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ISSUES IN SPACE PHOTOVOLTAIC RESEARCH AND TECHNOLOGY

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ABSTRACT

This paper will address key issues and opportunities in space photovoltaic research and technology relative to future NASA mission requirements and drivers. Examples will be given of future space missions and/or operational capabilities that are on NASA's planning horizon that present major technology challenges to the use of photovoltaic power generation in space. A brief description of the capabilities ascribed to the competing technologies of nuclear and solar thermal power systems will be given. The performance goals that space photovoltaic power systems must meet to remain competitive will be described.

INTRODUCTION

The value of a passive, maintenance-free, renewable energy source was immediately recognized in the early days of the space program, and the silicon solar cell, despite its infancy, was quickly pressed into service. Efficiencies of those early space solar arrays were low, and lifetimes shorter than hoped for, but within a decade significant advances had been made in both areas. Better performance was achieved because of a variety of factors, ranging from improvements in silicon single crystal material, better device designs, and a better understanding of the factors that affect the performance of a solar cell in space. Chief among the latter, particularly for geosynchronous (GEO) orbits, were the effects of the naturally occurring particulate radiation environment. For over two decades, from the first space array launched on Vanguard in 1958, scarcely 4 years after the first working solar cell was announced (ref. 1), to the present, it has been taken for granted that solar arrays are the power system of choice except for certain specialized space science missions.

The decade of the eighties has seen a rapid acceleration in the demand for more sophisticated technology in all aspects of the space program. Nowhere, however, is this trend more evident than in the field of space power system technology, 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 space missions become more "operational" in nature, as will be the case, e.g., for a manned space station. All of these factors, when coupled together, have spawned an intense interest in power generation using technologies which compete with photovoltaics - viz. nuclear and solar thermal systems. It is imperative that the space photovoltaic community understands fully the nature of future mission requirements and drivers, and that it seeks to develop enabling new photovoltaic power system technology to meet them.

The anticipated energy requirements of future missions are illustrated in figure 1. Research and technology programs are needed that address the applicability of photovoltaic power systems to a wide range of power requirements, from hundreds of watts to multihundred kilowatts, and to a variety of operating environments. Specific applicability to any given mission depends strongly on its exact nature, but there are certain system attributes for various mission subsets that can serve to focus the R&T program. Table I contains a breakout of some important mission subsets, their associated power level requirements, and the key attributes photovoltaic power systems 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.

To assure continued viability for the use of solar energy in space it is imperative that space photovoltaic R&T efforts provide both new technology for actual use on future missions, and a sufficient technology database so that mission planners can make system trades with confidence. The desired system attributes listed for each of the mission subsets should serve as guides for future technology thrusts. At the cell level, for example, the most important technology thrusts are high efficiency and radiation tolerance. At the array level the important thrusts are low mass, high strength, and durability. Needed are blanket and array structural components for high performance arrays; advanced concentrator array components and panel development; and a more pervasive understanding of the issues in total spacecraft/power system integration. The latter is important to assure that advances in technology at the various levels will result in net total system benefits that will have a real impact on mission planning and implementation.

Within the context of the planning horizon of NASA's Office of Aeronautics and Space Technology (OAST), which serves as the Agency's advanced technology development overseer, R&T activities in space power have been aggregated into three broadly defined categories relative to the array of mission subsets shown in table I. Two of the categories are High Capacity Power Systems and Spacecraft And Rover Power Systems, which are intended to provide focussed research that is more immediately responsive to anticipated Agency mission requirements. The longer term, less focussed, higher risk research is described as Base R&T, in which space mission requirements are addressed in a more generic way than in the former two categories. High capacity power systems are loosely defined to be those required to deliver in excess of 25 kW, while spacecraft and rover power systems are all those below that level. Obviously there is a certain amount of arbitrariness in such definitions, but they are useful reminders that there has been essentially no in-space experience with power levels above 25 kW. In what follows we shall review the more important mission drivers in the two categories described above, discuss the issues that arise as a result, and investigate the technological development required of space photovoltaics if it is to compete effectively with alternative power system approaches for use on future missions. Some attention will be given in this discussion to space power system requirements. The intent is to develop the context within which space photovoltaic technology improvements must be pursued, and to display and evaluate more readily the potential impact on future mission capability that those technology improvements may have.

HIGH CAPACITY SPACE POWER SYSTEMS

Projections of power system characteristics based on continued use of flat plate silicon solar cell arrays have been used to preclude photovoltaics as a power generation source for large space systems. One aspect of this is illustrated in figure 2, (ref. 2) which shows a comparison of projected specific power for a space nuclear power system (the SP-100), an advanced solar dynamic power system, an IOC space station photovoltaic system design, and advanced silicon photovoltaic power system technology. The precipitous drop in solar array performance at the mid altitudes is the result of radiation damage incurred while orbiting in the van Allen belts. It has been argued that such behavior precludes the use of solar arrays to provide power for any mission that must operate there, such as an electric propulsion orbit transfer vehicle, and that the only alternatives are either nuclear power or solar thermal systems. Photovoltaic power systems, if they are to compete effectively for this application, which will require power in the hundreds of kilowatts to several megawatts range, will need technology which significantly reduces radiation damage degradation at very high fluence levels. Advanced array technology must be developed which will allow the power system to spend from three to six months spiraling through the van Allen belts either without degradation, or with the ability to recover from any degradation that has occurred. In addition, most mission scenarios appear to require that the array, during each leg of the full round trip, be able to emerge with a minimum specific power of 100 W/kg. 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, or enables in flight annealing, or essentially eliminates radiation damage degradation altogether. Clearly those are ambitious technology challenges. The payoff is enormous, however, since it would open the way to multimegawatt applications of photovoltaics in space. A later section of this paper will outline some of the possible approaches for meeting the performance requirements set forth above.

Specific power is not the only driver for high capacity 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. Here, too, photovoltaic power systems face serious competition, this time because of the physical size of a conventional silicon cell array. Early space station system trade studies (ref. 3) showed that total mission costs of a space station equipped with a flat plate, single crystal silicon solar cell array would be excessive because of the continuing cost of reboost fuel resupply. As a result, the NASA space station program elected to undertake development of a solar dynamic power source, which, by virtue of its presumably higher efficiency and lower drag area, is projected to have more favorable lifecycle costs than a photovoltaic system. If PV is to compete effectively in this arena, photovoltaic/electrochemical storage systems are needed with orbital efficiencies approaching, and perhaps exceeding, 20 percent. Clearly, a significant fraction of the advance must come from more efficient, higher energy density storage technology. Nonetheless, arrays with area specific powers approaching 300 W/m^2 must become available at reasonable cost to be able to challenge the competing technologies effectively. Again, we shall deal with the question of what sort of PV technology developments are needed to achieve such performance in a later section of the paper.

SPACECRAFT AND ROVER POWER SYSTEMS

The vast majority of space activities from now through the first decade of the twentieth century, whether commercial, civilian, or military, will have power requirements in the range from a few hundred watts up to 20 or 30 kW. The key feature is that there will be hundreds of such missions, including interplanetary science, earth observation, and communication (both commercial and military), and as a result a megawatt or more of space power will be needed in that timeframe. There will also be precursor missions to help locate sites for establishing permanent manned bases on the moon and for manned visits to the surface of Mars, both of which may well occur early in the next century. Such a vast array of missions will impose an equally varied set of requirements on the power system needed for each application. In every case, however, the transportation system will be mass-limited, with the possible exception of earth to LEO launches on the Shuttle. Mass-limited missions will include LEO to GEO transfers, earth to Lunar or Mars transits, or virtually any interplanetary mission. There will also be an increasing need for a higher degree of reliability and autonomy on such spacecraft than in the past, since it will become more and more important to assure the lowest life cycle costs possible during the entire mission. One of the major contributors to such costs in many past missions has been that of operational ground support, which included constant monitoring of, and issuing commands to, the spacecraft throughout its flight. Future spacecraft will require power subsystems that can function for long periods of time, perhaps in harsh environments, and that can be fault tolerant and self-correcting. In a word, future spacecraft, including surface roving vehicles, will need power systems that are "lighter and smarter" to accomplish their objectives without undue restriction of their scope or capabilities.

Two of the more exciting 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. Accomplishing either will tax our ingenuity to devise a mission plan and to build the necessary spacecraft and associated equipment. Although the ultimate embodiment of such bases envisions power generated by nuclear reactors for the long term, an assumption which deserves to be challenged, 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 25 kWe or less for life and operational support during the construction or deployment of the initial outpost components, and for any early scientific investigations.

Tables II and III are comparisons of system specific powers for all the competing power system technologies. The column labeled "Current" is based on technology either already in hand, as is the case for a PV/EC system, or under substantial development, as is the case for solar dynamic and nuclear power systems. The column labeled "Future" represents the performance that could be expected of the various system types by the year 2000, assuming an appropriate level of technology development in the interim. In the case of the nuclear system, the "Current" option is a downrated (to 25 kWe) SP-100 class reactor system, while the "Future" option is a small reactor designed specifically for the expected power level and mission requirements. The reactor option assumes various levels of partial shielding built into the system, and would carry some associated operational constraints relative to its proximity to the outpost, and to any astronaut activity in certain restricted areas. The performance goals which the separate array technologies need to achieve are shown in figures 3 and 4. Improvements ranging from twice to more than five times the specific power of present technologies will be required.

It is clear that a major driver for the nonnuclear system options for either of the two outpost missions is that of energy storage. The Martian night is a little more than 12 hr long, while the lunar night is two weeks long. (For the latter, however, there are the polar regions where constant sunlight is available at least at grazing angles to the lunar surface.) Except for the latter possibilities as locations for an outpost on the moon, the storage system masses dominate the total power system masses on both the moon and Mars. Nonetheless, solar arrays with specific powers approaching 300 W/kg (at AM0) will be required for PV to remain competitive for these applications.

An issue developing in the space science community at the present time is that of our ability to perform deep space missions. Previous missions have been able to use radioisotope thermal 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 continuing availability of such power sources during the next decade and beyond, particularly in the face of growing interest in them for defense-related uses. Although not suitable for all such missions, photovoltaic power sources have the potential to meet some of the needs in this mission class. Figure 5 is a plot of very simple estimates of advanced technology specific power versus distance from the sun (1 au = 1 earth radius (mean) from the sun) for several competing power systems; a lightweight photovoltaic array at 300 W/kg, AM0,; a lightweight photovoltaic concentrator array at 100 W/kg, AM0; an advanced solar dynamic system without storage; a small reactor; and a radioisotope thermal generator. An ultralight solar array at 300 W/kg at the earth's orbit could, in principal, provide power even in the vicinity of Saturn and be competitive with RTG's. A great deal of detail has been left out of this comparison, and would 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 of it would help to make it an available alternative for future consideration.

CELL TECHNOLOGY REQUIREMENTS

As pointed out in the first paragraph of this section, the full spectrum of space missions envisioned for the next 15 years or so, each with individual requirements for less than 25 kW, could nonetheless consume a megawatt or more of power. Clearly it will become imperative to improve the capability and lower the cost of future space power systems, no matter what the conversion technology. Moreover, it is also probable that essentially all such systems will be photovoltaic power systems, particularly for earth orbiting applications such as communication satellites and so on. It therefore also becomes imperative to develop higher efficiency, lower cost, longer life solar cells and arrays. In particular, new, high efficiency, radiation hard solar cells will be necessary to be able to sustain the desired levels of space activity envisioned. A leading candidate in that regard is the InP homojunction cell, which recently has achieved 18 percent in the laboratory (ref. 4). The full development of of this cell type, and others like it yet to be discovered, will have a significant impact on the cost and capability of future space activity. Other cell types with the potential for major impact are multiple bandgap cells, which could make 30 percent AMO conversion possible, at least under modest concentration (100X), and thin (5 μm) GaAs cells, which would enable 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. Major barriers which must be overcome include not only the efficiency, but also the stability of the materials. If such cells are successfully developed, however, they could usher in a new era of low cost space photovoltaic power system technology as never before envisioned. The paragraphs that follow will discuss briefly some specific cell technologies and issues, and relate them to the system level issues described above.

INDIUM PHOSPHIDE CELL RESEARCH

Figure 6 shows a plot of calculated ideal efficiency as a function of bandgap in the AMO solar spectrum (ref. 5). The locations of the bandgaps of Si, GaAs, and InP are shown on the figure. Reason for the interest shown in GaAs by the space community is self-evident: it has a higher theoretical efficiency than silicon. An important property not depicted by this curve, however, is the efficiency of a solar cell after exposure to the naturally occurring charged particle radiation found in the space environment (primarily trapped electrons and protons, and solar flare protons). Calculations predicting that behavior are difficult to make, with the result that any cell material and design must undergo radiation testing to determine its spaceworthiness. Such testing is usually done in ground-based facilities, since the cost of spaceflight testing and verification is extremely expensive, and opportunities are limited. However, groundbased experiments suffer from some uncertainty because it is simply not possible to duplicate the particle and energy distribution that may be encountered at various orbits and at various times. Only after years of effort has it become possible to refer to an equivalent radiation dose for silicon solar cells using 1 MeV electrons from an accelerator. For example, it is now accepted that the accrued damage in a silicon solar cell after exposure in an accelerator to a 1 MeV electron fluence of $3x10^{14}$ cm-2 is equivalent to that acquired after 7 years in geosynchronous orbit with a 150 μm coverglass on the cell.

It is also common practice to quote the behavior of other cell types after exposure to the same laboratory fluence, so that initial comparisons can be made. The uncertainties caused by this approach can only be resolved by spaceflight testing coupled with extensive cataloging of laboratory irradiation results. With the preceding caveat, figure 7 depicts the projected behavior of InP, GaAs, and silicon cells as a function of orbit altitude (ref. 6). The comparison is made between specific powers for the same initial array output before exposure. The difference in BOL specific powers is caused by the reduced array area (and hence reduced balance-of-system mass) needed for higher efficiency solar cells. All array weights are based on an advanced lightweight array concept (ref. 7), the technology for which is currently being developed in the NASA PV program. The BOL efficiencies are measured numbers for Si and GaAs, and a predicted value of 20 percent for InP. As the figure shows, a lightweight InP array should have superior performance compared to either of the other two materials. Equally important, such an InP array will have a specific power in the radiation belts that is a factor of ten better than the best solar array that has been flown to date. As mentioned, actual efficiencies in InP (AMO) are near 18 percent (ref. 4). Figure 8 summarizes the situation. InP cells are in the very early stages of their development. Based on our experience with GaAs and Si,there is little reason to doubt that 20 percent AMO efficiencies can be achieved.

A very interesting application of InP may well be in a concentrator array, with the cell operating temperature kept above 100 °C. Figures 9(a) and (b) show why (refs. 8 and 9). Complete annealing of electron-induced radiation damage has been observed in early InP cells at temperatures slightly above 100 °C. If similar behavior can be maintained in high efficiency cells, and shown to apply to proton damage as well, the possibility exists to produce high efficiency, high specific power, radiation hard solar arrays for use in high radiation environments. Projected specific power for such arrays range as high as 100 W/kg, and with advanced storage capabilities, radiation insensitive earth orbiting system specific powers of 50 W/kg are a possibility. Realization of such goals would make photovoltaic power systems clear winners over any other technology now under investigation, as shown in figure 10.

ADVANCED SOLAR CELLS

The list of advanced solar cell candidates currently under investigation for space use is quite extensive, and cannot be discussed in detail here. Of interest, however, is the development of the Stanford point contact silicon cell (ref. 10), for two reasons. The first is the cell itself, which, with its high efficiency, could find use in radiation benign missions, or perhaps in a system which provides suitable protection from space radiation, such as in a concentrator array. Clearly, the sensitivity of that cell to radiation damage is a major issue. The second is whether that design could be utilized in any of the III-V cell materials, such as GaAs and InP. Weizer and Godlewski have shown that efficiencies exceeding 25 percent AMO are possible at one sun in such a cell, based on material and operating parameters already achieved in laboratory devices (ref. 11). Developing such a cell for use in concentrated sunlight could well result in efficiencies above 28 percent AMO. Again, a key issue to be addressed is the radiation tolerance of such a device, since its successful operation is critically dependent on maintaining diffusion lengths long enough to provide good current collection. A projected design calls for approximately 1 percent coverage by the junction area to achieve high open circuit voltage. If the dots are 1 μm in diameter, diffusion lengths on the order of 100 μm will be required. Such numbers have been observed in very pure, lightly doped material (ref. 12). Also critical is the development of a good passivation technique for the GaAs surface regions between the junction dots. Much work remains to be done on this cell before it is a practical reality, but its potential for improving the applicability of photovoltaics for space missions makes it an important technology to investigate.

Development of a super-high efficiency GaAs cell has another interesting implication. Figure 10 contains plots of the efficiency contours of a two junction tandem solar cell in a two terminal and a four terminal configuration (ref. 13). The bottom cell bandgap is the ordinate of each plot, and the top cell bandgap is the abscissa. The calculation is for 100X AM0, and a cell temperature of 80 °C. As with the terrestrial spectrum, the optimum bandgaps are near 1.75 and 1.1 eV, and as the figure shows, an ideal efficiency of 35 percent AM0 is expected. In this case the top cell must have about 20 percent conversion efficiency, with the remainder coming from the 1.1 eV bottom cell. The figure also makes clear the desirability of using four instead of two terminals: there is a wider range of acceptable bandgaps for the former case. Even more importantly, a four terminal cell will have a greater tolerance for radiation-induced damage. The reason is straightforward - a two terminal cell requires current matching between top and bottom cell for optimum performance. Anything, such as radiation damage, which causes a mismatch will lead quickly to degraded total performance. In a four terminal configuration, however, the two cells are electrically independent of each other so that the effect will not be compounded as rapidly. Complexity will increase at the array level, admittedly, because essentially two power conditioning circuits must be employed. The presumption is that the increased performance will be worth the extra effort. Also of interest is the performance that might be achieved by combining a dot junction GaAs concentrator cell with a slightly lower bandgap bottom cell of, e.g., InGaAs. A combination of full surface area junctions could well exhibit 30 percent efficiency under concentration, and output should be enhanced by the dot geometry to something well in excess of that. Even assuming that practical efficiencies require discounting the calculations by a few percentage points, efficiencies in the low to mid 30 percent range could be feasible.

A key element in much of what has been discussed above is the use of concentrated sunlight for space power systems. Properly designed concentrator arrays can provide substantial benefits for space power systems in terms of radiation protection and increased efficiency, and there is a major development program underway at the present time by the Air Force to demonstrate such technology (ref. 14). As presently envisioned, such arrays offer no improvement in specific power. They will be in the range from 20 to 30 W/kg, making them comparable to currently flying planar arrays. Meeting the space power system performance goals outlined earlier in this paper will require the development of space-qualified, lightweight, low cost, higher optical efficiency (e.g., refractive) elements, and low mass, high strength array structures. The increased optical efficiency of a refractive element compared to a double reflecting element is an enabling factor for array area specific powers approaching 300 W/m^2, and power to mass ratios approaching 100 W/kg. However, the burden of radiation resistance will still be a major cell issue, and is the reason for considering InP cells in this context. The degree of shielding provided by an advanced concentrator array will most likely be lower than that envisioned for some of the current designs, which rely on heavy optical elements for shielding. The space survivability of materials suitable for making such lenses is a major issue yet to be addressed, but the potential payoff in improved system performance is significant.

CONCLUSION

We have reviewed briefly the nature of the requirements that must be addressed for the successful application of photovoltaic power generation in space. The opportunities are challenging, but overcoming them should provide significant new capabilities for a variety of future space missions. Failure to address them increases the risk that mission planners will turn to competing technologies to accomplish their goals.

REFERENCES

1. D.M. Chapin, C.S. Fuller, and G.L. Pearson, J. Appl, Phys. 25 pp. 676-77 (1954).
2. H.W. Brandhorst, Jr., A.L. Juhasz, and B.L. Jones, Fifth European Conference on Photogenerators in Space, Sept. 1986 (to be published).
3. D.L. Nored and D.T. Bernatowicz, Proceedings of the 21st IECEC, p. 146, Aug. 1986.
4. I. Weinberg, et al., Proceedings of the 19th IEEE Photovoltaic Specialists Conference, May 1987 (to be published).
5. "Solar Cells-Outlook for Improved Efficiency," Report by the Ad Hoc Panel on Solar Cell Efficiency, National Research Council, National Academy of Sciences, Washington, D.C. (1972).
6. I. Weinberg and D.J. Brinker, Proceedings of the 21st IECEC, Aug. 25-29, 1986.
7. J. Scott-Monck, Proceedings of a Conference on Space Photovoltaic Research and Technology, NASA Conf. Pub. CP-2256, p. 201 (1982).
8. M. Yamaguchi, C. Uemura, and A. Yamamoto, J. Appl. Phys. 55, p. 1429, (1984).
9. M. Yamaguchi, K. Ando, A. Yamamoto, and C. Uemura, Appl. Phys. Lett. 44, p. 432, (1984).
10. R.M. Swanson, et al., IEEE Trans. Elect. Dev., ED-31, p. 661, (1984).
11. V.G. Weizer and M.P. Godlewski, J. Appl, Phys. 57, p. 2292 (1985).
12. R.J. Nelson, Gallium Arsenide and Related Compounds, C.M. Wolfe, ed., Inst. Phys. Conf. Series No. 45, p. 256, Bristol (1979).
13. J.C.C. Fan and B.J. Palm, Proceedings of a Conference on Space Photovoltaic Research and Technology, NASA Conf. Pub. CP-2314 (1983).
14. J. Geis, Proceedings of a Conference on Space Photovoltaic Research and Technology, Lewis Research Center, Oct. 1986 (to be published).

TABLE I. - SPACE POWER SYSTEM ATTRIBUTES

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 Cost, Low Mass
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. - EXPLORATION POWER SYSTEMS MANNED MARS OUTPOST SPECIFIC POWER COMPARISON 25 kWe, 12 HR STORAGE

System	Current, W/kg	Future, W/kg
IOC solar dynamic	1 to 3	4 to 7
PV array/regen. fuel cell	3 to 5	15 to 20
PV array/battery	1 to 2	5 to 8
Primary fuel cell (30 day operation)	0.5 to 1	1 to 1.5
Nuclear (small reactor)	7 to 15 (downsized SP-100)	15 to 20

TABLE III. - EXPLORATION POWER SYSTEMS LUNAR OUTPOST SPECIFIC POWER COMPARISON 25 kWe, 2 WEEK STORAGE

System	Current, W/kg	Future, W/kg
Solar dynamic	0.17 (5660 kg/kWe)	0.45 (2200 kg/kWe)
PV array/RFC	0.80	4
Primary fuel cell (requires resupply every four weeks)	1.12	1.65
Nuclear (small reactor)	7 to 15 (downsized SP-100)	15 to 20

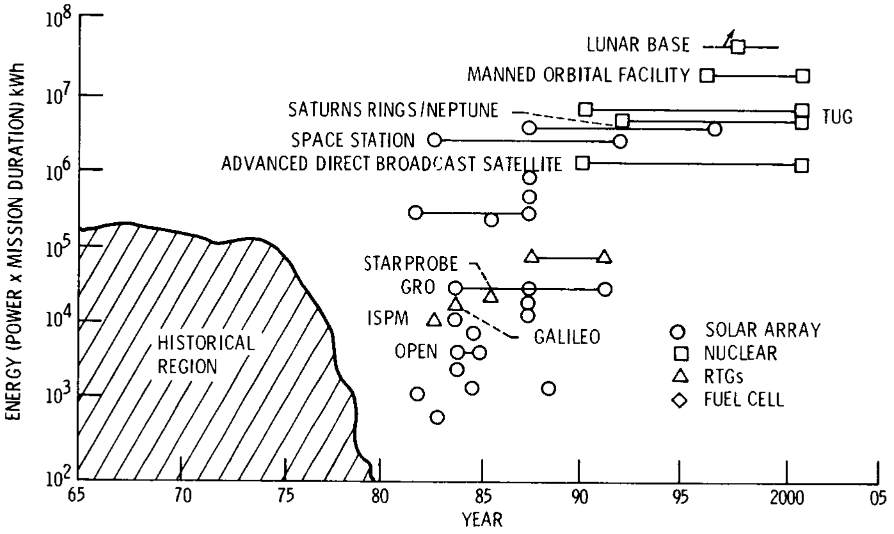


Figure 1. - Future space energy demands.

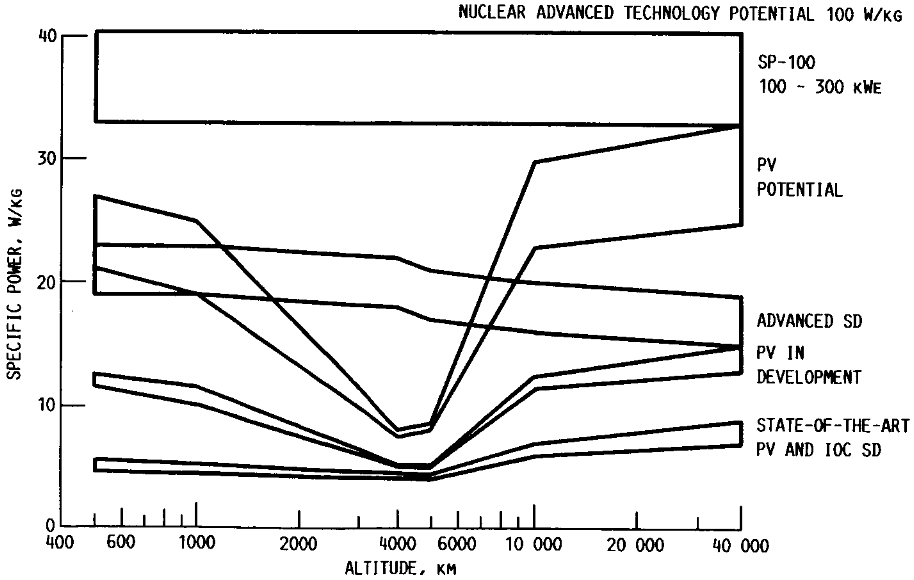


Figure 2. - System comparison, photovoltaic/solar dynamic/nuclear, 5 year life.

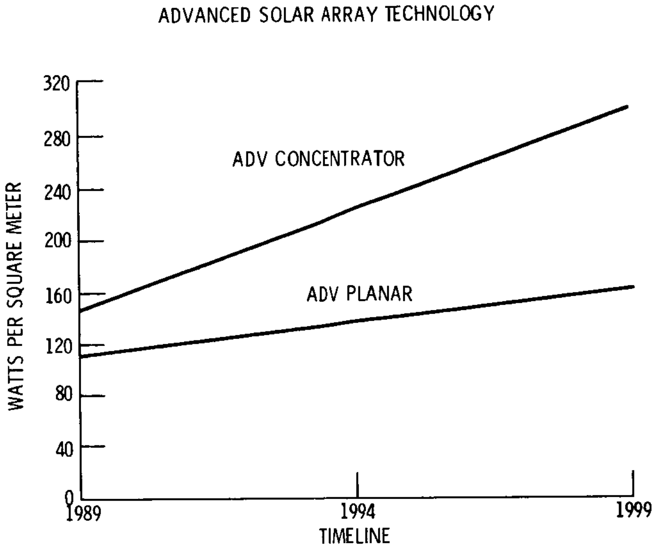


Figure 3. - Projected w/square meter improvements.

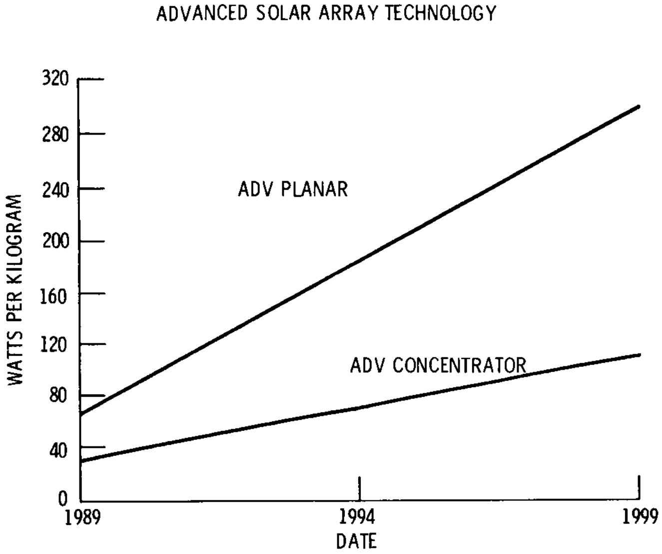


Figure 4. - Projected w/kg improvements.

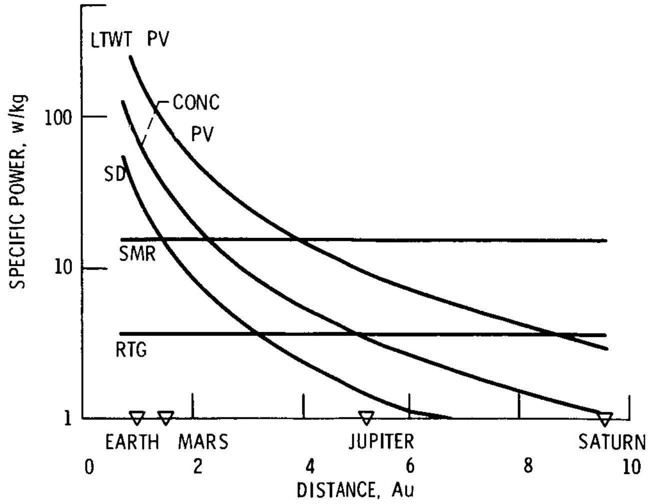


Figure 5. - Projected specific power comparisons for advanced photovoltaic, solar dynamic, nuclear, and radioisotope thermal generator power systems.

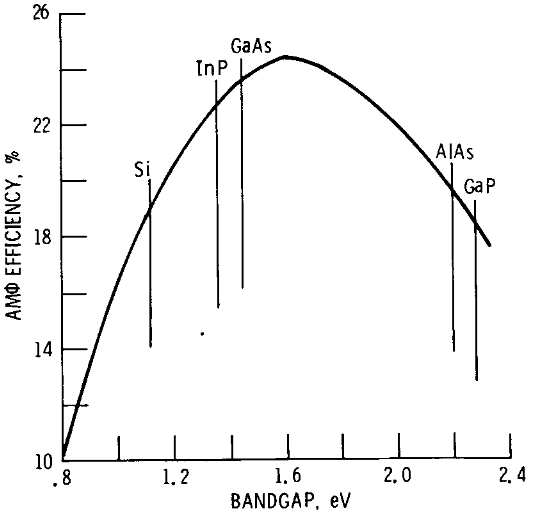


Figure 6. - Efficiency versus bandgap in AMO.

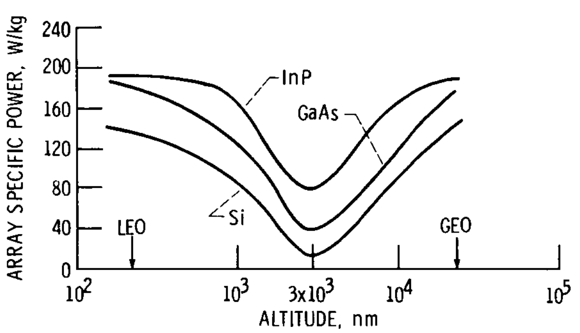


Figure 7. - Comparison of solar array calculated output as a function of orbit altitude, based on 1 MeV electron equivalent fluences. Time in orbit = 7 years, circular orbit, 30° inclination, T = 60 °C.

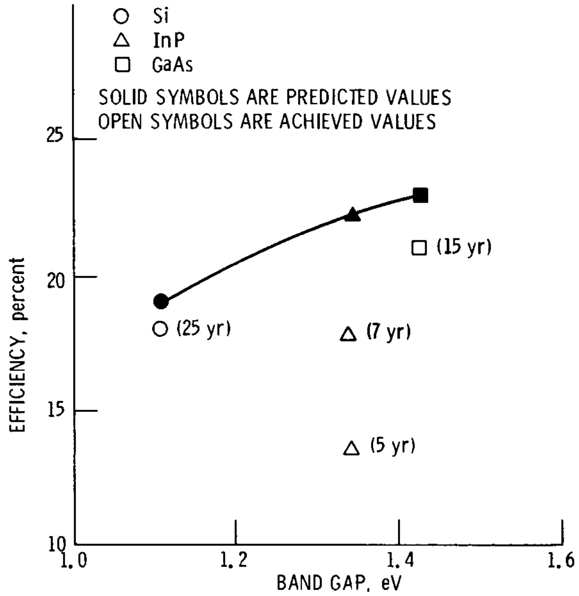
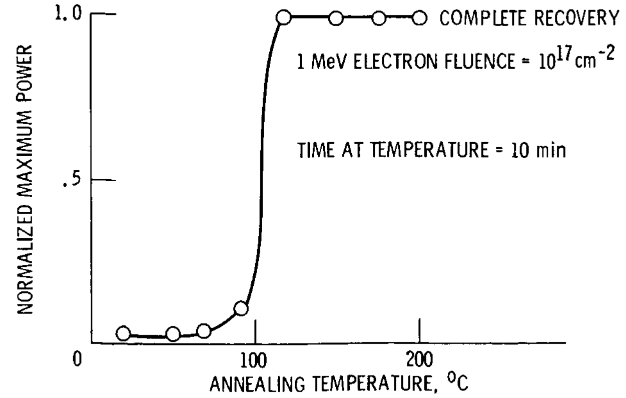
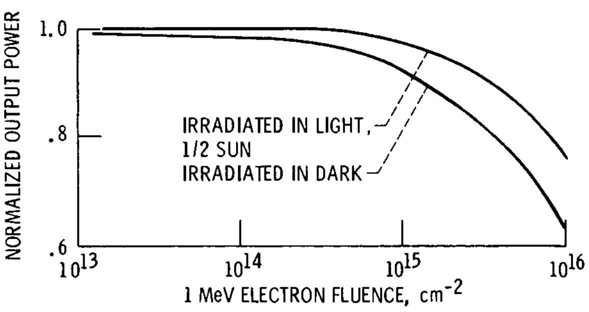


Figure 8. - Predicted and achieved AMO efficiencies.



(a) Low temperature heating.

Figure 9. - Radiation damage removal in InP.



(b) Incident light.

Figure 9. - Concluded.

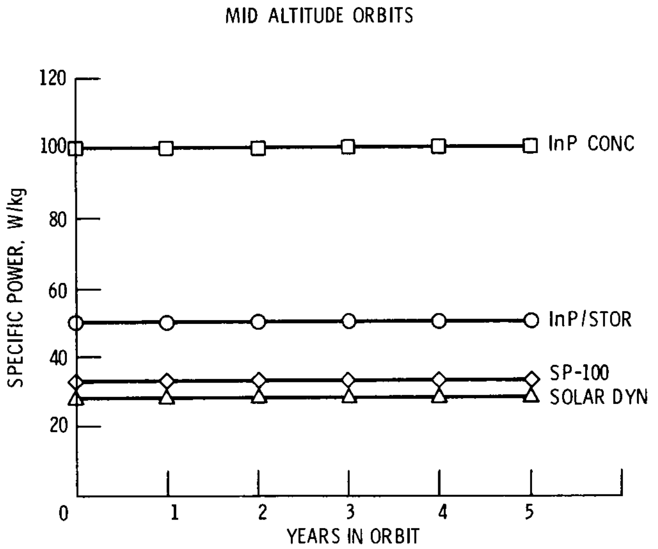


Figure 10. - Specific power versus time.

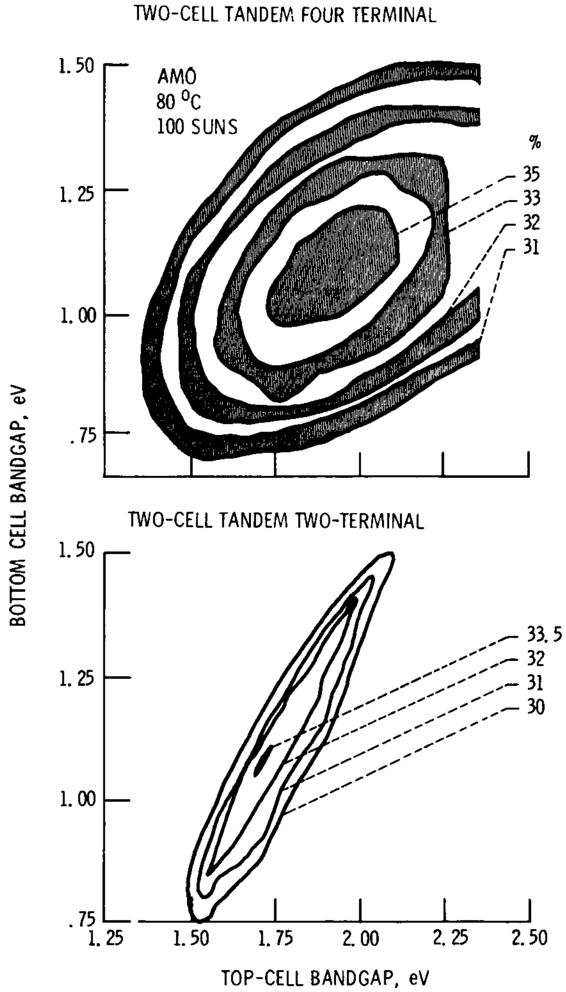


Figure 11. - ISO - efficiency curves.

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16. Abstract
This paper will address key issues and opportunities in space photovoltaic research and technology relative to future NASA mission requirements and drivers. Examples will be given of future space missions and/or operational capabilities that are on NASA's planning horizon that present major technology challenges to the use of photovoltaic power generation in space. A brief description of the capabilities ascribed to the competing technologies of nuclear and solar thermal power systems will be given. The performance goals that space photovoltaic power systems must meet to remain competitive will be described.

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