PHOTOVOLTAIC CELL AND ARRAY TECHNOLOGY DEVELOPMENT FOR FUTURE UNIQUE NASA MISSIONS

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ABSTRACT

A technology review committee from NASA, the U.S. Department of Energy (DOE), and the Air Force Research Lab (AFRL) was formed to assess solar cell and array technologies required for future NASA science missions. After consulting with mission planning offices, solar cell and array manufacturers, universities, and research laboratories, the committee assessed the state of the art of solar cells and arrays and made a comparison with projected needs. A technology development program was proposed in high-efficiency cells, electrostatically clean arrays, high-temperature solar arrays, high-power arrays for solar electric propulsion, low-intensity/low-temperature array conditions for deep-space mission, high-radiation missions, and Mars arrays that operate in dusty environments.

INTRODUCTION

NASA's Office of Space Science (OSS) requested the Jet Propulsion Lab (JPL) to lead an assessment of advanced power source and energy storage technologies that will enable future (beyond 2007) NASA Space Science missions and to prepare technology road maps and investment strategies. The objective of this effort was to assess the potential of solar cell and array technologies to enable or provide the most cost-effective power generation for NASA Space Science missions launched in the 2007 to 2020 time period and to define a roadmap for developing the needed technologies [1].

Solar array technology has made tremendous advances in the last three decades, starting from the 10%-efficient single-crystal silicon solar cell launched on Vanguard I in 1958 [2]. Driven by the rapid exploitation of space assets for both military and commercial applications, cell efficiencies have increased by a factor of 2.5, and the specific power (W/kg) at the array level has increased by a factor of about 5. Many NASA spacecraft have already benefited from these improvements. However, many future NASA OSS missions require power systems that must perform in harsh environments outside the conditions prevailing for most spacecraft, such as:

- Large dynamic range of solar intensity (e.g., Solar Probe)
- High intensity/high temperatures (Mercury and Solar missions)
- Low intensity/low temperature (LILT) (solar missions beyond Mars)
- Very high power for solar electric propulsion
- High radiation fields (Europa, Jupiter)
- Electrostatically clean arrays for fine magnetic measurements
- Solar power in dusty environments (surface of Mars).

The study began by selecting a technical assessment team of knowledgeable photovoltaics (PV) power experts and power system engineers. The Team was tasked with the following:

- Review NASA Code-S future mission needs for solar cell and array technologies.
- Assess the status of solar cell and array technologies presently being used in various space missions and establish a baseline.
- Assess the status and potential of advanced solar cell/array technologies to meet future mission needs.
- Conduct objective trade studies to define cost/benefit of various solar cell power system technology investments.
- Recommend to NASA appropriate investment strategies for developing advanced solar cell power system technologies to meet future mission needs.

POWER FOR NASA SCIENCE MISSIONS

NASA Science Missions are organized into the following themes: Solar System Exploration (SSE), Mars Exploration Program (MEP), Sun-Earth Connection (SEC), Astronomical Search for Origins (ASO), and Structure and Evolution of the Universe (SEU). Most missions that require solar arrays share common needs: low cost, low mass, high reliability, low stowage volume, and high efficiency. It should be noted that NASA Science Missions include many Earth-orbiting satellites with solar array requirements similar to many other commercial and government satellites. On the other hand, there are a number of planned missions that have unique solar array requirements that are only required by NASA. A major challenge is how to distribute limited NASA resources between being a very small contributor to a large activity where the benefits are broad, or being the sole contributor to a narrower activity that will not be accomplished without NASA support. This paper presents the unique challenges for solar cells and arrays for each program, including the range of environmental conditions encountered.

STATE OF THE ART AND RECOMMENDED DEVELOPMENT

The Team analyzed the state of the art and the recommended path for government fiscal years from 2003 to 2007 to advance those technologies needed by unique NASA missions in each of the following areas: high-efficiency cells and arrays, electrostatically clean arrays, high-temperature arrays, high-power arrays, low-intensity/low-temperature (LILT) arrays, high-radiation environments, arrays for the Mars surface, concentrating arrays, and NASA infrastructure. A discussion of some of these areas follows.

High-Efficiency Cells and Arrays

Dual-junction and triple-junction solar cells are presently available from several vendors. Commercially available dual-junction solar cells are 21%-22% efficient. Currently, triple-junction cells consisting of GaInP, GaAs, and Ge are grown in series-connected layers and are ~27% efficient in production lots. These high-efficiency cells were developed under programs funded primarily by the National Renewable Energy Laboratory (NREL), Air Force, and NASA. The advent of a new competitor in 1998 and other factors combined to reduce space cell costs by ~40% of their 1997 cost.

High-efficiency multijunction solar cells result in a power system that can either be made lighter by about 25% compared to single-junction GaAs cell technology for a given output, or can provide about 25% more power by maintaining the same mass as single-junction GaAs cell technology. Therefore, high-efficiency multijunction solar cells were rapidly adopted for use by the commercial satellite industry, and by many NASA and military missions. The benefits included system-level cost per watt comparable to silicon, better temperature coefficients, better radiation tolerance, and about one-half the required array area to produce a given power level, compared with silicon. Multijunction solar cells are the baseline for most NASA missions today, including the Mars Exploration Rovers (2003 launch).

Improvements in the efficiency of multijunction cells continue to be made. Large-area triple-junction cells of 29.3% have been achieved in the laboratory. Even without direct NASA support, there will probably be cells with 30% lot-average efficiency on germanium substrates within a few years, simply due to the military and commercial impetus to increase efficiency. There are three ways in which III-V cells are likely to be improved beyond this level.

- Addition of a fourth junction to the current lattice-matched GaInP/GaAs/Ge triple-junction cell.
- Use a more optimal set of bandgaps that can be grown if the lattice-matching constraint is relaxed.
- Develop a manufacturing process that uses a lighter, stronger, less expensive substrate than germanium. Silicon is the obvious choice, but there is a large lattice mismatch that must be accommodated. Ceramics represent another possible option.

The report recommends that NASA continue to partner with AFRL to pursue each of these ways to advance multijunction cell efficiency.

Electrostatically Clean Arrays

Sun-Earth Connection spacecraft frequently measure fields and particles. These spacecraft require electrostatically clean arrays. Such arrays do not allow the array voltage to contact, and thereby distort, the plasma. In addition, the entire exterior surface of an array is maintained at about the same potential as the spacecraft structure. This constancy of potential, chiefly obtained by replacing the array's insulating surfaces with conductive surfaces, is used to prevent distortion of the fields and particles that are measured by the spacecraft. Sun-Earth Connection spacecraft also tend to be placed in high-radiation orbits. This implies that the array's cells must be protected against the radiation with covers that are on the order of 0.75 mm to 1.5 mm thick, which is much thicker than the usual 0.10-mm-thick covers. Because electrostatically clean arrays tend to be body-mounted and their area is therefore limited, these spacecraft have a great need for high-efficiency cells.

A worthwhile goal for these spacecraft is to find or develop transparent plastic materials that may be able to withstand the space environment. These plastics can be coated with indium tin oxide (ITO) and can be used to cover large sections of solar arrays. This will readily produce the desired electrostatic cleanliness with a minimum of expense, weight, and cost. In addition, this approach will yield a readily repairable array. Further, such plastics are extremely desirable for thin-film arrays, so this work will facilitate that development. Transparent plastics may also serve as covers for dust mitigation on Mars.

A research area that is appealing but risky is extending typical glass or fused silica to cover several cells. This has been attempted in the past, but without

success due to delamination or failure of interconnects in thermal cycling. Also, such covers can cause difficulties for repairs because there is no cost-effective way to replace a broken cell under such a cover. These issues can probably be overcome with additional research. The report recommends both areas of research.

High Solar Intensities

Two mission destinations with a need for high-temperature/high-intensity solar arrays are Mercury and close encounters to the sun. At least two missions have already flown and functioned well at high intensities: Helios A, launched on 10 December 1974, which reached 0.31 AU; and Helios B, launched on 15 January 1976, which reached 0.29 AU. Both of these spacecraft used silicon cells that were slightly modified for high-intensity use in conjunction with second surface mirrors to cool the array. The remainder of their technology was close to that used on standard arrays. In addition to these missions, the MESSENGER Discovery mission (now in Phase C/D) is planned for travel to 0.31 AU. Its solar array design is already being developed.

At present, solar array technology is just sufficient to meet the needs of Messenger or other spacecraft that approach the sun to about 0.3 AU, but with substantially reduced performance and increased risk compared to other applications. Closer encounters to the sun will require further development.

One feature is present in the solar arrays that have operated at high intensities, namely, the replacement of a significant fraction of the solar cells by optical solar reflectors (OSRs). This helps to control the array temperature at small distances from the sun, but it reduces the areal power at larger distances.

In addition to the above, MESSENGER off-points the array as the spacecraft nears the sun. The array is designed to tolerate failures in the pointing mechanism, as the array can withstand pointing at the sun for a minimum of one hour and probably much longer, although it cannot function under these extremes. In normal operation, the array operates as high as 130°C; if the off-pointing fails, the array may point directly at the sun, reaching a temperature of 260°C.

One of the problems facing closer encounters to the sun is that the substrate adhesives weaken at high temperatures. Research is needed to identify and test adhesives that show promise of operating at higher temperatures than those encountered by the Helios and MESSENGER spacecraft, which are designed for about 0.3 AU.

Research may also be necessary to develop an entirely different type of substrate than those presently used, should temperatures finally exceed what is practical for low out-gassing substrate adhesives. An anodized, solid-aluminum structure will eliminate the troublesome substrate adhesives. Electroforming the structure will allow a mesh-mounting surface for the cells and possible attachment of the cells by mechanical means rather than glue.

In the recent past, the principal modifications to GaAs solar cells that improved high-temperature survivability were changes to the contact metallization, composition, and the introduction of diffusion barriers. Using this approach, 18%-efficient GaAs/GaAs cells were produced that degraded less than 10% in one-sun efficiency after annealing in vacuum for 15 min at 550°C. Concentrator cells were produced that survived repeated 7-min excursions to 600°C and showed only a 10% loss after a single exposure to 700°C. These types of modifications may assist more modern cells in operation at high intensities and temperatures. At high temperatures, cell contact metals can diffuse into the cell junction and short it out. The temperature at which this occurs for modern cells should be determined, and, if necessary, alternative metallization should be explored. As mentioned in the preceding paragraph, prior work has shown that GaAs/GaAs solar cells with special metallization can extend the nondestructive operating temperature range above 550 deg C. Applying these same methods to modern GaInP/Ge cells should be low risk because the growth of these cells occurs above 600°C. Nonetheless, the interaction between the metallization and the top cell must be checked. Further research is required to adapt second surface mirrors directly on cells. In particular, the cover itself, with proper metallization, can serve as a combined second surface mirror and neutral density filter. Long-term (i.e., several-year) exposures to the materials used in solar arrays in the high-temperature, high-intensity range have not been adequately studied. For missions requiring such exposure, testing needs to be carried out to check for unexpected effects.

The increased operating temperatures near the sun may make it possible to realistically achieve some degree of annealing of cell radiation damage. Tests on solar cells and associated calculations are needed to determine whether this is practical for missions traveling close to the sun.

Coatings may be developed further to limit the amount of unusable infrared (IR) entering the solar cells, and for controlling the solar array substrate temperature. Ideally, a switchable electrochromic coating could be developed that reduces or eliminates the need for array feathering. At the very least, a high-performance coating combined with louvers could be used to adjust the spacecraft emissivity as the distance from the sun varies.

Modern solar cells are increasing efficiency at an unprecedented rate. For any upcoming mission, up-to-date data are required for these cells at high temperatures and intensities. In addition, the performance of the cells, along with the covers and any coatings, at high incidence angles is also required. For example, filters that reduce the IR going into a cell perform differently at high angles of incidence.

Another approach for high-temperature conditions is to develop SiC solar cells. SiC is a semiconductor that is now being commercialized for high-power, high-temperature power electronics. The SiC material properties that make it attractive for these applications include the following: high thermal stability (>700°C), high

breakdown field strength, good radiation tolerance, high thermal conductivity, and hardness. The difficulties that exist presently are micropipe defects; high dislocation densities, making the material unusable for solar cells; low carrier mobility; limited availability; and high cost (~$500-$1000 per wafer, versus about $25 for a germanium wafer). SiC is clearly worthy of development investment due to its broad benefits in many areas of aircraft and space electronics.

High Power

Solar electric propulsion (SEP) has a very high power demand that could lead to massive photovoltaic arrays. Therefore, it is critical to minimize mass and maximize specific power. Stowage volume is also very important. It is projected that the SEP power demand may grow from ~20 kW in 2007 to ~40 kW in 2012, and ultimately, to ~100 kW by 2020.

High power for electric propulsion can be achieved with arrays of multijunction high-efficiency cells. However, the mass, stowage volume, and cost associated with this approach make other alternatives desirable. Two approaches for reducing these parameters are thin-film arrays and concentrating arrays.

At present, thin-film efficiencies are too low, and the current substrates are too heavy to make reasonable use of the light thin-film cells. The challenge is to reduce mass of the substrate and increase the efficiency of the cells, for example, by developing a process to deposit a high-efficiency cell on a lightweight substrate. This can be addressed by two approaches: (1) develop an appropriate substrate for current deposition systems, or (2) develop new deposition techniques for currently available substrates. Once the thin-film cells are available and space-qualified, moderate- to relatively high-efficiency thin-film cells on lightweight flexible substrates will offer significant mass and cost benefits. Only moderately efficient thin-film cells (~12%-15%) are necessary to match the mass performance of arrays using much more efficient (and heavier) crystalline cells, given a lightweight substrate. However, considerable challenge remains in this arena and further research is needed.

It is desirable to operate solar arrays for SEP at as high a voltage as is feasible. However, a number of unsolved issues remain in using high voltages. Preliminary research indicates that progress can be made in overcoming these problems, allowing operation of arrays at higher voltages. Continuation of this work is indicated.

A number of commercial companies are developing concentrating arrays for use in Earth orbit. Some of this technology can be adapted to NASA needs for SEP. Collapsible, self-erecting concentrators, using either v-trough reflectors or Fresnel refractors, appear to have a great deal of promise for future space applications. The primary use of the concentrators is to reduce the cost of arrays. They do little to decrease mass or size.

Low Intensity and Low Temperature

The terms low-intensity and low-temperature (LILT) are used to refer to solar arrays operating under conditions encountered at distances greater than 1 AU from the sun. Earth-orbiting spacecraft typically operate at about 70°C. Thus, "low-temperature" refers to temperatures well below this value. Under these conditions, two competing effects occur. The cell efficiency increases roughly linearly with decreasing temperature due to an increase in open-circuit voltage (Voc). However, the effective doping of the semiconductor is reduced due to the smaller number of thermally excited carriers generated by the dopant atoms, resulting in so-called "carrier freeze-out." This effect reduces cell efficiency through loss of conductivity in the various layers in the solar cell and a reduction in the junction electric field. A second effect occurs when small losses in current from shunt leakage become magnified at low intensities as the overall cell current decreases. Typically, the efficiency is found to increase down to temperatures of about –50°C (at a solar distance of ~3 AU) and then fall at lower temperatures. These effects are gradual and reproducible.

A LILT Test Plan geared to III-V cells (GaAs, triple-junction, etc.) should be developed. The primary goal would be for applications out to Jupiter, with secondary priority for Saturn. Radiation behavior needs to be a part of this work because the Jupiter environment can expose the cells to high electron and proton fluences. A three-step process should be used: (1) create a database for current high-performance cells under LILT conditions; (2) carry out investigations to determine the cause of the degradations, and possibly identify solutions; (3) develop cell processes to reduce/minimize/eliminate LILT degradation. Finally, the LILT behavior of optimized cells should be confirmed by testing, and the cells should be qualified for space use.

The degree to which various cell technologies lose performance under LILT conditions is difficult to determine *a priori*, and has even been found to vary on a lot-to-lot basis. Most cell types are useful under the temperature and intensity conditions existing out to about 3 AU, but with derated performance. Beyond this distance, concentrator arrays could be used to increase the effective illumination of the solar cells.

Mars Surface Solar Array

The surface area available on Mars Landers is very limited and is critical on a Mars Rover for hazard avoidance and ground clearance. Increasing the efficiency of the PV array to reduce its area may enable a mission to survive for much longer periods. The reduced stowed volume benefits both mass and volume for the mission because entry, descent, and landing (EDL) requirements to the surface of Mars tend to drive design. In addition, arrays required for Mars surface missions need devices that mitigate dust to enable long-term missions. At present, no work is in progress on

developing such technologies. The following development support is needed in three technology areas:

- Modify commercial 3-junction cells to optimize them for use in the blue-depleted spectrum on the surface of Mars. This technology program should be formulated so that as 4-junction cells become available, the same methodologies can be transferred to 4-junction cells.
- Develop a fundamental understanding of the physics of dust adhesion and accumulation. This understanding can be achieved by laboratory simulation studies of Mars dust deposition and removal processes, the relation between deposited amount and optical obscuration, the effect of surface dust on array performance, and the effectiveness of dust removal procedures.
- Develop a dust tolerance/mitigation approach, based on the fundamentals studied in the dust physics activity. This should be based on the mission needs and surface operations strategy. It may vary from developing dust-tolerant systems, such as arrays that can be periodically tilted, to arrays with overt dust-mitigation components, such as blowers, scrapers, covers, or electrostatics.

CONCLUSIONS

The focus of this review was to identify appropriate technologies for funding from NASA Science Missions. There were, however, less-developed technologies that would make good candidates for the more basic research funded by Aerospace Technology, such as photovoltaic solar sails, inflatable array structures, nanosat power systems, power beaming, spectral separators, quantum dot structures and devices, quantum well solar cells, inorganic/organic solar cells, and nanotube solar cells. In these cases, the timeline would be extended to missions a decade or more from the present.

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