar reflectors, such as the Orbital-ATK Cell Saver, DSS FACT (Functional Advanced Concentrator Technology), and Hughes 702 designs, which provide ~2× concentration. The latter suffered from higher than expected degradation which would need to be considered and mitigated in similar designs. In principle, reflective optics can utilize parabolic cylinders, paraboloids and non-imaging reflective surfaces.

Compound reflective/refractive optics. Compound optics have been developed for terrestrial concentrators but are not currently in use for space applications.

3.4 Summary

Space solar cell and solar array technology has advanced significantly since the first solar-powered satellite in 1958 with solar cell efficiency has increasing from less than 10% to over 30%. Arrays have grown in power from milliwatts to over 20 kW on spacecraft with the International Space Station arrays producing 120 kW. The efficiency of SOP triple junction cells, designed and optimized for Earth orbital missions, is typically 29.5 −2/+1% under standard test conditions (1 AU, 28°C). The specific power of the solar arrays has also improved from 30 W/kg to 100 W/kg during the past 25 years and have enabled several Mars (orbital and surface), small body (flyby and orbital), and inner planetary (flyby and orbital) missions during the past decade.

In spite of these advances, SOP solar arrays have limited operational capabilities in extreme environments. These include low solar irradiance and low temperature environments at the outer planets, high temperature, high or low solar irradiance at the inner planets, corrosive environments at Venus, and dusty conditions on Mars. In view of these limitations, the SOP solar power systems need improvements to achieve future outer planet, inner planet, and Mars missions under consideration for the next decadal planetary science missions. SOP solar arrays need to be reduced in mass and volume to power the next decadal solar electric propulsion missions to small bodies and outer planet destinations. Some, but not all, of this can be achieved with solar cell and solar array optimization for the particular environment.

4 Advanced Solar Cell and Array Technologies

4.1 Introduction

This section describes the various solar cell and solar array technologies currently under development in industry and at various national laboratories, universities, NASA, and JPL.

4.2 Advanced Solar Cell Technologies

Space solar cell technologies currently under development are focused on increasing solar cell efficiency and enabling operation in specific mission environments. A great deal of effort is being devoted to improving efficiency. As discussed below, substantial gaps are still present in addressing the key environments required for future planetary science missions.

4.2.1 Cell Efficiency

Background. The maximum theoretical efficiency, using thermodynamic considerations for black-body solar cells under terrestrial solar illumination (1-sun, AM1.5 spectrum), for a *single* junction solar cell with a bandgap of 1.1 eV is 30%[20]. For a *triple* junction cell, that limit is 49%.[21] For an *unlimited number of* junctions, the limit approaches 68%. Under extraterrestrial (AM0) illumination, the theoretical efficiency limit for a single junction GaAs solar cell is ~25%, as shown in Figure 4-1.[22] This is 17% lower than the terrestrial limit of 30%. Assuming similar behavior for a triple junction solar cell, its theoretical efficiency limit would be ~40% under AM0 illumination.

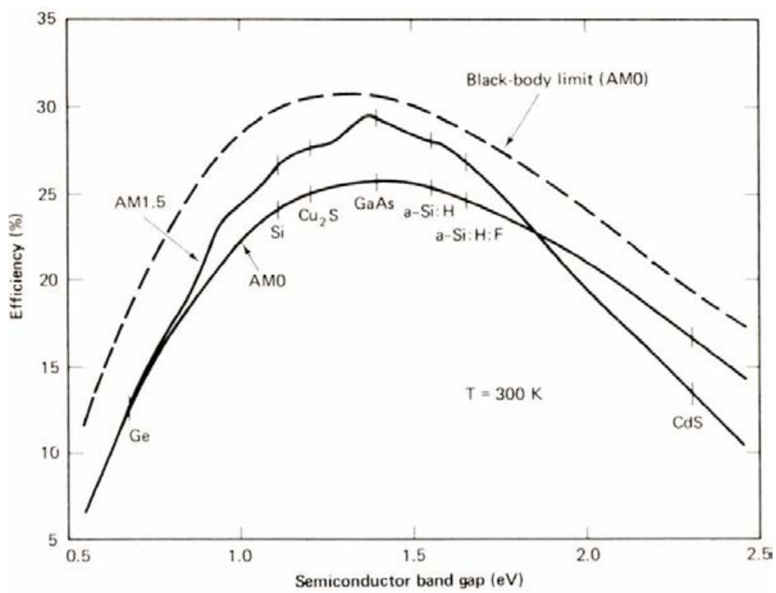

Figure 4-1. Solar cell efficiency limits versus semiconductor bandgap. The solid lines are semi-empirical limits for AM0 and AM1.5 illumination; the dashed line is based on thermodynamic considerations for black body solar cells under AM0 radiation.[13]

The highest reported efficiency for a single junction solar cell under terrestrial illumination (1-sun, AM1.5 spectrum) is 28.8%, reported by Alta Devices, Inc. for a GaAs cell.[23] For a triple junction solar cell, the highest reported efficiency is 37.9%, provided by Sharp Corp. The highest efficiency for a non-concentrator multi-junction cell is 38.8%, reported by Spectrolab, Inc., for a 5-junction cell. For concentrator cells, the highest reported efficiency is 46.0%, from Fraunhofer Institute for Solar Energy (ISE)/Soitec.

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[20] Shockley, W., H. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells", *J. of Appl. Phys.* 32, 510 (1961).

[21] De Vos, A., "Detailed Balance Limit of the Efficiency of Tandem Solar Cells", *J Phys. D: Appl. Phys.* 13, 839–46 (1980).

[22] Green, M., "Solar Cells – Operating Principles, Technology, and System Applications", Prentice-Hall, 1981.

[23] https://www.nrel.gov/news/press/2013/2226.html

Two trends are apparent in these results. First, actual cell efficiencies tend to approach closer to the theoretical limits as technologies mature. Second, the theoretical limits increase as new junctions are incorporated into cell designs.

Since space cells currently in large scale production provide ~30% efficiency, it is clear that there are significant opportunities for continued efficiency improvements. These improvements can be expected to include narrowing the gap between research and production cells, increasing the number of junctions, and developing new materials that can further approach the maximum possible efficiency.

Limitations of SOP cells. The primary approach to increasing cell efficiency is to optimize the bandgap of each subcell in the multi-junction stack. The greatest source of energy loss is the difference between the photon's energy and the junction bandgap. Hence, subcells must convert each photon in a material with a bandgap as close as possible to the photon's energy to maximize efficiency. At the same time, cell current in a series stack of subcells is limited by the junction with the smallest photocurrent. Hence, subcells must also be current-matched to maximize efficiency. Ongoing developments are focused on growing materials and developing devices that can simultaneously address both goals.

The limitation inherent in SOP cells is shown in Figure 4-2. As shown in the figure, the three subcells are not current-balanced. The maximum current obtainable from each subcell is represented by the area under each colored section of the spectral response curve. Specifically, the bottom junction (Ge) generates excess photocurrent due to its low (0.7 eV) bandgap. As a result, a substantial number of photons converted to current at 0.7 eV could be converted more efficiently at a higher energy level.

Most approaches under development include adding one or more junctions to the 3-junction structure and including a subcell with a bandgap ~1.0 eV (corresponding to 1,200 nm in Figure 4-2). Target efficiencies for next generation cells are ~36–37% under AM0 illumination at 28°C. In principle, higher efficiencies, above 40%, are possible in the longer term. Key approaches include the following technologies.

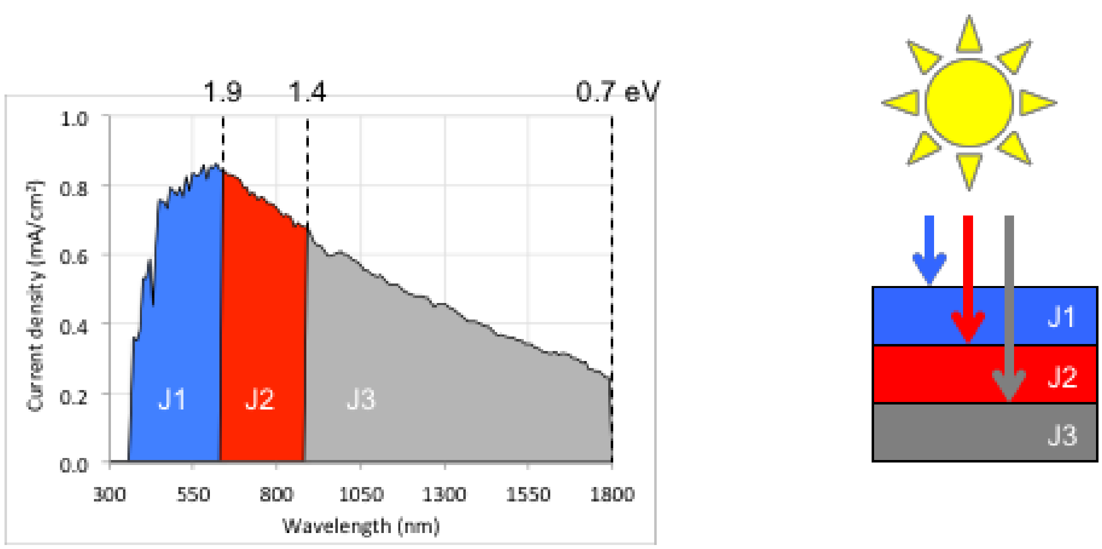


Figure 4-2. Shortcoming of SOP Solar Cells. The bottom junction generates excess current at a low potential due to its low bandgap (0.7 eV).

Inverted Metamorphic Multi-junction (IMM) Cells. IMM solar cells include a 1.0 eV bandgap, as shown in Figure 4-3. The term "metamorphic" refers to a mismatch is the crystal lattices of different materials in the structure. In this case, the crystal lattice of the 1.0 eV material is not matched to the top two junctions ($GaInP_2$ and GaInAs). This would generally introduce significant crystal defects if the top two subcells were grown on the 1.0 eV materials. However, the IMM approach addresses this difficulty by growing the structure on Ge or GaAs starting from the top subcell (i.e., in inverted order). The growth substrate is then removed, for example, by an etching process, as illustrated in Figure 4-2. As a result, the crystallinity of the top two subcells is preserved.

IMM solar cells have demonstrated up to 35% BOL efficiency (at AM0, 28°C). Space qualification is currently in progress. Production 4-junction IMM assemblies (with cover-glass and interconnects) are offered by SolAero Technologies with an average AM0 efficiency of 33.0%.[24] Five- and six-junction versions of the IMM technology are also under development, intended to achieve 36–37% efficiency. The key challenge for this technology has been achieving cost parity with SOP cells.

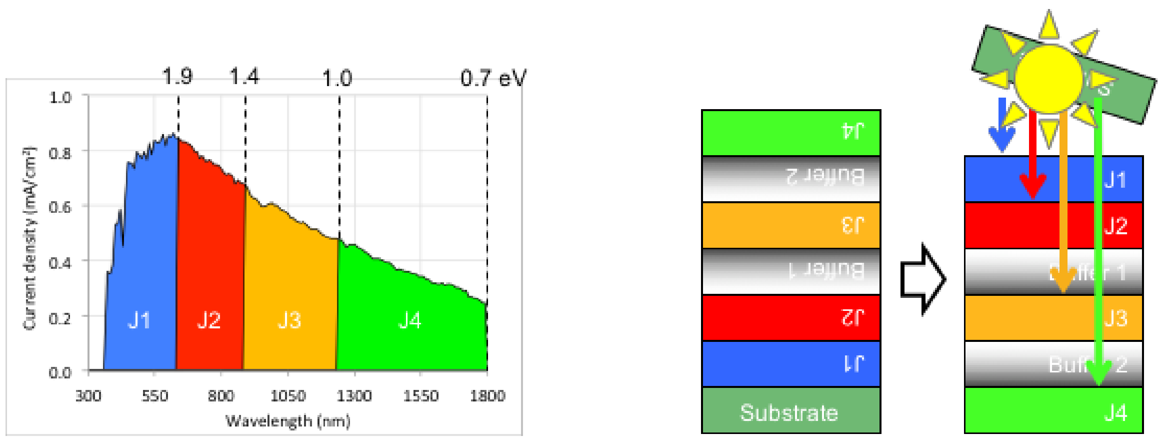


Figure 4-3. IMM Solar Cells. A 1.0 eV bandgap is added using the technique of inverted growth and subsequent removal of the growth substrate.

Upright Metamorphic Multi-junction (UMM) Cells. UMM materials generally include a 1.0 eV bandgap and at least four junctions but, in contrast to IMM cells, are fabricated by growing the structure in the same order as SOP cells, starting from the bottom subcell. The difficulty of lattice mismatch between the 1.0 eV material and the top two subcells is addressed by growing transparent buffer layers between the mismatched layers, as shown in Figure 4-4. Development of this technology is aimed at finding the buffer layer structure that minimizes propagation of defects into the metamorphic junctions. For example, buffer layers can be graded; i.e., stoichiometry can be varied as a function of depth. Efficiency from 29–30% at AM0 has been reported by Azur Space. Five- and six-junction structures are also possible in principle providing higher efficiency. The key challenge for this approach has been achieving sufficient crystal quality in the higher bandgap junctions.

Dilute Nitride Materials. The challenge of finding a material with a 1.0 eV bandgap with a crystal lattice matched to the SOP structure is solved by adding a small amount of nitrogen to the 1.0 eV material. Hence, these cells provide optimized bandgaps without sacrificing crystal quality or introducing inverted growth techniques. The cell structure is illustrated in Figure 4-5.

[24] https://solaerotech.com/products/space-solar-cells-coverglass-interconnected-cells-cic/

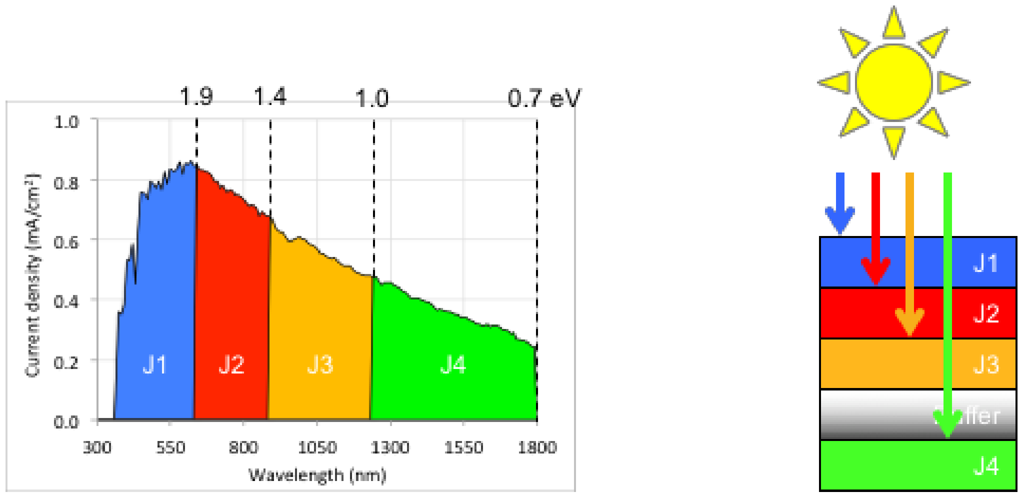


Figure 4-4. UMM Solar Cells. A 1.0 eV bandgap is added using lattice mismatched materials and buffer layers to minimize propagation of crystal defects.

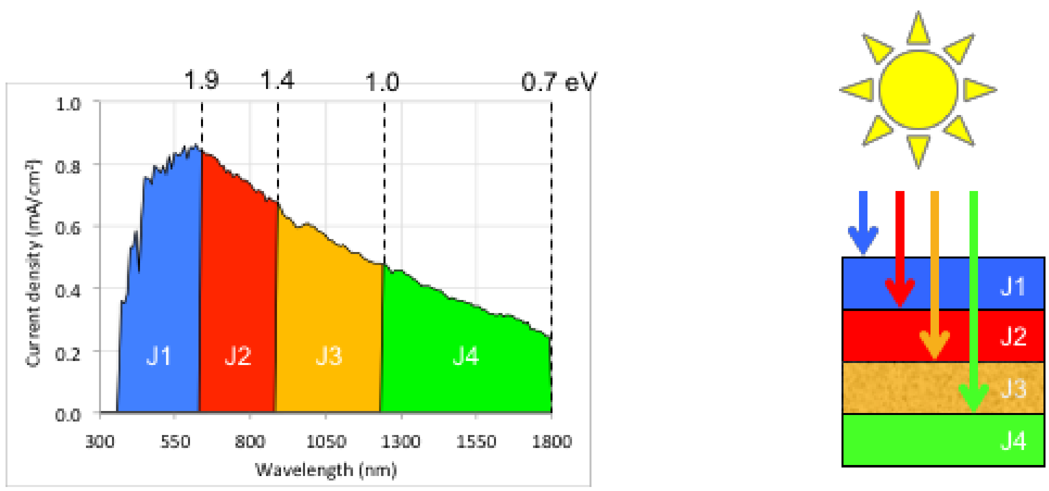


Figure 4-5. Dilute Nitride Solar Cells. A 1.0 eV bandgap is added using materials that are lattice matched to GaAs. Nitrogen in the 1.0 eV material is used to fine-tune the lattice constant.

Growth of these materials has been successful to date using molecular beam epitaxy (MBE) rather than MOVPE. As a result, growth rates have been substantially slower than SOP cells and scale-up for manufacturing has been a key challenge. Dilute nitride cells manufactured by Solar Junction, Inc. have set the record efficiency is 43.5% at 925 suns[25] for terrestrial concentrator cells grown on GaAs substrates. Development of cells for space application is underway; AM0 efficiencies from 30–31% have been reported. Five- and six-junction structures are also possible, in principle providing higher efficiency and meeting the goal of 37% at AM0.

Semiconductor Wafer Bonding. Semiconductor wafer bonding technology (SBT) refers to mechanical connection of one semiconductor wafer on top of another. This approach enables two wafers that are grown separately, with different lattice constants, to be combined into a multi-junction stack. As a result, difficulties associated with defects from metamorphic growth are avoided.

[25] Sabnis, V., et al., "High-Efficiency Multijunction Solar Cells Employing Dilute Nitrides", Proceedings of AIP Conference 1477, 14 (2012).

For example, a Ge or GaAs-based wafer can be bonded on top of an InP-based wafer. The resulting cell structure is illustrated in Figure 4-6. In general, removal of one growth substrate (e.g., Ge) is performed to provide a transparent optical path, as shown in the figure.

AM0 efficiencies from 34–35% have been reported by Spectrolab, Inc. Five- and six-junction structures are also possible, in principle providing higher efficiency and meeting the goal of 37% at AM0. The key challenge with this approach has been achieving cost parity, due to the need to grow two wafers to fabricate a single cell, the high cost of InP substrates, and the cost of substrate removal and inverted processing as in the case of IMM.

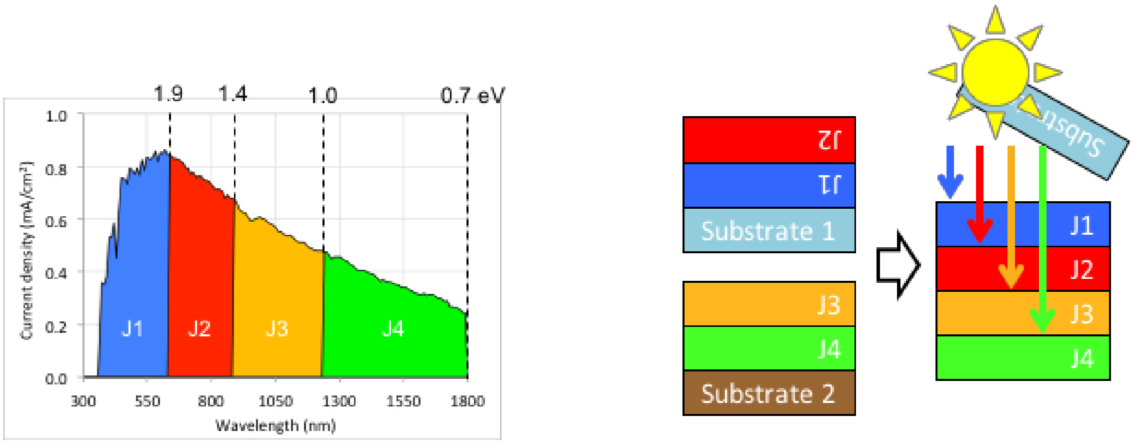


Figure 4-6. Semiconductor wafer bonding. Two separate wafers are bonded together to create single cell. As a result, semiconductor quality is not affected by lattice mismatch.

Near-IR Absorbers. Multiple approaches to increasing solar cell efficiency have employed techniques for generating current from photons with energy below the material bandgap. These techniques include introduction of quantum wells and quantum dots. Typically, these absorbers are added to the middle (GaInAs) subcell of the SOP solar cell, to address the shortcoming of excess photocurrent in the bottom (Ge) subcell. The principle of these approaches is illustrated in Figure 4-7.

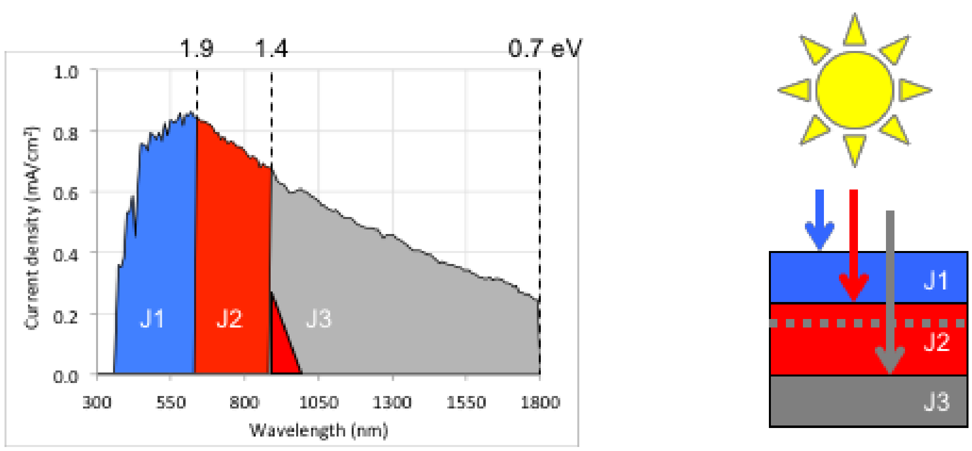


Figure 4-7. Near-IR Absorbers. Quantum wells or quantum dots are used to extend the absorptance band of a limiting junction.

AM0 efficiencies from 26–27% have been reported by Rochester Institute of Technology (RIT). In principle, these techniques could be applied to multiple junctions and cells with more than three junctions. The key challenge with this approach has been reaching the performance of current SOP cells.

4.2.2 Planetary Mission Environments

It is one thing to compare cell designs that can perform under terrestrial or AM0 conditions, but planetary science missions call for cells that perform under varying environmental condition. Not all cells technologies can be optimized for such a wide variety of environments and, therefore, cell technologies for operation in several specialized mission environments are in development or under study. Missions of interest include the inner planets, planetary surfaces, outer planets, and SEP missions. The relevant environments and developing technologies are described below.

Low Irradiance, Low Temperature (LILT) Conditions. LILT conditions degrade solar cell performance at the outer planets and the degradation varies significantly within a population of SOP cells. The primary mechanism for LILT-induced efficiency loss arises from low resistance current paths, or shunt paths, from base to emitter within the semiconductor. These paths can be caused by crystalline defects. Current losses through these shunts are generally proportional to the cell voltage and are negligible under 1 AU conditions as long as the shunt resistance is on the order of KOhms, However, at low irradiance, these losses become a larger fraction of the photocurrent and, hence, significantly impact efficiency. Cell voltage increases at low temperature, which partially compensates for the shunt-related losses.

Current missions such as Juno and the planned Europa Clipper address this issue using a screening process to select the subset of cells with acceptable LILT behavior. A significant quantity of cells do not pass the screening and are unusable. Furthermore, the usable cells are not optimized for LILT conditions; in principle, higher performance could be achieved by designing for the expected current and temperature.

Research is underway to better understand the LILT phenomena and develop cells that are optimized for LILT conditions. For example, research at JPL is focused on developing high-efficiency solar cells with LILT capability at Saturn.[5] The project employs advanced device architectures (such as upright and inverted metamorphic structures) with potential for high AM0 efficiency, in combination with LILT-optimized cell designs that reduce or eliminate performance-limiting features for the Saturn environment (9.5 AU, −165°C). The design optimization techniques being studied include: 1) eliminating any rectifying semiconductor-to-semiconductor interfaces that limit the I-V curve fill factor at LILT; 2) modifying the subcell base epitaxial layer thicknesses to ensure optimal current balance and maximal EOL/BOL efficiencies at low temperature; 3) taking advantage of the lower series resistance losses at low irradiance to implement low-obscuration grid designs for improved current production at LILT; and 4) identifying and mitigating the source of any low-current shunts that are insignificant at 1 AU but performance-limiting at LILT.

Ultra-Lightweight Arrays and SEP missions. Flexible, ultra-lightweight solar cells can be enabling for very large solar arrays and SEP missions to the outer solar system. In order to produce ~1 kW at these distances from the Sun, solar arrays are needed that produce ~100 kW at 1 AU. The dense packaging for stowage of these arrays allows for a mass reduction that has a dramatic system impact.

Aero-vehicles for exploration in the Mars and Venus atmosphere or high-altitude aircraft on Earth all would benefit from the development of thin, flexible, ultra-lightweight cells. The cells are typically installed directly on the wings or fuselage of these vehicles. The wings can themselves be flexible membranes and the cells must be flexible to survive. Minimum mass is also essential to the successful flight of these vehicles.

Cells fabricated using a substrate-removal processes, such as IMM cells, can be ultra-thin (e.g., <40 µm) and, therefore, flexible and extremely lightweight. Examples of ultra-thin cells are shown in Figure 4-8. These include ultra-thin GaAs cells from Alta Devices, Inc., epitaxial liftoff (ELO) cells from Microlink Devices, Inc., and IMM cells from Sharp Corp.

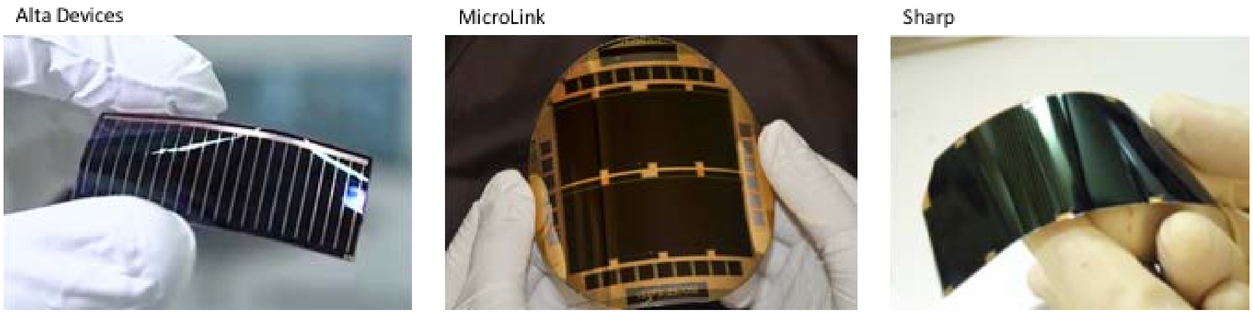


Figure 4-8. **Flexible ultra-lightweight solar cells.** Ultra-thin cells can be enabling for very large arrays, SEP missions to the outer solar system and aero-vehicles.[26,27,28]

High Temperature. Missions to the inner planets result in high temperature conditions. Landers or near-surface operations are unable to mitigate these conditions through off-pointing or active cooling. For example, a rover on Venus would need cells capable of operation at ~460°C. Temperature at an altitude of 25 km would be ~300°C. These temperatures affect survivability because they induce diffusion of materials, such as metallic contacts, into the semiconductor; diffusion of metals can cause internal shorting and culminate in failure. These temperatures also impact performance by decreasing cell bandgaps, and increasing bandgap-to-voltage offsets, reducing the cell voltage. Power versus temperature for a $GaInP_2$ cell is shown in Figure 4-9. As shown in the figure, operation would not be feasible on the venusian surface with existing cells due to the low light levels and high temperatures; however, operation at higher altitudes appears more feasible if survivability can be improved.

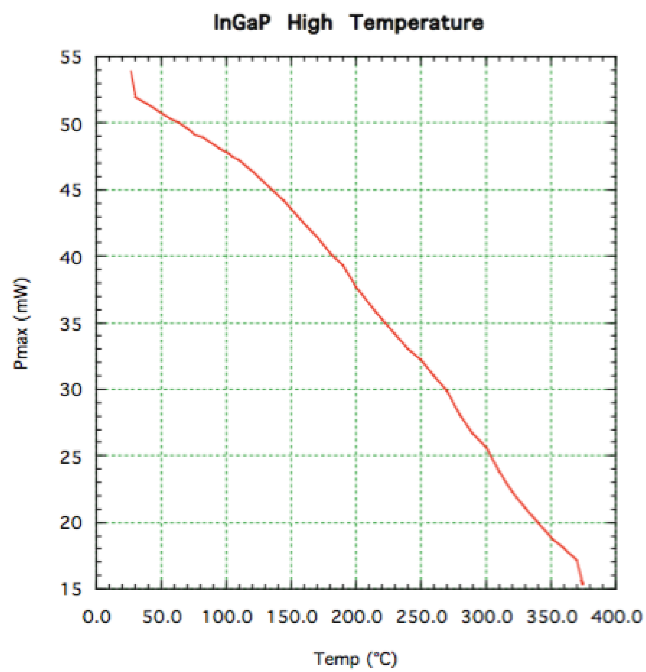


Figure 4-9. Power versus temperature for $GaInP_2$ **cell.**[29] Performance at temperatures above 300°C is severely limited for SOP cells.

Initial development of technology for high temperature operation was initiated by the ARPA-E Full-Spectrum Optimized Conversion and Utilization of Sunlight (FOCUS) program. Development of

[26] altadevices.com/technology
[27] mldevices.com
[28] Takamoto, T., "Reliability of space solar sheet with inverted metamorphic triple-junction cells," Proceedings of Space Power Workshop, 2016.
[29] Landis, G., NASA GRC

cells specifically for high temperature operation in the Venus atmosphere is underway under the NASA Hot Operating Temperature Technology (HOTTech) program. The HOTTech program is focused on low irradiance, high temperature (LIHT) conditions as well as the corrosive environment and solar spectrum on Venus (discussed in the subsections below). The technical approach for HOTTech is to implement contact materials that are stable at high temperatures and optimize bandgaps for the operating temperatures (and solar spectrum) on Venus. The projected performance advantages of the proposed LIHT solar cells are that they: a) operate efficiently (>16%) at high temperatures (i.e., 300°C), b) operate effectively at low solar intensities *characteristic* of Venus environments, c) survive and operate in Venus corrosive environments, d) provide long operational capability (>6 months), and e) survive at Venus surface temperature for more than a month. Comparison of the advantages of the proposed LIHT solar cells with SOP triple junction solar cells are given in Table 4-1.

Table 4-1. Comparison of Proposed LIHT Cell and SOP Triple Junction Solar Cell.

	SOP Cell	LIHT Cell Performance Goals	Advantages of LIHT Cells
Operating Temperature	−140°C to 150°C	25°C to 300°C	Operation at Venus temperature
Efficiency	2.75% at 300°C and solar intensities of 2600 W/m^2 [30] (AM0 at Venus)	16% at 300°C and at solar intensities of 200 W/m^2	5 times higher efficiency at 300°C
	30% at 25°C	25% at 25°C	
Solar Irradiance	1,365 W/m^2	200 W/m^2	Improved operational capability at low solar intensities and low temperature
Lifetime	15 years at 25°C Few hours at 300°C	15 years at 25°C 6 months at 300°C	
Survivability	~1 h at 460°C	1 month at 460°C	

Planetary Surface Spectra. The solar irradiance spectrum and the overall solar irradiance are modified by the presence of a planetary atmosphere for missions involving surface or near-surface operations. For example, the effect of the venusian atmosphere at various altitudes on the solar spectrum is shown in Figure 4-10. Solar cells optimized for operation on Venus are only conceptual at present. Solar cells optimized for the martian surface have been demonstrated[6] and can provide substantial benefits. Approximately 7% improvement in power output can be achieved for a typical point in the day, with the Sun at a 60° elevation angle; slightly reduced improvements can be achieved at lower Sun elevations.

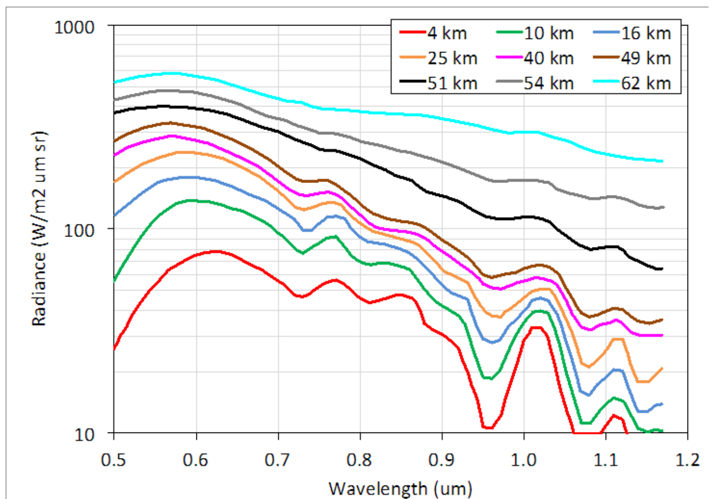


Figure 4-10. Measured Solar irradiance spectrum on Venus. Solar irradiance decreases at lower altitudes and energy at wavelengths below 600 nm is particularly diminished.

Corrosive Atmosphere. Clouds in the venusian atmosphere contain sulfuric acid (H_2S0_4) and can corrode SOP solar cell assemblies. For example, metallic electrical contacts are susceptible to

[30] Geoffrey, A.L. and H. Emily, Analysis of Solar Cell Efficiency for Venus Atmosphere and Surface Missions, in 11th International Energy Conversion Engineering Conference. 2013, American Institute of Aeronautics and Astronautics.

corrosion by H_2S0_4. Development of the solar cells for this environment would enable future solar powered missions to Venus, such as atmospheric measurements using high altitude balloons. Corrosion resistant cells are likely going to be covered with coatings, e.g., Al_2O_3 and an additional protective coating will cover the entire cell and contacts to provide the required resistance. These, along with novel metal contacts, are expected to be tested as part of the HOTTech program discussed above.

High Radiation. High radiation environments of interest include the jovian magnetosphere and Earth's Van Allen belts. The Van Allen belts are also significant for SEP missions that pass through these belts en route to planetary destinations. Electron and proton radiation degrades cell performance by creating defects in the semiconductor material. These defects become recombination sites for minority carriers, reducing the fraction of photons that are successfully converted to current in each junction.

Solar arrays with SOP solar cells incur a large mass penalty for shielding and/or a limited lifetime when exposed to these environments. For example, solar cells on the Juno mission utilize cover-glass that is three times the thickness of typical cover-glass (300 μm versus 100 μm). Future missions will incur either greater mass penalties or performance degradation. The Europa Clipper mission is preparing for a more severe radiation environment, approximately 2.7 times the radiation exposure of Juno (an equivalent 1 MeV electron fluence of 3.63E15 versus 1.35E15 e/cm^2), due to its orbit through the jovian magnetosphere. The Europa Lander mission is expected to be subject to an even more severe environment, approximately 4.4 times the exposure of Juno (5.9E15 e/cm^2). Development of cells optimized for high radiation involves modifications to the doping profile and layer thicknesses within the semiconductor. The technology for optimization for extremely high radiation doses is available in principle, but has not been implemented at present. Juno used, and the Europa missions are planning to use, SOP cells which are not optimized for the extremely harsh radiation environment at Jupiter.

4.3 Advanced Solar Array Technologies

Solar array technologies in development for space flight missions emphasize increasing specific power, reducing cost, and novel methods of deploying higher power arrays given existing constraints on launch volume and deployed stiffness. Flexible arrays, concentrator arrays, and array technology for specific environments are discussed below.

4.3.1 Flexible Arrays

A key trend in developing array technology is the growth in power capability for flexible arrays and a reasonable target for specific power of the next generation flexible array is 200 W/kg at BOL and 1 AU, assuming next generation solar cells. The following flexible array technologies are under development.

MegaFlex. The MegaFlex array is manufactured by Orbital-ATK and represents an extension of the UltraFlex array, described in the section on state-of-practice, to larger diameters and higher power capability. The MegaFlex deploys as a flexible fold-out array with a circular geometry, similar to the UltraFlex. However, to achieve a larger diameter, the MegaFlex deploys in two stages; the first stage extends the radius of the circle and the second stage unfolds along a circular path (same as UltraFlex). Deployment of a 10-m diameter MegaFlex, shown in Figure 4-11 has been demonstrated in ground test. The MegaFlex is intended to be scalable to diameters as large as ~30 m.

Figure 4-11 also shows a conceptual illustration of a large MegaFlex array on a flight system. The MegaFlex is intended to reach power levels up to 300 kW at BOL, 1 AU.

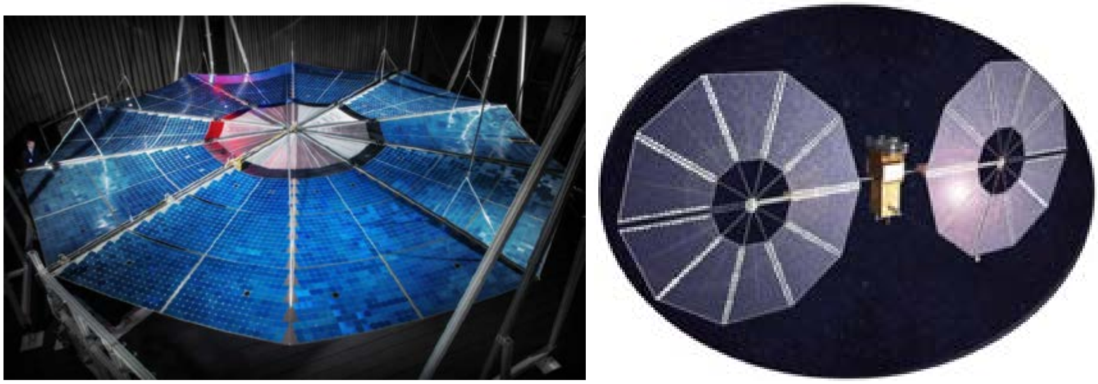


Figure 4-11. MegaFlex array. At left, a 10-m diameter MegaFlex demonstration unit was deployed in ground test.[31] At right is an illustration of a MegaFlex array on a flight system.[32]

A2100 Spacecraft. Lockheed Martin Corp. announced development of flexible solar arrays for an upgraded version of the A2100 spacecraft bus. The configuration, shown in Figure 4-12, uses the flexible fold-out technology similar to the ISS.

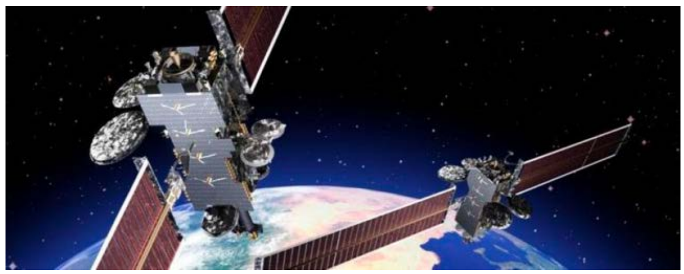


Figure 4-12. A2100 spacecraft. Flexible fold-out arrays based on the heritage ISS arrays, are in development for the Lockheed Martin A2100 spacecraft bus.[33]

Mega-ROSA. Mega-ROSA is manufactured by DSS, and represents an extension of the ROSA, described in the section on state-of-practice, to higher power. The Mega-ROSA is shown in Figure 4-13 and comprises a set of multiple ROSAs deployed from a central structural spine. The Mega-ROSA is intended to reach power capability exceeding 100 kW at 1 AU, BOL, and is also shown to be extensible to 300 kW.

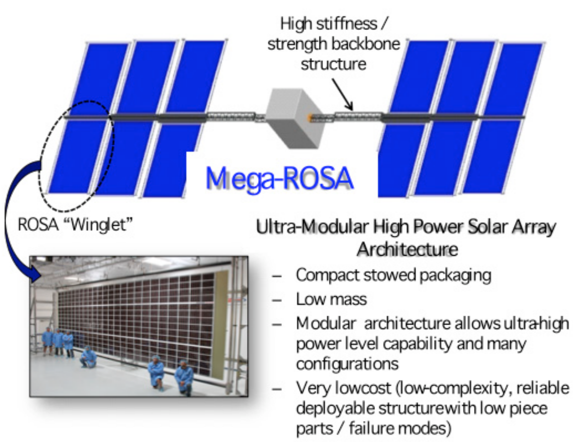


Figure 4-13. Mega-ROSA. The Mega-ROSA comprises multiple ROSAs deployed from a central structural spine.[21]

Composite Beam Roll-Up Solar Array (COBRA). The COBRA is manufactured by SolAero Technologies and represents a new approach to roll-out arrays. Solar cells are unrolled on a composite blanket and structural stiffness is provided by the blanket's curvature. The configuration is shown in Figure 4-14. The primary applications for this technology are

[31] http://www.orbitalatk.com/space-systems/space-components/solar-arrays/docs/FS008_15_OA_7463%20MegaFlex%20Solar%20Array.pdf
[32] https://www.nasa.gov/offices/oct/home/feature_sas.html#.WAmcEzKZOqA
[33] http://www.lockheedmartin.com/us/ssc/commspace.html

presently small satellites (SmallSats) with power output up to ~600 W at 1 AU. The COBRA configuration provides compact stowage for these applications.

Figure 4-14. COBRA. The COBRA array is designed to provide compact stowage for SmallSat applications.[34]

4.3.2 Concentrator Arrays

As noted in Section 3.3, concentrator arrays offer a potential approach for mitigating the losses associated with LILT conditions. Specifically, increasing the effective irradiance using concentrating optics would allow solar cells in the outer solar system to operate as if they were much closer to the Sun. As discussed in Section 3.3, several challenges with concentrating systems must be overcome. These include avoiding excessive illumination during portions of a mission that are closer to the Sun, sensitivity of the optics to pointing, and sensitivity of optics to degradation in the space environment.

Nevertheless, concentrating arrays provide an intriguing approach for planetary exploration at farther distances, such as those beyond Saturn. Hence, further development of this technology may be significant in the long term. The following paragraphs briefly describe developmental work on this technology.

Two developmental reflective concentrators are shown in Figure 4-15.

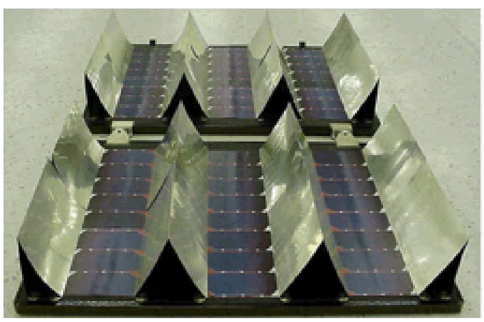
(a)


Figure 4-15. Reflective Concentrator Technologies.
(a) At left is a Cell Saver demonstration figure.[35]
(b) Below is a FACT demonstration figure.[36]
Both use ~2× concentration to reduce the required quantity of solar cells.

(b)


Cell Saver Solar Array. The Cell Saver provides ~2× concentration using the deployable optical reflectors shown in Figure 4-15. The Cell saver is manufactured by Orbital-ATK and is intended primarily for cost reduction. A flight experiment of a small module is currently in Earth orbit.

[34] http://www.solaerotech.com/wp-content/uploads/2016/08/COBRA-Datasheet-August-2016.pdf
[35] http://www.orbitalatk.com/space-systems/space-components/solar-arrays/docs/FS002_15_OA_3862%20CellSaver.pdf#search=%22Cell%20Saver%20Solar%20Array%22
[36] http://www.techbriefs.com/component/content/article/ntb/tech-briefs/manufacturing-and-prototyping/15070

Flexible Array Concentrator Technology (FACT). The FACT array is under development by DSS and is a ~2× reflective concentrator, similar to the Cell Saver. FACT incorporates the reflective concentrator into the ROSA deployment architecture, as shown in Figure 4-15.

Two developmental refractive concentrators are shown in Figure 4-16.

Stretched Lens Array (SLA). Development of the SLA has been conducted by Entech and Orbital ATK. Deployable Fresnel lenses provide ~7–10×, up to 25× for the Ecole d'Etudes Sociales et Pedagogiques (EESP) program for point focus Fresnel concentration, as shown in Figure 4-16 (left). The approach is similar to the array on the DS-1 spacecraft, which utilized rigid Fresnel lenses and was launched in 1998. The design for DS-1 was configured to operate at lower temperatures than planar arrays normally operate thereby avoiding degradation induced by high temperatures. The SLA replaces the rigid lens with a flexible lens that can be stowed more compactly for launch.

Solar Optical Lens Architecture on Roll-Out Solar Array (SOLAROSA). Development of the SOLAROSA has been conducted by DSS. This approach also uses a flexible Fresnel lens to provide ~7–10×, up to 25× for the EESP program for point focus Fresnel concentration. The flexible lens is incorporated into the ROSA architecture, as shown in Figure 4-16 (right).

Figure 4-16. Refractive Concentrator Technologies. At left is an SLA demonstration figure.[37] At right is a SOLAROSA demonstration figure.[38]. Both use flexible Fresnel lenses to achieve ~7–10×, up to 25× for the EESP program for point focus Fresnel concentration.

Novel ideas for concentrators are emerging, including gossamer or very large collectors, and may have potential that could substantially alter the ability to use solar power in the distant reaches of the solar system.

4.3.3 Specialized Planetary Mission Environments

Developing array technologies for special mission environments include dust mitigation for operation on Mars' surface and arrays for high irradiance conditions.

Dust Mitigation for Mars Surface Operations. Solar arrays on Mars are highly sensitive to accumulation of dust, as well as periodic removal of dust by martian winds. However, the unpredictable power output of arrays impacts the ability to perform surface operations. Hence,

[37] https://spinoff.nasa.gov/spinoff2002/er_7.html
[38] http://dss-space.com/products_solar_array.html

technology to control or mitigate dust accumulation is potentially extremely advantageous and could reduce surface operational costs.

Two approaches that formed the basis of previous research efforts are shown in Figure 4-17. At left is a technology that uses electric fields to remove dust.[39,40] At right is a technology that uses piezoelectric actuators to remove dust via mechanical vibration.[41] Both of these technologies require further development to enable implementation on flight solar arrays.

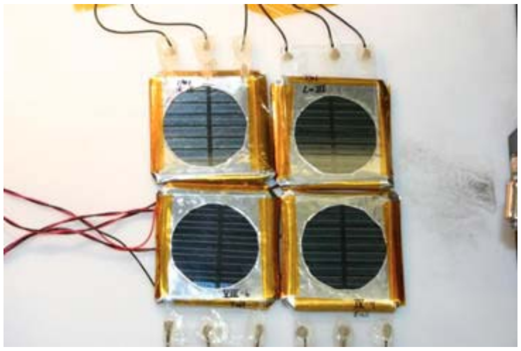


Figure 4-17. Martian Dust Mitigation Technology. At left is a technology utilizing electric fields for dust removal. At right is a technology using piezoelectric actuators and mechanical vibration.

High Irradiance High Temperature (HIHT) Environments. The Solar Probe Plus mission (renamed Parker Solar Probe) is intended for operation as close as 0.046 AU from the Sun. The solar irradiance will be roughly 500 times the solar irradiance in Earth orbit. As mentioned earlier, to survive and operate in this environment, the array is actively cooled by a pumped fluid loop. The array area is 1.6 m^2 and comprises two wings. An illustration of the spacecraft is shown in Figure 4-18. The ESA BepiColombo mission to Mercury is using high temperature solar arrays capable of operating at temperatures as high as 190°C. Further, the solar arrays contained solar cells and optical solar reflectors.

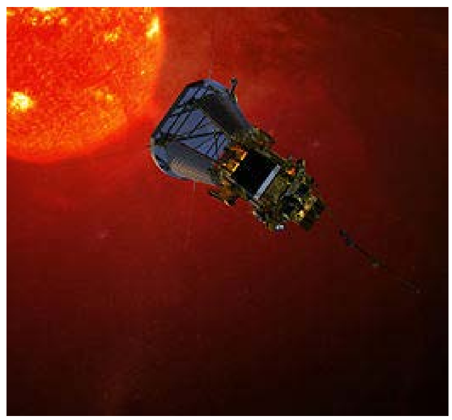


Figure 4-18. Solar Probe Plus (Parker Solar Probe). This is intended to reach a distance of 0.046 AU from the Sun.

4.4 Infrastructure

It is necessary that NASA maintain facilities and other required resources for solar cell/array measurement, analysis, and characterization. Special photovoltaic facilities are needed to develop, test, and assess PV technologies for the various NASA-unique mission requirements. In addition, NASA needs to maintain the required calibration methods and standards for these measurements. Special test facilities are required for testing and characterization of PV systems under special conditions, such as LILT (outer planets and their

[39] Calle, C. I., et al, "Dust Particle Removal by Electrostatic and Dielectrophoretic Forces with Applications to NASA Exploration Missions", Proc. ESA Annual Meeting on Electrostatics (2008).

[40] Mazumder, M., "Performance Restoration of Dusty Photovoltaic Modules using an Electrodynamic Screen", IEEE Photovoltaic Specialists Conference (2015).

[41] "Solar Array Dust Removal System (SADRS) for Long Life Mars Surface Missions Phase 2 Final Report", ATK Space, JPL Contract No. 1264237, 2005.

moons), HIHT (inner planets), LIHT (Venus aerial and surface), dusty environments (Mars), and/or high radiation environments (Jupiter and its moons).

Some limited capabilities exist at JPL, GRC, and GSFC. These capabilities should be maintained to conduct the required measurements and characterization of PV systems under unique planetary environments. NASA should augment simulation testing under combined space environments (thermal, radiation, plasma/charging, chemical, solar irradiance) for the characterization of solar cells, panels, and array materials. In addition to test capabilities, NASA needs to update the analytical tools for mission modeling under conditions unique to NASA spacecraft. GRC provides solar cell measurement, characterization, and standards. GSFC conducts array design exercises, costing estimates, and spacecraft integration trade studies. JPL maintains a world-class radiation effects laboratory. Relying on cell and array manufacturers for accurately predicting cell and array performance is costly and often lacks reliability. Early detection of problems for a given mission is extremely cost effective. Without the use of long-standing expertise and facilities, NASA cannot make the most intelligent mission design choices.

4.5 Summary

Taking into account the development status of ongoing solar cell and array technology programs at NASA, DoD, DoE, and in industry, the assessment team agreed on the following major findings:

a) Several types of advanced solar cells are under development at several companies and universities with support from DoD and private funding. NASA supports cell development through SBIR and, recently, other programs as well.
   - These include 4–5 junction cells, inverted metamorphic, dilute nitride, upright metamorphic and semiconductor wafer bonding.
   - Significant improvements in solar cell performance are envisioned:
     - Near-term (1–2 years): >33% efficient
     - Mid- to far-term (5–10 years): >37% efficient

b) Several types of advanced solar arrays are under development with support from DoD, commercial funding, and NASA:
   - Flexible fold-out, flexible roll-out, and concentrators
   - Major advances in solar array performance are possible:
     - Near-term: 150–200 W/kg
     - Mid- to far-term: 200–250 W/kg

c) The largest technology investments are focused on Earth-orbiting satellites.

d) Limited work is in progress currently on solar cells and arrays required for operation in the extreme environments that future planetary missions will incur. These include low solar irradiance and low temperature environments at the outer planets, high temperature, high- or low-solar irradiance at the inner planets, corrosive environments at Venus, and dusty conditions on Mars.

e) Currently, there is limited NASA STMD funding for the development of large solar arrays, particularly for SEP mission concepts requiring high power and for missions requiring large areas to provide power at the outer planets.

5 Findings and Recommendations

This section gives a summary of major findings of the assessment team on space solar power technologies for future planetary science mission concepts.

5.1 Major Findings

Findings are grouped into three major areas: a) Solar Power System Needs of Future Planetary Science Missions, b) Capabilities and Limitations of SOP Space Solar Power Systems, and c) Status of Advanced Solar Cell and Array Technologies.

a) Solar Power System Needs of Future Planetary Science Mission Concepts

The solar power systems required for solar system exploration missions have several unique needs compared to Earth orbital missions and their needs vary based on the destination and mission type. The major findings of the assessment team on the solar power systems required for future planetary science missions are:

1. Outer planet missions likely require high power solar power systems that can function efficiently in low solar irradiance, low temperature, and high radiation environments
2. Venus mid/low altitude aerial and surface missions generally require solar power systems that can survive and function in high temperatures, low solar intensities, and corrosive environments.
3. Many Mars surface mission concepts require solar cells tuned to the Mars spectrum and solar arrays with dust mitigation capability.
4. Many SEP mission concepts to small bodies and Asteroids require high voltage, high power solar power systems with low mass and volume.

b) Capabilities and Limitations of SOP Space Solar Power Systems

The major findings on the capabilities and limitations on SOP space solar power systems cell and arrays are:

1. Significant advances in solar power systems have occurred in the last twenty-five years mainly due to DoD funding.
   a. Solar cell efficiency has increased from less than 10% to over 30%.
   b. Solar array specific power has improved from 30 W/kg to 100 W/kg.
   c. Solar array power has increased from milliwatts to over 20 kilowatts.
2. The above advances have enabled some outer planetary (Jupiter orbital), inner planetary (flyby and orbital), Mars (orbital and surface), small body (flyby and orbital) missions over the last two decades.

   However, SOP solar power systems have limited performance capabilities at low irradiance and low temperature environments, and these limitations need to be overcome for future outer planetary missions beyond Saturn. PSD needs to concentrate its efforts to develop PV systems that can function under these extreme planetary environments.
3. SOP solar power systems are attractive for Venus orbital missions, but challenges exist for low altitude Venus aerial and surface missions due to their limited operational capabilities at high temperatures, high/low solar irradiance, and corrosive environments.

4. SOP solar arrays for long duration Mars surface missions would require dust removal capabilities.
5. SOP solar power are also not attractive to power the next decadal solar electric propulsion missions to small bodies and outer planet destinations, as they are heavy, bulky, and cannot function in LILT environments.

c) Status of Advanced Solar Cell and Array Technologies

The major findings of the review team on the status of advanced solar cell and array technologies are given below:

1. Several types of advanced solar cells are under development at various companies and universities, with support from DoD and corporate funding. NASA supports cell development through SBIR and other programs as well. These include 4–5 junction cells, inverted metamorphic, dilute nitride, upright metamorphic, and semiconductor wafer bonding. Significant improvements in solar cell performance are envisioned:
   - Near-term (1–2 years): >33% efficient
   - Mid- to Far-term (5–10 years): >37% efficient
2. Several types of advanced solar arrays are under development, with support from DoD, private corporate funding, and NASA. These include flexible fold-out, flexible roll-out, and concentrators arrays. Major advances in terrestrial and Earth orbiting solar array performance are envisioned:
   - Near-term: 150–200 W/kg
   - Mid- to Far-term: 200–250 W/kg
3. The largest technology investments in this area are mainly from DoD and they are focused on improving the performance capabilities of solar power systems for Earth-orbiting satellites only.
4. Limited research (funded by PSD) is in progress on the development of solar cells and arrays required for operation in low irradiance and low temperature environments of outer planets. However, more funding is required to advance these technologies to TRL 5.
5. Limited research (again funded by PSD) is also in progress to development (to TRL4) solar cells that can operate at the high temperature, high/low solar irradiance, and corrosive environments of Venus. However, more funding is required to advance these technologies to TRL 5/6.
6. No R&D projects are currently underway to develop solar cells optimized for the martian surface conditions and solar arrays that can operate in Mars dusty environments.
7. Some research is in progress to develop large high power solar arrays, required for SEP missions to small bodies.

5.2 Recommendations

From examining the current state of the art, state of practice and upcoming developments in solar power as well as the future mission needs, the assessment team formulated the following recommendations.

5.2.1 Overall Recommendations

1. Targeted investments should be made in the specific solar cell and array technologies needed to withstand the unique planetary environments.
2. 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.
3. Existing infrastructure for PV technology development, testing and qualification at various NASA Centers should be upgraded to support future planetary science missions, as needed.

5.2.2 Specific Recommendations

Specific recommendations on solar cell and array technologies required for future planetary science missions are:

1. 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).
2. Develop higher efficiency LILT solar cells and low mass, radiation resistant arrays for orbital missions to Jupiter, Saturn, and Ocean Worlds (Europa, Titan, etc.).
3. Develop LIHT cells and arrays tolerant of the sulfurous environment required for Venus aerial and surface missions.
4. Develop solar cells tuned to the Mars solar spectrum and solar arrays with dust mitigation capability for future Mars surface missions.
5. Leverage the DoD investment in higher efficiency solar cells (~38%) and array technologies to enhance next decadal planetary space science missions.

6 Acronyms

AFRL	Air Force Research Laboratory
AIAA	American Institute of Aeronautics and Astronautics
AM0	air mass zero
AM1.5	air mass 1.5
APL	Applied Physics Laboratory (John Hopkins University)
APSA	Advanced Photovoltaic Solar Array
ARL	Army Research Laboratory
ATK	Alliant Techsystems
AU	astronomical units
BOL	beginning-of-life
CMX, CMG, CMO	three types of ceria-doped borosilicate cover-glass material used in optical solar reflectors, made by Qioptiq Space Technology
COBRA	Composite Beam Roll-Up Solar Array
CP8 IPEX	Cal Poly 8 Intelligent Payload Experiment
DAVINCI	Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt e.V.)
DoD	Department of Defense
DoE	Department of Energy
DSS	Deployable Space Systems
ECSS	European Cooperation for Space Standardization
EESP	Ecole d'Etudes Sociales et Pedagogiques
ELO	epitaxial liftoff
EOL	end-of-life
EOS AM-1	Earth Observing System satellite; formerly named Terra
EPOXI	Combination of two extended mission components: Extrasolar Planet Extrasolar Planet Observation and Characterization Investigation (EPOCh) + Deep Impact Extended Investigation (DIXI)
ESA	European Space Agency
ESD	electrostatic discharge
FACT	Flexible Array Concentrator Technology (pages 6, 42, 43); Functional Advanced Concentrator Technology (page 31)
FOCUS	Full-Spectrum Optimized Conversion and Utilization of Sunlight
FRUSA	Flexible Rolled-Up Solar Array
GOES 7	geosynchronous satellite; also known as GOES H before becoming operational
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
H_2S0_4	sulfuric acid

HEOMD	Human Exploration and Operations Mission Directorate
HIHT	high irradiance high temperature
HOTTech	Hot Operating Temperature Technology
HQ	headquarters
IMM	inverted metamorphic multi-junction
ISE	Institute for Solar Energy
ISRO	Indian Space Research Organisation
ISRU	in-situ resource utilization
ISS	International Space Station
ITO	indium-tin-oxide
JPL	Jet Propulsion Laboratory
JUICE	Jupiter Icy Moons Explorer
LADEE	Lunar Atmosphere Dust and Environment Explorer
LaRC	Langley Research Center
LCROSS	Lunar Crater Observation and Sensing Satellite
LIHT	low irradiance, high temperature
LILT	low irradiance, low temperature
MAVEN	Mars Atmosphere and Volatile Evolution
MBE	molecular beam epitaxy
MESSENGER	Mercury Surface Space Environment Geochemistry and Ranging
MgF_2	magnesium fluoride
MOVPE	metal-organic vapor phase epitaxy
MSFC	Marshall Space Flight Center
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration
Near-IR	near-infrared
NF	New Frontiers
NH	New Horizons
NM-DS-1	New Millennium Deep Space 1
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRL	Navy Research Laboratory
OSIRIS-REx	Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer
OSR	optical solar reflector
PDR	Preliminary Design Review
PSD	Planetary Science Division
PSPS	Planetary Science Program Support

PV	photovoltaic
R&D	research and development
RACE	Radiometer Atmospheric CubeSat Experiment
RIT	Rochester Institute of Technology
ROSA	Roll-Out Solar Array
RPS	Radioisotope Power Systems
RTG	Radioisotope Thermoelectric Generator
SBAG	Small Body Assessment Group
SBIR	Small Business Innovation Research program
SBT	semiconductor wafer bonding technologies
SCARLET	solar concentrating array with refractive linear element technology
SEP	solar electric propulsion
SLA	Stretched Lens Array
SmallSat	small satellite
SMD	Science Mission Directorate
SOLAROSA	Solar Optical Lens Architecture on Roll-Out Solar Array
SOP	State-of-practice
STMD	Space Technology Mission Directorate
TRL	Technology Readiness Level
UMM	upright metamorphic multi-junction
UV	ultraviolet
VAMP	Venus Aerial Mid-Altitude Platforms
VERITAS	Venus Emissivity, Radio Science
VEXAG	Venus Exploration Analysis Group
VISE	Venus In-Situ Explorer
WISE	Wide-field Infrared Survey Explorer