NASA Contractor Report 3392

Satellite Power Systems (SPS) Concept Definition Study (Exhibit D)

Volume I - Executive Summary

G. M. Hanley

CONTRACT NAS8-32475
MARCH 1981

NASA

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Prepared for
Marshall Space Flight Center
under Contract NAS8-32475

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1981

FOREWORD

Volume I, *Executive Summary*, of the SPS Concept Definition Study final report is submitted by Rockwell International through the Space Operations and Satellite Systems Division. All work reported here was completed in response to NASA/MSFC Contract NAS8-32475, Exhibit D.

The SPS final report provides the NASA with additional information on the selection of a viable SPS concept, and furnishes a basis for subsequent technology advancement and verification activities. Other volumes of the final report are listed below.

Volume	
II	Systems/Subsystems Analyses
III	Transportation Analyses
IV	Operations Analyses
V	Research and Technology Plan and Systems Summary
VI	Cost and Programmatics
VII	Systems/Subsystems Requirements Data Book

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INTRODUCTION

The Department of Energy (DOE) is currently conducting an evaluation of approaches to provide energy that will meet demands in the post-2000 time period. The Satellite Power System (SPS) is a candidate for producing significant quantities of base-load power using solar energy as the source.

The SPS concept is illustrated in Figure 1 for a solar photovoltaic design. A satellite, located at geosynchronous orbit, converts solar energy to dc electrical energy using large solar arrays. The dc electrical energy is conducted from the solar arrays to a microwave antenna. At the microwave antenna, the dc energy is transformed to microwave RF energy. A large, 1-km-diameter, antenna beams the RF energy to a receiving antenna (rectenna) on the ground. The rectenna converts the RF energy, at very high efficiency, to dc electrical energy which is input to the utility network for distribution to terrestrial users.

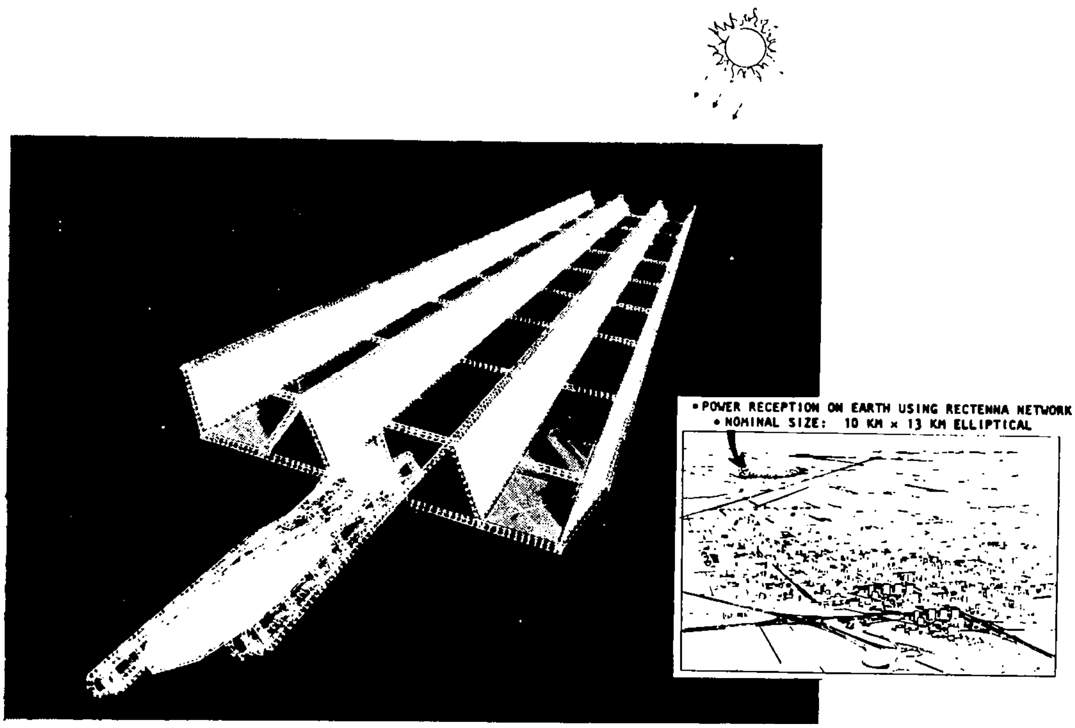

Figure 1. Rockwell Satellite Power System Concept

Typically, a single SPS provides 5 GW of power to the utility interface on the ground. Two satellite power systems could provide more power than is needed by large metropolitan areas such as Los Angeles, New York, or Chicago. Because of the large dimensions of the satellite (the solar array area is approximately 70 km^2) and the large mass (approximately 35 million kg), it is necessary to construct the satellite in space where zero-gravity allows very low structural mass. The ground-located rectenna is nominally in an elliptical array 10 km by 13 km. At the earth's surface, the microwave beam has a maximum intensity in the center of 23 mW/cm^2 (less than 1/4 the solar constant) and an intensity of less than 0.1 mW/cm^2 outside the rectenna fence line. (The current U.S. microwave exposure standard is 10 mW/cm^2.)

This study is a continuing effort to provide system definition data to aid in the evaluation of the SPS concept by DOE/NASA. The total concept development and evaluation program includes system definition (of which this study is a part); socioeconomic studies; environmental, health, and safety studies; and a comparative assessment of SPS with other candidate energy concepts. This is the third year of contract effort which is being conducted for NASA Marshall Space Flight Center. The first year's effort, completed in April 1978, is reported in Reference 1. One of the major results of the first year of effort was data used by NASA to define two reference concepts which are being used by DOE in their evaluation. The second year's effort (Reference 2) concentrated on a more detailed definition of the reference concept, trades relative to the reference concept, conceptual approaches to a solid-state microwave transmission alternative to the reference concept, and further definition of the program. This year's study resulted in an updating of the reference concept, definition of new system options, studies of special-emphasis topics, further definition of the transportation system, and further program definition.

STUDY OBJECTIVES

The objectives of this study are to provide data that enable assessment by NASA/DOE of the SPS concept, to evaluate concepts and subsystems that differ from the reference system, and to provide a basis for planning possible future SPS research efforts.

RELATIONSHIP TO OTHER NASA EFFORT

This study supports the in-house SPS system definition effort being conducted by NASA/MSFC. NASA/JSC also is conducting a system definition effort and is being supported under contract by the Boeing Company. Together, these studies help form the basis for the NASA inputs to the Department of Energy. This study also provides requirements for technology development in the large structure, solar array, power distribution, microwave transmission, space operations, and space transportation systems areas.

METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

The method of approach is illustrated in the time-phased flow diagram (Figure 2). Results of the Exhibit C effort and NASA SPS studies are the major inputs to this study.

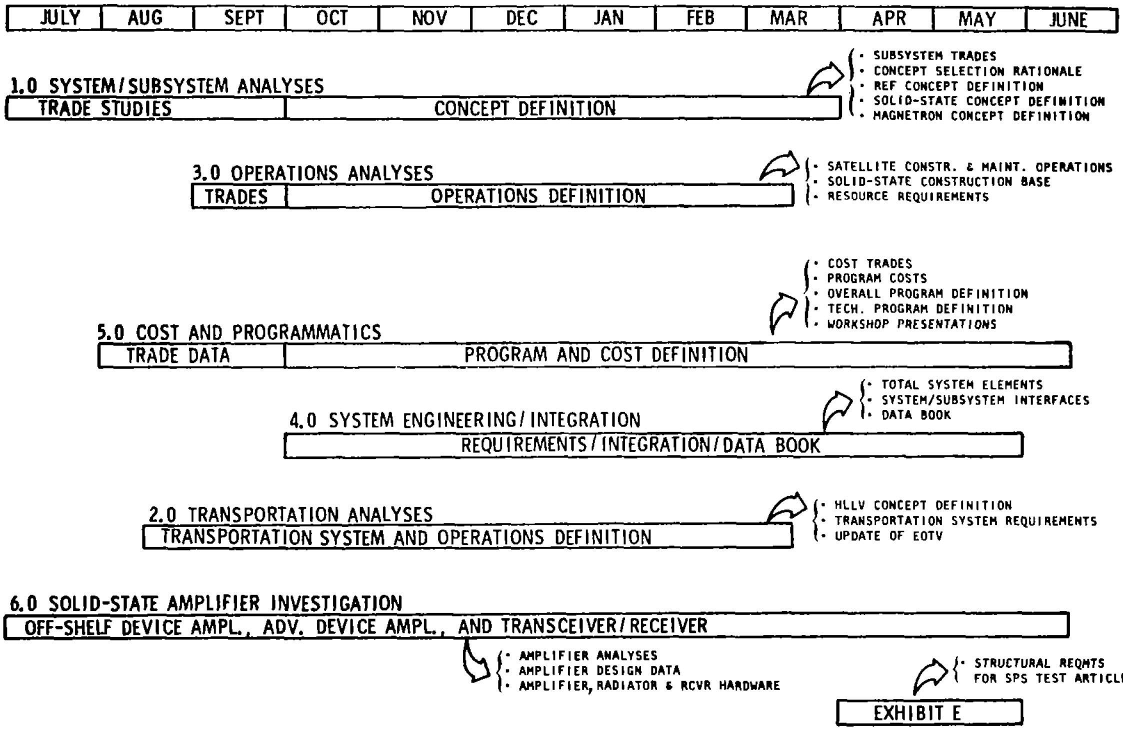

Figure 2. Time Phased Study Flow

Initial effort is concentrated in Task 1, where effort during the first three months of the study was concentrated on (1) development, analysis, and evaluation of solid-state SPS concepts, and (2) specific reference concept trade studies. At the end of three months, two solid-state concepts were selected for a more detailed definition during the next five months. Task 1 also resulted in the definition of a magnetron-powered antenna concept and determination of laser transmission capability through the atmosphere (including clouds). Results of the reference concept trade studies were used in Task 4 (Systems Engineering/Integration Analyses) to update the reference concept and to show its sensitivity to certain variations (such as multi-bandgap solar cells and maximum power density in the ionosphere). The Operations Analyses (Task 3), Transportation Analyses (Task 2) and Cost and Programmatics (Task 5) utilized the new solid-state concept and reference concept definition data to update supporting system requirements and concepts and programmatic and cost data. In addition, the transportation analyses resulted in a more detailed definition of the HLLV and a definition of its requirements. Task 4 (Systems Engineering/Integration Analyses) developed a total top-level description of the SPS system and its requirements. It also provided the end-to-end data needed to identify all elements of the system for program definition and costing.

An investigation of solid-state power amplifiers was conducted, resulting in the construction of four power amplifiers and their integration into a transmitting antenna. This system was tested and delivered to NASA/MSFC.

BASIC DATA GENERATED AND SIGNIFICANT RESULTS

Significant results of this contract are summarized in four major sections. The first section, system definition, summarizes an update of the Rockwell reference gallium arsenide (GaAs) concept and studies of alternatives to this concept. The second section contains the results of two special-emphasis areas. The third section presents the transportation study results. The final section summarizes the program definition effort, including program planning for alternative concepts.

SYSTEM DEFINITION

In addition to updating of the Rockwell GaAs reference concept, system definition effort was concentrated on the definition of alternative concepts. These alternative concepts included (1) a concept that uses magnetrons instead of klystrons for the dc to RF conversion on the satellite, (2) two concepts that have solid-state power amplifiers instead of klystrons, and (3) concepts that have improved-efficiency multi-bandgap solar arrays rather than GaAs solar arrays. Results of these studies are summarized in the following sections.

Rockwell GaAs Reference System Update

The updated Rockwell gallium arsenide reference system satellite is shown in Figure 3. A summary of the system characteristics is given in Table 1. The planform area approximates that of the silicon concept. The geometric concentration ratio is 2:1. Accounting for the end-of-life efficiency of the planar reflectors, the actual concentration of solar energy on the cells is 1.83 suns at end of life. The solar array configuration is arranged in three longitudinal troughs with planar reflectors on both sides of solar cells located in the center of each trough. The satellite mass properties are summarized in Table 2. The mass is about evenly divided between the solar array and microwave antenna.

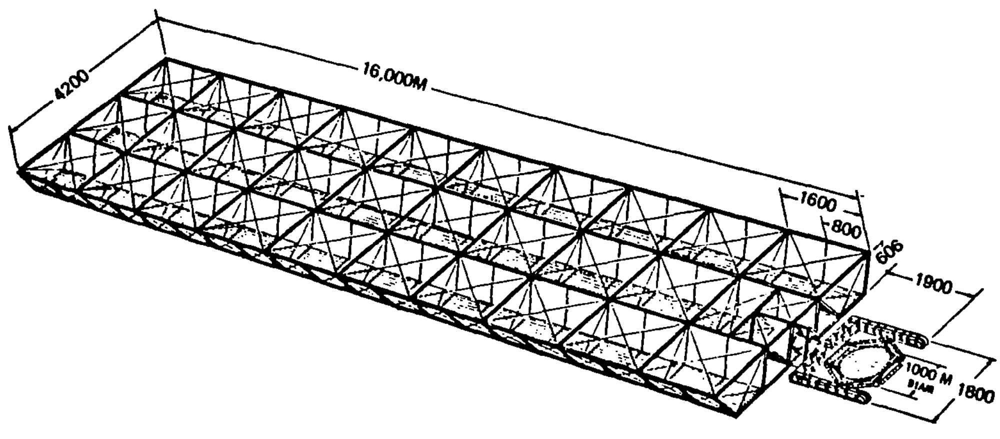

Figure 3. Rockwell GaAs SPS Reference Configuration

Table 1. Rockwell Reference Satellite Concept Description

OVERALL DESCRIPTION

- 5 GW POWER TO UTILITY INTERFACE
- GEOSYNCHRONOUS CONSTRUCTION LOCATION
- SINGLE END-MOUNTED MICROWAVE ANTENNA
- GEOSYNCHRONOUS EQUATORIAL OPERATIONAL ORBIT

SUBSYSTEMS

- POWER CONVERSION
  - GaAlAs SOLAR CELLS
  - CONCENTRATION RATIO = 1.83
- ATTITUDE CONTROL/STATIONKEEPING
  - PARTIAL SUN TRACKING
  - ARGON ION THRUSTERS
- POWER DISTRIBUTION
  - 45.5 KV DC
  - STRUCTURE/WIRING NOT INTEGRATED
- MICROWAVE ANTENNA
  - GAUSSIAN BEAM
  - 2.45 GHz FREQUENCY
  - ECLECTIC PHASE CONTROL
  - RCR WAVEGUIDE PANELS
  - KLYSTRON DC/RF CONVERTERS
- STRUCTURE
  - COMPOSITES
  - BEAM MACHINE CONSTRUCTION
- INFORMATION MANAGEMENT
  - DISTRIBUTED

Table 2. Reference Satellite Mass Summary

	MASS (MILLIONS KG)
COLLECTOR ARRAY	
STRUCTURES AND MECHANISMS	1.6
POWER SOURCE	8.2
POWER DISTRIBUTION AND CONTROL	2.8
MAINTENANCE	0.1
ATTITUDE CONTROL	0.1
INFORMATION MANAGEMENT AND CONTROL	NEG
TOTAL ARRAY (DRY)	12.8
ANTENNA SECTION	
STRUCTURES AND MECHANISMS	0.9
THERMAL CONTROL	0.7
MICROWAVE POWER	7.2
POWER DISTRIBUTION AND CONTROL	2.5
MAINTENANCE	0.1
INFORMATION MANAGEMENT AND CONTROL	0.6
TOTAL ANTENNA (DRY)	12.0
INTERFACE SECTION	
STRUCTURES AND MECHANISMS	0.2
POWER DISTRIBUTION AND CONTROL	0.3
MAINTENANCE	NEG
TOTAL INTERFACE (DRY)	0.5
TOTAL SPS DRY MASS	25.3
GROWTH (25%)	6.3
TOTAL SPS DRY MASS WITH GROWTH	31.6

The energy conversion concept characteristics are summarized in Figure 4. Because of the thin solar cell, which is produced by a chemical vapor deposition

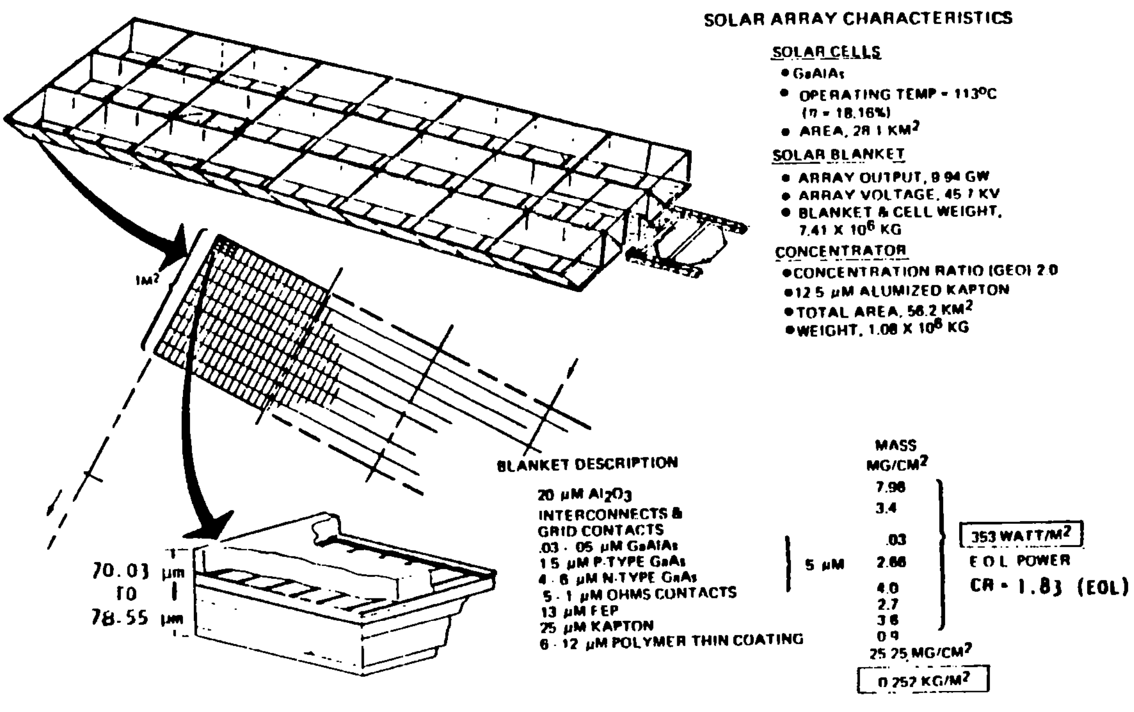

Figure 4. Photovoltaic Energy Conversion Subsystem

method, the mass of the solar cell is about 0.6 that of the reference silicon concept solar cell. The lower mass, combined with lightweight concentrators, results in a significantly reduced solar array mass for the GaAs concept. Additionally, test data have shown that the GaAs solar cells anneal space natural radiation at the normal operating temperature of the solar cells. Additional testing of the proposed SPS solar cells is needed to further validate annealing. The solar array structure is a graphite composite truss structure using beam machine construction.

Power is conducted from the solar array to the end-mounted microwave antenna at 45,000 V. Conversion of this power to the multiple voltages required by the klystron dc/RF converters is accomplished with dc/dc converters.

The microwave antenna concept and modules are illustrated in Figure 5. The antenna is a compression-frame/tension-web concept using a graphite composite structure for the external frame and tension web. A mechanical module, measuring 31 35 m, is attached to the tension web matrix. This is, in turn, comprised of 10.2x11.6-m subarrays. The subarrays are made up from the basic power module, each of which has a klystron providing 50 kW of RF energy to a resonant cavity radiator antenna element. The measurements of the power module vary from the center of the array to the edge as the power varies due to a 10-dB power taper. Heat pipes are used to dissipate the heat from the klystron body to the antenna radiator surface.

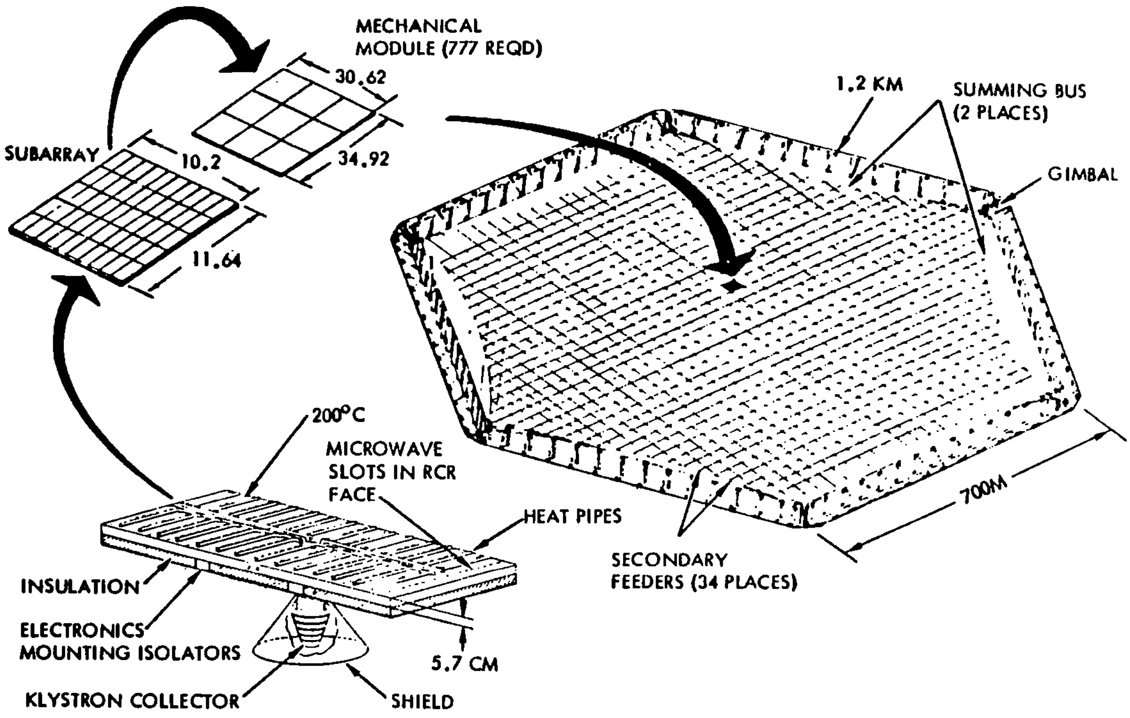

Figure 5. Rockwell Reference Concept Antenna

Power transmitted by the antenna is received on the ground at a ground receiving facility (rectenna) shown in Figure 6. This facility converts the microwave energy to dc energy using a field of flat plate phased arrays with diode rectifiers. A typical panel is shown in Figure 7 along with the structural support system. Nominal output from this facility to the utility interface is 5 GW. The maximum power density at the center of the microwave beam is 23 mW/cm^2, about 1/4 the solar constant. A buffer zone, which is surrounded by a security fence, has a maximum level of microwave radiation of only 0.1 mW/cm^2 at its edge.

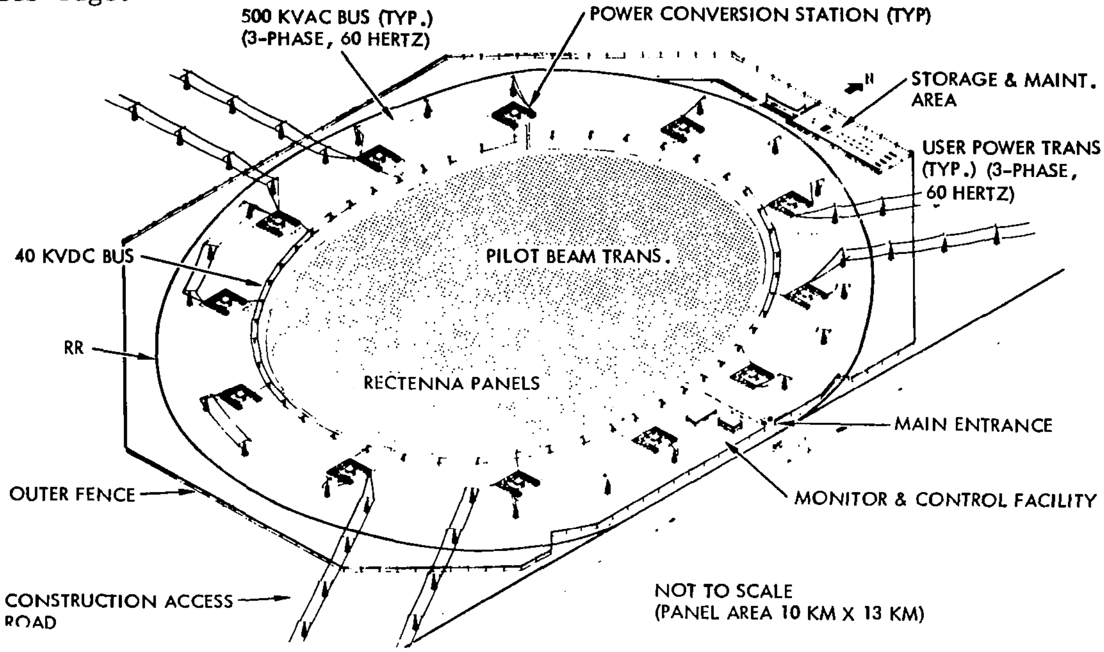

Figure 6. Operational Ground Receiving Facility

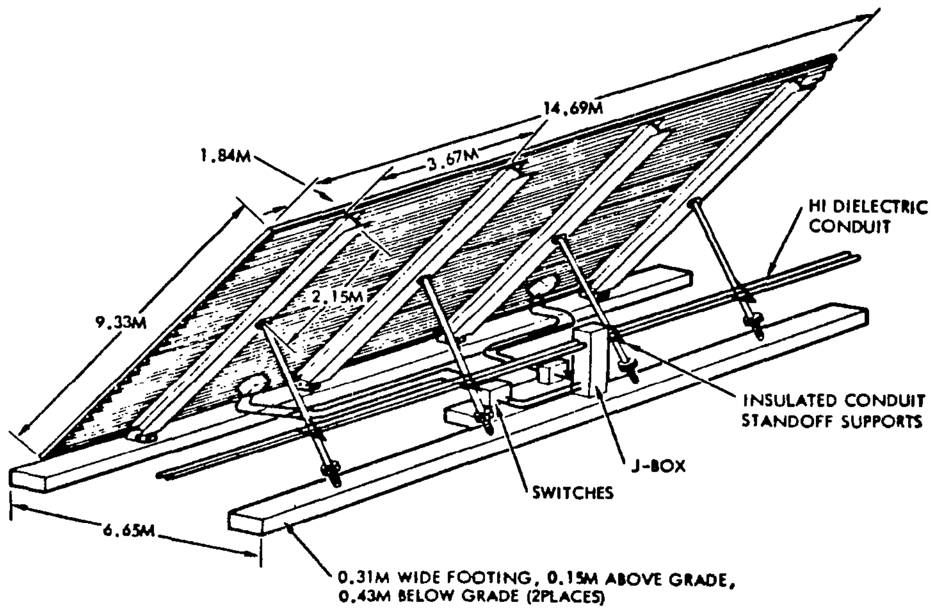

Figure 7. Panel Installation

Magnetron Antenna Concept

The Raytheon Company (Reference 3) conducted a preliminary study for NASA Marshall Space Flight Center to assess the potential application of magnetrons, rather than the reference system klystrons, for the conversion from dc to RF on the satellite antenna. Data from the Raytheon study were used as a basis for the overall magnetron system definition in this contract.

Magnetrons appear to have significant advantages compared to klystrons. It is estimated that klystrons will have to be replaced or repaired every 10 years on the average. Magnetrons may not have to be replaced during the assumed 30-year operational period because the heater, normally used to produce electrons from the cathode, is not used after initial start-up. Rather, the heater is disconnected during normal operation and free electrons are produced by secondary emission from the cathode. This results in reduced RF noise and longer cathode lifetime. Multiple voltages are required for the klystron, resulting in the need for significant dc/dc conversion on the antenna. The magnetron operates at a single voltage (20,000 V) and the use of dc/dc converters is an option, but not a necessity. Thermal dissipation of heat from a magnetron appears to be possible with passive pyrolytic graphite radiators (no heat pipes) attached to the body of the magnetron. The klystron requires heat pipes because of the high power output (50-70 kW compared to 3.5 kW for a magnetron). Finally, the efficiency of the magnetron has a greater potential for improvement than the klystron because of its already measured 85% efficiency compared to 75% for the klystron. It was assumed that the magnetron would have an efficiency of 90% for SPS compared to 85% for the klystron.

Figure 8 shows the resulting satellite design for a magnetron antenna. Although the satellite appears very similar to the reference concept, there

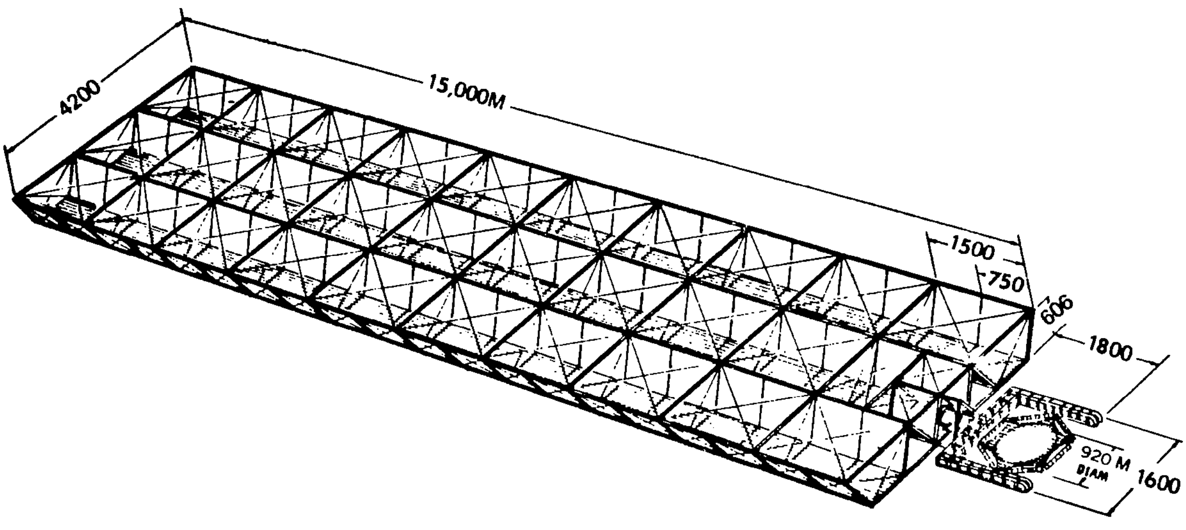

Figure 8. Magnetron-Antenna Satellite Concept

are some significant differences, which are summarized in Tables 3 and 4. Power at the utility interface is 5.6 GW compared to 5.0 GW for the reference concept. Higher power output is obtained because of the superior heat rejection and higher efficiency of the magnetron system, which allows higher power density at the center of the antenna. As shown in Table 4, the mass is 26.7 million kilograms, compared to 31.6 million kilograms for the reference concept.

Table 3. Magnetron-Powered Spacetenna Design Characteristics

- GaAs SOLAR ARRAY
- EFFECTIVE CR = 1.83
- MAGNETRON TUBE POWER LEVEL, 3.5 kW
- ANODE VOLTAGE, 20 kV
- MAGNETRON EFFICIENCY, 90%
- POWER DENSITY AT SPACETENNA CENTER, 28 kW/m^2
- NINE-STEP GAUSSIAN TAPER TRUNCATED AT -9.53 dB
- SPACETENNA DIAMETER, 920 m
- RECTENNA DIAMETER, 11.0 km (MINOR AXIS)
- POWER AT UTILITY INTERFACE, 5.6 GW

Table 4. Magnetron-Antenna Satellite Mass Summary

	MASS (MILLIONS KG)
COLLECTOR ARRAY	
STRUCTURES AND MECHANISMS	1.7
POWER SOURCE	7.9
POWER DISTRIBUTION AND CONTROL	4.1
MAINTENANCE	0.1
ATTITUDE CONTROL	0.1
INFORMATION MANAGEMENT AND CONTROL	0.1
TOTAL (DRY)	14.0
ANTENNA SECTION	
STRUCTURES AND MECHANISMS	0.6
MICROWAVE POWER	3.4
POWER DISTRIBUTION AND CONTROL	1.5
MAINTENANCE	0.1
INFORMATION MANAGEMENT AND CONTROL	0.3
TOTAL ANTENNA (DRY)	5.9
INTERFACE SECTION	
STRUCTURES AND MECHANISMS	0.3
POWER DISTRIBUTION AND CONTROL	1.2
MAINTENANCE	NEG
TOTAL INTERFACE (DRY)	1.5
TOTAL SPS DRY MASS	21.4
GROWTH (25%)	5.3
TOTAL SPS DRY MASS WITH GROWTH	26.7

Figure 9 shows the build-up of the antenna. As for the reference concept, a compression-frame/tension-web structure is employed with 25.2×25.2-m mechanical modules attached to the web structure. The mechanical module is comprised of a 3 by 3 of subarrays which are 8.4 m on a side.

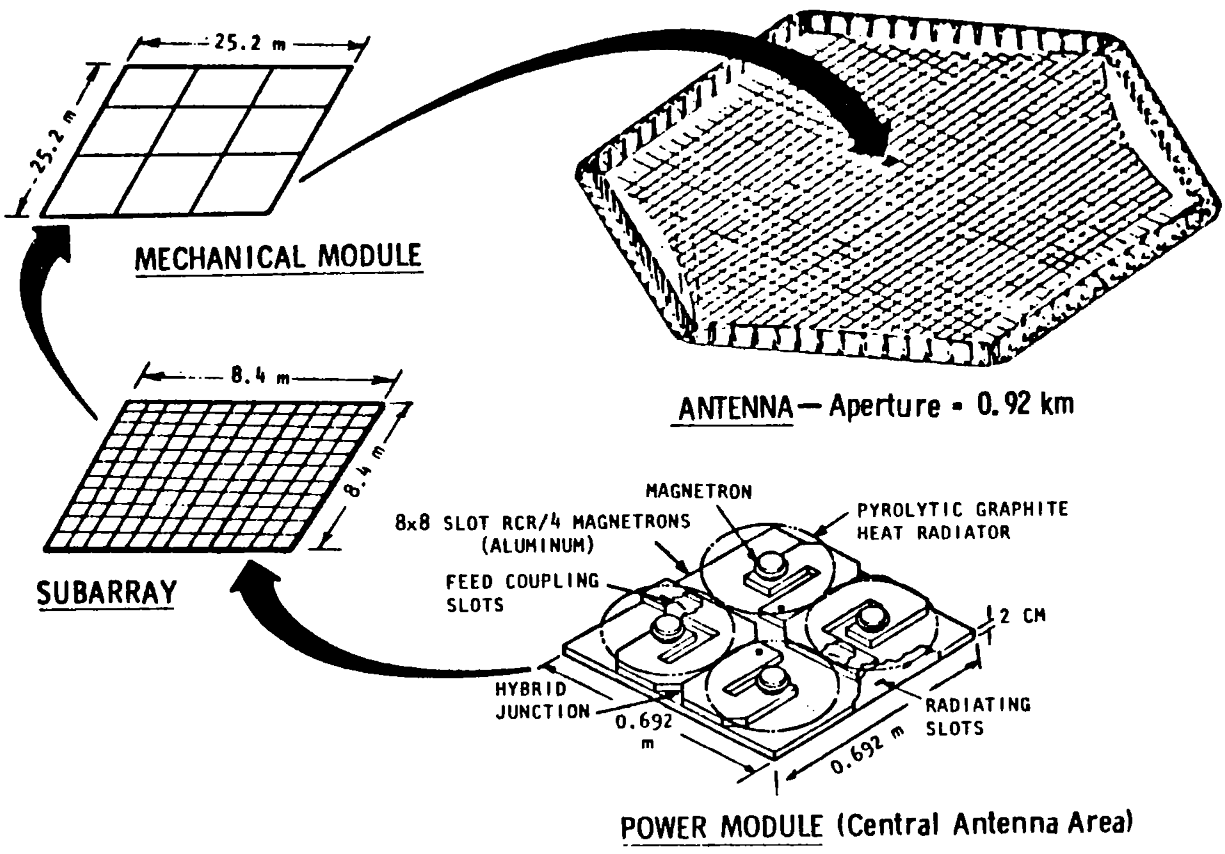

Figure 9. Magnetron Antenna Buildup

The basic building block is the power module, which varies in dimensions and power density from the center of the antenna to the edge (10-dB power taper). The power module illustrated in Figure 9 is designed for use in the high power density portion of the antenna. Four 3.5-kW amplitrons drive the power module. All magnetrons are identical throughout the system. The outputs of each pair of magnetrons are combined by means of a short-slot waveguide hybrid. Pyrolytic graphite discs conduct heat away from the magnetron's anodes and dissipate the waste heat by radiation. Since the magnetron design can dissipate greater heat than the klystron design and since the power transmission efficiency is higher for the magnetron, a higher power density is used at the center of the antenna (28 kW/m^2 compared to 21 kW/m^2 for the klystron). As a result, the antenna aperture is smaller (0.92 km compared to 1.0 km for the klystron antenna) and the power at the utility interface is greater (5.6 GW compared to 5.0 GW for the klystron). Although the rectenna is somewhat larger than the rectenna for the klystron (reference) system, the power per unit area is approximately the same.

Solid-State Antenna Concepts

Replacement of klystron dc/RF converters with solid-state dc/RF converters was a major alternative considered to the reference system. Because of the low voltages that are necessary to operate transistor devices (e.g., 10 V) and the low power output per device (e.g., 5 W), power distribution and control is a problem. Additionally, the base temperature of the devices needs to be about 125°C for high efficiency and reliable operation. This requires large areas for heat dissipation, resulting in larger antenna apertures and lower maximum power density.

Two concepts were studied that utilize solid-state devices, one which is similar to the reference concept approach (separate solar array and antenna) and one that integrates the solar array and antenna (sandwich concept). These concepts are described in the following sections.

Solid-State End-Mounted Antenna Concept

The solid-state end-mounted antenna concept is similar to the reference concept since power is conducted from the solar array across a rotary joint to the microwave antenna. An analysis showed that the 10 dB power taper used on the klystron antenna system resulted in installation costs that were similar to a 0 dB taper. Because of the lower sidelobes resulting from a 10 dB taper, the 10 dB taper was also selected for the solid-state concept. The resulting satellite concept is shown in Figure 10. Its characteristics are listed in Table 5, and mass properties given in Table 6. This concept has two microwave antennas which are greater in aperture diameter than the klystron antenna (1.35 km compared to 1.0 km for the klystron antenna). This larger area is required to dissipate the waste heat at a relatively low temperature (125°C) while providing rated power output. Because of the large aperture and lower maximum power density on the antenna, power at the utility interface is reduced to 2.61 GW per antenna, compared to a nominal 5 GW for the reference concept. Two antennas were provided to increase the total power of a single satellite.

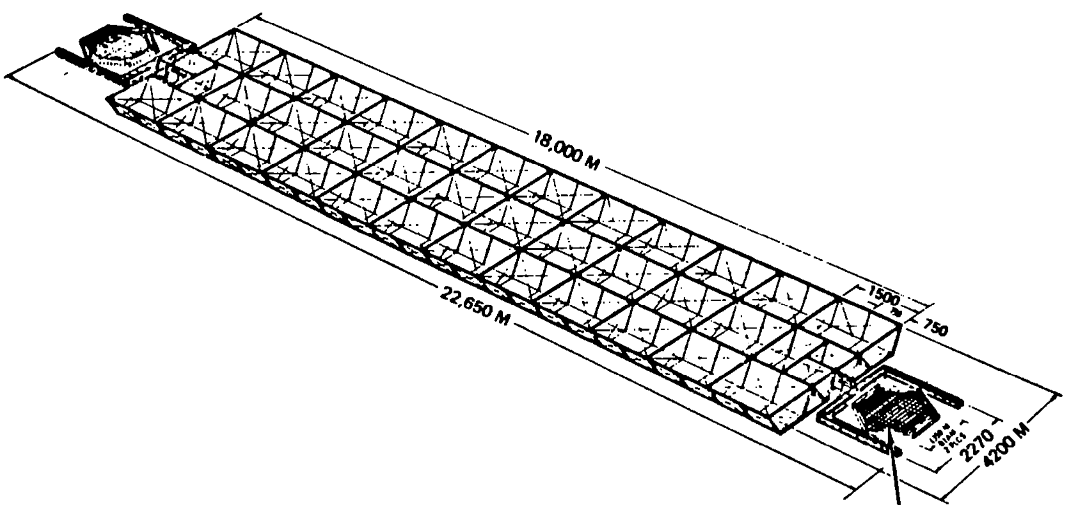

Figure 10. Solid-State End-Mounted Antenna Satellite Design

One half of the solar array feeds each antenna. Each antenna has a separate receiving station on the ground that has a rectenna boresight diameter of 7.5 km, compared to 10.0 km for the reference concept.

Table 5. Solid-State End Mounted Antenna System Characteristics

- GaAs SOLAR ARRAY
- EFFECTIVE CR_E = 1.83
- 640 V SERIES PARALLEL STRINGS (2600 W MAX.) WITH DUAL DC/DC CONVERSION FROM 40,000 V
- DUAL END-MOUNTED MICROWAVE ANTENNAS
- AMPLIFIER BASE TEMPERATURE = 125°C
- AMPLIFIER EFFICIENCY = 0.8
- ANTENNA POWER TAPER = 10 dB
- ANTENNA DIAMETER = 1.35 km
- POWER AT UTILITY INTERFACE = 2.61 GW PER ANTENNA (5.22 GW TOTAL)
- RECTENNA BORESIGHT DIAMETER = 7.51 km PER RECTENNA
- SPECIFIC MASS = 7.66 kg/kW

Table 6. Solid-State End-Mounted Antenna Satellite Mass Summary

	MASS (MILLIONS KG)
COLLECTOR ARRAY	
STRUCTURES AND MECHANISMS	1.6
POWER SOURCE	9.3
POWER DISTRIBUTION AND CONTROL	1.1
MAINTENANCE	0.1
ATTITUDE CONTROL	0.1
INFORMATION MANAGEMENT AND CONTROL	0.1
TOTAL ARRAY (DRY)	12.3
ANTENNA SECTION	
STRUCTURES AND MECHANISMS	1.4
MICROWAVE POWER	10.9
POWER DISTRIBUTION AND CONTROL	4.4
MAINTENANCE	0.5
INFORMATION MANAGEMENT AND CONTROL	1.6
TOTAL ANTENNA (DRY)	18.8
INTERFACE SECTION	
STRUCTURES AND MECHANISMS	0.3
POWER DISTRIBUTION AND CONTROL	0.5
MAINTENANCE	0.1
TOTAL INTERFACE (DRY)	0.9
TOTAL SPS DRY MASS	32.0
GROWTH (25%)	8.0
TOTAL SPS DRY MASS WITH GROWTH	40.0

One of the major trade studies was a determination of the approach to power distribution. Under any circumstances, it is necessary to connect the power amplifiers in series/parallel strings to increase the voltage and power input from about 10 V and 5 W required by each device. The final concept has 640 V and 2600 W (maximum) strings with dual dc/dc conversion from 40,000 V.

The antenna is made up of solid-state amplifier module panels illustrated in Figure 11. The dipole antenna is supported by a silica-fiber truss structure. A honeycomb sandwich, containing the RF drive distribution system, is bonded to the antenna truss structure. The bottom of the honeycomb sandwich has an aluminum sheet that acts as a ground plane as well as a heat sink and radiator for the solid-state power amplifiers which are attached to it. The dc power distribution system is located on the other side of the sandwich. Wires penetrate the sandwich to feed the power amplifiers.

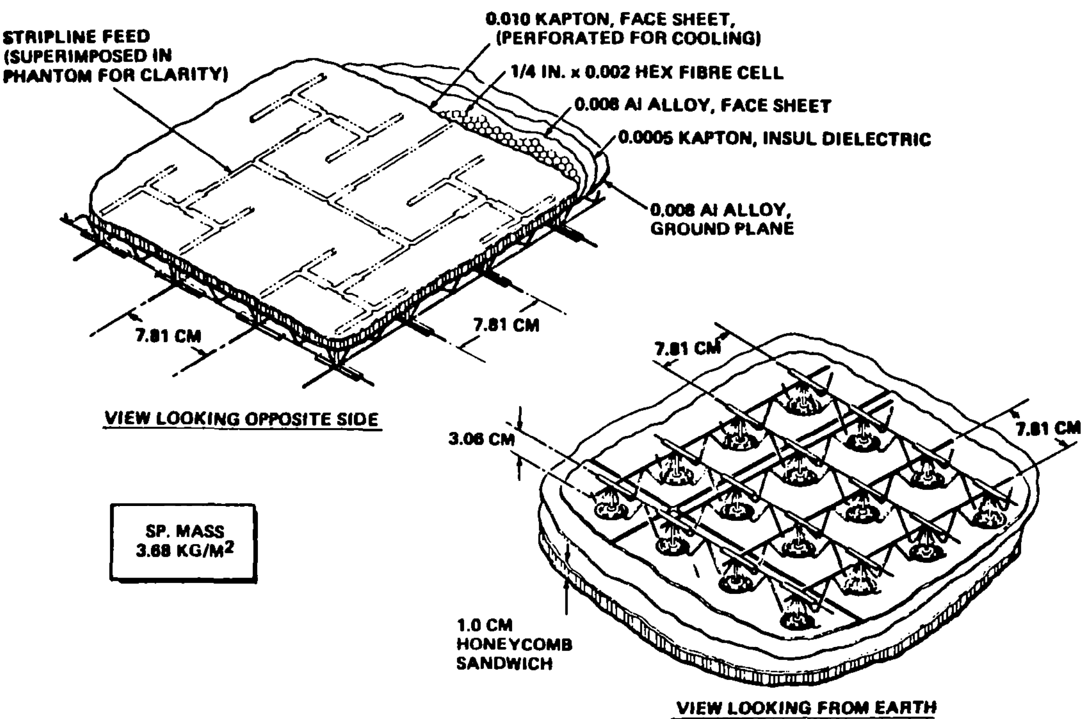

Figure 11. End-Mounted Antenna Module

Solid-State Sandwich Concept

One of the major problems related to the use of solid-state devices for dc/RF conversion on the satellite is the need to provide power to numerous power amplifiers which operate at low power levels. This leads to a much more complex and massive power distribution system when the reference concept approach of a separate microwave antenna and solar array are employed.

Because of this problem, an alternate solid-state concept was postulated, shown in Figure 12, which results in an integrated solar array and microwave

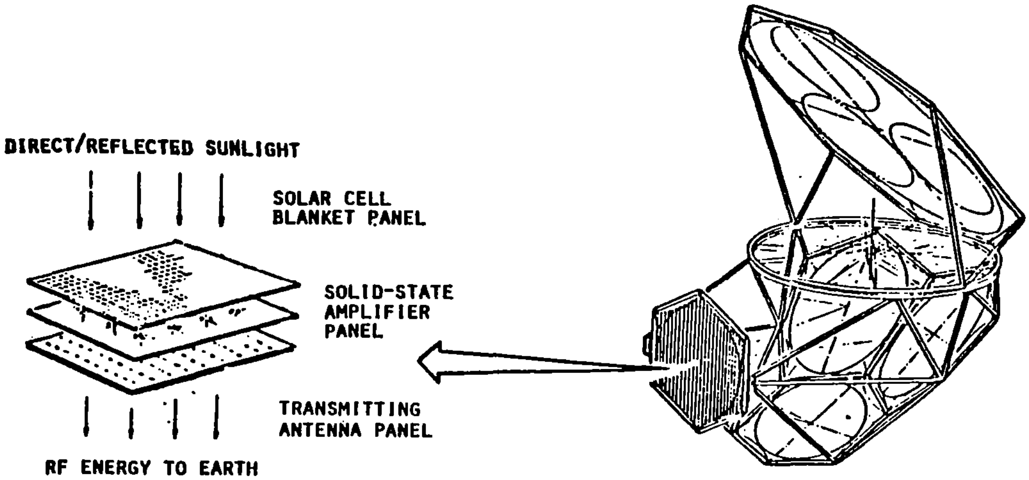

Figure 12. Sandwich Panel SPS Concept

transmission system. This concept utilizes a sandwich with the solar cells on one side and the microwave antenna on the other side. Since the antenna must focus at a point on the earth, it is necessary to use a set of two reflectors to direct sunlight on the solar cells continuously. One of the reflectors remains fixed relative to the sandwich array (secondary reflector), while the other remains pointed toward the sun (primary reflector) to reflect solar energy onto the solar array off of the secondary reflector. The solar cells provide electrical energy to solid-state power amplifiers located directly behind them. The power amplifiers feed the antenna. In order to provide any significant power at the utility interface on the ground for this type of concept, it is necessary to increase the available power density to the antenna from the solar array by concentrating solar energy on the sandwich. For this reason, such a concept requires GaAs solar cells or other solar cells that can operate efficiently at the high temperatures resulting from high concentration ratios. Silicon solar cells are not acceptable in this application.

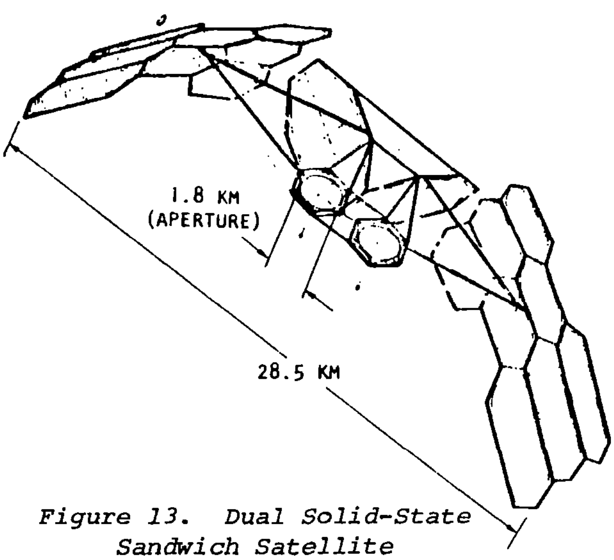

Figure 13. Dual Solid-State Sandwich Satellite Point Design Concept

After a series of trade studies, the concept shown in Figure 13 evolved. The characteristics of this concept are summarized in Table 7. The key characteristic is that an output of 2.42 GW at the utility interface is obtained from the solid-state sandwich concept (1.21 GW at each of two rectenna locations) compared to 5 GW for the reference concept (at one rectenna location) and 5.2 GW for the solid-state end-mounted concept (2.6 GW at each of two rectenna locations).

The sandwich panel configuration is shown in Figure 14. A dipole-type antenna system is fed by individual power amplifiers, located at the dipole center and mounted to a beryllium oxide

Table 7. Dual Solid-State Sandwich Point Design Characteristics

• SOLAR ARRAY TYPE	GALLIUM ARSENIDE
• EFFECTIVE CONCENTRATION RATIO	5.2 (EOL)
• MAX. SOLAR ARRAY TEMPERATURE	200°C
• MAX. POWER AMP. BASE TEMPERATURE	125°C
• AMPLIFIER EFFICIENCY	0.792
• REFLECTOR EOL EFFICIENCY	0.83
• ANTENNA TAPER RATIO	0 dB
• ANTENNA APERTURE	1.83 km
• TRANSMITTED POWER DENSITY	696 W/m^2
• MAX. PWR DENSITY AT RECTENNA	23 mW/cm^2
• RECTENNA BORESIGHT DIAMETER	4.8 km
• RECEIVING SITE DIMENSIONS (km)	10×13 (34°N LATITUDE)
• POWER AT UTILITY INTERFACE (GW)	2.42 (1.21 PER SITE)
• SATELLITE SPECIFIC MASS	8.48 kg/kW

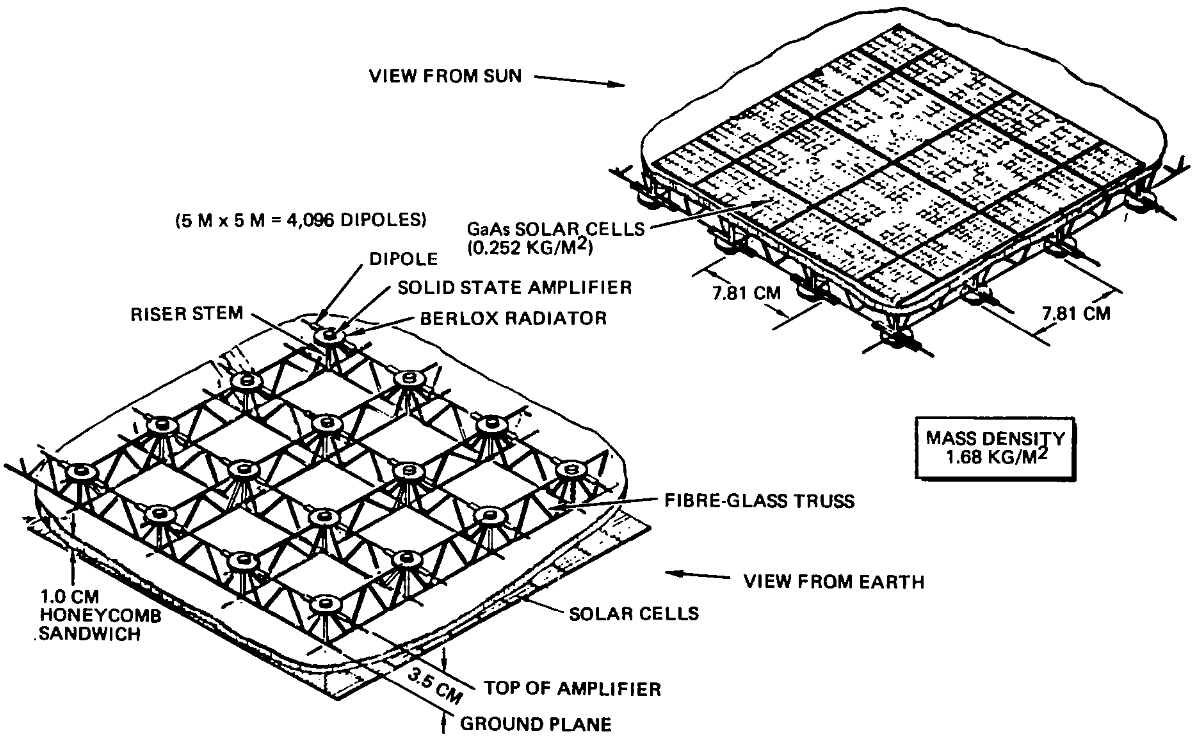

Figure 14. Solid-State Sandwich Design

disc heat sink/radiator. Power output of each power amplifier is 4.4 W. A silica-fiber truss structure supports the antenna and provides sufficient capability to withstand the launch environment. A honeycomb sandwich, containing the RF drive distribution system, is bonded to the antenna truss structure. The bottom of the honeycomb structure has a bonded aluminized kapton ground plane, and the top has a bonded GaAs solar array. The dc power and RF drive signal are brought to the power amplifiers through separate conductors in the silica-fiber amplifier support post. Most of the solar array waste heat is dissipated from the front of the solar array. Approximately one fourth of the heat is dissipated through the antenna side of the sandwich.

Mass properties of the satellite are shown in Table 8. As may be expected, most of the mass is in the sandwich panels.

Table 8. Sandwich Satellite Point Design Mass Summary

	MASS ($\times 10^6$ kg)
ENERGY CONVERSION & POWER TRANSMISSION	
• REFLECTOR SUPPORT STRUCTURE	3.33
• REFLECTORS	2.08
• AUXILIARY POWER	0.08
• POWER DISTRIBUTION AND CONTROL	0.01
• COMPRESSION FRAME/TENSION WEB STRUCT.	0.73
• SANDWICH MODULES	8.82
• PHASE CONTROL ELECTRONICS (TRANSMITTERS/RECEIVERS)	0.34
INTEGRATING STRUCTURE	0.11
MAINTENANCE	0.54
ATTITUDE CONTROL	0.10
INFORMATION MANAGEMENT AND CONTROL	0.29
SUBTOTAL	16.42
25% GROWTH	4.11
TOTAL MASS (DRY)	20.53

The receiving station on the ground is conceptually the same as for the reference concept. However, because of the lower power, the rectenna field is smaller in area (boresight diameter is 4.8 km compared to 10.0 km for the reference concept). Since the sandwich antenna has a uniform power distribution rather than the 10 dB taper used on the reference satellite antenna, the sidelobes have higher power densities. The outer perimeter dimensions needed to provide a 0.1 mW/cm^2 level are therefore 10.0×13.0 km.

Since the sandwich concept is quite different than the other concepts, a study was conducted to develop a top-level approach for its construction. The approach is summarized in Figure 15. The satellite construction base consists of two frame structures, each measuring 6900×4500×100 m, joined back-to-back. The outer third of each structure is capable of limited rotation to accommodate the angles between adjacent satellite reflector surfaces. Beam fabricators are mounted on the beams along the 4500-m axis and are capable of both translation and rotation.

Initially, the end legs of the first set of primary mirrors are fabricated on the face of the satellite construction base (SCB). Construction of the mirror longerons is then started; the longerons being joined to the forward set of end legs which then advance as the construction of the longerons progresses. Concurrently, 25-m-wide reflecting material, packaged in rolls and mounted on dispensing spindles, is attached to the end legs by catenaries and is played out from the dispensers as the beams advance away from the satellite construction base. Automatic equipment welds the edges of adjacent strips to provide a uniform reflecting surface. The second and third sets of reflectors are constructed similarly. Referring to illustration (1) of Figure 15, a small rotation of the completed mirrors relative to the SCB is required after completion of each set to conform to the change in angles.

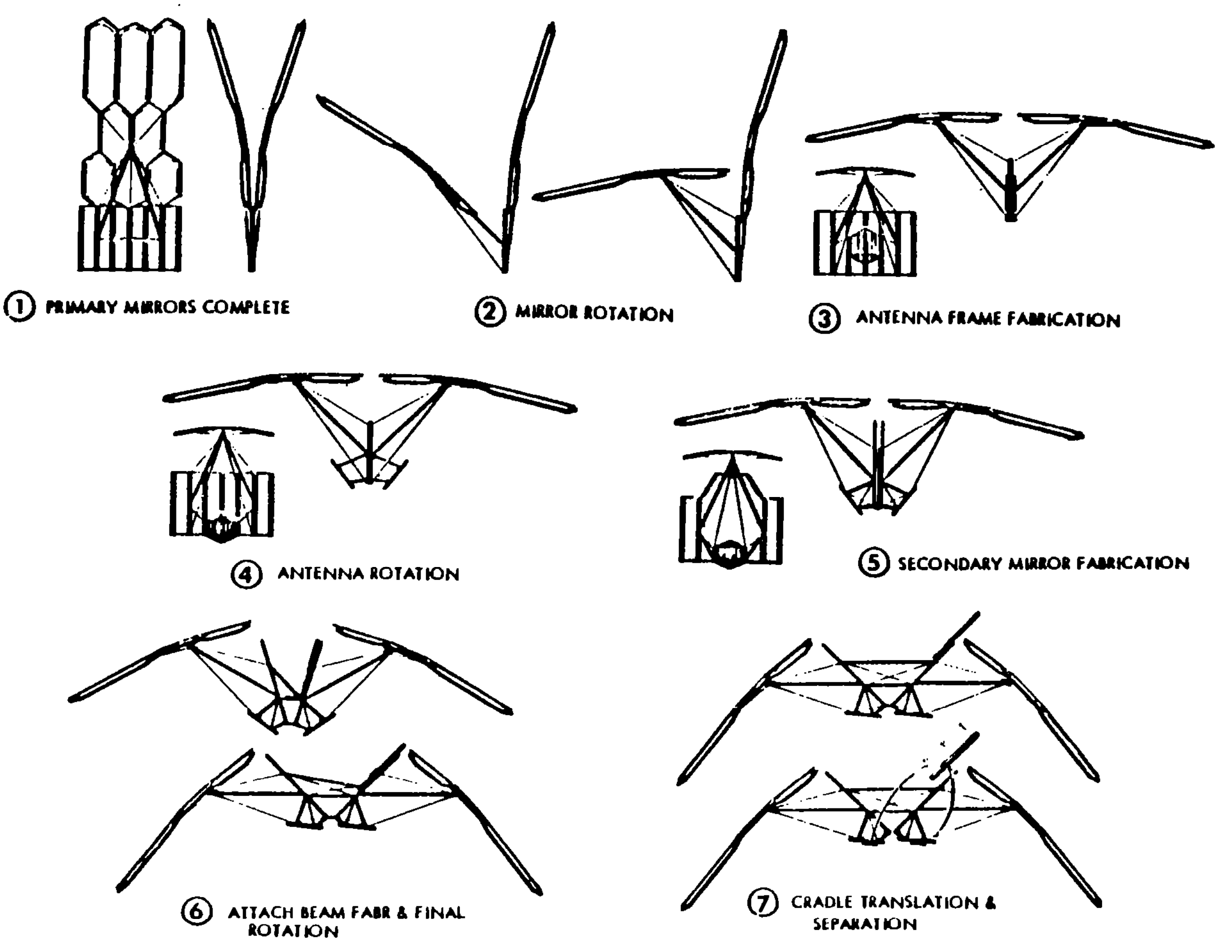

Figure 15. Dual Satellite Construction Sequence

Upon completion of the primary mirror, the supporting A-frame—shown partially fabricated in (1)—is completed. As the beams are constructed, a combination of beam forces and cable operation, augmented as required by RCS, effects the rotation shown in (2) of Figure 15.

Following rotation of each single mirror set, the antenna frames are constructed, tension webs incorporated, and a cable system installed (3). Upon completion of the antenna frame and webbing, and placement of the mobile RF panel assembly and installation facilities, the antennas are rotated into position by a combination of beam extension and cables (4).

The next step is to fabricate the secondary reflectors, shown in (5) of Figure 15. The supporting beams are fabricated and the reflectors are rotated sequentially (6) to achieve the configuration shown in (7). The SCB is then translated upward and detached. During this operation the mobile RF installation facilities are returned from the antenna to their parking place in the SCB.

Multi-Bandgap Solar Array Concepts

All of the concepts presented previously in this report used GaAs solar cells. Recent laboratory development has been conducted on multi-bandgap cells which are essentially a stack of two or more cells connected in series. Cell materials are selected so that each cell ideally utilizes a different portion of the solar spectrum and so that the lattice constants match. A good match of lattice constants greatly reduces material interface and maintains high short-circuit current output.

An analysis of multi-bandgap (MBG) solar cells was conducted by Research Triangle Institute on a subcontract. As a result of this study, a solar cell which is similar to the GaAs solar cell was selected. This cell has GaAs and GaAlAs cells in a series arrangement. At 68°C, the current GaAs design provides an efficiency of 20%; whereas, at a cell temperature of 68°C, MBG cells provide a 30% efficiency. This efficiency has not yet been demonstrated. The temperature coefficients for the two cells are similar. Estimated MBG mass is increased by only 5% over the GaAs cell, and the cost is estimated to increase by 10 to 20%.

As will be shown in the next section, which compares the concepts, the mass of the solar array of the satellites having end-mounted antennas is reduced by approximately the ratio of solar cell efficiencies. The benefits of the MBG solar array for the sandwich concept are much greater than they are for the end-mounted antenna concepts. Considerable research is required to produce the high efficiency, low mass, and radiation resistant solar cells for SPS. Early, probing laboratory effort has already been initiated.

Concept Comparisons

Table 9 compares the major characteristics of all of the concepts studied, including the Rockwell reference concept, the magnetron concept, the solid-state end-mounted antenna concept, and the solid-state sandwich concept. All concepts are shown with GaAs solar arrays and multi-bandgap solar arrays. One of the major variations is in the maximum power density which goes from 28 kW/m^2 for the magnetron concept to 0.70 kW/m^2 for the GaAs array sandwich concept. The maximum power density for the magnetron concept is greater than the klystron-powered reference concept because of the higher dc/RF conversion efficiency and more efficient dissipation of waste heat. Another major variation is in the power at the utility interface per antenna, which goes from 5.6 GW for the magnetron concept to 1.2 GW for the GaAs solar array sandwich concept. The solid-state sandwich concept requires three times more land area because of the higher sidelobes that are a characteristic of the 0-dB antenna taper.

The satellite masses also vary considerably, but the most significant mass relationship is the specific mass (kg/kW). Of the GaAs solar array concepts, the magnetron concept has the lowest specific mass (4.8 kg/kW) and the sandwich concept has the highest (8.5 kg/kW). Introduction of the MBG solar array has a significant impact on satellite specific mass for all concepts, but the solid-state sandwich concept shows an extremely large decrease (from 8.5 kg/kW for GaAs arrays to 5.4 kg/kW for MBG arrays). The reason that the sandwich shows

Table 9. Concept Comparisons

	ROCKWELL REFERENCE CONCEPT		MAGNETRON CONCEPT		SOLID-STATE END-MOUNTED CONCEPT		SOLID-STATE SANDWICH CONCEPT	
TYPE OF SOLAR ARRAY	GaAs	MBG	GaAs	MBG	GaAs	MBG	GaAs	MBG
EFFECTIVE CONCENTRATION RATIO	1.83	1.83	1.83	1.83	1.83	1.83	5.2	5.2
MAXIMUM TRANSMITTED POWER DENSITY (kW/m^2)	21	21	28	28	6.6	6.6	0.70	1.0
ANTENNA PWR TAPER (dB)	10	10	10	10	10	10	0	0
TRANSMITTING ANTENNA APERTURE (km)	1.0	1.0	0.92	0.92	1.4	1.4	1.8	1.6
RECTENNA BORESIGHT DIAMETER (km)	10.0	10.0	11.0	11.0	7.5	7.5	4.8	5.4
POWER AT UTILITY INTERFACE/SATELLITE (GW)	5.0	5.0	5.6	5.6	5.2	5.2	2.4	3.0
POWER AT UTILITY INTERFACE/ANTENNA (GW)	5.0	5.0	5.6	5.6	2.6	2.6	1.2	1.5
POWER PER UNIT LAND AREA (MW/km^2)	35	35	35	35	35	35	12	12
SATELLITE MASS (10^6 kg)	31.6	26.0	26.7	21.5	40.0	35.6	20.5	16.4
SATELLITE SPECIFIC MASS (kg/kW)	6.2	5.1	4.8	3.8	7.7	6.8	8.5	5.4

a larger reduction is due to a dual positive change resulting from the use of MBG arrays for the sandwich. For all concepts that have separate solar arrays and antennas, the benefit of MBG solar arrays is limited to a reduction in solar array mass. Power at the utility interface remains the same. For the sandwich concept, the antenna becomes small, the solar array also becomes proportionately smaller, and the power density across the antenna increases in proportion with the efficiency increase of the MBG array. The result is a reduction in satellite mass and an increase in power at the utility interface. Both of these factors reduce the specific mass.

SPECIAL-EMPHASIS AREAS

Two areas were given special emphasis in this contract and are summarized in the following sections: Solid-State Power Amplifier Technology Advancement, and Meteorological Effects on Laser Beam Propagation.

Solid-State Power Amplifier Technology Advancement

The objectives of this effort were to evaluate experimentally the performance of solid-state amplifiers for potential use as dc-to-RF power converters in Solar Power Satellite systems, and to develop a preliminary data base for further studies of high-efficiency solid-state power conversion. The hardware development consisted of two pairs of GaAs field effects transistor (FET) amplifiers and an antenna of the SPS type designed to demonstrate the free-space transmission, reception, and rectification of microwave energy at 2.45 GHz (see Figure 16). The amplifiers were developed by RCA Laboratories, Princeton, New Jersey, under subcontract to Rockwell.

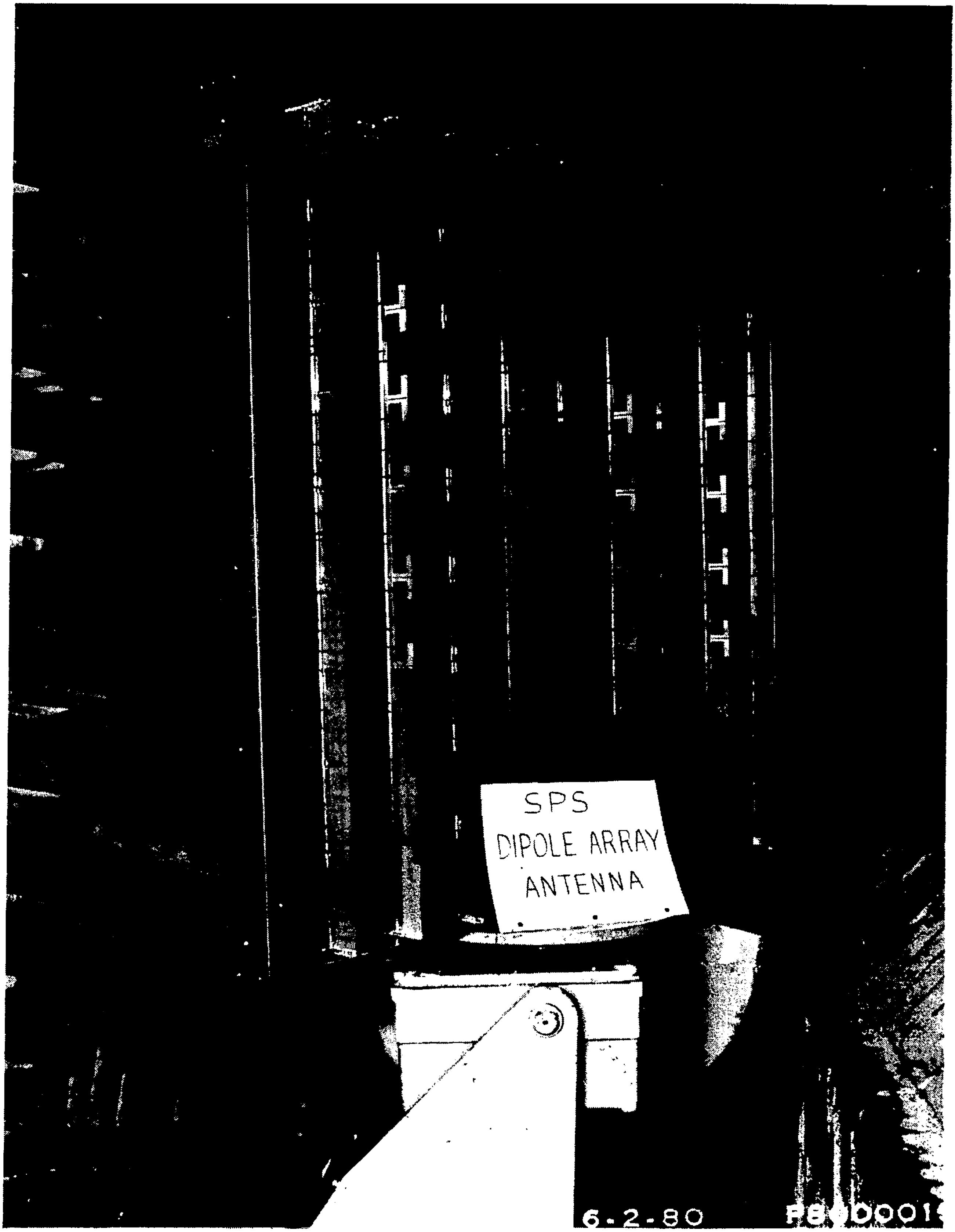

Figure 16. Test Antenna Hardware

The main emphasis of this amplifier design was high-efficiency operation. A preliminary analysis showed that a design in accordance with the classical Class C definition would reduce the power output to unacceptably low levels in the case of GaAs FETs. The Class E definition, which restricts the output circuit to lumped circuit configurations, is inappropriate at 2.45 GHz. In view of these considerations, an impedance approach was taken to achieve a switching mode of operation of the device. Such a mode of operation offers the potential of output power exceeding the power obtainable in a Class B type of operation by a factor of 1.27.

Extensive testing of numerous candidate devices narrowed the choice to three types of FETs—the Fujitsu FLS50 and FLC30, and the Mitsubishi MGF2150. The first set of amplifiers was designed using the FLS50 FET. The performance of these amplifiers, shown for Phase I in Table 10, is nominally 5 W output power, 55% power added efficiency, and 8 dB gain. The main problem that arose during the development of the amplifiers is a high incidence of device failures. The poor reliability seen so far is due in large measure to the fact that the devices have not been in production long enough to have undergone extensive reliability testing.

Table 10. Power Amplifier Performance

	POWER (W)	η (%)	GAIN (dB)
ØI - NO. 1	4.8	53	8.8
ØI - NO. 2	5.2	52	7.8
ØII - NO. 1	1.3	72	8.0
ØII - NO. 2	2.4	61	9.0

In view of the reliability problem which occurred during the Phase I effort, it was not considered advisable to emphasize an increase in power for the Phase II amplifiers. Instead, an improvement in the efficiency was emphasized. The devices which have yielded the best efficiency so far are the FLC30 and MGF 2150. The results of the Phase II effort, shown in Table 10, indicate the significant efficiency gain obtained at lower power levels.

The antenna design for the free-space transmission demonstration shown in Figure 16 is based on a two-dimensional 8×8 dipole array. The transmitting and receiving arrays are identical. The dipoles were printed on separate DICLAD-527 (glass fabric) boards, inserted vertically into the support structure.

Meteorological Effects on Laser Beam Propagation

Lasers are presently being evaluated as an alternate power beaming technique to microwaves for space-to-earth power transmission. Although preliminary studies indicate that laser power transmission has the advantages of negligible environmental damage and small land requirements associated with the receptor sites, meteorological conditions influence the transmission efficiency to a much greater extent than for microwaves of the selected frequency of 2.45 GHz. With proper selection of laser wavelength, clear-air propagation can be very efficient; however, haze, fog, clouds, and rain can severely attenuate the beam.

This study, conducted by Dr. Robert Beverly for Rockwell under subcontract, investigated potential mitigation techniques which may minimize this effect by a judicious choice of laser operating parameters. Alternatives investigated were laser wavelength, propagation zenith angle, receptor-site elevation, and the potential of laser hole boring. An extensive series of propagation calculations were performed to estimate the attenuation due to molecular absorption and scattering. All commonly encountered meteorological conditions were modeled, including haze, fog, clouds, rain, and snow.

Using the previously described techniques, preliminary receptor siting criteria were defined, and 22 candidate sites in the contiguous United States were selected for detailed study. A power availability model was developed which used statistical meteorological data for each site to calculate the annual and seasonal power availability (average transmission efficiency assuming constant power beaming), and the frequency for which the transmission efficiency exceeds a given value for a specified time. These results led to a redefinition of siting criteria and laser parameters such that the power availability is comparable to the microwave SPS concept or to conventional electric power plants.

Specific conclusions are as follows:

- At high elevations, atmospheric transmission windows in the wavelength region around 11 μm provide the best combined propagation efficiency considering both molecular absorption and aerosol extinction. At low elevations, laser operation at a wavelength near 2.25 μm is preferable.
- If the laser wavelength is properly optimized, operation at a propagation zenith angle of 0° instead of 50° does not afford a significant improvement in the power availability.
- High-elevation receptor sites are desirable although not essential to the laser-SPS concept because of the reduction in attenuation due to haze and molecular absorption.
- Laser hole boring through certain types of haze, fogs, and clouds may be possible consistent with safety and environmental concerns and without the need for weapon-quality laser beams; in particularly, all but the thickest cirriform clouds and all stratiform clouds with the exception of nimbostratus can be penetrated with power densities of 100-200 W/cm^2. All other cloud types will require substantially higher power densities for penetration, which is unacceptable given the present safety margins.
- Power availabilities in excess of 80% are unattainable in most geographical regions of the United States if only a single receptor site is available for each transmitted laser beam (the exception is the southwestern U.S.).

- Hole boring, as defined above, will increase the power availability by 6 to 20%, depending upon the cloud form frequencies of the individual sites.
- For the southeastern, south central, and central regions of the United States, two receptor sites separated by a distance of about 200 miles will be necessary to achieve a joint power availability greater than 80%; for the Atlantic, New England, midwest, north central, and northwest regions, three receptor sites separated by a centroid radius of about 300 miles will be necessary for the same joint power availability performance.
- The average time during which the prevailing meteorological conditions allow a high transmission efficiency is considerably shorter than eight hours at most sites, so that any viable laser SPS concept must be capable of frequent beam switching between sites with a minimum of downtime.
- Under the aforementioned circumstances, thermodynamic laser-energy conversion schemes on the ground may be unsuitable because of the long start-up times required by rotating turbomachinery.

TRANSPORTATION SYSTEM STUDIES

The transportation system in this study for the operational SPS period includes (1) a heavy-lift launch vehicle (HLLV) for personnel and cargo transport from earth to low earth orbit (LEO), (2) a single-stage LO_2/LH_2 rocket-powered personnel orbit transfer vehicle (POTV) for personnel transfer from LEO to geosynchronous equatorial orbit (GEO), and (3) an electric orbit transfer vehicle (EOTV) for cargo transfer from LEO to GEO. In Exhibit C, a Shuttle-derived personnel launch vehicle was used to transport personnel from earth to LEO. However, combining personnel and cargo transport on the HLLV reduced significantly transportation costs; consequently, this mode was adopted in determining transportation requirements and costs.

During Exhibit D, effort was concentrated on definition of a 114,000-kg payload HLLV. Previously, the HLLV had been sized for 227,000 kg of payload. An analysis was made of the ground operations for the HLLV to drive out the requirements of significance to transportation costs. Additionally, the EOTV concept was updated and traffic models were derived for the new system concepts and an updated model was developed for the reference concept. This effort is summarized in the following sections.

HLLV Configuration—114,000 kg Payload Option

The HLLV concept defined in Exhibit C (227,000 kg payload) and the 114,000 kg payload concept, which closely resembles the STS configuration, are compared in Figure 17. This configuration was adopted to permit the use of documented STS aerodynamic and performance data in order to address certain specific technical issues relative to VTO/HL vehicle concepts.

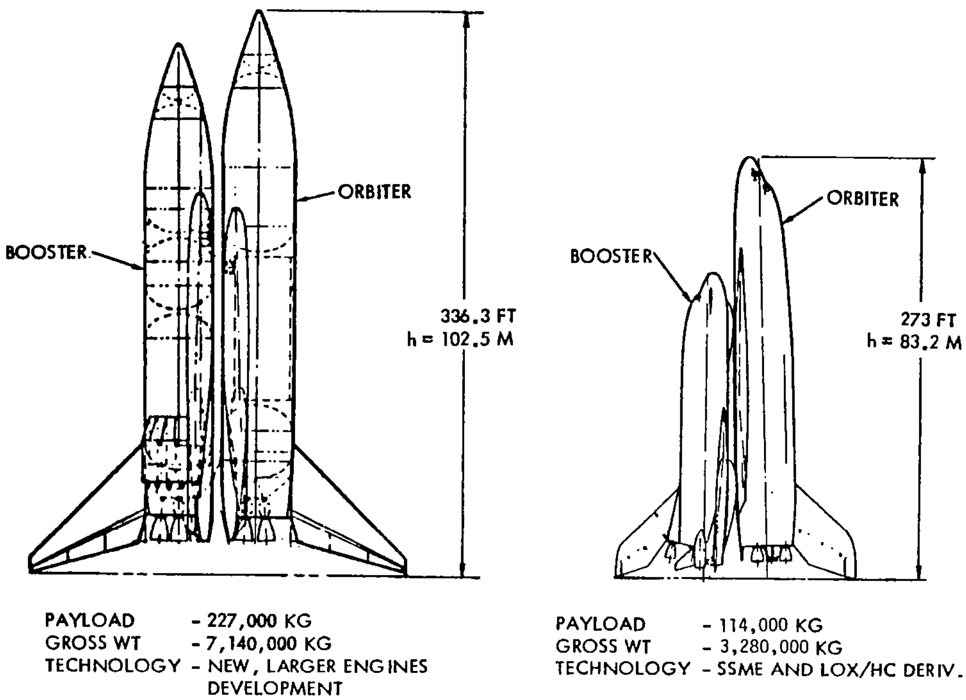

Figure 17. HLLV Concepts

The primary driver in establishing HLLV requirements is the timely delivery of construction material; thus, payload magnitude (mass and volume) becomes a major design parameter. While earlier designs were based on 227,000 kg of deliverable payload, the more conservative payload of 114,000 kg was selected for the present design study. This, of course, incurs an increased number of flights to deliver an equivalent mass to orbit. A final resolution of the most practical payload from overall considerations will have to await the results of future studies. The basic ground rules and assumptions employed are the same as used for the larger payload version.

Each of the two stages has a capability to return to base with vertical takeoff and horizontal landing characteristics. The orbiter is unpowered at landing while the boosters fly back to the launch site with an air-breathing engine propulsion system. The launch vehicle utilizes a parallel-burn propulsion mode with first-stage LO_2 and LH_2 being crossfed from the booster to the orbiter so that the orbiter propellant tanks are filled at staging. The booster utilizes high-chamber-pressure gas generator cycle LO_2/RP-1 fueled engines and the orbiter utilizes staged-combustion LO_2/LH_2 engines developed from the Space Shuttle main engine (SSME).

The staging velocity was selected from earlier trade studies to be compatible with a heat sink structural concept for the booster. Material selection and development consistent with the 1990 time frame will ultimately play a significant role in the final selection of staging velocity. Thrust-to-weight requirements are selected to minimize engine size and crew/passenger discomfort. Orbital parameters are consistent with SPS LEO base requirements.

The booster stage is approximately 61 m long and the orbiter, or second stage, is approximately 91 m long. Although the internal volume requirements are nearly the same, the boost vehicle employs eight LO_2/RP engines and, therefore, requires a wider base area. This wider base permits the application of "double-bubble" type propellant tanks to accommodate hypersonic aerodynamic stability requirements and, hence, a foreshortening of the entire vehicle.

The booster employs hot structure with metallic heat sink as required for the entry flight regime of the booster. Initial investigations indicate that utilization of advanced metal matrix technology will result in a substantial weight savings. The wing is sized to produce a nominal 93 m/sec landing speed and is optimized to minimize flyback propulsion requirements. Six turbojet engines are provided to accommodate the return-to-base mode after a launch. This flyback propulsion system weighs approximately 45,400 kg (with 9100 kg of JP-5 fuel). Ascent propulsion is provided by eight advanced-development engines of 4.45×10^6 N.

The orbiter configuration has been established to accommodate a payload of 114,000 kg in a volume of 1330 m^3 with a payload bay length of 21 m. The payload density is 85.7 kg/m^3.

The propulsion system employs six SSME engines which produce 2.1×10^6 N thrust each in a vacuum. The cryogenic tankage is non-integral to minimize the requirement for a high-risk development technology. However, additional weight savings could be realized through the application of integral cryogenic tankage, but would require an intense design and development program to achieve the reliability, inspectability, and maintainability required for a reusable system.

The substantial increase in orbiter size, when designed for transporting much heavier payloads than the present Space Shuttle orbiter (29,500 kg), is readily apparent when the SPS HLLV orbiter is compared to the Shuttle orbiter at the same scale, Figure 18. Dimensionally, such a comparison is somewhat misleading since the larger orbiter is a "wet" design, containing its own fuel, while the smaller is "dry," utilizing a drop tank for LO_2 and LH_2.

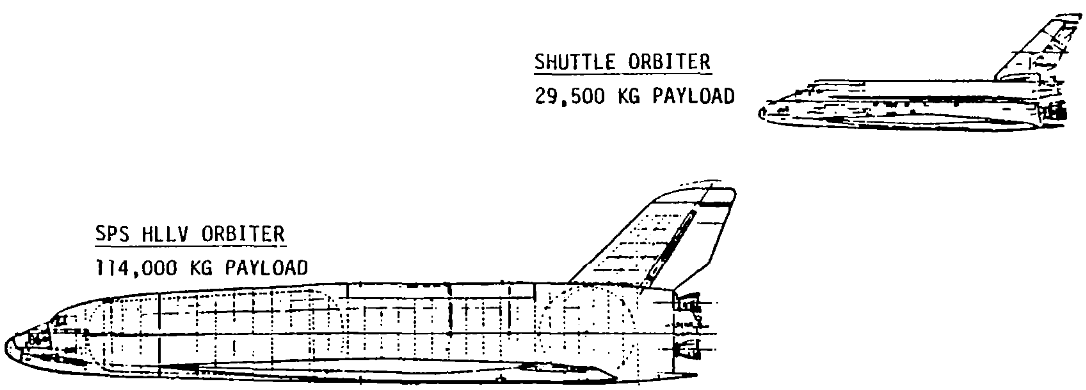

Figure 18. Size Comparison—Orbiters

The combined mass properties of the vehicle are presented in Table 11. At lift-off the HLLV weighs 3.28 million kg. At sea level, the thrust of the six orbiter engines is 10.0×10^{6} N, and the thrust of the eight booster engines is 36×10^{6} N. The total thrust at lift-off is 46×10^{6} N for a thrust-to-weight of 13.1 N/kg (1.31 lb_T/lb_m).

Table 11. Combined Mass Properties

CONDITION	MASS (MILLIONS KG)
BOOSTER @ L.O.	2.27
ORBITER @ L.O.	1.01
LIFT-OFF	3.28
• BOOSTER PROPELLANT	2.02
• CROSSFED ORBITER PROPELLANT	0.32
STAGING	1.26
• BOOSTER @ STG.	0.25
SOLO ORBITER	0.90
• ORBITER PROPELLANT	0.73
ORBITER @ B.O.	0.28
• INERT ORBITER	0.17
DELIVERED PAYLOAD	0.11

Electric Orbit Transfer Vehicle

The electric orbit transfer vehicle concept shown in Figure 19 is based on the same construction principles of the Rockwell reference satellite. The commonality of the structural configuration and construction processes with the satellite design is evident. The structural bay width of 700 m (solar array width of 650 m) is the same as that of the satellite. The structural bay length is reduced from 800 m to 750 m for compatibility with the lower voltage requirement of the EOTV. The concept utilizes electric argon-ion thruster arrays.

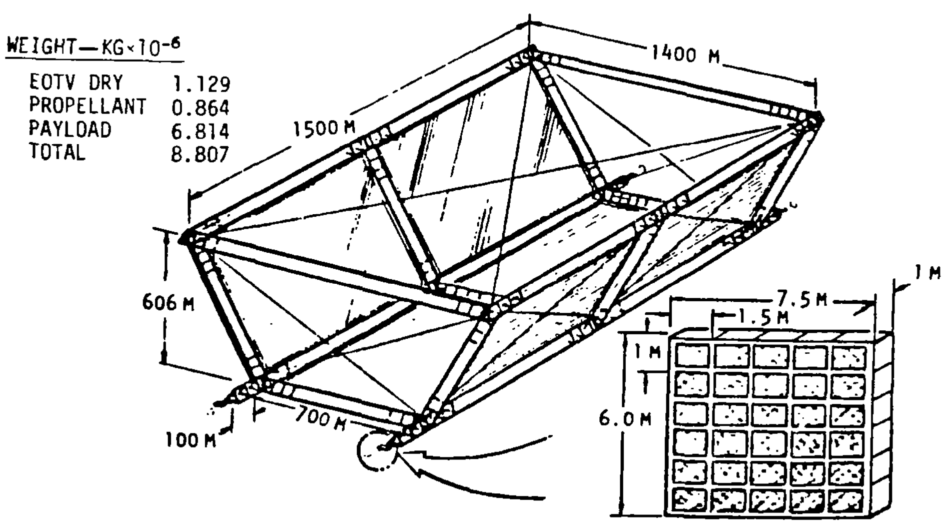

Figure 19. EOTV Configuration

The primary assumptions used in EOTV sizing are summarized in Table 12. The orbital parameters are consistent with SPS requirements, and the ΔV requirement was taken from previous SEP and EOTV trajectory calculations and include 0.75% margin. During occultation periods, only attitude hold is required (i.e., thrusting for orbital change is not required). Since it is currently anticipated that thruster grid changes will be required after each mission, a minimum number of thrusters are desired to minimize operational requirements.

Table 12. EOTV Sizing Assumptions

- LEO ALTITUDE - 4.87 KM @ 31.6° INCLINATION
- SOLAR INERTIAL ORIENTATION
- LAUNCH ANY TIME OF YEAR
- 5700 M/SEC ΔV REQUIREMENT
- SOLAR INERTIAL ATTITUDE HOLD ONLY DURING OCCULTATION PERIODS
- 50° PLUME CLEARANCE
- NUMBER OF THRUSTERS - MINIMIZE
- 20% SPARE THRUSTERS - FAILURES/THRUST DIFFERENTIAL
- PERFORMANCE LOSSES DURING THRUSTING - 5%
- ACS POWER REQUIREMENT - MAXIMUM OCCULTATION PERIOD
- ACS PROPELLANT REQUIREMENTS - 100% DUTY CYCLE
- 25% WEIGHT GROWTH ALLOWANCE

An excess of thrusters is included in each array to provide for potential failures and primarily to permit higher thrust from active arrays when thrusting is limited or precluded from a specific array due to potential thruster exhaust impingement on the solar array, or to provide thrust differential as required for thrust vector/attitude control. A 5% specific impulse penalty was also applied to compensate for thrust cosine losses due to thrust vector/attitude control.

An all-electric thruster system was selected for attitude control during occultation periods. The power storage system was sized to accommodate maximum gravity-gradient torques and occultation periods. A very conservative duty cycle of 100% was assumed for establishing ACS propellant requirements. A 25% weight growth margin was applied as in the case of the SPS.

EOTV performance is based on a 120-day trip time from LEO to GEO (obtained from trade studies). The vehicle is also sized to provide for the return to LEO of 10% of the LEO-to-GEO payload. The EOTV weight summary is presented in Table 13.

Since the EOTV solar array utilizes the same configuration, materials, and manufacturing processes as the satellite, common technology requirements are evident. One unique technology requirement is in the area of ion engine development. The key requirement is in large-size (1.0×1.5 m) high-current density (1000 A/m^2) thruster demonstration. The additional requirement for the solar array to pass through the Van Allen belt numerous times and self-anneal most of the radiation damage will have a significant impact on the design of the solar cell.

Table 13. EOTV Mass Summary (10^{-6} kg)

SOLAR ARRAY		0.333
THRUSTER ARRAY (4)		0.189
PROPELLANT TANKS & DIST.		0.085
EOTV (DRY)		0.607
GROWTH (25%)		0.152
EOTV, TOTAL		0.759
PROPELLANT		0.849
MAIN LEO-GEO	0.655	
MAIN GEO-LEO	0.130	
ATTITUDE CONTROL	0.064	
EOTV (WET), TOTAL		1.608
PAYLOAD		6.860
LEO DEPARTURE		8.468
GEO ARRIVAL		7.789
GEO DEPARTURE		1.603
LEO ARRIVAL		1.469

Transportation Operations

This analysis was directed toward the identification of major transportation system cost elements and the definition of design features that would enhance operations requirements. The technology advancement requirements needed to implement those design and operational features have been identified. Although all transportation elements were addressed, primary emphasis was placed on the HLLV.

The key operational technology requirements of the HLLV are in the areas of:

- Structural/thermal protection systems
- Propellant tank insulation systems
- Liquid rocket engine/component life
- Self-monitoring/diagnostic systems
- Ease of maintenance/low-cost maintenance

The materials required for the exterior of the vehicle must repeatably withstand an extreme thermal and stress environment. The materials available today which are capable of meeting some of these requirements cannot meet all of the desired criteria: coatings are subject to foreign object damage; embrittlement occurs after repeated exposure to environments, resulting in reduced physical strength; the materials are heavy, costly, and/or in short supply. The development of thermostructural systems capable of taking full advantage of the potentially available advanced materials must be pursued. A wide variety of candidates is already available, but the relative merits of each must be determined. TPS inspection and maintenance is the key operations driver in the current STS program. In addition, the projected structural life of the STS is limited by the thermal cycling environments.

In order to meet the postulated operational requirements of the SPS transportation system, the cryogenic tanks of both the booster and the orbiter must be designed such that they require little or no inspection outside of normal maintenance cycles. Similar requirements are placed on the tank insulation. The tanks of the present point design are identified as being non-integral structurally with the tank insulation system, permitting relatively easy inspection when required, but not allowing the buildup of icing on the external surfaces nor any cryopumping. A number of candidate insulation systems has been identified in past studies and, as in the case of the TPS, each has its own merits but none can completely satisfy SPS cryogenic tank insulation requirements. Materials and systems design technology must be pursued before any firm decision can be made on systems selection.

In order to minimize vehicle turnaround requirements and cost, all vehicle systems should require minimum inspection, maintenance, and replacement. This is especially true of the liquid rocket engines which are second only to the thermal protection system in turnaround operations requirements of the STS. Improvements in materials and design technology improvement in the critical areas of turbine pumps and seals, regulator valves, and precombustion chamber components are required to satisfy nominal turnaround operations and cost.

A great dependence must be placed upon on-board monitoring and fault detection/isolation systems in order to preclude the requirement for ground interfacing and checkout requirements. All previous ground and flight performance data must be computer analyzed to determine performance trend data indicative of potential impending failures. A major element of ground operations is related to launch vehicle turnaround requirements. The high launch frequency demands an airline operations concept which, in turn, dictates vehicle design requirements which will result in the near-elimination of post-flight refurbishment and checkout other than that required for payload installation, mating, and fueling. Methods of implementation and types of diagnostic monitoring equipment must be evaluated and defined.

The POTV shares common technology requirements with the HLLV (i.e., propellant tank insulation, engine component life, self-monitoring/diagnostic equipment, etc.), and can benefit from those technology programs implemented for the HLLV. A unique technology requirement of the POTV is in the area of orbital maintenance. Continuation of on-going orbital propellant transfer technology programs may satisfy this requirement. Engine overhaul/replacement should be an earth-based operation due to the potential complexity and limited advantages of performing those functions at the orbital bases. Emergency repairs only should be pursued.

The EOTV shares common operations technology features with the SPS (i.e., the EOTV utilizes the same power source and design features as the SPS). The unique operations requirement of the EOTV is that it must be capable of repeatedly transitioning the Van Allen radiation belt with small degradation. In addition, the low thrust engines employed for the EOTV are of a higher current density than the SPS (i.e., to achieve higher thrust) and must therefore be capable of periodic screen grid replacement at the orbital bases. The EOTV propellant distribution system is designed to permit fueled tank replacement in lieu of propellant transfer from an orbital propellant depot. This eliminates the need for additional orbital tank farms, minimizes propellant boil-off and transfer losses, and permits transport of lower density payloads with the high density loaded argon tanks.

COST DATA

Estimates of life-cycle costs were made for the several concepts previously described. These cost estimates assume 1979 dollars and are based on a composite of cost estimating relationships developed by NASA and Rockwell. The estimates are separated into DDT&E, theoretical first unit (TFU), average investment per satellite, and operations. DDT&E covers all cost through the construction and operation of the pilot plant. TFU costs include all capital expenditures to built the first commercial unit. These expenditures include the cost of all of the construction material for the satellite and ground receiving station, construction costs, transportation costs, management and integration costs, as well as the cost of the construction fixture and the space transportation fleet needed to provide transportation for the first unit. The average investment cost per satellite is the average cost of building a sufficient number of units to provide 300 GW of power. The number of satellites varies, depending upon the system' characteristics. Construction fixture costs and transportation fleet costs and their maintenance are amortized equally over all satellites. Operations costs include all costs related to system operations and maintenance, including replacement of capital investment.

DDT&E and TFU costs did not vary significantly from one concept to another. The reference (klystron) concept had a DDT&E cost estimate of $33.6 billion and a TFU cost of $53.6 billion. The highest values were $35.0 billion DDT&E and $56.0 billion TFU cost for the solid-state, dual end-mounted antenna concept.

Major differences in cost did occur for the average unit. The estimates are shown in Figure 20 for all of the concepts. This figure shows the costs in terms of installation cost per kilowatt of power at the utility interface. The highest value is $3670/kW for the GaAs solid-state sandwich concept, and the lowest value is $2310/kW for the multi-bandgap (MBG) magnetron concept. The Rockwell reference concept (GaAs solar array and klystron dc/RF converters) has a cost of $3020/kW. This figure also illustrates the distribution of the costs across the various cost elements.

The most significant cost comparator is the cost of energy at the utility interface which includes not only the contribution of the investment cost, but also the annual maintenance cost. Figure 21 shows a comparative estimate of the cost of energy at the utility interface in mills per kilowatt-hour. It is assumed that the system availability is 90% and that the rate of return on loans, stocks, and bonds averages 9.84% per year. The result is shown as a function of the installation cost, previously shown in Figure 20, and the annual maintenance cost per GW of power delivered at the utility interface. As shown, the cost of energy is approximately proportional to the installation cost. Annual maintenance cost is not a large contribution. The costs range from a high of 50 mills/kW-hr for the solid-state sandwich concept with a GaAs solar array, to a low of 32 mills/kW-hr for the magnetron concept with a multi-bandgap solar array. The Rockwell reference concept (klystron dc/RF converter and a GaAs solar array) has a cost of 41 mills/kW-hr. These values are provided for comparative purpose only, and should not be used as an absolute value of the cost of power or to make comparisons with other energy concepts.

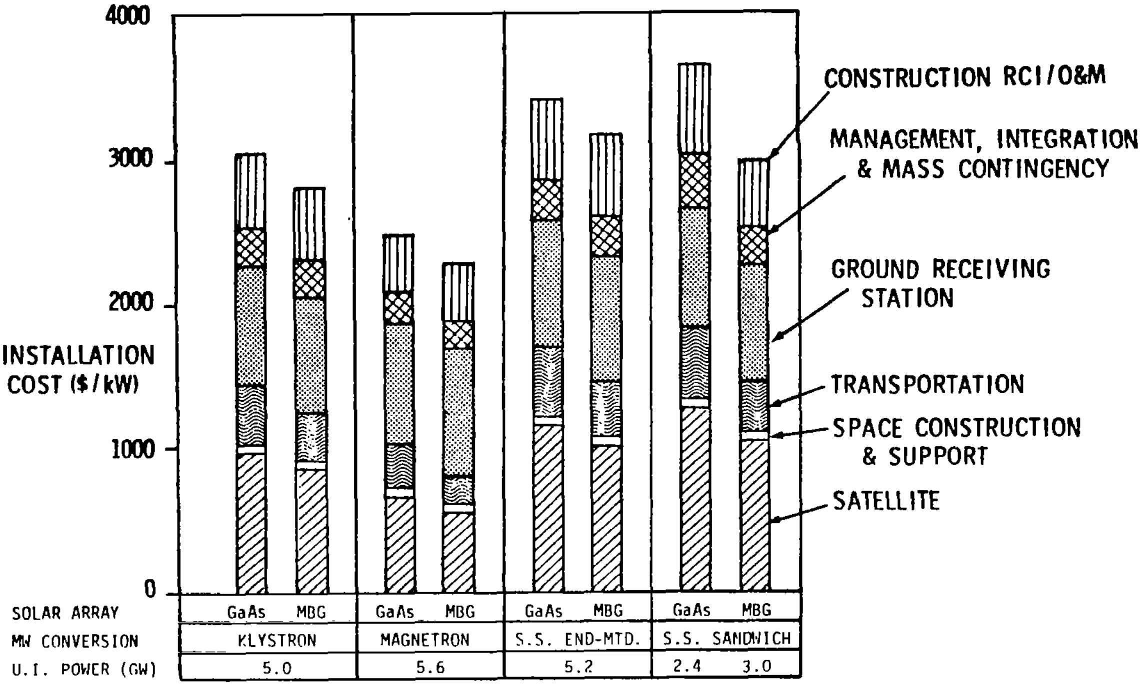

Figure 20. Installation Cost Comparisons

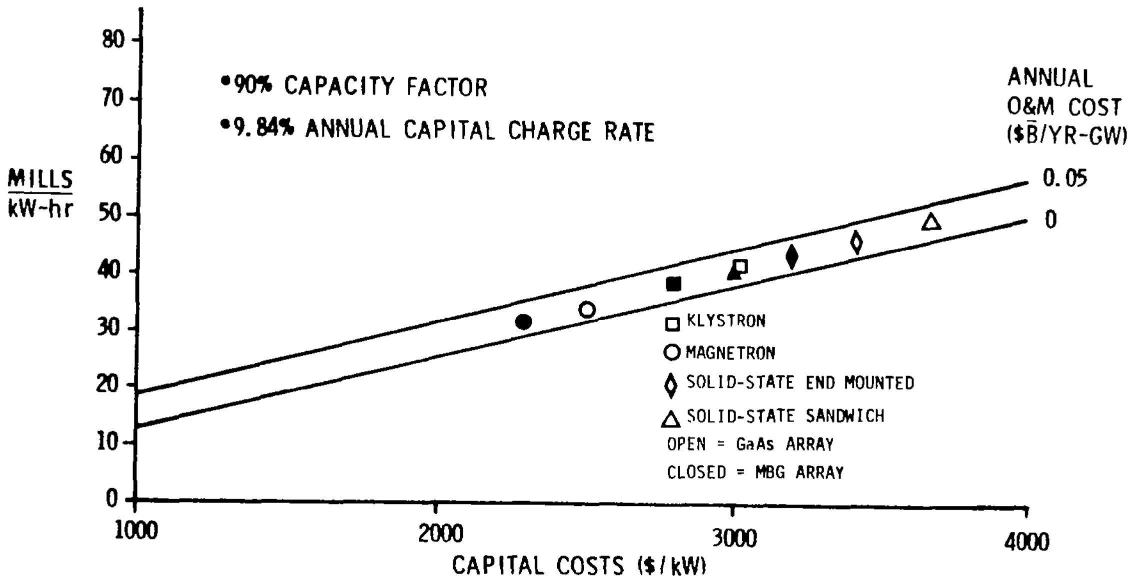

Figure 21. Utility Bus-Bar Cost Comparisons

IMPLICATIONS FOR RESEARCH

An overview of the SPS program from the present time through the year 2000 is shown in Figure 22 for the reference system. Commercialization of SPS was assumed to occur in the year 2000 with completion of construction of the first SPS unit as a guideline. A pilot plan SPS, located at geosynchronous orbit, would be tested in 1996. This plant would have an output in the megawatt range on the ground. This pilot plant would be built at low earth orbit in steps, starting with an early test using a full-scale antenna that is sparsely populated with microwave transmitting arrays. This proof-of-concept test, occurring in 1991, is conducted in low earth orbit and only kilowatts of power are received at a ground rectenna. From 1981 to 1987, a program would be required to develop and validate the key SPS technologies. Figure 22 also shows the introduction of major space facilities and transportation elements.

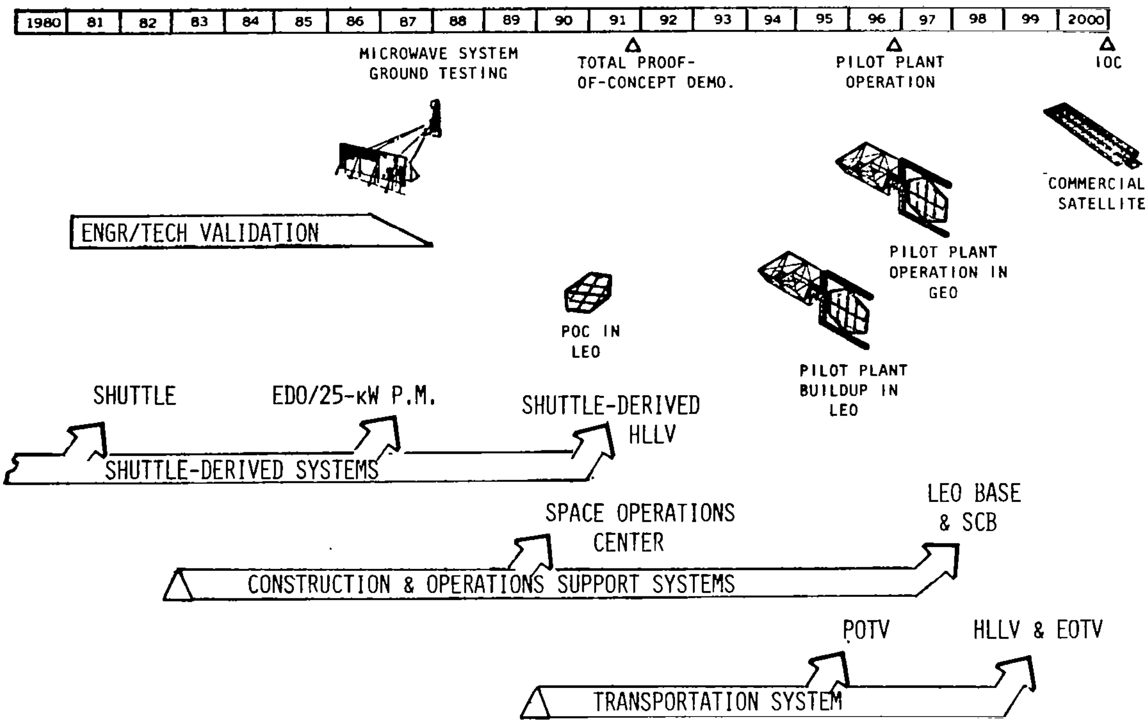

Figure 22. Overall SPS Program

Three major areas of research-oriented activity within this overall plan were studied:

1. Specific plans were prepared for the engineering/technology validation program (1981-1987).
2. A proof-of-concept program for the 1987-1991 time period was defined under a company-sponsored project.
3. Construction requirements were defined for two specific SPS test articles.

ENGINEERING/TECHNOLOGY VALIDATION PROGRAM

The objective of this program would be to conduct technology research in critical SPS technology areas, develop near-prototype hardware, integrate this hardware into specific ground test articles, conduct tests, and produce the performance data necessary to validate the key technologies.

Previously identified research and technology tasks were updated to include recent studies and to incorporate information from DOE/NASA workshops as summarized in the following areas:

- Solar Energy Conversion
- Electric Power Processing, Distribution, and Management
- Microwave Power Transmission and Reception
- Structures, Controls, and Materials
- Space Operations
- Space Transportation

Solar Energy Conversion

The attainment of a set of certain design parameters for the conversion system is critical to assuring SPS cost viability and the proof of feasibility. It is recommended that investigations be continued of concepts that offer a potential of significant advances in performance mass, and/or cost of photovoltaic energy conversion systems. A series of tasks are identified over the next six years in the areas of (1) basic solar cell research and development, (2) GaAs and multi-bandgap solar cell qualification program, (3) solar array demonstration program, (4) accelerated 30-year lifetime testing, (5) manufacturing processes analysis and cost evaluation, (6) multi-bandgap thin-film solar cell development, and (7) alternate advanced concept evaluation.

Electric Power Processing, Distribution, and Management

The primary objective of this early research would be to establish technical feasibility and economic practicability of high voltage operations of the SPS. Technical feasibility will depend on the technology readiness of techniques, components, and equipment to reliably distribute, process, and interrupt hundreds of megawatts of power at tens of thousands of kilovolts. Low mass power processors and power conductors are required. The combined requirements of dissipating concentrated heat and preventing breakdown or arc-overs are much more severe in space than in similar high power and high voltage ground applications. SPS power distribution and processing concepts depend upon successful realization of high power kilovolt ultra-fast protection switches. Tasks associated with this area include requirements definition, laboratory experimentation and feasibility test models, power devices and power transmission developments including brushes and rings, a study of plasma effects, molten salt electrolyte battery designs, and power management studies.

Microwave Power Transmission and Reception

The objective of this effort would be to conduct critical early analyses and exploratory technology relating to microwave energy transmission and reception key technical issues resolution and fundamental technical feasibility. The tasks in this plan address critical component definition issues relative to microwave power amplification and transmission, ground power rectification, and initial definition of microwave ground test range requirements and characteristics. Computer simulation modeling, experimental lab development, and engineering model evaluation are proposed.

Specific tasks include ground test range definition, 50- to 70-kW klystron and 3- to 10-kW magnetron definitions including resonant cavity radiator (RCR) concept evaluation, MPTS antenna pattern calculation, alternate concept technique investigation, and dipole optimization along with GaAs diode concept evaluation and power transistor preliminary definition. Other studies include phase control system definition, RF signal distribution system development, high-gain rectenna element and high-gain pilot receiver antenna development, pilot transmit system study and concept development, plus studies of alternate sensing techniques and aperture distribution functions, beam steering, and associated problem areas.

Structures, Controls, and Materials

The objective of this experimental research would be to develop technology associated with specific aspects of the satellite structural subsystem. Optimum structural element shapes will be developed based on design, analysis, and test data. Advanced composite material systems will be selected for SPS structures. Mathematical simulations of SPS configurations, utilizing test determined stiffnesses, damping values, etc., will be generated and subjected to simulated operational environments to determine as-designed structural integrity including operational stress levels and satellite distortions. SPS structure construction scenarios will be generated, construction equipment defined and conceptually designed, and a plan generated for the ground and on-orbit technology development of this equipment. (Attitude and figure control technology and ACS propulsion system research are also included in this effort.) Tasks include structural requirements definition and construction selection, composite materials development, beam-to-beam joining, ultra-large solar blanket/ reflector arrays, solid-state sandwich design development, and mathematical model development for structures and materials. In the controls area, tasks include ion thruster and power module laboratory testing, EOTV attitude and thrust vector control studies, figure control techniques and systems, control system development and hardware requirements, and ACS electric propulsion development.

Space Operations

Developing the capability for construction and assembly of large, low-density structures in space is an inherent requirement for the SPS program. The capability for installation of other subsystems (e.g., solar blankets, reflectors, power distribution lines and control equipment, microwave subarray hardware, etc.) on the structure also must be developed. Very little applicable data currently exist for this type of orbital and large-scale terrestrial construction and assembly. Test data are needed to validate operational requirements and cost estimates. Specific tasks during the program would address the areas of automated construction, operations and support, and hardware handling/ installation.

Space Transportation

The objective of this effort would be to conduct critical early analyses and exploratory technology relating to the various transportation system elements, resolve key technical issues, and determine fundamental technical feasibility. The tasks in this plan address critical systems and subsystems issues relative to earth to low earth orbit and orbit-to-orbit transfer vehicles for both cargo and personnel. The transportation elements considered in this plan include a Space Transportation System (STS) derived heavy-lift launch vehicle (HLLV), dedicated SPS HLLV configuration, an electric orbital transfer vehicle (EOTV) for cargo transfer, and a personnel orbit transfer vehicle (POTV) for personnel/priority cargo transfer from LEO-to-GEO and return. Systems and subsystems studies, computer analyses and modeling, experimental laboratory development, and engineering model evaluation are to be performed.

PROOF-OF-CONCEPT PROGRAM

A Rockwell company-sponsored study was conducted to define the requirements for an early SPS orbital demonstration that could provide a proof of concept sufficient to allow an SPS program commitment to be made about 1991. This study also developed a conceptual approach that satisfied the requirements. The concept was constrained to make maximum use of anticipated engineering/technology validation program results and to use Space Shuttle capabilities.

Demonstration requirements that were derived include:

- Significant and visible end-to-end demonstration of SPS system

  Validation of key technologies

  - Construction of large space structures
  - Phase control system performance
  - Microwave system performance
  - Solar array performance
  - Interfaces among systems
  - Microwave environmental interactions
  - Replication of system efficiency chain

- Demonstration within credible funding limits

These requirements for a program decision lead to a number of basic derived demonstration system requirements which are listed below.

- Convert a significant amount of solar energy to electrical energy on orbit and transmit to earth.

- Convert transmitted energy to electrical energy using a rectenna and provide useful power on earth.

- Use a construction technique that is a prototype of the operational system using Shuttle orbiter support.

- Satellite characteristics should include:
  - Low earth orbit operation
  - Large-aperture antenna
  - Similarity to operational satellite
  - Not dead-ended

The resulting system concept is illustrated in Figure 23. A large-aperture compression-frame, tension-web antenna (1 to 2 km in diameter) is located in a low earth orbit that overflies the ground site each day. The satellite can beam down about 19 kW of power (after ground site rectification) for a two-minute period each time it overflies the area.

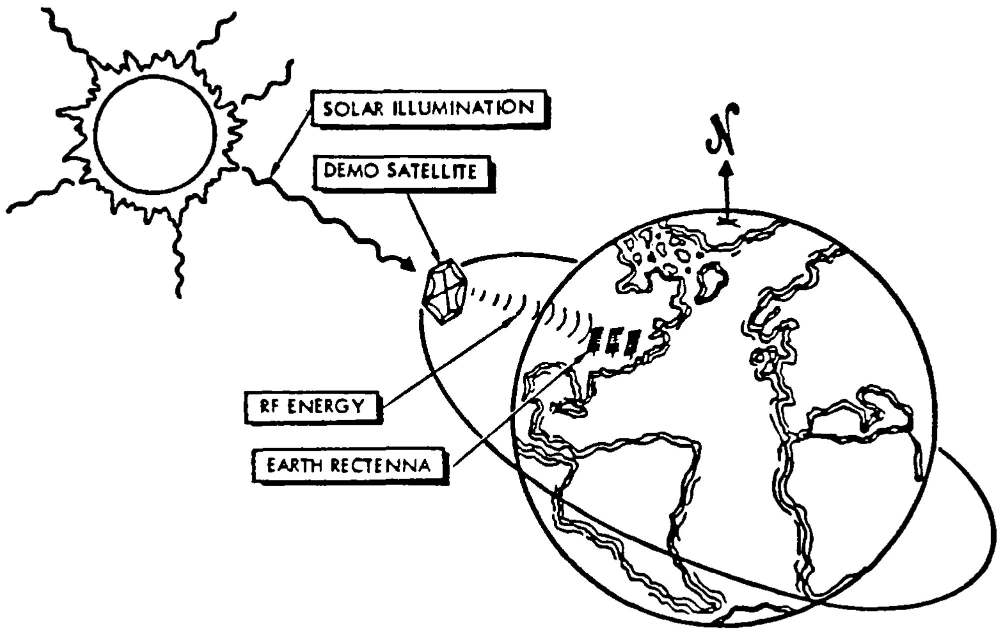

Figure 23. SPS Proof-Of-Concept Demonstration

The satellite configuration illustrated in Figure 24 is based on the Rockwell tension-web, compression-frame design. In this case, its structure is made up of 30-m composite struts, cross-braced with tension cables, as shown. A cruciform of 1800 m length by 5 m in width consists of 2.5- by 2.5-m sandwich panels supported by tension cables. Based on the solar cell and amplifier projected 1985 technologies, the power radiated from a panel is estimated to be 125 W/m^2 for a one-sun illumination. Four of these panels comprise a basic RF module which is phase controlled. Thus, there are 719 actively phase controlled RF modules in the satellite.

Assembly of the satellite structure on orbit was investigated and it was determined that some type of assembly jig would be required. Concepts were developed and an example structure jig for the triangular truss is illustrated in Figure 25. A docking adapter is stationed at one side of the jig to accommodate the Space Shuttle orbiter as it brings up the required payloads. As envisioned, the structural jig would be completely automated since the processes for satellite assembly are simple and highly repetitious. Assembly of the

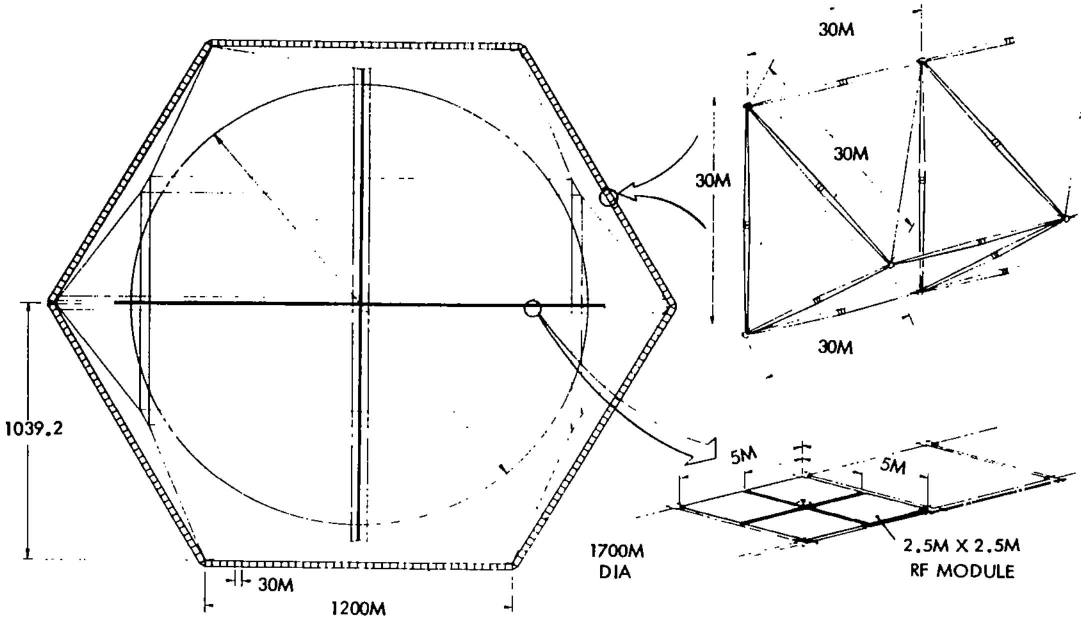

Figure 24. Antenna Structural Concept

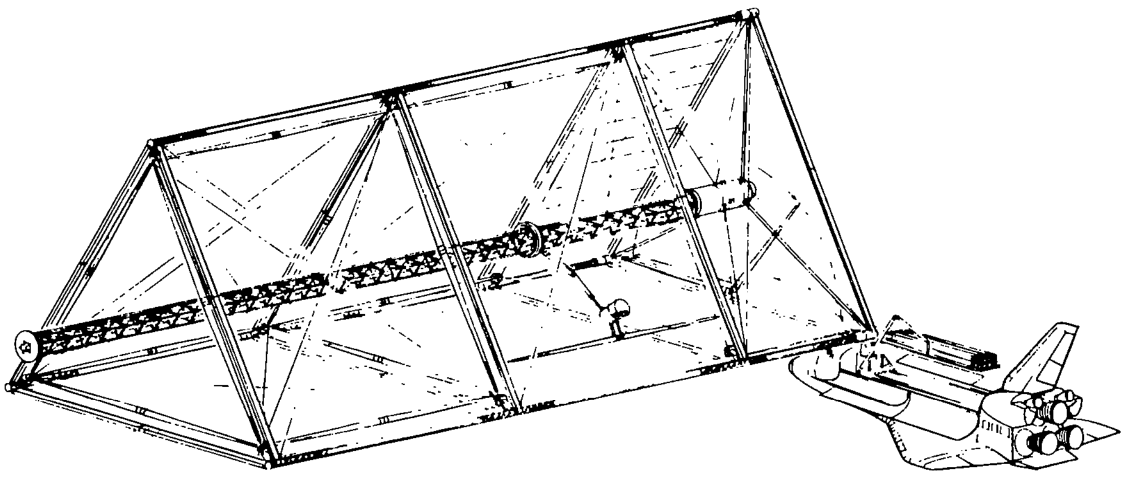

Figure 25. Structural Jig Concept for Triangular Truss

satellite structure, strut by strut, is accomplished within the jig framework shown. Basically, the jig consists of deployable Astromasts and hinged struts.

A major advantage of transmission across the large-aperture MW transmitting antenna is realized in the small size of the receiving antenna (i.e., the rectenna). Figure 26 illustrates the resulting rectenna size requirement which is approximately one-half the area of a football field. The rectenna panels are comprised of dipoles, appropriately spaced, on a ground plane of wire mesh. If desired, the rectenna could be built for transportability and demonstrated at sites thoughout the U.S. As shown in the lower center of the figure, the calculated maximum incident radiation level is low and unquestionably safe, yet MW energy capture over the 2500 m^2 will develop a maximum power level of 19 kW.

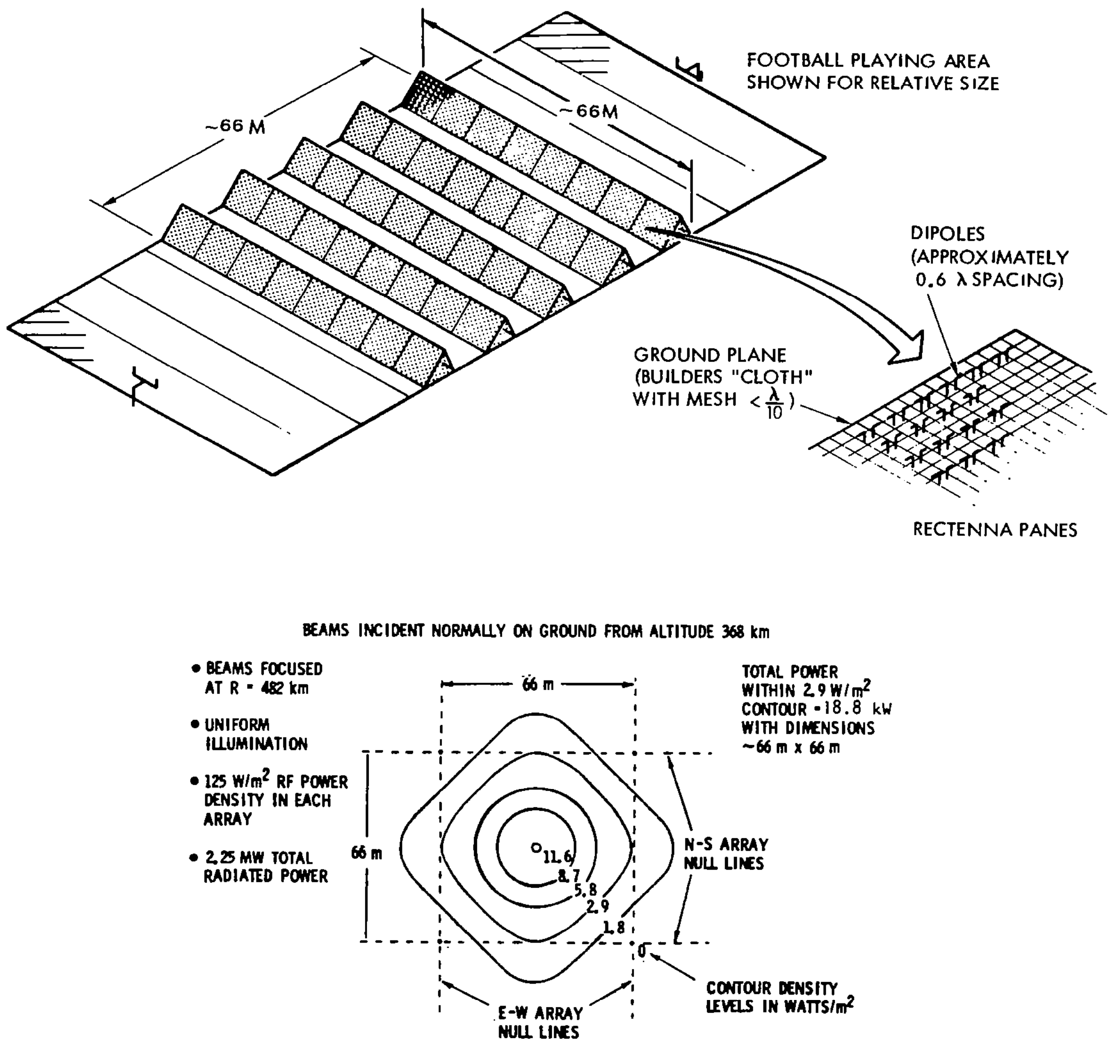

Figure 26. Rectenna Considerations

STRUCTURAL REQUIREMENTS FOR SPS CONCEPT DEMONSTRATION TEST ARTICLES

An additional contract requirement, Exhibit E, concentrated on a development of requirements for and description of the mission equipment, subsystems, configuration, utilities, and interfaces for two SPS flight test articles. These data will be integrated later into other program requirements for large structures to develop appropriate construction methods.

The two flight test articles shown in Figures 27 and 28 were utilized to develop the data. These test articles would be deployed in the 1990 time period. The concept shown in Figure 27 uses a cruciform pattern of solid-state sandwich panels mounted on a compression frame, tension-web structure to transmit significant power from low earth orbit to a rectenna on the ground. It also provides an end-to-end test of the SPS concept, subsystems, and technology. It is subsequently used in more advanced configurations to transmit more power to the ground, and ultimately is a building-block for an SPS pilot plant. The mission characteristics for this flight test article were described in the previous section.

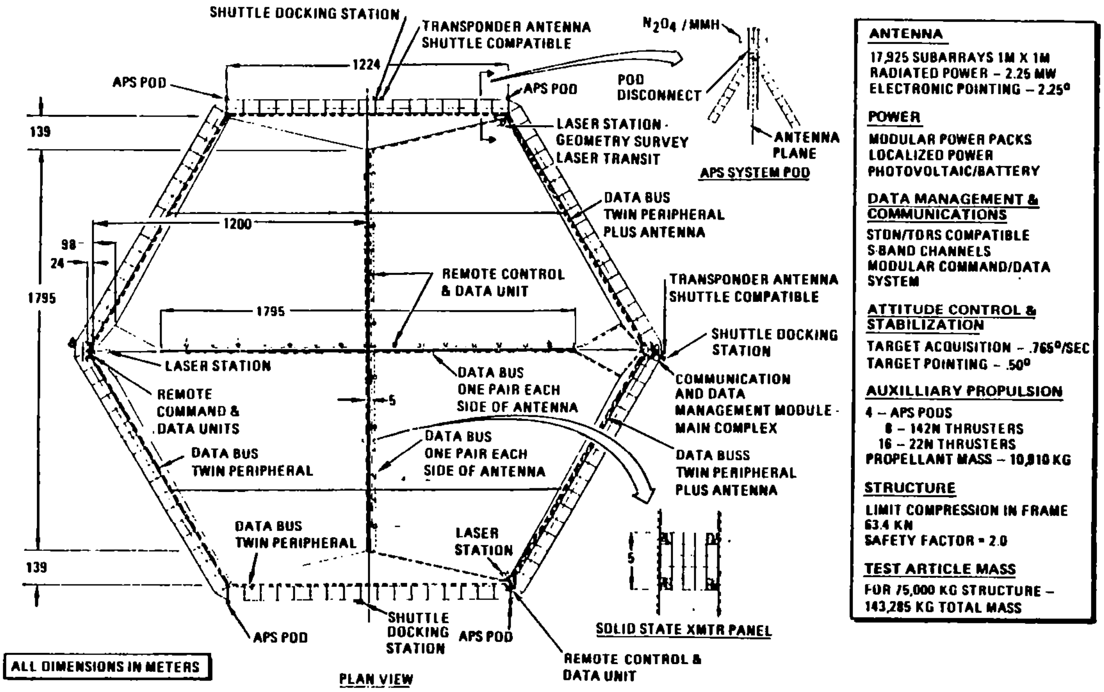

Figure 27. POC Test Article Configuration

The test article in Figure 28 provides a verification of the retrodirective phase control concept for beam formation, and demonstrates heat rejection in the high thermal flux region of the SPS antenna. Klystrons provide conversion of dc from the solar array to RF. Tests are completely conducted in orbit with transmission from the test article illustrated (Figure 28) to an orbiting rectenna.

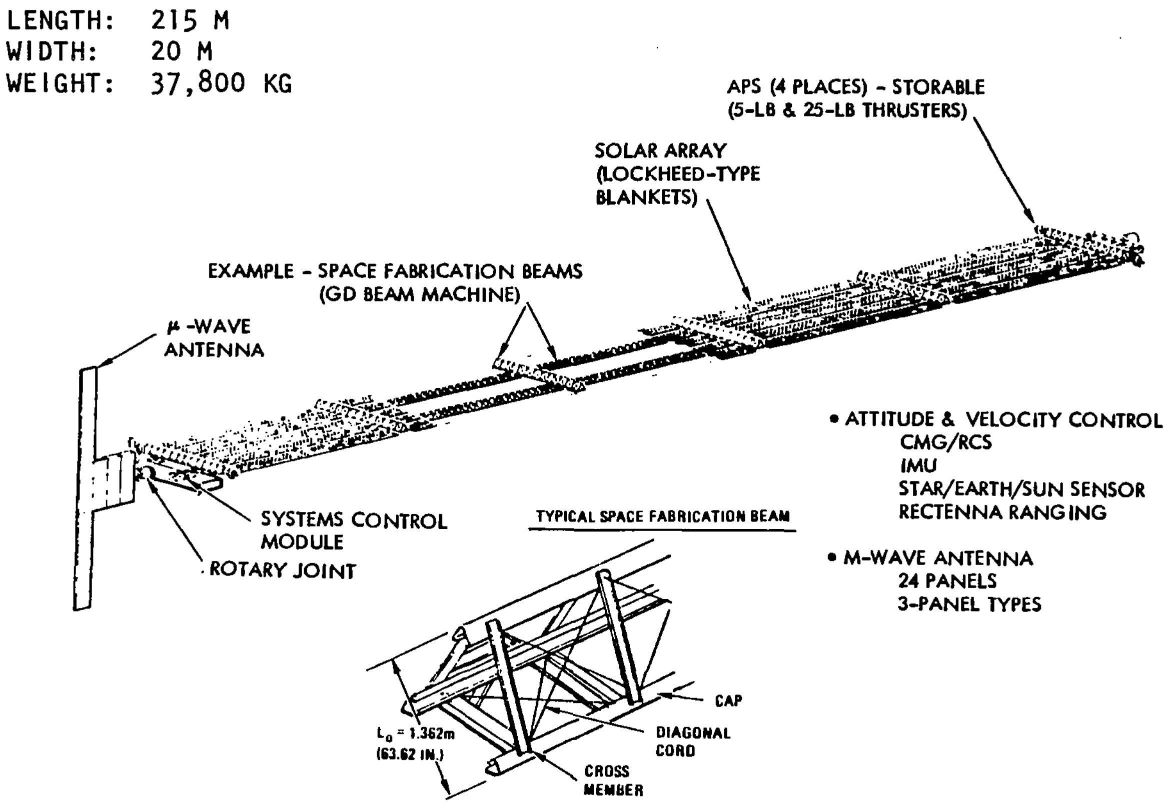

Figure 28. SPS Test Article General Configuration—LEO Configuration

STUDY LIMITATIONS

This study is only a portion of the total effort being conducted by the DOE to totally evaluate the SPS concept. In addition to this and other NASA SPS effort, the DOE is conducting studies of environment, health, safety, and socioeconomic issues as well as a comparative assessment of SPS and other energy options.

This study did not encompass the total system definition effort. In addition to the new concepts and reference concept (GaAs solar array) defined in this study, the Boeing Company has defined a silicon solar array version of the reference concept and has also studied solid-state concepts. Concepts utilizing laser power transmission also were defined in the Boeing study. Other concepts remain to be defined, including concepts that use gyrocon dc/RF microwave converters and advanced technology solar thermal systems. It is expected that additional new concepts will emerge as the program continues.

SUGGESTED ADDITIONAL EFFORT

As a result of this and other system definition effort during the past three years, a great deal has been learned about the SPS concept. The implications of these results on future effort are discussed separately for the systems and technology areas.

SYSTEM STUDIES

This study has indicated that the reference system using a GaAs solar array and klystron dc/RF converter devices is not the lowest-cost approach. Significant cost reductions resulted from the use of a multi-bandgap solar array and magnetron dc/RF converter devices. Other approaches will also lead to installation cost reductions and a reduction in cost uncertainties. These include (1) increases in concentration ratio from the current $CR_E = 1.83$ up to greater than 5 (reduces cost and cost uncertainty), (2) increase in concentrator reflectivity from 0.83 to 0.90 by using silver rather than aluminum on kapton, and (3) an increase in the maximum allowable power density at the rectenna from 23 mW/cm^2 to greater than 40 mW/cm^2 as suggested by Reference 4. A potential also exists in the rectenna and transportation areas for cost improvements.

Major emphasis during the next year should be placed on an updating of the reference SPS concept based on the data developed since its introduction and the key trade study areas mentioned above. Effort should continue to focus on photovoltaic concepts with microwave power transmission. Other energy conversion and power transmission concepts should be considered only when it is clear that the proposed technology is appropriate and that it may lead to significant cost reductions.

TECHNOLOGY DEVELOPMENT

Technology development toward the performance and cost goals of SPS has received very little emphasis at this time. Planning during the next year also reflects little effort in this area. However, based on the results of this study, it is clear that several areas of technology investigation can and should be initiated to validate the performance projections. These areas include:

- Advanced GaAs and multi-bandgap solar cells
- Magnetron
- Transportation and construction technology
- Structures and materials
- Microwave systems

The DOE initiated a moderate solar cell development during the past year that has some significance to SPS. This effort, being conducted by Rockwell, is focused on preliminary research of peeled-film GaAs technology. In this concept, a GaAs solar cell is produced on a high-quality (and cost) crystalline structure and is removed from the structure and reattached to a low-cost substrate such as glass. The high-quality crystalline structure is reused for the growth of numerous solar cells. This approach could conceivably lead to a low-cost solar array if film removal proves feasible and if the cost of removal and reattachment is not excessive. Although this research is beneficial to SPS, it is believed that development of GaAs and multi-bandgap solar cells having an overall construction similar to the previously proposed GaAs solar cell should be pursued in parallel with the peeled-film technology. Both programs need to be augmented with studies of low-cost manufacturing techniques and testing of solar cell radiation resistance and self annealing.

If the potential can be reached that is currently anticipated for magnetrons, these dc/RF converters may prove to be the optimum SPS approach. The major performance characteristics requiring validation are (1) noise reduction achieved through operation without a cathode heater, (2) efficiencies approaching 90%, and (3) lifetime approaching 30 years. Research should be initiated to determine whether these characteristics can be achieved.

Technology development related to the transportation system and space construction will be beneficial, not only to SPS, but to many other future space activities. Because of the long leadtime nature of these technologies, it is important that they be initiated early. Although considerably more study is needed to select a specific HLLV approach, technology development in the propulsion areas and heat protection system areas is important to significantly improve rocket engine lifetime, to determine the feasibility of air-breathing propulsion for single stage-to-orbit applications, and to reduce significantly heat protection system refurbishment and lifetime.

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1. Report No.
NASA CR-3392

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Satellite Power Systems (SPS) Concept Definition Study (Exhibit D)
Volume I - Executive Summary

5. Report Date
March 1981

6. Performing Organization Code

7. Author(s)
G. M. Hanley

8. Performing Organization Report No.
SSD 80-0108-1

9. Performing Organization Name and Address
Rockwell International
Space Operations and Satellite Systems Division
Downey, California

10. Work Unit No.
M-333

11. Contract or Grant No.
NAS8-32475

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546

13. Type of Report and Period Covered
Contractor Report

14. Sponsoring Agency Code

15. Supplementary Notes
Marshall Technical Monitor: Charles H. Guttman
Volume I of the Final Report on Exhibit D

16. Abstract

This report summarizes the Rockwell SPS Concept Definition Study results for Exhibit D, Contract NAS8-32475. This effort concentrated on updating of the Rockwell reference concept, definition of new system options, studies of special-emphasis topics, further definition of the transportation system, and further program definition. The Rockwell reference satellite concept has a gallium arsenide (GaAs) solar cell array having flat concentrators with an effective concentration ratio of 1.83 at end of life. Klystrons are used to convert the dc energy to microwave energy at 2.45 GHz. Alternatives to this concept included solid-state power amplifiers or magnetrons for dc/RF conversion and multi-bandgap solar cells for solar-to-dc energy conversion. Two solid-state concepts were studied. One of the concepts used the same basic satellite design approach as the Rockwell reference concept (separate solar array and antenna). The other concept integrated the solar array, microwave amplifiers. and antenna in a "sandwich" arrangement. As a result of these studies, it was determined that the magnetron approach was the lowest mass and cost system. Systems using solid state power amplifiers and GaAs solar arrays were higher in cost than the reference concept, but still in a competitive range. Multi-bandgap solar arrays led to a significant reduction in satellite mass and cost. Special emphasis areas included experimental evaluation of solid-state power amplifier performance and estimation of meteorological effects on laser beam propagation. This investigation resulted in the development of four amplifiers with efficiencies of 52 through 72 percent. The highest efficiency is achieved by driving the power amplifier at lower power. The study of meteorological effects on laser beam propagation led to the conclusion that low or high altitude receiving sites are acceptable and that there is very little advantage to locating the receiving sites near the equator. Laser hole boring through all but the thickest clouds is possible with power densities of 100-200 W/cm^2. Multiple receptor sites are needed to achieve 80 percent availability with laser systems.

Program planning activities were concentrated on specific plans for engineering/technology verification in the 1981-87 time period. A proof-of-concept demonstration was defined for the 1987-91 period, which provides an end-to-end demonstration of solar energy collection and conversion on orbit and transmission of microwave energy from space to ground.

17. Key Words (Suggested by Author(s))
Satellite Power System
Energy systems
Solar photovoltaic
Laser transmission
Microwave transmission

18. Distribution Statement
Unclassified - Unlimited

Subject Category 44

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
47

22. Price
A03

For sale by National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1981