JSC-11568

INITIAL TECHNICAL, ENVIRONMENTAL, AND ECONOMIC EVALUATION OF SPACE SOLAR POWER CONCEPTS

VOLUME I - SUMMARY

(NASA-TM-X-74309) INITIAL TECHNICAL, ENVIRONMENTAL, AND ECONOMIC EVALUATION OF SPACE SOLAR POWER CONCEPTS. VOLUME 1: SUMMARY (NASA) 129 p HC A07/MF A01 CSCL 10A N77-16442
Unclas
G3/44 11522

AUGUST 31, 1976

National Aeronautics and Space Administration

LYNDON B. JOHNSON SPACE CENTER

Houston, Texas

INITIAL TECHNICAL, ENVIRONMENTAL, AND ECONOMIC

EVALUATION OF SPACE SOLAR POWER CONCEPTS

VOLUME I - SUMMARY

VOLUME II - DETAILED REPORT

CONTENTS

PR[redacted]

Section | Page

Section Page

TABLES

FIGURES

Figure		Page
V-1	Beam builder machine concept	V-1
V-2	Typical SPS construction sequence - column/cable (POP) . . .	V-2
V-3	Partial construction of column/cable configuration	V-3
V-4	Concept for solar cell/concentrator deployment	V-4
V-5	Construction base concept for truss configuration	V-5
V-6	Typical SPS construction sequence - truss configuration. . .	V-6
V-7	Construction base concept for column/cable configuration	V-7
V-8	Operational schematic of construction base (column/cable)	V-10
VI-1	Modified single-stage-to-orbit launch vehicle	VI-4
VI-2	Two-stage winged launch vehicle	VI-5
VI-3	Two-stage winged launch vehicle	VI-7
VI-4	Personnel and priority cargo launch vehicle	VI-10
VI-5	LEO-to-GEO transfer time as a function of thrust/weight	VI-11
VI-6	Propellant burden contribution for high-thrust O_2/H_2 COTV	VI-13
VI-7	Cargo orbital transfer vehicle ($COTV_G$) characteristics	VI-14
VI-8	Crew module concept	VI-15
VI-9	Crew rotation passenger module	VI-16
VI-10	Personnel orbital transfer vehicle ($POTV_L$) characteristics	VI-17
VII-1	SPS mission scenario	VII-2
VII-2	SPS mission management concept	VII-12

Figure		Page

I. INTRODUCTION

The requirements for energy in the U.S. and the world will continue to increase to support a growing population and to improve the quality of life for that population. Projections indicate the U.S. requirements will grow by a factor of 2 to 3 between now and the year 2000.

The manner in which we will meet this requirement is not clear. Oil and gas are expected to be depleted within decades. Fuel for the present class of nuclear reactor systems will also be depleted in the same time frame. The breeder reactor system, when successfully developed, will greatly extend the natural fuel resource but presents continuing safety and environmental concerns, not the least of which is the disposal of nuclear waste as it accumulates from large-scale nuclear energy production. Fusion reactor systems also have potential, but these require significant scientific advances. Coal resources appear sufficient for several hundreds of years. The environmental concerns associated with mining coal, and the subsequent problems or costs in reducing air pollution to an acceptable level during its use, are well known. The logistics of a greatly expanded coal industry is also a significant although not unsolvable consideration.

In view of the problems or concerns related to obtaining the required energy from oil, gas, nuclear, and coal sources, the Nation is actively pursuing alternate sources of energy for the future. Solar energy is an obvious candidate for consideration. Solar energy is inexhaustible and clean, and the increasing costs of other sources will make solar energy more attractive in the future. The use of solar energy collected on the Earth has several basic limitations, however, which will tend to inhibit its widespread use. At any given location on the Earth, a solar collector will be limited by such factors as the day-night cycle, cloud cover, and atmospheric attenuation. The day-night cycle, particularly, requires the use of expensive storage capacity or limits the solar application by requiring additional power sources.

A concept has been presented ("Power from the Sun: Its Future," Dr. Peter E. Glaser, Amer. Assn. Advan. Sci., Vol. 162, Nov. 22, 1968, pp. 857-861) that is intended to alleviate limitations associated with the collection of solar energy on Earth. This concept involves placing large solar power satellites in geosynchronous orbit and beaming microwave energy down to collection stations on the Earth. Some of the advantages of this concept are that the satellite is in near-continuous sunlight that is not attenuated by the atmosphere, no electrical storage facilities are required, the land use requirement is reduced by a factor of 5 to 10, and the ground power output can be located near the user rather than in desert-type regions.

The space concept, while having advantages, also introduces new requirements. These include the need for transportation of the power station into space and the transmission of power from space to Earth by microwave radiation.

Several studies conducted in the past few years have been directed toward exploring the feasibility of this concept. The results of these studies have generally been favorable, while reflecting a need for significant technological advancement if the concept is to be economically competitive with ground-based systems.

Critical areas were identified during the course of these studies and research and development programs have begun to be formulated to investigate these areas. A particular effort was conducted at the NASA Lyndon B. Johnson Space Center (JSC) during the summer of 1975 to evaluate the need and feasibility of a Space Solar Power Development Laboratory. The study was done in support of the NASA "Outlook for Space" study and was documented in JSC-09991. Possible requirements for a development laboratory or "pilot plant" type solar power satellite were evaluated and the technical feasibility of such a plant was established.

In view of past study results, the 6-week study, and the conclusions of the "Outlook for Space" study, it was decided to implement at JSC a more detailed study of the Space Solar Power Concept. This document (Volume I) presents a summary of the results of that study. Volume II contains the detailed studies on which the summary was based. The study was conducted between September 1975 and June 1976, by JSC personnel.

The general objectives of Solar Power Satellite (SPS) studies include:

1. Establishment of realistic technical and economic design criteria and requirements for a full-scale SPS.
2. Definition of technology development and flight-test programs necessary to achieve the optimum SPS design.
3. Comparison of the SPS with other energy generation options to establish the relative economic, environmental, and social advantages/disadvantages of the SPS concept.

These objectives are quite broad and definitive answers will require a number of years of study augmented by technology efforts in a number of areas. Nevertheless, the present study provides further insight into a number of aspects of the concept and provides a point of departure for further work. This summary (Vol. I) presents a number of preliminary conclusions and a synopsis of the more detailed studies that are presented in Volume II.

Certain programmatic guidelines were chosen to initiate the study and bound the study effort.

1. Program plans and technology projections will be developed based on deployment of the first operational SPS as early as 1990.
2. The capability will be provided as early as 1995 to deploy two to four SPS's per year.
3. Dedicated transportation systems will be developed and optimized specifically for use in deploying and operating the SPS network.
4. Materials used in fabricating and operating an SPS will be obtained only from the Earth.
5. The SPS will be deployed in appropriate geosynchronous orbits only.
6. The lifetime of an SPS will nominally be 30 years, although liberal refurbishment/replacement of parts may be assumed.
7. The SPS will be designed in a manner to optimize participation of man in its fabrication, assembly, and operation.
8. Availability of scarce resources will be a major consideration in projecting technologies to be used in fabricating the SPS network.
9. Energy as well as economic payback will be assessed in determining the SPS development strategy.
10. Aspects of social and environmental impact will be assessed.
11. Assembly fabrication strategies for SPS will be developed such as to minimize overall costs.

The first two guidelines were modified slightly as the study progressed in that various scenarios were defined and evaluated.

Available resources defined the scope and depth of the study. For example, the study was primarily limited to consideration of the photovoltaic concept for solar energy collection and conversion, although a rather thorough review of past system studies involving the use of the thermal energy conversion concept was accomplished (Vol. II). Similarly, the more detailed design studies were limited to consideration of silicon solar cells. Given these restrictions, a range of power station sizes and weights was determined based on conservative and optimistic estimates of collection, conversion, transmission, and receiving efficiencies.

Analyses and/or design studies were conducted for each element of the systems to varying degrees. These studies included several satellite configurations, construction concepts, crew requirements, alternate microwave generator concepts, rotary joint designs, attitude and control concepts, and structural designs.

Several program scenarios were developed that defined the number and schedule of space power satellites required to provide varying percentages of the Nation's energy needs in the 1995-2025 period.

Satellite weights were then coupled with the number and schedules of satellites required to define a range of transportation requirements. These requirements were used to guide the study of various transportation elements and to estimate integrated transportation requirements such as fleet size. Transportation elements for which specific studies were conducted included multistage winged and ballistic heavy lift launch vehicles, a variety of orbital transfer vehicle thrusters, and personnel launch and transfer vehicle designs.

In a similar manner, the satellite and transportation system characteristics, number, and schedule were used as a basis to estimate the cost of design, development, test, and evaluation (DDT&E), total program, and mills per kilowatt hour. Preliminary estimates are also provided of natural resource requirements and pollutants emitted from processing and launch operations. Estimates of energy payback are also presented.

Figure I-1 presents the task structure that was used in the study effort. The present report (Vol. I) and Volume II are also organized according to this task structure.

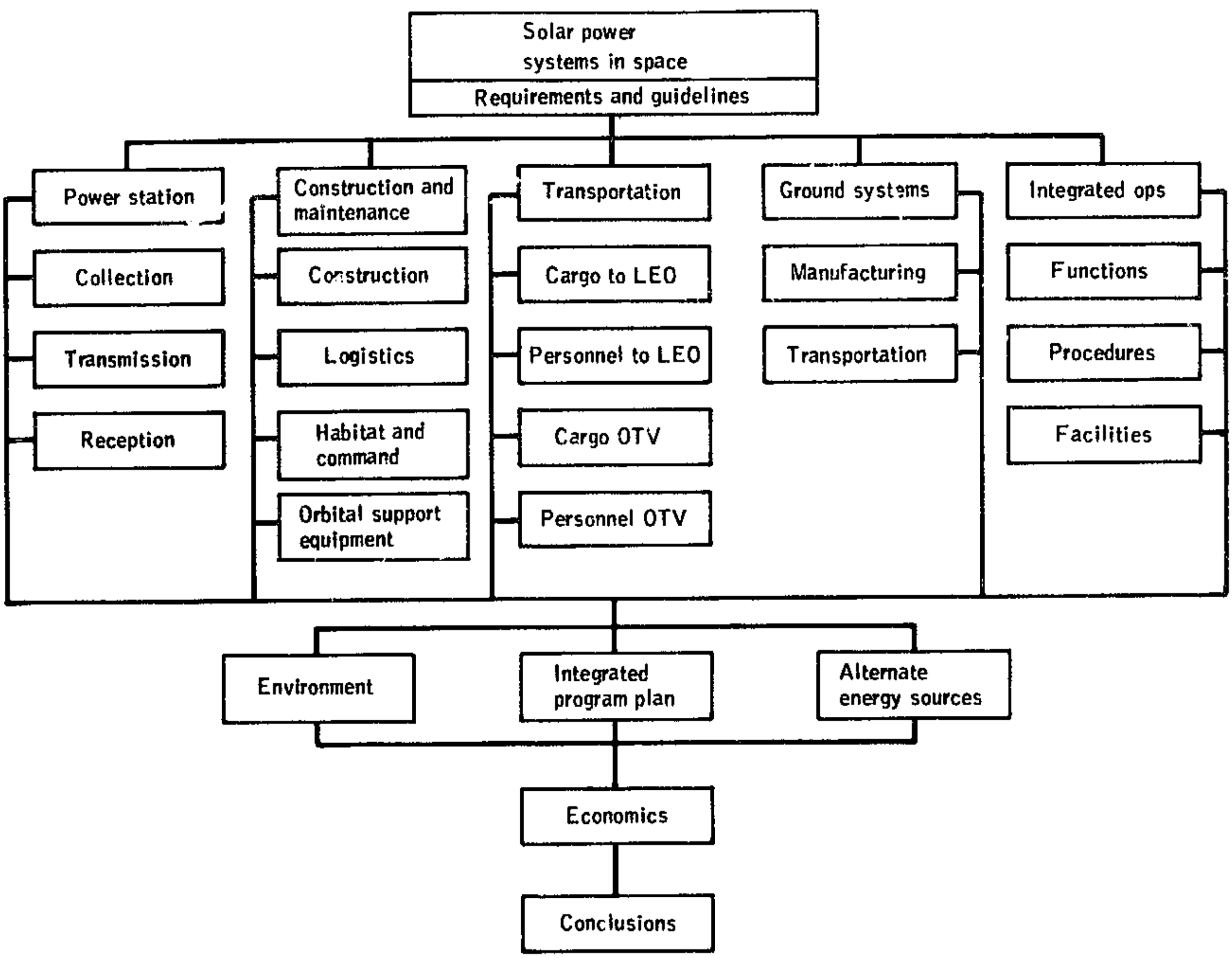


Figure I-1.- Study task structure.

II. CONCLUSIONS

The scope and complexity of the satellite power concept coupled with the limited depth of the present study would make it inappropriate to draw absolute conclusions. However, the SPS concept appears to be technically feasible in that no design or operational problems were encountered that did not appear amenable to solution. The economic viability of the system appears promising but is obviously dependent upon a combination of technology advancement and/or the costs of competitive sources.

Within the limitations of the study and based on a variety of assumptions and/or estimates, the following preliminary conclusions are presented.

1. The maximum power output of an individual microwave transmission link to Earth is about 5 GW and the transmitting antenna diameter is about 1 km, based on the following assumptions:

   a. An operating frequency of 2.45 GHz
   b. A maximum allowable power density at the ionosphere of 23 mW/cm^2
   c. A maximum allowable antenna waveguide temperature of 485 K resulting in a power density at the antenna of 21 kW/m^2
   d. A 10-dB Gaussian taper of the microwave beam

2. The estimated mass of a 10-GW SPS (incorporating solar energy converters sufficient for two 5-GW microwave power transmission systems) is between 47×10^6 and 124×10^6 kg, based on the following assumptions:

   a. Silicon cell arrays with an efficiency of 15 to 17 percent at 30° C and a concentration ratio of 2
   b. An overall system conversion and transmission efficiency range of 4.2 to 8.0 percent
   c. A weight growth of 50 percent over present estimates

The resulting solar array areas ranged from 96 to 183 km^2.

3. The silicon solar cell arrays make up well over half the weight and cost of the satellite. Consequently, additional effort on solar arrays offers the most potential for overall system improvement, particularly with respect to new approaches that could result in significant weight reduction.

4. Considerations of the structure indicated that minimum weight can be achieved if design loads are limited to those encountered on orbit and after construction. If this is done, the structure can be held to a very small percentage (~5 percent) of the SPS weight. The major factor in design will not be weight but the development of techniques for automated on-orbit construction and for conducting large electrical currents.

5. Development of automated construction techniques is complex and requires a great deal of further effort. A preliminary task evaluation based on a conceptual construction technique suggests that as many as 600 personnel may be required in space to construct an SPS in 1 year, with minor variations expected in personnel required due to configuration and construction location. Placing and supporting these personnel in orbit is a relatively small factor in the overall transportation requirement.

6. Past studies have indicated an apparent performance advantage of constructing, assembling, or deploying all or a portion of the solar arrays in low-Earth orbit and then utilizing solar energy with electric thrusters to propel the system or major elements thereof to geosynchronous orbit. The conclusion of the present study is that this area needs further study with full consideration given to the following factors:

a. Degradation of the exposed solar arrays during transit
b. Protection of unused arrays during transit
c. Earth shadowing during portions of transit possibly requiring nonsolar propulsion
d. Docking and assembly of large SPS sections at geosynchronous orbit and resulting impact on structural design
e. Relative simplicity of chemical stages for transfer of "containerized" packages to geosynchronous orbit
f. Radiation conditions at geosynchronous orbit

7. The SPS in equatorial orbit will be eclipsed both by the Earth and by other satellites. These eclipses result in as many as three brief (up to 75 min) power outages per day for two 6-week periods per year, although less than 1 percent of the available energy is lost. The SPS/grid system must be designed to accommodate these outages.

8. Conceptual designs and characteristics were developed for two-stage winged and ballistic heavy lift launch vehicles of varying payload capability. Although the ballistic systems are much smaller and lighter, recovery and reusability will be key issues in establishing the desired configuration.

9. Heavy lift launch vehicle design considerations established hydrocarbon fuel rather than hydrogen as the choice for first-stage propellant because of its greater energy density.

10. Considerations of I_{sp} and confidence in technical development of candidate electric engines indicate that the MPD arcjet engine appears to be the best choice for self-powered orbital tranfer. These engines are also suitable for subsequent use as thrusters for the SPS attitude control system.

11. The high launch rates required indicate that launch window and related operational considerations may become significant factors. Launch latitudes near the Equator greatly expand the launch window and offer performance advantages.

12. Based on varying assumptions as to performance, construction, location, orbital transfer modes, and reusability, achievable transportation costs to geosynchronous orbit are estimated to range from $75 to $300/kg. The major contributor to the total transportation costs for a given program was the cost of transporting the necessary material to low-Earth orbit.

13. The cost of producing electricity from solar power satellites as described herein is estimated to be in the range of 29 to 115 mills/kWh. This range of estimates is based on the following assumptions:

a. An implementation of 112 10-GW satellites over a 30-year period
b. A range of satellite weights and transportation costs as indicated earlier
c. A design, development, test, and evaluation (DDT&E) cost amortized over the 30-year implementation period
d. A space hardware repair/replacement rate of 1 percent annually
e. A plant factor of 92 percent allowing for eclipses and maintenance time
f. A return on capital investment of 15 percent

14. The cost of producing electricity with conventional (nuclear and fossil) plants is predicted to be in the range of 15 to 30 mills/kWh in the 1995 time period, depending upon the cost, fuel, and type of powerplant. The cost of producing electricity with potential ground-based powerplant concepts (ground solar, geothermal, wind) is estimated to be from 28 to 121 mills/kWh.

15. The introduction of SPS in lieu of meeting an equivalent portion of the Nation's energy needs with new nuclear and coal-burning electrical powerplants will result in significant reduction in emissions (particulates, NO_x, SO_x, and nuclear waste).

16. The microwave power density at the edge of the rectenna (1 mW/cm^2) is about one-tenth of the present U.S. standard for human exposure. The system is fail-safe in that the beam would be dispersed to harmless intensity levels should the microwave beam pointing control fail.

17. Implementation of SPS on a large scale would create an increased demand for resources such as aluminum and rocket propellant gases (hydrogen and argon). Also, production capacity would have to be substantially increased in the areas of solar cells and reduction of arsenic from oxides (for the manufacture of gallium arsenide diodes). However, there does not appear to be any critical shortages of resources for SPS construction based on world reserves.

III. PROGRAM REQUIREMENTS

A. Projected Energy Demand

Projections of the Nation's electrical energy demand have been made by the Federal Power Commission (FPC), the Energy Research and Development Administration (ERDA), and other Federal agencies and private organizations. Figure III-1 shows the FPC and ERDA projections for electrical energy demand through 1990 and 2000, respectively. The FPC projection was presented in the 1970 Federal Power Survey report, Volume I. The ERDA projection (presented in ERDA-48, Volume 1, June 1975) involves six different scenarios that are encompassed by the shaded area of figure III-1. The highest electricity generation scenario is based on intensive electrification and it has a 4.4 percent/yr growth rate in the year 2000. The lowest electricity generation scenario is based on improved efficiencies in end use and it has a 1.4 percent/yr growth rate in the year 2000. The FPC projection, which is higher than any of the ERDA projections, has an annual growth rate of 6.0 percent/yr in 1990. The FPC projection has been extrapolated to the year 2025 at the 6.0-percent growth rate in order to provide a reference for the development of solar power system implementation scenarios.

B. Implementation Scenarios

Effective use of space solar power implies an implementation program that will produce a significant portion of the future electrical program demand. Therefore, scenarios of SPS implementation rates were developed that would provide 25 percent of the new capacity by 2015 (scenario A), 50 percent of the new capacity by 2010 (scenario B), and all of the new capacity by 2005 (scenario C), in relation to the extrapolated FPC projection. Scenario B was used as an illustrative example by which to examine the SPS in terms of its program requirements and resulting economic analysis. This scenario results in providing a significant quantity of the total electrical energy by 2025. The SPS installed capacity by 2025 would be 1120 GW or about 30 percent of the FPC extrapolated projection. If the power output of each SPS is 10 GW (as described in sec. IV), implementation of Scenario B results in a total of 112 satellites in orbit by 2025. The construction rate varies from one per year initially (1995) to seven per year during the last 3 years of the 30-year period.

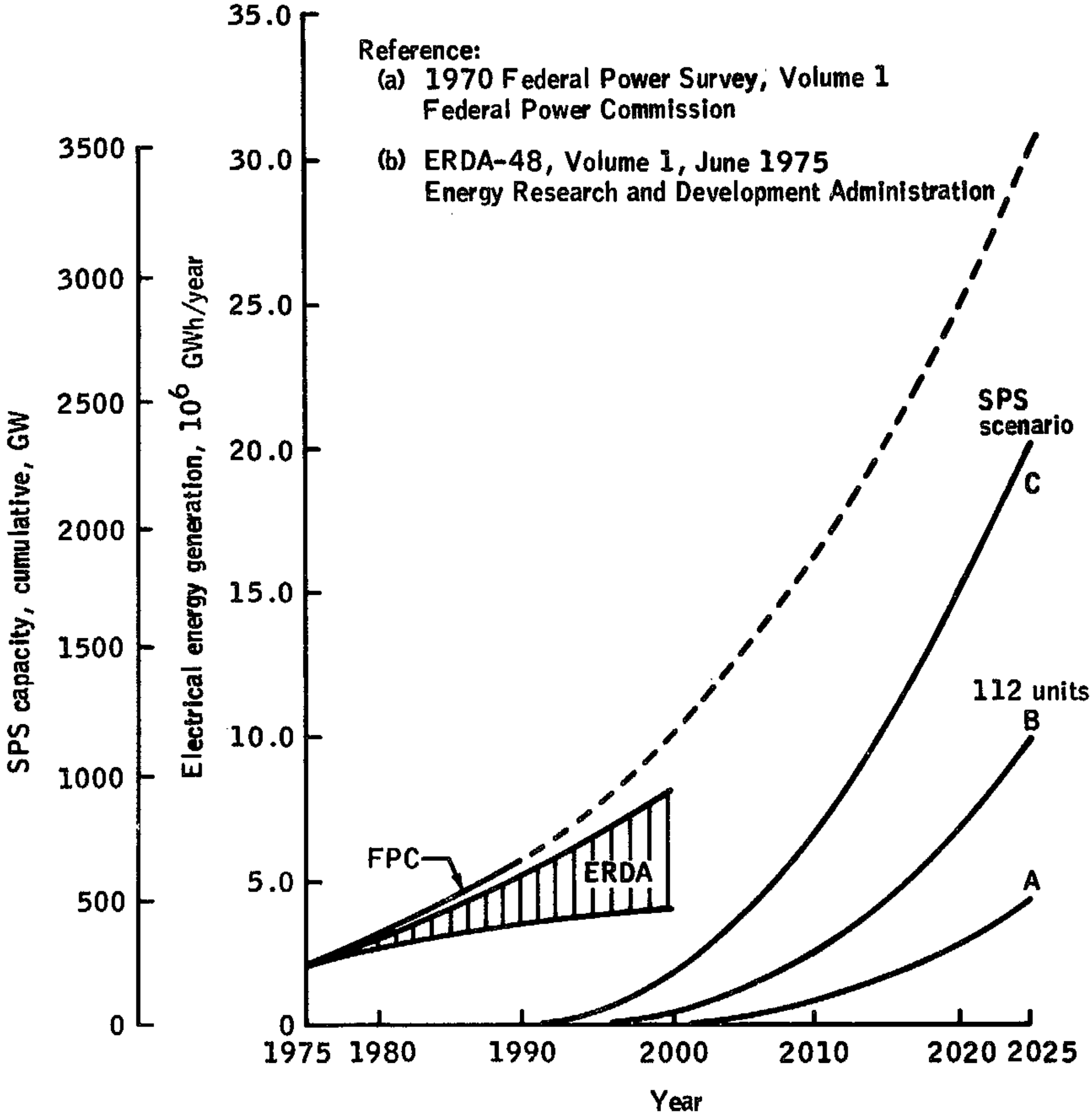


Figure III-1.- Projections of U.S. electrical energy requirements and possible SPS implementation scenarios.

IV. POWER STATION

The power station of the SPS consists of a Solar Energy Collection System (SECS), which converts solar energy into electricity; a Microwave Power Transmission System (MPTS), which converts the electricity into microwave energy and transmits it to Earth; and a Microwave Reception and Conversion System (MRCS), which converts the microwave energy into electricity suitable for interface with a distribution grid. These elements of the power station are depicted in figure IV-1.

The purpose of this part of the study was to explore the factors involved in the design of the power station. This involved evaluating the power output of individual satellites, methods and efficiencies of energy conversion and transmission, requirements and design approaches to system elements, weights of equipment and material in orbit, and the orbital characteristics of the satellites.

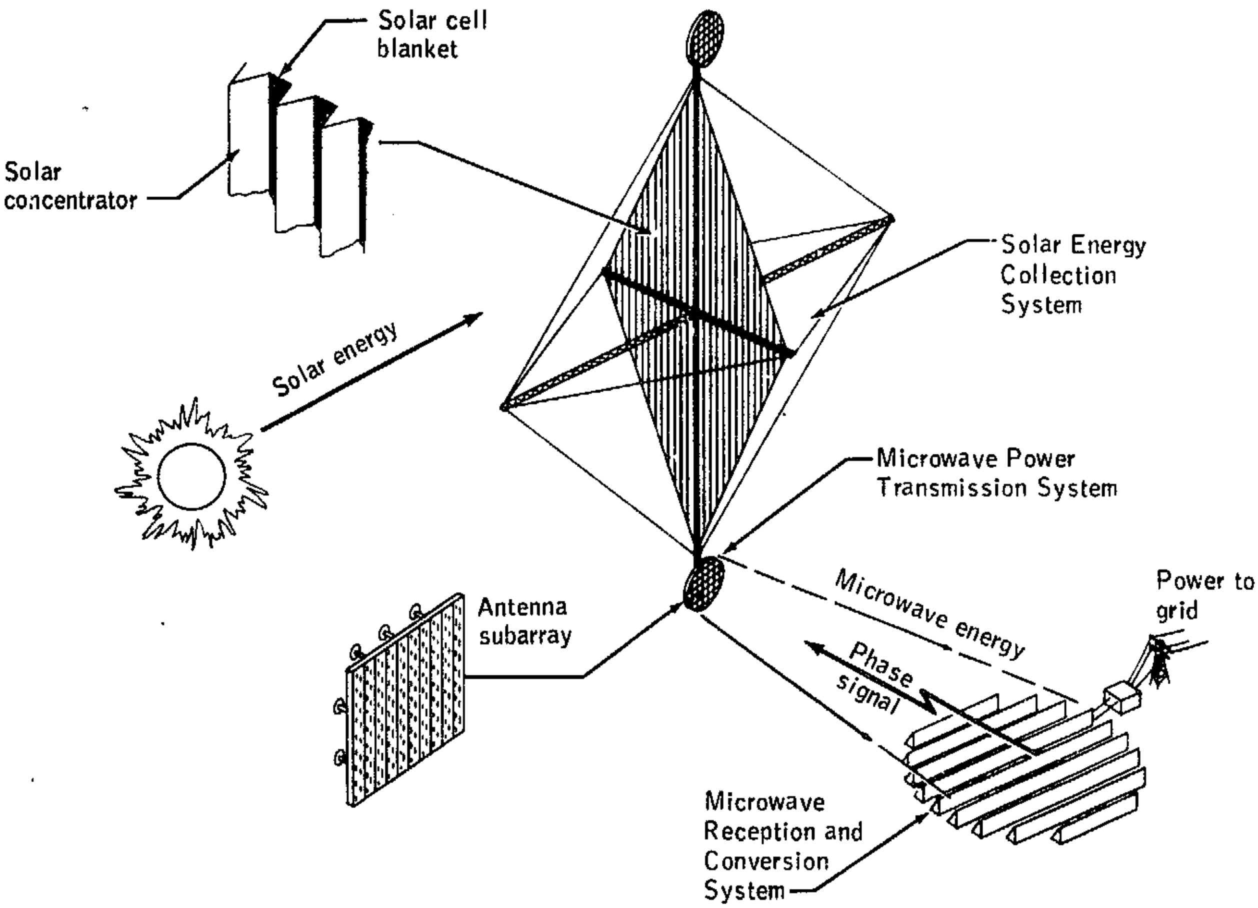


Figure IV-1.- SPS functional description.

Several configuration approaches were considered and two typical examples were studied in some detail for the purpose of defining ranges of weight, cost, and construction approaches. These two examples are referred to as the "column/cable" and "truss" configurations.

A. System Analysis

1. Efficiencies

The energy collection, conversion, and transmission process involves a number of steps, each having an associated efficiency. An initial task of the study was to estimate these efficiencies. Three estimates were made of the efficiency of each step, including a minimum efficiency that could be achieved with virtual certainty, a probably achievable (nominal) efficiency, and the best, or maximum, efficiency that might be achieved. These estimates are presented in figure IV-2. The estimated overall efficiencies from incident sunlight to dc output were 4.2, 5.4, and 8 percent for the "minimum," "probable," and "maximum" cases, respectively. The estimated efficiencies of the system excluding photovoltaic conversion of sunlight to electrical energy were 41, 52, and 69 percent, respectively. These estimated efficiencies were used for collector sizing and weight estimates. Revised efficiency estimates indicated that the "probable" achievable (nominal) efficiency was more appropriately 58 percent than 52 percent. The efficiencies of the various steps resulting in this revised "probable" estimate are also presented in figure IV-2.

2. MPTS/MRCS Analysis

An analysis was conducted to determine the appropriate size of the power station, defined in terms of the dc output power at the rectenna and the overall microwave system(s) parameters.

Two specific constraints were identified that would limit the maximum power output. These constraints were maximum allowable power densities of 21 kW/m^2 at the transmitting antenna and 23 mW/cm^2 at the ionosphere. The former is the result of the thermal limitations of the aluminum waveguides. The latter is the result of a theoretical analysis (ref. Meltz) which indicates that nonlinear interactions between the beam and the ionosphere will not exist below this level.

Given a system frequency (2.45 GHz) and the estimated efficiencies of steps in the transmission process, the two aforementioned constraints can be related to dc output power and transmitting antenna diameter. These relationships are illustrated in figure IV-3. It can be seen from the figure that the maximum power output that does not exceed the constraints is 5 GW, achieved with a transmitting antenna diameter of 1 km. Accordingly, a 5-GW dc output power at the rectenna and a 1-km antenna diameter have been used as nominal, or reference, values throughout the study.

Parameters	Efficiencies, percent			
	Minimum	Nominal		Maximum
		Original	Revised	
Photovoltaic conversion (from solar energy)				
At 30° C	15	15	15	17
At 100° C	10.3	10.3	10.3	11.6
SECS power distribution	85	92	92	93
Antenna power distribution	94	96	98	97
dc-rf conversion	85	87	87	94
Phase control	(a)	(a)	(a)	(a)
Waveguides (I^2R)	99	99	98	99
Mechanical alinement	97	98	98	99
Atmosphere	92	96	98	98
Energy collection	81	86	88	91
rf-dc conversion	85	87	90	94
Power interface (output power to grid)	99	99	99	99
Overall efficiency	4.2	5.4	6.0	8.0
Efficiency excluding photovoltaic conversion	41	52	58	69

[a]Combined with energy collection.

Figure IV-2.- Estimated efficiencies of the various steps in the collection, conversion, and transmission process.

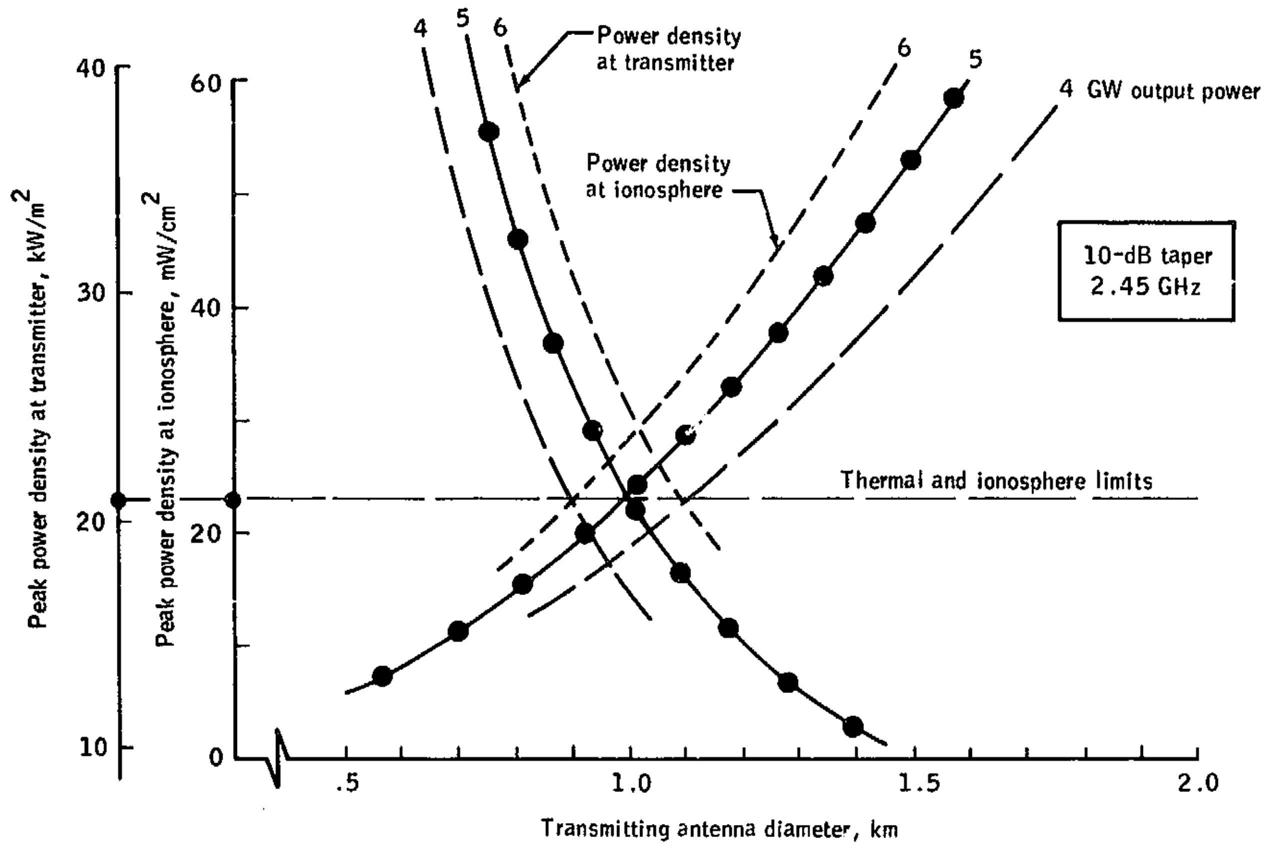


Figure IV-3.- Output power limits.

A microwave frequency of 2.45 GHz was selected for study purposes. This frequency is at the center of a 100-MHz band reserved for industrial, scientific, and medical use, so that interference with communications will be minimized. Atmospheric attenuation is also low at this frequency. A higher frequency, such as 3 GHz, offers higher gain for the same antenna diameter and should be considered, but would cause substantial interference with present users of this band.

The mainbeam pattern and sidelobe characteristics of the antenna will vary with the power density taper over the antenna. Increasing the amount of taper produces a lower boresight density, a wider mainlobe, and lower sidelobes. For a given rectenna radius, the collection efficiency increases with the amount of taper. A 10-dB taper has been adopted for this study. For a no-error/no-failure condition, this gives a 90-percent collection efficiency at a rectenna radius of 4300 m. An ideal continuous taper would be too complex to be practical and was replaced in this study by a 10-step approximation that gives virtually the same performance.

The transmitting antenna consists of a number of subarrays, each of which is phase controlled as a unit. Increasing the size of individual subarrays reduces the number of receivers and phasing electronics required, and therefore the cost of the phasing control system. Decreasing the size of the subarrays reduces thermal distortion and the probable need for active positioning to compensate for misalinement. Subarray sizes of 4, 10, and 18 m (square) were studied. The 10-m size was selected as a reference, because it required less phase-control equipment than the 4-m size while not needing the active mechanical alinement of the 18-m size.

A summary of the microwave system(s) parameters is presented in table IV-1. These parameters were utilized in the calculation of the power density distribution across the rectenna, which is presented in figure IV-4.

Power densities of 23 mW/cm^2 and 1 mW/cm^2 exist at the center and edge (5 km) of the rectenna, respectively. The latter density corresponds to one-tenth of the current U.S. standard for allowable human exposure to microwave radiation.

3. Orbit Considerations

There are three orbit perturbations of importance. The Earth's equatorial ellipticity, solar and lunar gravity gradients, and solar radiation pressure result in satellite movement that must be assessed and possibly counteracted.

The equatorial ellipticity causes a drift in longitude centered about either longitude 120° W or 60° E. Such a drift is unacceptable in view of an expected large number of satellites in this orbit and the need to maintain a proper relationship between the satellite and the receiving antenna. The velocity increment required to counteract this drift, however, is less than 1 m/s/yr.

Solar and lunar gravity gradients cause an initial inclination of zero to grow to about 15° in 27 years. Nonzero inclinations require larger rectennas (approximately 10 to 30 percent for 7.3° inclination). Zero inclination can be maintained with a velocity increment of 46 m/s/yr; this appears to be a reasonable price.

Solar radiation pressure produces an eccentricity in the orbit. To maintain the eccentricity at zero requires a velocity increment of a few hundred m/s/yr. The problems associated with a slightly eccentric orbit, primarily a moderate departure from constant velocity antenna rotation and a small (on the order of ± 1 percent) variation in rectenna output, do not appear to warrant the expenditure.

TABLE IV-1.- A SUMMARY OF MICROWAVE SYSTEM(S) PARAMETERS

Parameter	Remarks
Output dc power at rectenna	5 GW
Transmitting antenna diameter	1 km
Array aperture illumination	10-step, truncated Gaussian amplitude distribution with a 10-dB edge taper
Subarray size	100 m^2 (approximately 10 m by 10 m)
Number of subarrays	7850
Error budget	
Total rms phase error for each subarray for the phase control system	10°
Amplitude tolerance across subarray	± 1 dB
Inoperative microwave generators (random distribution)	2 percent
Phase control	Active, retrodirective array with phasing system using transmission lines combined with a subarray-to-subarray phase transfer scheme
Antenna radiators	Slotted waveguides
dc power distribution system, lateral configuration	40 kV
Antenna mechanical alinement requirements for a 2-percent loss in effective antenna gain	± 3 arc-minutes
Rectenna dimensions at 40° latitude	10 km by 14 km
Rectenna collection efficiency using the specified error budget	88 percent
Power density at center of rectenna	23 mW/cm^2
Power density at edge of rectenna	1.0 mW/cm^2
Nominal microwave system efficiency from dc output at rotary joint to collected dc output of rectenna	63 percent

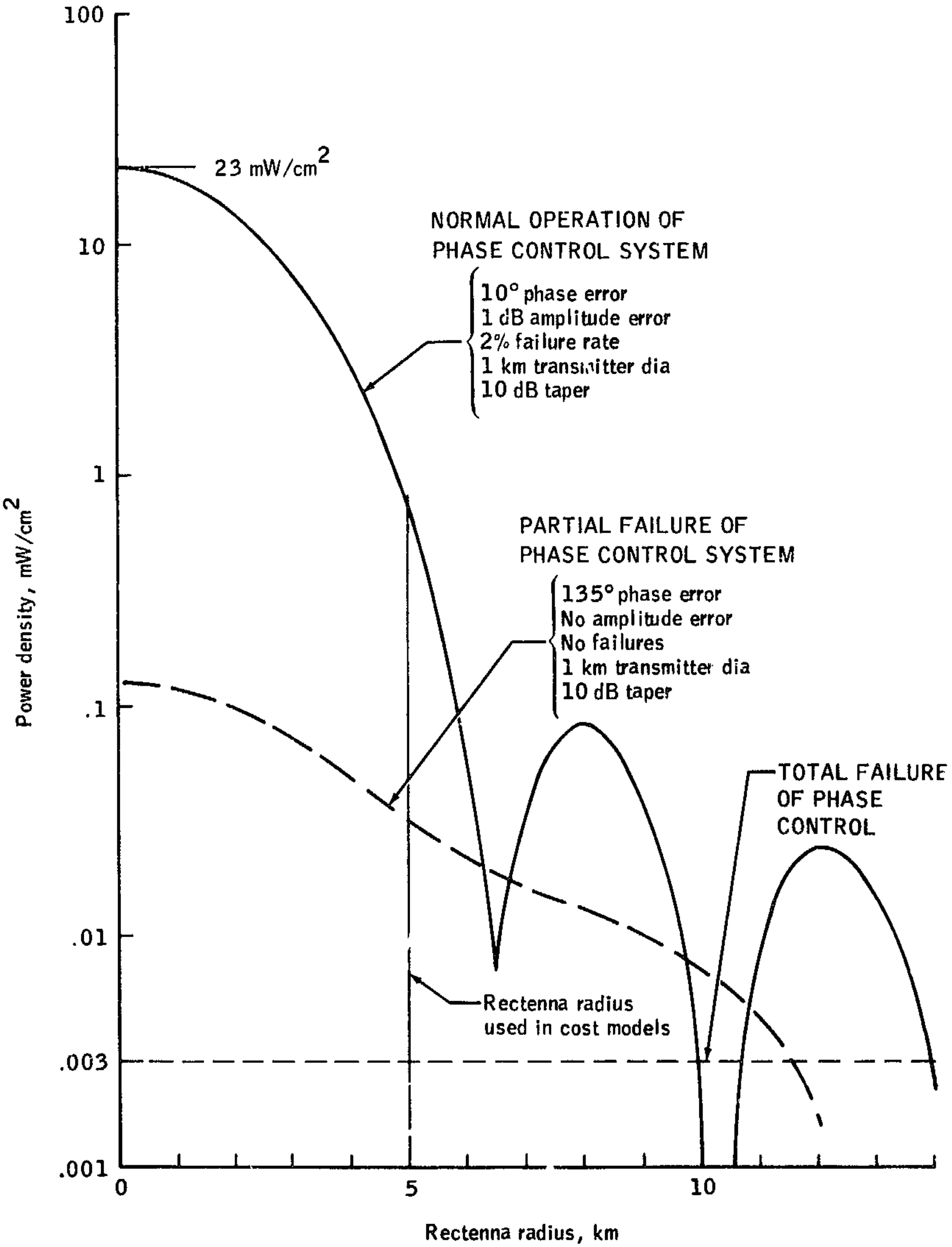


Figure IV-4.- Power density at rectenna.

The SPS, in synchronous equatorial orbit, will be eclipsed by the Earth daily for about 43 days at the spring equinox and 44 days at the fall equinox (fig. IV-5). The maximum duration is about 75 minutes. The eclipse is total and occurs at about local midnight. Because the maximum dimension of a typical SPS is 6 to 7 percent of the width of the penumbra, the illumination gradient is slight. Total power loss is slightly less than 1 percent of total annual output.

The close spacing (about 0.5° of longitude) that results from a large number of satellites (112 located to serve the United States) will cause the satellites to eclipse each other twice a day, at about 6 a.m. and 6 p.m., for about 2 weeks, at the equinoxes. This eclipse is shorter and is not total, but will cause almost complete microwave power loss for as long as 15 minutes. The penumbra is much narrower than the satellite dimensions, so that illumination gradients are steep. Differential thermal expansion must therefore be accounted for in the system design.

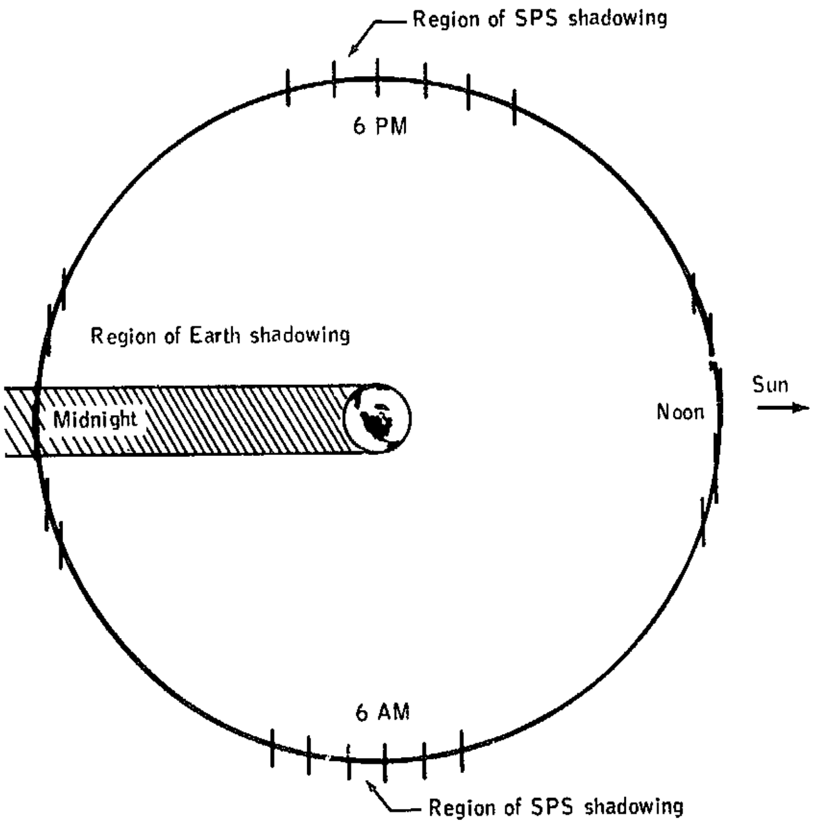


Figure IV-5.- Eclipse geometry.

Power loss is less than 0.1 percent of annual output; however, these eclipse conditions must be considered in integrating satellite-generated power with surface systems.

4. Configurations

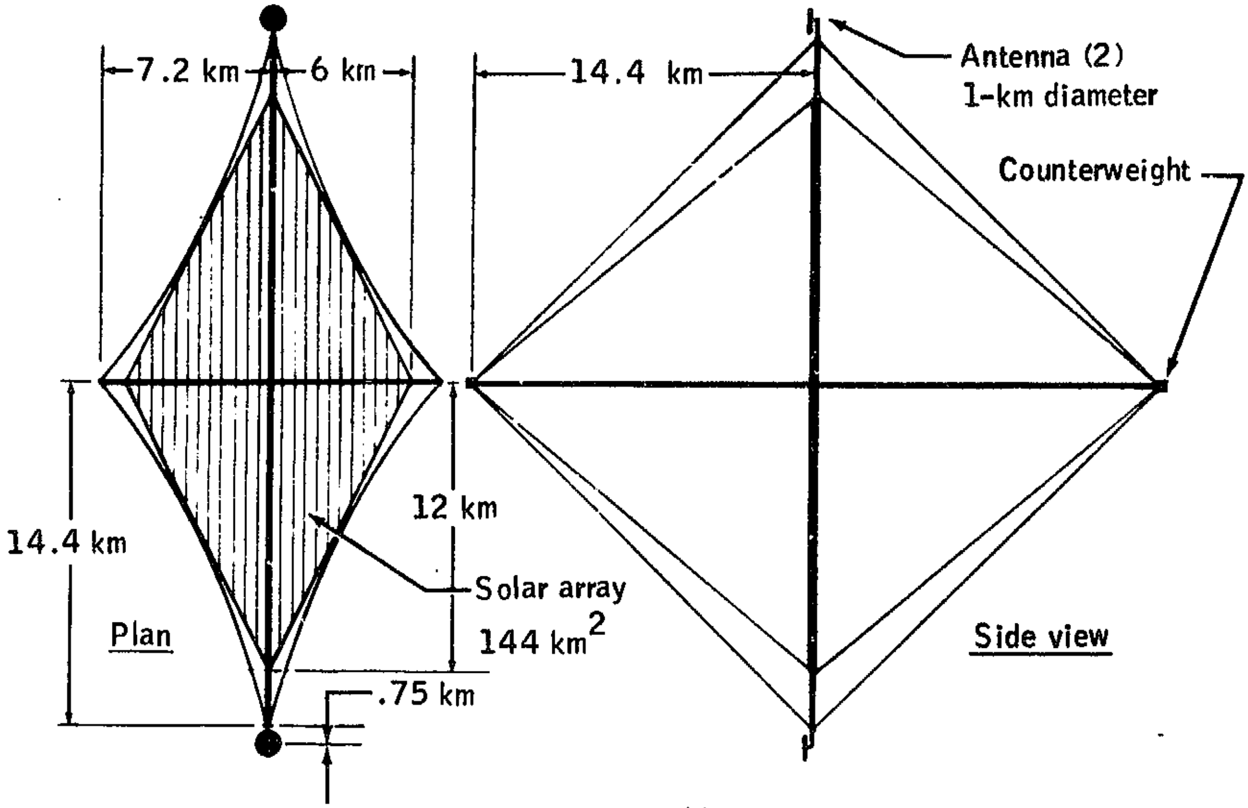
In an attempt to minimize structural weights, the concept illustrated in figure IV-6(a) (column/cable) was developed utilizing compression columns and supporting cables (see "SECS Structure," sec. IV-B-3). With this configuration, the transmitting antenna has to be mounted on the north or south end of the solar array to be able to view the Earth continuously. However, microwave recoil from the antenna (about 5 lb) causes a constant disturbing torque, and the offset in the center of mass also produces a solar radiation pressure torque. To eliminate these disturbances, the solar array area was doubled and an antenna was mounted on each end. The resulting configuration is essentially two 5-GW satellites sharing a commmon structure. For a given total power requirement, this approach has an additional advantage in that the number of satellites is halved and consequently the distance between satellites doubled. This simplifies traffic control and maintenance and reduces the impact of eclipse by other satellites.

This configurational approach did result in a very low structural weight, as will be seen in the subsequent presentation of mass properties; however, it should also be noted that the SECS structural weight is not a large percentage of the satellite total weight, ranging from 1 percent (minimum, column/cable) to 6 percent (maximum, truss) for the cases considered. The column/cable configuration has the potential disadvantage of being incompatible with a mission mode that involves construction of the satellite, or modules thereof, at low-Earth orbit, which then provides solar energy to propel the satellite to geosynchronous orbit.

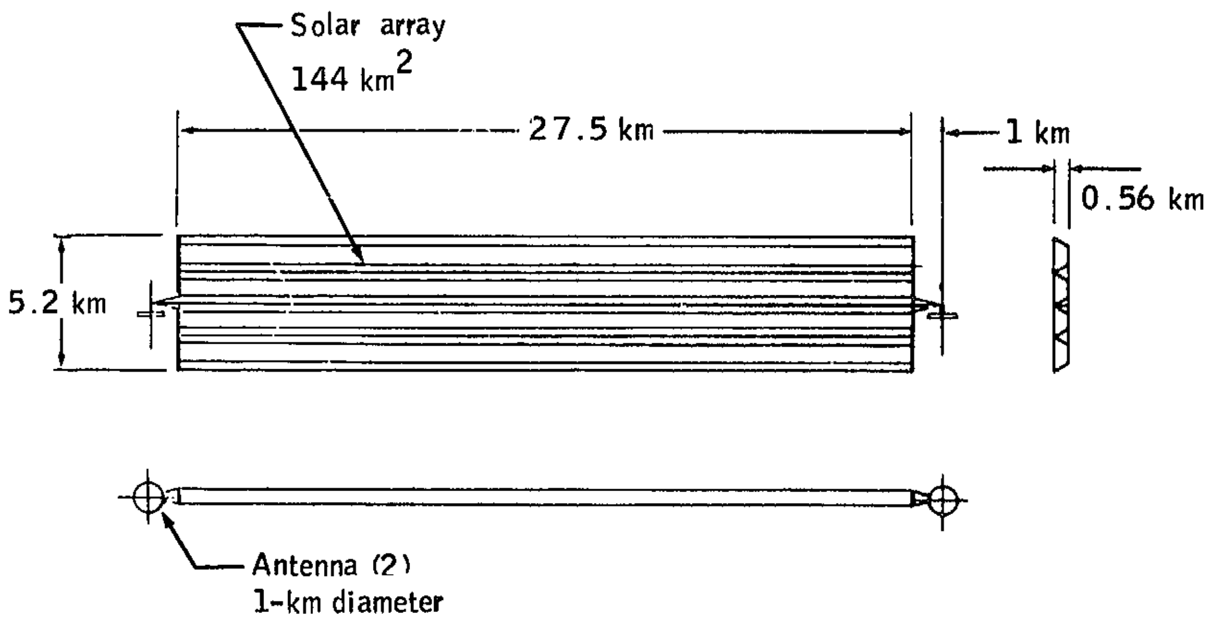
A second configuration was also considered in some depth (fig. IV-6(b)). It is referred to as the "truss" configuration. Like the column/cable, it has two 5-GW antennas and a "double-size" solar array, although a single 5-GW system with central antenna is also possible. It is built up as a three-dimensional truss and may be easier to construct in geosynchronous orbit than the column/cable configuration. It can also be built in modules at low-Earth orbit.

Several other configurations were considered briefly; they were adaptations of the two concepts described previously and did not appear to offer any overriding advantages.

The sizes of the configurations as presented in figure IV-6 are related to "probable," or nominal, efficiencies of conversion and transmission as discussed in section IV-A-1. The relationship between efficiency, array size, and mass will be presented in the next section.



(a) Column/cable.



(b) Truss.

Figure IV-6.- Example configurations.

5. Mass Properties

To determine the range of weights of the satellite, the following process was used. The three estimates of system efficiencies presented in figure IV-2 were used to define the solar array area necessary to provide 10-GW power output to two rectennas (5 GW each) for each estimate. The resulting areas were as follows.

Overall efficiency, percent	Array size[a], km^2
4.2 - minimum	183
5.4 - nominal	144
8.0 - maximum	96

[a]Increased 4.3 percent to compensate for solar angle-of-incidence losses (see sec. IV-B-IV).

For each subelement of the satellite, a "minimum," "nominal," and "maximum" unit weight was estimated. In this case, the minimum and maximum terms have the inverse meaning of that applied to the efficiency estimates. For example, the minimum weight is the best that might be achieved, whereas the maximum can be achieved with virtual certainty. Table IV-2 summarizes the minimum, nominal, and maximum unit weight estimates for the various subelements of the satellite.

If the three subelement estimates are applied to each of the three array sizes and the two different configurations, a total of 18 (3 by 3 by 2) weight estimates are obtained. The resulting range, or envelope, of weights is presented in figure IV-7. The satellite mass is seen to be in a range between 47 000 and 124 000 metric tons. Note that this weight is associated with a satellite that provides 10 GW of power to two rectennas via two 1-km transmitting antennas.

A satellite weight breakdown for 6 of the 18 estimates is presented in table IV-3. The six estimates presented are identified by symbols in figure IV-7. The breakdowns indicate the significance of the solar cell blankets to the total weight, approaching 50 percent in all cases. The SECS structure, on the other hand, is not a major contribution to the total, varying from 1 to 6 percent of the total for cases presented. The microwave generators contribute approximately 15 percent of the total weight. Note that the klystron was assumed for all estimates. Experience has shown that the total mass invariably grows during the course of any aerospace program, the amount depending on the degree of technology advancement involved. Fifty percent growth from the initial concept weight can reasonably be expected for a program of this nature. Accordingly, the totals obtained by summing the estimates of subelements have been increased by 50 percent. This weight growth has been included in the weights presented in figure IV-7.

TABLE IV-2.- SUMMARY OF UNIT MASSES

Component	Unit masses[a]			Remarks
	Minimum	Nominal	Maximum	
Solar energy collection system				
Primary structure (column/cable)	Nom.-10 percent	3.08 kg/m	Nom.+20 percent	x total column length
Primary structure (truss)	Nom.-10 percent	2764	Nom.+20 percent	Proportional to solar array area
Secondary structure	Nom.-10 percent	209	Nom.+20 percent	Proportional to solar array area
Mechanical systems	30	40	50	
Maintenance station	70	85	100	1000 m^3 enclosed volume
Control	150 (dry)	200 (dry)	300 (dry)	Dry mass plus 1 year of propellant
Instrumentation/communications	3	4	5	
Solar cell blankets	.31 kg/m^2	.40 kg/m^2	.46 kg/m^2	x solar cell blanket area
Solar concentrators	Nom.	.04 kg/m^2	Nom.	x concentrator area
Power distribution (column/cable)	Full use of solar concentrators	3886	No use of solar concentrators	Proportional to $(area)^{3/2}$
Power distribution (truss)		3000		
Microwave power transmission system				
Primary structure	Nom.-10 percent	392	Nom.+20 percent	
Secondary structure	Nom.-10 percent	518	Nom.+20 percent	
Subarray structure	Nom.-10 percent	300	Nom.+20 percent	
Thermal control	Nom.-10 percent	23	Nom.+10 percent	
Mechanical systems	Nom.-10 percent	30	Nom.+20 percent	
Rotary joints	363	635	907	
Pointing control	Nom.-20 percent	100	Nom.+30 percent	
Power distribution	Nom.-20 percent	167	Nom.+100 percent	Proportional to power at rotary joint
Phase control	Nom.-20 percent	358	Nom.+20 percent	
Microwave generators	Nom.-20 percent	8846	Nom.+20 percent	Proportional to power at generators
Waveguides	Nom.-20 percent	4002	Nom.+20 percent	

[a] Quantities represent total mass of component (for reference solar array area) in metric tons unless otherwise noted.

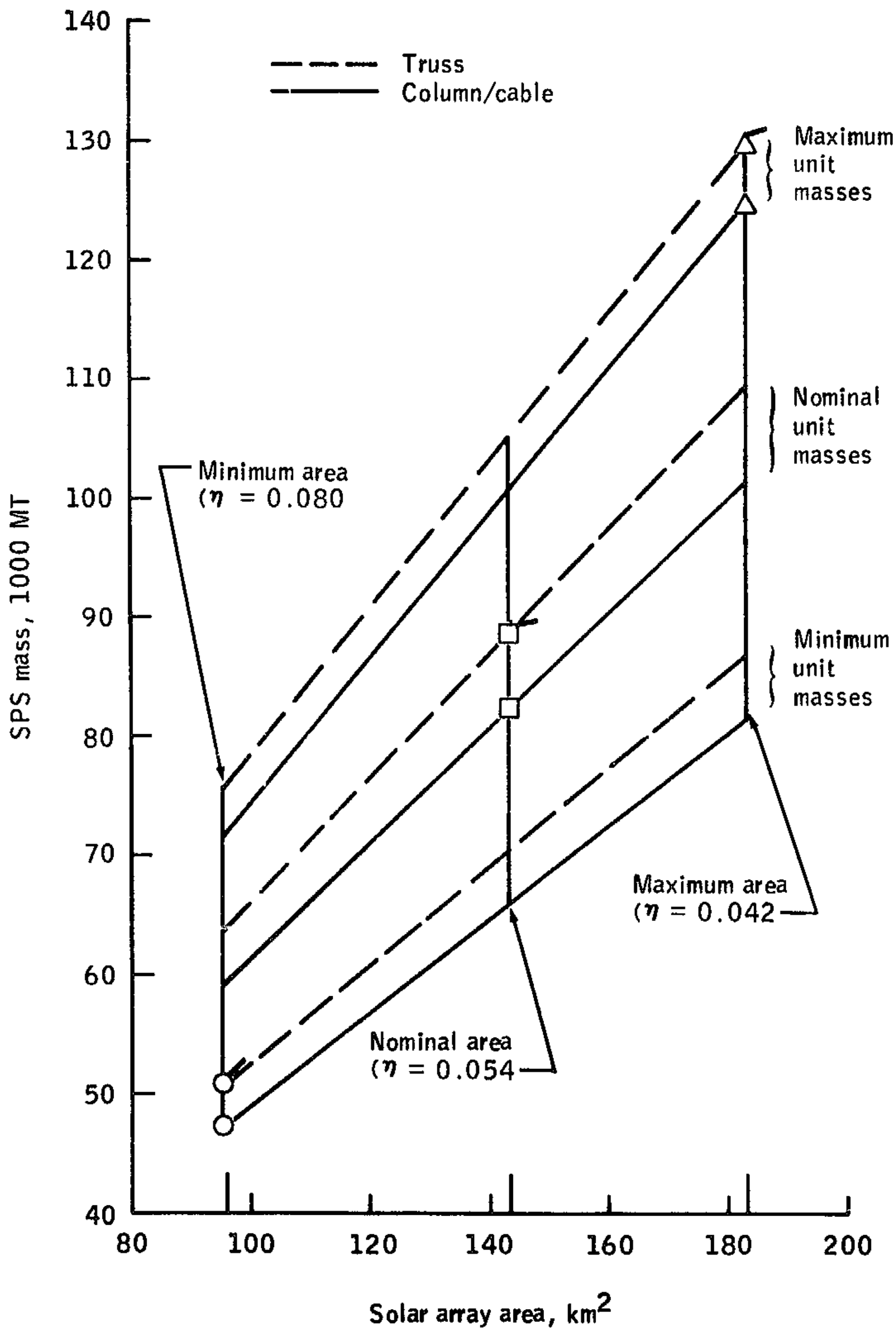


Figure IV-7.- Solar power satellite total mass.

TABLE IV-3.- MASS PROPERTIES SUMMARY

Component	Mass properties, metric tons					
	Column/Cable[a]			Truss[a]		
	○ Minimum	□ Nominal	△ Maximum	○ Minimum	□ Nominal	△ Maximum
Solar energy collection system	(20914)	(39171)	(62434)	(21443)	(40869)	(60936)
Solar cell blankets	14893	28677	42062	14893	28677	42062
Solar concentrators	3843	5735	7315	3843	5735	7315
Structure	290	431	621	1793	2973	4550
Power distribution	1568	3886	11802	575	3000	6327
Other systems	320	442	634	339	484	682
Microwave power transmission system	(10625)	(15371)	(20424)	(10625)	(15371)	(20427)
Microwave generators	5455	8846	12251	5455	8846	12251
Waveguides	3202	4002	4802	3202	4002	4802
Structure	1089	1210	1452	1089	1210	1452
Power distribution	102	167	394	102	167	394
Rotary joints	363	635	907	363	635	907
Phase control	286	358	430	286	358	430
Pointing control	80	100	130	1	1	1
Other systems	48	53	61	48	53	61
Solar power satellite total	31539	52542	82861	32068	56240	81363
Solar power satellite (including 50 percent growth)	47309	81813	124292	48102	84360	122045

[a]Symbols relate to size/efficiencies indicated by similar symbols on figure IV-7.

B. Solar Energy Collection System

The SECS includes the necessary elements for the collection and conversion of sunlight to electrical power, the distribution of that power to the antenna interface, structural loads, and attitude and orbit control.

A preliminary analysis indicated that the most promising conversion systems from the standpoint of current state of development were the photovoltaic silicon solar cell and the thermodynamic Brayton cycle. It was also recognized that more efficient and advanced systems might be required to establish SPS viability. For the purpose of the immediate study, however, systems effort was concentrated on the photovoltaic silicon solar cell approach to provide a departure point for comparative evaluation with other approaches in future studies.

1. Solar Array

Silicon solar cells have been developed and utilized in spacecraft for a number of years. More recently, under the impetus of proposed terrestrial use, an intensive effort has been initiated to improve the efficiency and reduce the cost of silicon cells. Typical characteristics of space operational solar arrays and those projected to result from the present development efforts for Earth use are as follows.

	Efficiency, percent	Thickness, mils	Cost, $/W
Present (1976)	12	8 to 12	100
Projected (1985)	8 to 10	4 to 6	.50

For the purposes of the present study, it has been estimated that efficiencies of 15 to 17 percent at 30° C are achievable within the projected SPS time frame.

Cost and weight of the total solar array can be reduced by concentrating the sunlight so that the entire area need not be covered with solar cells. Accordingly, a parametric study of performance as a function of concentration ratio for both silicon (Si) and gallium arsenide (GaAs) cells was performed. It was found that GaAs becomes cost competitive only above concentration ratios of 4 to 6. At these ratios, the solar array requires relatively complex structure and must be oriented toward the Sun more accurately to avoid excessive losses. Silicon cells were used, at a concentration ratio of 2, as a reference for the current study. At this ratio, a simple trough can be used (fig. IV-8). Nominal conversion efficiency, including losses within the cell blanket, is estimated at 10.3 percent for the 100° C cell temperature expected with 2:1 concentration. Cell degradation due to radiation damage and thermal cycling is expected to be a total of 6 percent for the first 5 years and 1 percent/yr thereafter.

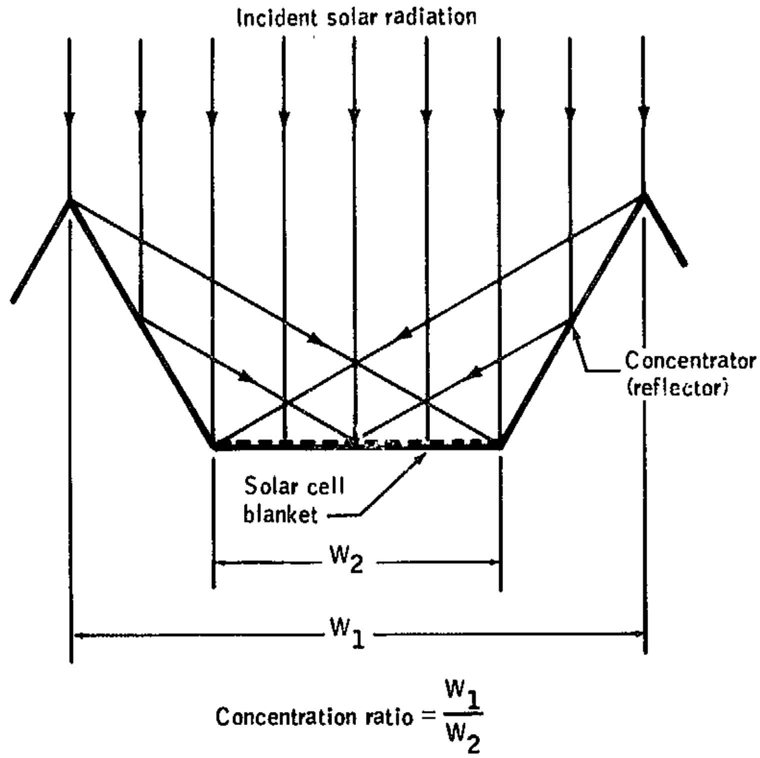


Figure IV-8.- Solar concentrator.

A typical solar cell blanket, used as a reference design, is shown in figure IV-9. The electrical connections between cells (copper or aluminum) are sandwiched between two layers of Kapton and welded to the cell through holes in the upper layer of Kapton. The cells are covered with a plastic such as FEP Teflon. Cell thickness is 0.1 mm (4 mil). Total blanket weight is estimated at 0.31 to 0.46 kg/m^2. Concentrators are 12.5 mm (0.5 mil) with a thin aluminum coating. Their weight is approximately 0.04 kg/m^2.

Considerable development will be required in cell manufacture and blanket assembly. The present technique of growing a single-crystal ingot about 3 in. in diameter, sawing it into disks, cutting the disks into square blanks, and lapping and polishing to make a cell, cannot hope to meet cost or quantity requirements of the program. Work has been done on growing silicon in thin sheets, but crystal defects, which reduce efficiency, are numerous.

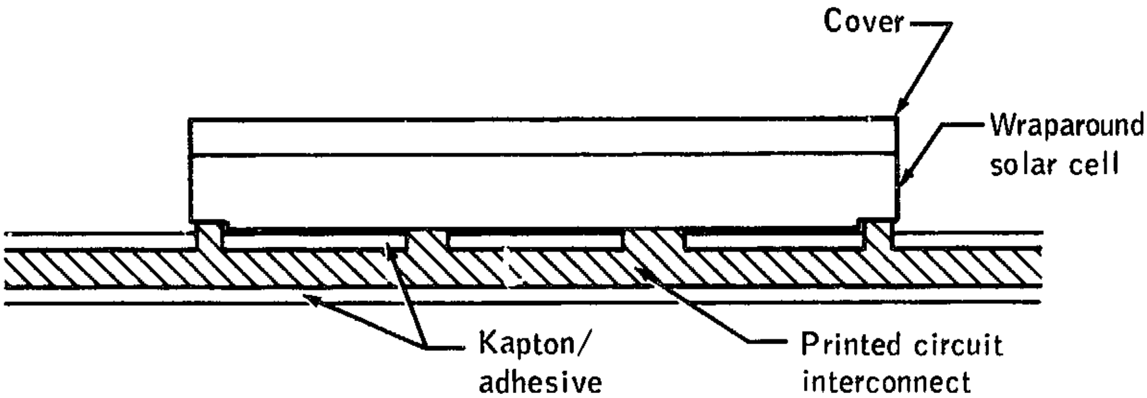


Figure IV-9.- Solar cell blanket.

2. Power Distribution

A nominal operating voltage of 40 kV was selected for this study. Other studies have used 20 kV to match the operating voltage of the amplitron microwave generator. However, the higher voltage offers a significant weight advantage and can presumably be used with amplitrons in series pairs. In addition, 40 kV is compatible with the klystron, an alternative to the amplitron. Still higher voltages could be used, but arcing and voltage breakdown could require more insulation weight.

Pure aluminum was used as the conducting material in preference to copper or silver on the basis of resistivity and density. If structural properties are required, 6061 aluminum is still preferable to copper or silver. Superconductors were not seriously considered because of the weight and complexity of the refrigeration system.

The ideal shape of a conductor is a thin, flat sheet for optimum heat dissipation. Thus, the aluminized solar array concentrator is an interesting candidate. A thickness of 12.5 mm (0.5 mil) should provide sufficient cross-sectional area. Positive and negative conductors can be separated by the width of the cell blanket over most of the array, but insulation would be required in some locations.

Magnetic effects between conductors have not been analyzed. It is possible that the resulting forces will distort the surface of the concentrators, causing uneven illumination of the cell blanket.

Because of the high current levels (220 000 A at the rotary joint), switching should not be done within the array distribution system. On-off switching can occur at the solar cell blanket interface with the distribution system. It is assumed that regulation to limit overvoltage will be done within this cell blanket.

The principal technology issue is the dc switching problem arising from the high voltage and current levels.

3. Structure

Operating structural loads on the SPS are very low, increasing the significance of transportation, assembly, and maintenance loads. The large scale of the SPS emphasizes the dynamic characteristics of the structure that must be addressed in design.

The primary natural load in synchronous orbit is gravity gradient torque; at low altitudes aerodynamic drag is also a consideration. Induced loads include propulsion/RCS thrust, current loop interactions with the Earth's magnetic field, microwave recoil from the antennas, and nonuniform antenna motion. Thermal transients and gradients arising from eclipses will produce differential expansion loads.

Two fundamentally different approaches have been considered. Two of the most efficient structural members are tension members (cables) and buckling-limited compression members. This fact is the basis of the column/cable structural concept, which consists of a small number of compression members that are held in position by a large number of cables.

An alternative approach is to maintain component alinement by providing local stiffness at the minimum level consistent with dynamic stability, such as in the truss configuration. This structure is less efficient from a weight standpoint but may offer advantages in assembly and modularization.

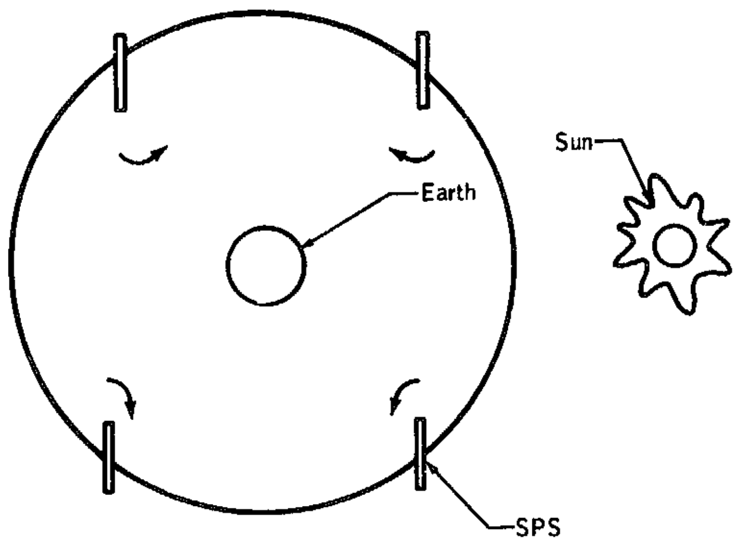
For either configuration, conventional aerospace structural concepts will be inadequate to achieve the low weight required. One possible approach applicable to the truss configuration is to accept occasional elastic buckling of individual members due to random loadings (e.g., docking), from which the member would recover after removal of the load (such as deformation of a venetian blind). Following this concept, the low operational stresses make it possible to design columns with $L/\rho = 200$.

The most significant dynamic loading frequency is the 12-hour (2.3×10^{-5} Hz) gravity gradient cycle. In selecting a minimum natural frequency of 2.3×10^{-4} Hz to keep the dynamic response to a reasonable level, it was found that the membrane stress in the array of the column/cable configuration should be on the order of 0.3 N/m (0.02 lb/ft), and that the minimum depth of the truss configuration should be on the order of 600 m.

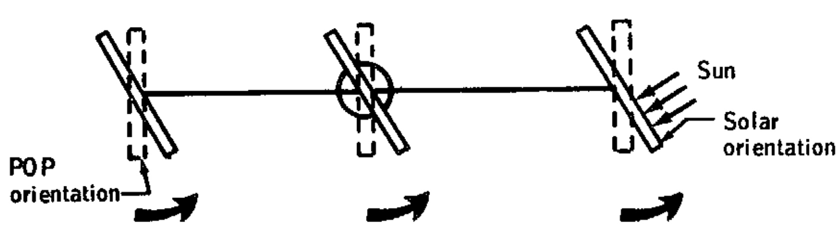
4. Attitude and Orbit Control

The control system must compensate for all forces acting on the SPS, both orbit perturbations and attitude disturbances. Orbit perturbations are discussed in section IV-A-3.

The predominant attitude disturbances are gravity gradient torques of two kinds: short-period (12 hour) torque about an axis perpendicular to the orbit plane, and long-period torque about an axis in the orbit plane (see fig. IV-10). Other attitude disturbances include solar radiation pressure and microwave recoil (if not acting through the center of mass) and antenna angular accelerations (if eccentricity or inclination is not zero).



(a) Short period.



(b) Long period.

Figure IV-10.- Gravity gradient torques.

Gravity gradient torques can be countered by a reaction control system, but at a substantial propellant cost. As an alternative, the column/cable configuration can eliminate the short-period torque by means of about 10^6 kg of counterweights at the ends of the columns perpendicular to the array (fig. IV-11). Purely on a weight basis, the counterweights are roughly equivalent to a 30-year propellant supply if specific impulse is about 98 000 m/s (10 000 lb-s/lb), assuming an array length/width ratio of 2. The long-period torque could be countered in a similar fashion by altering the length/width ratio, but the counterweight required is prohibitive (on the order of 7×10^6 kg). Orienting the long axis of the array perpendicular to the orbit plane (POP) eliminates the long-period torque at an annual average power loss of 4 percent; the weight of additional array required to make up the loss is much less than the propellant required. This is the preferred approach.

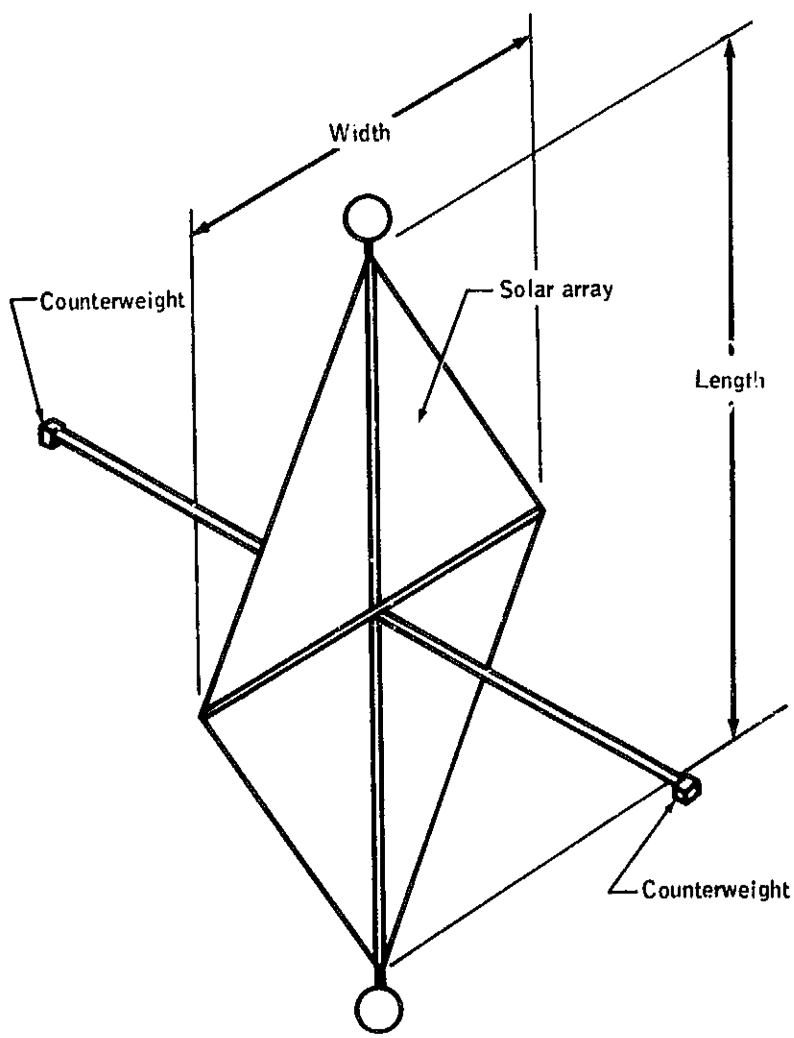


Figure IV-11.- Counterweight location.

Several electric propulsion/RCS systems were evaluated, including electrostatic (ion) thrusters, magnetoplasmadynamic (MPD) and thermal arc jets, and an O_2H_2 chemical system in which the propellant is launched as water and electrolyzed to produce the gases. The intent was not a complete survey of all possibilities, but a range of potential options in terms of weight, performance, and power requirements. Of the systems considered, the MPD arc jet appears most attractive. Although it is in an early stage of development and performance projections are uncertain, its low weight, high specific impulse and high unit thrust make it worth further consideration.

All the high-performance propulsion systems require large amounts of electrical power. It would be impractical to store sufficient electrical energy to operate these systems during eclipse. It appears feasible, however, to inhibit propulsive or RCS maneuvers during eclipse, except for short-period gravity gradient compensation. This small requirement can be satisfied by an H_2O_2 electrolysis system that produces and stores gases in sunlight; the system can also serve as a standby propulsion system.

Development is required for the RCS. Development will also be necessary in control of very large, flexible structures, a problem that cannot be completely simulated on Earth because gravity is much greater than the forces normally acting on the structure.

5. Instrumentation, Control, and Communications

A large quantity of subsystem status data will be required for ground monitoring and control. The depth of this study has not produced sufficiently detailed definition to permit meaningful identification of instrumentation, control, and communications requirements. However, present technology should be adequate for all foreseeable needs, and the weight impact on the SPS will be insignificant. As a consequence, this subsystem has been deferred for later study.

6. Maintenance Station

Because it would be impractical to design the SPS for a 30-year failure-free life, maintenance will inevitably be required periodically. The maintenance question has not been explored to any depth in this study, however, and the following comments represent a cursory consideration of the problem.

To minimize the payload of the maintenance spacecraft, as many maintenance support capabilities as possible should be incorporated into the SPS. These would include a normally unmanned, habitable control station, some repair and small spares storage facilities, and servicing and local transportation vehicles. All these capabilities will be similar, if not identical, to those used during construction, so that the same development program is applicable to both.

C. Microwave Power Transmission System

The MPTS consists of microwave generators, subarray elements, a phase control system, power distribution, a pointing control system, rotary joints, and structure.

1. Antenna Array

The antenna is a planar phased array with a diameter of 1 km, comprising about 7850 subarrays. Each subarray is individually phase-controlled by reference to a "pilot" beam transmitted from the rectenna so that a narrow, coherent beam is transmitted to the ground. Power density varies in a 10-step approximation of a 10-dB Gaussian taper to maximize the power in the main lobe of the beam.

2. Microwave Generators

Microwave generators convert dc electrical power to microwave power for transmission to ground. Several types were considered, but only two, the amplitron and the klystron, were considered likely candidates and examined in detail.

The amplitron's chief projected advantages are significantly lower specific weight (roughly 0.4 kg/kW versus 0.7 kg/kW for the klystron) and somewhat higher efficiency (88 percent vs. 86 percent). It uses a cold cathode, which enhances reliability, and can be passively cooled by a pyrolytic graphite radiator. However, it is relatively noisy and requires an absorptive filter. Tuning is accomplished by a motor-driven pole piece that is potentially unreliable.

The klystron is capable of ten times the power output per tube of the amplitron. Therefore, fewer tubes are required, greatly simplifying antenna assembly. The anode voltage is twice as high, permitting a reduction in distribution system weight (unless the amplitrons are connected in series). The gain is much higher; the resulting low-rf input drive power makes phase control easier. Arcing and breakdown are prevented automatically by internal discharge.

Although the kylstron was used for weight estimates in this study, it is too early to make a selection, and much work is needed on both tubes before a final choice is possible.

3. Subarrays

The transmitting antenna includes a large number of subarrays, each of which is controlled as a unit. To minimize losses, the subarray should be approximately square. Power density is varied over the antenna by adjusting the number of microwave generators in each subarray.

To achieve maximum uniformity of illumination of the antenna aperture, a resonant slotted waveguide array is used. The basic antenna element is illustrated in figure IV-12. The components are an input feed guide that distributes power from the tube to the radiating waveguides, a back face that contains slots for coupling power from the feed guide to the radiating guides, vertical walls that separate the radiating guides, a front face that contains the radiating slots, and end walls. Aluminum is used because of its conductivity, density, and cost. Close tolerances (about 0.001 in.) are required in slot dimensions and location and should be a factor in planning space versus ground construction of this element.

Waveguide technology is well established. However, manufacturing and on-orbit assembly techniques will require development if the necessary production rates and efficiencies are to be achieved.

4. Phase Control

The coherence and direction of the transmitted beam are maintained by reference to a pilot beam transmitted from the rectenna to a reference receiver in the center of the antenna and to each subarray. Loss of phase control immediately diffuses the transmitted beam (see fig. IV-4), so that the concentrated beam cannot wander away from the rectenna. Two methods of comparing the received phasing signals appear promising.

The first method (the "transmission line" approach) employs a separate transmission line from the central reference receiver to each small group of subarrays. This requires that transmission delay times be calibrated and maintained, requiring additional control circuitry. The second ("sequential") method transmits the reference phase from one subarray to the next; this can result in a large buildup of phase error.

The preferred approach appears to be a combination of these, in which several subarrays (perhaps 8 to 16) are connected in series as a group, and each group receives the reference phase via a separate transmission line. The rf cable distribution has been used for weight estimating purposes, but a fiber optics system is potentially lighter.

Areas of concern include phase control system requirements for each tube, phase stability of components outside the phase control loop, and transmitter rf interference with the phase reference system.

5. Pointing Control

In an eccentric orbit, the antenna must vary from constant velocity in order to track the rectenna; this requires a cyclic torque with a period of 1 day to be applied to the antenna. A more or less

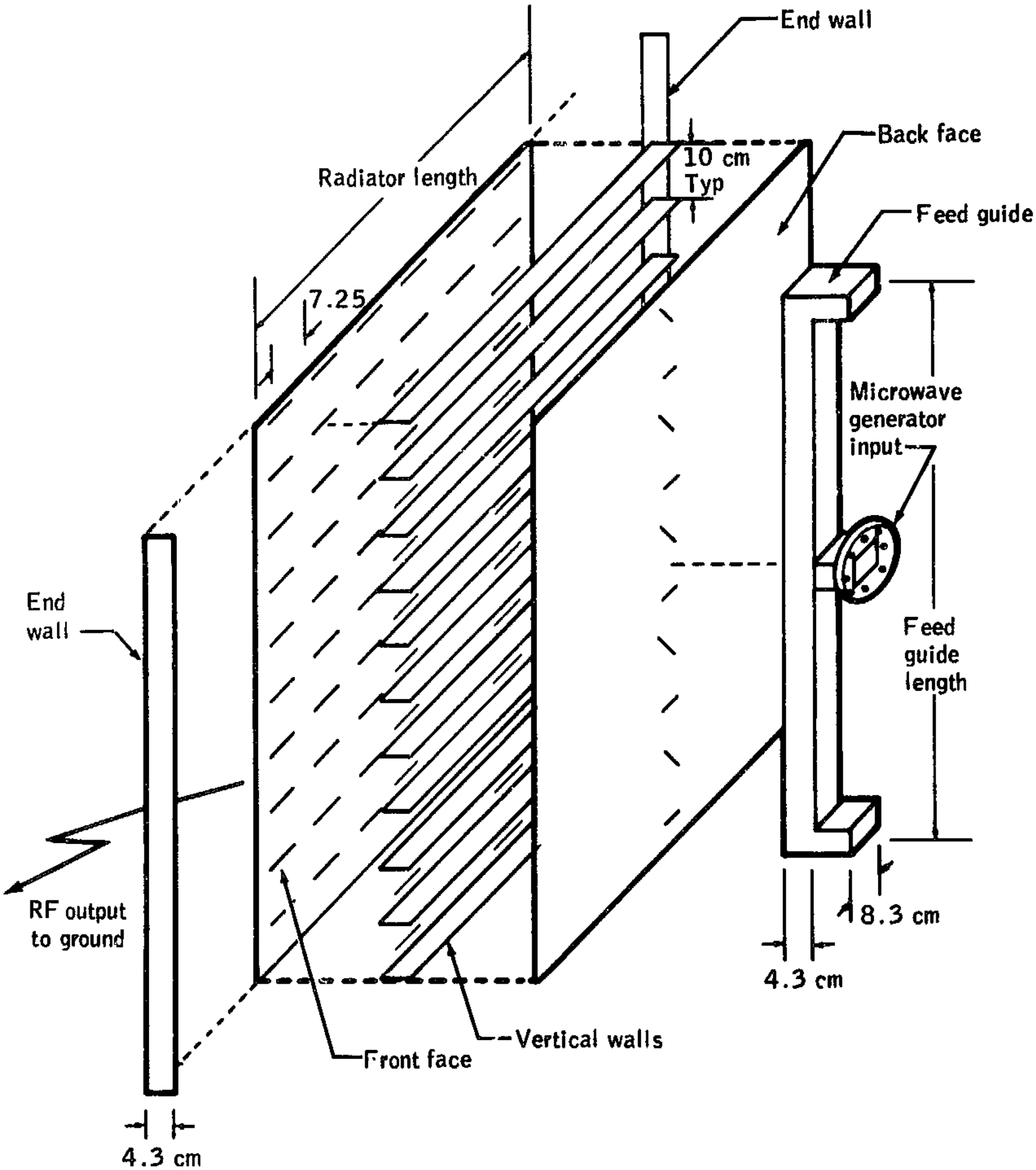


Figure IV-12.- Antenna element.

continuous torque is also necessary to overcome joint friction. It appears that these torques can be reacted by the structure without serious overall dynamic effects. However, there may be some local dynamic response that can be identified only by analysis of detailed design. If such problems exist, they can be circumvented by isolating the antenna drive from the SPS structure, either by "shock-mounting" the antenna or by reacting the drive torques against reaction jets or momentum storage devices on the antenna. To be conservative, the latter approach has been used for sizing purposes. Reaction jets would tend to create an atmosphere and would consume large quantities of propellant. Control moment gyros (CMG's) or other momentum storage devices are attractive for cyclic torques, although rotor masses of several tons are required. Friction is counteracted within the joint and does not affect the supporting structure.

Pointing command inputs can be derived from phase differences in the pilot beam as received at a set of four selected subarrays located 90° apart. A second set of subarrays is used to resolve phase ambiguities. Initial acquisition is based on the known position and attitude of the SPS, but this method is not accurate enough for antenna pointing.

The principal development required is the momentum storage device. A CMG for this application would be more than 200 times heavier (∿25 000 kg) than the CMG's used on Skylab if designed to the same stresses.

6. Power Distribution

A lateral flow distribution system was used to minimize weight (fig. IV-13). Each quadrant of the antenna is independent, with several switchgear per quadrant. Four switchgear per quadrant keep the current at a reasonable level (∿11 000 A) and were assumed for estimating purposes. The switchgear serve not only as distribution points, but can be used to bring power up to maximum in a controlled sequence during startup. Power is routed to distribution points (switchgear) serving from one to four subarrays, depending on the power density

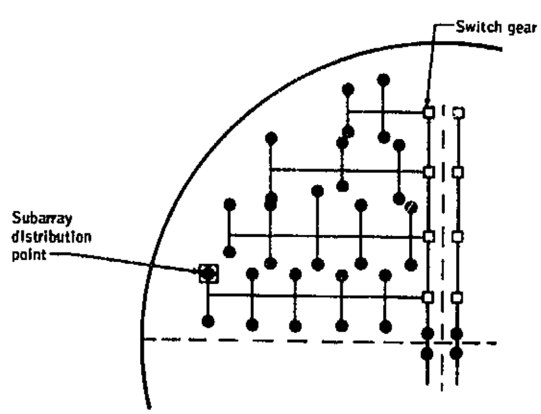


Figure IV-13.- Typical antenna distribution system.

in that part of the antenna. Further work will be required on a control system for the switchgear and on the degree and location of power supply regulation.

7. Structure

A compression hoop structural concept was developed in an effort to minimize structural weight. Primary structure consists of four concentric polygons of 6, 12, 18, and 24 sides joined by tension cables (fig. IV-14). The polygon sides are rectangular frames 65 by 130 m. A secondary structural matrix adapts the antenna subarrays to the primary structure such that each subarray is attached at three points. Thermal distortion should be minimized in view of the radial symmetry of the structure and the power density.

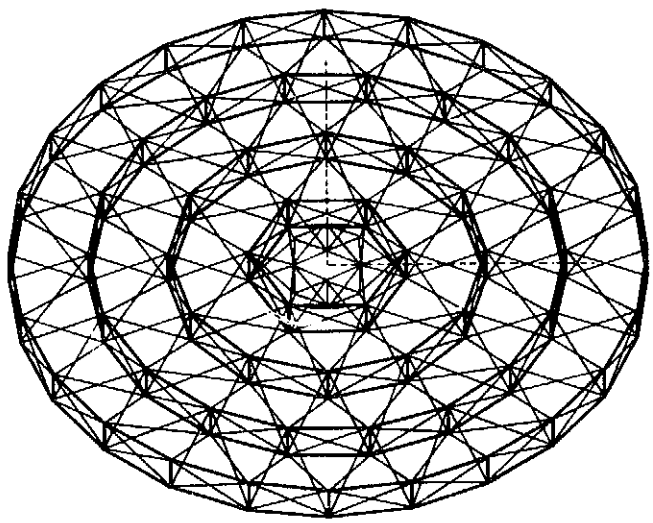


Figure IV-14.- Antenna primary structure.

8. Rotary Joint

The rotary joint provides a structural connection between the SECS and the transmitting antenna, a means of transferring electrical energy from the SECS to the transmitting antenna, and a drive system to rotate the joint continuously about one axis and roughly 1°, oscillating daily, about a second axis.

Several approaches were identified and evaluated in general terms, and a promising concept was selected for more detailed examination. This concept, illustrated in figure IV-15, consists of a ball joint approximately 25 ft in diameter. The spherical contact surface is split into two halves, and supports structural loads and transfers electrical energy by means of sliding brushes.

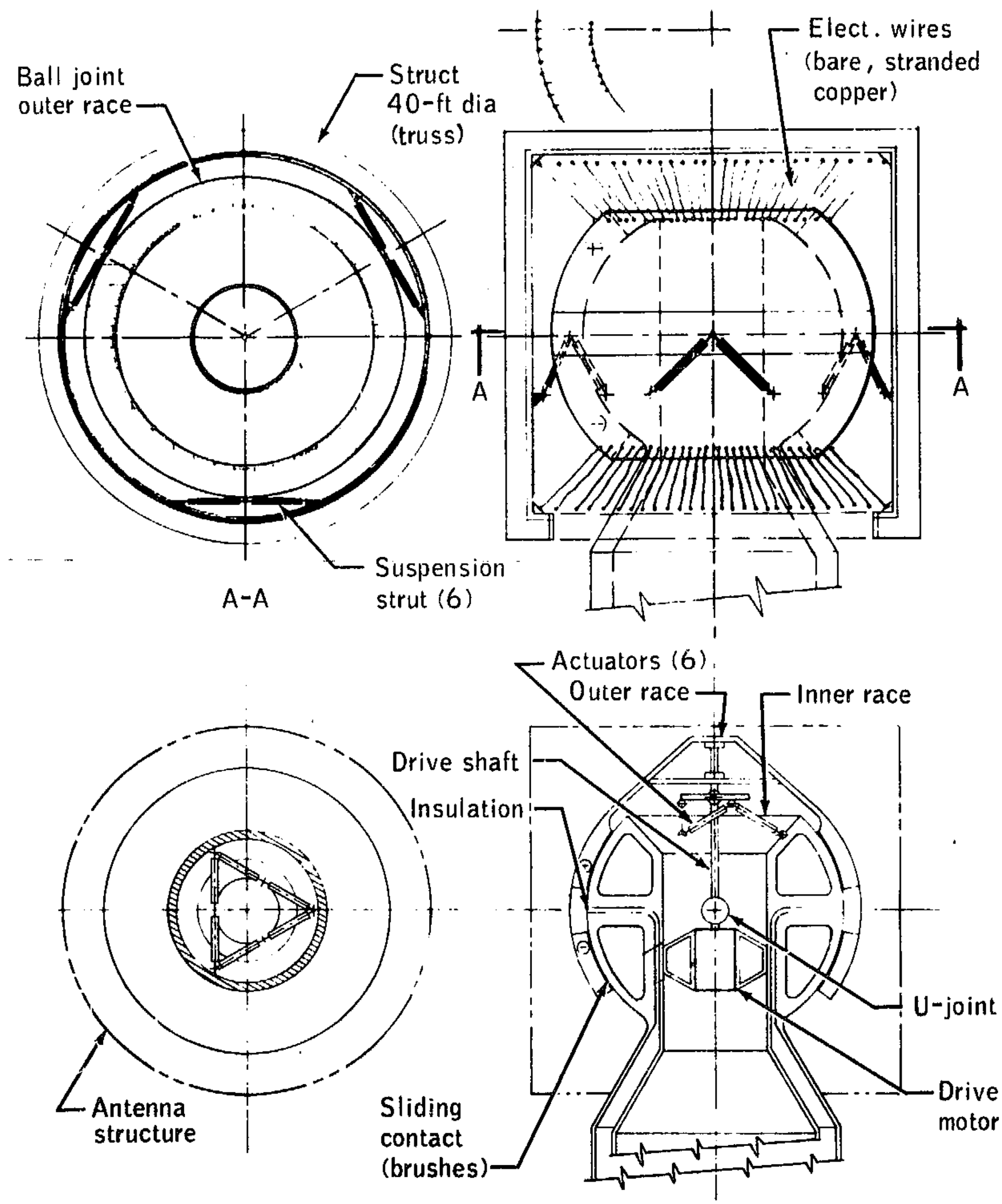


Figure IV-15.- Ball joint and drive concept.

The joint is rotated continuously by a drive motor in the center. Tilt is accomplished by six actuators at the top. The outer ball is suspended within its cylindrical cage by many small copper wires that resist translation but not small rotations, and also conduct electrical energy from the ball to the antenna. The suspension struts sense rotation of the ball and a computer converts these signals into joint drive commands to maintain the cage/ball relative orientation. Thus, the drive system overcomes friction but makes no other inputs.

A substantial design and development program is required. Heat rejection from the interior of the joint will be a major problem. Brush design and materials for a 30-year life will also require research.

9. Thermal Control

Passive thermal control of the transmitting antenna appears feasible, but a closely integrated design of the microwave generators, waveguides, electronics, and structure will be required. Three significant design considerations are waste heat rejection, thermal distortion from the daily solar orientation cycle, and thermal strain from eclipses.

The rotary joint presents the other major heat rejection problem. It has not been analyzed in depth, but appears to be a potential application for heat pipes.

D. Microwave Reception and Conversion System

The MRCS includes a large rectifying antenna, or rectenna, (fig. IV-16) to convert the microwave energy to dc electrical energy, a distribution system to collect the energy, and dc-ac inverters to convert the energy to a form compatible with the commercial power grid.

1. Rectenna

The rectifying antenna is an integrated system for collecting microwave power and rectifying this power into direct current. The rectenna consists of about 15 billion elements. Each rectenna element consists essentially of a half-wave dipole antenna and a half-wave rectifier (Schottky barrier diode). These elements are mounted on a wire mesh ground plane and connected in series to produce the required dc output voltage. The elements would cover an elliptical area typically 10 by 14 km (at 40° latitude) to produce 5-GW dc output power.

The efficiency of the rectenna falls off rapidly at low power densities. This, together with the power density distribution in the microwave beam, may place an upper limit on practical rectenna size. A major development item is an element that will operate efficiently at low power densities and is producible at low cost.

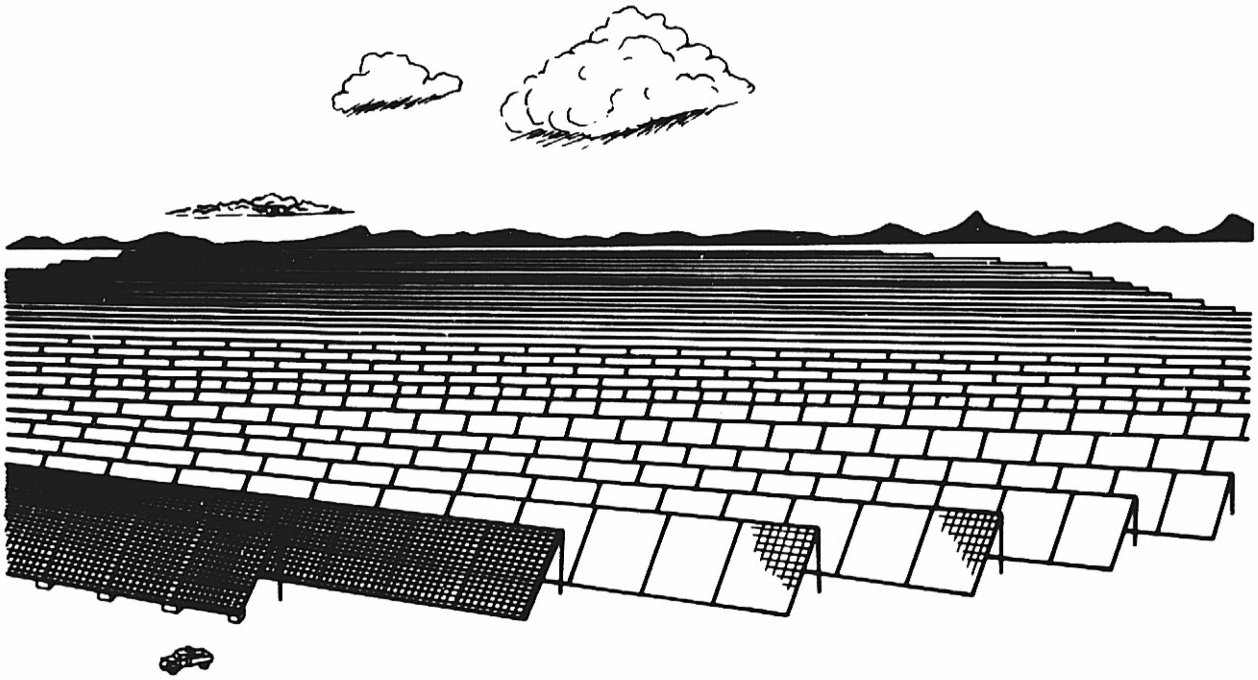


Figure IV-16.- Rectenna construction.

2. Grid Interface

It may be possible for the distribution grid to accommodate dc voltage directly; if not, the dc output may be inverted by either of two approaches. In the first approach, the rectenna is wired to produce 1000 V dc, which is used directly as the inverter input. This requires a large number of inverters to minimize conductor losses and cost.

In the second approach, the rectenna is wired to produce 250 kV dc. This allows an inverter location remote from the rectenna because of lower dc transmission losses, and requires fewer inverters for the same power output. It does, however, create new insulation requirements and structural modifications to separate the wiring from ground.

E. Operations

Ideally, SPS power would remain uniform at all times. In reality, however, there will be variations from several causes as illustrated in figure IV-17.

When the solar array is oriented perpendicular to the orbit plane, as has been found desirable from a weight standpoint (see sec. IV-B-4), the solar energy collected varies as the cosine of the Sun's declination, producing the 6-month cycle at the top of figure IV-17. Total variation is about 450 MW.

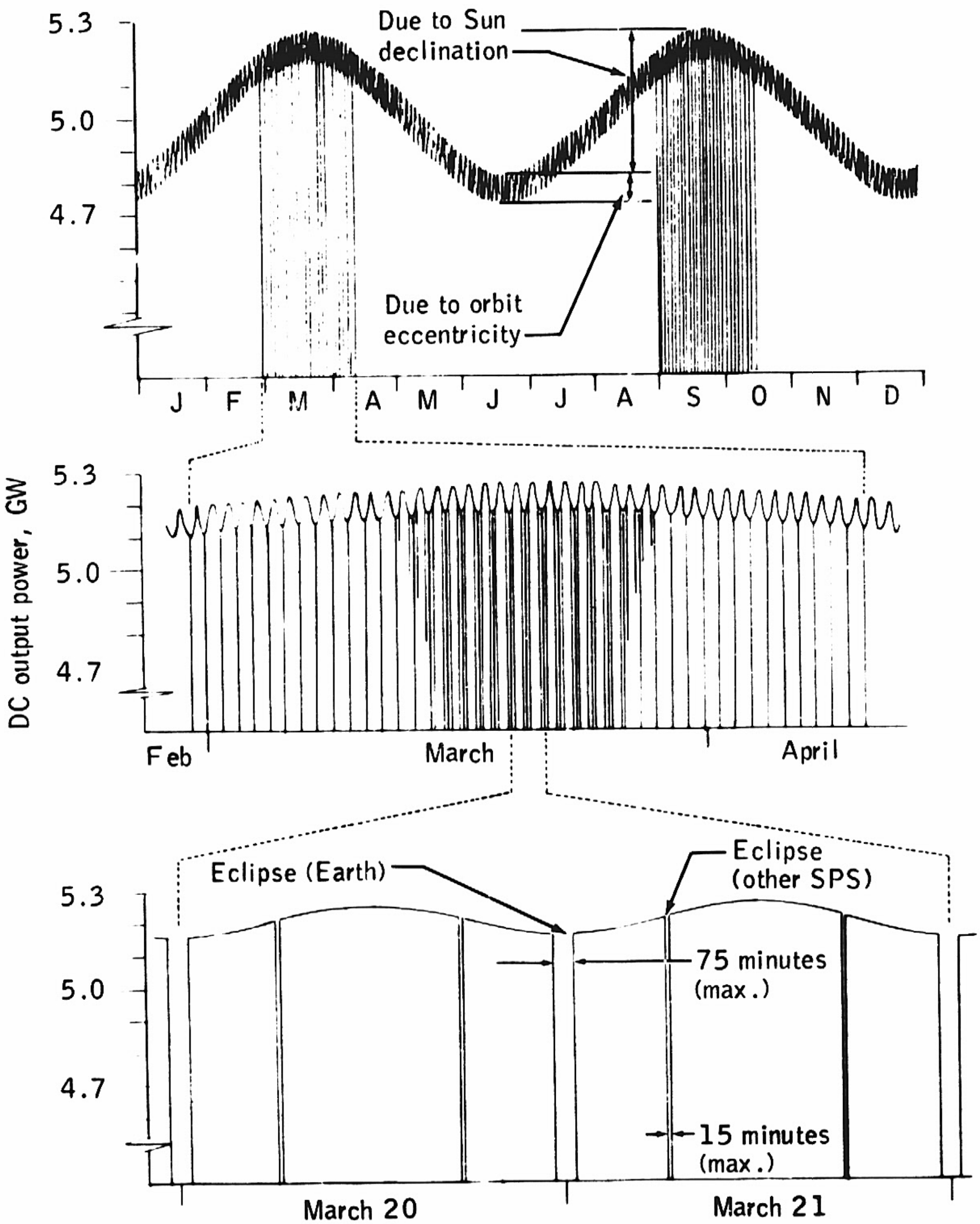


Figure IV-17.- Variation in ground dc power output.

Orbit eccentricity will cause a cyclic fluctuation in satellite-to-rectenna distance. For an expected eccentricity of 0.04, this results in a daily power output variation of about 100 MW superimposed on the 6-month variation.

Eclipses by the Earth (see sec. IV-A-3) will cause total shutdowns daily around local midnight for about 6 weeks in the spring and fall. Maximum duration is about 75 minutes. Eclipses by other satellites will cause shutdowns at about 6 a.m. and 6 p.m. local time for several days in the spring and fall, with a maximum duration of about 15 minutes.

Total shutdowns will also be required at times for maintenance. Duration of shutdown is conjectured to be a few weeks, and the frequency is about once every 5 years.

The primary operational problems will arise from the eclipses. At 0.5° spacing, as many as 38 SPS's of a total of 112 will be in the Earth's shadow simultaneously, so that power sharing will be of limited usefulness. A shifting, nonequatorial orbit that is never eclipsed is possible but has not been examined in this study; it is expected that orbit maintenance propellant will be prohibitively heavy. No entirely satisfactory solution to the eclipse problem is apparent, and further study is required. Maintenance shutdowns will be less frequent, can be planned for off-peak conditions, and should consequently present less of an operational problem.

The daily and 6-month cyclic variations in power output can be eliminated if necessary. A circular orbit avoids the daily fluctuation but at a cost in orbit maintenance propellant of some 200 metric tons/yr (I_{sp} = 10 000 lb-s/lb). The 6-month cycle can be eliminated by continuous solar orientation instead of POP. Additional reaction control propellant on the order of a few hundred tons per year would be required or, for the column/cable configuration, counterweights of some 7000 metric tons could be used (sec. IV-B-4). The system trade-offs relating to the power station have not taken into account any adverse impact of these fluctuations on the distribution grid. It is possible that inclusion of these considerations may alter the orbit and attitude control considered in this study, and further iterations of the trade-offs should be made.

F. Unit Costs

Table IV-4 shows a list of cost estimating relationships (CER's) utilized for initial SPS costing. These CER's were produced using historically derived CER's for similar space equipment. Because of the very high volume production rates required for items such as solar cells, Schottky diodes (rectenna elements), and microwave generators, the CER's for these devices were substantially reduced below current values for space systems. An example of this expected cost reduction is illustrated in figure IV-18 for silicon solar cells. The cost reduction is projected by ERDA as a result of a major terrestrial photovoltaic research

TABLE IV-4.- COST ESTIMATING RELATIONSHIPS

Category	CER			Source/derivation
	Minimum	Nominal	Maximum	
Solar energy collection system:				
Solar cell blankets, $/kW	100	300	500	ERDA terrestrial photo-voltaic goals
Solar concentrators, $/kW	--	25	--	($0.70/m^2)
Structure, $/kg	--	7.00	--	Space equipment
Power distribution, $/kg	--	4.00	--	Space equipment
Other systems, $/kg	--	1000	--	Electronic components; high reliability
Microwave power transmission system:				
Microwave generator, $/unit	--	2000	--	Manufacturer projection
Waveguides, $/kg	--	70	--	Design estimate
Structure, $/kg:	--	70	--	Space equipment
Power distribution, $/kg	--	40	--	Space equipment
Rotary joints, $/kg	--	100	--	Design estimate
Phase control, $/unit	--	56	--	Design estimate
Pointing control, $/kg	--	1500	--	Electronic components
Other systems, $/kg	--	1000	--	Electronic components; high reliability
Microwave reception and conversion system:				
Rectenna array (circuits) and diode assembly, $/m^2	6	8	8	Manufacturer projection
Real estate, $/m^2	--	.15	--	($ 650/acre)
Site preparation, $/m^2	--	.40	--	($1800/acre)
Power distribution and control, $/m^2	--	2.50	--	($ 45/kW); switchgear and inverters
Support structure, $/m^2	6	10	10	Design estimate

and development (R&D) program currently in progress. ERDA's 1985 goal is to produce solar cells in quantities of 500 MW for $500/kW peak. According to ERDA 48, Volume 2, a production capability of 50 GW (equivalent to 2.5 10-GW SPS's) should be achieved by 2000 with a market price in the range of $100 to $300/kW. While recognizing that the weight requirements for solar cells to be used in space are different from those for terrestrial use, the $100 to $500 range appears reasonable and was used in the present study.

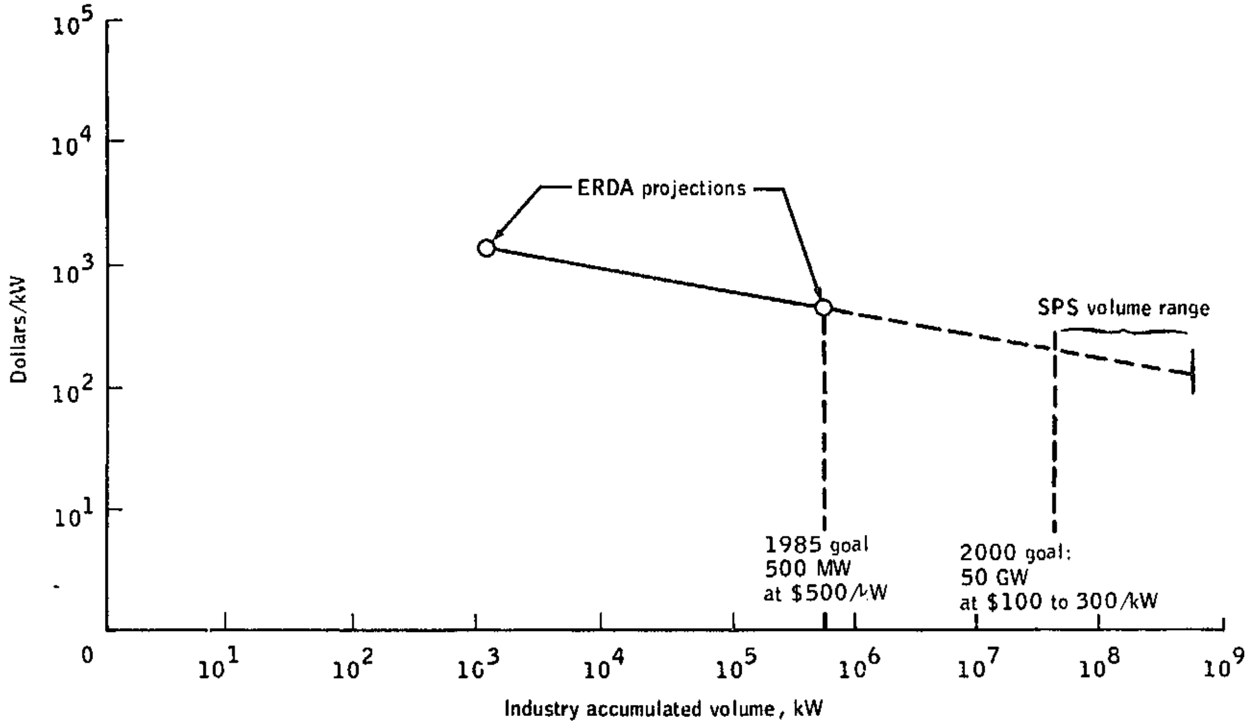


Figure IV-18.- Photovoltaic array cost projection.

V. SPS CONSTRUCTION AND MAINTENANCE SYSTEM

A. System Requirements and Analysis

The large size and low density of an SPS and the advantages of not designing for launch loads dictate an orbital fabrication and assembly approach to construction of the SPS. The complex elements or components such as antenna rotary joints and control system modules can be manufactured on the ground for assembly into the overall system. Other components such as the microwave generators, solar cell blankets, concentrator sheets, and power distribution harnesses are amenable to dense packaging for launch and deployment in orbit.

SPS structure is low density in its final configuration when designed for orbital loading conditions. The packing density of fold-deploy systems is much too low for efficient operation of the transportation system. In addition, structural joint design and launch loading conditions have an adverse effect on structural weight. An alternative is to manufacture the structure in orbit. Concepts under current consideration include the use of automatic machines that generate structural elements from preprocessed stock as illustrated in figure V-1. Combinations of the machines are utilized to build trusses for the primary structure.

Another candidate for orbital manufacture is the antenna subarray. The waveguides of the phased array must be built to very precise geometry, yet the finished product has very low density. By fabricating the subarrays on orbit, problems with launch loading and low density packaging can be avoided.

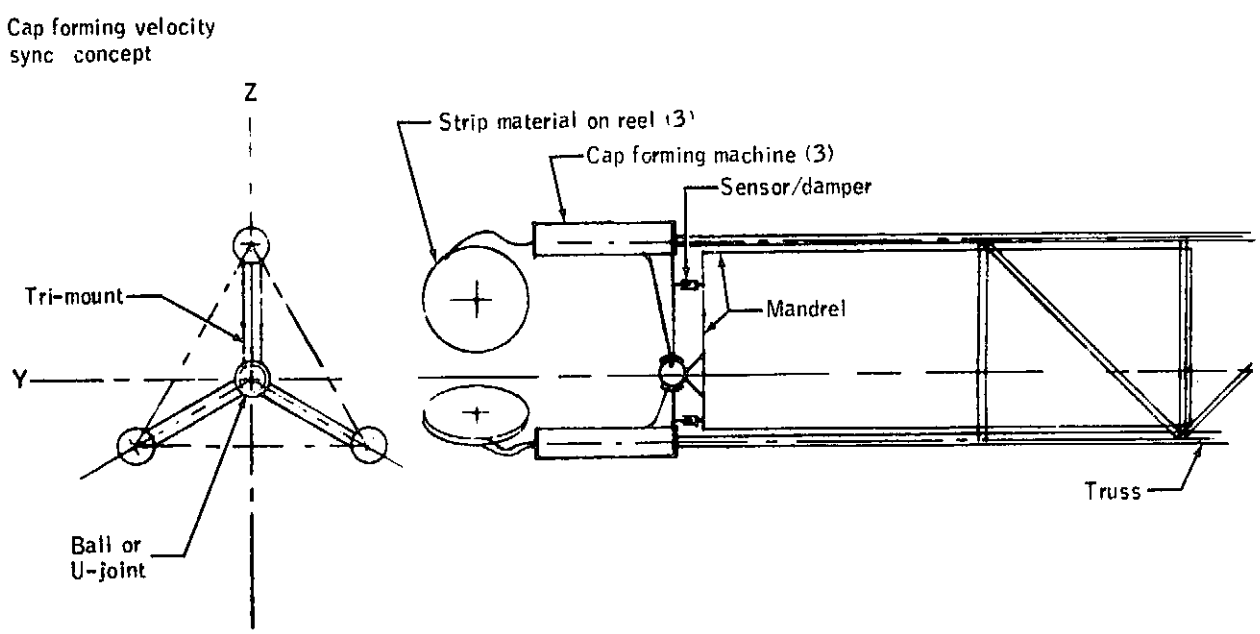


Figure V-1.- Beam builder machine concept.

The large size of the SPS requires a high degree of automation to achieve the necessary construction rates. The construction crew can be best utilized in servicing and maintaining automated equipment, evaluating the operation and output, and performing contingency operations. The construction and support crew operate a construction base consisting of construction and manufacturing facilities, orbital construction and support equipment, logistic facilities, integration management facilities, and crew habitability facilities.

A conceptual GEO construction sequence for the column/cable perpendicular-to-the-orbital-plane (POP) configuration is shown in figure V-2. The schedule is phased for completion in 1 year. The construction facilities are assumed to be operational. Construction facilities are provided at each end of the major columns (fig. V-3). These facilities move out from the center of the SPS by generating structural members. Stabilizing cables are attached and deployed as the columns are extended. Packages of solar cell blankets and reflectors are attached to the column and connected to the power distribution system by construction personnel. Deployment of the collector is gradual as the column length increases (fig. V-4). Deployment is aided and monitored by personnel.

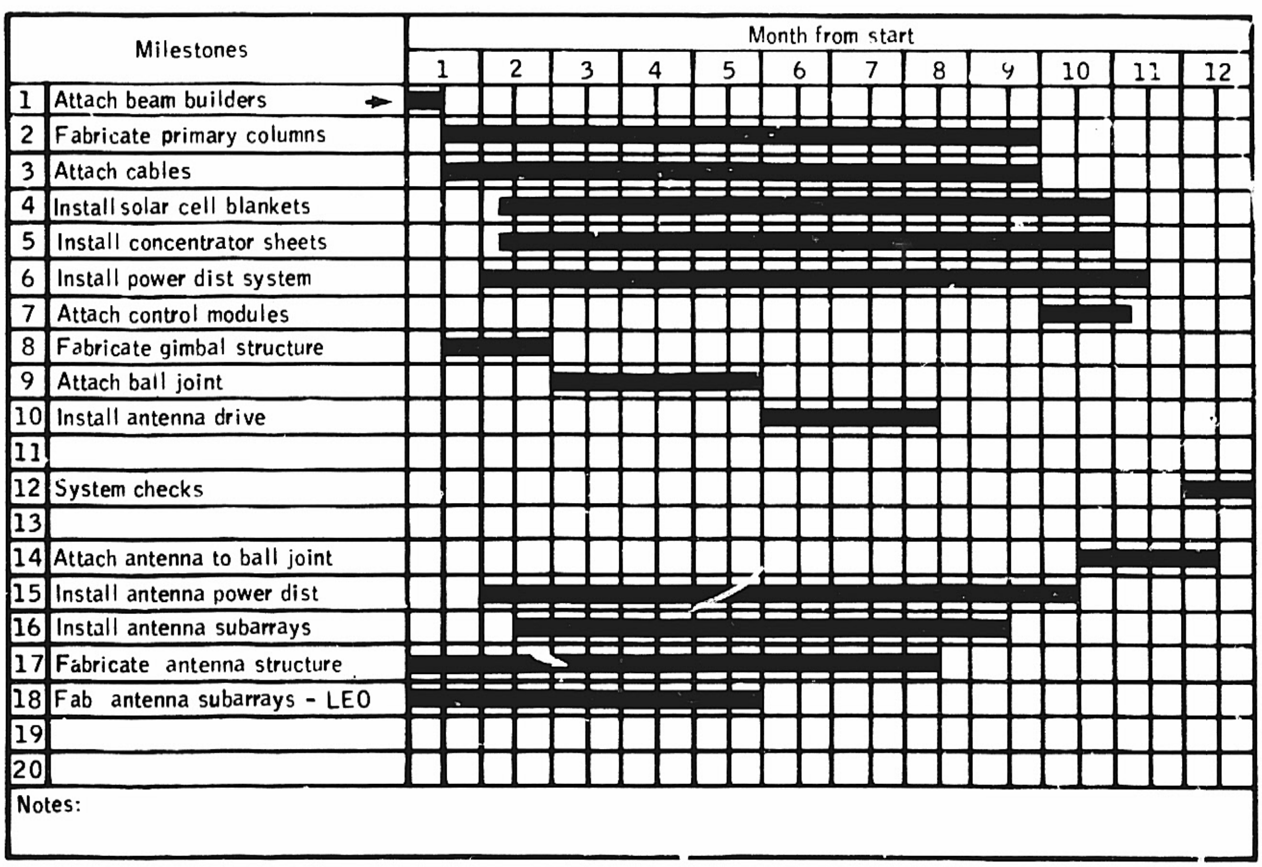


Figure V-2.- Typical SPS construction sequence - column/cable (POP).

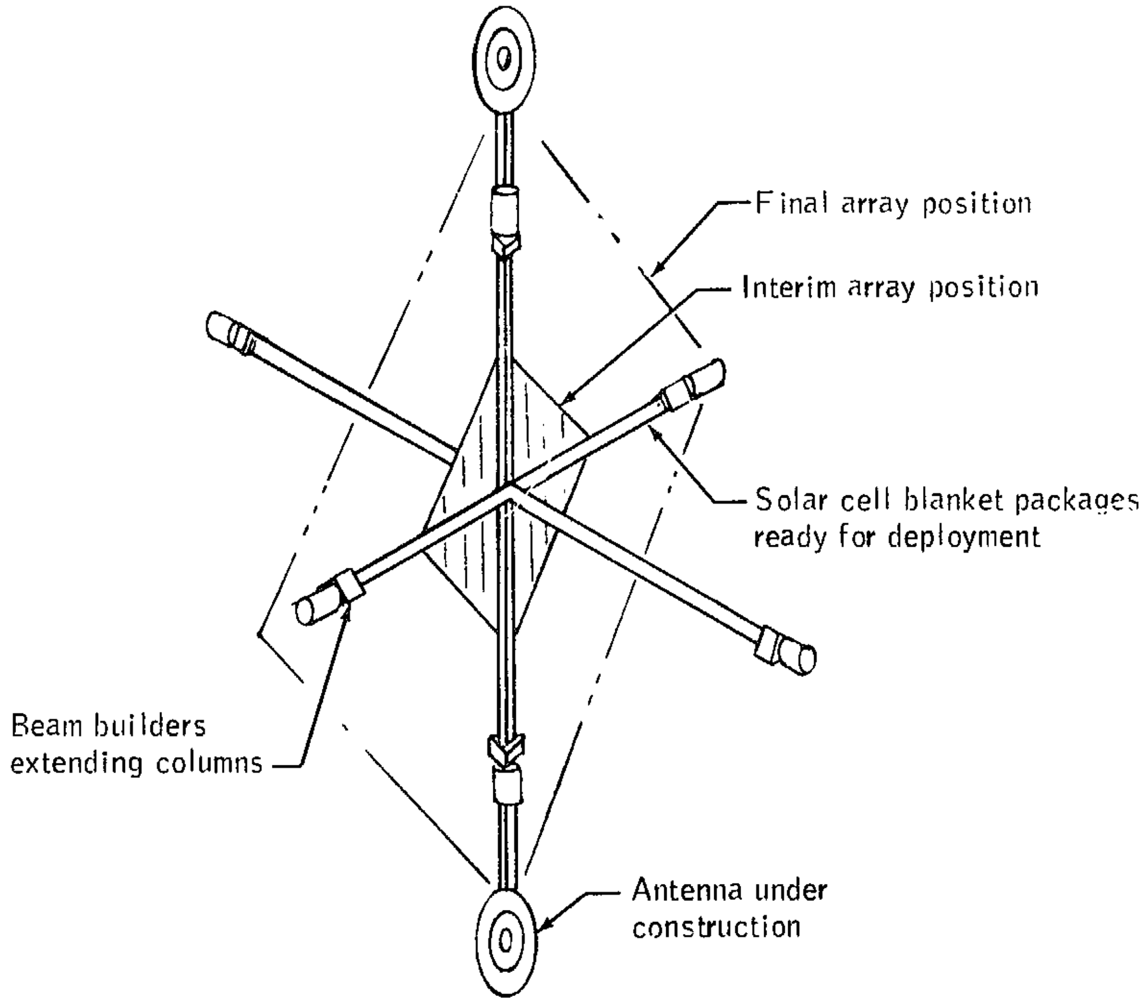


Figure V-3.- Partial construction of column/cable configuration.

Antenna construction takes place in parallel with the collector construction. The antenna construction facilities are attached to the appropriate column fabrication facilities. The antenna subarray support structure provides a construction framework for buildup of the concentric ring primary structure. As the concentric rings are completed, installation of the prefabricated antenna subarrays is performed. The antenna power distribution and phase control systems are connected. System checkout is completed and construction equipment is removed.

An alternative to the column/cable is the truss configuration. The truss configuration was conceived as an aid to on-orbit construction. With the regular geometry of the truss configuration, a construction base concept as shown in figure V-5 is possible. A large space frame supports the equipment necessary for completion of the collector array. Materials are received and distributed, trusses are manufactured with automatic machines, reflectors

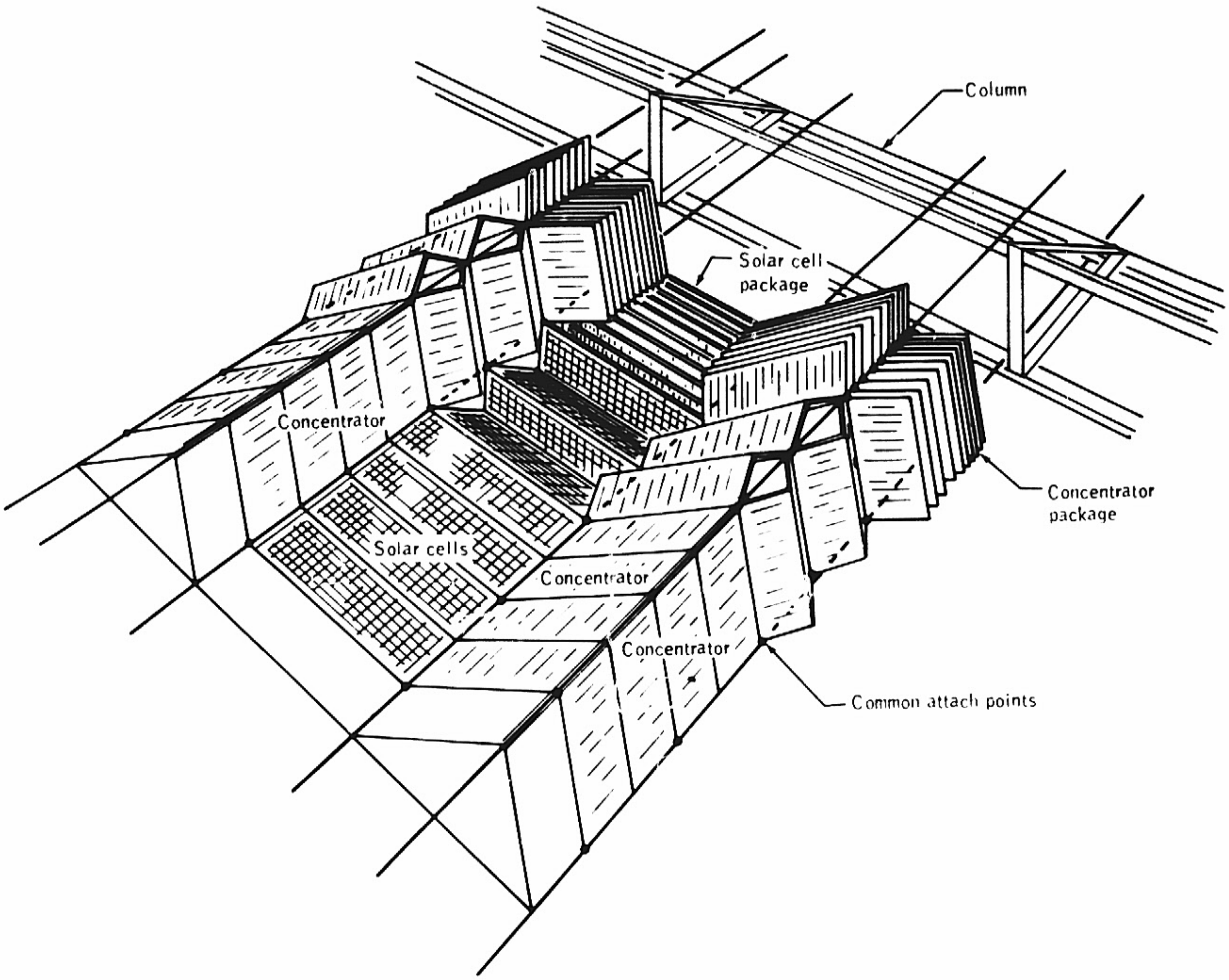


Figure V-4.- Concept for solar cell/concentrator deployment.

and solar cell blankets are deployed, power distribution cables are installed, and subsystems are checked out within the structural support of the construction base. Antenna fabrication takes place in a fashion similar to that described for the column/cable configuration. A construction sequence for the truss configuration is provided in figure V-6.

A potential advantage of the truss configuration is the use of modular construction at a small construction base in LEO. Then a bootstrap transportation mode can be used to power the modular segment to GEO with energy derived by deployment of some of the solar cell blankets. These solar cells are degraded during the traverse of the Van Allen regions, which must be considered in sizing the array.

Another principal issue with the modular approach is the docking and attachment of very large masses in GEO. The modular segments are very large and the relative motion between segments must be attenuated. A docking system would have to be provided that achieves low distributed loads.

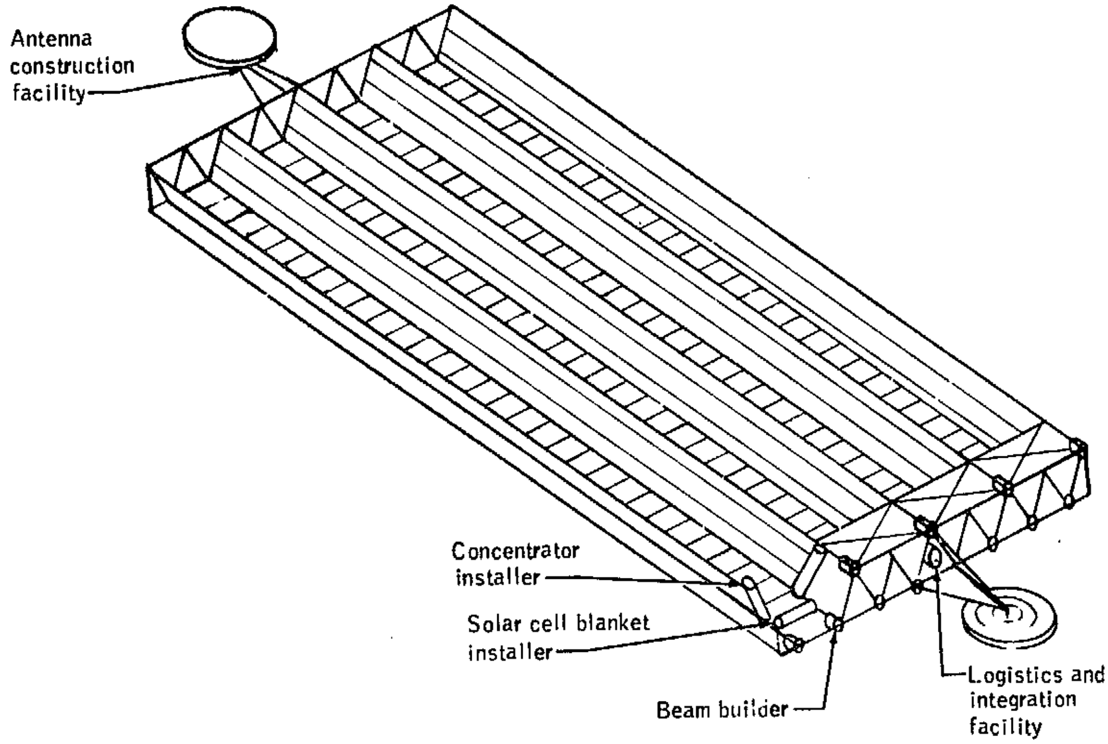


Figure V-5.- Construction base concept for truss configuration.

B. Construction Base

Construction base design is sensitive to the operational concept for its intended use in support of large structure manufacturing in a remote environment. Crew size and associated support are major considerations in sizing the construction base. Specific operations such as assembly docking of transport vehicles, propellant transfer, maintenance operations, crew rescue, and radiation environment monitoring and emergencies all contribute to design requirements. The physical configuration of the SPS will also be a determining factor in specific construction base design. The space radiation environment will be a driver in the design of manned facilities and equipment.

Five major elements of the orbital construction base are defined as follows:

1. Construction and manufacturing facility
2. Orbital construction and support equipment
3. Logistics facility
4. Integration management facility
5. Crew habitability facilities

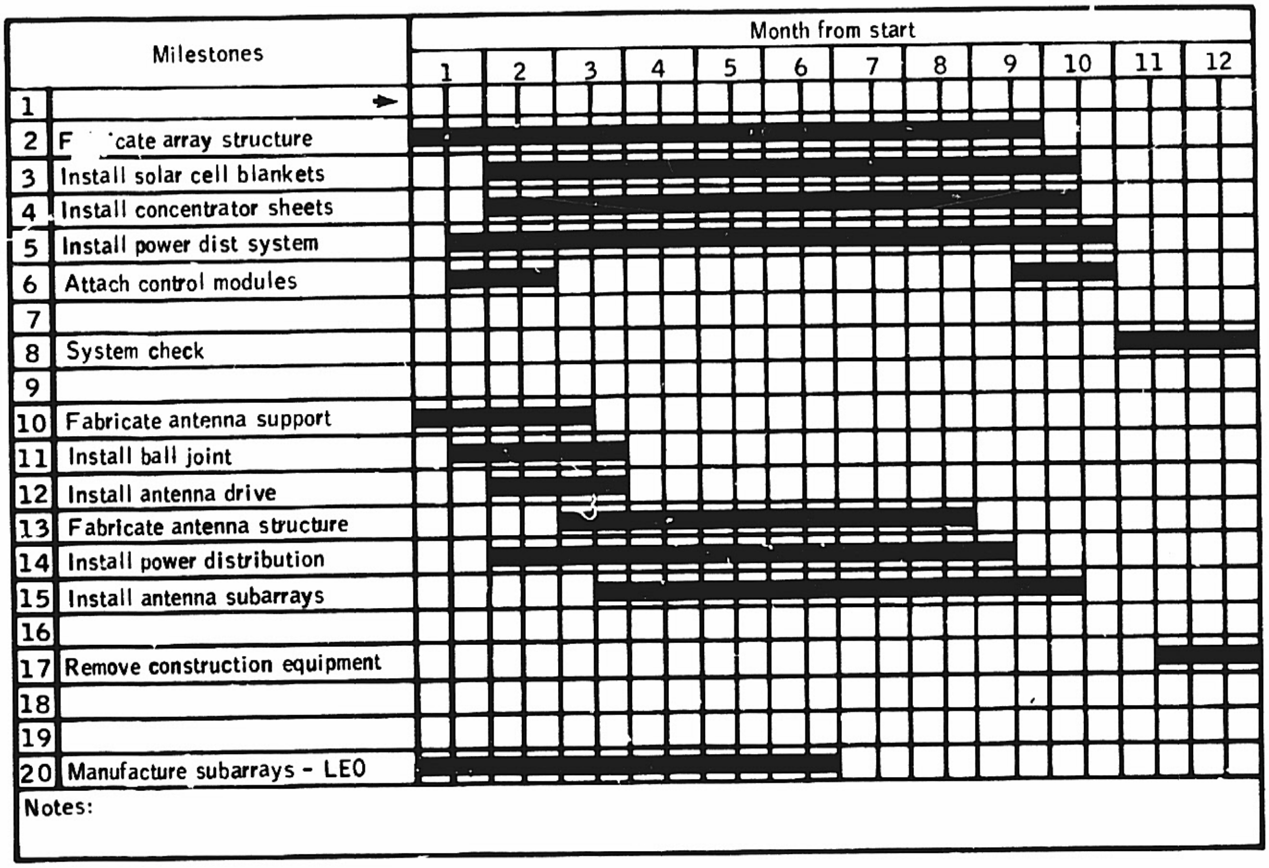


Figure V-6.- Typical SPS construction sequence - truss configuration.

Each element contains or consists of equipment that is used to perform certain functions and tasks commensurate with the required step-by-step sequential construction operations. Figure V-7 illustrates a construction base concept for a column/cable configuration. It consists of six construction facility sites for the solar energy collection system (SECS) and one for each microwave power transmission system (MPTS). Logistics and integration management facilities are combined at two locations. Habitability facilities are combined with each of the other facilities.

1. Construction and manufacturing facility.- The construction and manufacturing facility provides the capability for the direct construction operations. The crew monitors automated manufacturing and construction functions with a crew override capability in the event of malfunction.

The facility consists of six space frames supporting the machines for fabricating the structural elements of the SPS collector system. Preprocessed stock is supplied to the machines and processed into the final structural trusses. These trusses are connected to form the larger trusses of the primary structure. Cable rigging devices are also operated from the facility. The packages of solar cell blankets

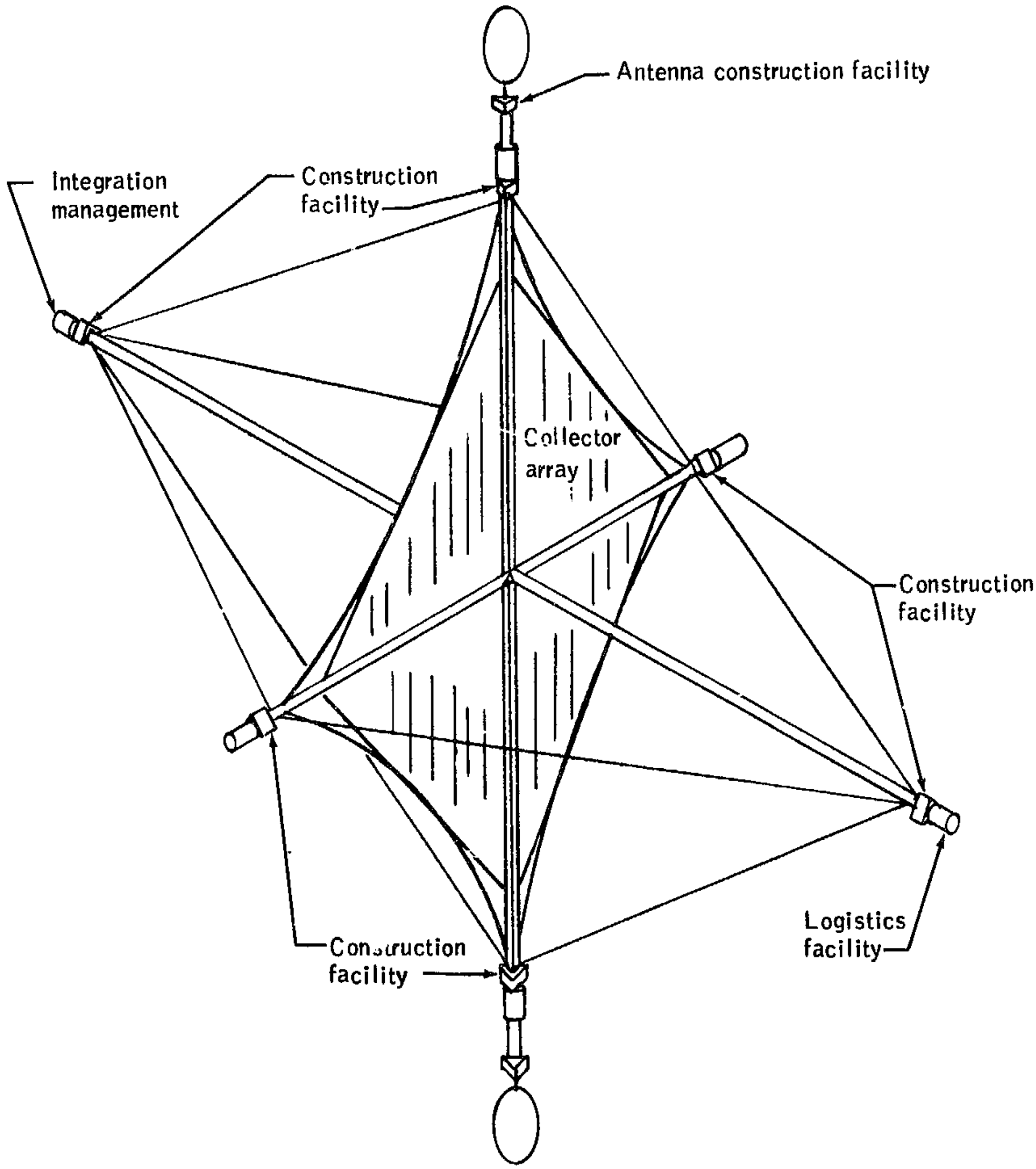


Figure V-7.- Construction base concept for column/cable configuration.

and reflectors are positioned by equipment on two of the facilities sites for deployment. The construction facility provides a platform for connection and deployment of the power distribution cabling.

Two portions of the facility are devoted to antenna construction. Machines for structural fabrication and assembly will build up the primary structure and subarray support structure. Other machines will install antenna subarrays. A part of the construction facility will be devoted to manufacture of the subarrays in a pressurized environment. This is conceived of as an assembly-line operation principally in a shirt-sleeve environment. Subarray manufacture could be done in low-Earth orbit (LEO) to reduce the personnel logistics requirements.

2. Orbital construction and support equipment.- The orbital construction and support equipment is the manned equipment required to monitor the machines in the construction base, to service them, to inspect subsystem installation, and to perform contingency operations. Manned remote-control manipulators will be provided with a shirt-sleeve environment for man-machine operations. Manipulators will be used for acquiring, positioning, alining, holding, and assembling of subsystem components. Conceptually, there would be facility manipulators attached to the construction facility and mobile manipulators able to move along the SPS structure. Extravehicular activity (EVA) capability for contingencies will be provided by EVA modules that house all of the associated EVA equipment hardware, its checkout facility, recharge, stowage and donning facilities, and an airlock to gain access to the vacuum environment. Manned maneuvering units (MMU) may be necessary to support contingency operations.

3. Logistics facility.- The principal function of the logistics facility is as a "warehouse" in orbit to provide the capability for receiving, storing, and distributing supplies, construction materials, fuels, spare parts, and maintenance tools. A storage and distribution capability will be needed because of the magnitude of materials traffic.

A docking port module will be an integral part of the logistics facility and will be used for loading/unloading and servicing arriving and departing orbital transfer vehicles. Materials and personnel will be transferred to other elements of the construction base by means of the attached transit system.

Maintenance, repair, refurbishment, and servicing for construction equipment and vehicle systems will be done in the docking/servicing maintenance module. Fuel storage and fuel transfer operations will also be provided by this module.

4. Integration management facility.- Because of the number of daily arriving and departing orbital transfer vehicles, the displacement of construction base elements, timing or sequence of construction operations, and communications between construction base elements, transportation vehicles, and the ground, a management facility "air traffic control center"

will be needed to integrate all operations in orbit. This facility will provide a communications capability to construction base elements, other satellites, transportation systems, and major ground facilities network.

Centralization for overall mission and operations control for the construction base and its interfaces is a key element in the organization of the base. Mission and operation control will include activities such as transportation and docking control, construction activity scheduling, consumables management, safety operations, laser alinement, and mission logistics. The physical combination of the management facility with the logistics facility is likely.

5. Crew habitability facilities.- Crew habitability facilities consist of a number of elements — the habitation module, subsystems module, and power module. The habitation modules will provide a shirt-sleeve environment for personnel at the eight major worksites. The subsystem modules will contain the necessary subsystems for support and operation of the construction base.

C. Construction Operations

The configuration of the SPS and the sequence of construction will generally define the requirements for the construction base. Construction operations will drive the configuration of the construction base. The financial advantages of a short construction time will interact with the launch rate to define the construction schedule and the construction facility. Guidelines used in developing a staffing plan are as follows.

1. Each construction base in geosynchronous Earth orbit (GEO) will have an autonomous organization unto itself.
2. All modules needed to construct an SPS will be resident and attached to the structure.
3. Nominal construction operations will consist of three shifts, 24 hours/day.
4. There will be four crews to provide for maintenance and off duty time.
5. The crew stay time on orbit will be 180 days.
6. There will be cross training.
7. Construction crews will live at their worksite.

An operational schematic for a construction base is shown in figure V-8.

From the schematic and construction sequence are developed the numbers of machines, the number of operations, and the personnel requirements. All estimates were based on the "nominal" size configuration, which has a solar array area of 142 km^2 (see fig. IV-7). These estimates for a "nominal" size configuration have also been used for the "minimum" (96 km^2) and "maximum" (183 km^2) sized arrays in other sections of the report. Later studies will obviously have to evaluate the effect of array size on crew requirements.

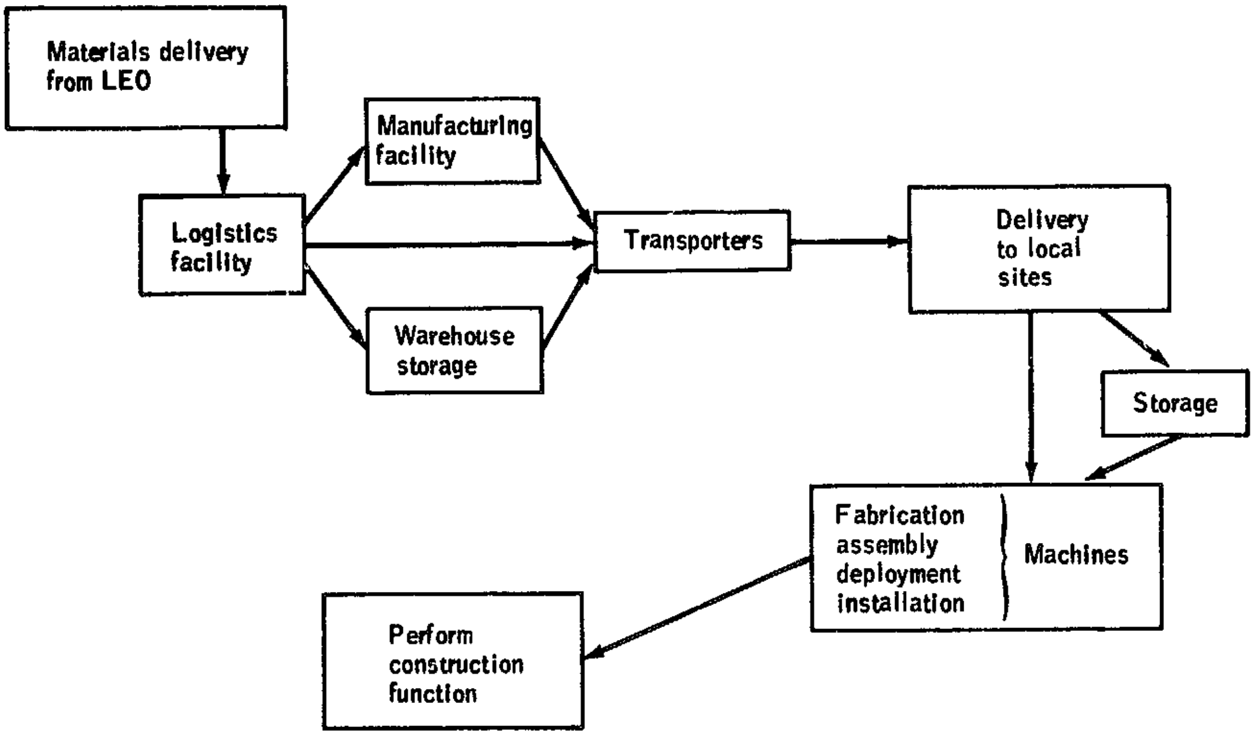


Figure V-8.- Operational schematic of construction base (column/cable).

Table V-1 shows a comparison of the construction equipment requirements for the column/cable and truss configurations. Table V-2 provides an estimate of the personnel requirements for the column/cable configuration construction and support. A typical peak staffing estimate for the truss configuration is provided in table V-3. Typical staffing for manufacture of antenna subarrays in LEO is shown in table V-4.

The peak staffing needed for the typical truss construction base reflects the number and isolation of activity regions. These personnel will generally have passive functions that may be done remotely. The column/cable base activity regions are less numerous but will require greater mobility and more active crew functions. For these reasons, there is greater potential for reduction in crew size for the truss base and less probability of growth in numbers.

TABLE V-1.- ORBITAL CONSTRUCTION EQUIPMENT REQUIREMENTS

Equipment	No./configuration	
	Column/Cable	Truss
SFCS		
Beam-building machines	30	61
Cable-rigging devices	8	0
Solar cell blanket package installers	4	4
Reflector package installers	4	8
Power distribution harness installers	4	4
Mobile manned manipulators	8	5
Facility manned manipulators	12	2
MPTS (two antennas)		
Subarray manufacturing (two/hour)	8	8
Beam-building machines		
Subarray support structure	18	18
Primary structure	8	8
Cable-rigging devices	12	12
Power distribution harness installers	4	4
Subarray installers	4	4

It is expected that more personnel will be required in space for modular construction in LEO with final assembly in GEO. The same construction functions must be performed in LEO; in addition, the assembly of the modules in GEO must be accomplished. A summary of peak crew requirements for the two configurations and different construction locations are as follows.

Configuration	Primary construction location	Peak personnel/SPS GEO	LEO	Total
Column/cable	GEO	474	176	650
Truss	GEO	574	176	750
Truss	LEO	200	740	940

The estimated crew requirements for the truss configuration with primary construction in LEO were done in less detail than the other two cases.

TABLE V-2.- COLUMN/CABLE CONFIGURATION TYPICAL MAN LOADING

Category	Estimated man loading/month (construction personnel)											
	1	2	3	4	5	[a]6	7	8	9	10	11	12
Tasks												
Attach beam builders to hub	48											
Build primary structure		48	48	48	48	48	48	48	48			
Rig cables		24	24	24	24	24	24	24	24			
Install solar blankets			48	48	48	48	48	48	48	48		
Install reflectors				48	48	48	48	48	48	48	48	
Install power distribution system				16	16	16	16	16	16	16	16	
Build antenna substructure		16	16	16	16	16	16	16	16	16		
Build antenna primary structure			16	16	16	16	16	16	16			
Install subarrays				16	16	16	16	16	16	16		
Systems checks											8	8
Subtotal	48	88	152	232	232	232	232	232	232	144	72	8
Support functions												
Management	10	20	20	20	20	20	20	20	20	20	20	10
Food service	32	36	44	48	48	48	48	48	48	48	32	28
Control center	40	40	40	40	40	40	40	40	40	40	40	30
Warehouse	40	40	40	40	40	40	40	40	40	40	40	30
Motor pool	30	40	40	40	40	40	40	40	40	40	40	30
Medical	10	10	10	10	10	10	10	10	10	10	10	10
Other support	36	44	44	44	44	44	44	44	44	44	44	36
Subtotal	198	230	238	242	242	242	242	242	242	242	226	174
Total	246	318	390	474	474	474	474	474	474	386	298	182

[a]Peak staffing.

TABLE V-3.- TRUSS CONFIGURATION TYPICAL MAN LOADING (GEO CONSTRUCTION)

Category	Estimated man loading/month (construction personnel)											
	1	2	3	4	5	[a]6	7	8	9	10	11	12
Tasks												
Beam builders	78	117	156	156	156	156	156	156	156			
Solar cell blanket installers	8	32	32	32	32	32	32	32	32	32		
Concentrator sheet installers	12	61	64	64	64	64	64	64	64	64	64	
Mobile manipulators	12	16	16	16	16	16	16	16	16	12		
Facility manipulators	20	40	40	40	40	40	40	40	40	20		
Antenna primary structure		16	16	16	16	16	16	16	16	16		
Antenna support structure		16	16	16	16	16	16	16	16	16		
Antenna harness and array installers		16	16	16	16	16	16	16	16	16		
System checks											10	10
Subtotal	130	269	356	356	356	356	356	356	356	176	74	10
Support functions												
Management	10	20	20	20	20	20	20	20	20	20	15	10
Control center	40	40	40	40	40	40	40	40	40	40	35	30
Warehouse	40	40	40	40	40	40	40	40	40	40	35	30
Motor pool	30	40	40	40	40	40	40	40	40	40	35	30
Medical	10	10	10	10	10	10	10	10	10	10	10	10
Food service	18	20	28	28	28	28	28	28	28	20	15	10
Other support (laundry, R&R facility, shop, equipment issue)	32	40	40	40	40	40	40	40	40	36	32	28
Subtotal	180	210	218	218	218	218	218	218	218	206	177	148
Total	310	479	574	574	574	574	574	574	574	382	251	158

[a]Peak staffing.

TABLE V-4.- TYPICAL PEAK STAFFING (LEO)
FOR ANTENNA SUBARRAY FABRICATION

Function	Personnel	
	No./shift	Total
Subarray manufacture	16	64
Warehouse	4	16
Management	--	3
Medical personnel	--	4
Control center	3	12
Other support	4	16
Food service	2	8
		123

Considering the current lack of task definition, the degree of automation that can be achieved, and the configuration effects, it is believed that the peak crew personnel requirement in space is between 200 and 800.

The construction study did not include a definition of the weights of the construction base. As an input to the program model, gross estimates were made for LEO and GEO bases. Those crude estimates were obtained as a percentage of the weight of the SPS as follows.

Configuration	Construction location	Mass, metric tons×10^3		
		SPS	GEO base	LEO base
Column/cable	GEO	81.8	6.0	1.0
Truss	GEO	84.4	7.0	1.0
Truss	LEO	84.4	1.0	8.0

It was assumed that each base would require a replacement, refurbishment, or repair mass of 1000 metric tons per year or per SPS constructed.

Maintenance operations for each SPS were estimated to require 12 man-years/year for each SPS at GEO and 0.5 man-years/year at LEO. It was further assumed that the mass to orbit associated with maintenance would be 800 to 900 metric tons per year.

Personnel provisions requirements were estimated to be 2 or 3 metric tons/person/year, with the larger number being required at the primary construction location.

VI. SPACE TRANSPORTATION SYSTEMS

A. Systems Requirements and Analysis

The SPS transportation system is required to transport building material, subassemblies, equipment, supplies, and personnel to geosynchronous orbit (GEO) at a rate sufficient to establish as many as seven stations per year (assuming a moderate rate of buildup, or scenario B), having masses ranging from 47×10^6 to 124×10^6 kg/station. The largest and most massive payload element is now expected to be the rotary joint between the transmitting antenna and the solar energy collection structure (SECS). This rotary joint measures up to 12 by 10 by 10 m and weighs up to 450 metric tons.

Performance and economic considerations dictate that the Earth to low-Earth orbit (LEO) transportation be accomplished by heavy lift launch vehicles (HLLV) designed for the appropriate flight rates and the loads associated with launch, atmospheric flight, reentry, and landing, whereas the LEO-to-GEO transportation vehicles (orbital transfer vehicles (OTV's)) be designed for nonatmospheric loads and high specific impulse (possibly low thrust) propulsion. A single transportation vehicle design suitable for both flight regimes would be a difficult feat with present technology and would be, at best, a compromise design that would not be cost effective compared with separate vehicles.

The alternatives open to the power satellite designers that have the largest impacts on the transportation system are (1) construction of the station in GEO, (2) construction of the station in LEO and transporting it to GEO in modules for final assembly, and (3) construction of the station completely in LEO and transporting it to GEO as a single unit. The first alternative is considered to be required by the column/cable structure, whereas the first, second, and third are permitted by the truss configuration.

These alternatives affect the OTV design because assembly in LEO, either partial or complete, offers the possibility of using payload-supplied power for LEO-to-GEO propulsion. This is expected to reduce transportation costs because it permits effective use of high-specific-impulse, low-thrust electrical propulsion systems that require relatively small quantities of propellant to be lifted from the Earth's surface. If power is not available from the payload, as in the case of the first alternative, electrical propulsion is still possible, but requires a heavy dedicated power source, the expense of which dictates round-trip flight. Under such conditions, chemical and nuclear propulsion systems become competitive.

Two cargo OTV concepts are considered. One is for the SPS configurations that involve primary construction at GEO and therefore requires independent OTV propulsion systems. The second is for SPS configurations that involve construction at LEO, either total or in modules, which can provide energy for propulsion for orbital transfer.

Crew transportation from Earth to LEO will be accomplished by a personnel launch vehicle (PLV), which may be a Space Shuttle derivation, and from LEO to GEO by a chemically powered personnel OTV (POTV). The POTV is expected to incorporate a conventional chemical rocket, probably O_2/H_2, to provide a short transit time system (1 day or less). The thrust level necessary to achieve the short time of flight precludes high-specific-impulse, low-thrust electrical systems.

B. Heavy Lift Launch Vehicle

The HLLV is designed for transporting all SPS freight, except crews and high-priority cargo, from Earth to LEO. The launch site is assumed to be the NASA John F. Kennedy Space Center (KSC), and payloads are launched into an approximately 90 by 500 km, 28.5° inclination nominal insertion orbit. Payload rendezvous capability is provided by the orbital maneuvering system (OMS) to decrease second-stage velocity requirements. This imposes a weight penalty of approximately 3 percent on the payload for the OMS, including propellant, and requires a subsequent return to Earth for the OMS engines and avionics. The cost of OMS recovery has not been investigated. The HLLV will provide a payload environment, such as acceleration, shock, vibration, temperature, etc., similar to that provided STS payloads, but will provide no additional services.

The key figure of merit for the HLLV is the cost per pound of payload to LEO. Minimizing this cost requires attaining as much reusability as possible with as little refurbishment and parts replacement as can be achieved. Reuse goals of 300 and 500 flights were considered from a structural design (fracture mechanics) standpoint and are suggested as the range for launch vehicle replacement calculations and costing purposes.

No particular requirements for advanced technology were assumed in the HLLV studies. Hydrocarbon fuel engines are considered best for launch vehicle first stages because the greater fuel density relative to hydrogen allows enough decrease in structure with related cost advantages to outweigh the higher specific impulse of hydrogen fueled engines. The engines that were considered are presented in table VI-1. The HLLV candidate configurations are presented in table VI-2.

These candidates represent the range of launch vehicle concepts suggested by the section on Technology Forecast of the Outlook for Space report and by NASA and industry experts. Other candidates, such as mixed ballistic and winged systems and very large (450-ton payload) single stage to orbit (SSTO) vehicles were considered in a study contracted by Boeing (NAS 9-14710). Study analyses conducted to date did not identify the mixed systems as leading candidates, although the large SSTO was considered a close competitor to the two-stage ballistic vehicle.

The modified SSTO is an SSTO launch vehicle with a 100- to 175-metric ton payload capability. It features an expendable external hydrogen tank (hence "modified" SSTO) and uses 15 uprated (4000-psia chamber pressure)

TABLE VI-1.- HLLV CANDIDATE ENGINE CHARACTERISTICS

Engine	Fuel	Oxidizer	I_{sp}		T_{VAC}/dry weight
			Sea level	Vacuum	
F-1 (ϵ=10)[a]	RP-1	O_2	262	288	93
SSME[b,c]	H_2	O_2	363	455	74
New RP-1[a]	RP-1	O_2	313	344	90
New RP-1[b]	RP-1	O_2	280	313	107
New Propane[a]	C_3H_8	O_2	303	338	100
Growth SSME[b,c]	H_2	O_2	-	466	75

[a]Gas generator.

[b]Staged combustion.

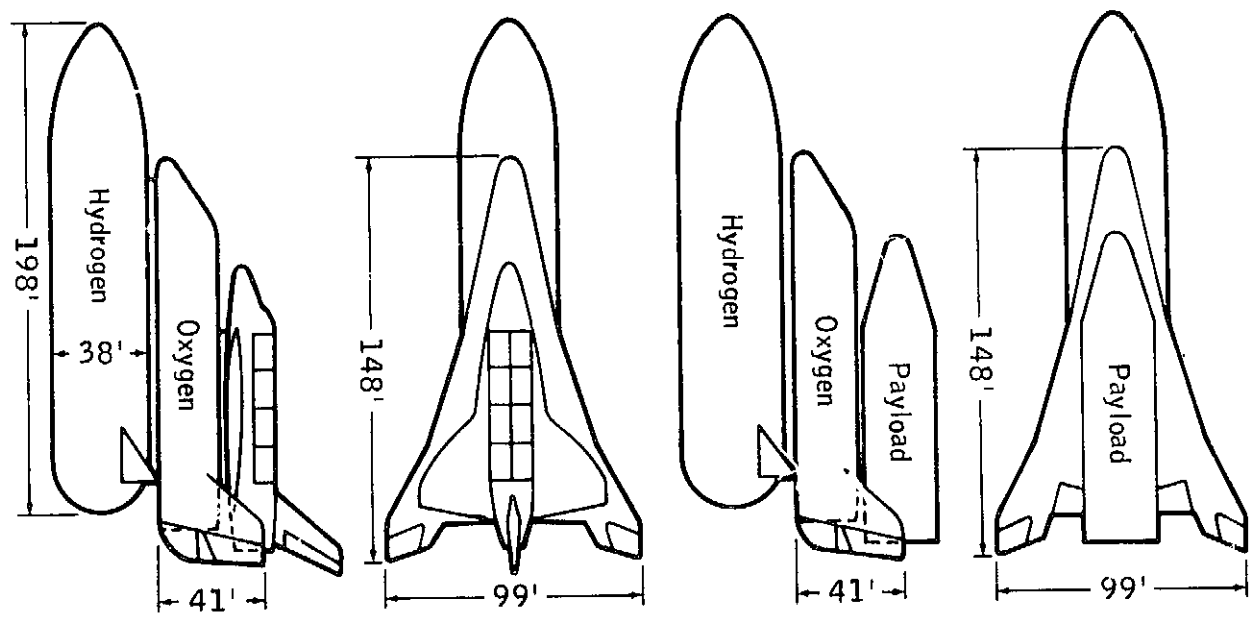
[c]SSME = Space Shuttle main engine.

TABLE VI-2.- HLLV CANDIDATE CONFIGURATION CHARACTERISTICS

Configuration	Propellants		Payload, Metric tons
	Stage 1	Stage 2	
Modified SSTO	O_2/H_2	-	100 to 175
Two-stage winged	O_2/H_2	O_2/H_2	450
	O_2/RP-1	O_2/H_2	450
	O_2/propane	O_2/H_2	450
Two-stage ballistic	O_2/RP-1	O_2/H_2	450
	O_2/propane	O_2/H_2	450
	O_2/RP-1	O_2/H_2	900
	O_2/propane	O_2/H_2	900

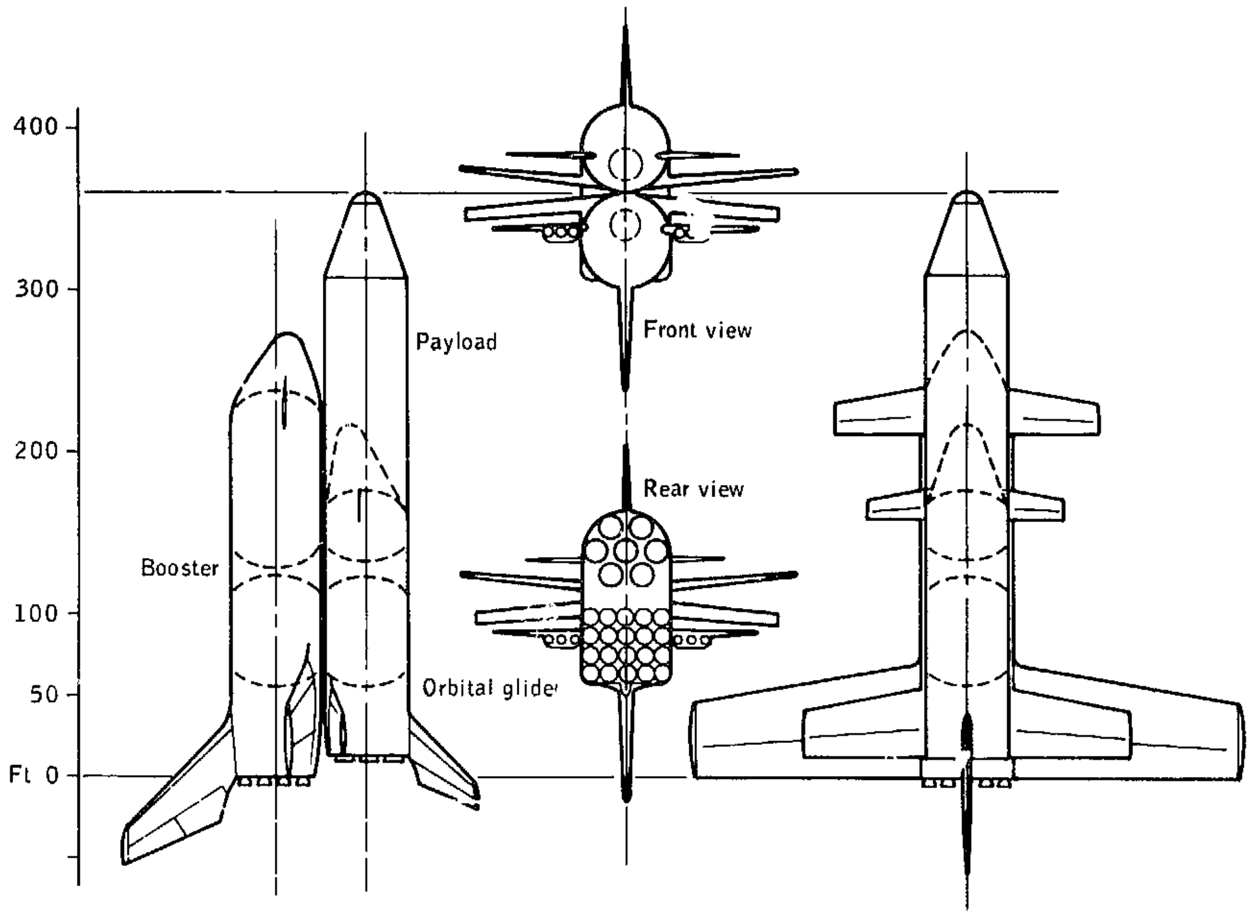
SSME's. Its payload can be a modified Orbiter (which does not require a main propulsion system) with a 45-ton payload or a personnel carrier module carried internally in the payload bay or a much larger payload in an aerodynamic shroud. The external hydrogen tank is separated and reentered in a remote ocean region as is the Space Shuttle external tank. The configuration and characteristics are shown in figure VI-1.

The two-stage winged candidate is a 450-metric ton payload launch vehicle that accepts a potentially higher unit cost than water-recovered vehicles in order to acquire the operational advantages of airplane-like recovery. Several configurations, burn sequences, and engines were investigated and are described in Volume II. The characteristics and configuration of a selected design using 20 LOX/propane (C_3H_8) engines are shown on figure VI-2, along with the characteristics



Payload, tons, 185 x 185 km, tons	140 (shroud) - 45 (in Orbiter)
Modified Orbiter inert, tons	61
Stage inert, tons	166
Stage oxidizer, tons	2352
External tank inert, tons	69
External tank fuel, tons	392
Gross lift-off weight, tons	3143
Number of engines (uprated SSME's)	15
Tank staging altitude, km	111
Tank staging velocity, km/sec	7.82
Thrust/weight ratio	1.25

Figure VI-1.- Modified single-stage-to-orbit launch vehicle.



	Booster type		
	LH_2	RP-1	Propane
Payload tons, 90 x 500 km	477	477	477
Stage 1 inert, tons	1602	1331	1347
Stage 1 propellant tons	7034	9279	9580
Stage 2 inert, tons	368	432	444
Stage 2 propellant, tons	1570	1838	1891
Gross lift-off weight, tons	11,051	13,357	13,738
Number of engines, stage 1	18	22	20
Number of engines, stage 2	6	7	7
Staging altitude, km	70.83	58.4	57.2
Staging velocity, relative	2.93	2.70	2.65
Booster maximum down range	--	--	--

Figure VI-2.- Two-stage winged launch vehicle.

of LH2 and RP-1 systems. The design, development, test, and evaluation (DDT&E) cost is estimated to be about $10 billion with a first unit cost of about $900 million. This is high compared to the similar preliminary estimates of two-stage ballistic system costs (see the cost summary in table VI-3), but the selection discriminator will likely be the operational costs, for which the dry-land, launch-site recovery advantages of the winged system may prevail.

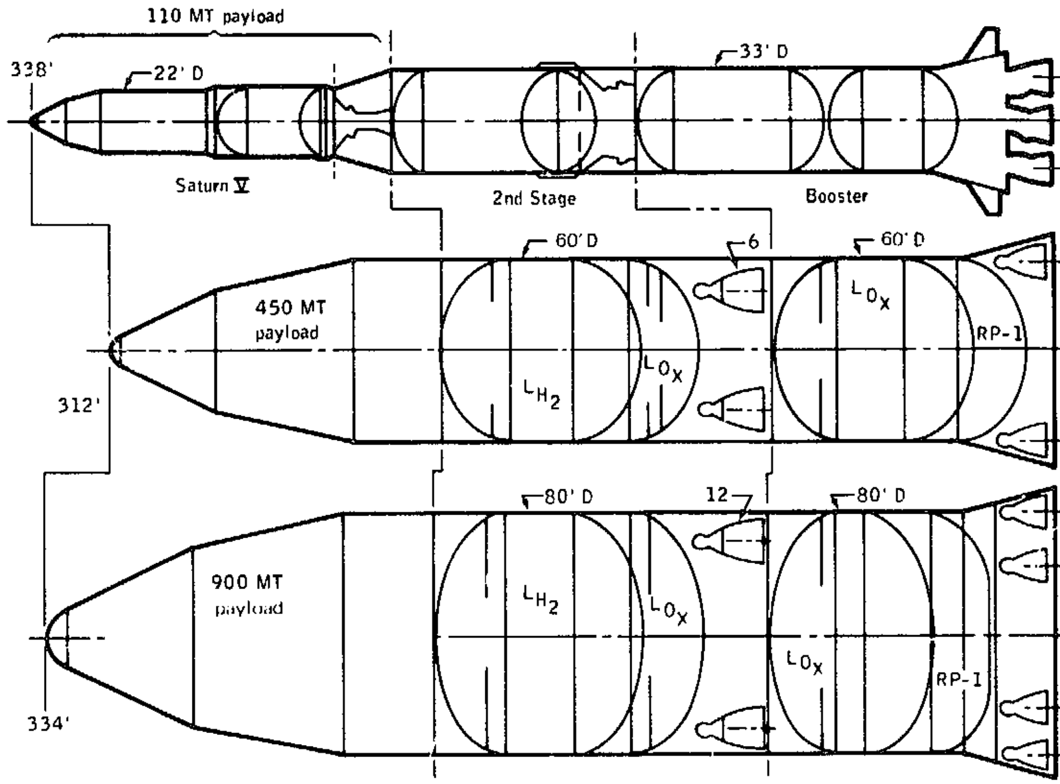
For the two-stage ballistic configuration, in which both stages are recovered ballistically, Saturn V weight and geometry technology and aerodynamic data were used. Both 450- and 900-metric ton payload capability vehicle concepts were studied. Both LOX/RP-1 and LOX/C_3H_8 first-stage engines were evaluated. Outline drawings of each size vehicle and their characteristics are shown in figure VI-3 with a Saturn V for comparison. The DDT&E cost is estimated to be less than $5 billion with a first unit cost of less than $500 million for the smaller version, which has the same payload as the winged configuration. As mentioned before, operational costs will be the discriminator, and considerably more study is required on the cost of vertical water landing and the resultant refurbishment costs.

Study results to date indicate that the goal expressed in the satellite power team study of $20/lb ($44/kg) to LEO is attainable for large-payload, high-launch-rate systems. It is not yet possible to determine the favored launch vehicle concept from among the modified SSTO, two-stage winged, or two-stage ballistic candidate systems studied. Operating costs must be much more carefully estimated. At this point, the two-stage ballistic vehicle is chosen to represent the minimum cost HLLV and the two-stage winged the maximum. A summary of estimated costs is shown in table VI-3. The indicated total cost per flight is preliminary and a more accurate determination will be a goal of future studies. In particular, operational costs must be determined, based on operational scenarios, including specific launch and recovery sites and manpower requirements. This analysis is required to determine whether the possible lower operating costs of winged recovery and SSTO systems will outweigh the lower initial costs of ballistic systems.

TABLE VI-3.- HLLV COST ESTIMATES

Configuration	Stage-1 propellant	Payload, metric tons	Cost, $ billion		
			DDT&E	TFU	Per flight (a)
Two-stage winged	O_2/propane	450	10.5	0.9	0.03
Two-stage ballistic	O_2/propane	450	4.2	.5	
Two-stage ballistic	O_2/propane	900	4.8	.7	.02

[a]Includes vehicles, operations, and amortized spares/refurbishment.



	O_2/RP-1 Booster		O_2/Propane Booster	
Payload, tons, 90 x 500 km	454	907	454	907
Stage 1 inert, tons	500	889	485	865
Stage 1 propellant, tons	4441	8236	4410	8177
Stage 2 inert, tons	233	400	245	421
Stage 2 propellant, tons	1937	3599	2065	3832
Gross lift-off weight, tons	7565	14031	7659	14203
Number of engines, stage 1	12	24	12	24
Number of engines, stage 2	6	12	6	12
Staging altitude, km	43.4	43.5	41.3	40.6
Staging velocity (REL), km/sec	1.84	1.91	1.70	1.78
Booster maximum down range	381	396	346	357

Figure VI-3.- Two-stage ballistic launch vehicle.

C. Personnel and Priority Cargo Launch Vehicle

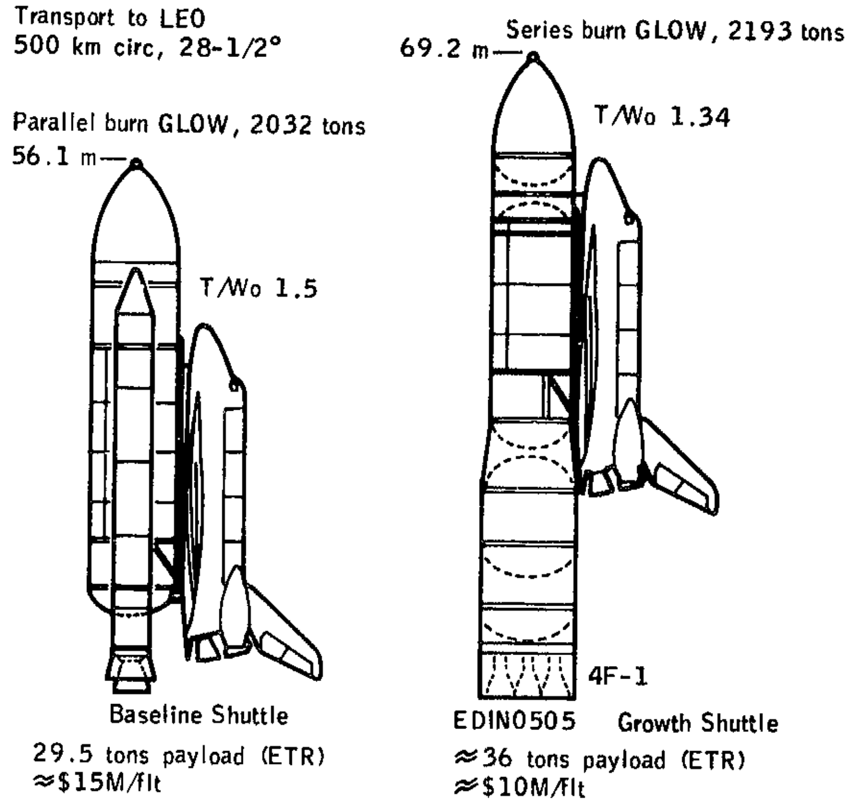
The PLV will be utilized to transport all personnel to LEO and can, in addition, fulfill high-priority delivery functions of a modest scale. The approach taken in this study was to modify the current Space Shuttle vehicle to fulfill these requirements. Past studies have indicated that the baseline Shuttle system can be improved in both payload capability and operating cost by replacement of the two solid rocket boosters with a liquid rocket booster (LRB) utilizing oxygen and kerosene propellants. If available for heavy lift vehicle use, a new, more efficient, oxygen/hydrocarbon engine can be advantageously employed to increase the payload capability of this growth Shuttle booster or enable a decrease in propellant requirements. The LRB is a 33-ft-diameter stage with integral propellant mounted beneath the Shuttle external tank (ET). It uses four F-1 class engines and provides series burn operation. The stage is recoverable down range following a parachute water landing.

The reference mission for the study is the Shuttle Reference Mission 1, with an Orbiter modified for a payload of up to 100 000 pounds (45 metric tons). The LRB is sized according to weight estimating relationships based on Saturn technology. The Orbiter is modified to include the additional structural weight necessary to accommodate the increased up payload.

Both series burn and parallel burn Shuttle/LRB configurations were studied. The series burn mode achieved minimum gross lift-off weight (GLOW) in the design cases simulated and is expected to be significantly less expensive due to the smaller expendable ET. The design simulation designated EDIN0505 was chosen as the reference PLV configuration. This configuration and characteristics are shown on figure VI-4. A concept has been proposed by Rockwell International for a 68-passenger Orbiter transport vehicle. Although as many as 100 passengers may be possible for a modified Orbiter, a range of 40 to 80 passengers is assumed in the present study. The estimated cost per flight is $8 to $12 million.

D. Cargo Orbital Transfer Vehicle

The COTV is a space-based system designed for transporting from LEO to GEO all the material required for SPS construction or assembly, but does not transport personnel. Two basic COTV systems may be identified, distinguished by whether or not power is available from the payload. The first system, $COTV_L$ applies to SPS configurations that involve construction at LEO, either total or in modules, which can provide energy for propulsion for orbital transfer. The second system, $COTV_G$, applies to SPS configurations that involve primary construction at GEO and consequently cannot provide payload power for transfer from LEO to GEO.



Payload, tons	36 (internal orbiter)
Payload, passengers	40 to 50
Orbiter, inert, tons	85
External tank, inert, tons	33
External tank, propellant, tons	567
Liquid rocket booster, inert, tons	138
Liquid rocket booster, propellant, tons	1325
Gross lift-off weight, tons	2193
Number of engines, (F-1's)	4
Staging altitude (booster), km	45.54
Staging velocity, km/sec	1.40

Figure VI-4.- Personnel and priority cargo launch vehicle.

The characteristics of the thruster systems studied are presented in table VI-4. Attractive systems are those with the highest specific impulse, because less propellant must be transported to LEO. However, these systems (ion thrusters) are extremely low thrust units and their acquisition costs cannot be quantified with the same confidence as chemical systems. The thermal and magnetoplasmadynamic (MPD) arcjets appear to enjoy relatively high specific impulse levels with significantly lower hardware weight, complexity, and cost.

Because the COTV does not have human factors restrictions on transit time, it is possible to use the thruster systems with high specific impulse, even if the corresponding thrust-to-weight ratio (T/W) is extremely low and

TABLE VI-4.- OTV CANDIDATE THRUSTER CHARACTERISTICS

Type	Propellant	I_{sp}, sec	Thrust/weight	Electrical efficiency, percent
Chemical	O_2/H_2	460 to 470	37	--
Nuclear-thermal	H_2	760 to 780	3	--
Resistojet	H_2	800 to 1 000	1	65
Thermal arcjet	H_2	2 000 to 3 000	.01	50
MPD arcjet	Ar	2 000 to 10 000	.01	50 to 70
Ion	Ar	5 000 to 20 000	4×10^{-4}	85

the trip times are measured in months. In the case of LEO assembly or partial assembly, the acceleration placed on the structure by the $COTV_L$ must be less than 0.001g, which dictates a low T/W. The transit time variation with T/W is shown in figure VI-5. Other implications of using a low thrust level, which results in an acceleration several orders of magnitude less than the local gravity, are: (1) continuous thrusting and acceptance of gravity losses is necessary rather than the three burn impulsive transfers normally practiced, (2) thrust may be horizontal to the ground for simplicity, because this is very close to the ideal velocity vector, and (3) the delta velocity required is approximately equal to the actual difference in the circular velocities of the original and new orbits.

A problem associated with systems using solar energy and exerting a continuous low thrust is the occultation of the Sun by the Earth. This interrupts thrusting and may require that a system reacquire solar orientation each time the satellite emerges from the shadow. Another factor affecting the photovoltaic system is that solar cells exposed during passage through the Van Allen belts will suffer a performance degradation estimated to be as high as 30 percent for the long transit times considered. This effect is reduced because the $COTV_L$ does not require that all the array be exposed during orbital transfer. These problems can be avoided if a reusable chemical propulsion system is used to take the payload to a higher orbit, perhaps as high as 5000 km; then the switch to the solar-powered system is made.

The $COTV_L$'s, using payload-supplied power, can take full advantage of the more advanced thruster concepts, such as the MPD arcjet, because they do not pay the penalty of the necessarily heavy power supplies and the round-trip mission. These systems have the advantage of low propellant requirements, thus decreasing the orbital burden factor, but must pay some economic penalty because of their long transit time. Additionally, an MPD thruster/argon-propellant system operating from its own nuclear reactor appears to hold promise for low thrust, nuclear-electric payload transfer. Key factors, presently

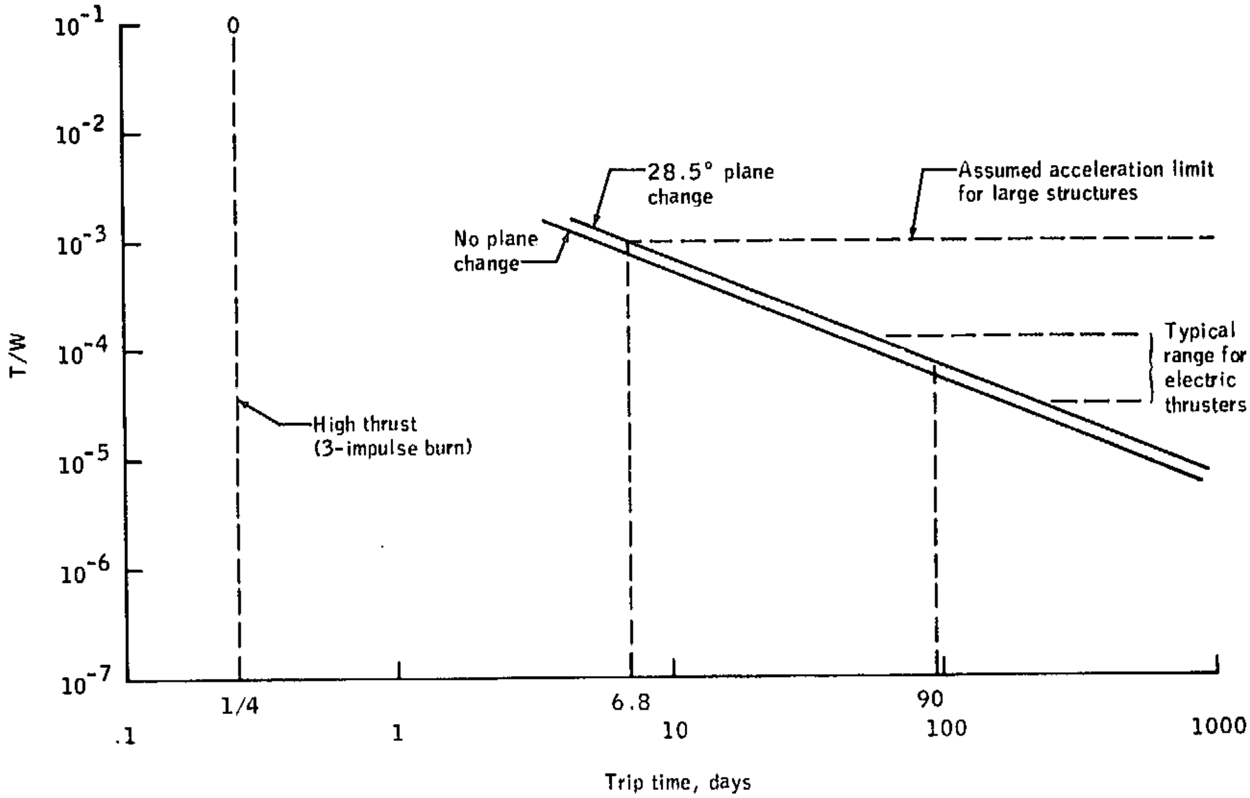


Figure VI-5.- LEO-to-GEO transfer time as a function of thrust/weight.

unresolved and directly affecting the cost competitiveness of this approach, include the following.

1. Thruster efficiency and specific jet power
2. Thruster specific impulse
3. Thruster refurbishment and total operating life
4. Nuclear reactor disposal after useful life
5. Allowable orbit transfer time

The configuration and construction concept that allows the SPS to be at least partially assembled in LEO allows the $COTV_L$ to use payload-supplied power. Its structural acceleration limits are expected to be so low (0.001g or less) that the low thrust level orbital mechanics computations are necessary. The $COTV_L$ candidates are primarily defined by the characteristics of their thrusters. At this time, an MPD arcjet configuration has been identified as the "best case" option, with the electrically driven thermal arcjet as the fallback position, or "worst case" option.

The $COTV_G$, applicable to SPS construction in GEO, need not handle payloads in as large segments or with as low acceleration limits, but it does need to supply its own energy. Possibilities are solar energy collected by solar cells or thermal systems, nuclear reactors, and chemical propulsion systems. Present analyses indicate that an O_2/H_2 chemical $COTV_G$ may be the least expensive option.

A comparison of various stages and reusability versus expendable choices in terms of propellant-to-payload ratio versus stage mass fraction is shown on figure VI-6. It is seen that the two-stage reusable system requires more propellant than does a single-stage expendable system but it has the advantage of reusing the hardware.

Two primary O_2/H_2 chemical propulsion $COTV_G$ configurations have been investigated. The first is a two-stage reusable system with both stages returned to LEO. The second is a 2-1/2 stage vehicle, which is based on the assumption that an empty drop tank may be left with the SPS as parasitic weight without penalty, or perhaps even utilized in the SPS construction at GEO. The configuration and characteristics of the two and one-half stage system, as shown on figure VI-7, are represented as the "nominal" $COTV_G$ for the program model work presented in section VII.

Partial recovery concepts may be devised. One example suggested by Rockwell International may merit further consideration. In this concept, the engine (modified SSME) and avionics are returned from GEO to Earth ballistically and recovered at sea.

The propellant-to-payload weight ratio as a function of stage mass fraction for a NERVA solid core nuclear propulsion OTV was investigated, and its advantages in propellant weight brought to LEO over the O_2/H_2 system appeared to be small and may not be preserved if longer reactor life than 10 hours is specified. The reduced propellant requirement, if any, must be balanced against the greater vehicle and space operations cost of nuclear stages and the performance penalty and operations costs associated with disposal of the reactor at the end of its useful life. In the Future Space Transportation System Analysis Study (NAS 9-14323), it was concluded that the solid-core nuclear OTV was a higher cost option than O_2/H_2 stages.

E. Personnel Orbital Transfer Vehicle

The POTV will be utilized to transport all personnel from LEO to GEO and return to LEO and to transport high-priority cargo to GEO. The short trip time (less than 1 day) and small payload requirement of the POTV preclude commonality with the high-specific-impulse, low-thrust cargo OTV systems being considered. Therefore, except in the case of the independent high-thrust, chemical-propulsion cargo OTV, the POTV is considered as a special-purpose device optimized for personnel transfer between LEO and GEO.

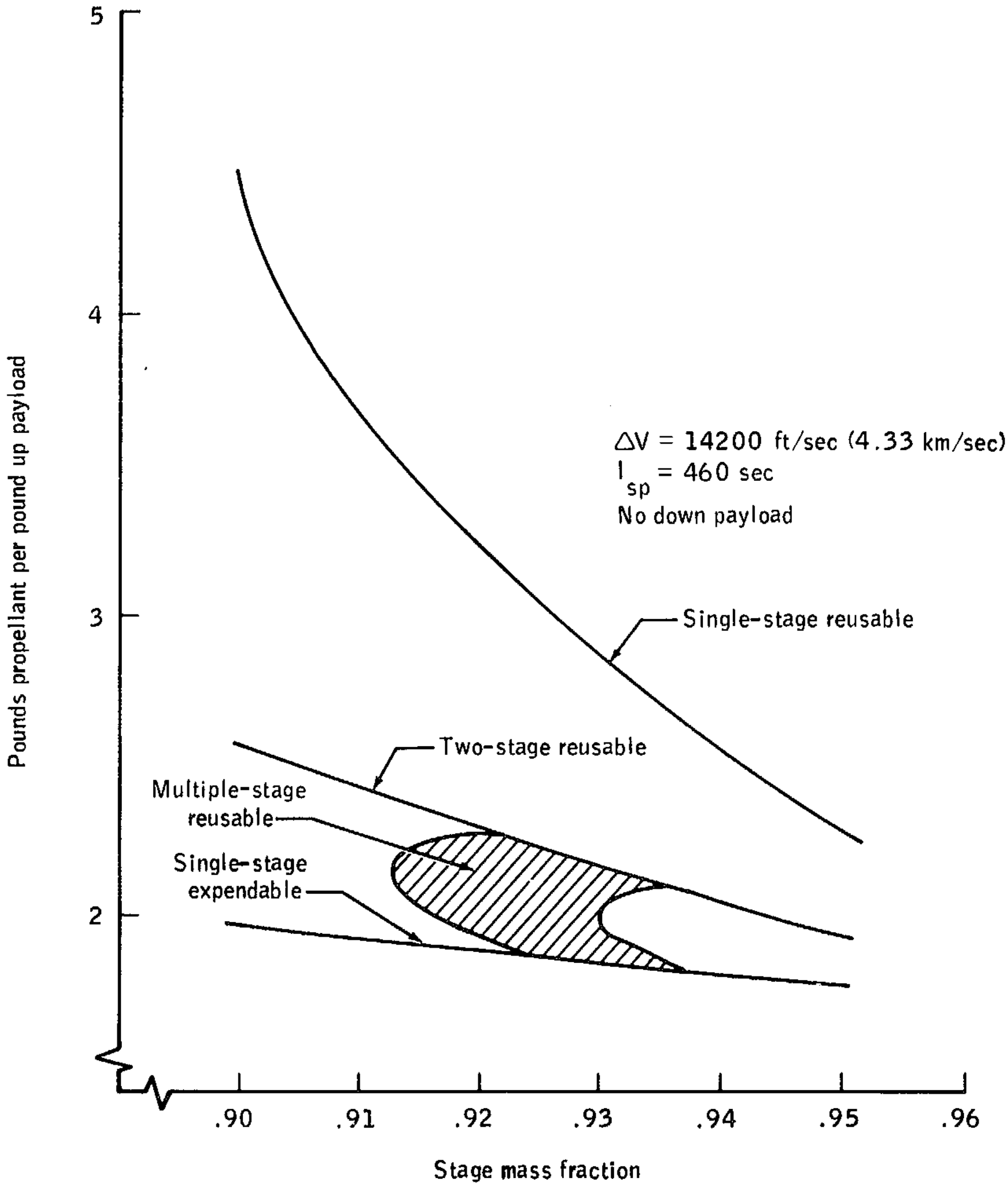
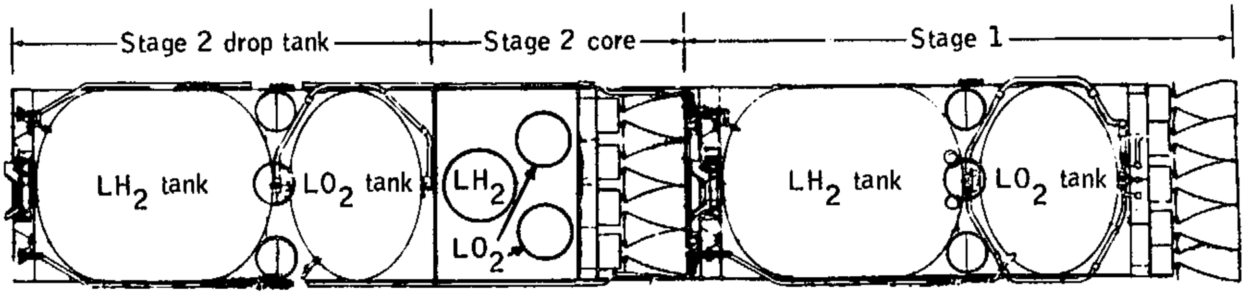


Figure VI-6.- Propellant burden contribution for high-thrust O_2/H_2 COTV.



2-1/2 stage LO_2/LH_2
Life: 30 missions
Payload: 250 tons
≈$10M/flt

Length: 48 m
Diameter: 8.4 m
Total weight: 510 tons
Propellent weight: 475 tons

Figure VI-7.- Cargo orbital transfer vehicle ($COTV_G$) characteristics.

The POTV LEO-to-GEO mission is assumed to be initiated at the LEO orbit transfer operation base. Modular OTV elements are docked and propellants tanks topped off. A two-burn injection places the OTV and payload on the synchronous transfer ellipse with a trip time of 8 to 9 hours. At apogee, the circularization maneuver is performed and rendezvous with the GEO SPS construction base is accomplished. GEO orbital stay for a typical mission is between 2 and 7 days. Orbital stay time can be extended for GEO refueling applications. Return to the LEO base is all-propulsive.

For the purpose of this study, the conservative choice was made to employ conventional chemical propulsion with all-propulsive return of the vehicle and crew to LEO. Single-stage, 1-1/2 stage (outbound propellant tanks expended), and common-stage configurations are all candidates for this mission. Additionally, for those cases where economic cargo transportation is available, significant advantages may accrue to the POTV by storing propellants in GEO (having previously been delivered by the cargo OTV) for the return journey.

A crew module concept layout is shown on figure VI-8. During the operational program phase, the crew module will be used as the manned control compartment for the POTV, now transporting the crew rotation passenger module, which is shown on figure VI-9. High-priority cargo may be carried as POTV payload instead of, or in addition to, the crew rotation passenger module.

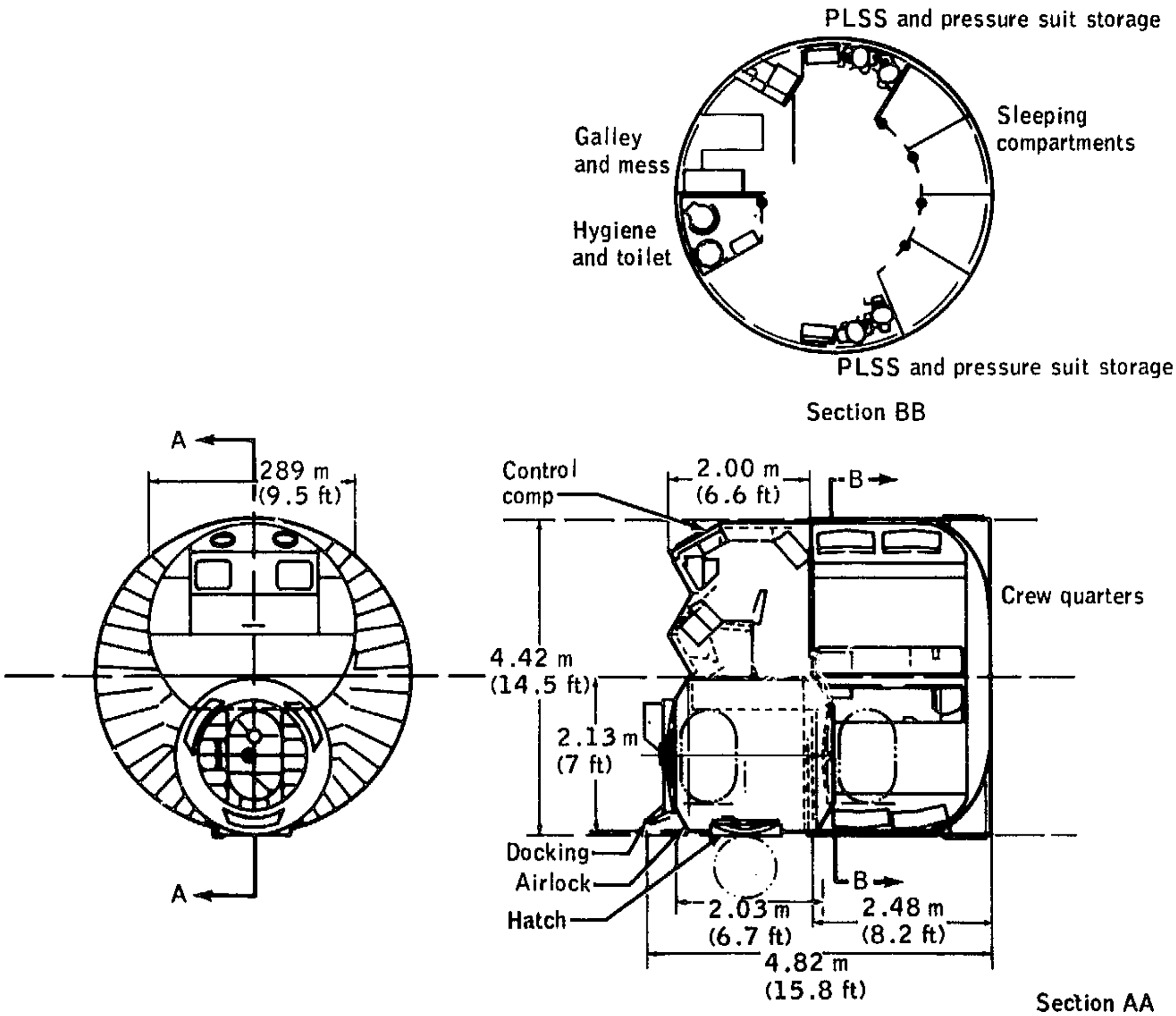


Figure VI-8.- Crew module concept.

Results of a parametric sizing study indicate that, although the 1-1/2 stage candidate required less LEO start-burn mass, the common-stage (two identical stages) candidate may provide more versatility to the transportation fleet with its capabilities for operation as a single stage (each stage individually), its total reusability to LEO, GEO sortie missions operations, and GEO refueling of second stage for return to LEO. In addition, the individual stages are compatible with the Shuttle payload bay. The sizing mission for the POTV is assumed to be the GEO manned sortie mission with total reusability and turnaround at LEO.

No. of passengers	Dim "A" length, m	Gross weight, tons
25	6.51	7.54
50	9.29	13.28
100	14.85	24.28

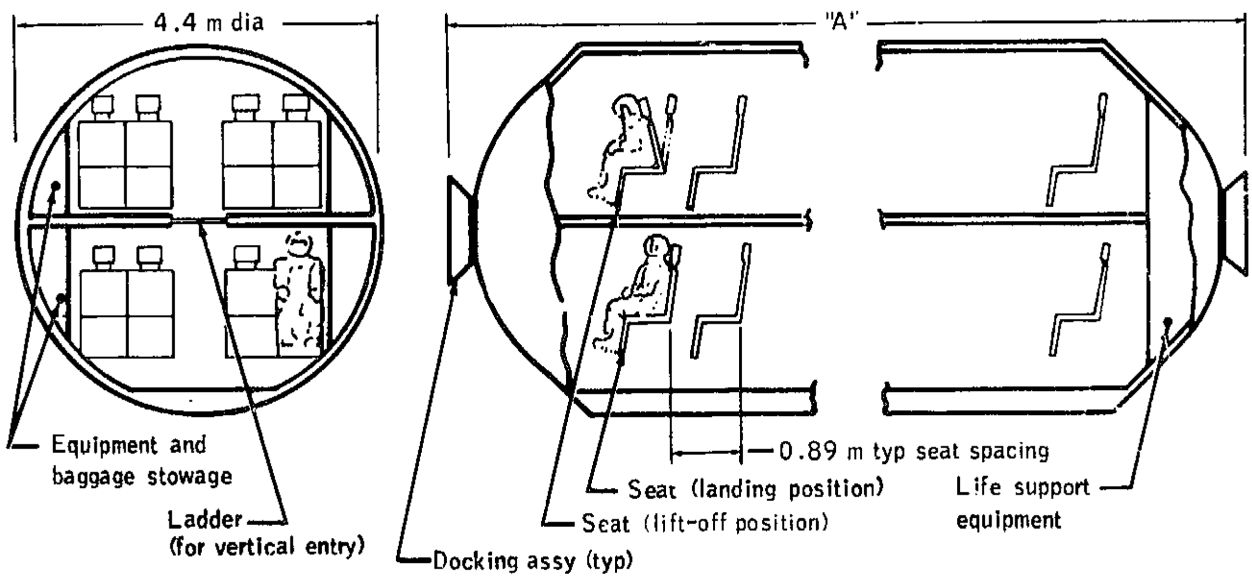
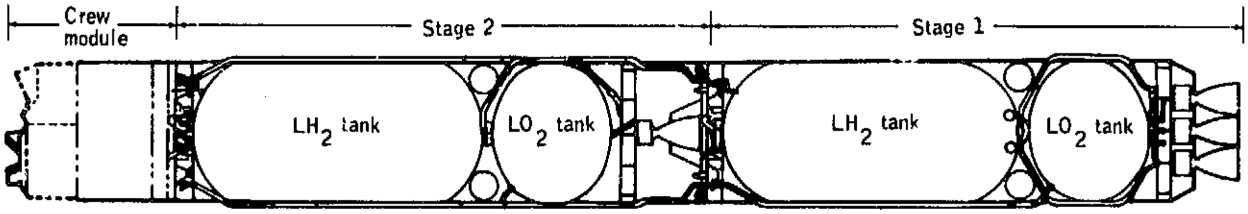


Figure VI-9.- Crew rotation passenger module.

The common-stage concept consists of two nearly identical stages used in series to provide the required mission delta velocity. The first of these stages is used to provide approximately 85 percent of the delta velocity required for acquiring the elliptical geosynchronous transfer orbit on a crew rotation flight. The second stage provides the remainder of the transfer delta velocity as well as that required for circularization at the destination orbit and both of the return maneuvers. Following separation from stage 2, stage 1 is retrograded into the Earth-circular departure orbit. Splitting the delta velocity in the above manner results in the stages having identical propellant capacities. Subsystems design approaches are also common between the stages, including the size of the main engine.

A representative $POTV_L$ configuration and characteristics are shown on figure VI-10, together with the crew module. The dimensions of the stages are Shuttle compatible but due to their propellant requirements will require on-orbit fueling/refueling. A 75-man crew rotation module plus over 20 metric tons of priority cargo can be carried to GEO in the operating mode wherein stage 2 is refueled at GEO.



Common stage LO_2/LH_2
Life: 30 missions
Payload: 75 passengers + 20 tons (up)
75 passengers (down)
(2nd stage GEO refuel)
≈$12 M/flt

Length: 33.28 m
Diameter: 4.42 m
Total weight: 123 tons
Propellant weight: 106 tons
Number of engines at 66 720 newtons each:
Stage 1: 4 engines
Stage 2: 2 engines

Figure VII-10.- Personnel orbital transfer vehicle ($POTV_L$) characteristics.

Current cost estimates, in $ million, are as follows.

DDT&E	$478
Total first unit	$ 31
Total operating cost/ flight, maximum	$ 20
Total operating cost/ flight, minimum	$ 7

F. A Summary of Projected Transportation System Characteristics

The results of studies of the various transportation elements necessary to support the SPS program have been presented in the previous sections. In this section, the results are used to develop maximum, nominal, and minimum estimates of characteristics for each transportation element (HLLV, PLV, $COTV_G$, $COTV_L$, $POTV_G$, $POTV_L$). The MINIMUM estimates are the most optimistic combination of characteristics, whereas the MAXIMUM estimates are the most pessimistic, with the NOMINAL estimate lying between these extremes.

The nominal estimates of tables VI-5 to VI-8 were used to derive the nominal cost of transportation for implementing a nominal network of SPS units and to develop the overall program model presented in section VII. The minimum, nominal, and maximum estimates were used with SPS's of minimum, nominal, and maximum weights to develop the range of estimates of the "cost of electricity," presented in section XI.

The nominal estimates of tables VI-5 to VI-8 were also used to derive the nominal cost of transportation for implementing nominal weight SPS's with different configurations and construction locations. These results are presented in table VI-9 and indicate the expected reduced costs of constructing the system in LEO and utilizing energy from the system to provide power for orbital transfer. The calculations also indicate the small percentage (<5 percent) of costs involved in personnel transfer. It is also apparent that the cost of cargo transport to LEO dominates the space transportation cost elements.

TABLE VI-5.- HLLV RANGE OF PROJECTED ESTIMATES

Characteristics	Minimum	Nominal	Maximum
Payload/flight, metric tons . . .	900	700	450
Flight cost:			
$ million/flight	20	23	25
$/kg	22	33	56
Flight turnaround, days	5	6	9

TABLE VI-6.- PLV RANGE OF PROJECTED ESTIMATES

Characteristics	Minimum	Nominal	Maximum
Passengers/flight	80	50	40
Flight cost, $ million/flight . . .	8	10	12
Flight turnaround, days	7	11	14

TABLE VI-7.- COTV RANGE OF PROJECTED ESTIMATES

Characteristics	$COTV_G$			$COTV_L$		
	Minimum	Nominal	Maximum	Minimum	Nominal	Maximum
Payload/flight, metric tons	250	250	250	1000	1000	1000
Total inert weight, metric tons	29	35	43	122	166	215
Expended inert weight, metric tons	7	9	11	79	110	138
Propellant/flight, metric tons	453	475	494	691	800	902
Preflight propellant loss, metric tons	136	143	147	207	240	271
Flight cost:						
$ million/flight	5	10	20	20	30	70
$/kg	20	40	80	20	30	70
Flight turnaround, days	5	7	10	5	7	10
Mission life, missions	50	30	20	20	10	5

TABLE VI-8.- POTV RANGE OF PROJECTED ESTIMATES

Characteristics	$POTV_G$			$POTV_L$		
	Minimum	Nominal	Maximum	Minimum	Nominal	Maximum
Passengers/flight, no.	[a]240	[a]230	[a]215	75	75	75
Inert weight, metric tons	29	35	43	17	19	23
Propellant up, metric tons	453	475	494	93	106	126
Propellant down, metric tons	--	--	--	47	53	63
Preflight propellant loss, metric tons	136	143	147	50	58	69
Flight cost, $ million/flight	10	15	25	7	12	22
Flight turnaround, days	5	7	10	5	7	10
Mission life, missions	50	30	20	50	30	20

[a]The listed passenger-only capability of the $POTV_G$ (identical to $COTV_G$) is developed from the GEO-to-LEO down-payload capability of the complete second stage (drop tank and core) of the 2-1/2 stage $COTV_G$. In actual operations, only 50 to 100 passengers might fly as part of the $COTV_G$ outbound cargo.

TABLE VI-9.- RELATIVE TRANSPORTATION COSTS FOR SEVERAL SPS CONFIGURATIONS AND CONSTRUCTION LOCATIONS

Transportation vehicle	Configuration and construction location					
	Column/cable GEO		Truss GEO		Truss LEO	
	$/kW	$/kg	$/kW	$/kg	$/kW	$/kg
HLLV	996	119	1076	120	661	73
PLV	26	3	30	3	37	4
COTV	345	41	373	41	273	30
POTV	6	1	7	1	6	1
Total	1373	164	1486	165	977	108

Note: For SPS's emplaced at nominal cost and weight.

VII. INTEGRATED OPERATIONS

A. Systems Requirements Analysis

The capability to manufacture and construct large solar power stations in space will require a new dimension in space operations where innovative and advanced concepts can produce gains measured in orders of magnitude rather than percentages. The physical requirements for Solar Power Satellites (SPS) call for large microwave transmission antennas on the order of 1 km in diameter and large surfaces on the order of 100 to 200 km^2. Because of these physical requirements, the location for the manufacture and construction of the SPS will be expanded to include both low-Earth orbital and geosynchronous orbital locations as well as ground-based factory and plant activities. Therefore, space operations will be greatly influenced by the manufacturing and construction concept selected, which in turn will determine requirements for construction time, space equipment, transportation system, ground support system, and personnel and material resources.

The basic elements needed to define and develop an integrated operations and mission management concept for the manufacture, construction, quality control, checkout, operation, and maintenance of a large number of SPS's are: the Solar Power Satellites operating at geosynchronous Earth orbit (GEO); Operational Bases in GEO and low-Earth orbit (LEO), consisting of construction, manufacturing, maintenance, and logistics facilities; a Space Transportation System to transport material, equipment, and personnel between Earth and the operational bases in LEO and GEO; and a Ground Support System consisting of the Communications and Data Network facilities, Launch and Recovery operation facilities, Program Headquarters Mission Control facilities, industrial and warehouse facilities, the ground transportation systems, and the SPS ground receiving stations and operations control facilities; and the materials, equipment, supplies, and personnel resources. A number of these elements are discussed in detail in other sections of this report. A very general SPS operations scenario is shown in figure VII-1 to describe the mission sequence and basic elements of the SPS production and operation system.

B. Program Model

To develop an estimate of the overall program requirements for the creation of a Solar Power Satellite System, this study has assumed an SPS implementation rate that calls for the construction of 112 SPS units (scenario B, sec. III) producing 10 GW power each at the ground over a 30-year time frame from 1995 to 2025. Three alternative construction and assembly concepts, involving two configurations, were evaluated during the study to identify program requirements. These three alternatives are defined as follows.

Concept 1: The "COLUMN/CABLE" SPS configuration constructed and assembled primarily in GEO. Chemical COTV transportation from LEO to GEO.

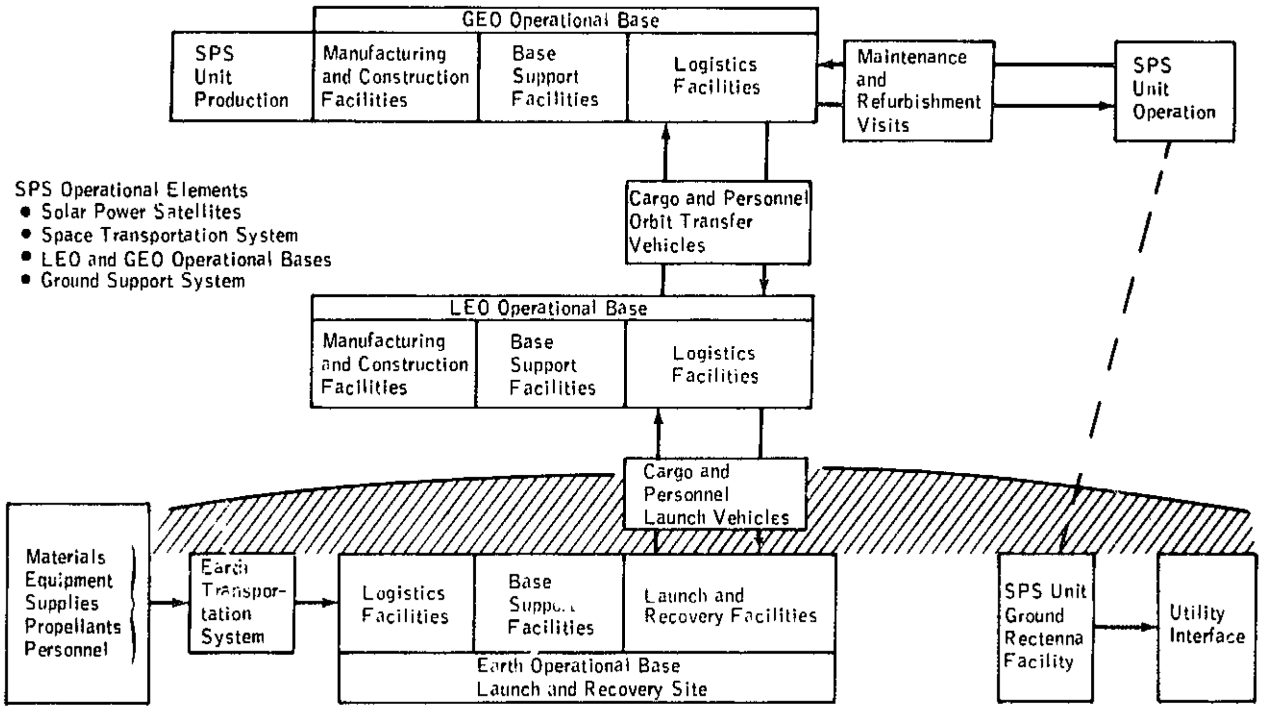


Figure VII-1.- SPS mission scenario.

Concept 2: The "TRUSS" SPS configuration constructed and assembled primarily in GEO. Chemical COTV transportation from LEO to GEO.

Concept 3: The "TRUSS" SPS configuration constructed and partially assembled in LEO with final assembly in GEO. Self-powered transportation from LEO to GEO.

Program models have been developed for each of the preceding concepts to identify the following program requirements for each year.

1. SPS units constructed
2. Total SPS units on line
3. Mass to GEO and LEO
4. Operational base units implemented and total on line
5. Personnel in GEO and LEO for production and maintenance
6. New POTV, COTV, PLV, and HLLV units required
7. Personnel and cargo launch vehicle total flights and flight rate to LEO
8. Personnel and cargo orbital transfer vehicle total flight and flight rate to GEO
9. Personnel and cargo launch and orbital transfer vehicles fleet size

The program models utilize the results of the systems analysis of the basic SPS elements conducted during this study. The guidelines and assumptions are listed in table VII-1. For each construction and configuration concept, a "nominal" weight and size SPS (sec. IV) was used in the calculations. The resulting program models are listed in tables VII-2 to VII-4.

C. Mission Management Concept

In developing a philosophy for an overall mission management concept that can satisfy the basic system requirements and conduct the program model as presented above, the following guidelines have been identified and assumed.

1. Personnel-operated and automated machines for manufacturing and construction tasks in space
2. Operations and control authority delegated throughout the ground- and space-based facilities
3. Program and overall operations and control authority maintained on ground
4. Dedicated synchronous satellite communications relay system

In general, all past space programs and the approaching Shuttle Orbiter, Spacelab, and IUS Space Transportation System (STS) missions can be regarded as ground-based space operations; that is, the complement of flight systems is prepared for flight in ground-based facilities and is largely controlled in accordance with plans and procedures developed and managed from ground-based facilities. The development of continously manned permanent space facilities in LEO and GEO conducting the SPS program model and detailed functions as discussed in sections IV, V, and VI requires that the authority for operations and control of daily ongoing activities must be delegated to the primary operational sites, basically the launch and recovery site, the LEO and GEO operational bases, and the SPS satellite ground rectenna sites.

The mission management concept that has been developed to incorporate this philosophy is illustrated in figure VII-2. This concept applies only to the production/operational phase of implementing the 112 SPS's.

D. Mission Management Functions

The decentralization and assignment of SPS mission management functions are allocated and identified as follows from figure VII-2.

1. Program Headquarters Mission Control

It is envisioned that one element of the basic Ground Support System will be a control function and facility for the overall program management, operations, administration, program planning, resource

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TABLE VII-1.- SPS PROGRAM MODEL INPUTS, ASSUMPTIONS, AND GUIDELINES

Characteristics	Concept		
	1. Column/cable GEO	2. Truss GEO	3. Truss LEO
SPS characteristics			
Number of SPS units, total	112	112	112
SPS 'nominal' unit mass each, M tons X 10^3	83.582 [a](81.8)	90.123 [a](84.4)	90.123 [a](84.4)
SPS unit mass repair each, M tons X 10^3 per year	.836	.901	.901
Operational base characteristics			
GEO base mass each, M tons X 10^3	6.000	7.000	1.000
LEO base mass each, M tons X 10^3	1.000	1.000	8.000
GEO and LEO base mass repair each, M tons X 10^3 per year (construction facilities only)	1.000 (GEO)	1.000 (GEO)	1.000 (LEO)
Personnel characteristics			
24 hours/7 days/week operations			
3 shifts/day, 4 orbital teams			
180-day orbital tour per person			
Construction, base support, and logistics operations			
GEO personnel, total, each new SPS unit per year	474	574	200
LEO personnel, total, each new SPS unit per year	176	176	740
Maintenance operations			
GEO personnel, total, each operational SPS per year	12	12	12
LEO personnel, total, each operational SPS per year	.53	.53	.43
Provisions			
GEO personnel provisions, M tons per person per year	3.0	3.0	2.0
LEO personnel provisions, M tons per person per year	2.0	2.0	3.0

[a]Numbers in parentheses are final masses, but the program model was not updated.

TABLE VII-1.- Concluded

Characteristics	Concept		
	1. Column/cable GEO	2. Truss GEO	3. Truss LEO
HLLV characteristics, nominal			
Two-stage ballistic:			
Payload, M tons	700	700	700
Flight turnaround, days	6	6	6
Vehicle life, missions	300	300	300
Flight cost, $M/flight	23	23	23
PLV characteristics, nominal			
Modified Shuttle:			
Payload, passengers	50	50	50
Flight turnaround, days	11	11	11
Vehicle life, missions	100	100	100
Flight cost, $M/flight	10	10	10
COTV characteristics, nominal	(2-1/2 stage chemical)	(2-1/2 stage chemical)	(Electric/chemical)
Payload, M tons	250	250	1000
Inert weight, M tons	35	35	166
Expended inert weight, M tons	9	9	110
Propellant/flight, M tons	475	475	300
Propellant loss in LEO storage/flight, M tons	143	143	240
Flight duration, days	TBD	TBD	50
Flight turnaround, days	7	7	7
Vehicle life, missions	30	30	10
Flight cost, $M/flight	10	10	30
POTV characteristics, nominal	(passenger module for 2-1/2 stage chemical)	(passenger module for 2-1/2 stage chemical)	(special purpose)
Payload, passengers	230	230	75
Inert weight, M tons	35	35	19
Propellant weight, M tons	475	475	106/up, 53/down
Propellant loss in LEO storage/flight, M tons	143	143	58
Flight turnaround, days	7	7	7
Vehicle life, missions	30	30	30
Flight cost, $M/flight	15	15	12

TABLE VII-2.- PROGRAM MODEL SUMMARY FOR "COLUMN/CABLE" SPS IN GEO

Year	SPS units		OPS base units in LEO and GEO		Total personnel in space					Total mass to space, M tons X 10^3/yr	
					LEO		GEO				
	No./yr	Total on line	No./yr	Total on line	Production	Maintenance	Production	Maintenance	Total/yr	LEO	GEO
1995	0.5	0	1	1	88		237	0	325	172	49
1996	.5	0	0	1	88		237	0	325	151	43
1997	1	1	0	1	176	1	474	12	663	305	87
1998	1	2	0	1	176	1	474	24	675	308	88
1999	1	3	0	1	176	2	474	36	688	311	89
2000	1	4	0	1	176	2	474	48	690	314	90
2001	1	5	1	1	176	3	474	60	703	323	96
2002	2	6	0	2	352	3	948	72	1375	621	177
2003	2	8	0	2	352	4	948	96	1400	627	179
2004	2	10	0	2	352	5	948	120	1425	634	181
2005	2	12	1	2	352	6	948	144	1450	661	188
2006	3	14	0	3	528	7	1422	168	2125	948	270
2007	3	17	0	3	528	9	1422	204	2163	957	273
2008	3	20	0	3	528	10	1422	240	2200	966	275
2009	3	23	1	3	528	11	1422	276	2237	996	284
2010	4	26	0	4	704	13	1896	312	2925	1286	366
2011	4	30	1	4	704	15	1896	360	2975	1320	376
2012	5	34	0	5	880	17	2370	408	3675	1613	459
2013	5	39	0	5	880	20	2370	468	3738	1628	465
2014	5	44	1	5	880	22	2370	528	3800	1664	474
2015	6	49	0	6	1056	24	2844	588	4512	1960	558
2016	6	55	0	6	1056	27	2844	660	4587	1978	563
2017	6	61	0	6	1056	30	2844	732	4662	1996	569
2018	6	67	0	6	1056	33	2844	804	4737	2015	574
2019	6	73	0	6	1056	36	2844	876	4812	2033	579
2020	6	79	0	6	1056	39	2844	948	4887	2051	584
2021	6	85	1	6	1056	42	2844	1020	4962	2091	595
2022	7	91	0	7	1232	45	3318	1092	5687	2390	680
2023	7	98	0	7	1232	49	3318	1176	5775	2411	686
2024	7	105	0	7	1232	53	3318	1260	5863	2433	692
2025		112		7		56		1344	1400	342	96

TABLE VII-2.- Concluded

Year	POTV flights to GEO				COTV flights to GEO				PLV flights to LEO				HLLV flights to LEO			
	No./yr	Total	Fleet size	New units	No./yr	Total	Fleet size	New units	No./yr	Total	Fleet size	New units	No./yr	Total	Fleet size	New units
1995	2	2	2	2	196	196	4	7	13	13	2	2	245	245	4	4
1996	2	4	2	0	172	368	4	6	13	26	2	0	216	461	4	0
1997	4	8	2	0	347	715	7	11	26	52	2	0	435	896	8	4
1998	4	12	2	0	351	1066	7	12	27	79	2	0	440	1336	8	0
1999	4	16	2	0	354	1420	7	12	28	107	2	0	444	1780	8	0
2000	4	20	2	0	357	1777	7	12	28	135	2	0	448	2228	8	0
2001	5	25	2	0	385	2162	7	13	29	164	2	0	483	2711	8	15
2002	9	34	2	1	709	2871	14	24	55	219	2	1	888	3599	15	0
2003	9	43	2	0	716	3587	14	24	56	275	2	0	897	4496	15	0
2004	10	53	2	0	722	4309	14	25	57	332	2	1	906	5402	15	0
2005	10	63	2	1	753	5062	14	25	58	390	2	0	946	6348	15	0
2006	14	77	2	0	1080	6142	22	36	85	475	3	2	1354	7702	23	23
2007	14	91	2	0	1091	7233	22	37	87	562	3	1	1367	9069	23	0
2008	14	105	2	1	1101	8334	22	37	88	650	3	1	1380	10449	23	0
2009	15	120	2	1	1135	9469	22	38	90	740	3	1	1423	11872	23	0
2010	19	139	2	0	1465	10934	29	49	117	857	4	2	1837	13709	31	31
2011	20	159	2	1	1503	12437	29	50	119	976	4	1	1885	15594	31	0
2012	24	183	2	1	1837	14274	37	62	142	1123	5	2	2303	17897	39	8
2013	25	208	2	1	1854	16128	37	62	150	1273	5	1	2325	20222	39	0
2014	26	234	2	1	1895	18023	37	64	152	1425	5	1	2377	22599	39	0
2015	30	264	2	1	2233	20256	44	75	181	1606	6	2	2800	25399	49	38
2016	31	295	2	1	2253	22509	44	76	184	1790	6	2	2826	28225	46	0
2017	32	327	2	1	2274	24783	44	76	187	1977	6	2	2852	31077	46	11
2018	32	359	2	1	2294	27077	45	77	190	2167	6	2	2878	33955	49	0
2019	33	392	2	1	2315	29392	45	78	193	2360	6	2	2904	36859	49	0
2020	34	426	2	1	2336	31728	45	78	196	2556	6	2	2931	39790	49	38
2021	34	460	2	1	2380	34108	45	80	199	2756	6	2	2987	42777	49	0
2022	39	499	2	1	2721	36829	54	91	228	2984	7	2	3414	46191	57	19
2023	39	538	2	1	2745	39574	54	92	231	3215	7	2	3444	49635	57	0
2024	40	578	2	1	2769	42343	54	93	235	3450	7	2	3475	53110	57	0
2025	12	590	2	0	385	42728	8	13	56	3506	2	0	489	53599	8	0

TABLE VII-3.- PROGRAM MODEL SUMMARY FOR "TRUSS" SPS IN GEO

Year	SPS units		OPS base units in LEO and GEO		Total personnel in space					Total mass to space, M tons X 10^3/yr	
					LEO		GEO				
	No./yr	Total on line	No./yr	Total on line	Production	Maintenance	Production	Maintenance	Total/yr	LEO	GEO
1995	0.5	0	1	1	88	0	287	0	375	187	54
1996	.5	0	0	1	88	0	287	0	375	163	47
1997	1	1	0	1	176	1	574	12	763	329	94
1998	1	2	0	1	176	1	574	24	775	333	95
1999	1	3	0	1	176	2	574	36	788	336	96
2000	1	4	0	1	176	2	574	48	790	339	97
2001	1	5	1	1	176	3	574	60	803	366	105
2002	2	6	0	2	352	3	1148	72	1578	672	191
2003	2	8	0	2	352	4	1148	96	1600	678	193
2004	2	10	0	2	352	5	1148	120	1625	685	195
2005	2	12	1	2	352	6	1148	144	1650	715	204
2006	3	14	0	3	528	7	1722	168	2425	1024	292
2007	3	17	0	3	528	9	1722	204	2463	1034	295
2008	3	20	0	3	528	10	1722	240	2500	1044	297
2009	3	23	1	3	528	11	1722	276	2537	1077	307
2010	4	26	0	4	704	13	2296	312	3325	1389	396
2011	4	30	1	4	704	15	2296	360	3375	4175	495
2012	5	34	0	5	880	17	2870	408	4175	1742	495
2013	5	39	0	5	880	20	2870	468	4238	1758	500
2014	5	44	1	5	880	22	2870	528	4300	1799	512
2015	6	49	0	6	1056	24	3444	588	5122	2117	602
2016	6	55	0	6	1056	27	3444	660	5187	2136	608
2017	6	61	0	6	1056	30	3444	732	5262	2156	614
2018	6	67	0	6	1056	33	3444	804	5337	2176	619
2019	6	73	0	6	1056	36	3444	876	5412	2195	624
2020	6	79	0	6	1056	39	3444	948	5487	2215	630
2021	6	85	1	6	1056	42	3444	1020	5562	2260	543
2022	7	91	0	7	1232	45	4018	1096	6387	2581	734
2023	7	98	0	7	1232	49	4018	1176	6475	2603	741
2024	7	105	0	7	1232	53	4018	1260	6563	2626	747
2025		112		7		56		1344	1400	367	104

TABLE VII-3.- Concluded

Year	POTV flights to GEO				COTV flights to GEO				PLV flights to LEO				HLLV flights to LEO			
	No./yr	Total	Fleet size	New units	No./yr	Total	Fleet size	New units	No./yr	Total	Fleet size	New units	No./yr	Total	Fleet size	New units
1995	2	2	2	2	241	241	4	8	15	15	2	2	268	268	5	5
1996	2	4	2	0	186	427	4	6	15	30	2	0	233	501	5	0
1997	5	9	2	0	376	803	8	13	31	61	2	0	471	972	8	3
1998	5	14	2	0	380	1183	8	13	31	92	2	0	475	1447	8	0
1999	5	19	2	0	383	1566	8	13	32	124	2	1	480	1927	8	0
2000	5	24	2	0	387	1953	8	13	32	156	2	0	485	2412	8	5
2001	6	30	2	1	418	2371	8	14	33	189	2	0	524	2936	9	1
2002	11	41	2	0	765	3136	15	26	63	252	2	1	960	3896	16	7
2003	11	52	2	0	773	3909	15	26	64	316	2	0	969	4865	16	0
2004	11	63	2	1	780	4689	15	26	65	381	2	1	979	5844	16	0
2005	11	74	2	0	815	5504	16	28	66	447	2	1	1022	6866	16	11
2006	16	90	2	1	1166	6670	23	39	97	544	3	2	1463	8329	25	7
2007	17	107	2	0	1177	7847	23	40	98	642	3	1	1477	9809	25	7
2008	17	124	2	1	1188	9035	23	40	100	742	4	2	1491	11297	25	0
2009	17	141	2	1	1227	10262	24	41	112	854	4	1	1540	12837	25	0
2010	22	163	2	1	1582	11844	31	53	133	987	5	2	1985	14822	33	19
2011	23	186	2	1	1625	13469	32	55	135	1122	5	1	2039	16861	33	7
2012	29	215	2	1	1980	15449	39	66	167	1289	5	1	2488	19349	42	16
2013	29	244	2	1	2001	17450	39	67	170	1459	6	2	2512	21861	42	0
2014	29	273	2	1	2048	19498	40	69	172	1631	6	1	2570	24431	42	0
2015	35	308	2	1	2409	21907	47	81	205	1836	7	2	3025	27456	50	27
2016	36	344	2	1	2432	24339	47	82	208	2044	7	2	3053	30509	50	17
2017	36	380	2	1	2454	26793	48	82	211	2255	7	2	3082	33591	51	17
2018	37	417	2	1	2476	29269	48	83	214	2469	7	2	3109	36720	51	0
2019	38	455	2	1	2498	31767	49	84	217	2686	7	2	3137	39857	51	0
2020	38	493	2	1	2521	34288	49	85	220	2906	7	2	3165	43022	53	29
2021	39	532	2	1	2571	36859	50	86	223	3129	7	2	3227	46249	53	7
2022	44	576	2	1	2937	39796	57	98	256	3385	8	3	3687	49936	61	25
2023	45	621	2	1	2963	42759	57	99	259	3644	8	2	3720	53656	61	0
2024	46	667	2	1	2989	45748	58	100	262	3906	8	2	3753	57409	62	0
2025	12	679	2	1	415	46163	8	14	56	3962	2	0	525	57934	9	0

TABLE VII-4.- PROGRAM MODEL SUMMARY FOR "TRUSS" SPS IN LEO

Year	SPS units		OPS base units in LEO and GEO		Total personnel in space					Total mass to space, M tons X 10^3/yr	
					LEO		GEO				
	No./yr	Total on line	No./yr	Total on line	Production	Maintenance	Production	Maintenance	Total/yr	LEO	GEO
1995	0.5	0	1	1	370	0	100	0	470	104	46
1996	.5	0	0	1	370	0	100	0	470	101	45
1997	1	1	0	1	740	1	200	12	953	203	91
1998	1	2	0	1	740	1	200	24	965	205	93
1999	1	3	0	1	740	2	200	36	978	207	94
2000	1	4	0	1	740	2	200	48	992	209	95
2001	1	5	1	1	740	3	200	60	1003	214	97
2002	2	6	0	2	1480	3	400	72	1955	415	189
2003	2	8	0	2	1480	4	400	96	1980	419	191
2004	2	10	0	2	1480	5	400	120	2005	423	192
2005	2	12	1	2	1480	6	400	144	2030	429	194
2006	3	14	0	3	2220	7	600	168	2995	632	286
2007	3	17	0	3	2220	9	600	204	3033	639	289
2008	3	20	0	3	2220	10	600	240	3070	645	292
2009	3	23	1	3	2220	11	600	276	3107	653	295
2010	4	26	0	4	2960	13	800	312	4085	859	388
2011	4	30	1	4	2960	15	800	360	4135	869	393
2012	5	34	0	5	3700	17	1000	408	5125	1076	487
2013	5	39	0	5	3700	20	1000	468	5188	1087	492
2014	5	44	1	5	3700	22	1000	528	5250	1099	498
2015	6	49	0	6	4440	24	1200	588	6252	1309	592
2016	6	55	0	6	4440	27	1200	660	6327	1322	598
2017	6	61	0	6	4440	30	1200	732	6402	1334	604
2018	6	67	0	6	4440	33	1200	804	6477	1347	609
2019	6	73	0	6	4440	36	1200	876	6552	1359	615
2020	6	79	0	6	4440	39	1200	948	6627	1372	621
2021	6	85	1	6	4440	42	1200	1020	6702	1387	627
2022	7	91	0	7	5180	45	1400	1092	7717	1597	723
2023	7	98	0	7	5180	49	1400	1176	7805	1612	729
2024	7	105	0	7	5180	53	1400	1260	7893	1627	735
2025		112		7		56		1344	1400	235	106

TABLE VII-4.- Concluded

Year	POTV flights to GEO				COTV flights to GEO				PLV flights to LEO				HLLV flights to LEO			
	No./yr	Total	Fleet size	New units	No./yr	Total	Fleet size	New units	No./yr	Total	Fleet size	New units	No./yr	Total	Fleet size	New units
1995	3	3	2	2	46	46	1	5	19	19	2	2	149	149	3	3
1996	3	6	2	0	45	91	1	5	19	38	2	0	146	295	3	0
1997	5	11	2	0	91	182	2	10	38	76	2	0	290	585	5	2
1998	6	17	2	0	93	275	2	10	39	115	2	1	293	878	5	0
1999	6	23	2	0	94	369	2	10	39	154	2	0	296	1174	5	0
2000	6	29	2	0	95	464	2	10	40	194	2	1	299	1473	5	3
2001	7	36	2	1	97	561	2	10	40	234	2	0	305	1778	5	0
2002	13	49	2	0	189	750	4	19	78	312	3	2	592	2370	10	7
2003	14	63	2	1	191	941	4	19	79	391	3	0	598	2968	10	0
2004	14	77	2	0	192	1133	4	19	80	471	3	1	604	3572	10	0
2005	15	92	2	1	194	1329	4	29	81	552	3	0	613	4185	10	3
2006	20	112	2	0	286	1613	6	29	120	672	5	3	903	5088	16	13
2007	21	133	2	1	289	1902	6	29	121	793	5	1	912	6000	16	0
2008	22	155	2	0	292	2194	6	29	123	916	5	1	921	6921	16	0
2009	23	178	2	1	295	2489	6	30	124	1040	5	1	933	7854	16	0
2010	29	207	2	1	388	2877	8	39	163	1203	6	2	1226	9080	21	8
2011	31	238	2	1	393	3270	8	39	165	1368	6	2	1241	10321	21	13
2012	38	276	2	1	487	3757	10	49	205	1573	7	2	1537	11858	26	5
2013	39	315	2	1	492	4249	10	49	207	1780	7	2	1552	13410	26	0
2014	41	356	2	2	498	4747	10	50	210	1990	7	2	1570	14980	26	0
2015	48	404	2	2	592	5339	12	60	250	2240	9	3	1869	16849	31	13
2016	50	454	2	2	598	5937	12	60	253	2494	9	2	1887	18736	31	13
2017	52	506	2	2	604	6541	12	60	256	2749	9	2	1905	20641	34	8
2018	53	559	2	2	609	7150	12	61	259	3008	9	3	1923	22564	34	0
2019	55	614	2	2	615	7765	12	62	262	3270	9	2	1941	24505	34	0
2020	57	671	2	2	621	8386	12	62	265	3535	9	3	1959	26464	34	13
2021	59	730	2	2	627	9013	12	63	268	3803	9	2	1980	28444	34	13
2022	66	796	3	2	723	9736	14	73	308	4111	11	3	2282	30726	39	13
2023	68	864	3	2	729	10465	14	73	312	4423	11	3	2303	33029	39	0
2024	71	935	3	2	735	11200	14	74	315	4738	11	3	2324	35353	39	0
2025	36	971	3	0	106	11306	2	10	56	4794	2	0	336	35689	6	0

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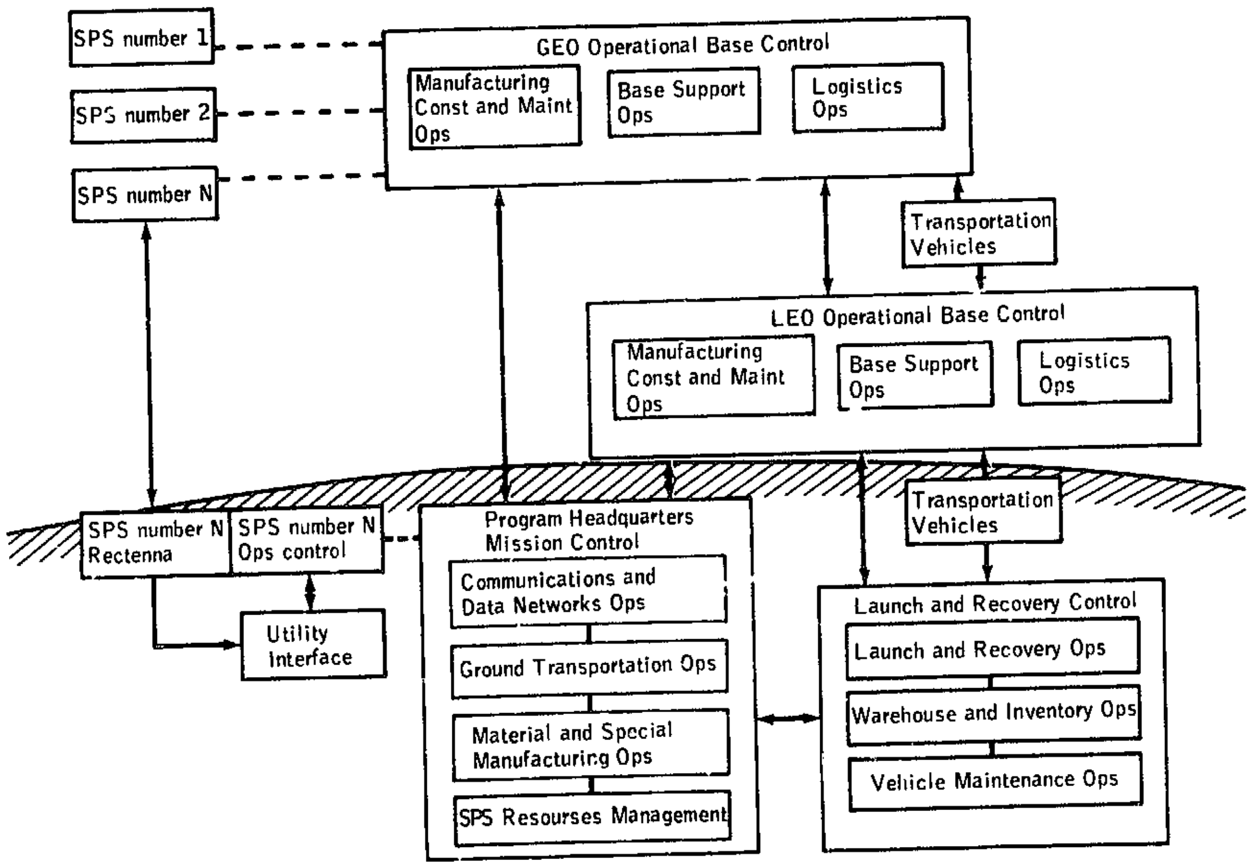

Figure VII-2.- SPS mission management concept.

control, mission planning, etc. type of SPS activities. This control element would also manage and direct all the ground-based manufacturing required, would obtain necessary materials for orbital construction, and in general manage the overall ground support requirements for ensuring that all the basic cargo elements are accounted for and in the system. This control element would also manage the ground transportation operations required to transport cargo elements to the launch site. This element would also manage the overall selection, training, simulation activities, and assignment of all personnel in their respective job functions and tasks. This element would manage the overall orbital construction and assembly operations being conducted on the ground and in LEO and GEO on an overall project basis. The coordination of the Communications and Data Network relay satellites and ground station would be assigned to this element for overall SPS responsibility.

2. <u>Launch and Recovery Control</u>

The second major element of the SPS ground support system is the operations and control of the launch and recovery operations.

The basic function of this control element is to manage all the ground operations involved with the preparation, launch, and return of all personnel and cargo to and from the LEO operational bases and the maintenance of the cargo launch vehicles (HLLV) and the personnel launch vehicle (PLV). This element will also manage and conduct the training and simulation for all transportation vehicle flight crews.

3. <u>LEO Operational Base Control</u>

The LEO and GEO operational bases utilize the same basic elements for operations and control authority, with the major differences being due to the nature of the functions and tasks required in their respective orbital location for manufacturing and construction operations, logistics operations, and base support operations. Each space operational base (LEO or GEO) is envisioned to manage its own day-to-day activities involved with manufacturing, construction, logistics, and transportation operations and its interfaces with the other major elements in the SPS system.

It is expected that the LEO operational base will be predominantly concerned with logistics and transportation operations because its position in LEO links it directly to the ground and to the GEO operational base. This base will be the primary "space traffic control center" handling all cargo and personnel arriving and departing via the launch vehicles from Earth and then, in turn, acting as a warehouse in space until transferring required cargo and personnel to orbital transfer vehicles (OTV) for departure to the GEO operational base and handling arriving OTV's returning from GEO. It is therefore expected that significant authority for operations and control over all the SPS logistics and transportation operations will be delegated to the LEO operational base.

Because of its ongoing full range of space operation activities and its ready access to the ground, the LEO operational base is the prime candidate for implementing and conducting training and simulation for all new orbital crew personnel.

4. <u>GEO Operational Base Control</u>

The GEO operational base, similar to the LEO operational base, will manage its own day-to-day activities involved with manufacturing, construction, logistics and transportation operations, and its interface with the other major elements in the SPS system.

It is expected that the GEO operational base will be predominantly concerned with the manufacturing, construction, and final checkout and operational go-ahead for each SPS satellite because its position in GEO is the resident operational location for the SPS satellites. Therefore, it is expected that significant authority for operations and control over all the SPS manufacturing, construction, checkout, and maintenance will be delegated to the GEO operational base.

The GEO operational base will also conduct the routine maintenance and "onboard" inspection of all individual SPS satellite units after they are operational by sending resident GEO base crewmembers to visit several SPS units on periodic inspection and maintenance tours. Emergency visits to any SPS unit would also be managed by the GEO base.

5. SPS (Individual Unit) Ground Control

The primary authority for operations and control of each individual SPS unit after it becomes operational will reside with a ground control facility located at the ground rectenna station. The SPS ground control elements for each of the 112 SPS units complete the basic elements comprising the ground-based support system.

It is expected that the SPS control facility will manage the power transmission from the SPS unit in orbit to the rectenna and into the interface with a ground-based utility distribution system. This control facility will monitor the performance and status of the SPS systems and will coordinate as required with the Program Headquarters Mission Control facility for assistance and with the GEO operational base for "revisit" operations.

Position and tracking information for all 112 SPS units will be managed and coordinated by the Program Headquarters Mission Control facility. Potential conflicts or potential in-orbit collisions will be identified and the necessary operations required to correct the situation will be determined and implemented by the Program Headquarters Mission Control and the respective SPS Ground Control facilities of each involved SPS unit.

E. Key Considerations and Areas For Further Investigation

During the development of the SPS program model and the overall mission management concept for SPS operations and control, many new and challenging functions and tasks have been identified that are lacking in technology development and/or analysis in significant depth; therefore, many critical areas requiring operational and design trade-offs cannot be evaluated at this stage of our understanding. However, the following concerns have been selected as having the most significant impact on the SPS design and operations concept during this study effort.

1. Prelaunch, Launch, and Recovery Operations

The Program Model discussed in subsection VII-B implies the magnitude of ground support operations involved in the daily flow of personnel and material, equipment, etc. in various packaged forms, which have to be transported from the original location by some ground transportation element to the launch site, where they are received, unloaded, processed, and stored for assignment to a launch vehicle. (See also fig. VII-1.) Preparations for launch commence when the launch assignment is made. Recovery operations for returning vehicles are also handled at the launch and recovery facilities. It is recognized that the personnel and facilities involved in the ground operations of the SPS system will be an important element in the operational assessment and cost of the SPS; however, no in-depth analyses of these operational elements have been conducted during this study. Significant attention needs to be devoted to this area in follow-on efforts to this study.

2. Space Manufacturing and Construction Options

This new area of technology and its operational considerations have been discussed in previous sections. However, the concepts and options selected for accomplishing the space manufacturing and construction tasks have "significant" influence on the operational requirements of the SPS system in such areas as operational base manning, crew skill mix, construction sequence and mission activity schedules, simulation and training, etc. Early design, development, test, and evaluation (DDT&E) programs must be directed at developing and demonstrating this new area of space technology.

3. Operational Space Base Control Operations

The magnitude of operational activity required in LEO and GEO to accomplish the implementation and operations of the 112 SPS systems, when considering total personnel operating on Earth and in space; multiple vehicles moving between, to, and from Earth, LEO, and GEO bases; the space manufacturing and construction tasks; and the massive cargo requirements as discussed in previous sections, has led to a mission management concept assigning significant operations and control authority to the space base elements of the SPS system. The implications of basing control, operations, and management functions in space will have philosophical, programmatic, economic, and technical repercussions upon the composition of future space program concepts, particularly when examined in the context of resource requirements, costs, systems definition, and relatable requirements for advanced technology development. In this study, the concept of in-space operational control has only been identified and further analysis is required.

4. Simulation and Training Operations

The operation of space manufacturing and construction equipment will require manned and automated tasks involving a broad range of skill mix activities that have not been exercised or required in past or current space programs. With the involvement of thousands of ground and orbital crew personnel in conjunction with the large and massive space structures and equipment required for SPS production and operations, the area of simulation and training operations and facilities has only been identified in this study and further analysis is required.

5. Safety in SPS Operations

This study has not included a safety analysis associated with the manfacturing, construction, checkout, operations, or with the associated space logistics operations of cargo and personnel transfer, vehicle servicing, refurbishment, maintenance and operations, and propellant storage and servicing tasks. Potentially hazardous situations need to be identified and examined in depth to assess all the natural and induced hazards associated with all mission phases and elements of the SPS system.

VIII. ENVIRONMENTAL CONSIDERATIONS

A. Methodology

An evaluation of the space solar power concept must involve an assessment of the potential impact on the environment and the people living within that environment. This impact can be either positive or negative in an absolute sense or in relation to other potential sources of energy. The present study has identified those environmental topics that must be addressed in the solar power concept assessment and has presented estimates of relative environmental impact in selected areas for the solar power concept and other sources.

B. Environmental Questions

Solar energy is considered a "clean" form of energy; however, the collection, conversion, and transmission of this energy introduce environmental questions. These questions or topics may be grouped into four categories.

Vehicle Emissions/Operations
Microwave Beam
Space Operational Environment
Earth Activities

A detailed listing of topics related to each of these categories is presented later in the report (fig. X-2, D.1 through D.4) in the context of areas needing analysis and testing to provide definitive answers to environmental questions.

Considerable experience has been developed in the course of analyzing emissions from the Shuttle propulsion systems and this potential impact on the environment. Reflecting Shuttle experience, SPS studies have emphasized consideration of fuels that are projected to be compatible with the natural environment. For example, launch vehicles have previously considered the use of hydrocarbon, hydrogen and oxygen propellants, whereas orbital transfer vehicle studies have considered argon in preference to mercury. SPS environmental studies must emphasize the size and quantity of vehicles and launches involved as well as the particular emissions from a given vehicle in view of the large numbers involved in a significant size commercial program. Specific topics to be considered include noise, gas cloud formation, and thermal effects in the launch area; emission effects on the stratosphere; and noise and NO_X production during reentry.

Transmission of large amounts of power by microwave radiation from the SPS to Earth introduces questions related to its effects. Preliminary analyses of the beam-ionosphere interaction have indicated a power density level beneath which nonlinear interactions are not expected to occur. This level has been used in this and other studies as an upper limit with a resulting effect on the sizing of the microwave transmission system. Similarly, current U.S. standards have been taken into consideration in the conceptual design of the system such that power levels outside of the area of the rectenna are one-tenth or less of the existing U.S. standards. A substantial effort will be required to investigate the long- and short-term effects of low-level microwave radiation on humans, plants, and animals. Studies and tests will also be required to assess the effects of the radiation on radio astronomy, communications, and electronic equipment.

Although environmental questions related to the Earth and its populations are of particular concern, questions related to operations in the space environment must also be considered. It has been estimated in earlier sections that hundreds to thousands of personnel will be required in space depending upon the scope of the commercial construction program. Many of these personnel may be required in geosynchronous orbit where the converging radiation environment is significantly different from that existing in low-Earth orbit. This subject is treated in some detail in Volume II. Consideration of this environment is reflected in conceptual construction concepts that emphasize automated techniques with most crew activity taking place in "protected" locations.

C. Comparisons With Conventional Systems

The introduction of satellite power systems will yield environmental benefits in the areas of air pollution caused by combustion of fossil fuels, cooling water requirements and associated thermal pollution, and nuclear waste disposal.

Table VIII-1 presents the results of a preliminary analysis and comparison of a 10-GW SPS system with coal and nuclear powerplants of the same capacity. The data of table VIII-1 illustrate the relatively minor quantities of air pollutants (oxides of sulfur and nitrogen and particulates) resulting from launch vehicle engine exhaust in comparison to a coal-burning plant.

The air pollutants from the vehicle launches required to implement an SPS are seen to be negligible compared to the pollutants from a coal-burning plant.

TABLE VIII-1.- ENVIRONMENTAL COMPARISON OF 10-GW POWERPLANT OPERATIONS

Parameter	Nuclear	Coal	SPS
Primary fuel, MT/yr	112	42×10^6	[a]3.49×10^6
Waste, MT/yr	330	8×10^6 ash [b]3.6×10^6 sludge	
Airborne emissions, MT/yr . . .	--	[c]1.5×10^6	
SO_2		[b]$.3 \times 10^6$	
NO_X	--	[c]$.6 \times 10^6$ [b]$.3 \times 10^6$	[a]1800
Particulate	--	[d]$.8 \times 10^6$	
Thermal loss total, Btu/hr . . .	770×10^{12}	700×10^{12}	[a]102×10^{12} 15×10^2
Land use, km^2			
Fixed	40 to 50	3.6	64
30 years	3.9	900	200

[a]Launch year only.

[b]Control (SO_2 or NO_X).

[c]No control.

[d]Present controls.

IX. MANUFACTURING CAPACITY, NATURAL RESOURCES, TRANSPORTATION, AND ENERGY CONSIDERATIONS

A. Requirements

The implementation of a large-scale SPS program (scenario B, sec. III) will require a significant increase in industrial capacity in certain areas and require assessment of the impact on natural resources and the transportation system. In addition, a measure of the "efficiency" or desirability of the SPS concept is the length of time required for an SPS to produce an amount of energy equivalent to that required for its implementation. The results of preliminary analyses of each of these topics are presented in the following paragraphs.

B. Manufacturing Capacity

An analysis of a conceptual design of the SPS was conducted to determine the fabricated components and processed materials required. The results indicated that a "mass production" capability would have to be developed and installed to produce the approximately 1 billion solar cells required. A greatly expanded processing capacity would be required for the large amounts of hydrogen, oxygen, and possibly argon needed for the transportation systems. A new industrial base would be required in selected areas for the production of gallium arsenide diodes and for the reduction of arsenic from oxides.

C. Natural Resources

Table IX-1 presents an estimate of the natural resources required for the implementation of an SPS of "nominal" weight. The resources required for a program involving 112 SPS's (scenario B) will not seriously impact U.S. and/or world resources with the possible exception of aluminum. Aluminum ore (bauxite) is currently being imported for the production of nearly all U.S. aluminum. Imports would have to be expanded to meet SPS requirements. The implementation of an SPS would result in the use of approximately 3 percent of world demand in the year 2000. It should be noted that the conceptual design assumed for this analysis used aluminum as the support structure for the rectenna (224 required for 112 SPS's). This use constitutes practically all of the 3 percent cited previously. Future studies should obviously consult alternates to the use of aluminum for this purpose if the amount required represents a significant problem to aluminum resources.

D. Surface Transportation

The transportation of raw materials, fabricated components, and assemblies to the launch site must be considered. A study was conducted

TABLE IX-1.- NATURAL RESOURCE DEMANDS OF A 10-GW SPS COMPARED TO NATIONAL AND WORLD DEMANDS IN THE YEAR 2000

Material	SPS demand (two SPS's/yr), metric tons	Total demand, percent		Comments
		U.S.	World	
Aluminum (Al)	2.14×10^6	7.1	2.77	94 percent of mass is in rectenna
Argon (Ar)	2.82	16	6.57	Production capacity required
Arsenic (As)	125	356(?)	.11	Reduction of metal from oxides required
Copper (Cu)	2.6×10^4	.2	.09	
Gallium (Ga)	116	16764(?)	5640(?)	Production to date based on demand
Oxygen (O_2)	2×10^7	38.6	14.4	Production capacity required
Platinum (Pt)	8	14.8	5.17	
Silicon (Si)	$.43 \times 10^5$	3714(?)	(a)	Production Capacity required
Tungsten (W)	2500	.71	.27	

[a]Not applicable.

TABLE IX-2.- ENERGY PAYBACK OF A 10-GW SPS

Item	Quantity, kg	Total energy to produce, $kWh \times 10^{10}$
Rocket propellant and gasses	3.42×10^{10}	2.78
Rectenna	1.12×10^9	2.70
Other SPS materials	8.64×10^8	1.20
Total		6.7

SPS electrical energy output = 8.05×10^{10} kWh/yr

$$\text{Payback time} \quad \frac{6.7 \times 10^{10} \text{ kWh}}{8.05 \times 10^{10} \text{ kWh/yr}} = 0.83 \text{ year}$$

which showed that, at peak SPS production rate (seven/yr, scenario B) on the order of 12×10^9 metric ton-km/yr of transport would be required. This compares with a total U.S. transportation projection of 5×10^{12} metric ton-km/yr in 2000. Therefore, the maximum SPS impact would be less than 1 percent of the year 2000 total requirement. Warehousing and handling facilities at intermediate and end points should be considered in future studies.

E. Energy Payback

A preliminary study was conducted to assess the energy required for the implementation of an SPS and the time required for the SPS to generate an equivalent amount of energy. Table IX-2 is a list of the energy-intensive materials required for the implementation of an SPS of "nominal" weight and the energy involved in its production. To process the material for an SPS, 6.7×10^{10} kWh are required. Approximately 80 percent of the total is involved in the production of the necessary propellants and aluminum for the rectenna. Previous comments regarding the use of aluminum for the support structure of the rectenna should be noted.

The SPS produces 8.1×10^{10} kWh/yr; consequently, the 6.7×10^{10} kWh used in implementation of the SPS would be generated or "paid back" in less than 10 months. This figure compares favorably with estimates for conventional ground systems, which range from 0.2 to 1.0 year for payback.

X. PROGRAM DEVELOPMENT PLAN

A. Program Phasing

The SPS program plan has been divided into four phases as illustrated in figure X-1. The four phases include an initial phase of system definition and exploratory technology followed by a technology advancement phase. These two phases would provide the information required to make a decision in the 1987 time period to proceed with full-scale development of the system. Assuming a positive decision at this time, an initial system might be in operation in the 1995 time period. The subsequent and final phase would be one of commercialization involving multiple SPS's such as identified in the various scenarios described in section III.

B. System Definition and Exploratory Technology Phase

This immediate phase would include improved definition and assessment of satellite power system concepts; transportation, construction, and operational support systems; design, development, test and evaluation (DDT&E), and recurring costs and environmental impact. A further description of activities in these four areas is presented in figure X-2.

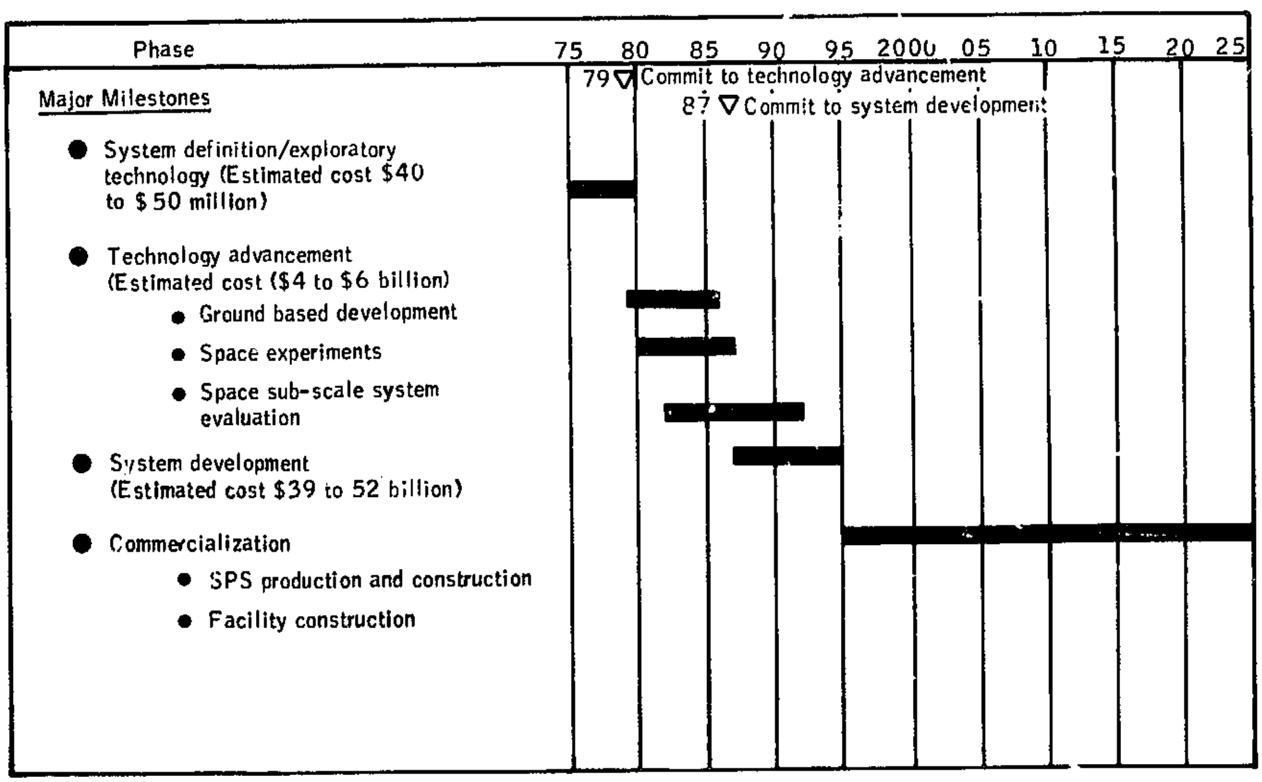

Figure X-1.- Space solar power projected program phasing.

A. SATELLITE POWER SYSTEM CONCEPTS

- o DEFINITIVE COMPARATIVE ANALYSIS AND ASSESSMENT OF THE SEVERAL POWER-GENERATION CONCEPTS
  - SOLAR CELLS (SILICON, GALLIUM ARSENIDE)
  - THERMAL (BRAYTON)
- o RELATIVE MERITS OF LOW-EARTH ORBIT AND GEOSYNCHRONOUS-ORBIT CONSTRUCTION LOCATIONS
- o CONCEPTUAL DESIGN AND ANALYSIS OF A VARIETY OF CONFIGURATIONS
- o DETAILED STRUCTURAL, THERMAL, AND ATTITUDE STABILIZATION AND CONTROL ANALYSES (INCLUDING MODELING AND SIMULATIONS) FOR CONSTRUCTION, MAINTENANCE, AND OPERATION PERIODS
- o IN-DEPTH ANALYSIS AND EVALUATION OF EACH SUBSYSTEM/MAJOR COMPONENT EFFICIENCIES
- o RECTENNA ANALYSES WITH EMPHASIS ON REDUCING COSTS AND CONSTRUCTION ENERGY AND NATURAL RESOURCE REQUIREMENTS
- o DEVELOPMENT AND OPTIMIZATION OF SYSTEM AND DETAILED CONCEPTS FOR SPS-POWER GRID INTERFACE AND OPERATION

B. SUPPORT SYSTEMS

- o CONCEIVE AND EVALUATE TECHNIQUES AND DEVICES FOR CONSTRUCTION, INSPECTION, AND MAINTENANCE OF SATELLITE POWER SYSTEMS, INCLUDING DESIGN CHARACTERISTICS OF A CONSTRUCTION FACILITY WITH ASSOCIATED UTILITY, HABITATION, AND CONTROL FEATURES
- o REFINE STUDIES OF HEAVY LIFT LAUNCH VEHICLES
  - WINGED LAND LANDING VS. BALLISTIC WATER LANDING
  - PAYLOAD/FLEET SIZING
  - OPERATION COST ANALYSIS
  - FACILITY REQUIREMENTS
  - LAUNCH LOCATIONS
- o EVALUATE AND ASSESS ORBITAL TRANSFER MISSION MODES, INCLUDING DESIGN, LIFE, AND COST OF ELECTRICAL, CHEMICAL, AND NUCLEAR PROPULSION SYSTEMS

C. DDT&E AND RECURRING COSTS

- o TOTAL DDT&E COSTS HAVE NOT BEEN DERIVED IN ANY DETAIL. ROUGH ESTIMATES RANGE FROM $30 TO $70 BILLION OVER 10- TO 20-YEAR PERIOD. PLANNED STUDIES WOULD TARGET FOR AN ESTIMATE WITH +20 PERCENT ACCURACY
- o PRESENT STUDIES INDICATE AS MUCH AS A FACTOR OF 3 TO 4 (30 TO 110 MILLS/KWH) SPREAD IN ESTIMATES OF THE COST OF COMMERCIAL POWER FROM SOLAR POWER SYSTEMS
- o SYSTEMS STUDIES AND OTHER ACTIVITIES SHOULD REDUCE THIS ESTIMATE SPREAD TO APPROXIMATELY 2 (30 TO 60, 50 TO 100) IN THE NEXT 2 YEARS

Figure X-2.- System definition and exploratory technology phase activities.

D. ENVIRONMENTAL IMPACT

- o PRELIMINARY ASSESSMENT OF THE SYSTEM RESULTS IN MODEST IMPACTS AND/OR QUESTIONS TO BE ANSWERED
- o ENVIRONMENT AREAS MAY BE GROUPED AS FOLLOWS:
  - VEHICLE EMISSIONS/OPERATIONS
  - MICROWAVE BEAM
  - EARTH ACTIVITIES
  - SPACE OPERATIONAL ENVIRONMENT
- o WITHIN THE NEXT 2 YEARS, ANALYSES SHOULD PROVIDE INFORMATION FOR A FIRST-ORDER IMPACT ANALYSIS IN ALL AREAS. TEST DATA RELATED TO THE BIOLOGICAL EFFECTS OF THE MICROWAVE BEAM ON HUMANS ARE PROBABLY THE MOST TIME-CRITICAL AREA
- o SUBSEQUENT FIGURES OUTLINE QUESTIONS TO BE TREATED IN EACH ENVIRONMENTAL AREA

D.1 VEHICLE EMISSIONS/OPERATIONS

o TROPOSPHERE	- LAUNCH AREA GAS CLOUD, RAINOUT CONDITIONS, AND BIOLOGICAL EFFECTS - METEOROLOGICAL EFFECTS AND ECOLOGICAL CONSEQUENCES
o STRATOSPHERE	- PHYSICAL AND BIOMEDICAL OZONE DEPLETION EFFECTS - WEATHER MODIFICATION ASSESSMENT
o IONOSPHERE	- ASSESSMENT OF 'PUNCH OUT' EFFECT
o THERMOSPHERE/ MAGNETOSPHERE	- PREDICTED DISTRIBUTIONS
o SONIC BOOM/ LAUNCH NOISE	- PREDICTED LEVELS - POSSIBILITY OF SEISMIC EFFECTS
o VEHICLE FAILURE EFFECTS	- ATMOSPHERE/SURFACE EFFECTS

D.2 MICROWAVE BEAM

- o IONOSPHERE/BEAM INTERACTION
- o EFFECTS ON HUMANS, ANIMALS, PLANTS
- o EFFECTS ON ASTRONOMY, COMMUNICATIONS, ELECTRONIC EQUIPMENT
- o WEATHER EFFECTS AT SURFACE AND IN TROPOSPHERE

Figure X-2.- Continued.

D.3 EARTH ACTIVITIES

- o RESOURCE EXTRACTION, MANUFACTURING, AND TRANSPORTATION EFFECTS
- o LAND USE - RECTENNA
  - LAUNCH AND RECOVERY SITES

D.4 OPERATIONAL SPACE ENVIRONMENT

- o IONIZING RADIATION
  BIOLOGICAL AND EQUIPMENT EFFECTS
  DOSAGE AND SHIELDING ASSESSMENT
- o MICROWAVE RADIATION
  REFLECTED/SCATTERED
- o MAGNETOSPHERE PLASMA
  SPACECRAFT CHARGING
  HIGH VOLTAGE - PLASMA INTERACTION
- o METEOROIDS
  CREW/HABITAT
  EQUIPMENT/SOLAR CELLS
- o SPACE "TRAFFIC"
  MULTIPLE SPS'S AND THEIR LOGISTICS SUPPORT
  OTHER SATELLITES

Figure X-2.- Concluded.

More definitive comparisions of the relative merits of space solar power with other systems such as coal, nuclear, and solar terrestrial are also required in the present phase. Detailed areas in which these comparisons should be attained are presented in figure X-3.

This phase will also involve the detailed definition and cost of the subsequent technological advancement phase. Key activities to support this definition will include solar power system studies, space station analyses as related to subscale system evaluation, technology studies, and program analyses.

A number of significant test activities are proposed to be conducted in this initial phase. A partial listing of these tests is included in figure X-4.

REFINE PRESENT PRELIMINARY COMPARISONS IN FOLLOWING AREAS:

- o COST AND RELATED ECONOMIC CONSIDERATIONS
- o TECHNOLOGY REQUIREMENTS
- o ENVIRONMENTAL CONSIDERATIONS
- o SAFETY
- o LOGISTICS IMPLICATIONS
- o NATURAL RESOURCE REQUIREMENTS
- o ENERGY PAYBACK
- o INTERNATIONAL CONSIDERATIONS
- o REGULATORY CONSIDERATIONS
- o INTERFACE WITH PRESENT STRUCTURE

Figure X-3.- The relative merits of space solar power and other systems - coal, nuclear, solar terrestrial.

- o MICROWAVE BEAM - IONOSPHERE INTERACTION TEST
  - ARECIBO AND POSSIBLY NEW OR MODIFIED SYSTEMS
- o DEMONSTRATE PHASED-ARRAY CONCEPT
  - GOLDSTONE
- o COMPLETE LABORATORY PERFORMANCE EVALUATION OF GaAs SOLAR CELLS
- o LABORATORY-SCALE TESTING OF IMPROVED HIGH-RATE SOLAR CELL PRODUCTION TECHNIQUES
- o THERMAL-VACUUM TESTING OF ADVANCED RADIATOR CONCEPTS
- o DESIGN AND TESTING OF PROTOTYPE SPACE FABRICATION DEVICE
- o EVALUATION OF GRAPHITE EPOXY CASTINGS
- o TESTING AND EVALUATION OF MPD AND THERMAL ARC THRUSTERS
- o PRELIMINARY WIND-TUNNEL TESTING OF CONCEPTUAL LAUNCH, REENTRY, AND LANDING CONFIGURATIONS
- o COMPLETE INITIAL TESTS OF BIOLOGICAL EFFECTS OF 'HIGH Z' RADIATION
- o PRELIMINARY TESTS OF MICROWAVE RADIATION ON EQUIPMENT, VEGETATION, AND ANIMALS
- o THERMAL-VACUUM TESTING OF TYPICAL STRUCTURES
- o ADDITIONAL CRITICAL TEST AS IDENTIFIED IN STUDIES

Figure X-4.- Significant test activities, initial phase, July 1976 to July 1978 (partial listing).

C. Technology Advancement Phase

The technology advancement phase (FY80-87) consists of three elements: ground-based developments, space experiments, and a subscale system evaluation in space. The results of these activities must also be integrated into a continuing program and system analysis and evaluation. A more detailed breakdown of activities that will be required in each of the three elements is presented in figure X-5.

TYPICAL ACTIVITIES

GROUND-BASED DEVELOPMENT

MICROWAVE POWER TRANSMISSION/ RECEIVING TECHNIQUES

MICROWAVE GENERATOR DEVELOPMENT

EFFICIENT, LIGHTWEIGHT, LOW-COST SPACE SOLAR CELLS

THERMAL CONVERSION SYSTEM, COMPONENT TECHNOLOGY

POWER PROCESSING AND DISTRIBUTION COMPONENTS

MATERIALS INVESTIGATION

ORBITAL TRANSFER THRUSTER TECHNOLOGY

ENVIRONMENT
- BIOLOGICAL EFFECTS
- IONOSPHERE IMPACTS
- RADIOFREQUENCY INTERFERENCE

SPACE EXPERIMENTS

STRUCTURAL ELEMENTS AND FABRICATION TECHNIQUES

ELECTRONIC/MECHANICAL COMPONENTS
- ADVANCED SOLAR CELLS
- MATERIALS
- MICROWAVE GENERATORS
- THERMAL CONVERTER COMPONENTS

HIGH-VOLTAGE PLASMA EFFECTS

ORBITAL TRANSFER THRUSTER FLIGHT EVALUATION

PROPELLANT TRANSFER

EMISSIONS - ATMOSPHERE COMPATIBILITY

SPACE SUBSCALE SYSTEM DEVELOPMENT AND EVALUATION

CONSTRUCTION/ASSEMBLY OF LARGE SYSTEMS

LOGISTICS OF LARGE-SCALE SPACE OPERATIONS

IN-SPACE PRODUCTIVITY AND ASSEMBLY COSTS

END-TO-END POWER SYSTEM PERFORMANCE

Figure X-5.- Technology advancement phase.

Comments pertinent to the activities in this phase are presented in the following paragraphs.

Solar energy conversion.- The most significant contribution to technical and economic feasibility of SPS can be obtained by increase of solar cell array power per unit mass (kilowatts/kilogram) and decrease in cost. It is also expected that solar cell life will play a key role in determining economic feasibility.

Structures.- Although structures appear to be a relatively low weight item in current SPS configurations, it is expected that significant analytical and test efforts will be required to develop and qualify these systems. The main difficulty in this area is the inability to ground test (simulate) the large, lightweight systems.

Microwave conversion and control.- The satisfactory performance of dc/rf power converters is essential to the success of the SPS concept. The key performance parameters are efficiency, lifetime, and noise characteristics. Low component weight is desirable, but it is of secondary importance to conversion efficiency, which directly affects solar array size and weight.

Environmental impact.- The design and performance of SPS is directly influenced by allowable microwave radiation intensity levels on the ground and in the upper atmosphere. It is expected that a major test program will be required to resolve environmental issues and to establish practical but safe design criteria.

Space transportation.- The installed cost of SPS is strongly influenced by space transportation costs. Although the HLLV development appears to be primarily a scale-up and product improvement of existing rocket technology, such as was accomplished in the Saturn V development, significant testing and development will be required to demonstrate low-cost operations and efficient equipment reuse concepts. Development of a suitable low-cost, long-life OTV propulsion system is also mandatory regardless of SPS design configuration.

D. System Development

Detailed plans for the system development phase would be developed during the Technology Advancement phase of the program. The scope of the effort would exceed that required for the Apollo Program, particularly since a continuing commercial phase would be envisaged requiring a large industrial capacity. The ability to accomplish this in the period between 1985 and 1987 will be dependent upon the planning, organization, and long lead-time activities conducted during the preceding phase. The transportation and associated launch and recovery (or landing) facility development will constitute a particularly significant theme of the overall activities of this phase.

E. Program Costs

The program plan (fig. X-1) shows preliminary estimates of costs by major phase. The initial phase (system definition and exploratory technology) is estimated to cost between $40 and $50 million. The major elements in this estimate are as follows:

1. System studies - $10 to $14 million
2. Environmental analysis and tests - $5 to $6 million
3. Microwave conversion and control - $10 to $12 million
4. Structure (thermal and materials) - $7 to $9 million
5. Orbit transfer propulsion, exploratory technology - $7 to $9 million

Commitment to the technology advancement phase would occur in 1979, assuming favorable results from the initial program phase. The technology advancement phase is estimated to cost $4 to $6 billion over a period of about 10 years. The peak annual funding for this phase would be about $2.0 billion in the 1985-87 time frame. The major cost element of the phase would be the development of techniques and the subsequent construction and evaluation of a subscale system in orbit.

The system development phase (initiated 1987) would involve commitment to a multibillion per year program of 8 to 10 years' duration. The total cost is estimated to be $45 to $55 billion, with the major cost elements being development and verification of space transportation systems ($9 to $12 billion), solar power satellite systems ($19 to $22 billion) and orbital construction facilities ($16 to $19 billion).

Expenditures for the final commercialization phase would depend primarily upon SPS unit costs, space transportation costs, and rate of installation. Initial estimates of these costs are given in section XI of this report.

XI. PROGRAM COST AND ECONOMIC ANALYSIS

A. Methodology

The SPS design concepts evaluated involve improved technology in several areas as well as new and vastly expanded space activities over those which have been accomplished to date. The economic analysis and evaluation of SPS are based on projections of capability and technology resulting from a major development program as described in section X. For analytic purposes, it was assumed that the SPS ground-receiving stations (rectennas) would be operated as baseload power sources in a large power grid. This grid would include conventional powerplants (nuclear and fossil fuel) for both baseload and peaking requirements. The general approach adopted was to derive program costs and the associated power production costs for the implementation of 112 10-GW power stations over a period of 30 years beginning in 1995. The program costs were used to determine SPS unit costs. Annual operating and maintenance (O&M) costs were also determined as were the return rates necessary to amortize design, development, test, and evaluation (DDT&E) costs. These costs are then compared with costs of conventional baseload and other future power systems.

B. SPS Costs

The major cost elements of the SPS are as follows:

1. Power Station System - consists of capital cost of Solar Energy Collection System, Microwave Power Transmission System, and the Microwave Reception and Conversion System.
2. Space Transportation System - consists of capital cost and operation cost of HLLV's, COTV's, logistic vehicles (PLV's, POTV's) and associated launch, recovery, and refurbishment facilities.
3. Space Construction System - consists of capital costs of space facilities and equipment for construction and assembly of power station systems, including manpower requirements.
4. Operational Costs - consists of costs of manpower, transportation, consumables, and repair/replacement hardware for sustaining and maintaining operation of the power station system.
5. DDT&E Costs - consists of all nonrecurring research and development funds expended prior to initiation of commercialization (1995).

The preceding cost elements may be expressed in mills/kWh and combined to obtain a total cost of electricity (COE) at the busbar as follows:

$$\text{COE (mills/kWh)} = \text{capital recovery} + \text{O\&M} + \text{DDT\&E}$$

This equation with definition of all terms is shown in figure XI-1.

Capital costs.- The capital cost $\overline{CC}$ of an SPS consists of satellite hardware, satellite construction, space transportation, and ground system (rectenna) costs. The satellite hardware costs were determined using the cost estimating relationships (CER's) and satellite weight characteristics given in section IV. A range of costs was determined based on satellite weight, satellite configuration and construction location (LEO or GEO), and unit cost of solar cells varying from $100 to $500/kW.

The cost of satellite construction was based on requirements delineated in section V. This cost item includes space construction facilities and equipment and space construction personnel.

The space construction facilities are to house construction personnel and equipment and are located in LEO and GEO, as required by the particular construction location and configuration. The costs of these facilities were prorated over the number of satellites constructed because they are reusable. The facilities were estimated at the rate of $250/kg recurring hardware cost.

The space transportation costs and cost variables are discussed in detail in section VI. The transportation cost per SPS was determined by summing the total space transportation cost for 112 satellites and dividing by 112 to reflect the reusability of launch and orbit transfer vehicles.

The rectenna costs were based primarily upon the recurring costs of diodes, circuits, and the support structure. Unit costs utilized are given in section IV. As indicated in figure XI-1, a plant lifetime of 30 years was assumed in the computation of capital recovery rate. Also, a fixed rate of return of 15 percent for principal, interest, taxes, and insurance was utilized in all cases. The SPS plant factor utilized was 0.92, which is based on an average downtime of 4 weeks/yr for maintenance and repair. This downtime period would include the loss of power during the brief eclipse periods.

<u>O&M costs</u>.- The primary operation of SPS will be conducted from the ground receiving station. It is anticipated that routine, but infrequent, "onboard" monitoring and inspection may also be required. This may be accomplished by a crew that services several SPS's, thus reducing the costs attributable to a single SPS.

As a baseload power system, SPS will be designed to operate at full capacity year round. It is anticipated, however, that scheduled shutdowns of several days' duration will be required annually to replace or repair failed or malfunctioning components (klystron tubes, solar array blanket sections, etc.). In such cases, an HLLV and the selected COTV concept could be scheduled to deliver the hardware. Personnel and consumables would be delivered by the personnel transportation vehicles. Preliminary estimates of annual O&M costs were based on the following assumptions:

Cost of electricity (mills/kWh) = Capital recovery + O&M + DDT&E

$$\text{Capital recovery} = \left[\frac{r}{1-\left(\frac{1}{r+1}\right)^{y}}\right]\left(\frac{\overline{CC}}{E}\right)(1000)$$

r = rate of return, 15 percent assumed
y = plant lifetime, 30 years assumed
$\overline{CC}$ = satellite materials + construction + space transportation + rectenna
E = (plant capacity, kW) (plant factor) (hours/yr)

Operation and maintenance

$$\text{O\&M} = \frac{\text{(Manpower + materials + space transportation)/yr}}{\text{Annual electrical energy, kWh/yr}}$$

Design, development, test and evaluation

$$\text{DDT\&E} = \frac{\text{Total funding outlay}}{\begin{pmatrix}\text{Average no. of SPS's} \\ \text{over first 30 years}\end{pmatrix}(E)(30)}$$

Figure XI-1.- Cost equations.

1. Ground O&M staff	48 man-yr/yr/10-GW system
2. On-orbit maintenance/repair	12 man-yr/yr
3. Repair/replacement/maintenance	1 percent of SPS mass/yr (per sec. VII)

DDT&E costs.- The DDT&E cost was based on development cost estimates for the major program elements. The estimates utilized are given in table XI-1. The estimates shown are the cumulative funding requirements from the start of technology advancement through system development (1995). The amortization of these costs over the initial 30 years of SPS operation per scenario B was accomplished using the equation shown at the bottom of figure XI-1. The numerator of the equation (total funding outlay) may include interest on capital expended during the 20-year development program. If a 9-percent interest charge is used, the effect is to increase the actual cost by a factor of about 1.4. However, as will be shown later, the DDT&E amortization cost is a small fraction of the cost of electricity.

Cost summary.- Table XI-2 shows a summary of the cost estimates for the range of design parameters investigated. Note that the total COE ranges from 29 to 115 mills/kWh. The COE for the "nominal" system is 50 to 59 mills/kWh, which consists of 46 to 52 mills/kWh for capital recovery, 3 mills/kWh (6 percent) for O&M, and 1 mill/kWh (2 percent) for amortization of DDT&E. The capital recovery cost breaks down to about 45 percent for space transportation, 40 percent for satellite and construction, and 15 percent for the rectenna. In the highest cost combination (COE = 115 mills/kWh), transportation costs increase to 60 to 70 percent. The satellite capital recovery is 25 to 30 percent and the rectenna only 8 to 10 percent.

The SPS capital cost expressed in \$/kW varies from a low of \$1400/kW to a high of \$5780/kW. This cost is the primary driver in establishing the cost of electricity for the SPS.

This nominal cost system results from an overall SPS efficiency of 5 percent, solar array weight of 0.4 kg/m^2, \$300/kW for solar cell blankets, and a transportation cost from Earth to GEO of \$108 to \$164/kg. The construction location and satellite configuration are seen to have little effect on COE.

Figure XI-2 illustrates the range of possible cost combinations for the SPS weight range investigated.

C. Comparison With Conventional and Other Advanced Systems

The economic viability of SPS will be dependent upon the costs and economics of alternative conventional and other future power systems.

Figure XI-3 shows a summary of typical power-generation costs for baseload conventional systems and several advanced concepts receiving research and development interest (and funding) at this time. The range of costs shown for each of the conventional systems corresponds to site-specific variations such as local environmental constraints, local labor and materials costs, land and site preparation costs, and fuel cost varia- The cost of coal-fired plants varies greatly depending upon the degree of stack gas scrubbing required and the type of cleanup system utilized. The conventional nuclear systems shown are light water reactors (pressurized water and boiling water). It is expected that the fast breeder reactor (liquid metal cooled) will have a capital cost in the \$800 to \$900/kW range.

The highest cost conventional systems are coal and nuclear, which are becoming the major electrical power sources for the last quarter of this century. As with SPS, the other advanced power systems shown generally have higher capital costs (\$/kW) than the conventional systems, but have zero-to-minimal fuel costs. The technical and economic feasibility of these systems is currently being investigated by ERDA and others. Although not shown in figure XI-3, nuclear fusion is another advanced power-generation system that

TABLE XI-1.- DDT&E COST ESTIMATE SUMMARY

Element	Estimated cost, $ billion
Power station systems	19.0 to 22.0
HLLV	5.0 to 10.0
COTV	1.0 to 2.0
PCTV	1.0 to 1.5
PLV	0.5 to 1.1
Construction facilities and equipment (orbital)	16.0 to 19.0
Total program	42.5 to 55.6

TABLE XI-2.- SUMMARY OF COST ESTIMATES AND RELEVANT PARAMETERS FOR 10-GW SPS

Construction configuration (a)	Parameters						Capital cost,	Cost, mills/kWh						
	Efficiency, percent	Size, km^2	Weight, $kg \times 10^6$ (b)	Solar array		Transportation, $/kg	$/kW	Capital recovery				DDT&E	O&M	Total
				kg/m^2	$/kW			Rectenna	Satellite	Transportation	Total			
Maximum range														
G-CC	4	183	129 (124)	0.46	500	293	5560	8	27	69	104	1	6	111
G-T	4	183	133 (122)	.46	500	294	5780	8	28	71	107	1	7	115
L-T	4	183	133 (122)	.46	500	209	4660	8	28	51	87	1	6	94
Nominal range														
G-CC	5	144	84 (82)	0.40	300	152	2800	8	19	25	52	1	3	56
G-T	5	144	90 (84)	.40	300	164	3000	8	20	27	55	1	3	59
L-T	5	144	90 (84)	.40	300	108	2500	8	20	18	46	1	3	50
Minimum range														
G-CC	8	96	48 (47)	0.31	100	105	1500	5	11	12	28	1	2	31
G-T	8	96	52 (48)	.31	100	106	1600	5	12	12	29	1	2	32
L-T	8	96	52 (48)	.31	100	71	1400	5	12	9	26	1	2	29

[a] G-CC = Construction in geosynchronous Earth orbit; column/cable construction.
G-T = Construction in geosynchronous Earth orbit; truss configuration.
L-T = Construction in low-Earth orbit; truss configuration.

[b] Numbers in parentheses are final numbers, but cost model was not changed.

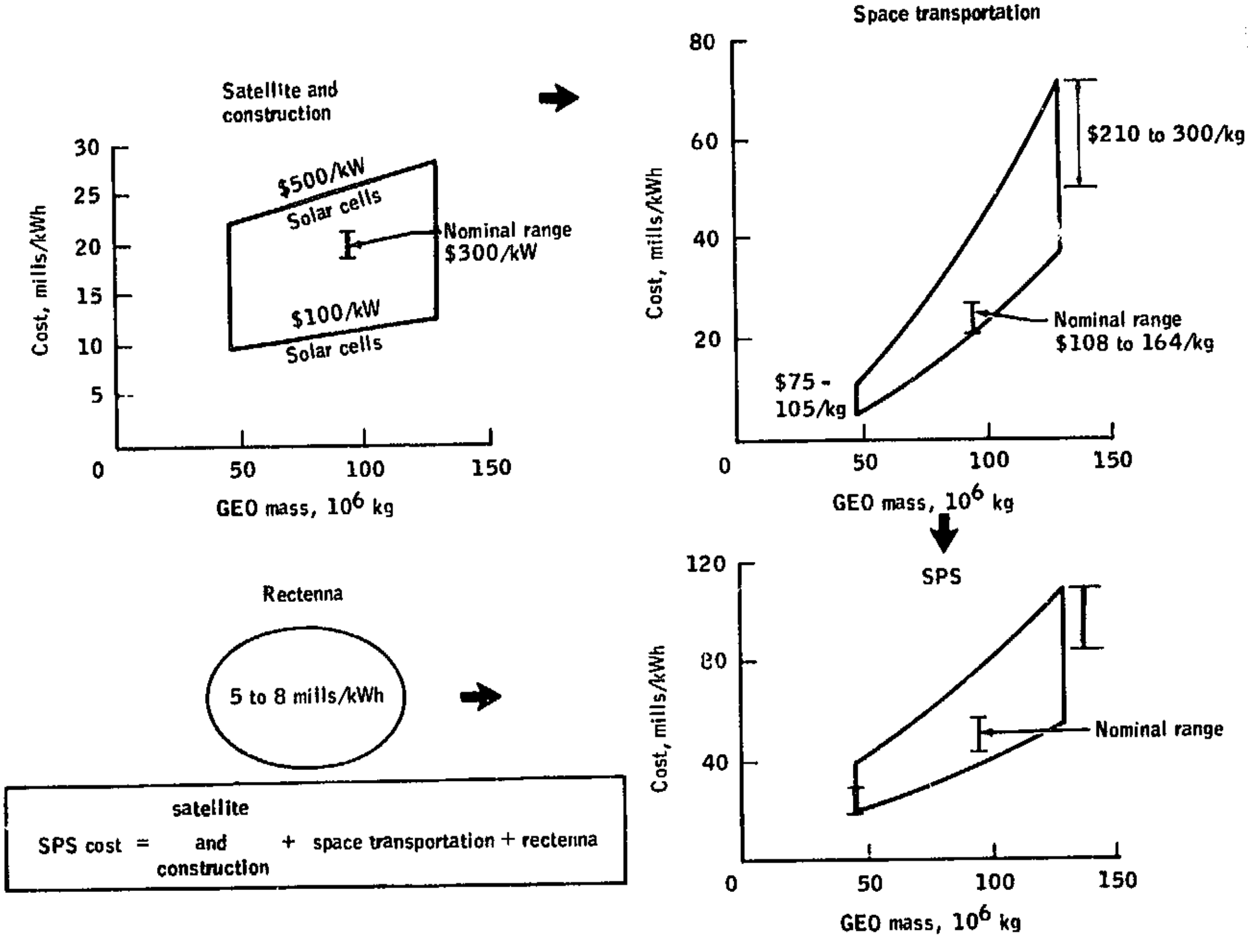

Figure XI-2.- SPS cost parametrics.

currently receives significant research and development funding; however, major technological breakthroughs are still required before total system definition may be accomplished.

The range of power-generation costs for the advanced systems is 28 to 55 mills/kWh for the ocean thermal system to 97 to 121 mills/kWh for ground-based solar thermal systems. The solar thermal systems could not be strictly classified as a baseload system because only limited (short-term) energy storage is provided. The wind power-generation system cost is based on the "fuel saver" operational mode wherein the wind system operates in parallel with conventional plants when windspeeds are within a specified range, thus effecting a reduction of fuel consumption in the conventional plants. In this mode of operation, the wind plant annual capacity factor, which is a measure of equipment utilization, is very low (30 to 40 percent at best).

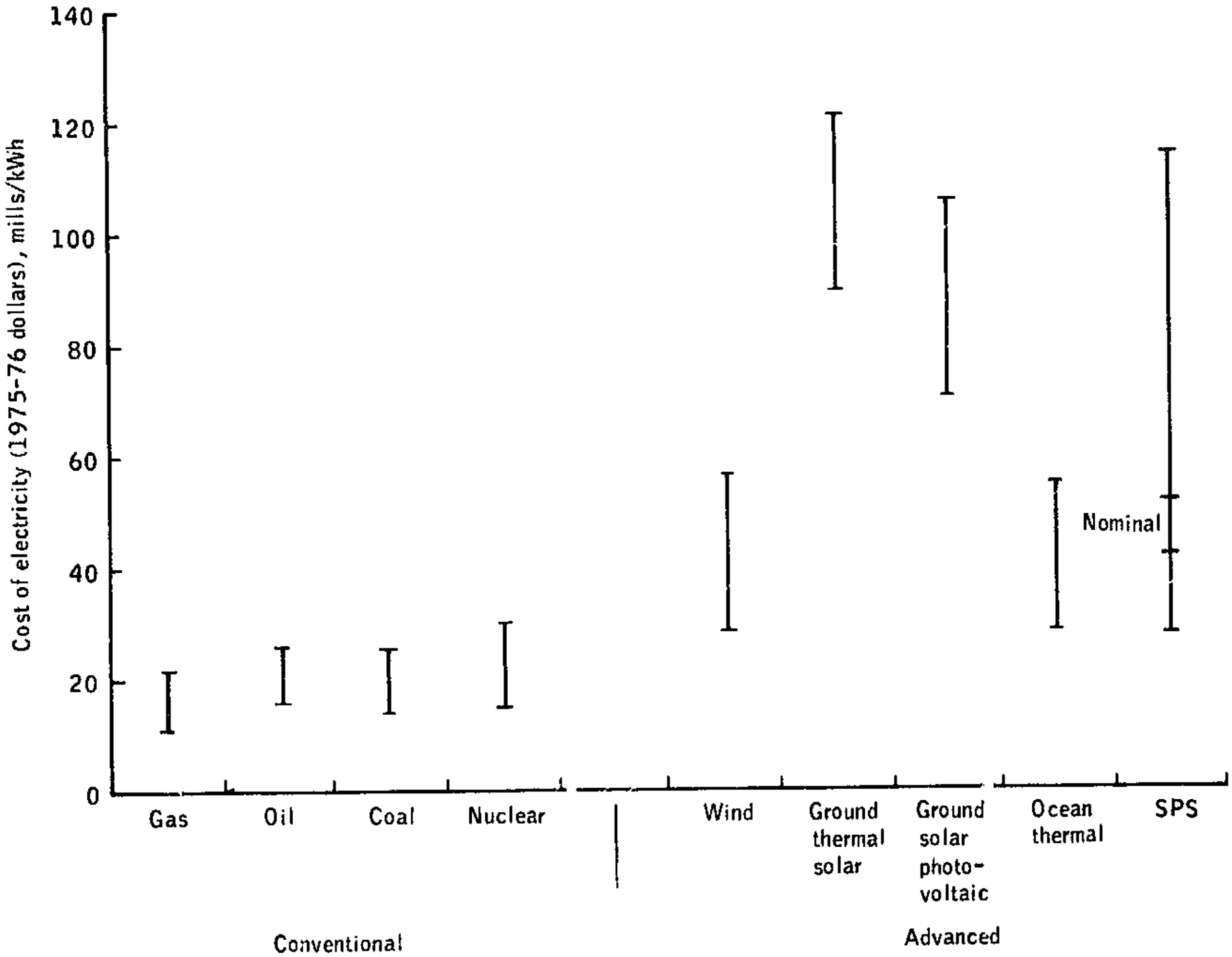

Figure XI-3.- Conventional and advanced power generation system costs.

Also shown in the figure is the range of costs estimated for the SPS. The possible SPS costs span the range from a low of 29 mills/kWh for the lightest weight, lowest transportation and unit cost system to 115 mills/kWh for the highest weight, highest transportation and unit cost system. At the low range, the SPS cost is competitive with current conventional systems, and the highest estimated cost is no greater than that of other advanced systems presently receiving research and development support.

Terrestrial solar power.- A brief design and evaluation study was performed to determine the relative cost of electricity for alternate terrestrial solar power concepts. Figure XI-4 illustrates a generalized energy flow diagram for a terrestrial solar power system. As two example cases, a photovoltaic and a thermal cycle (steam Rankine) were analyzed to determine the cost of electricity for these systems.

The systems were sized to 5 GW to be comparable with a 5-GW SPS rectenna. In both cases, it was assumed that the plants were located in the southwestern region of the United States, where plant factors of as high as 0.16 to 0.25 may be obtainable. Figures XI-5 and XI-6 show the energy flow diagrams for hydro pumped storage and fuel cell/water electrolysis cell (hydrogen) storage terrestrial solar power systems. In the solar thermal case, a hybrid system consisting of a combination solar plant and coal-burning steam powerplant was analyzed. Figures XI-7 and XI-8 show the estimated COE for these cases as a function of storage time. It was assumed that with no storage the plant factor varied from 0.16 to 0.25, which is optimistic for such systems. The terrestrial photovoltaic system was costed based on $300/kW solar cells operating at 11-percent efficiency.

Note on figure XI-8 that the nominal SPS cost (50 to 60 mills/kWh) is lower than the solar thermal terrestrial system by a substantial margin. The hybrid solar - coal plant has about half the cost of electricity of the SPS, but it saves only 13 percent in thermal energy (coal), whereas the SPS is a 100-percent substitution for the coal.

Figure XI-9 shows the estimated land requirements for the two cases mentioned above together with SPS land requirement. The terrestrial photovoltaic system requires about three times the land area of the solar thermal system because of its lower conversion efficiency.

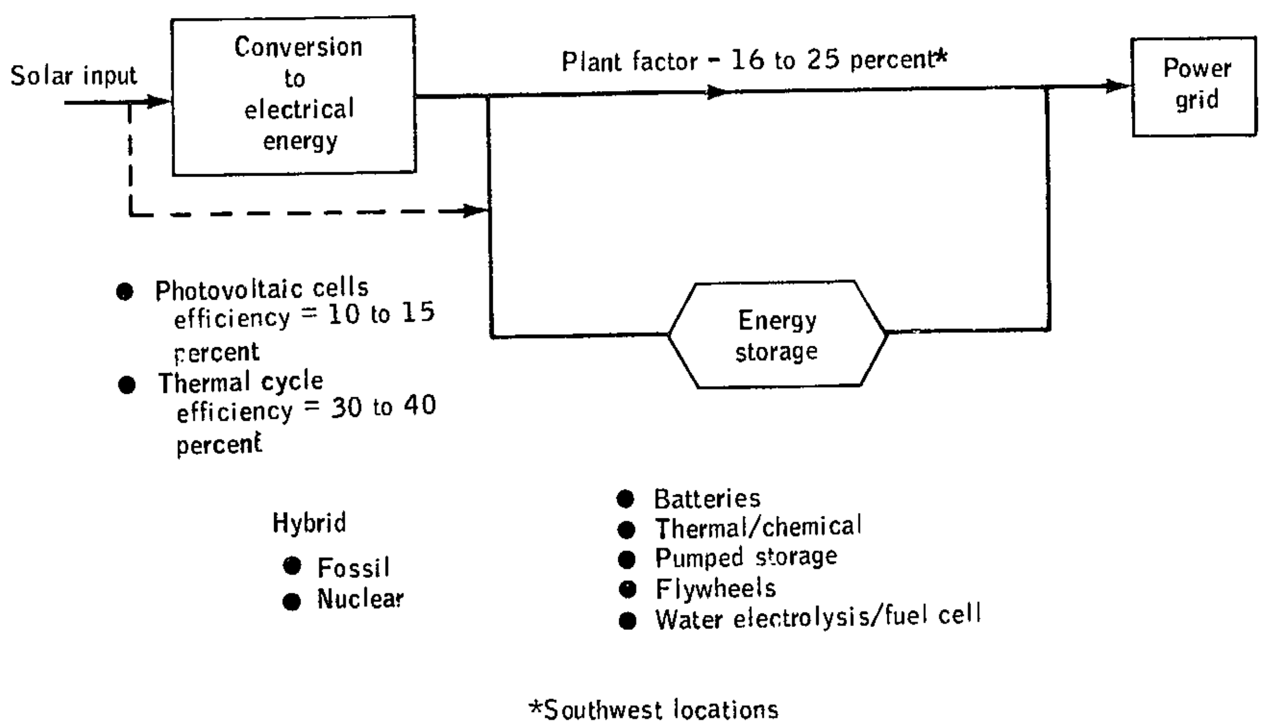

Figure XI-4.- Terrestrial solar power.

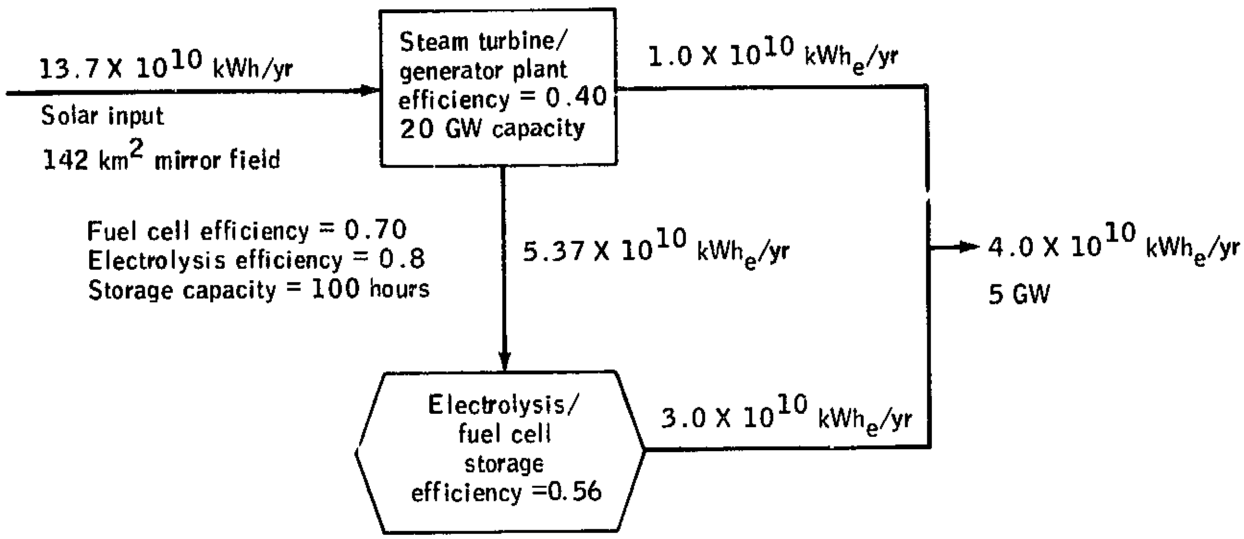

Figure XI-5.- The 5-GW solar power tower concept with electrolysis cell/fuel cell energy storage.

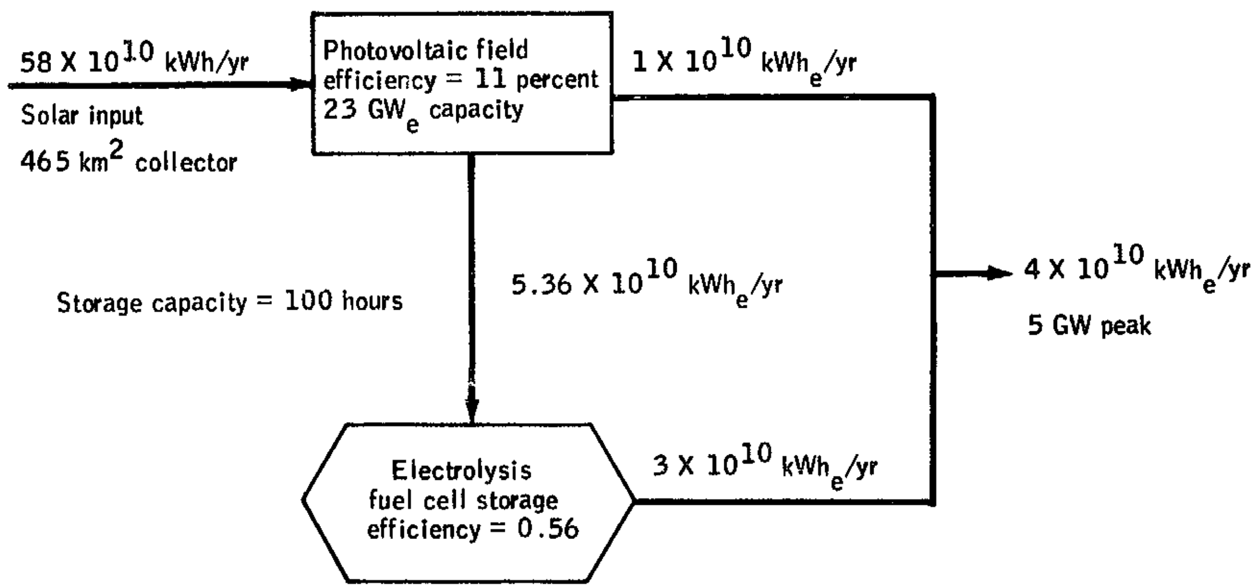

Figure XI-6.- The 5-GW solar photovoltaic-fuel cell/electrolysis cell system.

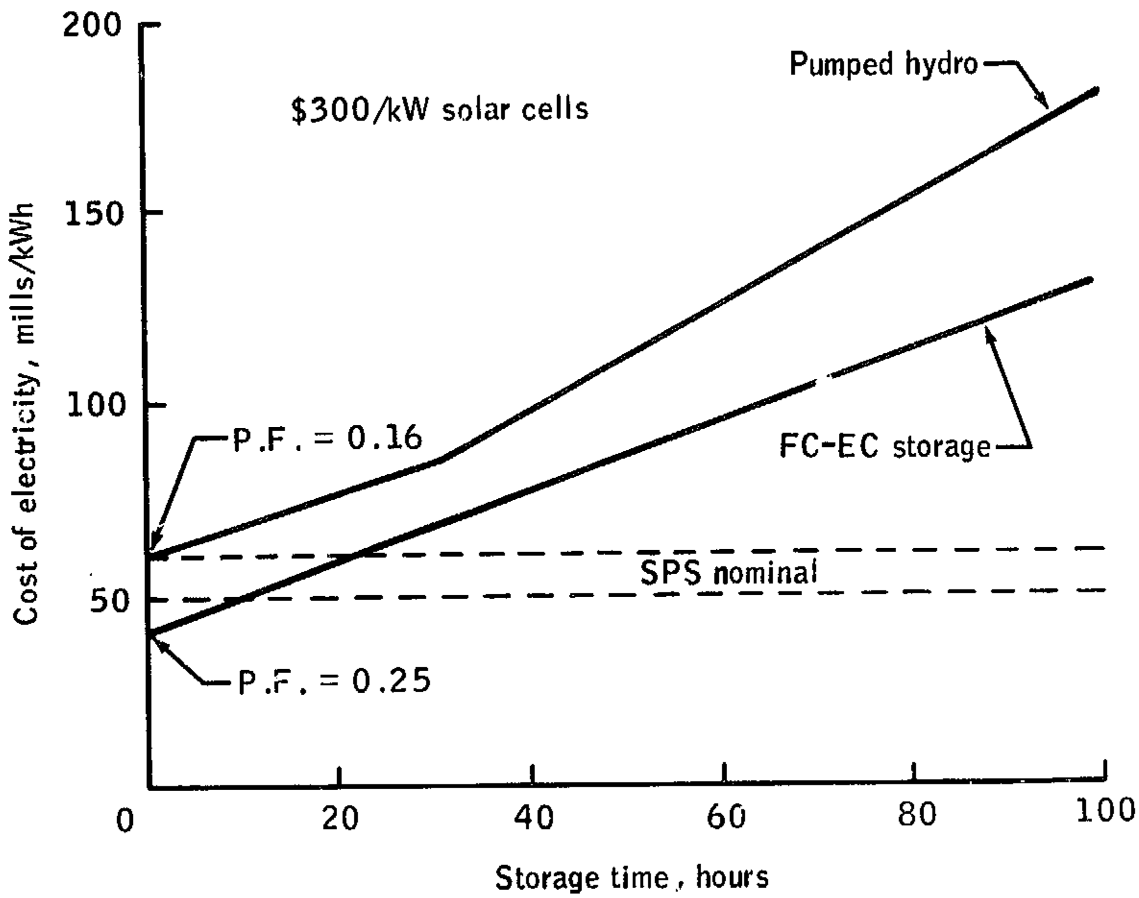

Figure XI-7.- Terrestrial solar photovoltaic power cost for 5-GW plant.

D. Summary Remarks

Preliminary SPS cost and economic analyses indicate the following:

1. The SPS appears to be an economically viable electrical power generation system for the early 2000 time period. The cost to produce electricity is 29 to 115 mills/kWh based on a 15-percent rate of return on capital investment and a 0.92 plant capacity factor. The COE based on nominal system characteristics (weight, efficiencies, transportation, etc.) is 50 to 60 mills/kWh. These costs are in the competitive range with the 28 to 121 mills/kWh for other advanced systems of current interest and, at the lowest values, compete with conventional coal and nuclear costs (15 to 29 mills/kWh).

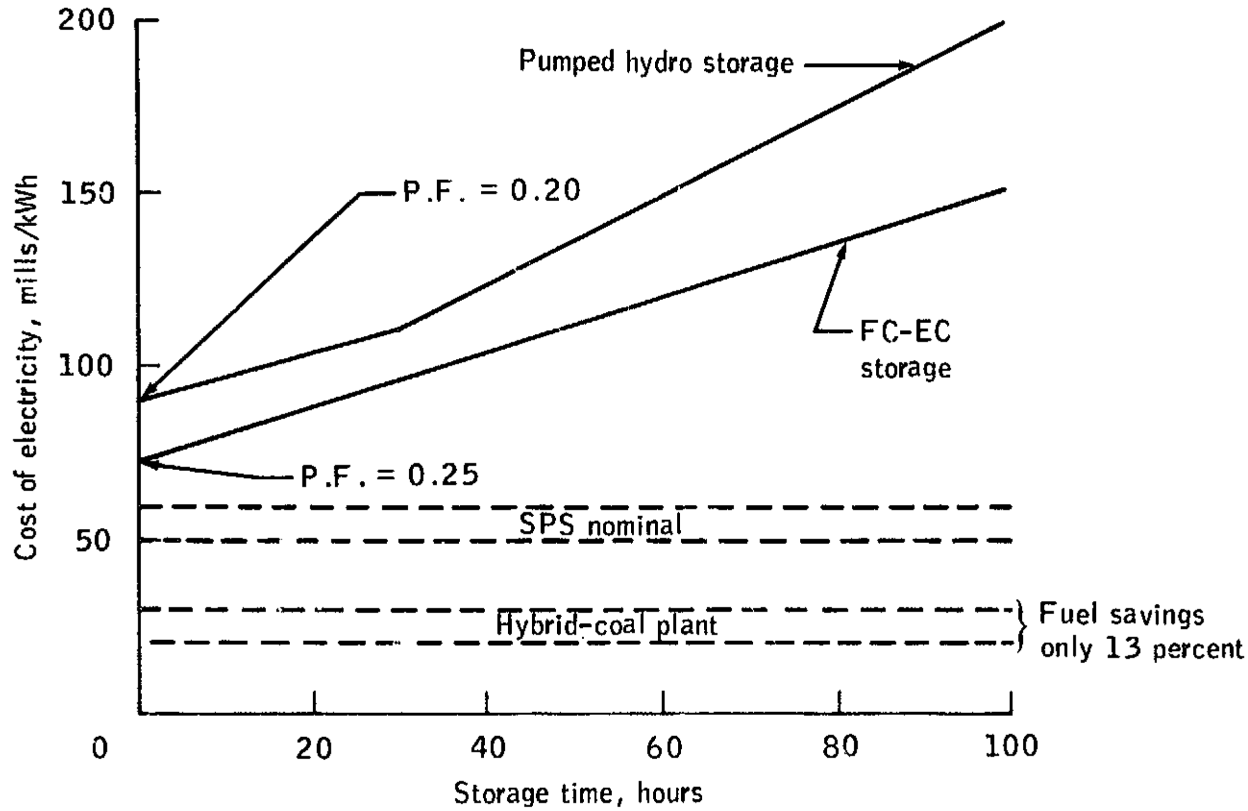

Figure XI-8.- Terrestrial solar thermal power cost for 5-GW power tower concept.

2. The highest cost component in the SPS concepts investigated is the solar cell blankets, comprising up to 81 percent of the SPS capital cost. Figure XI-10 shows this relationship together with the relative cost contribution of the other components.

3. DDT&E costs represent a substantial investment (up to $50 billion); however, when this cost is amortized over the 30-year implementation period (112 power stations), the amortization cost is only 2 percent of the COE.

4. SPS O&M costs are 2 to 7 mills/kWh, which do not appear excessive based on initial estimates.

5. Concept 3 (truss structure, LEO construction, electric COTV) results in the lowest cost design; however, further analysis is required because of the very preliminary nature of this study.

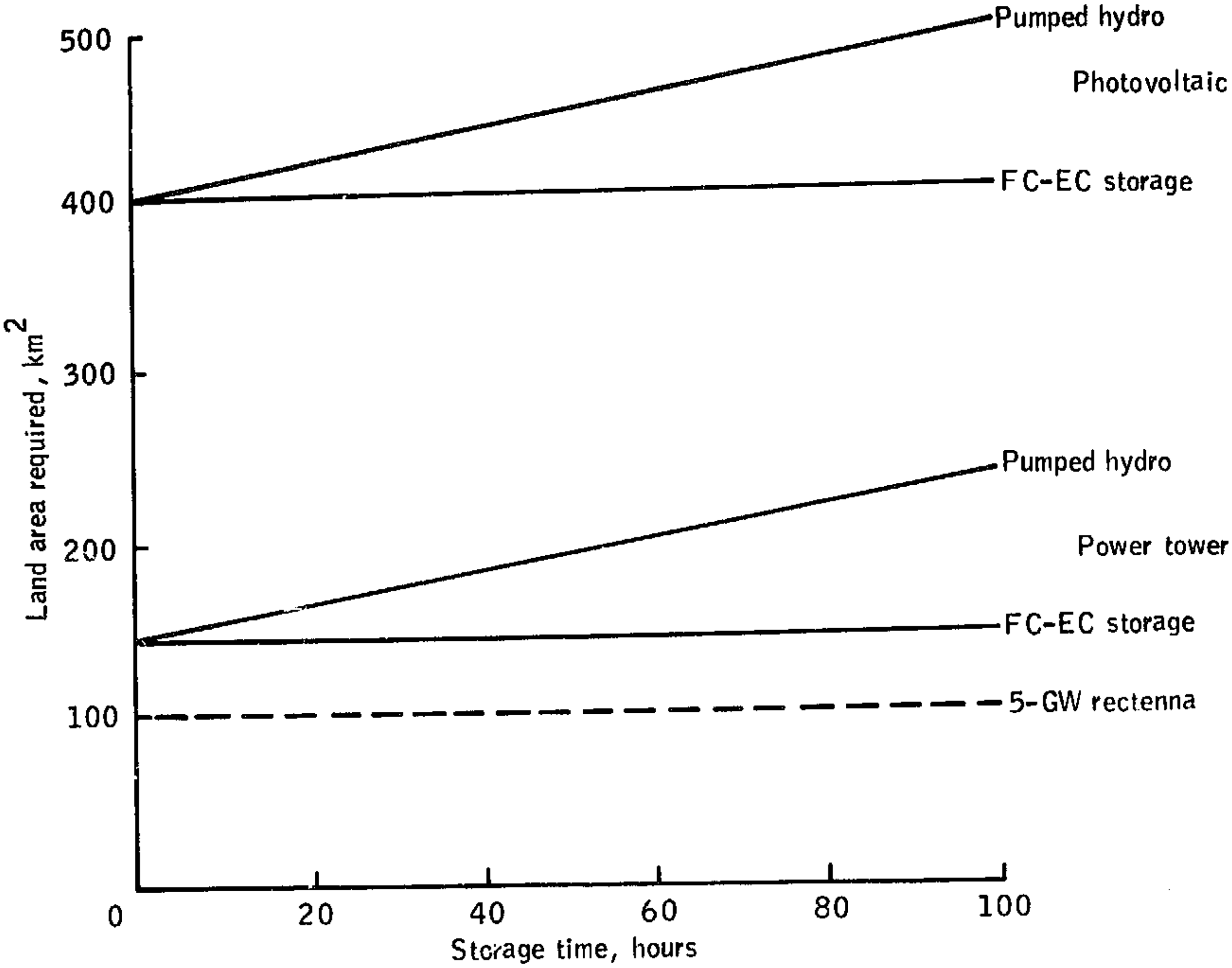

Figure XI-9.- Land area requirements for 5-GW plant.

6. The assumptions used in the "nominal" cases (50 to 60 mills/kWh) are worthy of mention because they represent a set of assumptions that are believed to be attainable and do not represent any extreme breakthroughs in technology. For instance, the silicon solar cell for this nominal design case was 10.4 percent efficient at the operating temperature of 100° C. The cost of the array was $300/kW (ERDA goals: $500/kW in 1985 and $100 to $300/kW in the year 2000)[1] and the basic cell was 4 mils thick. The total system end-to-end efficiency was 5.4 percent, which represented a total satellite weight of 84 000 metric tons. The transportation cost used was $164/kg to GEO compared to the projected current Shuttle cost of $550/kg to LEO.

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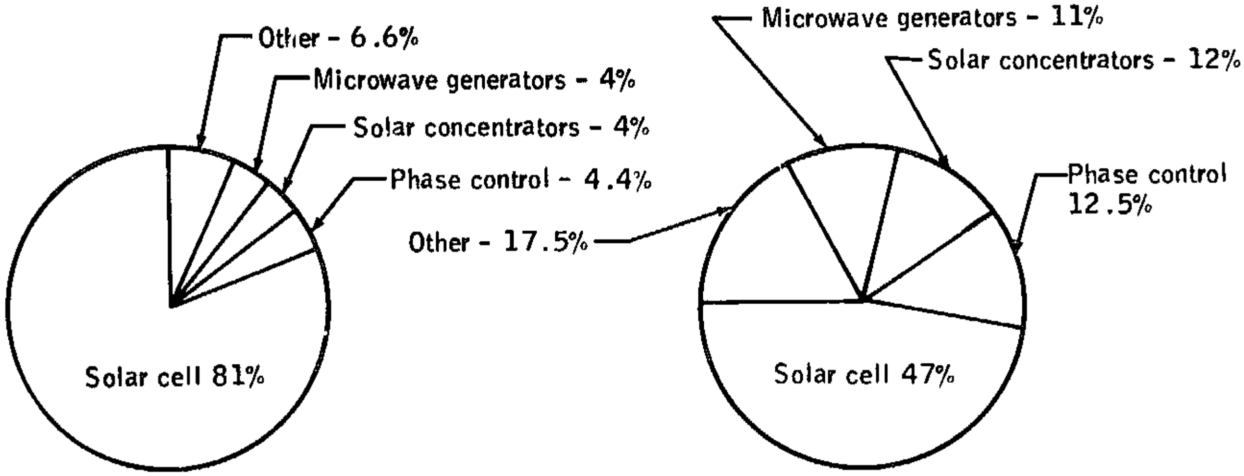
[1] Reference ERDA 48, vol. II.



Satellite cost breakdown
Solar cells at $500/kw

Satellite cost breakdown
Solar cells at $100/kw

Figure XI-10.- Satellite cost breakdown.