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SPACE POWER FOR SPACE

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ABSTRACT

The total energy demanded by space missions of the future is expected to exceed past needs by orders of magnitude. The unit costs of this energy must be reduced from present levels if these missions are to be carried out at projected budget levels. The broad employment of electric propulsion and the capability to utilize novel high power sensors hinge on the availability of systems lighter by factors of ten or more than have flown to date. The NASA program aimed at providing the technological basis to meet these demands is described in this paper. Research and technology efforts in areas of energy conversion, storage and management are covered. In addition, work aimed at evolving the understanding necessary to cope with space environment interactions and at advanced concepts is described.

INTRODUCTION

As has been seen all too clearly in the last few years, energy here on Earth is critical to the ability of society to function -- it is also critical in space, where the only energy source available is the Sun. This means that conversion systems or power sources must be carried, and to be practical, they must be acceptable in both weight and cost. These criteria increase in importance as higher total energy and more difficult missions are planned. The current space power technological state-of-the-art is inadequate to meet the full range of opportunities presently under consideration by mission planners. From analysis of these candidate opportunities two principle directions for space power research and technology emerge, toward very high capacity orbital systems at low cost and toward very high performance.

In the paragraphs which follow the two principle program directions are discussed. This is followed by an overview of the NASA Space Power Technology Program. This program is focussed on achieving progress in areas of photovoltaic energy conversion, chemical energy conversion and storage, thermal-to-electric energy conversion and power systems management and distribution. In addition, efforts to evolve the understanding necessary to cope with power systems interactions with the space environment are carried out, as are investigations of advanced power concepts.

HIGH CAPACITY LOW COST ENERGY SYSTEMS

It has been broadly contended that the availability of copious quantities of low cost energy has been the principal factor in the evolution of our society during the past century. It is contended here that similar considerations are of great importance to the realization of the full beneficial potential of space. The prospective importance of energy to the development of space is suggested by the results of an analysis(1) of past and projected mission energy requirements displayed in Figure 1. Earlier missions, were either of short duration at high power or of long duration at low power and in any case required a total energy of about 10^4 KW-HR or less. Future missions which are expected to commence in the mid 1980's will require energies of 10^5 to 10^7 KW-HR or greater. This increased energy requirement stems from both increases in power level and extensions in mission duration. Many of the missions envision semi-permanent facilities which would have characteristics similar to ground power systems, that is ruggedness, reliability, maintainability and most important, low cost. Achievement of this latter characteristic will be difficult if past space power system costs can be considered an indicator of the future. These costs have been in the range of 10^3-10^4 \$/KW-HR(2). If these historical costs remain unchanged and are applied against the future needs displayed in Figure 1 energy system costs for single future missions would clearly imply unacceptable aggregate expenditures.

In spite of the foregoing concern there are sound reasons for optimism with regard to our ability to meet future space energy needs at reasonable costs. First the extension of mission duration with only modest technology changes will surely provide a major reduction in unit energy cost. Second, the price of ground power at less than 10^{-1} \$/KW-HR is some four orders of magnitude less than that experienced to date in space and a series of recent studies have suggested that future large satellite power systems may in the future become competitive with ground power. Third, the national concern with energy futures has stimulated significant investment in critical technologies such as photovoltaics and chemical energy storage aimed at achieving major cost reductions. Finally, there is still adequate time to undertake technological investment aimed at reducing risk and uncertainty in this area.

HIGH PERFORMANCE ENERGY SYSTEMS

While the criticality of system weight for low earth orbit missions is expected to be reduced by the near future availability of the Shuttle it remains an important concern for many missions to explore the solar system and to utilize geosynchronous space for earth applications. If we are to perform a Comet Rendezvous mission with electric propulsion for example, there is a need to significantly advance solar array specific weight. In the further term, as illustrated in Figure 2, nuclear electric propulsion provides the only known method of conducting intensive study of the far reaches of the solar system(3). For such missions lightweight and long life are paramount.

High power (> 1000 W) isotope power systems may be required by future NASA missions for which solar power systems are impractical, and if these systems are to be used , their cost must be reduced to acceptable levels through the development of high-performance conversion systems. Other missions will require untended long-life operation of power systems in hostile environments such as those of Mercury or Jupiter. Finally, advanced sensors such as LIDAR may demand power levels of 10 KW or greater.

Realization of the performance levels required to carry out these difficult missions demands a sustained commitment to advanced power research and technology.

THE NASA SPACE POWER TECHNOLOGY PROGRAM

Photovoltaic Energy Conversion

The objective of the NASA photovoltaic research effort is to improve conversion efficiency, reduce mass, reduce cost, and increase operating life of photovoltaic converters and arrays.

The rapid advances of the last two years in photovoltaic technology are evident from the curve of Figure 3 which displays the trend in silicon solar cell power density since the formation of the NASA. This recent acceleration in performance has been largely due to the embodiment of past research results in the OAST thin cell.

As shown in Figure 4, the best flight cells used to date have been silicon devices 300-micrometer (μm) thick and about 13 percent efficient. The successful pilot production of the thin cell conclusively demonstrated that a 50μm cell can be manufactured in quantity and is by no means a laboratory curiosity. The actual average efficiency of the 2000-cell production run, which was based on technology frozen early in 1977, was 10.3 percent. Subsequent research has achieved 14 percent efficiency in the 50μm size.

In other silicon cell research, efficiencies of about 14 percent have been demonstrated on 200μm cells utilizing a number of low-cost technologies such as printed rather than vacuum-evaporated electrical contacts. Large area cells are also being investigated for space use. This work promises increased performance at lower cost. In the area of alternative photovoltaic materials, small laboratory type gallium arsenide cells achieved an efficiency of over 18 percent. Further work will be required to establish long-term space performance and production feasibility of such cells.

A rewarding characteristic of research is the realization of unanticipated gains from such investment. The thin cell research work was aimed at establishing a technology for a substantial weight reduction in space solar arrays. However, the cells produced are considerably less fragile than traditional space cells, which should lead to lower breakage rates (and costs) in handling. Since the cells can be made from much thinner slices of the basic silicon crystal ingot, it is possible that many more cells could be produced from the same amount of basic material, thus achieving major cost reductions. The cost reduction area is, central to the Department of Energy (DOE), low-cost silicon solar array work, and they are supporting the development of the necessary thin wafer sawing technology.

Advanced solar array technology efforts are also continuing to progress toward the goals of high specific power and reduced cost. The basic technology demonstration of the 12.5 KW, 66 W/kg SEPS fold out solar array is nearing completion and plans to test a full scale wing aboard an early Shuttle flight are under consideration. This array has about five times the specific power output of the Skylab array and is estimated to have less than half the specific cost (\$300/W).

The SEPS array provides both a baseline technology for early electric propulsion applications and a design basis for efforts to augment Shuttle orbiter power in order to extend useful mission capability.

In other advanced solar array research and as shown in the top part of Figure 5, thin cells have been incorporated into a lightweight blanket which consists of thin plastic substrates, the cell and interconnections, a thin encapsulant for protection against the space radiation environment, and adhesives. This blanket has provided an initial technology base for space planar solar array designs capable of producing 200 watts per kilogram of array mass.

Design and technology testing of concentrator solar arrays has recently been initiated. A design concept for such an array is illustrated in the lower part of Figure 5. These arrays function by reflecting incident light off surfaces set at appropriate angles to the active solar cell surface. This concept offers potential weight and cost advantages over planar arrays. These advantages stem essentially from the use of lightweight, low-cost reflector material to replace part of the more expensive and heavier solar cell blanket. The models tested to date have shown encouraging results in that acceptable thermal gradients exist, and the consequences of even severe maldistribution of light are minimal.

NASA also maintains a national testing capability for the evaluation of space solar cells. This capability includes calibration of new space solar cells by balloon and aircraft, as well as evaluation of new space solar array technology in zero-g aircraft.

Plans are now underway to extend advanced solar power test capability beyond current ground, aircraft and balloon facilities directly to space facilities. As illustrated in Figure 6, hardware for the three solar power experiments planned for flight on the Shuttle-launched Long Duration Exposure Facility (LDEF) will be delivered. These experiments include an active photovoltaic experiment which is aimed at space evaluation of advanced technology solar cells, a passive solar array material experiment which evaluates a broad range of candidate materials such as encapsulants, substrates, etc., and a solar power experiment which aims at evaluating low-cost terrestrial-and avionic- based components for space use. In addition, preparation of the SEPS array experiment is expected to be complete. The experiment aims to evaluate deployment, retraction and dynamic characteristics of this array.

Chemical Energy Conversion and Storage

The objective of the NASA chemical energy conversion and storage research and technology effort is to achieve improved performance, energy density, life, operational capability, and cost of space systems. The nickel-cadmium (Ni-Cd) battery has been the workhorse space energy storage system; it remains, however, both heavy and severely limited in life. As illustrated in Figure 7, a program to attack the problems of both limited life and low energy density of the Ni-Cd battery is in progress. Emphasis will be placed on evaluating candidate separators and electrodes, as well as design variables and operational techniques. The plans are to achieve the goals of nearly doubled usable energy density or life by 1981. Work will also continue to investigate low-cost nickel-cadmium batteries for high-capacity applications and advanced electrochemical couples involving sodium and lithium, ultimately aimed at increasing primary and secondary battery energy density by a factor of 10 or more.

Our studies have shown that in very high-capacity applications, such as may be encountered in bulk energy storage for an Earth-orbital power plant in the 100-kw range, batteries become both massive and excessively costly. An alternative which reduces both mass and cost is the fuel cell-electrolyzer system illustrated in Figure 8. In the charge cycle of such a system, water is electrolyzed into its constituent gases of hydrogen and oxygen by the input of electric power. Upon discharge these gases recombine in a fuel cell to produce water and electrical power. The initiation of the necessary effort to establish the technology basis for this type of system is also planned.

Thermal-to-Electric Energy Conversion

The thermal-to-electric conversion program includes thermoelectric, Brayton, and thermionic research and technology efforts. The objective of the program is to provide dynamic and static nuclear and solar thermal conversion technology that is cost and mass competitive with solar arrays or is required in applications for which alternatives are impractical. An additional objective is to provide the thermal-to-electric conversion technology basis for out-of-core nuclear power, as may be required for nuclear electric propulsion.

Thermoelectric materials which offer promise of efficiencies greater than 15% are currently being investigated. Such materials would offer twice the power output of the selenides currently baselined for the Galileo mission.

In Brayton technology life test of a 10 KW rotating unit continues past 34,000 hours toward the goal of 50,000 hours. Under the joint DOE/NASA program illustrated in Figure 9 progress continues on a high performance Brayton isotope power system at the .5-2.0 KW level. Critical components have been delivered to DOE for ground testing. If successful in ground test, this unit is a planned candidate for a DOE/AF flight test. In addition to conversion system research progress in the underlying materials also has continued. For example, research aimed at understanding the rapid loss of strength of superalloys at high temperature in vacuum is in progress.

As illustrated in Figure 10 the thermionic technology program is aimed at establishing technology feasibility of an advanced lightweight, static, thermionic conversion system compatible with a remote solar or nuclear heat source. Key areas of investigation include thermionic converters, heat pipes for transport of heat to and from the converter, insulators to allow electrical isolation of multiple converters and high-temperature radiators to reject waste heat. Studies have shown that such a system, with a properly designed heat source, could provide up to 500 kw of electrical power in one Shuttle launch.

POWER SYSTEMS MANAGEMENT AND DISTRIBUTION

The two major thrusts in power system management and distribution are toward automated management and toward providing critical technologies for long-life, high-power and high-voltage power systems. Automated Power Systems Management (APSM), as illustrated in Figure 11 is the capability of a spacecraft power system to automatically perform monitoring, computational, command and control functions without the need for ground intervention. The expected benefits of APSM are an increased ability to accommodate real-time changes and fault correction autonomously, and a reduction in flight operations cost and susceptibility to human error. Activities will focus on the modification of spare Viking Orbiter 75 solar array/battery power system equipment to accommodate APSM hardware and software. Tests to evaluate the modified equipment will be conducted as will the preparation of a handbook to allow power system designers to utilize APSM hardware and software for future solar array/battery power systems.

The critical technologies and system management capabilities for large Earth-orbital power systems are also being developed in this program. The potentially large energy requirements for space construction, materials processing, etc., dictate that future power systems adopt a utility-like philosphy of power management. For example, the advantage of increased voltage on power management and distribution system cost and weight is shown in Figure 12. Operation at these voltage has not previously been possible due to lack of suitable switchgear. During the past year NASA has developed switchgear to fill some of this need. Units developed at 120 V dc include 5-ampere and 30-ampere sizes packaged suitably for flight qualification. A 300-volt unit capable of 1 to 2 amperes has also been breadboarded.

Work will continue to evolve critical switchgear, semiconductors, capacitors, and other components along with processing, distribution and conditioning concepts which optimize specific performance and minimize the risk associated with higher voltage levels in future large power systems. A major objective will be to complete by 1980 the design of a breadboard in the 100-kw range to demonstrate central and substation power management.

ENVIRONMENTAL INTERACTIONS

A program to increase understanding of and devise engineering solutions for the interaction of the space plasma environment with high-voltage systems is also underway.

The potential significance of these space environmental interactions is indicated by the photograph in Figure 13 which illustrates arcing encountered in ground-based, solar array experiments. In addition to ground-based experiments, two planned space experiments are expected to contribute to the understanding needed to control these phenomena. These experiments are the Plasma/Interactions Experiment, which is a secondary payload on the Landsat-C Delta launch vehicle, and a space plasma high-voltage interaction experiment on LDEF. These experiments are designed to provide data for the voltage range up to 1000 volts for a variety of plasma densities.

A second environmental interaction concern derives from the discharge generated anomalies experienced on geosynchronous satellites. A comprehensive effort is being pursued with the Air Force to evolve design criteria to minimize these spacecraft charging effects. Ground results will be correlated with flight test data from the Air Force SCATHA (Spacecraft Charging at the High Altitudes) which is currently scheduled for launch in January 1979.

Recent analytical and experimental work has suggested that a local depletion of damaging energetic charged particles in the region of a space vehicle may be possible. Investigation of this VLF particle precipitation concept is also underway.

ADVANCED POWER CONCEPTS

Research in a number of advanced power concepts involves new and novel ways to generate, store, control, transmit, and distribute energy. Lasers offer a novel means of transmitting power from a central ground or space power "utility" to various remote space users. Research has resulted in the development of an efficient, visible wavelength, copper halide laser, which allows transmission over large distances (e.g., 1000's kilometers) without appreciable spreading of the beam. Another technique which can be utilized to minimize beam-spreading over long transmission distances utilizes a number of lower power lasers which are phased locked to maintain a coherent single output beam. Recently, experimental measurements of a closed-loop CO_2 laser have shown the optical quality of the laser beam suitable for phase locking of separate high-power beams, extracted simultaneously from the laser cavity.

Research is also aimed at the conversion of the power in a laser beam to electrical power with maximum possible efficiency. The operation of a laser-powered heat engine having a target efficiency greater than 50 percent, and an electrodeposited array of tuned diodes for coherent laser radiation conversion are planned in the near future.

Work on nuclear-pumped lasers will also continue. In the past, gas lasers were energized by fission fragments originating from the coating of laser tubes by enriched uranium, or by the energetic particles that are liberated when an isotope of helium splits. Emphasis will now be put on laser excitation by fission fragments from gaseous uranium-hexafluoride, UF_6. While in this case UF_6 is a source of energy, it also tends to quench the population inversion of excited states in the laser gas. The reconciliation of these counteractive phenomena will be a difficult but necessary task on the way toward high-power and highly efficient nuclear-pumped lasers.

CONCLUSION

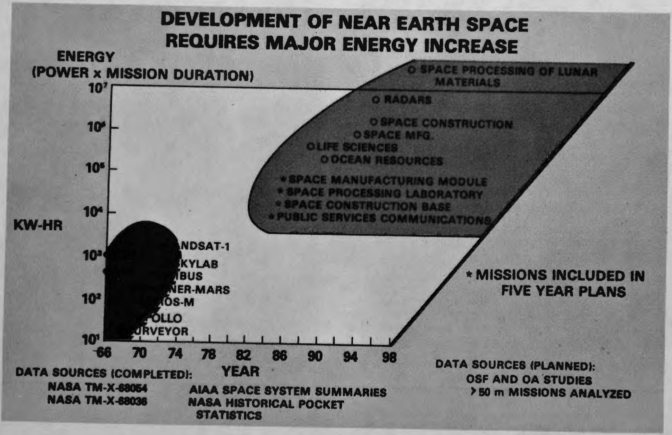
If the capability to operate economically in near earth space is to be utilized successfully, the need exists for high power systems at low cost. If the discoveries made in understanding our solar system are to be followed up, the performance levels required to power our craft to distant and hostile places must exist. In order to increase the likelihood that these missions can be conducted with acceptable cost and risk, continued aggressive investment in space power technology is required now.

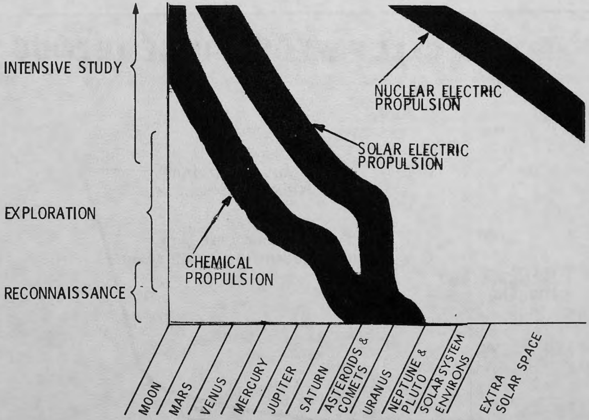
REFERENCES

1. Private Communication, Zakrzewski, T., General Research Corporation, McLean, VA., 1 March 1977.

2. Bernatowicz, D. T., "Cost Study of Solar Cell Space Power Systems", NASA TMX-68054, May 1972.

3. Dipprey, Dwayne F., "Advanced Propulsion for Future Planetary Exploration", AIAA 14th Annual Meeting and Technical Display, AIAA Paper No. 78-317, February 1978.





PROPULSION CAPABILITIES

FIGURE 2

SOLAR CELL PERFORMANCE TRENDS

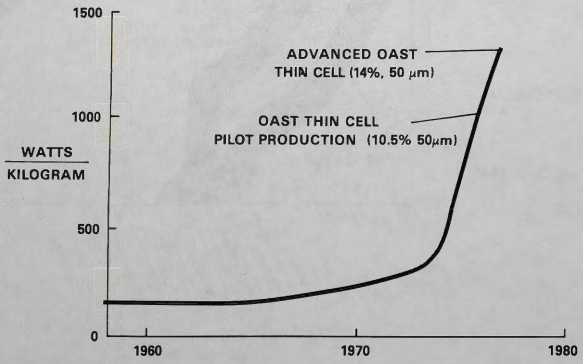


FIGURE 3

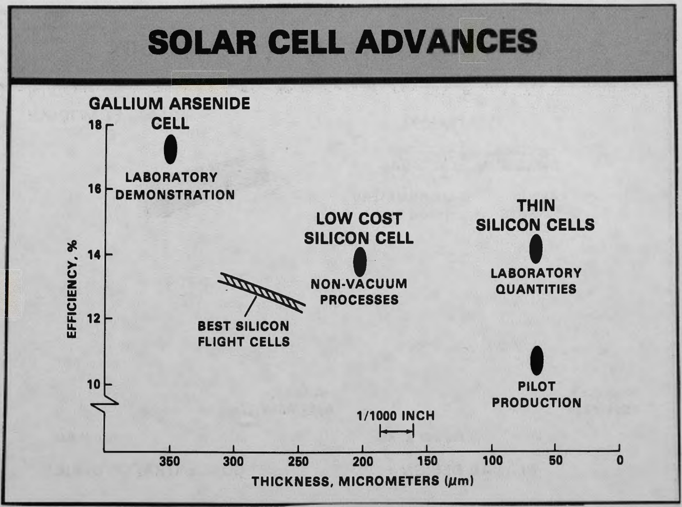
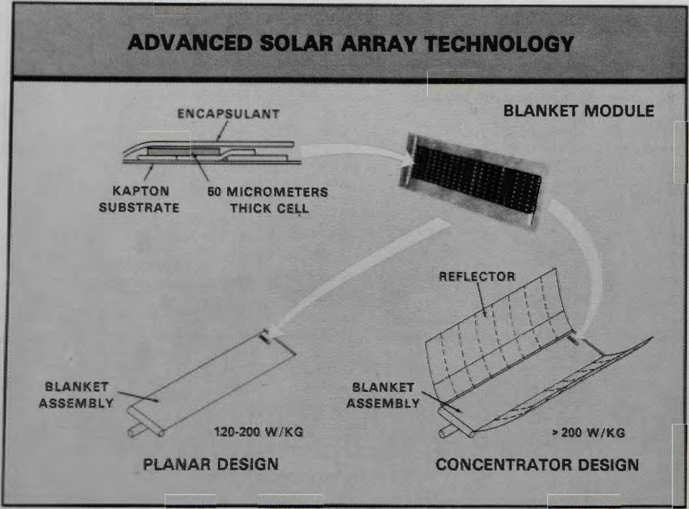

SOLAR CELL ADVANCES
GALLIUM ARSENIDE CELL
LABORATORY DEMONSTRATION
LOW COST SILICON CELL
NON-VACUUM PROCESSES
THIN SILICON CELLS
LABORATORY QUANTITIES
PILOT PRODUCTION
BEST SILICON FLIGHT CELLS
1/1000 INCH
EFFICIENCY, %
18
16
14
12
10
350
300
250
200
150
100
50
0
THICKNESS, MICROMETERS (μm)

FIGURE 4



ADVANCED SOLAR ARRAY TECHNOLOGY

ENCAPSULANT

KAPTON SUBSTRATE

50 MICROMETERS THICK CELL

BLANKET MODULE

REFLECTOR

BLANKET ASSEMBLY

120-200 W/KG

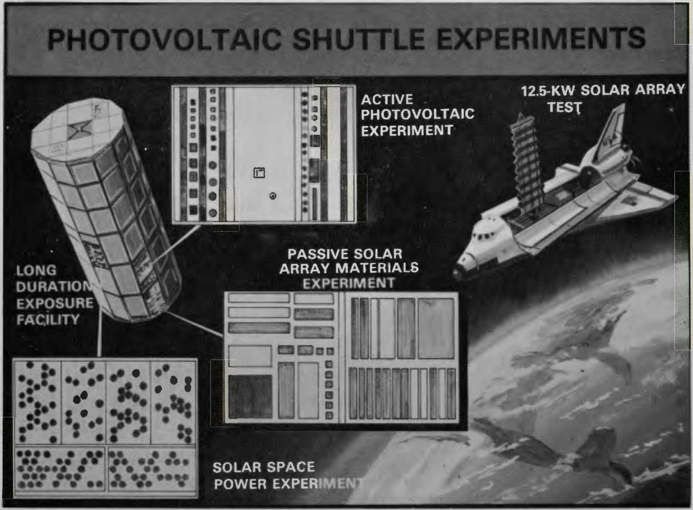
PLANAR DESIGN

BLANKET ASSEMBLY

> 200 W/KG

CONCENTRATOR DESIGN

FIGURE 5



PHOTOVOLTAIC SHUTTLE EXPERIMENTS

ACTIVE PHOTOVOLTAIC EXPERIMENT

12.5-KW SOLAR ARRAY TEST

PASSIVE SOLAR ARRAY MATERIALS EXPERIMENT

LONG DURATION EXPOSURE FACILITY

SOLAR SPACE POWER EXPERIMENT

FIGURE 6

ADVANCED NICKEL CADMIUM BATTERY

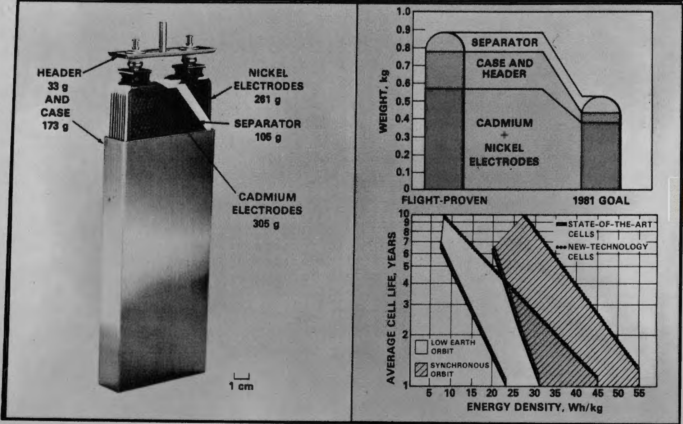
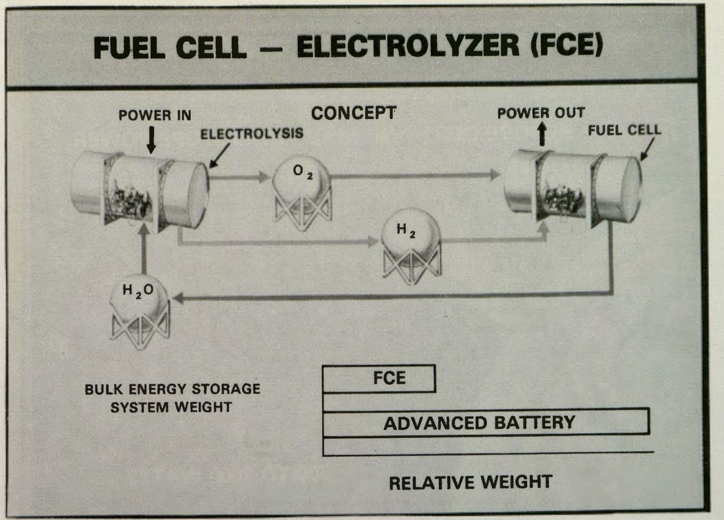


FIGURE 7

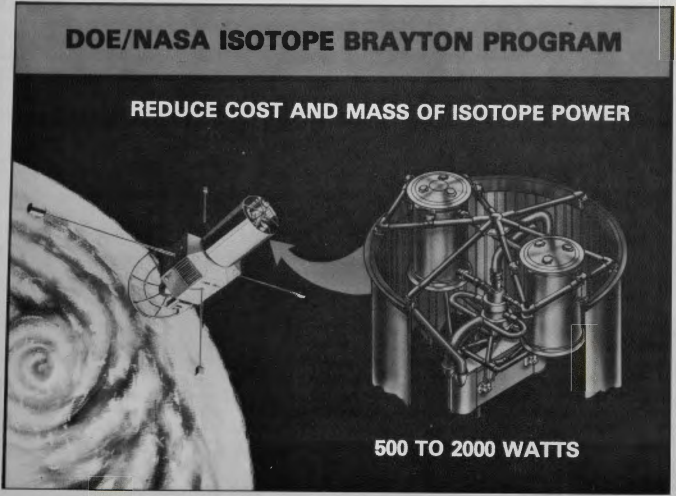


FUEL CELL — ELECTROLYZER (FCE)

CONCEPT

BULK ENERGY STORAGE SYSTEM WEIGHT

FIGURE 8

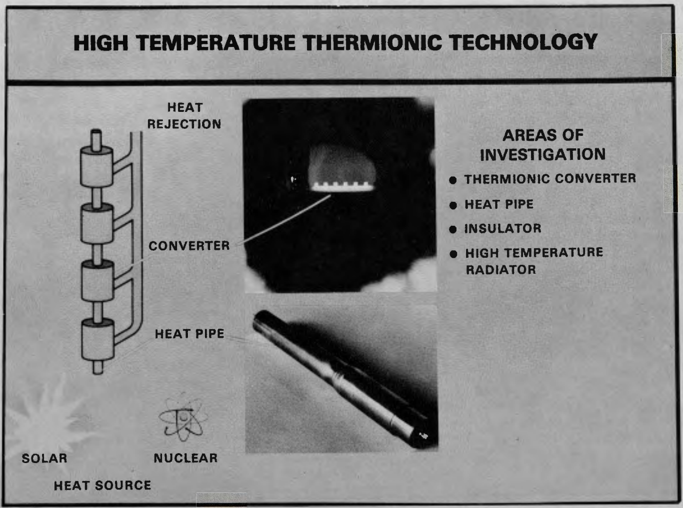


DOE/NASA ISOTOPE BRAYTON PROGRAM

REDUCE COST AND MASS OF ISOTOPE POWER

500 TO 2000 WATTS

FIGURE 9

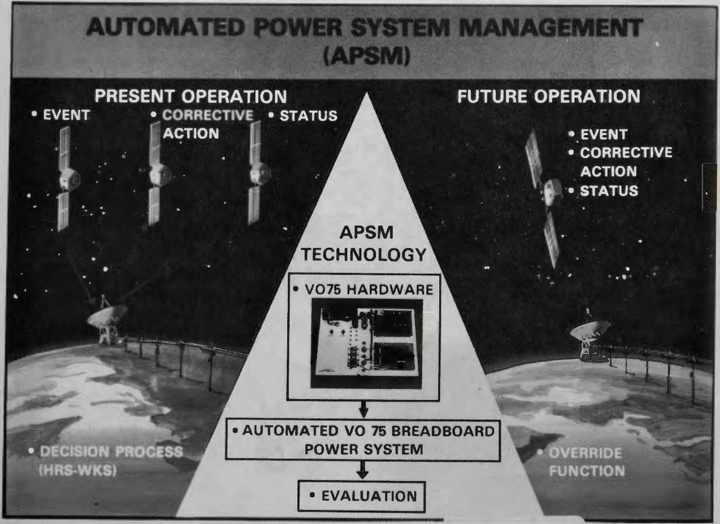


HIGH TEMPERATURE THERMIONIC TECHNOLOGY

AREAS OF INVESTIGATION

- THERMIONIC CONVERTER
- HEAT PIPE
- INSULATOR
- HIGH TEMPERATURE RADIATOR

FIGURE 10



AUTOMATED POWER SYSTEM MANAGEMENT (APSM)

PRESENT OPERATION

- EVENT
- CORRECTIVE ACTION
- STATUS
- DECISION PROCESS (HRS-WKS)

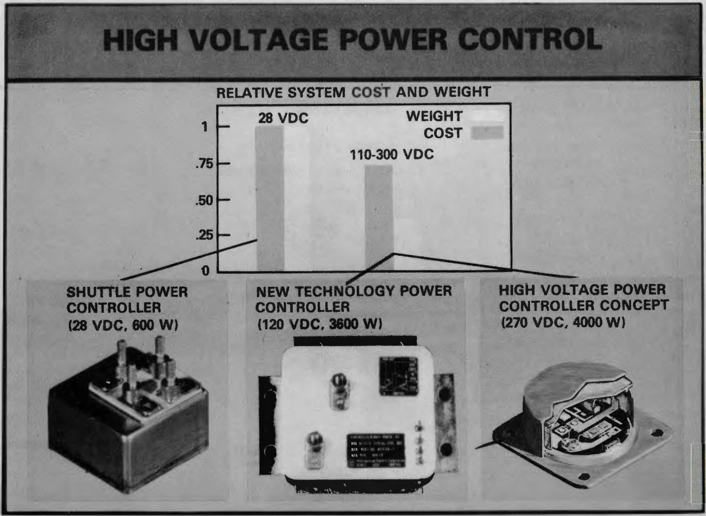
APSM TECHNOLOGY

- VO75 HARDWARE
- AUTOMATED VO 75 BREADBOARD POWER SYSTEM
- EVALUATION

FUTURE OPERATION

- EVENT
- CORRECTIVE ACTION
- STATUS
- OVERRIDE FUNCTION

FIGURE 11



HIGH VOLTAGE POWER CONTROL

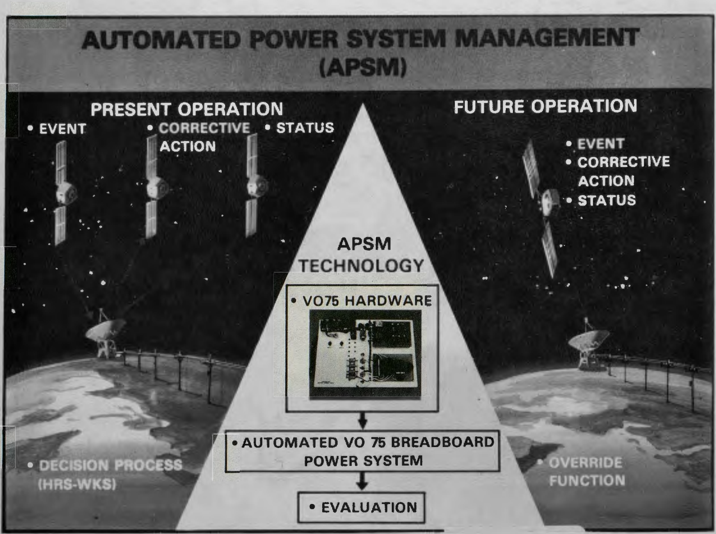
RELATIVE SYSTEM COST AND WEIGHT

SHUTTLE POWER CONTROLLER
(28 VDC, 600 W)

NEW TECHNOLOGY POWER CONTROLLER
(120 VDC, 3600 W)

HIGH VOLTAGE POWER CONTROLLER CONCEPT
(270 VDC, 4000 W)

FIGURE 12



AUTOMATED POWER SYSTEM MANAGEMENT (APSM)

PRESENT OPERATION

- EVENT
- CORRECTIVE ACTION
- STATUS
- DECISION PROCESS (HRS-WKS)

APSM TECHNOLOGY

- VO75 HARDWARE
- AUTOMATED VO 75 BREADBOARD POWER SYSTEM
- EVALUATION

FUTURE OPERATION

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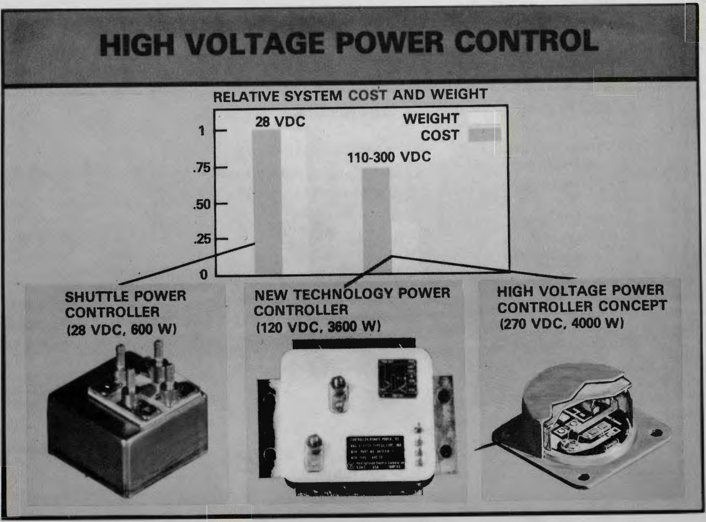
FIGURE 11



HIGH VOLTAGE POWER CONTROL

RELATIVE SYSTEM COST AND WEIGHT

SHUTTLE POWER CONTROLLER
(28 VDC, 600 W)

NEW TECHNOLOGY POWER CONTROLLER
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HIGH VOLTAGE POWER CONTROLLER CONCEPT
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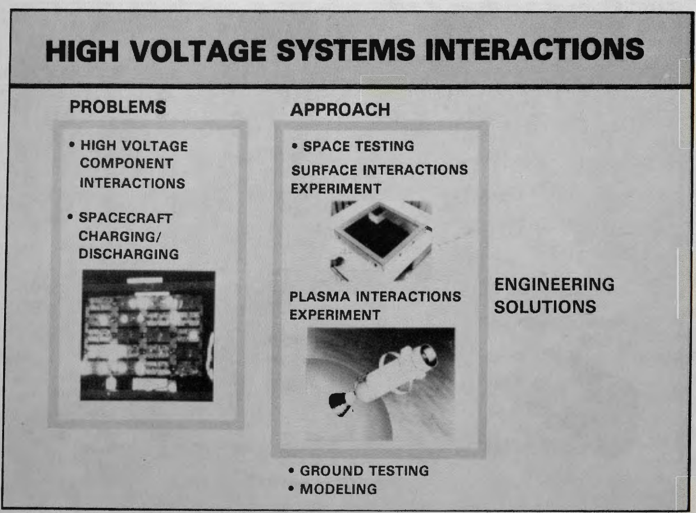

HIGH VOLTAGE SYSTEMS INTERACTIONS

PROBLEMS

- HIGH VOLTAGE COMPONENT INTERACTIONS
- SPACECRAFT CHARGING/ DISCHARGING

APPROACH

- SPACE TESTING

SURFACE INTERACTIONS EXPERIMENT

PLASMA INTERACTIONS EXPERIMENT

- GROUND TESTING
- MODELING

ENGINEERING SOLUTIONS

FIGURE 13