STATUS OF THE SPACE STATION POWER SYSTEM

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Summary

The manned Space Station is the object of the next major NASA program. It presents many challenges to the 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 Spation 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 trade study selections of photovoltaic system technologies are described. A summary of the present solar dynamic and power management and distribution systems is also given for completeness.

1. Background

The Space Station System is the next major step in the manned space program. The Space Station will be a multi-purpose facility which will result in advancement 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 1960s and 1970s [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 silicon-solar-cell-based photovoltaic systems. A few deep space interplanetary missions and manned spacecraft such as 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 for the current Space Station and for defining its power system.

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2. 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 [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 Complex shown in Fig. 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 manoeuvering 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 has grown. These power requirements have changed as the mission definition has evolved. The current user power levels are shown in Table 1. User power or bus power is expressed in kilowatts electric (kWe) in Table 1 and elsewhere in 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 Skylab. Skylab, the first U.S. manned space station, launched in 1973, is the largest (8 kWe user

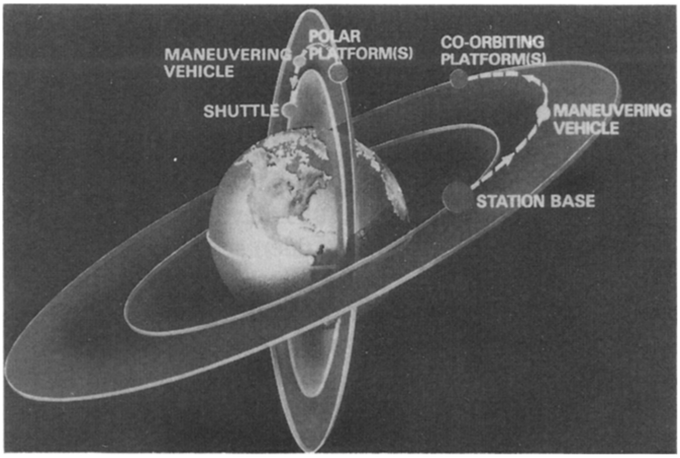


Fig. 1. Space Station complex, early 1990s.

TABLE 1

Space Station system power requirements

Element	User power average	kWe peak
Manned core		
IOC	75	100
Growth	300	350
Platforms		
Polar		
IOC	8	16
Growth	15	24
Co-orbiting		
IOC	6	6
Growth	23	23

power, 22 kWe array) solar power system flown in space to date. The 75 kWe requirement for the planned Space Station is the most challenging factor facing the power system designer.

Additional challenges arise from programme requirements imposed on the power system designer (Table 2). These additional requirements are management and/or engineering related. They include cost (both initial and life-cycle), schedule, and technical-development risk, weight, and safety requirements, as most large spacecraft projects do. 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. Commonality results in cost savings by reducing development, qualification, and production costs. It was an important factor in selection of technologies for use on Space Station. Future replacement and growth of the station systems requires 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 its decay, assembly and buildup, lifetime, and logistics and sparing.

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 this 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 kWe), resulted in the adoption of solar dynamic (SD) generators with thermal energy storage in addition to photovoltaic arrays with electrochemical energy storage for detailed study in the definition phase.

TABLE 2

Power system management/engineering considerations

Initial cost	Schedule
Life-cycle cost	Orbit altitude and decay
Development risk	Growth capability
Commonality	Contingency requirement
Weight	Load types and location
Maintainability	Logistics and sparing
Failure criteria	Orbital assembly and buildup
Safety	Interfaces
Verification	Lifetime

3. Definition phase

The present Space Station configuration and the hybrid power system (Fig. 2) 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. Because of the size and drag area of the power system, it 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 was necessary to reduce costs. Most important of all, the Station must be passively controllable, *i.e.*, gravity gradient stabilized. From these diverse and sometimes contradictory requirements, the

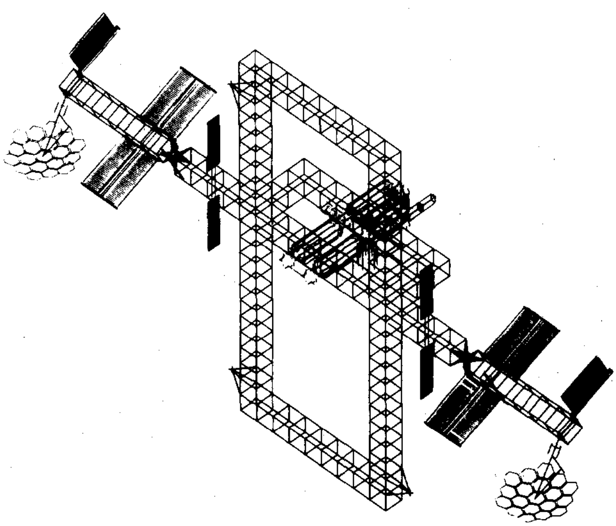


Fig. 2. Space Station dual keel configuration 1986.

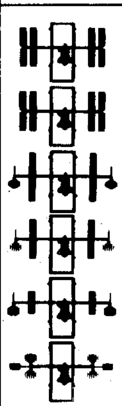
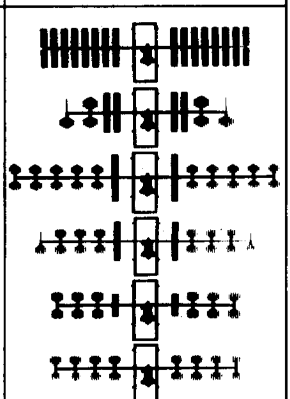
Power Tower and later the Dual Keel configurations were developed and studied by NASA. At the same time, the NASA Lewis Research Center, along with its two major Phase B Contractors, TRW and Rocketdyne, studied numerous power system types. These Phase B definition studies are described below.

3.1. Power system configuration definition

Early in Phase B, six power system options were defined for study (Fig. 3). 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 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 was considered in these system studies.

The primary selection criteria for these sytem 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 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 would

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	

Fig. 3. Cases evaluated for Space Station power system.

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 kWe. Overall, the technologies for the photovoltaic system are low risk and space proven, whereas the solar dynamic technologies offer reduced drag and cost.

3.2. Photovoltaic system technology studies

3.2.1. 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 power output would be about 13 - 14 kWe 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 ref. 3.

3.2.2. 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 contingency requirements. Building-in greater contingency capability was unnecessarily expensive. Energy storage options studied included nickel–cadmium (Ni–Cd) batteries, regenerative fuel cell (RFC), and nickel–hydrogen (Ni–H_2) batteries.

Ni–Cd batteries are established, flight-proven, low-risk devices. However, their low depth of discharge results in high storage system weight. Space-type cells up to 100 A h 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, they 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. However, the RFC is not as efficient as batteries (60% compared with 80%) so that the solar arrays must be larger. Also, the RFC is more complex (*i.e.*, pumps, valves, etc.) and not as reliable as batteries. RFCs 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 Ni–H_2 battery has been used in geosynchronous (GEO) spacecraft in the individual pressure vessel (IPV) type. (The bipolar Ni–H_2 battery has low technology maturity and was screened out by the early trade studies.) IPV, 3.5 in. dia., 50 A h GEO-type cells are in production. Other sizes and capacities are available using scaled-up existing components. The uncertainty with the Ni–H_2 battery stems from its charge–discharge cycle life. GEO spacecraft experience only a fraction of the cycles of that of a LEO spacecraft. However, the Space Station Advanced Development Program is beginning to test "LEO type" cells with a goal of a minimum lifetime of five years.

As a result of the Phase B trade studies, IPV Ni–H_2 batteries were selected for the platform. Weight, cost, reliability, development risk, and schedule were the primary considerations. They are about half the weight and lower in cost than Ni–Cd batteries and more reliable than the RFC. An identical IPV Ni–H_2 battery was also selected for the Station on the basis of cost and commonality with the platform. IPV Ni–H_2 was lower in IOC cost and only slightly higher in life-cycle cost for the Station. The recent evolution of Space Station storage system selection is shown in Table 3. This selection is strongly influenced by power level, commonality, weight, and cost.

3.3. Solar dynamic technology studies

The solar dynamic system consists of an offset parabolic concentrator mirror which focuses the sun's heat into a receiver. The receiver stores the heat in a salt (*e.g.*, LiOH) and also 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 a.c. 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 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 trade studies were therefore higher risk than for the PV system.

Design considerations for the SD system studied in Phase B and being worked 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 writing, both the CBC and ORC systems are still being considered. More detailed study is required because cost and performance are nearly identical.

TABLE 3

Evolution of Space Station electrochemical energy storage system

Date	Station solar dynamic system	Station photo-voltaic system	Polar platform		Co-orbiting platform	Station	Platform	Comments
			Average	Peak		Electrochemical storage		
	Power level (kW)							
Oct. 1985	0	75	8	18	6	H_2O_2 RFC	Ni–Cd	Lacks commonality
Jan. 1986	37.5	37.5	8	18	6	H_2O_2 RFC	Ni–H_2	Platform weight reliability
Mar. 1986	50	25	8	18	6	Ni–H_2	Ni–H_2	65 A h; 3.5 in. dia.
Oct. 1986	50	37.5	3.8	3.8	2	Ni–H_2	Ni–H_2	40 A h; minimum weight 62 A h; minimum cost
Mar. 1987	50	75	3.8	3.8	3[a]	Ni–H_2	Ni–H_2	65 A h: 23 cells/pack (28 V); 2 packs/platform; 4 packs/station Commonality with orbital manoeuvering vehicle, flight telerobotic services, and mobile support center

[a]To be added in Phase 2 of the program.

3.4. 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-type 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 d.c., 400 Hz a.c., and 20 kHz a.c. were studied. Component efficiency, size, and weight, as well as technology readiness, availability of space type 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 multi kWe busses supplying power to load areas on the upper and lower keels and the transverse boom. Busses supplying the manned modules are rated at 30 kWe. The PMAD system contains numerous switching assemblies 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.

4.0. Conclusion

The present Space Station program traces its 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 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-type system approach for maximum friendliness for the station users.

The technologies selected for PV, SD and PMAD result in the lowest IOC costs 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.

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