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Power Systems for Production, Construction, Life Support, and Operations in Space

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POWER SYSTEMS FOR PRODUCTION, CONSTRUCTION, LIFE SUPPORT, AND OPERATIONS IN SPACE

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INTRODUCTION

As one looks forward to mankind's future in space, it becomes obvious that unprecedented amounts of power will be required for the exploration, colonization, and exploitation of space. Activities envisioned include interplanetary travel, LEO to GEO transport using electric propulsion, lunar and Mars bases, advanced communications, planetary surface rovers, mining, construction, and manufacturing in space or at planetary surfaces. Power levels required for these applications vary from a few kilowatts (kWe) to 4 or 5 megawatts (MW_e) electric. Significant advancements must be made over the present state of space power technology in order to enable or significantly enhance these missions. The purpose of this paper is to discuss the advanced power system technologies being pursued by NASA to fulfill these future needs. Technologies discussed will include photovoltaic, solar dynamic, and nuclear power systems.

MISSIONS

The most stressing of the currently envisioned missions is the establishment of permanent bases on the lunar or Mars surface. As currently envisioned, these bases would be established through a scenario that includes Mars/lunar observers, rovers and sample return missions, establishment of an initial outpost, extended human presence, and a self-sustained base. It is currently envisioned that the early power systems will be advanced solar and the eventual high-capacity power systems will evolve to be nuclear. Since developing power systems to meet these needs encompasses all the technologies for the other missions, we will focus our attention on the lunar/Mars base applications. A. Friedlander, of SAIC, has recently completed studies of power needs for an evolving lunar base and the activities are highlighted in table I.

Following unmanned precursor missions, the scenario follows with an interim tended-manned outpost camp with a habitat and pilot plants for production of oxygen from the lunar soil, soil movers and drills, rovers, and some science experiments. The majority of the power required is for the habitat and LOX plants. Though the next stages of the scenario, the habitats, and LOX production capabilities are increased and the science and laboratories increased. Oxygen production meets needs for life support and propulsion systems. Closed environment and life support systems research is developed in the second phase, an outpost is installed on the far side of the moon, larger rovers are developed, mining operations begin, and ceramics and metallurgy pilot plants are begun. In the sustained base food production is added and the environment and life support systems are closed. Full-scale ceramic, metallurgical, and LOX capabilities are in place and product export is initiated. The required power levels grow from 100 → 500 → 2000 KWe.

POWER SYSTEMS

There are four types of space power systems in use or under development at the present time. They are Radioisotope Thermoelectric Generator (RTG's), photovoltaic, solar dynamic, and nuclear space power systems. RTG's have been used for planetary exploration missions, and have operated for up to 12 years in space. Their specific power is ~4 W/kg and generally they are limited to low power applications (~500 W). Photovoltaic (PV) power systems have been flown extensively in a variety of orbits at power levels of a few KWe and below. Present PV power systems provide 50 to 60 W/kg in areas of continuous sunlight. In LEO missions where energy must be stored in batteries for the dark side of the mission the specific power drops to 3 to 6 W/kg. Solar dynamic (SD) power systems use a concentrator to concentrate solar energy into a high-temperature receiver. This energy is used to heat the working fluid of a dynamic energy conversion system (Brayton, Rankine, and Stirling) and to heat a thermal energy storage (TES) material which provides heat for the dark portion of the mission. Thermal Energy is efficiently converted to electricity (20 to 30 percent) using the dynamic energy conversion and the excess heat is removed by a radiator. In Nuclear Reactor Space Power Systems (NRSPS) the reactor provides the thermal energy directly to a static or dynamic energy conversion system and a high-temperature radiator is used to remove the excess heat. For a given inlet temperature the efficiencies and temperature ratios for the various conversion systems are chosen to minimize the overall system mass. Each of the above mentioned power systems have their attributes and shortcoming and all are being developed to meet the wide variety of mission needs. RTG's and PV power systems have been flown extensively in space, SD and NRSPS are still in development.

PRESENT STATUS OF POWER SYSTEMS

RTG power systems have been used extensively for long duration missions at power levels of 500 W and below. Use of these power systems could be extended to power levels of 1 or 2 kWe using a dynamic energy conversion system (such systems are presently under study). RTG's are an attractive power system for space exploration, rovers, and remote bases requiring relatively small power levels. They will not be discussed further because of the low power limitation.

The present state-of-the-art of photovoltaic power is Silicon solar cell arrays with specific powers of 40 W/kg and NiH_2 batteries at 40 W-hr/kg (100 percent DOD). These are attractive in applications with a high percentage sunlight or at low power levels but can result in some very massive systems as one goes to longer night cycles or significantly higher power levels.

This technology is being used for the Space Station. The specific mass of the PV power system broken into components is shown in figure 1. The figure shows that a 100 kWe PV system would weigh 30 000 kg. The deployed area of the system would be 2500 m^2.

It should be pointed out that due to the large and complex number of interfaces on the Space Station, the auxiliary equipment accounts for ~40 percent of the power system mass. The Space Station is also considering using a relatively low-temperature solar dynamic (SD) Closed Brayton Cycle (CBC) for the second generation power system. Its mass breakdown is also shown in figure 1.

Major mass contributors to the SD system are the concentrator, receiver, power conversion unit, and radiator. The SD system is being pursued because of its reduced area - (and hence reduced propellant make-up for drag cancellation) and predicted lower life cycle costs.

Advancements in Silicon planar array technology have been demonstrated that can provide 70 to 140 W/kg arrays at roughly a 30 percent improvement in overall efficiency. These advancements would allow 9 or 10 W/kg LEO space power systems with an exposed area of ~2000 m^2 for a 100 kWe system.

ADVANCED POWER SYSTEMS

As was mentioned earlier, NASA's new advanced power systems technology research efforts are aimed at developing power systems that can enable or greatly enhance the lunar and Mars base missions. It is felt that the technology needs for these systems would encompass those of the other missions. In the new Civilian Space Technology Initiative (CSTI) and Pathfinder programs aggressive programs are being carried out in photovoltaics, advanced solar dynamics (ASD), regenerative fuel cells (RFC), and nuclear space power. Specific data for these systems for lunar and Mars bases are shown in table II. The solar systems are advanced PV and ASD with 500 W-hr/kg (100 percent DOD) regenerative fuel cells, the nuclear systems are based on use of the SP-100 reactor.
The nuclear system results are given for two cases, (1) full 4π shield carried from Earth and (2) a shield manufactured from lunar soil. The masses of the power systems for lunar and Mars base applications are shown in figures 2 and 3, along with that of a state-of-the-art (SOA) solar system for the initial outpost.

The figures show that it would be prohibitive to use SOA technology for the lunar and Mars initial bases. A SOA solar lunar base would require over 16×10^6 kg to LEO (mass in LEO = 5 x mass on lunar surface). Therefore NASA is following the following philosophy - the early missions and initial outposts will be powered by advanced solar and/or RTG systems, the surface will be prepared for nuclear, and the high-capacity power will be provided by nuclear reactor power systems. The nuclear power plant will also run electrolysis plants to provide an H_2-O_2 economy and surface transport systems would run on fuel cells. The savings in mass to LEO by evolving to nuclear power are shown in figure 4. The savings are given in both kg to LEO and number of Heavy Lift Launch Vehicles saved. It should also be pointed out that the development of advanced solar systems would provide a surface transportation option that could replace RTG's as shown in figure 5.

PHOTOVOLTAIC

Research on photovoltaic power systems is aimed at developing radiation tolerant, high-performance (>20 percent), lightweight arrays (~300 W/kg) and increased capacity electrochemical storage systems. Major efforts include development of Indium Phosphide, Amorphous Si (Am Si) and GaAs solar cells, Na/S batteries and H_2-O_2 regenerative fuel cells.

Efficiencies of 18.8 percent have been demonstrated in InP cells as well as excellent radiation tolerance. In the area of GaAs concentrator arrays efficiencies of 23.5 percent have been obtained with projected specific powers of 88 W/kg. Lower efficiency (~10 percent) Amorphous Si arrays have been identified that are extremely lightweight (6 kg/kW) and very compact when launched. In the area of energy storage systems, the next generation battery would appear to be the Na/S battery which is presently under aggressive development by the Air Force Wright Patterson Aero Propulsion Laboratory (WPAPL). If sufficient lifetime can be obtained, the development of this 100 W-hr/kg (100 percent DOD) battery would allow LEO PV power systems with specific masses of ~16 W/kg. This would truly be a major advancement in national space power capability.

NASA will not duplicate the storage technology being developed by WPAPL and is focusing its advanced technology development on photovoltaic arrays and H_2-O_2 regenerative fuel cells. The technologies being pursued in the Pathfinder program and some key milestones are shown in figures 6 and 7. It is felt that the specific power increases as shown in figure 6, can be obtained with 13.3 percent cell efficiencies and thinner cells (130 W/kg), reducing the interconnector and structure mass (200 W/kg) and finally using very thin (5 μm) 20.5 percent efficient GaAs cells. The H_2-O_2 fuel cell development is aimed at developing single unit regenerative H_2-O_2 fuel cells. For gaseous storage systems it is felt that 300 W-hr/kg could be obtained for metal tanks, and 1000 W-hr/kg for advanced fiber wound tanks. Cryogenic storage is required for further improvements to 1500 W-hr/kg.

ADVANCED SOLAR DYNAMIC

Solar dynamic power systems also offer the potential for efficient, lightweight, survivable, relatively compact, long-lived space power systems applicable to a wide range of power levels (3 to 100's kWe), and a variety of orbits. The successful development of these systems could satisfy the power needs for many of the projected NASA, Civil, Commercial, and Military missions. These systems are competitive with PV technologies in the very small sizes but become increasingly attractive for higher power applications (50 to 100 kWe) where increased efficiency, compact size, and reduced drag are required.

In addition to the space station, NASA is also pursuing an aggressive advanced solar dynamic (ASD) technology development program to provide power systems to meet future mission needs. As is shown in figure 8 this program will provide significant growth from the Space Station and will provide a factor of 5 or 6 increase in the specific power over that of the IOC Space Station, with an area of 773 m^2 (~1/4 of IOC PV area). These advanced power systems will also be applicable to a wide range of sizes and orbits.

As shown in figure 8, key elements of the ASD program are to increase operating temperature and efficiency of these systems as well as to develop more efficient and lighter weight components. Improvements over IOC Space Station are initially obtained by using advanced concentrators and a Brayton system. The maximum performance is obtained by adding an advanced receiver and developing free piston Stirling Engine technology. The NASA Lewis program is highly synergistic with the IOC Station, the SP-100, and the DOE Terrestrial solar dynamic programs and is focused on developing power systems in the 1025 to 1400 K temperature range with minimum efficiencies above 25 percent.

For lunar/Mars base applications the ASD power systems would also use the RFC technology for energy storage and the performance numbers would be approximately the same as the PV systems.

NUCLEAR POWER SYSTEMS

NASA has greatly increased its efforts in technology development for nuclear power systems because of their significant importance in meeting NASA's future needs. NASA has increased its support for the SP-100 GES Program shown in figure 9 by $135 M over the next 5 years in the Pathfinder program. As indicated in figure 9, the SP-100 program is the national program aimed at developing a nuclear reactor space power capability. The SP-100 Ground Engineering System Program is focused on demonstrating the technology readiness of nuclear space power system for moving into the flight demonstration phase in the early 1990's. The SP-100 GES power system uses a lithium-cooled reactor at 1350 K and thermoelectric energy conversion. The reactor thermal power is 2.5 MW_t for a 100 kWe system and the specific mass goal is 30 W/kg. In order to expand the capability of the SP-100 technology to meet NASA's future needs, NASA is carrying out an aggressive SP-100 Advanced Technology Program (ATP) under the CSTI initiative. The goals and some of the key elements of the ATP are shown in figure 10. The ATP is a focused technology program aimed at increasing the capability of space power systems using the SP-100 GES reactor. Elements of the program include advanced Stirling and thermoelectric energy conversion, advanced radiators, materials, power conditioning and control, and space environmental effects. This ATP will enable 80 W/kg space power systems in 500 to 800 kWe modules using GES technology.

CONCLUDING REMARKS

It was asserted at the beginning of this paper that significant advancements over the SOA of space power systems are necessary to meet future needs. The nation recognizes this, and is carrying out a broad based technology development program to provide these necessary power system options.

TABLE I. - EVOLUTIONARY POWER REQUIREMENTS FOR LUNAR SURFACE BASE OPERATIONS

Unmanned precursor, 2 kWe	Manned outpost, 100 kWe	Interim base, 500 kWe	Sustained base, 2000 kWe
Orbiter Rover Sample return Farside COMSAT	Habitat (6 crew) Laboratory Science experiments LOX pilot plant Site preparation Rovers/trailers Lander/ascent vehicle	Habitat (15 crew) Additional laboratories Extended science In-situ resources plant CELSS research Surface surveys Mining LOX production Materials pilot plant Reusable LEM cargo vehicle	Habitat (24 crew) Research facilities Sustained science Increased LOX production Metals production Manufacturing Ceramics production Food production Product export Mass driver

TABLE II. - POWER SYSTEMS CHARACTERIZATION SPECIFIC MASS, kg/kWe

Type	SOA solar	Advanced solar	Nuclear					
Description	PV with NiH_2 battery energy storage	PV or dynamic with RFC energy storage	SP-100 with man-rated 4π shield transported from Earth and man-rated materials shield					
			Power level, kWe					
			100		500		2000	
			Surface	4π	Surface	4π	Surface	4π
Lunar surface	33 000	740	40	119	24	41	12.5	18
Mars surface	1 190	150	40	119	24	41	12.5	18

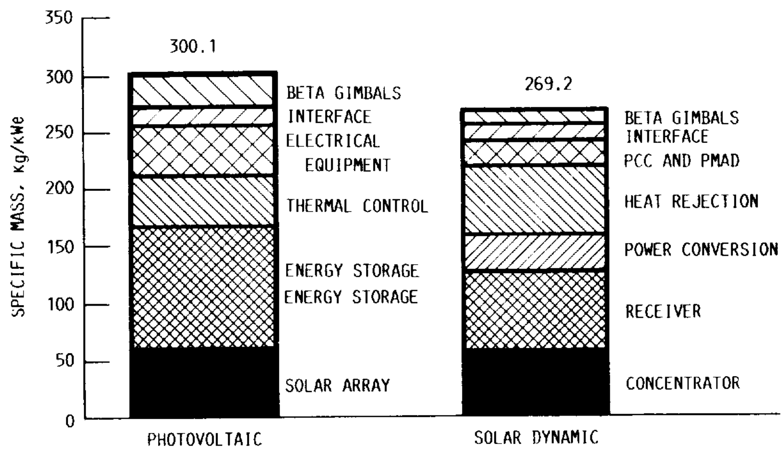


FIGURE 1. - COMPARISON OF SPACE STATION PV AND SD-CBC POWER MODULES.

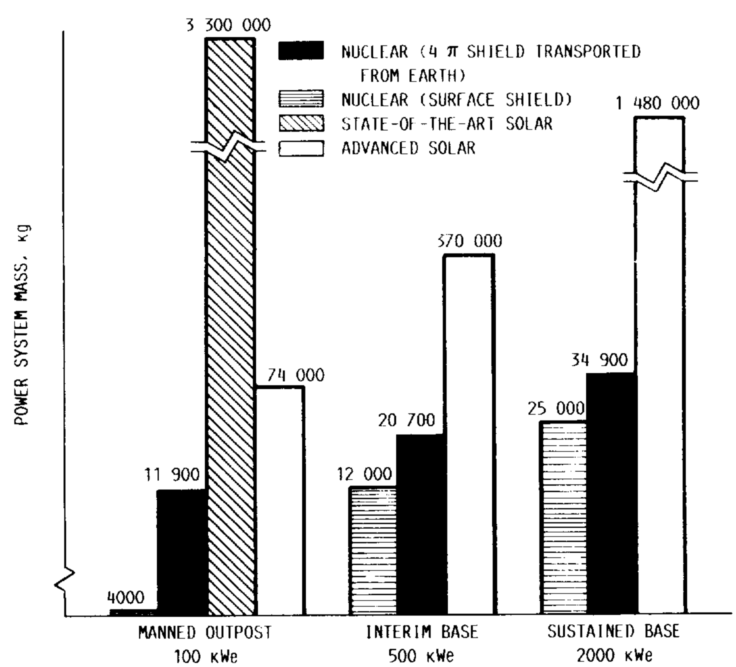


FIGURE 2. - MASS COMPARISON OF LUNAR SURFACE POWER SYSTEMS.

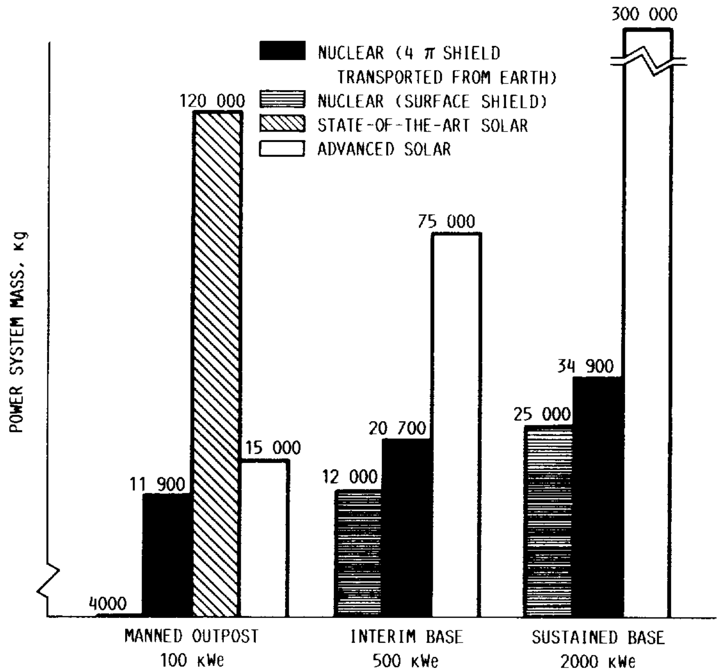


FIGURE 3. - MASS COMPARISON MARTIAN SURFACE POWER SYSTEMS.

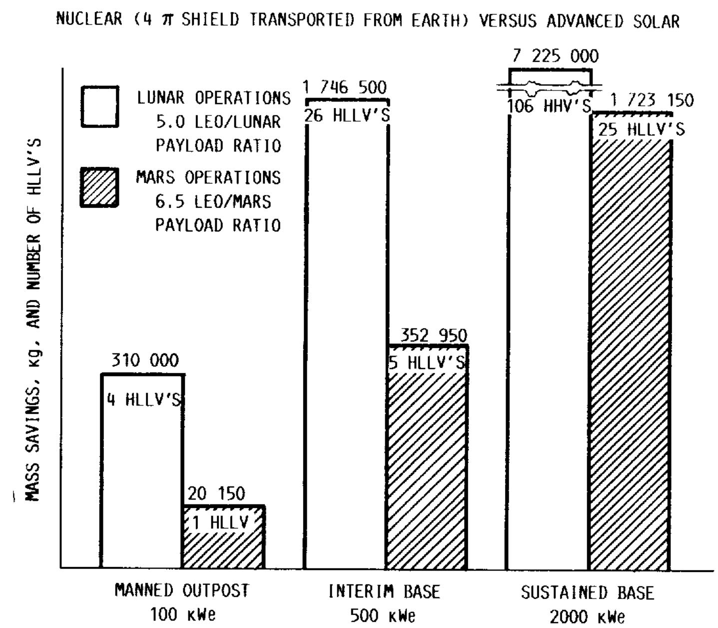


FIGURE 4. - MASS SAVINGS IN LOW EARTH ORBIT FOR LUNAR AND MARS OPERATIONS.

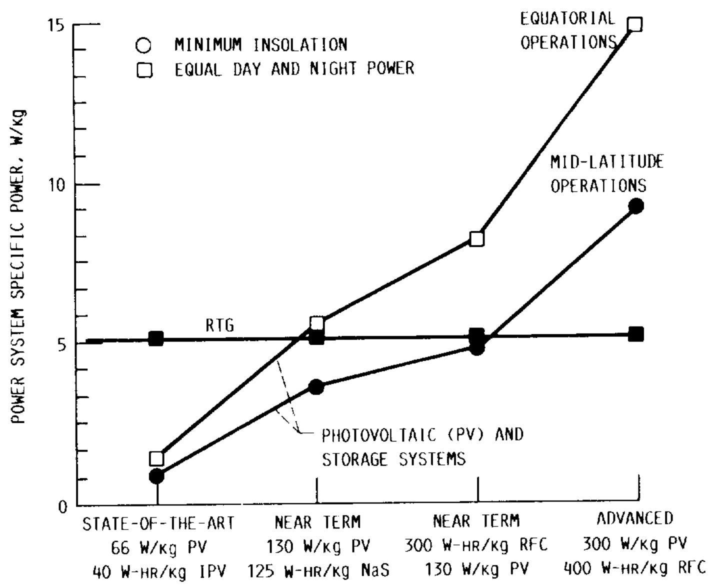
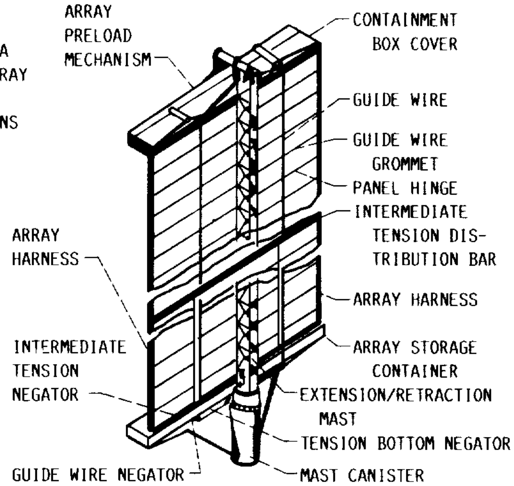


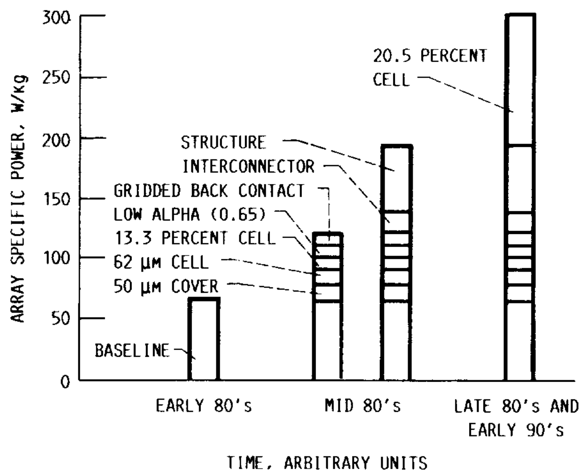
FIGURE 5. - POWER SYSTEM COMPARISON SMALL MARS ROVER.

OBJECTIVE:

DEVELOP DATA BASE POTENTIAL OF ULTRA LIGHTWEIGHT PV ARRAY TECHNOLOGIES FOR LUNAR/MARS MISSIONS



HIGH-PERFORMANCE SOLAR ARRAY RESEARCH AND TECHNOLOGY



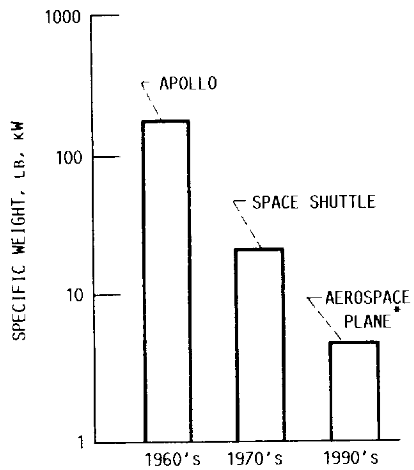
APPROACH:

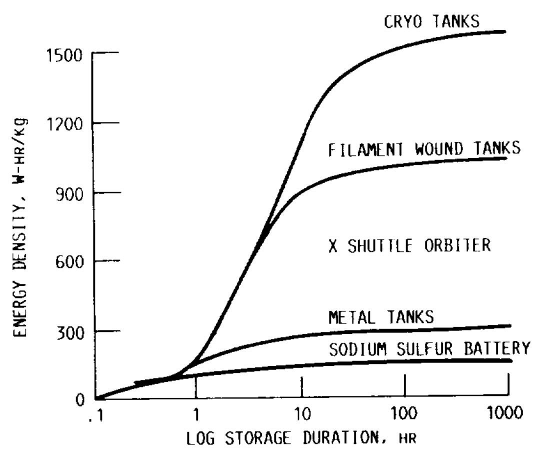
- PV CELLS/MODULES
  - THIN GaAs
  - AMORPHOUS SILICON
- ARRAY STRUCTURE/DEPLOYMENT
  - APSA
  - OAST 1
  - OTHER

FIGURE 6. - PATHFINDER SURFACE POWER PHOTOVOLTAICS.

OBJECTIVE:

DEVELOP HIGH SPECIFIC ENERGY ELECTROCHEMICAL STORAGE TECHNOLOGY DATA BASE NECESSARY TO ENABLE LUNAR AND MARS MISSION



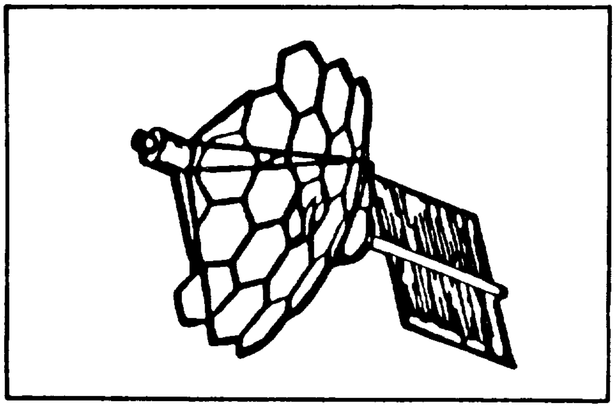


APPROACH:

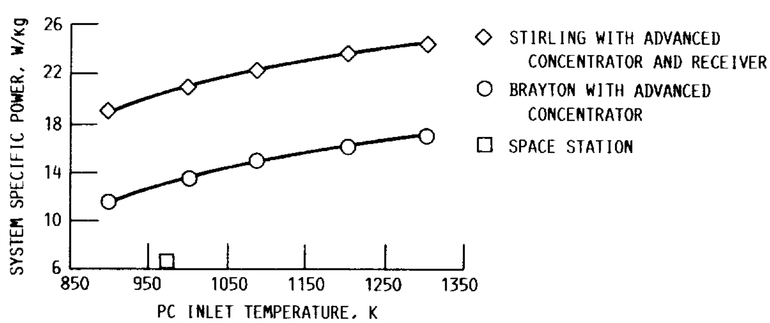
- H_2 - O_2 REGENERATIVE FUEL CELLS
- CRITICAL COMPONENTS TECHNOLOGIES
  - CATALYSTS
  - GES/LIQUID HEAT MNGT.
- LIGHTWEIGHT, ROBUST REACTANT TANKAGE
  - FILAMENT WOUND
  - CRYO
- SUBSYSTEM INTERACTIONS

FIGURE 7. - PATHFINDER SURFACE POWER REGENERATIVE FUEL CELL.

GOAL: TECHNOLOGY DEVELOPMENT FOR ADVANCED HIGH TEMPERATURE SOLAR DYNAMIC POWER FOR FUTURE SPACE MISSIONS IN THE POWER RANGE OF 1-100 kWe AND SPECIFIC POWER DENSITY OF 8-25 W/kg



TYPE: 35 kWe ADVANCED SOLAR DYNAMIC SYSTEMS
SYSTEM SPECIFIC POWER VERSUS PC INLET TEMPERATURE



APPROACH:

- LIGHTWEIGHT, ACCURATE CONCENTRATORS AND MATERIALS
- HEAT RECEIVERS, TES, MATERIALS
- ADVANCED CONVERSION
- MICROGRAVITY AND SPACE ENVIRONMENTAL EFFECT AND ASSESSMENT

FIGURE 8. - ADVANCED SOLAR DYNAMICS.

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PURPOSE:

- TO DEVELOP AND DEMONSTRATE MULTI-HUNDRED KILOWATT ELECTRIC CLASS (~ 10-1000 kWe) SPACE REACTOR POWER SYSTEM TECHNOLOGY IN SUPPORT OF A BROAD RANGE OF EMERGING CIVIL AND MILITARY MISSIONS IN THE EARLY TO MID 1990's AND BEYOND

- SP-100 IS A JOINT DOD/DOE/NASA PROGRAM

- SP-100 IS PART OF THE PRESIDENT'S STRATEGIC DEFENSE INITIATIVE (SDI)

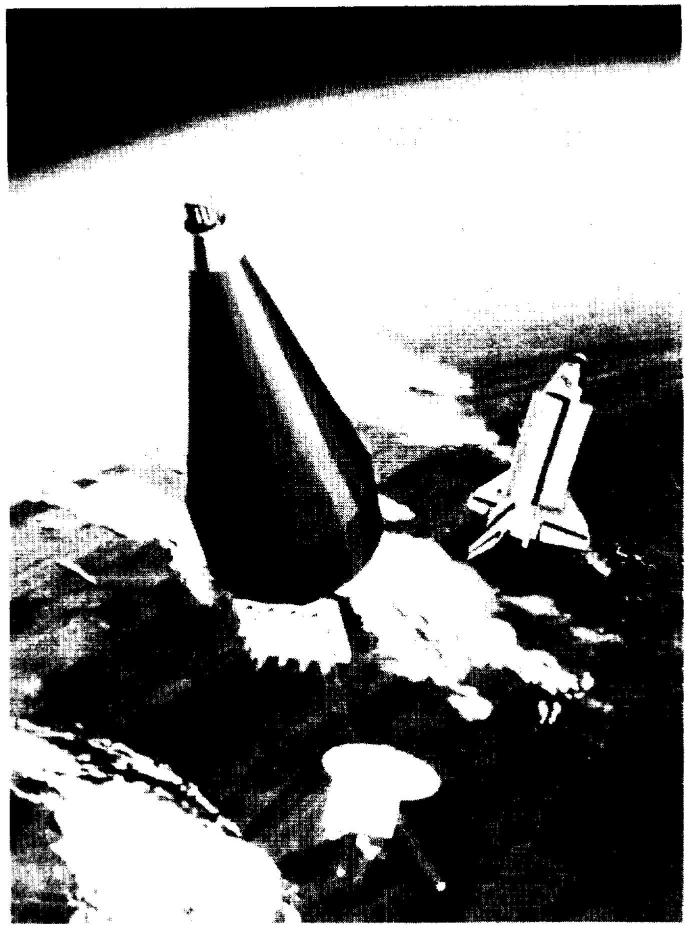
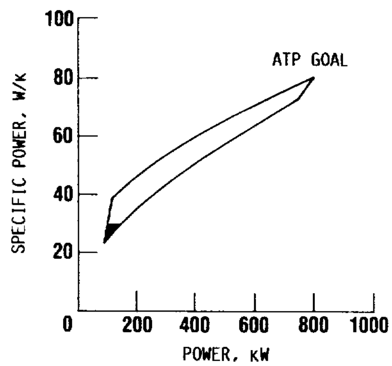


FIGURE 9. - SP-100 SPACE REACTOR PROGRAM.

- FOCUSED TECHNOLOGY DEVELOPMENT TO INCREASE CAPABILITY OF SPACE POWER SYSTEMS USING GES REACTOR

25 → 80 W/K
100 → 800 KW



- FREE PISTON STIRLING ENGINES
- ADVANCED RADIATOR
- POWER CONDITIONING AND CONTROL
- MATERIALS

FIGURE 10. - NASA SP-100 ADVANCED TECHNOLOGY PROGRAM.

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16. Abstract

As one looks to man's future in space it becomes obvious that unprecedented amounts of power are required for the exploration, colonization, and exploitation of space. Activities envisioned include interplanetary travel and LEO to GEO transport using electric propulsion, earth and lunar observatories, advanced space stations, free-flying manufacturing platforms, communications platforms, and eventually evolutionary lunar and Mars bases. These latter bases would start as camps with modest power requirements (kWe's) and evolve to large bases as manufacturing, food production, and life support materials are developed from lunar raw materials. These latter activities require very robust power systems (MWe's). The purpose of this paper is to describe the advanced power system technologies being pursued by NASA to fulfill these future needs. Technologies discussed will include nuclear, photovoltaic, and solar dynamic space power systems, including energy storage, power conditioning, power transmission, and thermal management. The state-of-the-art and gains to be made by technology advancements will be discussed. Mission requirements for a variety of applications (LEO, GEO, Lunar, and Martian) will be treated, and data for power systems ranging from a few kilowatts to megawatt power systems will be presented. In addition the space power technologies being initiated under NASA's new Civilian Space Technology Initiative (CSTI) and Space Leadership Planning Group Activities will be discussed.

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