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Future Mission Opportunities and Requirements for Advanced Space Photovoltaic Energy Conversion Technology

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ENERGY CONVERSION TECHNOLOGY

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SUMMARY

A description is given of future mission requirements that will impact advanced space photovoltaic technology development. Recent results in NASA's space solar cell technology program will be summarized.

INTRODUCTION

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The last decade has seen rapid growth in the demand for more sophisticated technology as space missions have become more complex. At the same time, such increased complexity has greatly expanded the range of mission requirements that new space technology must satisfy if it is to compete successfully. Nowhere is this trend more evident than in space power systems, where projected power requirements span the range from a few hundred watts to megawatts, with increased emphasis on high performance, reliability and extended lifetime. At the same time, there has been an increased awareness of the impact of life cycle costs on the total cost of a space mission, particularly as missions become more "operational" in nature, as will be the case for a manned space station or a permanently manned lunar base. All of these factors, when coupled together, have created intense interest in power generation using technologies which compete with photovoltaics - viz. nuclear and solar thermal systems - particularly when large power requirements are considered. Earlier studies by NASA (refs. 1 to 3) have argued that alternate, advanced technologies would provide substantial system benefits when compared to the silicon solar cell array and storage technologies available when the studies were conducted. Photovoltaic power system technology has not remained static, however, with the result that new capabilities are beginning to emerge which make it applicable to a very wide range of future missions. Succeeding sections of this paper will highlight the important advances that have been made, discuss their potential applications, and indicate what problems yet remain to be resolved before full confidence in the technology can be established.

Specific applicability of a given technology to any particular mission depends strongly on the exact nature of the mission, but there are certain system attributes for various mission subsets that can serve to focus an R&T program. Table I contains a listing of some important mission subsets, their associated power level requirements, and the key attributes that a space power system, photovoltaic or otherwise, should have to be useful there. The key attributes for a given mission subset have been listed in relative priority order, with the caveat that the relative importance of any particular system feature for an actual mission depends in a critical way on the outcome of system trade-off studies.

The desired system attributes listed for each of the mission subsets should serve as guides for future technology thrusts. In space photovoltaics, for example,

the most important technology thrusts at the cell level are seen to be high efficiency and radiation tolerance. At the array level the important thrusts are low mass, high strength, durability, and in some cases, minimum stowage volume. To assure the continued viability of solar energy for use in space it is imperative that R&T efforts provide not only new technology for actual use on future missions, but also a sufficient database on advanced technology so that mission planners can make system trades with confidence. Doing so will help to assure that the advances that are made will result in net total system benefits which can have a real impact on mission planning and implementation.

SYSTEM CONSIDERATIONS

High power levels are loosely defined to be many tens of kilowatts to many hundreds of kilowatts and above. Low power levels range from hundreds of watts to a few tens of kilowatts. Intermediate power levels span the range between them. Obviously there is a certain amount of arbitrariness in the definitions, but they do serve as a reminder that there has been essentially no in-space experience in the U.S. program with power levels above ~ 25 kW. In what follows we shall review the more important mission drivers, discuss the issues that arise as a result, and investigate the technological developments that should be pursued in space photovoltaics to make it competitive with other advanced technologies.

The precipitous drop in solar array performance caused by radiation damage in the van Allen belts is well known. If photovoltaic power systems are to be useful for orbit transfer missions from LEO to GEO, then technology is needed which not only significantly reduces radiation damage degradation after very high fluence levels, but significantly increases array specific power (W/kg) as well. Storage is not required, since the OTV would be allowed to coast during eclipse. Lightweight photovoltaic cell and array technology must be developed that either provides better shielding than is now available, or enables in-space annealing, or essentially eliminates radiation damage degradation altogether. Clearly those are ambitious technology challenges. The payoff is enormous, however, since orbit transfer missions could ultimately consume multimegawatts of power. A later section of this paper will outline some of the possible approaches for meeting the performance requirements set forth above.

Specific power and radiation damage are not the only drivers for future space power systems, however. As is well known, total mission costs have become a major concern for the NASA space station, and a significant contributor to such costs is that of reboosting the station periodically in its orbit. Reboost becomes necessary because of the orbit-decaying drag produced by the residual atmosphere present at projected space station altitudes. For this reason it becomes important to minimize the cross-sectional area of the station, since the drag forces will be directly proportional to it. Arrays with area specific powers significantly higher than presently available (~ 110 W/m²) must become available at reasonable cost to be able to compete with alternate solar thermal technologies effectively. As a result, NASA is pursuing the development of concentrator array technology to meet this challenge. A more complete discussion appears in a later paragraph.

Two mission possibilities now being considered are the establishment of a permanent base on the Moon, and manned visits to the Martian surface to explore the potential for establishing a base on that nearby planet. Although the long range plan envisions power generated by nuclear reactors, there will most likely be a need

for interim power which is easily deployed or erected, and which is available essentially instantly with the arrival of the first astronaut crews at the sites. Such power systems will have to be as light as possible (high power to mass ratio, W/kg,) not only to minimize the cost of transporting it to the moon or to Mars, but also to allow for as much other cargo and payload delivery to the surface as possible. The first visits will most likely require power systems delivering up to 50 kW for life and operational support during the construction or deployment of the initial outpost components, and for any early scientific investigations. Improvements are needed which will increase array specific power by a factor of five or more.

An issue developing in the space science community at the present time is that of our ability to perform deep space missions, or Martian surface explorations using robotic spacecraft. Previous missions have been able to use radioisotope thermoelectric generators, or RTG's, to provide payload power for journeys beyond Mars. Although such systems are heavy, typically 3 to 5 W/kg, they are compact, and can be located at the center of mass of the spacecraft. At issue is the availability of such power sources during the next decade and beyond. Although not suitable for all such missions, photovoltaic power sources have the potential to meet some of the needs in this mission class. An ultralight solar array at 300 W/kg in earth orbit could, in principal, provide power even in the vicinity of Saturn and be competitive with RTG's. Recent work has shown conclusively that solar arrays are viable power sources on the surface of Mars (ref. 4). A great many issues need to be investigated - such things as environmental interactions, low temperature-low intensity solar cell operation, array survivability and operability, and so on. Although there is no mission push for such technology at the present time, demonstration of key elements would help to make it an available alternative for future consideration.

CELL TECHNOLOGY REQUIREMENTS

The full spectrum of space missions envisioned for the next 15 years or so, each of which may have individual requirements for less than 25 kW, could easily require deployment of a megawatt or more of power. Clearly it will become imperative to improve the capability and lower the cost of future space power systems. It is also probable that most of the missions will use photovoltaic power systems, particularly for earth orbiting applications. It therefore becomes imperative to develop higher efficiency, lower cost, longer life solar cells and arrays. A leading candidate in that regard is the InP homojunction cell, which recently has achieved over 19 percent in a prepilot production setting (ref. 5). The full development of this cell has the potential for a significant impact on the cost and capability of future space photovoltaic power systems.

Other cell types with the potential for major impact are multiple bandgap cells, which have recently been shown to achieve over 30 percent at 100X AMO (ref. 6), and thin (5 μ m) GaAs cells, which would make possible ultrahigh specific power arrays with good radiation resistance. Also of interest are certain of the thin film solar cells, such as amorphous silicon and copper indium diselenide. Although of lower efficiency than single crystal solar cells, they have shown evidence of radiation hardness which would make their lower efficiencies acceptable in many cases, provided they can be made to exceed 10 percent AMO. If such cells are successfully developed, however, they could make possible the mass production of low cost space photovoltaic arrays for low power (i.e., few kW) applications. The paragraphs that follow will discuss briefly some specific cell technologies.

SOLAR CELL OPTIONS

Table II displays several solar cell types that are potential candidates for use on lightweight planar arrays in high natural radiation environments. The most mature of the cell types listed, in terms of production experience, commercial availability and spaceflight experience, is the thin (62 μm) silicon cell, followed closely by the "standard" gallium arsenide solar cell. The laboratory efficiencies quoted for all cell types are for 2 by 2 cm cells except where noted. The expected date of availability in each case is a purely subjective estimate of the time required to move the technology from the laboratory through a successful demonstration on a pilot production line, assuming that R&D funding levels do not constrain any efforts to do so. Given sufficient funding, modest yields of cells with efficiencies at or near their projected values could be achieved in commercial production within a year or two of those dates. Based on the experience with GaAs cells, high yields of cells with efficiencies approaching 90 percent of projected values could reasonably be expected to be available within that same period.

Because of the wide ranging developmental status of the various cell types listed in Table II, there is still some uncertainty about expected in-space cell lifetimes. Definitive array performance predictions therefore cannot be made for cell types other than silicon until the equivalence between laboratory radiation damage tests and actual degradation under spaceflight conditions has been established in each case. Comparison of cell performance at the same levels of laboratory fluences and energies is still a useful guide, however, since promising cell technologies can be identified for further development and testing. As long as the caveat on 1 MeV electron equivalence is acknowledged, array end-of-life (EOL) performance estimates can be made, and are useful in identifying any potential system level advantages or disadvantages that may be associated with a given solar cell technology. In addition, the comparisons help to make clear what the desirable cell characteristics are from a system point of view, so that efforts to develop new cell types can be properly focussed on all the relevant technology issues.

One of the difficulties attendant with a brief survey such as this is that the full complexity of the situation regarding any particular cell technology cannot be represented adequately. The factors which affect a given cell's performance, as well as its usefulness for a given mission application, range from its microscopic electronic and material properties to the macroscopic configuration of the device itself. Hence any attempt to establish a comparison between cell types must be carried out with extreme care. For example, there is a substantial body of evidence which suggests that the fraction of power lost by thin silicon cells and essentially all GaAs cells (i.e., whether on GaAs or Ge substrates and whether p/n or n/p), is very nearly the same after equal doses of 1 MeV electrons or high energy protons in laboratory tests. A significant advantage accrues to GaAs cells, however, when the expected array on-orbit operating temperature is taken into account, and the comparison is made on an absolute basis. Figure 1 shows such a comparison. In this case, the factor which is important is the higher bandgap of GaAs, which results in cells with higher actual output at modestly elevated temperatures compared to Si cells. The value of this advantage is quickly lost, however, when considering lightweight array technology such as the Advanced Photovoltaic Solar Array (APSA) under development by NASA, because of the higher density of GaAs compared to Si (approximately a factor of two). Unless the GaAs cells are made thin, or mounted on a thin, lightweight substrate or superstrate, higher array EOL power is available with thin silicon. GaAs on thin Ge substrates, or CLEFT GaAs cells (ref. 7) on thin Si substrates can provide substantially higher BOL and EOL array specific powers than thin silicon cells, however. GaAs on 75 μm thick Ge substrates are currently under development in an Air

Force manufacturing technology program at Applied Solar Energy Corporation. CLEFT GaAs cells on 62 μm silicon substrates have been demonstrated by the KOPIN Corporation (private communication). Efficiencies approaching 20 percent AMO (at 25 C) can be expected to be achieved in both cases, with radiation damage resistance similar to that already observed in GaAs.

InP cells have only slightly lower projected efficiencies than GaAs because of the slightly lower energy bandgap (1.35 versus 1.43 eV for GaAs). Although the density of InP is about 15 percent lower than that of GaAs, so that some improvement in array specific power could be realized by directly substituting InP for GaAs, the major reason for interest in cells made from this material is their dramatic resistance to electron and proton radiation damage, as revealed in laboratory tests (ref. 8). The significantly higher EOL/BOL power ratio observed more than compensates for the slightly lower BOL power such cells can be expected to have. Figure 2 shows some recent results from 1 MeV electron irradiations. The small degradation in normalized power approaches that observed in the thin film technologies such as CuInSe_2 and amorphous silicon (refs. 9 and 10). Also of significance, all of the approaches available for reducing the mass of GaAs cells are also available for InP cells: heteroepitaxial InP on alternate (most likely Ge or Si) substrates, and CLEFT (or other peeled film) InP cells on Si or glass. Each of the above approaches are under investigation, and feasibility has been established in every case. What remains is to achieve the expected efficiency of each of the devices and to test their radiation resistance. Success in developing an InP on Si structure, whether mechanically attached or heteroepitaxially grown, would result in a device with the mass equivalence of 75 μm of silicon, an AMO efficiency approaching 20 percent, and a relative power loss from radiation damage perhaps less than 1/10 that observed in thin silicon or GaAs. Such a cell would be especially useful in the high fluences that would be encountered in a LEO to GEO transfer orbit. Considerable cell development and testing is required before reliable engineering estimates of array performance can be made, but the potential payoff for the effort will be a totally new photovoltaic power system capability: long term operation in high radiation flux environments. Array EOL specific powers approaching 200 W/kg after a year in the mid latitudes may be possible.

In principle, certain of the thin film cells are projected to have single junction efficiencies approaching single crystal cells. In practice, all have fallen far short of that level of performance. The currently favored candidate for achieving relatively high performance in a thin cell is CuInSe_2 (CIS). AMO efficiencies slightly above 11 percent have been measured in small area devices (ref. 11). The resistance of such cells to damage from both 1 MeV electrons and 1 MeV protons is outstanding (ref. 12). The normalized power degradation in GaAs cells after a fluence of $1\text{E}12$ 1 MeV protons is nearly five times greater than in CIS cells, while there is essentially no power loss in CIS after a fluence of $1\text{E}17$ 1 MeV electrons. There is at present no suitable explanation for the observed behavior of such cells. Although present CIS devices are made on thick glass substrates, the possibility exists to produce them on 50 μm thick glass. No effort is currently underway to produce them on thin, flexible substrates, which would be a logical extension of technology, both to increase array specific power, and to reduce cost. The lower CIS cell efficiency will result in lower values of area specific power (W/m^2) compared to that of the high efficiency single crystal cells, but EOL values can in fact be higher, depending on the total fluence accumulated during the mission. Again, data are insufficient to make precise predictions, but CIS cells are clearly promising enough to warrant further development and testing.

Amorphous silicon is a second thin film cell type that has been of interest for space applications, primarily because of its potential for achieving extremely high specific power, even at modest efficiencies. Amorphous silicon single junction cells are projected to have efficiencies around 12 percent AMO, and can be deposited directly on flexible, lightweight, large area substrates. To date, small area cells have been fabricated on stainless steel and glass substrates with efficiencies approaching 10 percent AMO, (ref. 13) while direct deposition on Kapton has produced cells with efficiencies ranging up to 5.5 percent AMO (ref. 14). The latter have been produced on 50 μm thick Kapton in a roll-to-roll process, and have a blanket specific power (with a nonspace qualified encapsulant) of 800 W/kg. Improvement in efficiency to 10 percent and deposition on 25 μm thick Kapton substrates has the potential for achieving 3 Kw/kg at the blanket level. Radiation damage resistance has not been fully characterized, but appears to be quite good, especially to proton damage (ref. 12). Early results indicate behavior comparable to that observed in CIS. A major problem that remains unresolved is the large light-induced degradation known as the Staebler-Wronski effect. Long term exposure (hundreds of hours) to light causes ~15 to 25 percent loss of power (a significant fraction of which can be recovered by annealing in the dark), depending on the specific cell design. It can be expected that better control of the effect can be achieved, so that degradation may well be limited to less than 10 percent over the first few hours of operation, but no clear understanding of this phenomenon yet exists to assure its elimination.

CONCENTRATOR CELLS

Although concentrator arrays cannot compete with advanced, lightweight planar array designs for high specific powers (W/kg), they can provide a potentially cost-effective approach for achieving extremely high area power densities (W/m^2) at specific powers exceeding today's lightweight planar array technology (e.g., the Space Station Freedom baseline is 66 W/kg). They are presumed to be cost-effective on the basis that the total area to be covered by expensive semiconductor devices can be reduced by the concentration ratio, and that less expensive optical devices can be fabricated to achieve the performance desired. Lightweight optical elements will also be required, with the result that significant radiation resistance will still be required of the solar cell structure itself, since the optical element will not provide a major amount of shielding. The addition of small area, thick coverglasses to the concentrator cells can be of substantial benefit, however, and will not add greatly to the total mass of such an array. This approach may work well with the high efficiency tandem cell structure previously mentioned. Area power densities of 300 W/m^2 or more are feasible with this approach, with concurrent values of specific power exceeding 100 W/kg (ref. 14). There are insufficient data to accurately project radiation damage degradation for such an array, particularly to the optical element, but the cell can reasonably be expected to incur little or no degradation for fluences equivalent to long term exposure in the radiation belts.

The second approach for achieving radiation hardness with lightweight concentrator array technology takes advantage of the unique annealing behavior exhibited by InP solar cells at temperatures in the range from 100 to 125 $^{\circ}\text{C}$, and of the potential for light-induced annealing at concentrated sunlight levels (ref. 15 and 16). Although both effects need further investigation in the newer OMCVD cells, the potential exists to achieve complete radiation hardness through continuous annealing of the damage as it occurs. If successfully demonstrated, such cells would be able to operate indefinitely in the heart of the radiation belts, or any other naturally occurring radiation environment. There are as yet no data on the survivability of

the rest of the array components, particularly the optical element itself, but development continues at a modest pace. This approach would make feasible a radiation-hard concentrator array with a specific power greater than 90 W/kg, and an area power density in excess of 200 W/m².

CONCLUSION

Future space missions will continue to rely primarily on solar arrays for spacecraft power. A variety of new cell technologies now under investigation will give future mission planners a set of alternatives from which to choose so that mission performance can be optimized.

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TABLE I

Mission subset	Power level	System attributes
Unmanned near earth (LEO, HEO, GEO) and planetary applications	Low to intermediate	Low mass, long life
Space station	High	Minimum area, low mass, low cost
GEO platform	Intermediate	Long life, low mass
Lunar base, manned planetary	Intermediate to high	Low mass portability long life
Electric Propulsion Orbit Transfer (OTV)	High	Reusability, minimum area, low mass

TABLE II

Cell type	Cell structure	Projected efficiency, percent	Laboratory efficiency, percent	Commercial efficiency, percent	Normalized maximum power, P/P ₀		Estimated date available
					1E15 cm ⁻² 1 MeV electrons	1E12 cm ⁻² 10 MeV protons	
Thin silicon	62 μm substrate n/p diffused, BSF, BSR	14.5	14.5	13.7	0.74	Damage equivalence to 1 MeV protons known	Now
GaAs	300 μm substrate n/p, p/n OMCVD, LPE	23	21.5	20	0.74	0.8	Now
GaAs/Ge	75 μm substrate ^a 10 μm cell, p/n OMCVD	23	20.5	20	0.74	0.8	Now
Cleft GaAs/Si	62 μm substrate, 6 μm cell n/p, p/n OMCVD	23	20	----	0.74	0.8	1994
InP	300 μm substrate n/p OMCVD	22	19	----	0.975	0.9	1993
InP/Ge	75 μm substrate ^a 10 μm cell, n/p OMCVD	20.5	9	----	0.975	-----	1995
InP/Si	62 μm substrate ^a 10 μm cell, n/p OMCVD	18.5	7	----	-----	-----	1997
CuInSe ₂	5 μm film, 50 μm glass substrate ^a	16	11	----	>0.96	0.9 (1 MeV)	1993

^aProjected value.

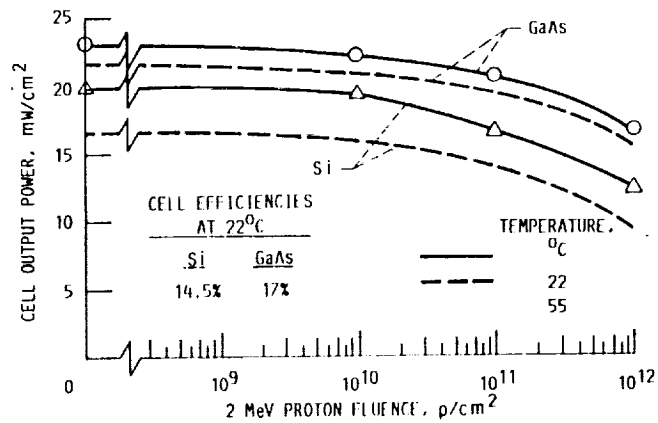


FIGURE 1. - ABSOLUTE POWERS OF SILICON AND GaAs SOLAR CELLS AFTER 2 MeV PROTON IRRADIATION.

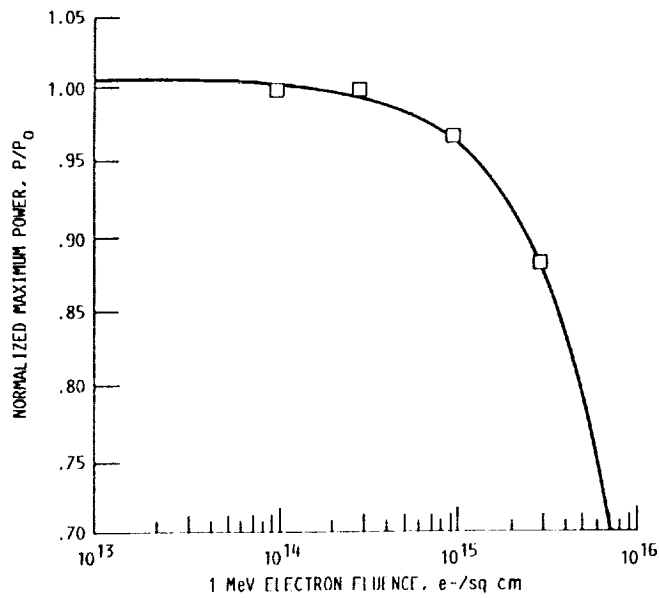


FIGURE 2. - NORMALIZED POWERS VERSUS 1 MeV ELECTRON FLUENCE FOR InP n/p SOLAR CELLS.



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16. Abstract <p>The variety of potential future missions under consideration by NASA will impose a broad range of requirements on space solar arrays, and mandates the development of new solar cells which can offer a wide range of capabilities to mission planners. Major advances in performance have recently been achieved at several laboratories in a variety of solar cell types. This paper will review many of those recent advances, examine the areas where possible improvements are yet to be made, and discuss the requirements that must be met by advanced solar cells if they are to be used in space. The solar cells of interest include single and multiple junction cells which are fabricated from single crystal, polycrystalline and amorphous materials. Single crystal cells on foreign substrates, thin film single crystal cells on superstrates, and multiple junction cells which are either mechanically stacked, monolithically grown, or hybrid structures incorporating both techniques will be discussed. Advanced concentrator array technology for space applications will be described, and the status of thin film, flexible solar array blanket technology will be reported.</p>			
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