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SPACE STATION POWER SYSTEM

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The manned space station is the next major NASA program. It presents many challenges to power system designers. The power system, in turn, is a major driver on the overall configuration. In this paper, the major requirements and guidelines that affect the station configuration and the power system are explained. The evolution of the space station power system from the NASA program development-feasibility phase through the current preliminary design phase is described. Several early station concepts, both fanciful and feasible, are described and linked to the present concept. The recently completed phase B trade study selections of photovoltaic system technologies are described in detail. A summary of the present solar dynamic system and the power management and distribution system is also given.

BACKGROUND

The space station system is the next major step in the manned space program. The space station will be a multipurpose facility that will enable advancements in science, technology, and space transportation capabilities. It will promote commercialization of space and open new avenues not yet fully explored.

Space stations have existed in the minds of writers, scientists, and engineers for decades. In a series of fictional articles beginning with the October 1869 issue of the Atlantic Monthly, a fanciful space station was described by the Rev. E.E. Hale from Boston. "The Brick Moon" articles described a hollow sphere 200 ft in diameter. It was whitewashed on the outside to serve as an aid to navigation and was launched into orbit by water wheels. The articles made no mention of a power source for the brick moon after it left the Earth. The brick moon concept did not have a sound basis by today's standards, but it was entertaining and thought provoking!

In 1928, Hermann Noordung published "Befahrung des Weltraums" (The Problem of Space Travel). He described a manned toroidal space station that rotated to produce artificial gravity. The idea was further developed in the March 22, 1952 issue of Collier's magazine and was described in the book, "Across the Space Frontier" (Viking Press, New York, NY 1952) (fig. 1). Walt Disney Studios produced television programs that were based on Noordung's concept. In this concept, power was produced by a large parabolic mirror which focused solar energy to heat steam and operate a turbine generator. In today's terminology, this was a form of a solar thermal-dynamic power system. At that time, practical photovoltaic (PV) cells had not yet been invented!

These early works, as well as numerous studies conducted in the 1960's and 1970's after the creation of NASA (ref. 1), helped establish a role for a manned space station. The solar dynamic power source described in 1952 was primitive but functional. However, most unmanned satellites launched since the beginning of the space age in 1957 have been powered by silicon solar-cell-based photovoltaic systems. A few deep space interplanetary missions and manned spacecraft like Mercury, Gemini, and Apollo are exceptions. During this era, technology has been developed for photovoltaic, solar dynamic, and nuclear systems as well. The primary thrust of these developments has been toward lighter weights, lower volumes, higher efficiencies, longer lifetimes, and greater reliability. These technologies and flight experiences formed the starting point for establishing the feasibility of the current space station and for defining its power system.

FEASIBILITY PHASE

The current space station program had its beginnings in 1981, when technology steering committees were formed to identify candidate technologies. These committees were staffed with people from the NASA field centers. In early 1982, the Space Station Task Force was formed at NASA Headquarters, Washington, DC, to determine the feasibility of a space station. This was referred to as phase A in the program development process.

In August 1982, the task force sponsored contracts with eight major aerospace companies to analyze the uses or missions for a manned space station. Specific missions were determined and studied extensively, but these are too numerous to describe in detail here (ref. 2). These missions included materials processing, Earth and space observations, and servicing and repair of satellites and other payloads. The mission analysis studies showed that the station would serve as an assembly facility, a storage depot, and a transportation node (or way station) for payloads intended for higher Earth orbits or for interplanetary missions.

These diverse missions led to the space station complex shown in figure 2. It is composed of a manned core and an unmanned co-orbiting platform (both in a 28.5° orbit), another platform in a polar orbit, and a system of unmanned vehicles for maneuvering payloads near the station or for transferring them to other orbits.

The mission analysis studies identified resource requirements, such as crew time, thermal control, and power, for each projected experimenter and each scientific and commercial user of space station. The sum of the power requirements of each of these missions defined the total requirement for each station element. Power levels were determined as a function of time from the initial operational capability (IOC) through some future power level when the station and the number of missions would have grown. These power requirements have changed as the mission definition has evolved. The current user power levels are shown in table I. User power or bus power is expressed in kilowatts electric (kWe) in table I and throughout this paper. User power means all system losses for generation, storage, conditioning, and distribution have been taken into account. Note that the station IOC power of 75 kWe is about an order of magnitude higher than for Skylab. Skylab, the first U.S. manned space station, was launched in 1973 and is the largest (8-kWe user power, 22-kWe array) solar power system flown in space to date. This 75-kWe requirement for the planned space station is the most challenging factor facing the power system designer.

Additional challenges arise from programmatic requirements imposed on the power system designer. These additional requirements are management and/or engineering related. They include (as do most large spacecraft projects) cost (both initial and life cycle), schedule, technical-development risk, weight, safety and contingency requirements. However, the permanent nature of space station results in some new and unique requirements such as growth capability, maintainability, and commonality of hardware and software across all station elements. Future replacement and growth of the station systems require that they be designed so that they can accept future changes in technology (i.e., technology transparency) yet still provide the same functions. Other considerations are the station orbit altitude and decay, assembly and buildup, lifetime, load types and location, and logistics and sparing.

In the spring of 1983, the task force was expanded to include a concept development group (CDG). This group took the results from the mission analysis studies and, with the help of all the NASA centers and many aerospace companies, synthesized them into several candidate space station configurations. They also further studied and sharpened technology selection for all the station systems including the power system: PV planar, PV concentrator, microwave power transmission, solar dynamic, and nuclear systems. The power tower, or gravity gradient stabilized, and many other configurations were studied as candidate station geometries. At this time, photovoltaics appeared to be the leading candidate for the power system.

As a result of the CDG feasibility work, on January 25, 1984, President Reagan, in his State of the Union message, gave NASA approval to build the space station and have it operational by 1994. In rapid succession a new program office was formed in Washington from the core task force group and the focus of the concept development activities was enlarged and shifted to the "Skunk Works" near NASA Johnson Space Center in Houston, Texas. The skunk works expanded and refined the definition of the space station systems. They wrote a reference configuration description and a request for proposals for the next phase of the program. During this period, the importance of drag area on reboost and life-cycle cost, coupled with the very large growth power requirements (as high as 450 kWe), resulted in the adoption of solar dynamic (SD) generators with thermal energy storage and photovoltaic arrays with electrochemical energy storage for detailed study in the definition phase.

DEFINITION PHASE

The present space station configuration and the hybrid power system (fig. 3), using both PV and SD technologies, were selected in the definition, or phase B, studies which began in 1984. Nuclear and other power systems were ruled out on the basis of schedule, cost, risk, and other factors. The large size and drag area of the power system is a major consideration for selection of the overall space station geometry. This geometry must allow the station and the power system to grow. It must minimize the impact of the power system on viewing angles for experimenters and for communications. The space station and its power system must be controllable and structurally sound. The maximum degree of commonality between the station and platform power systems is necessary to reduce costs. Most important of all, the station must be passively controllable, that is, the gravity gradient must be stabilized. From these diverse and sometimes contradictory requirements, the Power Tower and later the Dual-Keel configurations were developed and studied by NASA. At the same time, the NASA Lewis Research Center and its two major phase B contractors, TRW and Rocketdyne, studied numerous power system types. These phase B definition studies are described below.

Power System Configuration Definition

Early in phase B, six cases for power system options were defined for study (fig. 4). The IOC power level of 75 kWe and the growth power level of 300 kWe were selected. The six cases were established on the basis of IOC power system type (either SD or PV) and the method of growing from 75 to 300 kWe. Case 1 was all PV. Case 6 had minimum PV (12.5) kWe) at IOC and all SD at growth. An all SD system is not feasible because power is needed on the first launch when the accurate sun tracking required for the SD system is not possible. Cases 2 through 5 had various proportions of SD to PV. Commonality between the station and the platform solar arrays was also considered in these system studies. A solar array optimized for the platform would be smaller than one optimized for the station. As a cost saving measure, platform arrays could be used on the station so that only one development cost would be incurred. The use of SD on the platform was not feasible because of microgravity, weight, and other requirements. Also, the platform power level requirements were incompatible with a practical-sized SD unit.

The primary selection criteria for these system studies was both IOC and life-cycle cost for the station and the platforms. Development, manufacturing, verification testing, overhead, and launch costs for all the space station system hardware and software was included. An especially important life-cycle cost savings resulted from the reduced aerodynamic drag associated with the SD system. Reduced drag allowed lower orbit altitude and higher shuttle payload capacity.

As a result of these system studies, the case-5 hybrid was selected. In this case, the PV portion of the power system generates 25 kWe with four solar array wings (array power, approximately 57 kWe). The station wing is identical in design to those optimized for the platform. The station also uses nickel-hydrogen batteries identical to those designed for the platform. This commonality of hardware results in design and development cost savings for the space station program.

The SD portion of the case-5 power system generates about 50 kWe. The exact size of each SD unit will depend on the power management and distribution (PMAD) system efficiency. The SD units will use either the Brayton or Rankine system and an offset parabolic concentrator. The exact design will depend on the results of ongoing preliminary design studies. The detailed trade studies which helped define the technologies of the case-5 hybrid are described briefly in another section of this paper. These trade studies occurred at about the same time as the system level studies previously described. Overall, the technologies for the photovoltaic system are low risk and space proven, whereas the solar dynamic technologies offer reduced drag and cost.

Photovoltaic System Technology Studies

Solar array. - Several array concepts were evaluated during the phase B studies. They included planar arrays, simple flat mirror concentrators, Cassegranian concentrators, and trough concentrators. Preliminary trade studies considered all known degradation factors including optical, electrical, and mechanical effects. Packing factors, pointing and structural requirements, number of components, drag area, costs and technology readiness were also considered. On the basis of these factors, a planar array with silicon cells was selected. A Cassegranian array with gallium arsenide cells looked promising, but cell efficiencies of about 30 percent were required to compete with the planar silicon design. This cell efficiency is beyond that projected for production cells available at the start of the space station IOC array fabrication in 1988-1989.

The issue of deployable/erectable versus deployable/retractable arrays was also studied. Combinations of types of array substrate, masts, construction methods, on-orbit assembly methods, and means of integrating the substrate to the mast were devised for study. Both articulated and continuous longeron masts were considered. Evaluation factors included complexity of building and testing, cost, on-orbit (extra-vehicular activity) assembly time, array retractability, mast stiffness, reliability, damage tolerance, repairability, atomic oxygen resistance, technology readiness, and other factors. When all these factors were considered, a planar, deployable, fold-out array with a coilable, continuous longeron mast was selected. The array wing design for the station and the platform will be the same. It will have two flexible blankets and a center mast. Each blanket will be stored in a containment box/cover assembly during launch.

This array design is similar to the NASA Office of Aeronautics and Space Technology (OAST) flight experiment, OAST-1 (fig. 5). This solar array flight experiment was performed on a space shuttle mission (STS 41D) launched in August 1984. A 13- by 105-ft array consisting of 84 hinged panels was deployed and retracted on-orbit several times. The array blanket panels were flexible. The deployment mast was a coilable longeron type. This array was built by the Lockheed Missiles & Space Company. To reduce cost, only three panels contained solar cells. If fully populated with cells, the array power output would be about 13 to 14 kWe at the wing root.

The OAST-1 flight experiment was completely successful. It showed that the array behaved well dynamically. Its performance, in general, was as predicted, and the solar cells were not damaged during the mission. This flight experiment demonstrated that this array type is technology ready and established that space station planners can have a high degree of confidence in it. A more detailed description of the array and the flight experiment results can be found in reference 3.

The OAST array has several advantages compared with other array types. It is lighter in weight and packs in a small volume for launch. It has sufficient stiffness to meet space station structural and dynamic requirements. The flexible substrate is made from Kapton, which is transparent to infrared radiation. This allows the solar cells to operate at a lower temperature and thus with higher power output per unit area.

A disadvantage of the OAST-1 array is its need for protection from the atomic oxygen present at space station altitude. The Kapton substrate and other components that contain epoxy (e.g., the mast longerons, the blanket hinge pins and containment box, and several smaller components) are attacked by atomic oxygen. These components, if unprotected, may have very limited lifetimes. The Space Station Advanced Development Program (ref. 4) is beginning a contract to demonstrate practical methods to protect the array. The primary emphasis will be on coatings that are resistant or inert to atomic oxygen attack. These coatings must also meet other array performance requirements and must be compatible with other parts of the space environment such as ultraviolet radiation and micrometeoroids. These coatings are being developed by the Space Station Advanced Development Materials community. The planned array protection contract will provide an engineering solution to the atomic oxygen problem. It will demonstrate that the protection methods are compatible with array manufacturing and that they survive that process and still protect the array. The most critical need is for the Kapton blanket.

If suitable coatings cannot be demonstrated, alternate blanket approaches are possible. These approaches include laminating Kapton sheets over an inner layer of material that is resistant to atomic oxygen or using aluminum as the substrate. These approaches might result in higher weight and/or decreased cell power output due to loss of infrared transmission through the substrate.

Solar cell. - Detailed solar cell assembly design options were studied: silicon versus gallium arsenide; base resistivity; back surface field (BSF); infrared (IR) reflector versus transparent back contacts; conventional top-bottom, wraparound, or wrapthrough contacts; cell size and thickness; and cover glass material type and thickness. Evaluation criteria were IOC and life cycle cost, development status, and performance achieved by 1988-1989 when array fabrication will begin.

The array design features selected were N on P silicon cells with 2-Ω-cm base resistivity, 8 by 8 cm size, 8 mil thick, IR-transparent gridded back contacts, a BSF, and a wrapthrough front contact using a 6-mil cerium-doped coverglass. The wrapthrough front contact and the large cell size reduce array assembly time and cost. The gridded back allows IR transmission through the array blanket resulting in higher array power output for a fixed area.

Silicon solar cells have been used on many spacecraft in the past. They have extensive operational, assembly, and manufacturing experience. Although the selected cell is larger than those used previously, it is still a very low risk approach. The Space Station Advanced Development Program will demonstrate pilot production of these cells in early 1987. Efficiencies of 14 percent are expected.

Energy storage system. - The PV system will store energy electrochemically. This stored energy is needed during the dark portion of the orbit and for contingency purposes when the power system cannot produce and/or deliver power. The phase B studies showed that the inherent storage capability or residual energy of the electrochemical system was adequate to meet expected contigency requirements. Building in greater contingency capability would be unnecessarily expensive. Energy storage options studied included nickel-cadmium (NiCd) batteries, a regenerative fuel cell (RFC), and nickel-hydrogen (NiH_2) batteries.

NiCd batteries are established, flight-proven, low-risk devices. However, their low depth of discharge results in high storage system weight. Space cells up to 100 A-hr sizes have been produced so that development risk would be low.

The RFC uses a fuel cell and an electrolyzer to store energy in the form of hydrogen and oxygen. In the dark portion of the orbit, the hydrogen and oxygen are recombined in the fuel cell to produce water and electricity. During the lighted portion of the orbit, excess array power is used to electrolyze the water and charge the system with hydrogen and oxygen. The cycle is closed so that the fluids are not consumed. The RFC is lighter than batteries and allows storage of large amounts of contingency power with small changes in tank volume. Since the RFC is not as efficient as batteries (60 percent compared with 80 percent), the solar arrays must be larger. Also, the RFC is more complex (i.e., pumps, valves, etc.) and not as reliable as batteries. RFC's also have higher heat rejection needs. Reliability was a major consideration for the platform, where three years of operation without repair were required. However, commonality between the station and the platform to reduce development, resupply, and sparing costs was also considered.

The NiH_2 battery has been used in geosynchronous orbit (GEO) spacecraft (fig. 6) in the individual pressure vessel (IPV) type. (The bipolar NiH_2 battery has low technology maturity and was screened out by the early trade studies.) IPV, 3.5 in. diameter, 50 A-hr GEO cells are in production. Other sizes and capacities are available using scaled-up versions of existing components. The uncertainty with the NiH_2 battery stems from its charge-discharge cycle life. GEO spacecraft experience only a fraction of the cycles that LEO spacecraft experience. However the Space Station Advanced Development Program is beginning to test LEO cells with a goal of demonstrating minimum 5 year lifetimes.

As a result of the phase B trade studies, IPV NiH_2 batteries were selected for the platform. Weight, cost, reliability, development risk, and schedule requirements were the primary considerations. These batteries are about half the weight of the NiCd batteries, lower in cost than NiCd batteries, and more reliable than the RFC. An identical IPV NiH_2 battery was also selected for the station on the basis of cost and commonality with the platform. IPV NiH_2 was lower in IOC cost and only slightly higher in life-cycle cost.

Solar Dynamic Technology Studies

The solar dynamic system consists (fig. 7) of an offset parabolic concentrator mirror which focuses the suns heat into a receiver. The receiver stores the heat in a salt (e.g., LiOH) and transfers it to a working fluid (e.g., toluene or helium-xenon gas). The heated fluid drives a turbine which spins an alternator to generate electrical energy. The turbine also drives a pump which recirculates the working fluid. Excess heat is rejected to space by a radiator.

In the trade studies the two conversion cycles considered were the closed Brayton cycle (CBC) and the organic Rankine cycle (ORC). These systems have not been used in space, but a technology data base for the heat engines has resulted from terrestrial and aircraft applications. Estimating costs, schedules, and other factors during the phase B trade studies were therefore higher risk than for the PV system.

Design considerations for the SD system studied in phase B and being developed in the Advanced Development Program include low-gravity effects for two-phase (gas-liquid) flow, heat flow and distribution in the receiver, lifetime for thermal energy storage (salt) capsules, weight and optical quality of the concentrator, pointing accuracy (0.1°) for the mirror gimbals, atomic oxygen protection, launch packaging, on-orbit assembly, and other factors.

At the time of this writing both the CBC and the ORC systems were still being considered. More detailed study is required because cost and performance are nearly identical.

Power Management and Distribution Studies

The power management and distribution (PMAD) system must cope with load types and sizes that will be unknown as the station users change and increase in number. Therefore the PMAD system must be user friendly and adaptable to change and growth. The PMAD system for the space station must resemble a terrestrial utility power system rather than the PMAD system of previous spacecraft. Distribution voltages higher than the 28 V previously used are mandatory to reduce losses.

During phase B, distribution frequencies of dc, 400 Hz ac, and 20 kHz ac were studied. Component efficiency, size, and weight as well as technology readiness, availability of space components, acoustic noise, electromagnetic interference, and plasma coupling were all considerations. After much consideration, 20 kHz was selected for the PMAD distribution frequency.

The overall PMAD architecture selected is a dual-ring system with 15-kWe busses supplying power to 10 load areas on the upper and lower keels and on the transverse boom. Busses supplying the manned modules are rated at 30 kWe. The PMAD system contains numerous switching and control assemblies, as well as a control system for sensing and commanding the loads. Isolators and power controllers will sense faults and protect the system.

SUMMARY

The present space station program traces its roots back before the dawn of the space program. The station configuration and the power system for the present program have been studied extensively in the feasibility and definition phases.

The hybrid power system selected will meet initial and future station and platform requirements. The 25-kWe PV system (57-kWe array power) will be larger than any system flown to date. The SD system will facilitate economics and growth for the power system and the station. The PMAD system enables a growable, balanced utility system approach to maximize user friendliness.

The technologies selected for PV, SD, and PMAD result in the lowest IOC cost and life cycle costs with acceptable development and schedule risk. This hybrid system also meets programmatic and technical considerations driving the power system definition. The space station power system may set the standard for future spacecraft power systems.

REFERENCES

1. Hook, W.R.: Space Stations - Historical Review and Current Plans. ASME Winter Meeting, Phoenix, AZ, Nov. 14-19, 1982.

2. Space Station Mission Synthesis Workshop. NASA Proceedings, Hampton, VA, Mar. 5-8, 1984.

3. Solar Array Flight Experiment, Final Report. Lockheed Missiles and Space Co., LMSC-F087173, Apr. 1986.

4. Forestieri, A.F.; Baraona, C.R.; and Valgora, M.E.: Space Station Power System Advanced Development. Energy for the Twenty-First Century (20th IECEC), SAE P-164, Vol. 1, SAE, 1985, pp. 1.9-1.16.

TABLE I. - SPACE STATION SYSTEM POWER REQUIREMENTS

Element	User power average, kWe		User power peak, kWe	
	Initial operational capability, (IOC)	Growth capability	Initial operational capability, (IOC)	Growth capability
Manned core	75	300	100	350
Polar platform	8	15	16	24
Co-orbiting platform	6	23	6	23

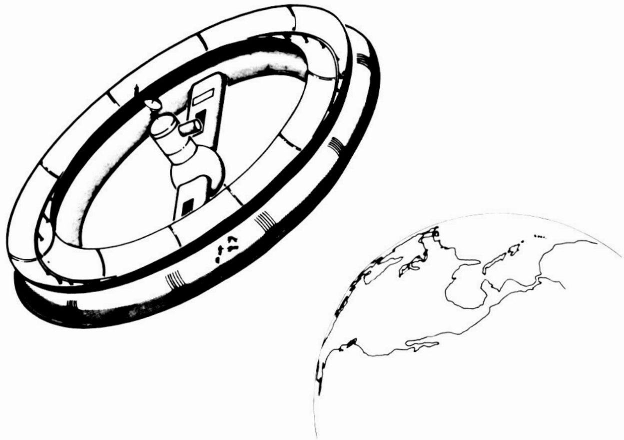


FIGURE 1. - A STATION IN SPACE; A 1952 CONCEPT.

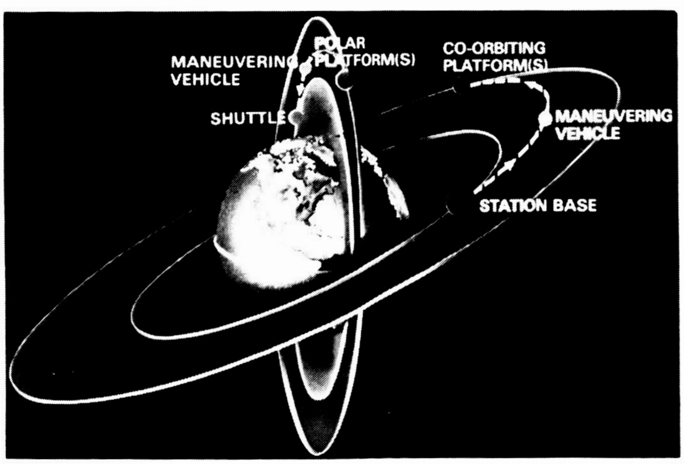


FIGURE 2. - SPACE STATION COMPLEX, EARLY 1990'S.

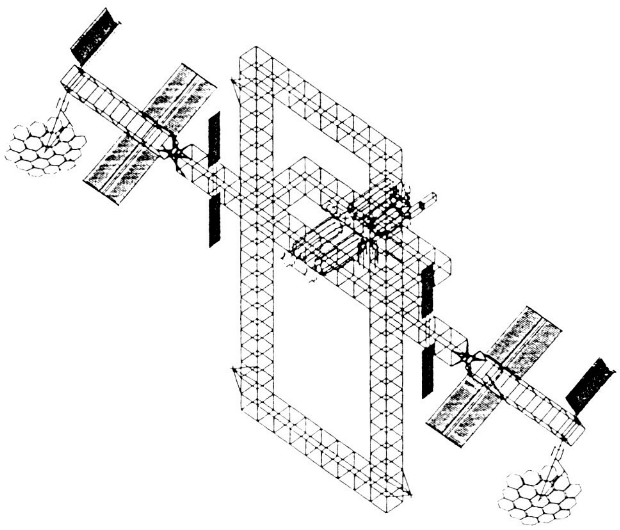


FIGURE 3. - SPACE STATION DUAL KEEL CONFIGURATION 1986.

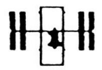
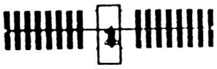
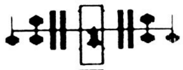
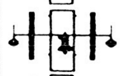
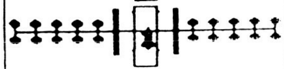
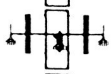
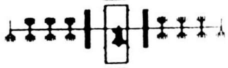
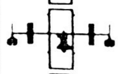
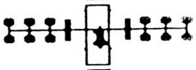
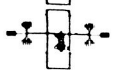
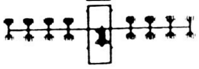
CASE	INITIAL OPERATIONAL CAPABILITY, IOC	PHOTOVOLTAIC (PV) AND SOLAR DYNAMIC (SD) CAPABILITIES, kWe	GROWTH
1		IOC PV GROWTH PV	
2		IOC PV GROWTH SD	
3		IOC 50 PV-25 SD GROWTH SD	
4		IOC 37.5 PV-37.5 SD GROWTH SD	
5		IOC 25 PV-50 SD GROWTH SD	
6		IOC 12.5 PV-75 SD GROWTH SD	

FIGURE 4. - CASES EVALUATED FOR SPACE STATION POWER SYSTEM.

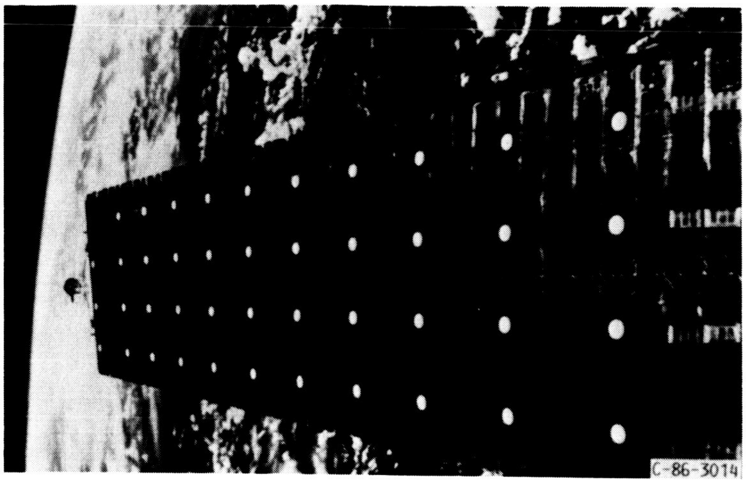


FIGURE 5. - OAST-1 SOLAR ARRAY FLIGHT EXPERIMENT, 1984.

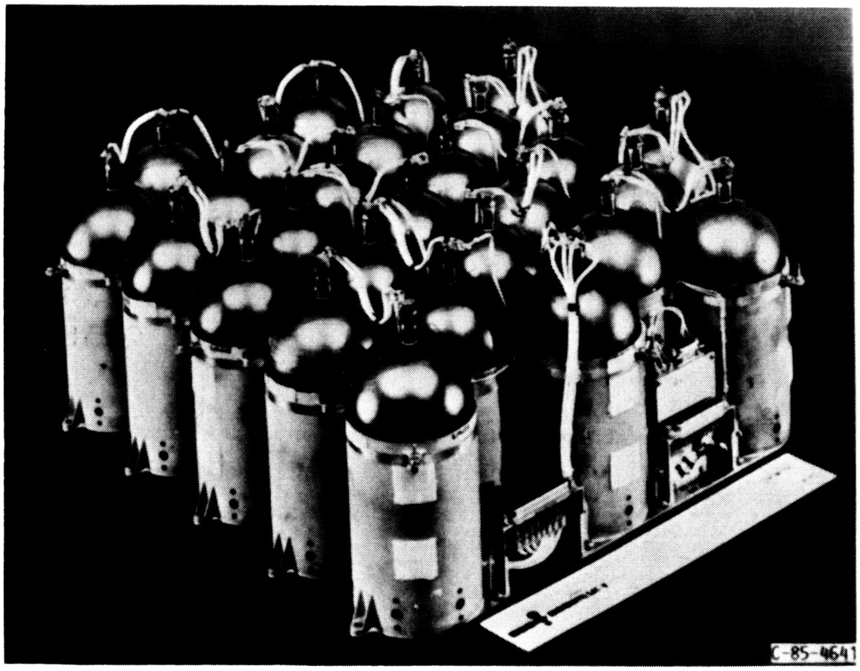


FIGURE 6. - INTELSAT V NICKEL HYDROGEN BATTERY.

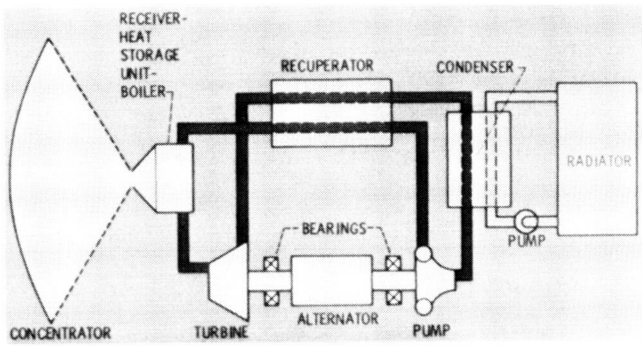


FIGURE 7. - SOLAR DYNAMIC SYSTEM SCHEMATIC, ORGANIC RANKINE CYCLE.

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