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AN OVERVIEW OF PHOTOVOLTAIC APPLICATIONS IN SPACE

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Power is certainly the backbone, the vital force of our program in space. As on earth, there is little we can do without it. Of all our space power sources, by far the most important is photovoltaic (PV) power (Fig. 1). Radioactive thermoelectric generators (RTG's) are also necessary for outer planetary missions where solar power is less effective. Not shown here but potentially an important power source of the future is the small nuclear reactor. Significant DOE and DOD funds are being utilized to develop a system capable of producing over 100 KW of power (SP-100) in the early 1990's. But little will occur in the near future to change this predominance of PV power, in fact there are environmental concerns that could lead to limitations on the use of RTG's, adding to the requirements for PV systems.

Fortunately for the satellite managers, PV system technology is improving at an impressive rate. Considering all the advanced spacecraft technologies, it is certainly among the leaders in performance improvements. NASA is a major participant in supporting PV technology and we are a primary user. The NASA PV effort is carried out in three parts: cell research at our Lewis Research Center (LeRC); concentrator research at our Marshall Space Flight Center (MSFC); and the lightweight array program at the Jet Propulsion Laboratory (JPL). LeRC acts as our Lead Center for overall coordination. Significant improvements have been made in all three areas and more are on the horizon.

PV systems contribute at all levels of NASA mission requirements (Fig. 2). Low to intermediate power levels are required for unmanned low earth orbit and inner planetary missions. Intermediate to high power levels are necessary for geostationary, lunar, outer planet, space station and electric propulsion thrusters. Incidentally, electric propulsion offers an interesting symbiosis with PV if they are selected for an outer planet mission. The PV system must be sized to produce a given power level in the low-solar intensity at the operating area. This array would be dramatically oversized in the early phase of the mission, near earth. The surplus could be used to power an electric thruster, shortening the trip time or increasing the payload. For example, if 500 watts are required at the end of a year of orbiting in the radiation environment of Jupiter, the required array could produce over 20 KW in the earth orbit for high efficiency electric thrusters.

NASA PV technology has developed along two paths (Fig. 3), one toward high power, the other high efficiency. High power will be attained through concentrator cells and reflecting arrays. Our goal here is to produce 200 watts/m^2, twice the level demonstrated in the collapsible array flown on the Space Shuttle in the SEPS experiment. For applications where weight is at a premium, we will use our most efficient, radiation tolerant cells with advanced deployment systems to attain our goal of 300 watts/Kg. JPL currently has designs in hand that are capable of 130 watts/Kg, almost twice the level of the SEPS flight test.

For high power requirements in earth orbit, like the Space Station, drag area becomes a consideration. Figure 4 shows the size advantage that the advanced concentrator cells offer. By using these 5mm square GaAs cells and efficient concentrator lenses, the required cell area is reduced, not only to less than half that required for current planar silicon arrays, but to even less area than that projected for the large focusing dish liquid organic rankine cycle power generators which are candidates for the Space Station.

In addition to the development of the lightest and highest efficiency arrays, lifetime characteristics are increasing in importance. Current arrays, if exposed to radiation, are certain to lose performance capability. Missions in the Van Allen belts or near Jupiter may see 50% degradation during a year, meaning that the initial array must be twice the normal size and weight. In this case an improvement in cell radiation resistance is a direct payload increase. In Figure 5, note that current silicon cells are almost destroyed by seven years in the radiation belts. GaAs offers a significant improvement, and Indium Phosphide (InP) is probably the best material tried to date. Of course the ultimate objective is a cell that is completely unaffected by radiation, or one that anneals or heals itself at ambient temperature.

The attendees at this meeting have made great strides in PV technology. Some of these are shown on Figure 6, and a number of additional ones are in store, perhaps to be reported at this meeting. What are the next mission opportunities? Several are illustrated in Fig. 7. The Space Station and its "satellites," the polar and co-orbiting platforms. These could be opportunities for advanced concepts, but may be restrained by conservatism or modularity for interchangeability. RTG's have the spectre of radioactive-during-launch to contend with, but are so remarkably efficient for outer-solar system missions that it would be a real challenge to replace them. SDI applications are not yet defined, but are sure to be interesting.

In addition to these, NASA has been getting a great deal of encouragement from advisory committees to expand its programs and research efforts. The prestigious National Commission on Space (NCOS Chairman Dr. Thomas Paine) after noting that the funding of Space R&T at NASA had dropped from over $800M in 1965 to less than $200M in 1986, stated that "NASA'S space research and technology program should be tripled, moving from its current 2% of NASA's budget to 6%." In terms of our 1987 budget this would be an increase from $170M to over $500M. Other advisory committees showed a remarkable concensus - that there should be a 2-3 times increase in NASA Space R&T to correct technology deficiencies. This advise was received from the Aeronautics and Space Engineering Board of the National Academy of Sciences, NASA's Space Systems Technology Advisory Committee, the American Institute of Aeronautics and Astronautics and the National Security Study Directive Team.

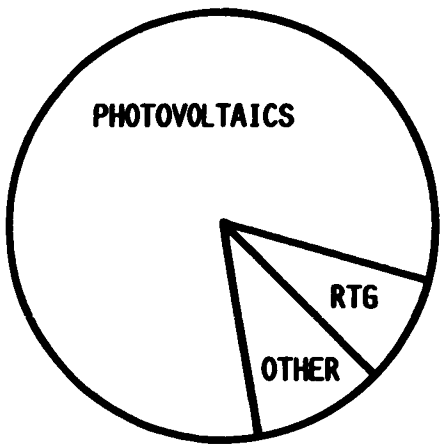
The NCOS also recommended an ambitious series of projects to be added to the NASA mission plan. Fig. 8 shows the NASA future mission blueprint with the NCOS additional proposed missions in boxes. NASA has already responded to this NCOS challenge and a proposal for a significant R&D program increase is being considered for FY 1988. Photovoltaic systems will obviously be an important part of any acceleration of space technology effort. The Initial Operational Configuration (IOC) Space Station will depend on PV systems for one half of its 75 Kw power. The system design is extremely conservative (about 25 w/kg), so a great deal of improvement is possible, ideally in time to contend for the "Growth" Station in the late 1990's which will require several hundred kilowatts. The next major NASA undertaking may be a Lunar base, potentially in 2010. Next to life support, power may be the most important issue. Power not only for the occupants and their experiments but possibly for on-site operations such as propellant manufacturing. PV systems would be a reasonable contender for generating some of this power, probably in the hundreds of kilowatts, particularly if there is an efficient lightweight, low cost, transportable concept by that time. It might be shipped in a roll like a window shade and simply layed on the surface.

Meanwhile, the United States is not alone in space or in the development of PV systems for space. Fig. 9 shows the USSR Salyut 7 manned space craft with an appended module, currently in orbit as part of their manned station program. Salyut 7 was launched in 1982 with silicon cell solar arrays capable of generating 4KW. Within the next two years, this solar array was supplemented by the small extendable arrays shown beside the central array. These were reported to be gallium arsenide (GaAs) cells, the first to be used operationally in space. The GaAs arrays produced about 4 KW. This USSR capability should be a very sobering challenge to the attendees of this meeting, the technologists, researchers and managers of PV programs in this country.

In summary, PV has made possible much of our scientific accomplishments in space and with proper support and progress in the R&D community it will continue its contributions.

POWER IS THE BACKBONE/VITAL FORCE BEHIND THE SPACE PROGRAM

• PV IS THE PRIMARY POWER SOURCE



POWER PRODUCED FOR NASA MISSIONS
(DOES NOT INCLUDE SPACE SHUTTLE)

Figure 1.

PHOTOVOLTAIC POWER GENERATION IS APPLICABLE ACROSS THE NASA MISSION MODEL

MISSION SUBSET	POWER LEVEL	SYSTEM ATTRIBUTES
UNMANNED NEAR EARTH (LEO, HEO, GEO) AND PLANETARY	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, LONG LIFE, PORTABILITY
ELECTRIC PROPULSION ORBIT TRANSFER (OTV)	HIGH	REUSABILITY, MINIMUM AREA, LOW MASS

Figure 2.

DUAL TECHNOLOGY PATHS SPAN THE NASA MISSION MODEL

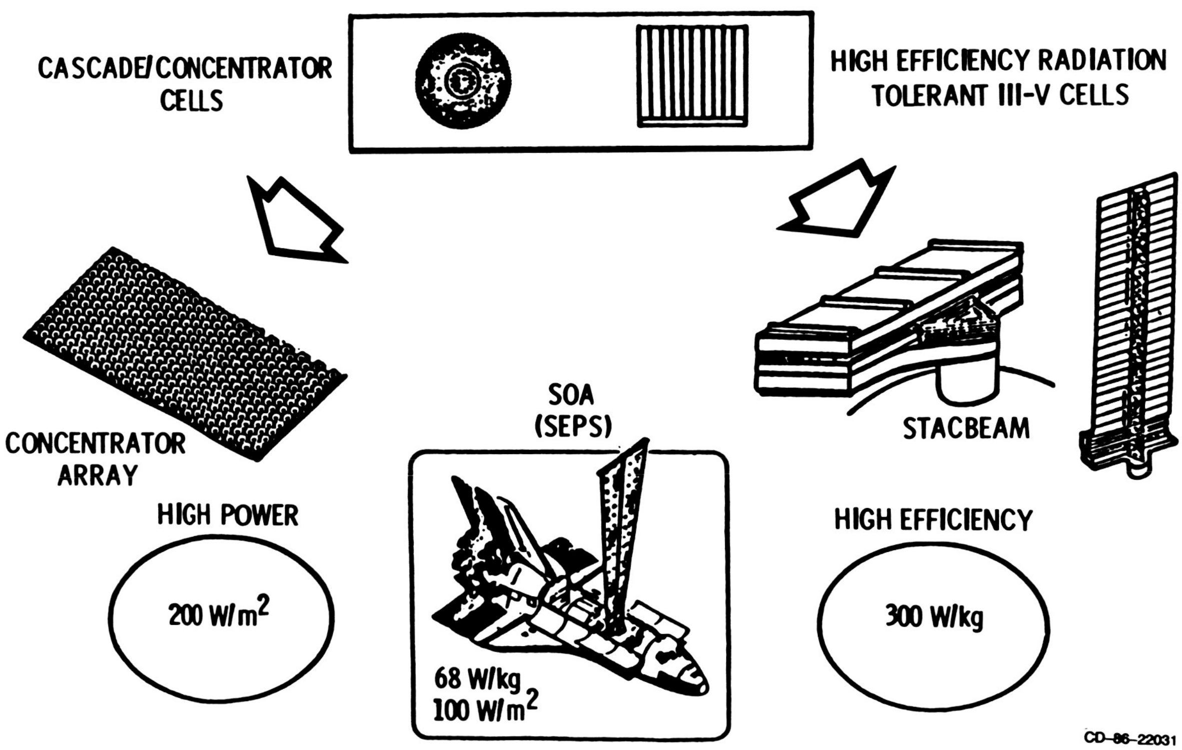
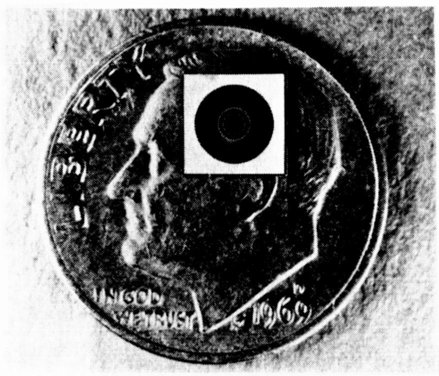
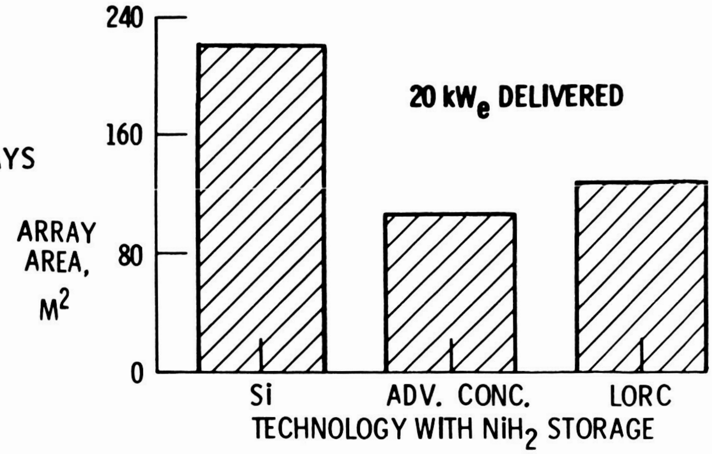


Figure 3.

THRUSTS

- o HIGH EFFICIENCY, SMALL AREA CELLS
- o LIGHTWEIGHT, EFFICIENT OPTICS
- o RIGID; DEPLOYABLE, LIGHTWEIGHT ARRAYS
- o REDUCED POINTING REQUIREMENTS





PLANAR Si:

14 % CELL

ADVANCED CONCENTRATORS:

> 30 % CELL
> 94 % OPTICAL EFFICIENCY

Figure 4.

COMPARISON OF SOLAR ARRAY CALCULATED OUTPUT AS FUNCTION OF ORBIT ALTITUDE BASED ON 1 MeV ELECTRON EQUIVALENT FLUENCES

TIME IN ORBIT = 7 YEARS, CIRCULAR ORBIT, 30^0 INCLINATION, T = 60 ^{0}C

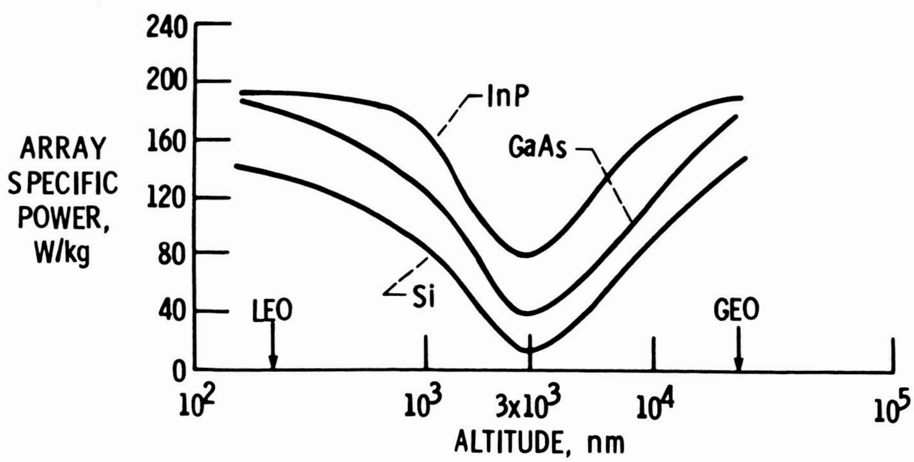


Figure 5.

SIGNIFICANT IMPROVEMENTS MADE AND MORE ARE COMING

	IMPROVEMENT	SIGNIFICANCE
DONE:	2 MIL SILICON CELL	RADIATION RESISTANCE, LIGHTWEIGHT ARRAYS
	GAAS CONCENTRATOR CELL	>20% EFFICIENCY, LOW COST/WATT
	SEP/OAST-1 ARRAY	>60% W/KG FLEXIBLE ARRAY TECHNOLOGY
	LARGE AREA SI CELL	LOW ARRAY COST
COMING:	>20% INP CELLS	RADIATION BELT SURVIVABLE ARRAYS
	CONCENTRATOR ARRAY	HIGH EFFICIENCY, HIGH POWER, RADIATION TOLERANCE
	STACBEAM, APSA	ULTRALIGHTWEIGHT ARRAYS

Figure 6.

WHAT'S NEXT

- SPACE STATION - LARGE SYSTEM, BUT POOR PERFORMANCE (5 W/KG 10C)
- CO-ORBITING AND POLAR FREE-FLYERS (CONSTRAINED BY MODULARITY?)
- RTG REPLACEMENT?
- ELECTRIC PROPULSION ORBIT TRANSFER?
- SDI APPLICATIONS (HOUSEKEEPING, RADIATION/BLAST RESISTANCE)

Figure 7.

BLUEPRINTS TO THE FUTURE

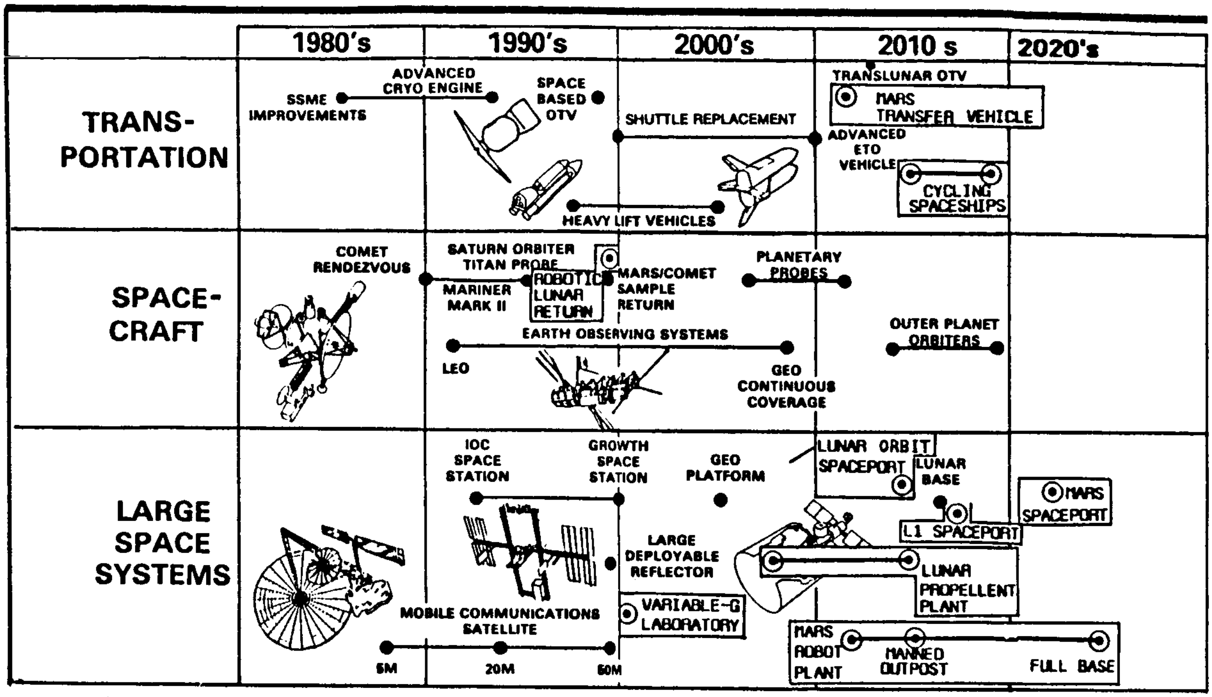


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Figure 8.

CONCEPTUAL DRAWING OF INTERIOR OF KOSMOS 1443-TYPE MODULE, SALYUT 7, AND A SOYUZ T FERRY CRAFT

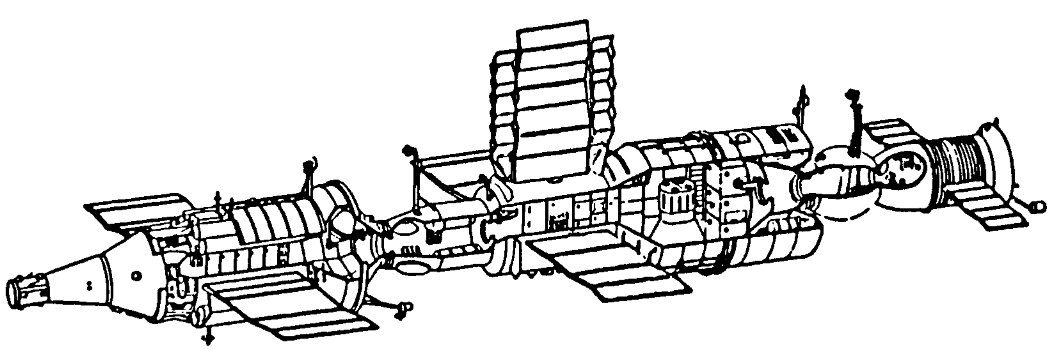

Figure 9.