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SUMMARY

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. The status of cell R&D and the performance goals that space photovoltaic power systems must meet to remain competitive will be described.

High Capacity Photovoltaic Space Power Systems

The anticipated energy requirements of future space missions will grow by factors approaching 100 or more, particularly as we establish a permanent manned presence in space. The advances that can be expected in solar cell efficiency, lightweight structures and array lifetime, when coupled with advanced, high energy density storage batteries and/or fuel cells, will continue to make photovoltaic energy conversion a viable power generating option for the large systems of the future.

Table I shows a more detailed breakout by subset of potential missions in the high capacity mission class, and lists the system attributes that are important in each case. The key attributes for a given subset are listed in relative priority order, with the caveat that the actual prioritization within any subset depends in a critical way on the outcome of system trade studies. Cost in this case is meant to include life cycle costs, as well as initial deployment cost. The total delivered electric power in kilowatts, divided by the total system mass, or specific power, We/kg, provides a way to make top-level comparisons between competing system concepts for future space missions. State-of-the-art specific powers for current earth orbiting satellites are under 10 We/kg, on a system basis, and the IOC space station is projected to have a specific power of 5 We/kg for its photovoltaic power system.

The specific technological advances required to achieve any particular set of desired attributes will vary from mission to mission. Nonetheless, in almost all cases the technology push will be toward lighter weight and higher efficiency, whether of solar arrays or storage devices. Since the architecture of space photovoltaic power systems will be vastly different depending on the storage requirements, it is necessary to examine the potential for improvement within each of the subsystem technologies. Tables II to IV summarize the current capabilities of various cell, storage, and array options, and their predicted performance levels. It is possible, based on such data, to estimate system-level performance for specific power system requirements in each of the above mission subsets.

Earth-orbiting missions with large power requirements, such as growth space station and other large LEO platforms, have already been shown to require high area power density to minimize life cycle costs if they must orbit at altitudes where residual atmospheric drag is significant (below approx. 270 nmi). Power systems for such missions need not only high efficiency, lightweight solar arrays, but also high energy density, high efficiency batteries or fuel cells. The combination of advanced concentrator arrays utilizing mechanically stacked, dual junction solar cells, with advanced high capacity storage devices such as HBr fuel cells, NaS, or Li secondary batteries, has the potential for area power densities approaching 200 We/M^2, an improvement by a factor of nearly 3 over current system technology. Specific powers for the same advanced solar array/electrochemical system concept approach 50 We/kg, a phenomenal factor of ten improvement over today's large system state-of-the-art.

Spacecraft and Rover Power Systems

Although there will be a need for a few high capacity 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 hundreds of kilowatts 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, either or 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.

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 will tax our ingenuity to devise and build the necessary spacecraft and associated equipment. Although the ultimate embodiment of such bases commonly envisions power generated by nuclear reactors for the long term, 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 output components, and for any early scientific investigations.

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 similar in duration to the Earth's, and the lunar night is about two weeks long. As a result, e.g., the storage subsystem for a lunar power system accounts for more than 95 percent of the total system mass. The situation for a Martian outpost is shown in figure 1. The reduced storage time, coupled with the reduced solar insolation level at Mars, effectively increases the fraction of the total system mass that is attributable to the array. Array technology capable of 300 W/kg (at AMO) is required along with advanced storage to make PV systems competitive with alternate systems. The figure also shows that two photovoltaic cell/array options are possible contenders for this application: thin GaAs and amorphous silicon.

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 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 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 2 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). 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.

Silicon

Most satellites, currently in space, are powered by silicon solar cells. On the other hand, gallium arsenide solar cells are being manufactured and several missions are planned using these cells. This follows from the latter cell's increased efficiency, increased radiation resistance and decreased sensitivity to temperature. Possibly the biggest drawback to use of GaAs cells in space are their increased cost and weight when compared to silicon. This coupled with the conservative nature of most spacecraft designers, is a major reason for the expectation that many future satellites, at least in the near term, will be powered by silicon solar cells. Hence, improvements in efficiency and radiation resistance are still of importance for these cells.

The earliest calculations of efficiency, based principally on bandgap considerations, resulted in a predicted air mass zero efficiency of 19 percent for Si (ref. 1) A more realistic calculation based on use of low resistivity silicon predicted an expected maximum efficiency of 18 percent for cells whose p-base resistivity was 0.1 Ω-cm (ref. 2). Most recently, AMO efficiencies of 18.1 percent have been reported for silicon cells with 0.2 Ω p-base resistivity (refs. 3 and 4). Figure 3 shows progress, through the years, in achieving high efficiency for silicon solar cells. Due to the present emphasis on space photovoltaics, the figure shows only cell efficiencies measured at air mass zero. It is noted that efficiencies of 27.5 percent at air mass 1.5 and 100 suns concentration have been reported for "point contact" silicon cells (ref. 5). This latter efficiency, when corrected for concentration and further reduced by referring measurements to air mass zero, turns out to be slightly less than that of the most efficient cell shown in figure 3.

Although the highest efficiencies have been achieved with low resistivity cells (refs. 3 and 4) they may not be suitable for use in space environments where radiation is a significant cell degradation factor. The rationale behind this conclusion is demonstrated in figure 4, where silicon solar cells of varying thicknesses and resistivities are compared under 1 MeV electron irradiation. In terms of normalized efficiencies, the thinner cell exhibits the highest radiation resistance, while the effects of decreased base resistivity are demonstrated by comparing the performances of the remaining cells. The increased radiation resistance of the thinner cell can be understood by noting that diffusion lengths in 10 Ω-cm p-type silicon, in the uniradiated state, range from approximately two to six times the thickness of the 2-mil cell. Hence use of the thinner cells tends to decrease the effects of radiation in reducing minority carrier diffusion lengths. With respect to the variation with p-base resistivity, it is noted that addition of the p-dopant boron to silicon tends to decrease radiation resistance. This has been attributed to the presence of a radiation induced boron-oxygen defect whose production rate increases as cell base resistivity decreases (ref. 6). Several remedies have been suggested to alleviate this situation. For example, it has been shown that decreased oxygen content could lead to a substantial decrease in annealing temperature (refs. 7 and 8). If this were accomplished, cell recovery by annealing could be a viable procedure in space (ref. 7). Counterdoping of p-type silicon with lithium has also been shown to increase radiation resistance (ref. 9). However, the most practical solution, to date, lies in the use of thin silicon cells to increase radiation resistance. The relatively long diffusion lengths encountered in silicon renders this purely dimensional approach practical.

In addition to increased radiation resistance, thinner cells offer the advantage of higher array specific powers. Specific powers of several U.S. satellite arrays, flown in space are shown in figure 5. To date, the highest specific power of a U.S. space flow array, used to power a functioning satellite, is 35 W/kg. This refers to the array on TDRSS (Tracking and Data Relay Satellite System). More efficient arrays have been tested for short periods of time in space. For example, the SEP (Solar Electric Power) array, whose dynamic characteristics have been evaluated on a shuttle flight, achieved a specific power of approximately 60 W/kg. A schematic of one wing of the SEP array, rated at 13.5 kW is shown in figure 6. Using the SEP flexible fold out array as a baseline, the U.S. Jet Propulsion Laboratory has initiated a program aimed at ultimately achieving an array specific power of 300 W/kg (fig. 7). Currently, an array designed to achieve 130 W/kg is under fabrication and will shortly be evaluated. This array differs from the SEP array in its use of the much lighter Stacbeam boom and deployment mechanism rather than the heavier Astromast configuration. In addition, thin silicon cells, thinner interconnects and a 2-mm cover glass are employed in the lighter weight structure now being processed. Additional steps required to reach the 300 W/kg goal are illustrated in the figure.

Requirements for a projected lunar base place great emphasis on the array mass and stowed volume of the array while in transit from earth to the base site. In this respect, amorphous silicon solar cells, which have achieved AMO efficiencies of 10 percent, appear to be viable candidates for powering the proposed lunar base (ref. 10). Advantages in weight and volume are possible for a photovoltaic system, provided that it can be operated without the weight penalty of battery storage. This would be possible if the photovoltaic array were continuously exposed to sunlight. Examination of lunar conditions indicates that there are regions of the moon which are continuously exposed to sunlight. Specifically this continuous daylight condition occurs at the lunar poles (ref. 11). A comparison of an amorphous silicon array, using state-of-the-art amorphous cells with a photovoltaic array using Cassegranian concentrators and 21 percent (100X, 80 °C) GaAs solar cells is shown in figure 8. Also shown are data for a 100 kW nuclear system and a solar dynamic system using the Brayton cycle (ref. 12). From the figure it is seen that the photovoltaic systems are superior in terms of mass and volume and that the amorphous silicon solar cell array would be preferable.

It is appropriate here to include some remarks on the forthcoming U.S. Space Station. Figure 9 is a schematic representation of a photovoltaic option for the initial space station scheduled to be launched sometime in the 1990's. Specifically, the array for this system is intended to deliver 75 kW of electrical power to the space craft bus. However, the array power will be sized at approximately 225 kW. Silicon cells are planned for this photovoltaic option. One current cell design calls for the large area, 8-cm by 8-cm wrap-through silicon cells (ref. 13). Cell modelling data indicate that use of 2 Ω-cm passivated cells with gridded back contact should make possible the fabrication of a large area, 13.8 percent efficient cell (ref. 13). The use of the large area cell with all contacts on the rear surface is intended to facilitate array assembly and thus reduce costs.

In concluding the present discussion of silicon cells, it is well to note the ever present need, and desirability, of increasing radiation resistance, even for the thinner cells. The methods suggested in references 7 to 9 offer concrete suggestions to reach this goal, i.e., lithium counterdoping and decreased oxygen and carbon content. In addition use of cells thinner than 2 mils may offer advantages especially if their reduced BOL efficiencies can be tolerated. With regard to efficiency, some of the techniques used in achieving 18.1 percent efficiency, in the 0.2 Ω-cm cells, such as passivation, would possibly result in higher efficiencies for the 10 Ω-cm space qualified cell whose current efficiencies are slightly higher than 15 percent (refs. 3 and 4).

Advanced Cell Technology Requirements

As pointed out earlier, 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 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 nearly 19 percent in the laboratory (ref. 14). The full development 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 missions. 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, or so), 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.

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. J.J. Loferski: J. Appl. Phys. **27** (1956) 777.

2. H.W. Brandhorst, Jr.: 9th IEEE Photovoltaic Specialists Conference, (IEEE, New York, 1972) 37.

3. M.A. Green, A.W. Blakers, S.R. Wenham, S. Narayanan, M.R. Willison, M. Taouk, and T. Szpitalak: 18th IEEE Photovoltaic Specialists Conference, (IEEE, New York, 1985) 39.

4. M.A. Green, A.W. Blakers, J. Shi, E.M. Keller, and S.R. Wenham: Appl. Phys. Lett. **44** (1984) 1163.

5. R.A. Sinton, Y. Kwark, J.Y. Gan, and R.M. Swanson: Electron Device Lett. **7** (1986) 567.

6. P.M. Mooney, L.J. Cheng, M. Suli, J.D. Gerson, and J.W. Corbett: Phys. Rev. B **15** (1977) 3836.

7. I. Weinberg and C.K. Swartz: Appl. Phys. Lett. **36** (1980) 693.

8. I. Weinberg and C.K. Swartz: 15th IEEE Photovoltaic Specialists Conference, (IEEE, New York, 1981) 490.

9. I. Weinberg, S. Mehta, and C.K. Swartz: Appl. Phys. Lett. **44** (1984) 1071.

10. J.J.Hanak, E. Chen, C. Fulton, A. Myatt and J.R. Woodyard: Space Photovoltaic Research and Technology 1986, NASA CP-2475 (National Aeronautics and Space Administration, Washington, D.C., 1986) 99.

11. J. Green: The Future United States Space Program, Advances in the Astronautical Sciences, Vol. 38, Pt. 1, eds. R.S. Johnston, A. Naumann, Jr. and C.W.G. Fulcher (Univelt, San Diego, 1978) 385.

12. H.W. Brandhorst, Jr., A.J. Juhasz, and B.I. Jones: Photovoltaic Generators in Space, 5th, ESA-SP-267, ed. W.R. Burke (European Space Agency, Paris, France, 1986) 13.

13. J.R. Lillington, G.F.J. Garlick, J.R. Kukula, and S. Bunyan: 19th IEEE Photovoltaic Specialists Conference, (IEEE, New York, 1987), to be published.

14. I. Weinberg, et al: 19th IEEE Photovoltaic Specialists Conference, (IEEE, New York, 1987) to be published.

15. R.M. Swanson, et al.: IEEE Trans. Elect. Dev. **31** (1984) 661.

16. V.G. Weizer and M.P. Godlewski: J. Appl. Phys. **57** (1985) 2292.

17. R.J. Nelson: Gallium Arsenide and Related Compounds 1978, ed. C.M. Wolfe, (Institute of Physics, Bristol, England, 1979) 256.

TABLE I. - SPACE POWER SYSTEM ATTRIBUTES

Mission subset	Power level	System attributes
Growth space station	High	Minimum area, low mass, low cost
GEO platform	Intermediate	Long life, low mass
Lunar base, manned	Intermediate to high	Low mass, portability, long life
Electric propulsion orbit transfer (OTV), interplanetary travel	High	Reusability, minimum area, low mass

TABLE II. - PHOTOVOLTAIC POWER SYSTEMS - STORAGE TECHNOLOGY SUMMARY EARTH ORBITING APPLICATIONS

Storage system	Now		Goal	
	W-Hr/kg	Eff/DOD, percent	W-Hr/kg	Eff/DOD, percent
NiH (IPV)	13.9	70/35	20	80/50
NiH (Bipolar)	In dev	In dev	35	80/80
RFC:				
H2-02				
Eff. opt.	30	60/90	---	-----
Wt. opt.	55	50/90	---	-----
HBr	In dev	In dev	80	80/90
NaS batteries	In dev	In dev	100	85/80

TABLE III. - PHOTOVOLTAIC POWER SYSTEMS PV CELL TECHNOLOGY SUMMARY

Cell type	Now		Goal	
	Eff., percent	Rad. deg., percent	Eff., percent	Rad. deg., percent[a]
GaAs	>22	10 to 15	25.5	<10
Tandem cell	In dev	In dev	>30	<10
InP	19	In dev	>20	0
Thin film cells	<6	<10	>10	<5

[a]After 10 years in GEO.

TABLE IV. - PHOTOVOLTAIC POWER SYSTEMS ARRAY TECHNOLOGY SUMMARY

Array type	Now		Goal	
	kg/kW	M^2/kW	kg/kW	M^2/kW
Planar:				
TDRSS (Tracking and Data Satellite System)	30	9	----	---
OAST-1 (Formerly SEP)	15	9	----	---
APSA (Advanced Photovoltaic Solar Array)			7.0	7.6 (Bol)
Concentrator:				
Miniature Cassegrainian/GaAs	43	6.8	34.5	5.3
Advanced Refractive Concentrator				
91% Optics/GaAs cells	In dev	In dev	13.3	4.2
96% Optics/30% cells	In dev	In dev	9	2.8

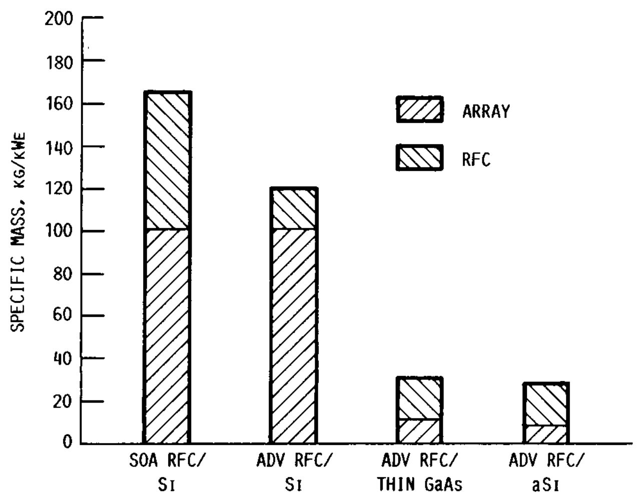

FIGURE 1. - SPECIFIC MASS COMPARISONS ON MARS. 12 HR REGENERATIVE FUEL CELL STORAGE.

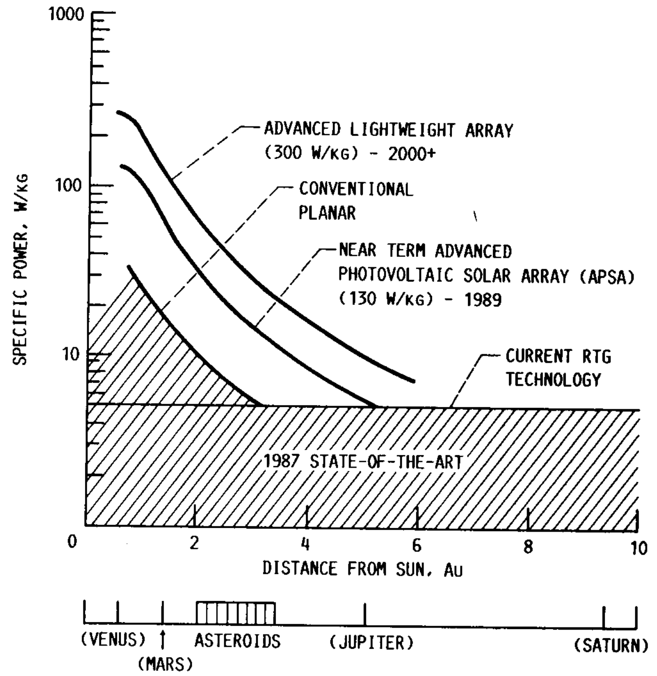

FIGURE 2. - PHOTOVOLTAIC ARRAY PERFORMANCE FOR INTERPLANETARY APPLICATIONS.

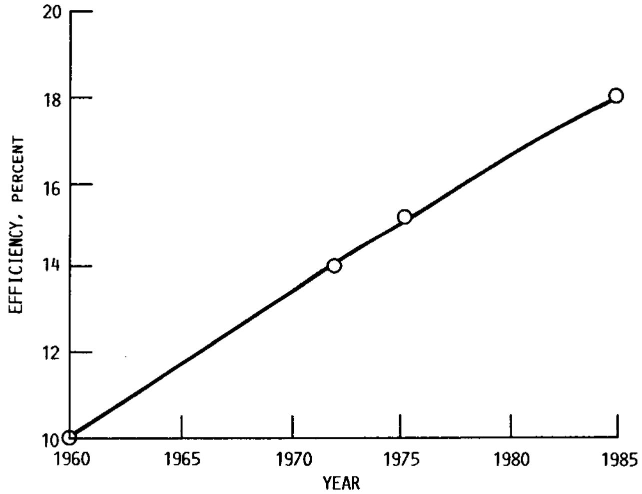

FIGURE 3. - SILICON SOLAR CELLS - PROGRESS IN ACHIEVING HIGH EFFICIENCY.

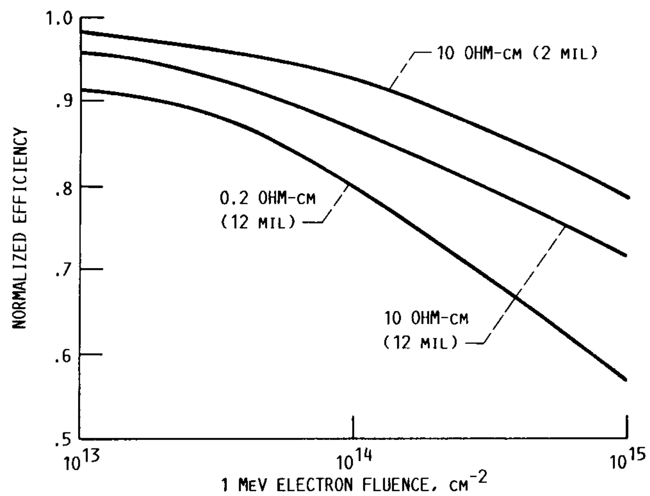

FIGURE 4. - NORMALIZED EFFICIENCIES OF SILICON SOLAR CELLS AFTER 1 MEV ELECTRON IRRADIATION.

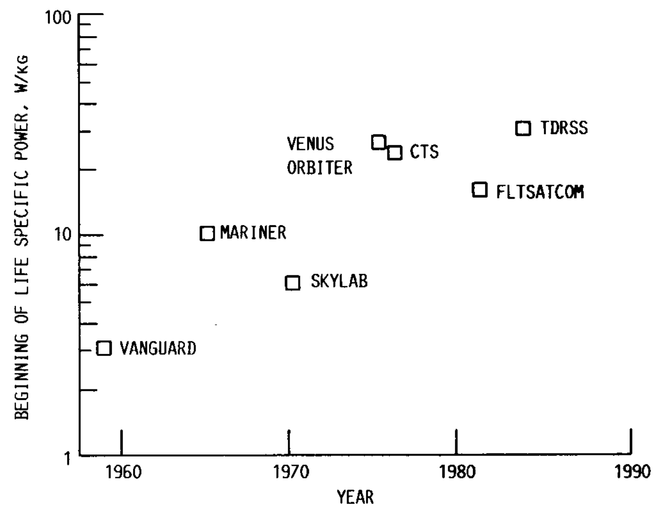

FIGURE 5. - SPECIFIC POWER OF SOME SILICON ARRAYS USED ON U.S. SPACECRAFT.

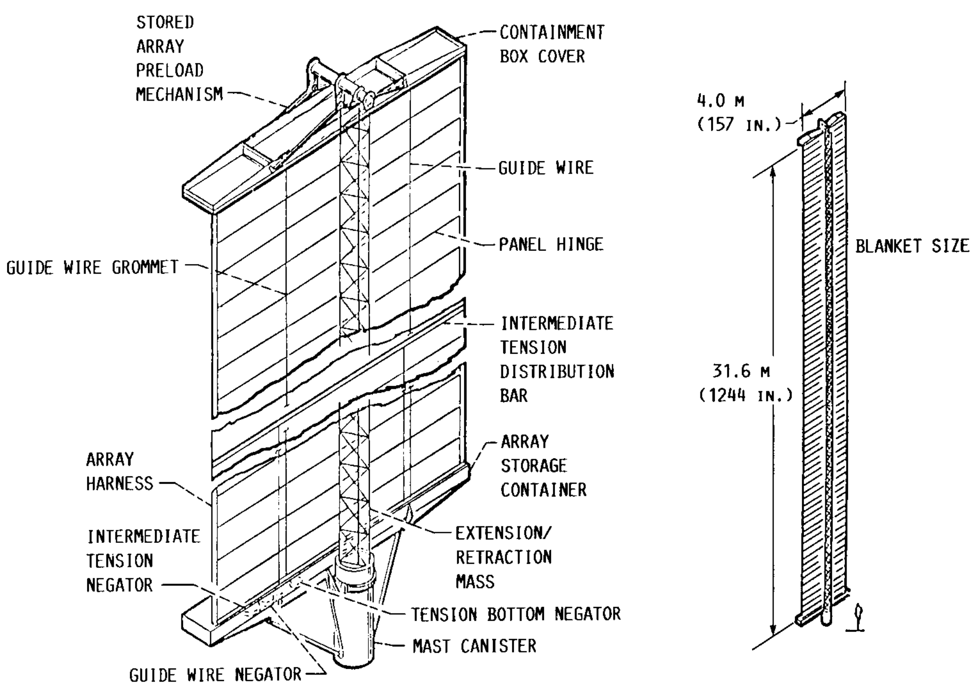

FIGURE 6. - SEP ARRAY WING DETAILS.

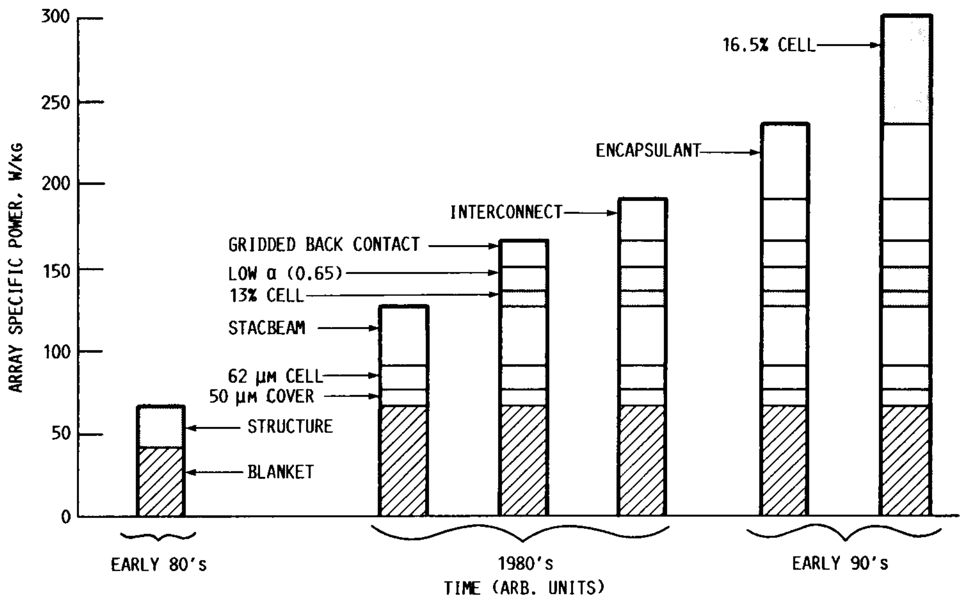

FIGURE 7. - PLANNED PROGRESS IN ACHIEVING LIGHTWEIGHT ARRAYS.

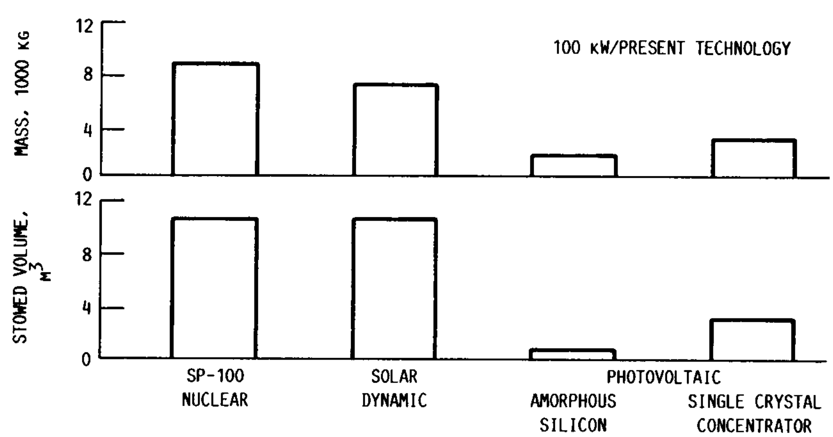

FIGURE 8. - COMPARISON OF POSSIBLE POWER SYSTEM FOR A LUNAR POLAR BASE. ALL SYSTEMS WITHOUT STORAGE.

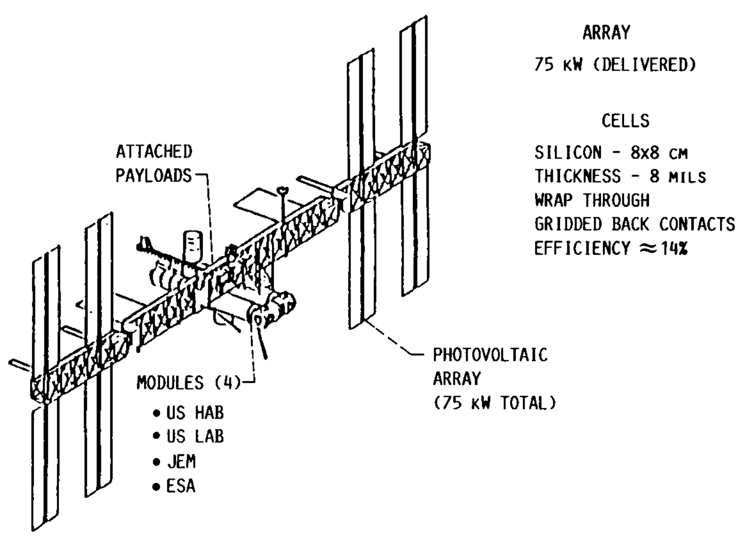

FIGURE 9. - REPRESENTATION OF PHOTOVOLTAIC OPTION - INITIAL SPACE STATION.

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16. Abstract

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