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ABSTRACT

Silicon cell Photovoltaic (PV) power modules are key components of the Space Station Electrical Power System (EPS) scheduled to begin deployment in 1994. Four PV power modules, providing 75 kWe of user ac power, form the cornerstone of the EPS; which is comprised of Photovoltaic (PV) power modules, Solar Dynamic (SD) power modules, and the Power Management and Distribution (PMAD) system. The PV modules are located on rotating outboard sections of the Space Station (SS) structure and each module incorporates its own nickel-hydrogen energy storage batteries, its own thermal control system, and some autonomous control features. The PV modules are a cost-effective and technologically mature approach for providing reliable SS electrical power and are a solid base for EPS growth, which is expected to reach 300 kWe by the end of the Space Station's 30 year design lifetime.

INTRODUCTION

The Space Station Electrical Power System (EPS) will be the largest orbital power system ever assembled. Electrical power will be used for materials processing, manufacturing, scientific and industrial experiments, and other customer operations. The NASA Lewis Research Center is responsible for EPS development and is working closely with its prime contractor-Rocketdyne Division of Rockwell International-to assure that the EPS is ready to begin deployment in 1994. Space Station (SS) power requirements (75 -300 kWe) and the 30 year design lifetime present new challenges for spacecraft power system designers. In addition to being an order of magnitude larger than past systems, the EPS must be engineered as an adaptable system capable of meeting evolving user load requirements. For this reason, the EPS design emphasizes high reliability, on-orbit repair or replacement, and modular componentry.

Design of the SS Photovoltaic (PV) power modules reflects these new spacecraft power system requirements. The PV power modules utilize proven technology to supply 75 kWe of power to SS users. A brief look at the PV modules will illustrate how these design challenges are being met.

ELECTRICAL POWER SYSTEM OVERVIEW

The PV power module is one of the three basic subsystems which make up the EPS. These modular subsystems are shown in Fig. 1. The PV power modules and the Solar Dynamic (SD) power modules generate electrical power, which is managed by the Power Management and Distribution (PMAD) System. The EPS will be assembled in low Earth orbit (LEO) from PV, SD, and PMAD components carried aloft by the Space Shuttle Orbiter.

The 75 kWe initial operational configuration (IOC) EPS utilizes four PV power modules each supplying 18.75 kWe of ac power to Station users. Two SD power modules, each supplying 25 kWe, will be added in a later phase of EPS development for an enhanced SS capability of 125 kWe. SS power requirements are expected to grow to 300 kWe with only a small fraction (25 kWe) of the avaliable power dedicated to housekeeping loads such as environmental control and life support (1). (Unless otherwise stated, power levels are delivered ac power to SS users.) Fig. 2 shows the 75 kWe IOC as well as the 125 kWe enhanced hybrid configuration (PV plus SD).

The SD power modules, still under development, use solar thermal energy to drive a closed Brayton cycle (CBC) power generation system. A large mirrored solar concentrator focuses sunlight on a receiver. The thermal energy is collected and used to heat a working fluid which drives a turbine and an alternator (Fig. 3). Thermal energy is stored in the receiver to supply power during orbital eclipse.

The PMAD system is responsible for overall EPS control and power flow. PMAD system components accept power from the PV and SD modules, condition it, and distribute it to all SS loads in a safe and controlled manner, much like a terrestrial utility-type power system. PMAD components are located throughout the Station.

THE PHOTOVOLTAIC POWER MODULES

The PV power modules are designed to provide 30 years of reliable electric power in LEO. SS LEO will vary between 180 and 250 n mi. (330 and 458 km) at a 28.5 inclination. This orbit provides roughly 60 minutes of direct insolation and 36 minutes of eclipse during each 90 minute orbital period. Each PV module delivers 18.75 kWe average ac power per orbit and weighs approximately 12,800 lb (5818 kg) (2). The PV module is comprised of two solar array assemblies (SAA), an integrated equipment assembly (IEA), two beta joints, and electrical and interface hardware. A detailed view of the module is shown in Fig. 4. The SAA contains the planar solar arrays (or blankets) and the deployment mast. The IEA contains the nickel-hydrogen (NiH_2) battery energy storage assembly (ESA), the PV module thermal control system (TCS), and PMAD components. The beta joint attaches the SAA to the SS truss structure.

Peak power capability of each module is 48 kWe at the beginning of life. While supplying ac power to SS users, the PV module must simultaneously provide enough dc power to fully charge the NiH_2 batteries by the end of the 60 minute sunlit portion of each orbit. Electric power for the SS is provided by the batteries during orbital eclipse. The PV module must also offset parasitic losses incurred in battery charging and in dc to ac inversion for distribution. It must be capable of providing 30 kWe ac peak power for up to 15 minutes per orbit with no limit to the number of consecutive peaking orbits, and it must be able to supply 6.7 kWe for one complete orbit with no solar energy input without the batteries exceeding an 80 percent depth of discharge (DOD) (3). The module is also capable of delivering up to 156 kWe of peak power generated by the SD and PV modules combined. This requirement is in anticipation of SS EPS growth to 300 kWe (350 kWe peak) (4).

The thermal control system (TCS) design requirements are driven by the combined thermal loads of the ESA and the PMAD components in the IEA. The batteries must be maintained at 5 ^{o}C (+15/-5 ^{o}C) under all conditions.

Design lifetimes differ among PV module components. The SAA is designed for 15 years of on-orbit operation, and the beta joint for 20 years. PV module electrical equipment and all ESA hardware have a minimum operational lifetime of 5 years. TCS components are designed for 10 years of operation. Standard interfaces on all components allow on-orbit service in LEO using remote manipulators or astronaut extra-vehicular-activity (EVA).

THE SOLAR ARRAY ASSEMBLY

The solar array assembly (SAA) weighs roughly 1400 lb (632 kg) and supplies raw dc power from 53,368 silicon solar cells mounted on two dual-blanket planar arrays. The array blankets are attached to a central deployment mast and canister which is held by the beta gimbal. A sequential shunt unit (SSU), also mounted on the mast canister, controls solar array output by shunting excess power when the SS loads plus the ESA charging load is less than the avaliable array power. The SSU also prevents the array output voltage from exceeding 200 V dc and allows the array to be turned off to allow astronaut EVA near the array. The SSU is controlled by the PMAD system.

Each solar array blanket weighs 490 lb (224 kg) and contains 76 active panel sections with 192 cells on each panel for a total of 14,592 cells per blanket. The individual solar cells are 8x8 cm (3.15 by 3.15 in.) with truncated corners and gridded back-surface contacts. Cell efficiency is 14 percent at 20 °C at BOL (5). The 8 mil thick cells are protected by 6 mil thick ceria-doped glass covers held on by a transparent adhesive, as shown in Fig. 5. Cell mounting tape attaches the cells to an outer layer of Kapton[1] polyimide film. A thin copper circuit, encapsulated between this outer Kapton layer and an inner layer, allows welded electrical connection to the back surface of the cells through pre-punched holes in the film. A polyester adhesive bonds the inner and outer Kapton layers.

The cells are mounted on blanket panels which allow accordian-style folding of the arrays for compact stowage in the shuttle payload bay during launch. Fig. 6 shows the solar array blanket physical and electrical configuration. Each panel is 14.7 in. long (37.3 cm) and 164 in. (416.6 cm) wide. Adjacent panels are hinged together to form the 95.5 ft (29.1 m) long solar array blanket. Two flat-conductor-cable (FCC) electrical harnesses are routed along the blanket edges to carry bulk dc power to the SSU. The cells are electrically connected in a series string of 192 cells (an entire panel) with every 16 cells protected from shadowing or damage by redundant by-pass diodes. The strings (192 cells) from two adjacent panels are then wired in series to produce 160 V dc. Each panel pair is wired in reverse current direction, relative to adjacent panel pairs, to reduce magnetic field interference. The individual solar cells have a base contact resistance of 2 Ω-cm to minimize cell interaction with the LEO radiation environment (6).

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[1]Kapton is a registered trademark of DuPont.

SAA MAST AND CANISTER

The solar array mast is a coilable, continuous-longeron design design utilizing three S2-glass/epoxy longerons, connected by short battens of the same material, and diagonal tension wires, as shown in Fig 7. The mast extends and retracts the two solar array blankets which are connected to protective blanket box covers on either side of the mast. The mast is stored in a canister and is deployed or retracted by a rotating deployment mechanism. This mechanism has internal spiral grooves which guide the mast roller lugs located on the mast longerons at each batten attachment point. The solar array blankets fold or unfold continuously as the mast is retracted or deployed. The mast is attached to a rotating baseplate in the bottom of the canister so that the mast does not rotate. The SAA mast and canister weigh 361 lb (164 kg).

The solar array mast is the primary structural support for the arrays at any extended position. The arrays are maintained in a planar surface by the extended mast and by tensioned cables. The mast canister is attached to a rotating beta joint which mechanically and electrically connects the entire SAA to the SS truss structure.

THE INTEGRATED EQUIPMENT ASSEMBLY

The IEA provides the mounting structure and the thermal interface for the ESA batteries, the TCS, and PMAD compoments. The ESA is comprised of NiH_2 cell batteries and power charge and discharge control electronics. Ninety-two 65 A-hr cells, packaged in four groups of 23 cells each, provide 380 A-hrs of total storage capacity. When fully charged, the ESA can provide full ac power (18.75 kWe) during orbital eclipse without exceeding a 35 percent depth of discharge (DOD). ESA total weight is 3470 lb (577 kg). The NiH_2 cells utilize a 31 percent by weight potassium-hydroxide electrolytic solution and are housed in individual Inconel 718 pressure vessels. Cell operating pressure is 900 psi with a nominal 3:1 design safety factor. The IEA is thermally regulated by a TCS serving all active components. A two-phase ammonia (NH_3) refrigerant loop transfers waste heat to a condenser heat exchanger. Batteries and electrical equipment are mounted on individual cold plates which transfer waste heat, via heat pipes, to separate TCS cold plates containing the circulating ammonia. Mechanical pumps circulate the ammonia between the TCS cold plates and a condenser heat exchanger. The heat exchanger transfers refrigerant heat to an aluminum heat-pipe radiator for rejection into space. Each IEA has one dedicated 560 ft^2 (52 m^2) radiator positioned outside of the SS truss bays to minimize thermal interaction with other components. The TCS is capable of removing 7 kWt of waste heat from the IEA.

THE PV MODULE BETA JOINT

The beat joint is an actively controlled, motor-driven bearing joint which attaches the solar array assembly to the SS structure and allows the solar arrays to track the sun over seasonal variations (+28.5°). (Orbital sun tracking is accomplished by the SS alpha joints.) It utilizes its own controller and motor drive and is capable of 360° rotation. The joint also contains the electrical roll rings which transfer dc electrical power from the solar arrays to the IEA and which allow data and communication flow between the SSU (on the solar array mast canister) and PMAD system components in the IEA. The beta joint weighs ~600 lbs (273 kg) and is designed for 20 years in LEO.

LOW EARTH ENVIRONMENTAL EFFECTS

The LEO environment has a significant impact on the materials selected for construction of the solar arrays and their supporting structural elements. Table I indidicates the materials used in the SAA. The most important environmental concerns are: atomic oxygen (AO) interaction, micrometeoroid and space debris impacts, and radiation and plasma interactions (7). The PV module solar arrays are oversized by roughly 15 percent to allow for anticipated damage from all LEO environmental hazards.

AO degrades organic polymer materials (like Kapton) through energetic interaction with hydrogen-carbon and hydrogen-oxygen bonds (8). AO energies of 4 to 5 eV are encountered at SS altitudes. Protection for the Kapton will be provided by transparent protective coatings which block AO. (An optimal AO coating for the Kapton has not yet been selected but is the focus of continued advanced development research.) AO protection for the mast and other structural components will be provided by adhesive aluminum tape or fine aluminum braiding.

Micrometeoroids and space debris in LEO can collide with the SAA and cause major damage. micrometeoroids are distinguished from space debris by their average particle density and their kinetic energy. Space debris has an average density of 2.7 gm/cm^3 (0.098 lb/in^3) and travels at orbital velocities (10 km/sec or 22,370 mph.) Micrometeoroid average density is much less, 0.5 gm/cm^3 (0.002 lb/in^3), but these particle have velocities of up to 20 km/sec (44,740 mph) (9). The 6 mil glass covers on the solar cells protect the cell from micrometeoroid damage. The by-pass diodes ensure a continuous electrical collection path in case solar cells are damaged by space debris impact.

Radiation damage to silicon solar cells results in a predictable performance degradation over time. Array oversizing takes care of this degradation. Plasma interactions with the solar array include: current collection, arcing, and charging effects. Maximum solar array voltage is limited to 200 V to prevent possible arcing between the array and local plasma build-up (10). Normal array operating voltage is 160 V dc. Plasma effects are strongest near the Earth's north and south poles, where the magnetic field lines converge.

CONCLUDING REMARKS

The PV power modules offer low technical risk for SS electrical power production through demonstrated performance, high reliability, and on-orbit serviceability. They are a cost-effective and technologically mature approach to providing reliable power in LEO. The PV modules also provide a solid base for evolutionary SS EPS growth. The PV modules are designed to accommodate the increased power levels for the enhanced (125 kWe) SS currently envisioned as the next step in SS development.

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TABLE I. - SOLAR ARRAY ASSEMBLY MATERIALS

[TBD = to be determined.]

Component	Material	Size
Blanket		
Cell cover	Ceria-doped	6 mils nominal thickness
Cover adhesive	DC 93-500	2 mils maximum thickness
Solar cell	Silicon, 2 Ω-cm base resistance grided back, rear contact, solderless	8 x 8 cm (60.4 cm^2 effective area) x 8 mils
Interconnect	Photo-etched copper	1.5 mils thick
Substrate	Protective coating Kapton Polyester adhesive Kapton Protective coating	TBD 1 mil 0.5 mils 1 mil TBD
Harness	Flat conductor cable (copper or Al)	3 mils
Hinge Pins	S2-glass/epoxy	TBD
Panel frame Stiffeners Sleeves	 Graphite/epoxy Kapton	 TBD TBD
Springs	Steel	TBD
Grommets	TBD	TBD
Guide wires	Steel	TBD
Blanket box		
Cover/base	Perforated Al honeycomb core Gr/Ep facesheets	164.1 x 14.7 in. 1 in Al 36 mils graphite/epoxy
Latches	Aluminum	TBD
Cable/guide wire reel	Magnesium	TBD
Negator spring reel	Delrin	TBD
Cables	Steel	TBD
Array deployment mechanism		
Mast Longerons Battens Diagonals Rollers Pivots	 S2-glass/epoxy S2-glass/epoxy 7 x 7 steel cable Vespel 7075 aluminum	 0.39 in per side 0.30 in per side 0.10 in per side TBD TBD
Canister	6061 aluminum	33.8 in max diam. x 61 in max length
Positioning mechanism	6061 aluminum	TBD

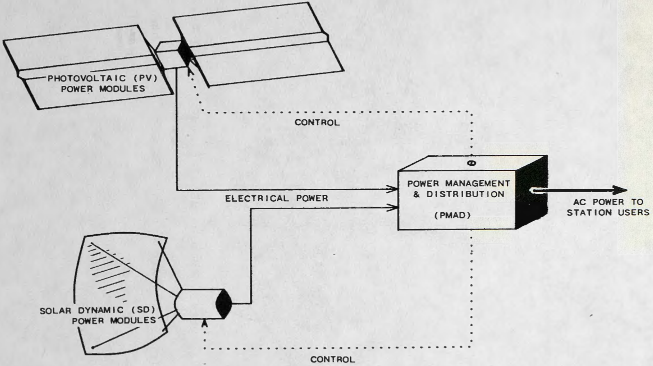
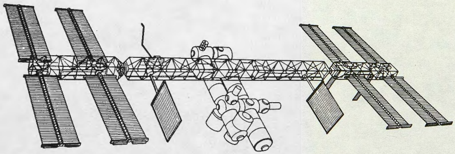
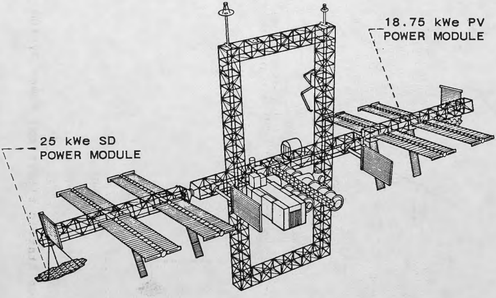


Figure 1. Space Station Electrical Power System (EPS).



75 kWe PV Initial Operational Configuration (IOC)



125 kWe Hybrid (PV plus SD) Enhanced Configuration

Figure 2. Space Station EPS Configurations.

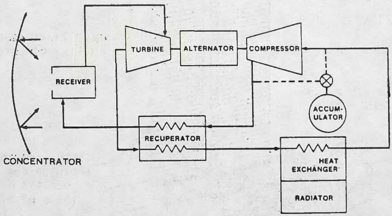
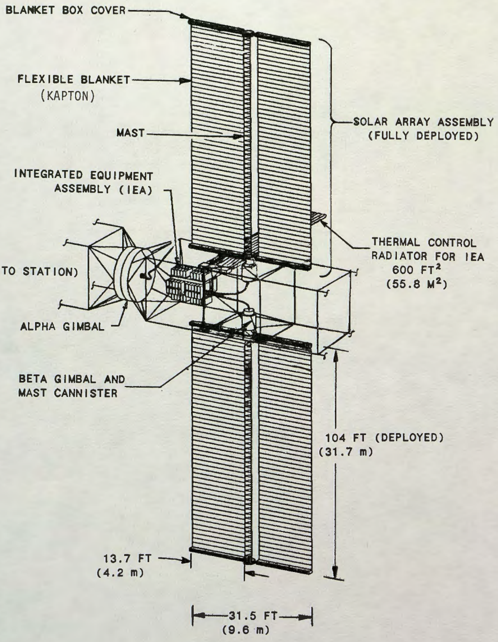


Figure 3. SD Power Module Closed Brayton Cycle (CBC) Schematic.



DIMENSIONS TAKEN FROM NASA LeRC
POWER SYSTEM DESCRIPTION DOCUMENT (REF. 2).

FIGURE 4. 18.75 kWe STATION PV POWER MODULE.

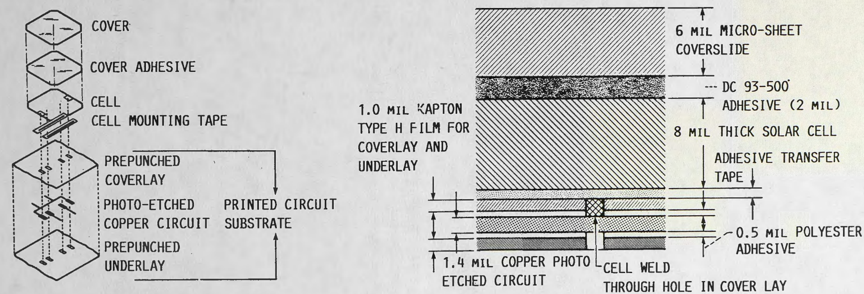


FIGURE 5. - SOLAR CELL ATTACHMENT TO BLANKET - EXPLODED VIEW AND TYPICAL CROSS-SECTION.

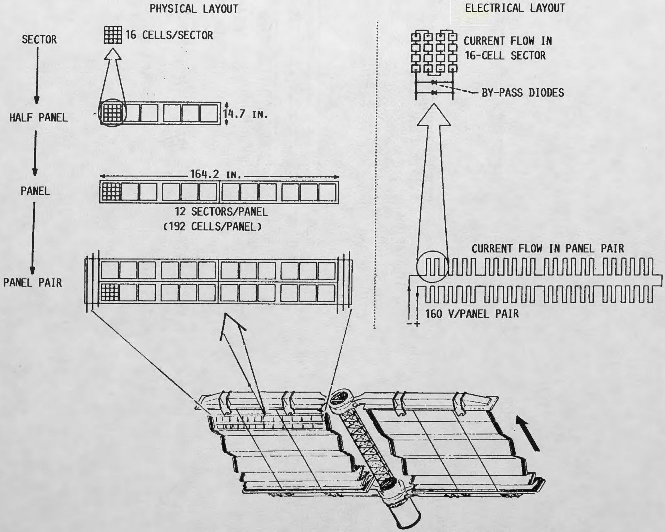


FIGURE 6.- SOLAR ARRAY BLANKET PHYSICAL AND ELECTRICAL CONFIGURATION.

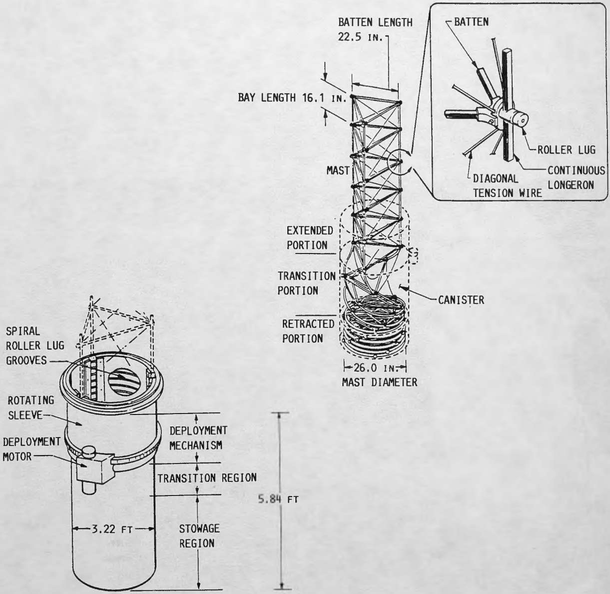


FIGURE 7. - SOLAR ARRAY MAST AND CANISTER.