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STATUS OF SPACE STATION POWER SYSTEM

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The manned space station is NASA'S next major 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 are described and linked to the present concept. The recently completed phase B tradeoff study selections of photovoltaic system technologies are described. The present solar dynamic and power management and distribution systems are also summarized for completeness.

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 realized.

Numerous studies conducted in the 1960's and 1970's (ref. 1) have helped establish a role for a manned space station. Most unmanned satellites launched since the beginning of the space age in 1957 have been powered by photovoltaic systems based on silicon solar cells. A few deep space interplanetary missions and manned spacecraft like Mercury, Gemini, and Apollo are the 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 weight, lower volume, higher efficiencies, longer lifetimes, and 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 can trace its roots back to 1981, when technology steering committees were formed to identify candidate technologies. In early 1982, the Space Station Task Force was formed to determine the feasibility of a space station (phase A in the program development process). The task force analyzed the uses or missions for a manned space station. Specific missions to be performed were determined and studied extensively (ref. 2). These 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 concept shown in figure 1. It is composed of a manned core and an unmanned co-orbiting platform, both in a 28.5° orbit. Another platform is in a polar orbit. A system of unmanned vehicles for maneuvering payloads near the station or for transferring them to other orbits is part of the space station system.

The mission analysis studies identified 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 will have grown. These power requirements have changed as the mission definition has evolved. The current user power levels are shown in table 1. User power means that all system losses for generation, storage, conditioning, and distribution have been taken into account. Note that the IOC station power of 75 kW is about an order of magnitude higher than that used on Skylab. Skylab, the first U.S. manned space station, launched in 1973 is the largest (8-kW user power, 22-kW array power) solar power system flown in space to date. The 75-kW 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 engineering related. They include cost (both initial and life cycle), schedule, technical development risk, weight, and safety requirements as most large spacecraft projects do. However, the permanent nature of the space station results in some new and unique requirements such as growth capability, maintainability, and commonality of hardware and software across all station elements. Commonality reduces development, qualification, and production costs. It was an important factor in selecting the technologies for use on space station. Replacement and growth of the station systems requires that they be designed so that they can accept changes in technology (i.e., technology transparency) yet still provide the same functions. Other considerations are the station orbital altitude and decay, orbital assembly and buildup, lifetime, logistics and control of spare parts, failure criteria, verification, contingency requirements, load type and location, and interface.

In 1983 the task force took the results from the mission analysis studies and synthesized them into several candidate space station configurations. They also further studied and sharpened technology selection for all the station systems including power.

As a result of the feasibility work NASA received approval to build the space station and have it operational by 1994. The importance of drag area on reboost cost and life-cycle cost coupled with the very large growth power requirements (as high as 450 kW) resulted in the adoption of solar dynamic generators with thermal energy storage in addition to 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. 2) using both photovoltaic and solar dynamic 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 size and drag area of the power system were major considerations in selecting the overall space station geometry. This geometry must allow the station and the power system to grow. It must minimize the effect 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 was necessary to reduce costs. Most importantly, the station must be passively controllable (i.e., gravity gradient 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, along with its two major phase B contractors, TRW and Rocketdyne, studied numerous power system types. These phase B definition studies are described below.

Definition of Power System Configuration

Early in phase B six power system options were defined for study (fig. 3). The IOC power level of 75 kW and the growth power level of 300 kW were selected. The six cases were established on the basis of IOC power system type (either solar dynamic (SD) or photovoltaic (PV)) and the method of growing from 75 to 300 kW. Case 1 was all PV. Case 6 had minimum PV (12.5 kW) 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 to 5 had various proportions of SD to PV. Commonality between the station and the platform was considered in these system studies.

The primary selection criterion 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 were included. An especially important life-cycle cost saving resulted from the reduced aerodynamic drag associated with the SD system. This reduced drag allowed lower orbital 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 kW with four solar array wings (array power, N57 kW). The station would also use 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 kW. 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 and concentrators. A planar array with silicon cells was selected. This array design is similar to the NASA Office of Aeronautics and Space Technology (OAST) flight experiment, OAST 1, launched in August 1984. If fully populated with cells, the array would have a power output of 13 to 14 kW at the wing root. 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.

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 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 contingency requirements. Building in greater contingency capability would be unnecessarily expensive.

Energy storage options studied included nickel-cadmium (NiCd) batteries, regenerative fuel cells (RFC), and nickel-hydrogen (NiH_2) batteries. Although NiCd batteries are established, flight-proven, low-risk devices, their low depth of discharge results in high storage system weight. Space cells in sizes up to 100 A-hr have been produced, so development risk would be low.

RFC's use a fuel cell and an electrolyzer to store energy in the form of hydrogen and oxygen. In the dark portion of the orbit these elements 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. RFC's are lighter than batteries and allows storage of large amounts of contingency power with small changes in tank volume. However, because RFC's are not as efficient as batteries (60 vs 80 percent), the solar arrays must be larger. Also, RFC's are more complex (i.e., contain 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 3 yr of operation without repair were required. However, commonality between the station and the platform to reduce development, resupply, and the cost of controlling spare parts was also considered.

The individual pressure vessel (IPV) type of NiH_2 battery has been used in geosynchronous (GEO) spacecraft (fig. 4). (The bipolar NiH_2 battery has low technology maturity and was screened out by the early tradeoff studies). IPV, 3.5-inch-diameter, 50-A-hr GEO cells are in production. Other sizes and capacities are available by 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 a LEO spacecraft experiences. However, the Space Station Advanced Development Program is beginning to test LEO cells with a goal of demonstrating 5-yr lifetimes.

As a result of the phase B tradeoff studies IPV NiH_2 batteries were selected for the platform. Weight, cost, reliability, development risk, and schedule were the primary considerations. Nickel-hydrogen batteries weigh about half as much and cost less than NiCd batteries and are more reliable than RFC's. 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 for the station.

The recent evolution of space station energy storage system selection is shown in table II. The selection was strongly influenced by power level, commonality, weight, and cost.

Solar Dynamic Technology Studies

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

In the tradeoff studies the two conversion cycles considered were closed Brayton cycle (CBC) and 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 tradeoff studies therefore involved higher risk for these systems than for the PV system.

Design considerations for the SD system studied in phase B and being worked on 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, and on-orbit assembly. At the time of this writing both the CBC and the ORC systems are 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 unknown load types and sizes 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 deliberation, 20 kHz was selected for the PMAD distribution frequency.

The overall PMAD architecture selected is a dual-ring system with multikilowatt buses supplying power to load areas on the upper and lower keels and the transverse boom. Buses supplying the manned modules are rated at 30 kW. 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.

CONCLUDING REMARKS

The present Space Station Program traces it roots back to 1981. 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 the station and platform requirements initially and into the future. The 25-kW photovoltaic system (57-kW array power) will be larger than any system flown to date. The solar dynamic system will facilitate economics and growth for the power system and the station. The PMAD system enables a growable, balanced utility type of power system approach for maximum friendliness for the station users.

The technologies selected for the photovoltaic, solar dynamic, and power management and distribution systems result in the lowest initial-operating-system 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.

TABLE I. - SPACE STATION SYSTEM
POWER REQUIREMENTS

Element	Average	Peak
	User power, kW	
Manned core:		
IOC station	75	100
Growth station	300	350
Polar platforms:		
IOC station	8	16
Growth station	15	24
Co-orbiting platforms:		
IOC station	6	6
Growth station	23	23

TABLE II. - EVOLUTION OF SPACE STATION ELECTROCHEMICAL ENERGY STORAGE SYSTEM

Date	Station solar dynamic system	Station photovoltaic system	Polar platform: Average	Polar platform: Peak	Co-orbiting platform	Station	Platform	Comments
	Power level, kW					Electrochemical storage		
Oct. 1985	0	75	8	18	6	H_2O_2 RFC	NiCd	Lacks commonality
Jan. 1986	37.5	37.5	8	18	6	H_2O_2 RFC	NiH_2	Platform weight reliability
Mar. 1986	50	25	8	18	6	NiH_2	↓	65 A-hr; 3.5-in. diameter
Oct. 1986	50	37.5	3.8	3.8	2	NiH_2	↓	40 A-hr; minimum weight 62 A-hr; minimum cost
Mar. 1987	(a)	(a)	(a)	(a)	(a)	NiH_2	↓	65 A-hr; 23 cells/pack (28 V); 2 packs/platform; 4 packs/station Commonality with orbital manuevering vehicle, flight telerobotic services, and mobile support center

[a]To be determined.

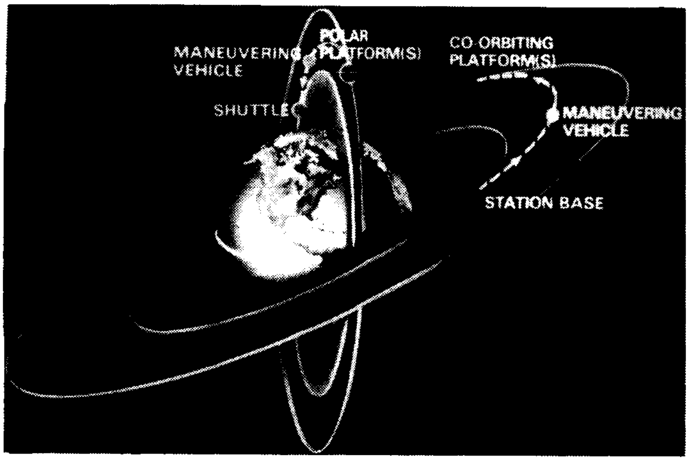


FIGURE 1. - SPACE STATION COMPLEX, EARLY 1990's.

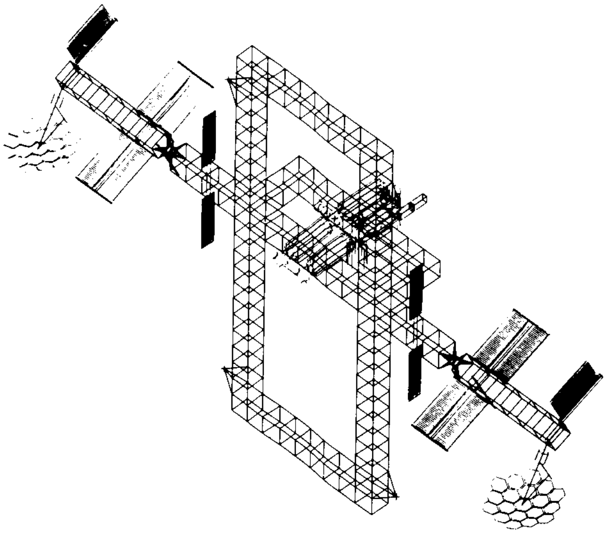


FIGURE 2. - SPACE STATION DUAL KEEL CONFIGURATION 1986.

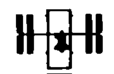
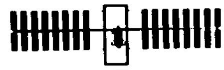
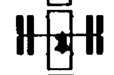
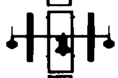
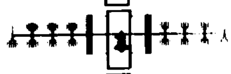
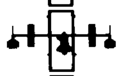
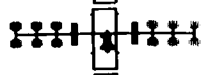
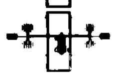
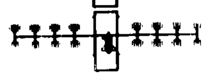
CASE	INITIAL OPERATIONAL CAPABILITY, IOC	PHOTOVOLTAIC (PV) AND SOLAR DYNAMIC (SD) CAPABILITIES, KWE	GROWTH
1		IOC PV GROWTH PV	
2		IOC PV GROWTH SD	
3		IOC 50 PV-25 SD GROWTH SD	
4		IOC 37.5 PV-37.5 SD GROWTH SD	
5		IOC 25 PV-50 SD GROWTH SD	
6		IOC 12.5 PV-75 SD GROWTH SD	

FIGURE 3. - CASES EVALUATED FOR SPACE STATION POWER SYSTEM.

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FIGURE 4. - TYPICAL NICKEL-HYDROGEN CELL.