POWER MODULES AND PROJECTED POWER SYSTEMS EVOLUTION

Lott W. Brantley
NASA Marshall Space Flight Center

SUMMARY

Photovoltaic, solar thermal, and nuclear power systems are being considered to supply future Earth orbital electrical power requirements. A growth scenario from a 25-kW Power Module in the early Shuttle era to the 5- to 10-GW Satellite Power System in the year 2000 is presented. Photovoltaic systems are presently baselined in this evolution. The Photovoltaic Power System and subsystem growth projections, consistent with this scenario, have been developed and are summarized.

INTRODUCTION

The Space Shuttle and Spacelab Systems are expected to open the door to low-cost space transportation and experimentation. This together with the requirement for low-cost orbital operations is expected to result in the increase in scope, size, and consolidation of Earth orbital operations. These large concentrations of space activity will result in large centralized power modules. The early time frame is driven by NASA support requirements. Later requirements may be dominated by the needs of the industrial or space commercialization sectors. The Satellite Power System in the scenario presented here is envisioned as such a venture.

SYMBOLS AND ACRONYMS

kW	kilowatts of power (electrical or thermal, depending on context)
kW_t	kilowatts of thermal power
Wh	watthours of energy
PM	power module
SCB	space construction base
SPS	Satellite Power System
Si	silicon solar cells
GaAlAs	gallium arsenide solar cells with a gallium aluminum arsenide window
LEO	low Earth orbit
GEO	geosynchronous Earth orbit
CMG	control moment gyro
STS	Space Transportation System
FF	free flyer
Pk	peak power
EOL	end-of-life power

SEPS solar electric propulsion stage

ECS environmental control system

25-kW POWER MODULE

Out of a 1977 space construction base study to be described later, in particular, the Power Systems Special Emphasis Task,* came the requirement for 25 kW average electrical power during the man-tended mode, the first few years of operation. From this and particular space-processing Shuttle payloads came the requirement for an early 1980's 25-kW Power Module that could support Shuttle-orbited payloads to extend the on-orbit time of the Shuttle and payload, to provide higher average power for a nominal 7-day mission, or to support a shuttle-delivered free-flyer payload.

The 25-kW Power Module (fig. 1) is designed to provide 25 kW average power in a 235-n mi, 50^{o}-inclination low Earth orbit; therefore, the solar array is oversized to compensate for the orbit dark time and energy storage is provided. A control moment gyro (CMG) system provides stabilization and maneuvers for the Power Module and Power Module/Orbiter Configuration. A heat rejection system dissipates waste heat in excess of that which can be rejected by the Shuttle.

The Power Module is designed for several operational modes (fig. 2). Power levels, heat rejection, and mission time are varied to support a power module/orbiter/payload sortie of up to 60 days, a high-power pallet-deployed sortie of up to 7 days or a free-flying power module mission of months or years duration. The power module is electrically and mechanically compatible with the Shuttle Orbiter. It is designed for Shuttle delivery to orbit, on-orbit maintenance, or return by Shuttle to Earth.

Presently, a power module evolution study is under way. Emphasis is on near-term steps, identifying driver missions, defining growth through modular steps, and/or modification to the baseline 25-kW Power Module. Figure 3 illustrates modification and modular growth to the 100-kW level and support of an on-orbit-assembled large multihundred-kilowatt power module.

LARGE POWER MODULE

In 1977, study efforts emphasized a permanent manned space construction base, and the special emphasis task of that study compared a solar photovoltaic, a solar thermal, and a nuclear reactor power system in the hundred-kilowatt range. The mission power requirements are illustrated in figure 4. Figures 5 to 7 illustrate the power systems compared and their interface with the space construction base. Figure 8 gives a quantitative comparison of competing system characteristics. It was concluded that either system could be built to meet the system requirements by the projected mission launch date ('83-'86). However, both of the other systems have a lower development status than photovoltaics. Since they did not offer a significant or mission-required improvement and their total cost was significantly higher, photovoltaics was selected as the baseline

*This task was initiated by OAST and supported also with a DOE nuclear power system definition study.

system. Indirect political and economic pressures are resulting in a widening technical gap between photovoltaic and competing systems. Reduced technology funding and increasing concern over launch, operation, and disposal of nuclear sources from Earth orbit together with continuing emphasis and success with photovoltaic systems have resulted in photovoltaics displacing the nuclear systems as a baseline to the hundreds-of-kilowatts power level. An earlier space base study had baselined a reactor-Brayton system for use at this power level. From a cost viewpoint, it is interesting to note that the recurring cost of nuclear systems is equal to or lower than all competing systems. Also, not surprising is that photovoltaics show much lower nonrecurring costs. The implication is that a space program with many like units in the power range required could show economic benefit from the nuclear option over all but the GaAlAs photovoltaic system.

The photovoltaic system at this power level and higher must contend with a high drag, gravity gradient torques, and an increasing energy storage system complexity and heat rejection impact on the ECS system.

SATELLITE POWER SYSTEM

POWER TECHNOLOGY GROWTH PROJECTIONS

Figure 9 illustrates a 5-GW (on Earth) Satellite Power System being considered for the year 2000. Photovoltaic collectors are used to power a microwave transmitter to illuminate rectenna receiving sites on the ground, 7 to 8 GW are produced by the solar array at GEO. Figure 10 illustrates the power growth projection consistent with this technology. A factor of greater than 3 increase every year is required for 20 years to achieve this goal. Figures 11 and 12 show the technology advances required in specific cost, specific weight, array area, conditioning and distribution voltages, etc., that must be achieved versus time and power levels, respectively.

Power conversion cost/watt is expected to experience the reduction due to large terrestrial system buys that result in automated, high, continuous production facilities. The space system is expected to require an order of magnitude less material than an equivalent ground-based system. The required reduction in W/kg is to be achieved by going to on-orbit fabrication and assembly of support structures, reuse of deployment and storage equipment, increasing cell efficiency with thinner cell stacks, and use of thin-film concentrators.

Higher Wh/kg energy storage will be achieved by using electrolysis-fuel cell maintainable systems and molten salt or metal batteries. Power conditioning increases in W/kg are to be achieved by going to higher voltages. Power distribution voltages are seen to be pushed to that allowable in space plasma and under space charging conditions. A limit of about 2 kV DC in LEO and 40 kV DC at GEO is projected based on limited measured data now available in this area.

Power transmission by hardwire is projected until circumstances require electromagnetic transmission. Current studies are evaluating ground-to-space, space-to-space, and space-to-ground transmission by laser or microwave for electric power, thermal power, or propulsion.

Power levels to hundreds of kilowatts are expected in LEO. In a SPS development scenario, multimegawatt and multigigawatt systems are expected in GEO. In LEO, large multimegawatt systems are expected to have more problems with drag, gravity gradient torques, array distribution voltage limits, and large energy storage systems - with attendant large heat rejection systems.

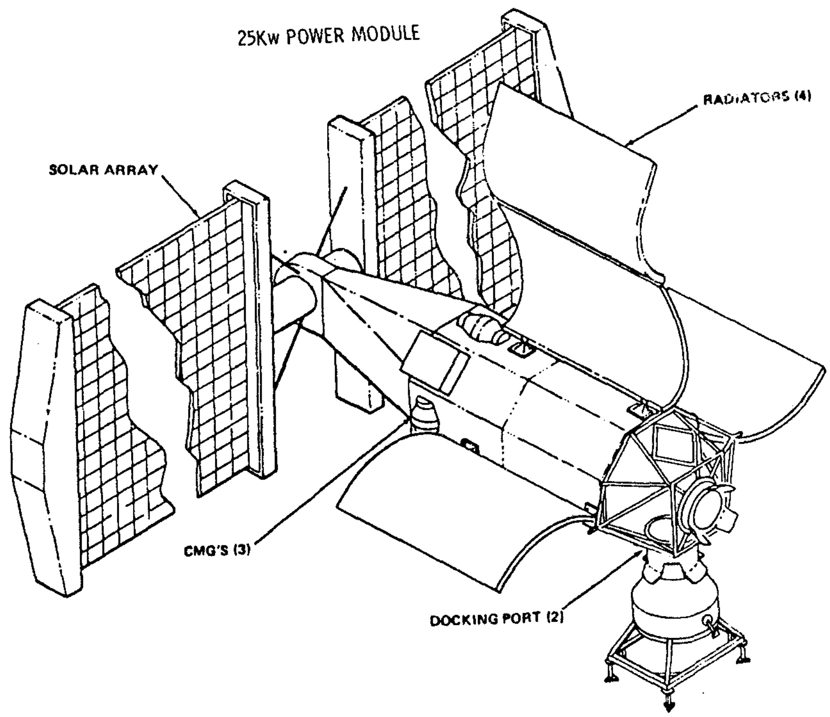
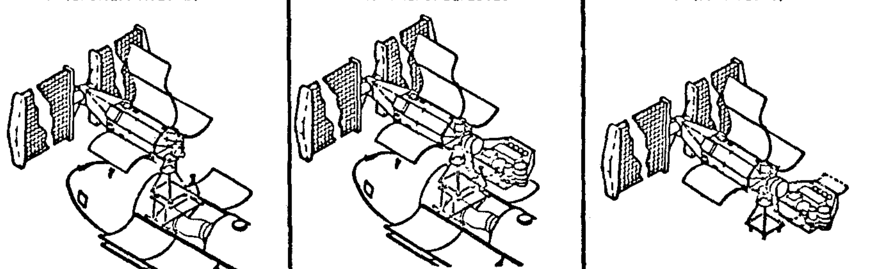


Figure 1.

BASELINE POWER MODULE PRIMARY OPERATIONAL MODES



RESOURCES AVAILABLE TO PAYLOAD	SORTIE SUPPORT MODE (PM/ORBITER/PAYLOAD)	SORTIE SUPPORT MODE WITH PALLET DEPLOYED	FREE FLYING MODE (PM/FF PAYLOAD)
POWER	11KW	32KW	25KW
HEAT REJ.*	17.5KW–19.5KW	17.5KW–19.5KW	12KW–14KW
STAB & CONT.	CMG	CMG	CMG
ORB DURATION	60 DAYS	7 DAYS	INDEFINITE

*HEAT REJECTION INCREASES WITH A REDUCTION IN 25KW PM ELECTRICAL LOAD AND BETA ANGLE. 8.5 KW_t FROM ORBITER (SPEC) INCLUDED HERE.

Figure 2.

25 KW POWER MODULE GROWTH POTENTIAL

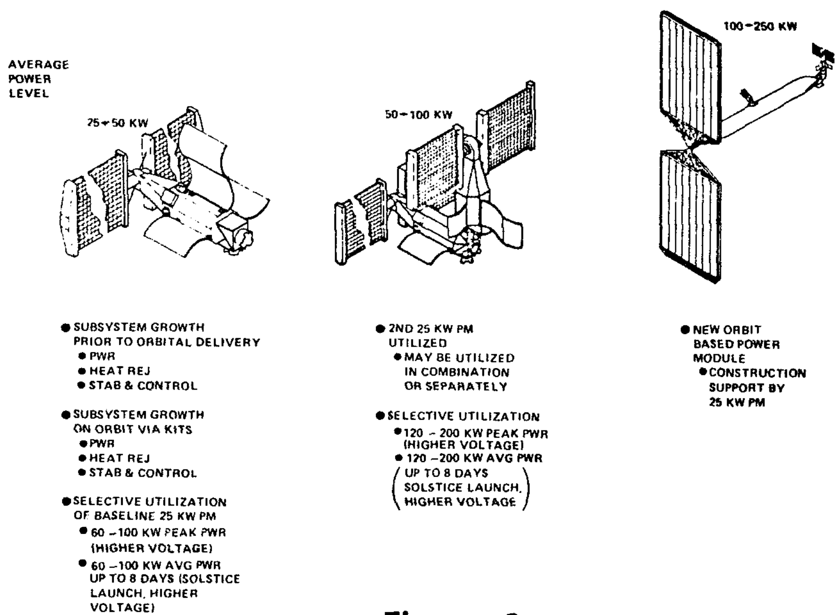


Figure 3.

BASELINE LEO MISSION POWER REQUIREMENTS (APRIL '77)

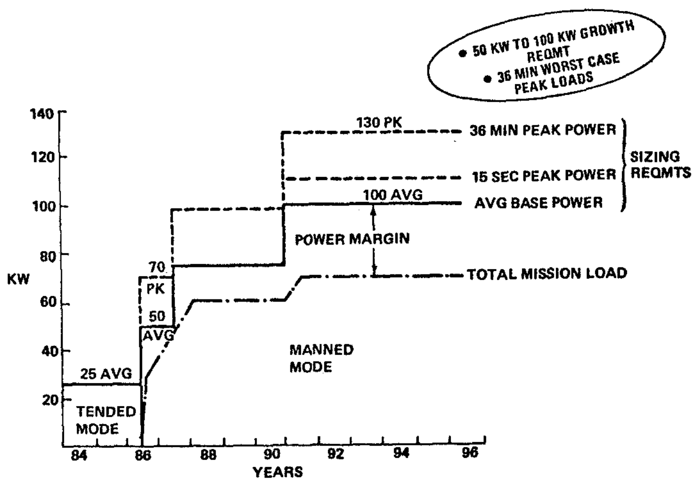


Figure 4.

SPACE STATION – PHOTOVOLTAIC POWER SYSTEM

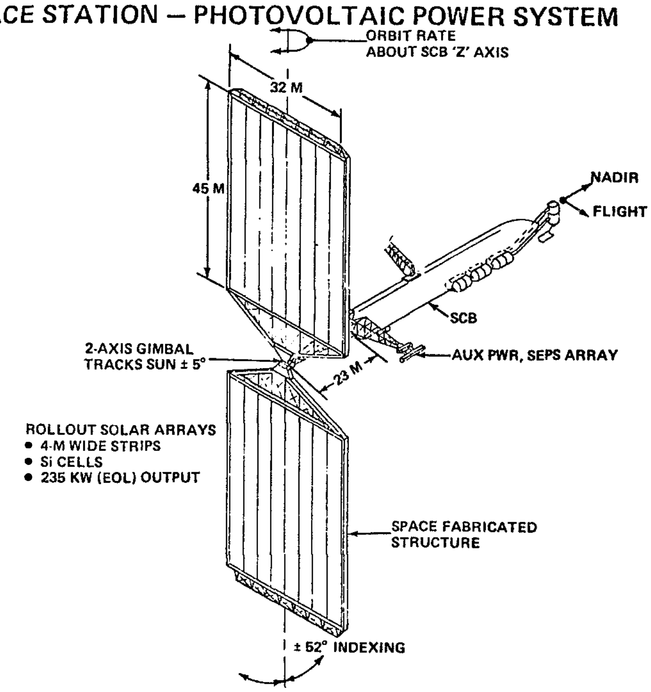


Figure 5.

SPACE STATION SOLAR-BRAYTON POWER SYSTEM

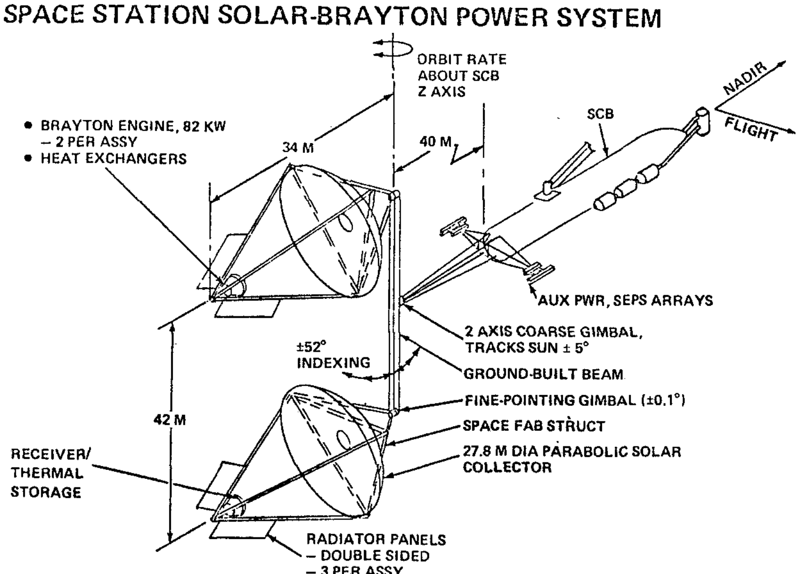


Figure 6.

SPACE STATION REACTOR-BRAYTON POWER SYSTEM

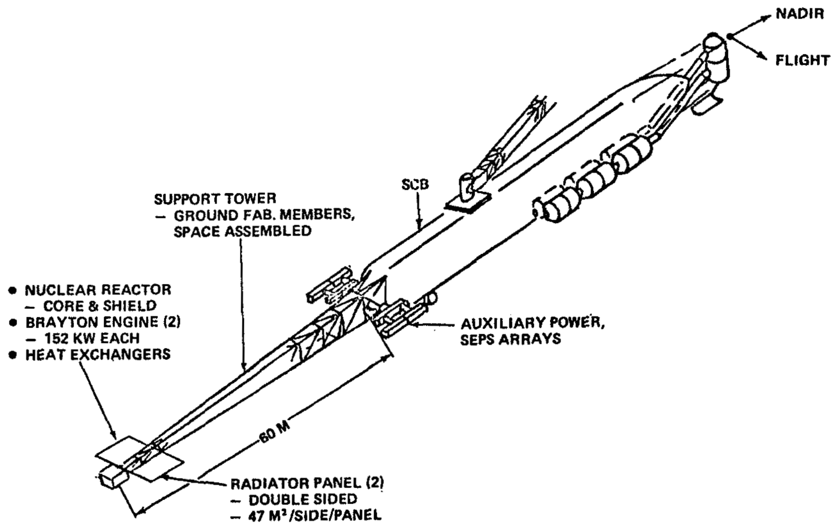


Figure 7.

POWER SYSTEM SUMMARY COMPARISON

	PHOTOVOLTAIC		SOLAR-THERMAL		NUCLEAR-REACTOR		
	Si	GaAlAs	BRAYTON	THERMIONIC	BRAYTON	THERMIONIC	THERMOELECT
CAPABILITY, KW – EARLY LOADS – ADV LOADS	70 130	70 130	70 140	70 140	130 130	130 130	130 130
COST ('77 $M) – TOTAL PROGRAM – DDT&E	254 97	203 91	344 182	411 236	410 295	502 390	459 343
SAFETY HAZARDS	HI-PRESS NiH_2		HOT SURFACES, LOSE SUN POINTING		HOT SURFACES, NUCLEAR RADIATION & DISPOSAL		
PERFORMANCE MASS (EARLY/ADV)10^3KG GROWTH POTENTIAL	9.1/14.2 GOOD	10.8/18.4 GOOD	12.8/21.6 POOR	12.8/19.9 POOR	24.6 GOOD	26.3 GOOD	26.3 GOOD
DESIGN COMPLEXITY	HI-DRAG, ECS IMPACT		MED DRAG, TIGHT PTG, MANY COMPONENTS		LOW DRAG, SPEC HDLG EQUIP.		
OPERATIONS COMPLEXITY	HI-VIEW FACTOR BLOCK, EASY MAINT		LONG BUILDUP, MOD VIEW FACT. BLOCK		NO BLOCKAGE BUT SPEC MAINT & DISPOSAL PROCED		
DEVELOPMENT RISK	LOW	MED	MED	HIGH	HIGH	HIGHEST	HIGH
PROGRAM FLEXIBILITY	GOOD POTENTIAL				TRANSPORT LIMITED		

Figure 8.

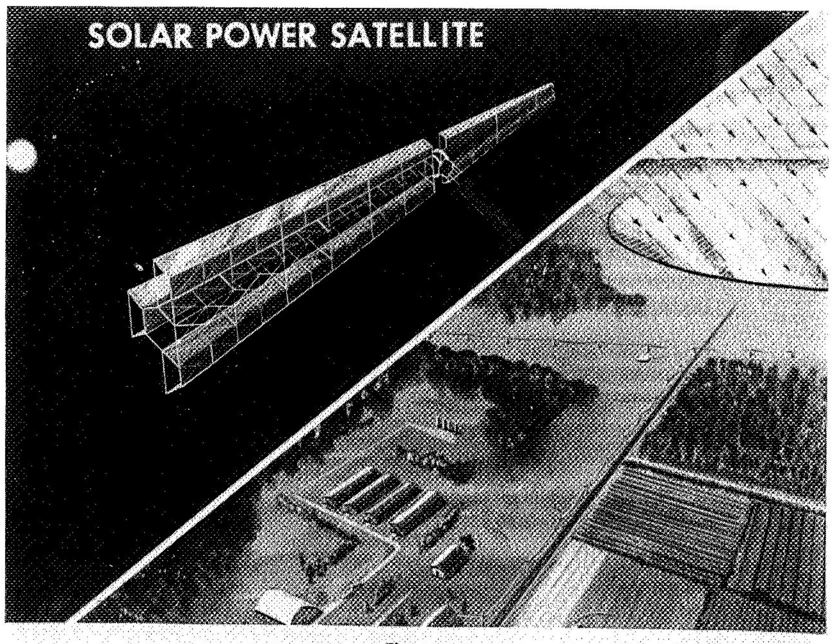
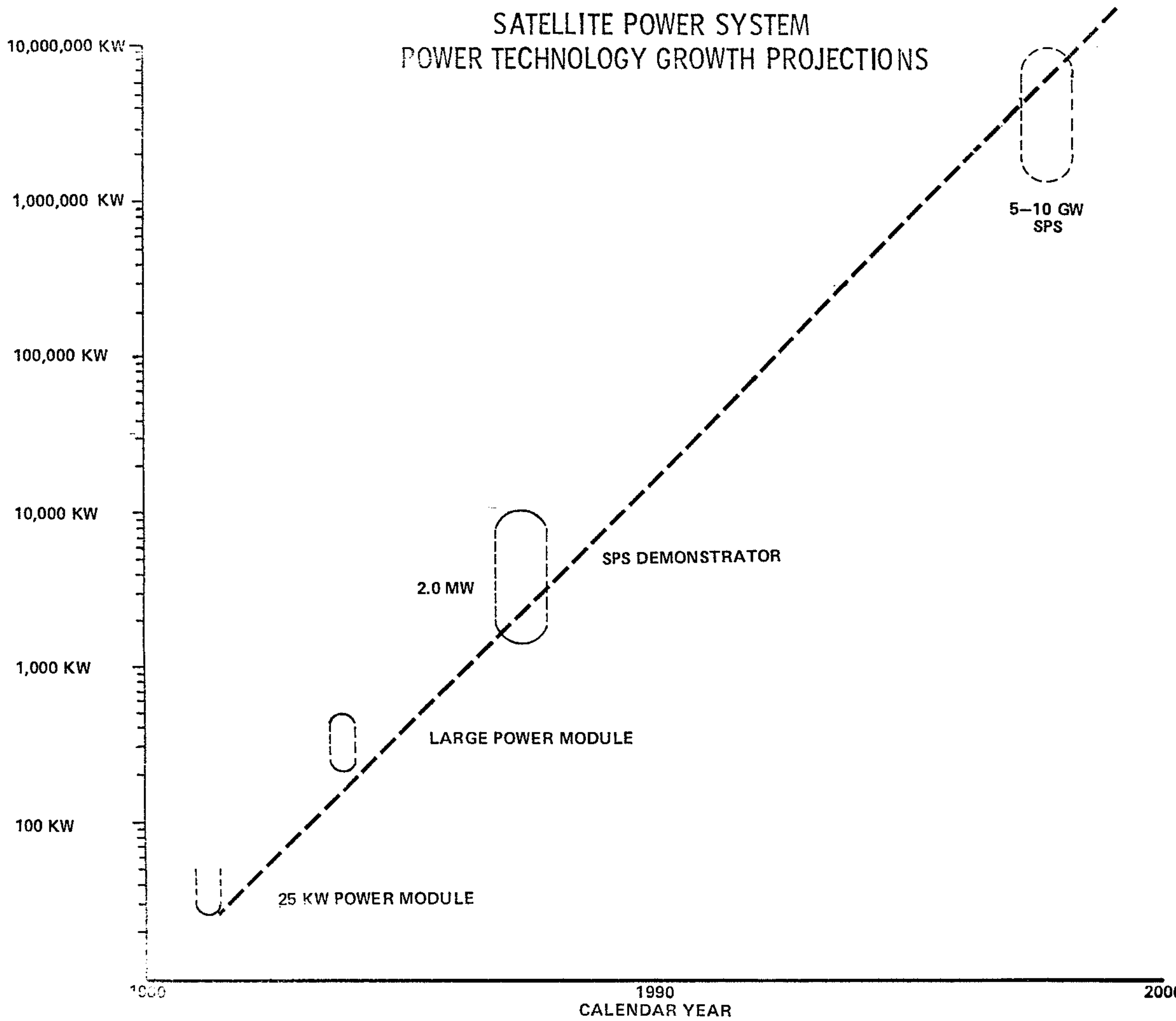


Figure 9.



SATELLITE POWER SYSTEM
POWER TECHNOLOGY GROWTH PROJECTIONS
10,000,000 KW
1,000,000 KW
100,000 KW
10,000 KW
1,000 KW
100 KW
5–10 GW
SPS
SPS DEMONSTRATOR
2.0 MW
LARGE POWER MODULE
25 KW POWER MODULE
1990
2000
CALENDAR YEAR

Figure 10.

TECHNOLOGY ADVANCEMENT REQUIRED

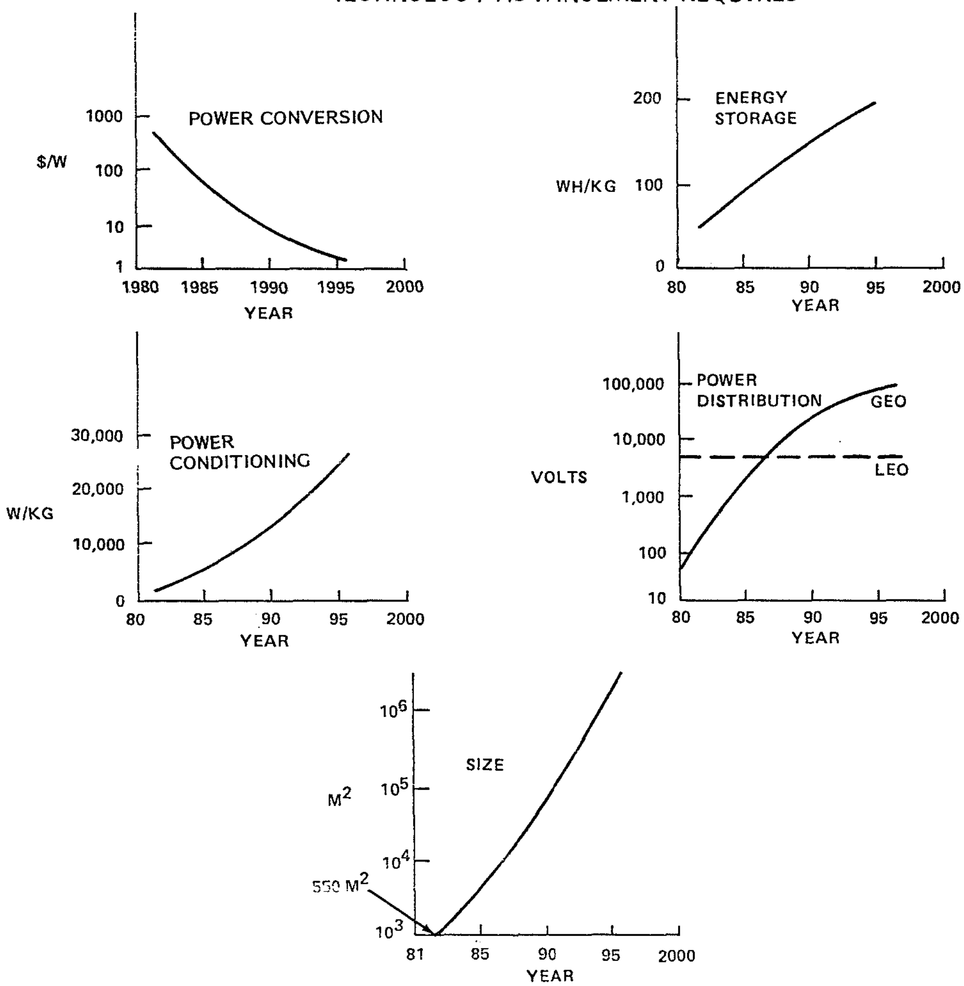


Figure 11.

POWER SYSTEM EVOLUTIONARY
TECHNOLOGY REQUIRED

	TENS OF KILOWATTS	HUNDREDS OF KILOWATTS	MULTI-MEGAWATT	MULTI-GIGAWATT
POWER CONVERSION	\$300/WATT 66 W/KG	\$30/WATT 150 W/KG	\$10/WATT 300 W/KG	\$0.75/WATT 600 W/KG
ENERGY STORAGE	KWH; 44 WH/KG	KWH; 80 WH/KG	MWH; 150 WH/KG	MWH; 200 WH/KG
POWER CONDITIONING	800 W/KG	5000 W/KG	10,000 W/KG	26,000 W/KG
POWER DISTRIBUTION	115V DC	2K VDC	12K VDC	40K VDC
POWER TRANSMISSION	HARDWIRE	HARDWIRE	HARDWIRE LASER	HARDWIRE LASER RF
ORBIT	LEO	LEO/GEO	GEO	GEO
CONSTRUCTION	DEPLOYABLE	ON-ORBIT ASSY(?)	ON-ORBIT ASSY	ON-ORBIT ASSY
SIZE	550 M^2	4200 M^2	30,000 M^2	30 KM^2

Figure 12.