NASA Contractor Report 3317

Satellite Power Systems (SPS) Concept Definition Study

Volume I - Executive Summary

G. M. Hanley

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**Scientific and Technical
Information Branch**

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FOREWORD

Volume I, *Executive Summary*, of the SPS Concept Definition Study final report is submitted by Rockwell International through the Satellite Systems Division. All work was completed in response to NASA/MSFC Contract NAS8-32475, Exhibit C, dated March 28, 1978.

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

Volume	Title
II	System Engineering
III	Experimentation/Verification Element Definition
IV	Transportation Analyses
V	Special-Emphasis Studies
VI	In-Depth Element Investigation
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 concept. 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 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.

Typically, a single SPS provides 5 GW of power to the utility interface on the ground. Two satellite power systems could provide more power then 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 75 km^2) and the large mass (approximately 35 million kg), it is necessary to construct the satellite on orbit where zero-gravity allows

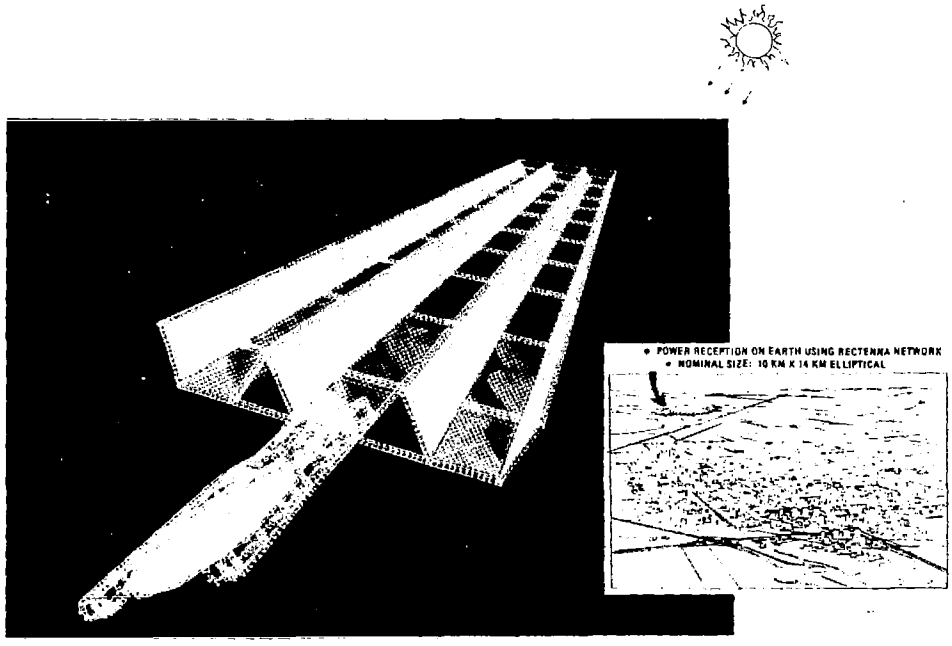


Figure 1. Satellite Power System Concept

very low structural mass. The ground-located rectenna is nominally 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 1 mW/cm^2 outside of the rectenna fenceline (10 mW/cm^2 is the current United States microwave exposure standard).

This study is a continuing effort to provide system definition data to aid in the evaluation of the SPS concept by DOE. The total DOE 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 second 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 for their evaluation. This year's effort 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 volume summarizes that effort.

STUDY OBJECTIVES

The objective of this effort is to provide system definition data to NASA/MSFC to support DOE evaluation of SPS. Two major NASA milestones were supported: Reference Concept Definition (Reference 2) and Program Plan Recommendations.

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 parallel system definition effort and is being supported under contract by the Boeing Company. Together, these studies form the basis for the NASA Office of Energy Programs inputs to the Department of Energy. This study also will provide 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

A time-related study flow diagram that summarizes the study approach is shown in Figure 2. The major data base was documentation from the previous Rockwell SPS Concept Definition Study (Exhibits A and B). Additional data included documentation of the Boeing Company SPS Concept Definition Study and results of NASA (MSFC and JSC) in-house SPS studies.

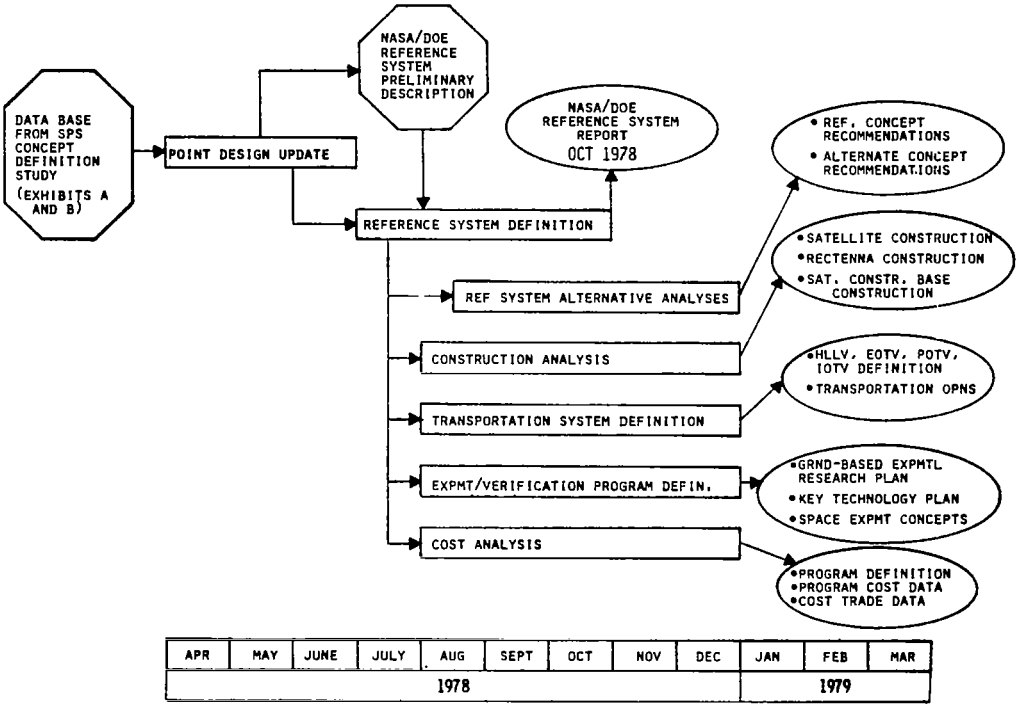


Figure 2. Study Flow

During the first 3 months of the study, major emphasis was placed on an update of the point design defined in Contract Exhibits A and B. The update resulted from additional trade studies conducted during the first 3 months. The updated point design and similar data from the Boeing Company studies and NASA in-house studies resulted in a preliminary description by NASA and DOE of a reference system. The purpose of the reference system is to provide a specific single data base for the SPS concept evaluation being conducted by DOE. The reference system was then defined and a report was issued by NASA/DOE that describes this system and contains key trade studies leading to definition of this system. This system description formed the basis for a series of studies (construction, transportation, experiment/verification program, and cost) that further defined the concept and program. In addition, a series of trade studies at the total system level and at the subsystem level were conducted to identify modifications to the currently-defined reference system and to define alternative system concepts which have the potential for significant improvements.

The major outputs of the study are shown in Figure 2. The constructability studies resulted in the definition of the concepts for satellite, rectenna, and satellite construction base construction. Transportation analyses resulted in definition of heavy-lift launch vehicle (HLLV), electric orbit transfer vehicle (EOTV), personnel orbit transfer vehicle (POTV), and intra-orbit transfer vehicle (IOTV) as well as overall operations related to transportation systems. The experiment/verification program definition resulted in the definition of elements for the Ground-Based Experimental Research (GBER) and Key Technology plans. These studies also resulted in conceptual approaches for early space technology verification. The cost analysis defined the overall program and cost data for all program elements and phases.

This data will form the basis for further program definition and is the basis for recommended future effort.

BASIC DATA GENERATED AND SIGNIFICANT RESULTS

This section summarizes the significant study results. First, an overview of the system definition effort is presented. This is followed by a description of the special emphasis studies, which concentrated on system construction; a summary of the space transportation system; and a total program and program cost summary.

SYSTEM DEFINITION

The major output of the previous Rockwell SPS Concept Definition Study (Exhibit B) was a point design definition. The resulting satellite concept is shown in Figure 3. The major characteristics of the concept are summarized in Table 1. The satellite concept has gallium arsenide (GaAs) solar cells with reflectors (concentration ratio of 2) for energy conversion and uses klystrons for dc to RF conversion. The microwave antenna is centrally located to reduce power distribution mass. Three troughs, containing the solar array, are arranged in a triangular manner to reduce gravity gradient torques. The rectenna uses a stripline phased array to reduce significantly the number of diodes compared to individual dipoles. Five gigawatts (GW) of power are delivered at the utility interface.

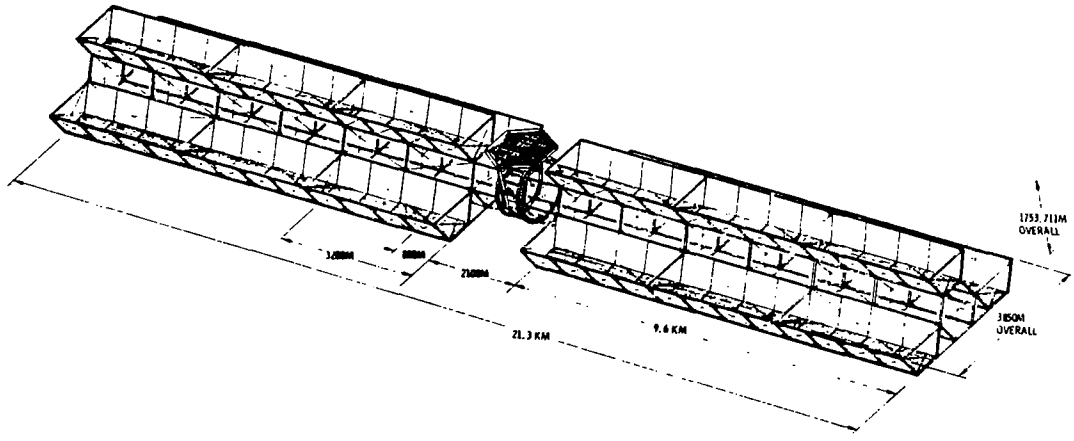


Figure 3. Rockwell Satellite Point Design

The transportation system consists of a heavy lift launch vehicle (HLLV) for earth to low earth orbit (LEO) transportation, an electric orbit transfer vehicle (EOTV) for LEO to geosynchronous equatorial orbit (GEO) cargo transfer, and a personnel orbit transfer vehicle (POTV) for LEO to GEO transportation of the construction base crew. Construction of the satellites is accomplished completely at GEO.

Table 1. Rockwell Point Design Description

OVERALL DESCRIPTION

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

SUBSYSTEMS

- POWER CONVERSION
  - GaAlAs SOLAR CELLS
  - CONCENTRATION RATIO = 2
- ATTITUDE CONTROL/STATIONKEEPING
  - Y-POP
  - ARGON ION THRUSTERS
- POWER DISTRIBUTION
  - 45.5 KV DC
  - STRUCTURE/WIRING NOT INTEGRATED
- MICROWAVE ANTENNA
  - GAUSSIAN BEAM
  - RCR WAVEGUIDE PANELS
  - 2.45-GHz FREQUENCY
  - TENSION-WEB, COMPRESSION FRAME STRUCTURE
  - ECLECTIC PHASE CONTROL
- STRUCTURE
  - ALUMINUM (GRAPHITE/THERMAL PLASTIC ALTERNATE AS NEEDED)
  - BEAM MACHINE CONSTRUCTION
- INFORMATION MANAGEMENT
  - DISTRIBUTED

This approach along with data from the Boeing Company SPS study and the NASA/MSFC and JSC in-house studies were used to arrive at a reference system.

Reference System

The reference system defined by NASA and DOE contains the two satellites shown in Figure 4. The reference system has the characteristics shown in Table 2. The major difference between the two satellites is the energy conversion approach; one uses silicon solar cells in a planar, non-concentrated array and the other uses GaAs solar cells in a planar array with CR=2. The microwave antenna on both satellites is located at one end of the satellite. Power at the utility interface on the ground is 5 GW. A phased array is used for the rectenna.

The construction location, GEO, is the same as previously described for the Rockwell system. The transportation system is comprised of elements similar to those described for the Rockwell point design.

The purpose of the reference system is to provide DOE with a specific and consistent set of data on the SPS for purposes of evaluation. Following preliminary definition of this concept, trade studies were conducted on this contract to further define the characteristics of the system. These studies were concentrated on the GaAs system concept. The following section describes trade studies relative to the satellite and rectenna. Trade studies on the

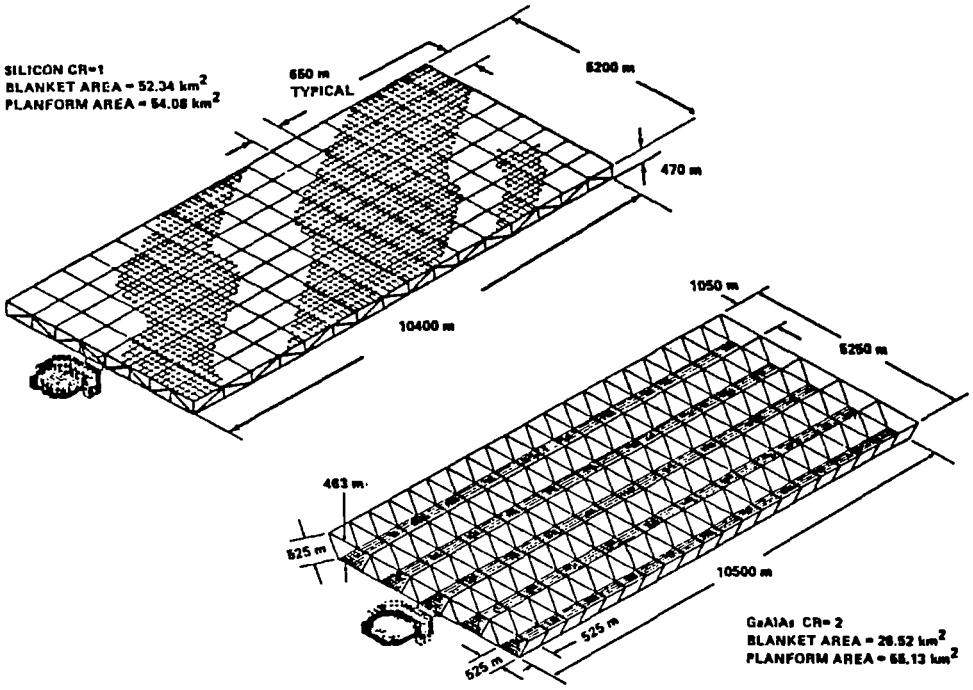


Figure 4. SPS Reference System Satellites

Table 2. SPS Reference System Description

SPS GENERATION CAPABILITY (UTILITY INTERFACE)	5 GW	
OVERALL DIMENSIONS (KM)	5.3×10.4	
SATELLITE MASS (KG)	34×10^6	51×10^6
POWER CONVERSION-PHOTOVOLTAIC	GaAlAs (CR=2)	SILICON (CR=1)
STRUCTURE MATERIAL	GRAPHITE COMPOSITE	
CONSTRUCTION LOCATION	GEO	
TRANSPORTATION		
• EARTH-TO-LEO -CARGO (PAYLOAD)	VERTICAL TAKE-OFF, WINGED 2-STAGE (424,000 KG)	
-PERSONNEL (NUMBER)	MODIFIED SHUTTLE (75)	
• LEO-TO-GEO -CARGO	DEDICATED ELECT. OTV	
-PERSONNEL (NUMBER)	2-STAGE LOX/LH_2 (75)	
MICROWAVE POWER TRANSMISSION		
• NO. OF ANTENNAS	1	
• ANTENNA POINTING/CONTROL	CONTROL MOMENT GYROS (CMGs)	
• DC-RF CONVERTER	KLYSTRON	
• FREQUENCY (GHZ)	2.45	
• RECTENNA DIMENSIONS (KM)	10×13	
• RECTENNA POWER DENSITY (MW/CM^2)		
-CENTER	23	
-EDGE	1	

transportation system are described in the Transportation Analysis section and trade studies related to construction are contained in the Special Emphasis Studies section. Two areas where major departures from the reference system were studied are laser energy transmission environmental impacts and solid-state microwave transmission. These results are contained in two separate sections following the next section.

Major Alternative Study Results

Major alternatives to the reference system that were studied following its preliminary definition include the following:

- Coplanar versus triangular solar array trough arrangement
- Number of solar array troughs
- Central versus end-mounted antenna
- Aluminum versus composite structure
- Antenna structural concept
- Alternative rectenna phased arrays

The results of these studies are described below.

Coplanar Versus Triangular Solar Array Trough Arrangement. The main purpose of the triangular trough arrangement in the Rockwell point design was to reduce the attitude control requirements due to gravity gradient torques. Continued studies of the attitude control requirements and integration of these requirements with stationkeeping requirements revealed that stationkeeping for solar pressure perturbations was the dominant requirement. It also was determined that the attitude control requirements could be met even for a coplanar trough with no further propellant impact than that required for solar pressure stationkeeping. Therefore, the coplanar trough arrangement of the baseline concept is the recommended concept.

Number of Solar Array Troughs. Trade studies related to the number of troughs considered the impact on the construction facility and on the SPS system weight and cost. Location of the microwave antenna (central versus end-mounted) also is a consideration in this trade study. The impact of number of troughs and antenna location on mass are shown in Table 3 for GaAs, CR-2 concepts. For the centrally-located antenna, the mass is slightly less for a 3 trough concept when compared to 4 trough concept. The 3 trough concept has a slightly greater mass than the 4 trough concept for an end-mounted antenna.

The smaller number of troughs is desired from the construction base point of view regardless of the method of construction. (Two methods of construction, single-pass and serpentine, were considered and will be described later in this Summary Report.) In the serpentine construction approach, one trough is completed before the next is started. The greater the number of troughs, the greater the complexity because of the complexity of operations for transfer of the facility to initiate construction of another trough. In the single pass

Table 3. Effect of Antenna Location and Number of Troughs on Satellite Mass (Million kg)

	CENTRAL ANTENNA		END ANTENNA	
	3 TROUGHS	4 TROUGHS	3 TROUGHS	4 TROUGHS
ANTENNA SECTION	16.3	16.3	16.3	16.3
COLLECTOR ARRAY	12.3	12.5	14.0	13.7
25% GROWTH	7.1	7.2	7.6	7.5
TOTAL	35.7	36.0	37.9	37.5

construction approach, all troughs are constructed simultaneously and the size of the construction facility and the amount of construction equipment is approximately proportional to the number of troughs.

Because of the small difference in mass related to the number of troughs, the construction facility considerations were paramount. For this reason, 3 troughs are preferred for both the end-mounted and center-mounted antenna concepts.

Central Versus End-Mounted Antenna. The location of the antenna may have an influence on several system characteristics including: (1) satellite mass, (2) attitude control and stationkeeping, (3) microwave transmission, (4) thermal control, and (5) satellite construction.

The impact on mass was already shown in Table 2. As shown, a three trough end-mounted concept has a mass 2.2×10^6 kg greater than the center-mounted antenna concept. The mass difference is attributable to increased power distribution mass caused by longer distribution distances for the end-mounted antenna concept.

Stationkeeping requirements are virtually identical for end- or center-mounted antenna concepts. The major stationkeeping requirement is due to solar pressure perturbation. Although the solar pressure perturbation is cyclical over a year, the orbital excursions are unacceptable because of the increased amount of geosynchronous space occupied by the satellite without corrections. Because of the assymetry of the end-mounted antenna concept, the attitude control requirements due to solar pressure are large. If these torques were controlled separately from stationkeeping, 4.0% of the spacecraft mass would be required in propellants over 30 years (as compared to a total of 5.6% for all attitude control requirements). By combining the solar pressure and other stationkeeping corrections with attitude control corrections, the center-mounted and end-mounted concepts have virtually the same propellant mass requirements because of the dominance of solar pressure stationkeeping, which is the same for both concepts. Because of the amount of solar pressure stationkeeping correction required, the SPS troughs can be partially pointed toward the sun to reduce losses due to excursions of the sun north and south of the equator without an attitude control propellant penalty.

Microwave transmission interference with the inboard collector array structure also was considered as a potential penalty for the center-mounted antenna concept. However, because of the large antenna aperature, spreading

of the beam and side lobe formation is negligible in the neighborhood of the satellite. As long as no structure is located such that a normal from the antenna intersects it, no interference should occur. The center-mounted concept is designed to satisfy this constraint.

Because carry-through and rotary joint structure is located directly behind the microwave antenna where waste heat from the klystrons is being rejected, there is some concern of the thermal impacts. Thermal control can be achieved to an acceptable level for either aluminum or graphite composites by surface coating or surface covering at a negligible weight penalty.

Satellite construction studies indicate some additional construction complexity due to the center located antenna. At this time, the complexity is difficult to trade off against the additional mass required for the end-mounted concept.

As a result of these trade studies, it was concluded that either antenna location results in a feasible concept. The only significant penalty identified was the mass increase for the end-mounted antenna of 2.2×10^6 kg. For this reason, the center-mounted concept is preferred, but either satellite concept is acceptable.

Aluminum Versus Composite Structure. The triangular trough arrangement concept (Rockwell point design) previously shown in Figure 3 was used to conduct a detailed structural analysis using the NASTRAN computer model. It was assumed that construction occurred at a uniform temperature of 0°C, that calculated equilibrium temperatures occurred during normal operation in the sun, and that a minimum temperature of -150°C occurs during an eclipse of the sun by the earth. Results of this analysis showed maximum structural deflections at the solar array tips of 100 m for aluminum structure and 1.1 m for composite structure. Detailed analysis of tribeam loading revealed that local loading for aluminum structure caused by deflections exceeded crippling allowables of the elemental caps for a 10 mil thickness aluminum structure. For some regions, material thicknesses up to 30 mils would be required. If all members were constrained to a 30 mil aluminum material thickness, a structural weight of up to 10×10^6 kg would result for aluminum structure compared to 1.2×10^6 kg for composite structure. This maximum value for aluminum could be reduced by about one-half by selectively using 30 mil structure only in the lateral structure where crippling allowables are exceeded and 10 mil structure in the longitudinal structure.

The major problem with the composite structure is the current lack of knowledge on lifetime in orbit. The 30-year SPS requirement is much more severe than for other spacecraft.

As a result of these trade studies, it was concluded that either aluminum or composite structure can be used for SPS. Because of the lower deflections, induced stresses, and lower weight of composite structure, it is recommended for the satellite structure. Research is required to assure either that current composite structure applicable to SPS will survive the space environment for 30 years or that composite structure materials can be formulated that will survive the space environment for 30 years. Aluminum structure can be carried as a viable alternative.

Antenna Structural Concept. Two concepts, shown in Figure 5, have been proposed for the antenna basic structure: a tension web, compression frame structure proposed by Rockwell and a spaceframe structure proposed by JSC.

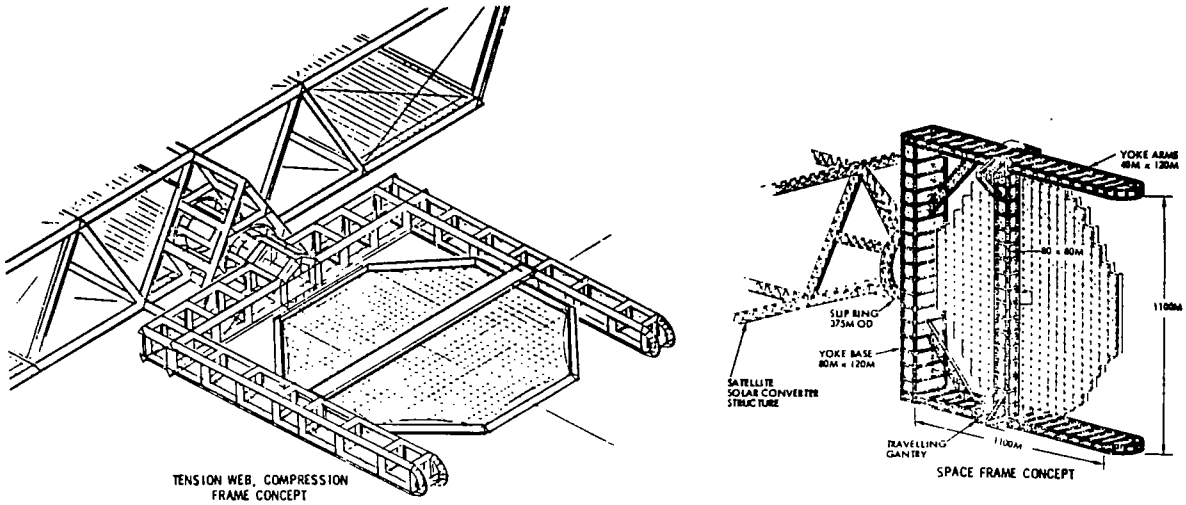


Figure 5. Alternative Antenna Structural Concepts

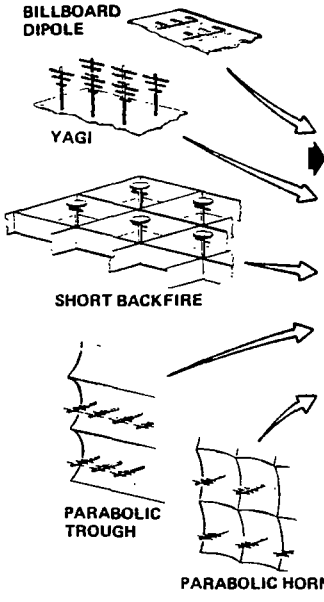
The tension web, compression frame structure is essentially like a tennis racket. The microwave antenna elements are attached to a square matrix formed by the composite tension web. Sufficient flatness is maintained against perturbations by applying proper tension to the web. Loads from the web are carried in compression in the frame surrounding the web by catenary cables.

The spaceframe structure is a box-grid truss network. The microwave antenna elements are attached to the structure by a secondary supporting structure. Because of the large amount of study conducted under contract to JSC and internally at JSC, the characteristics of the spaceframe are well defined. The tension-web structure has not been sufficiently analyzed to assess the dynamic characteristics of the structure under annual cyclic loads. Such an analysis is needed to assure feasibility of the design. Estimates indicate that the tension web, compression frame structure has lower mass than the spaceframe structure. (0.067×10^6 kg for the tension web compression frame compared to 0.250×10^6 kg for the spaceframe.) Although a detailed analysis has not been accomplished, it is expected that construction may be faster and simpler for the tension web, compression frame structure.

One major area of difference for the two approaches is heating of the structures due to thermal radiation from the microwave antenna. The tension web does not see the thermal radiating elements of the antenna and can reradiate solar heating from both sides; whereas, the spaceframe structure is directly below the antenna and is blocked by the antenna on one side for reradiation. A thermal analysis revealed that the spaceframe structure would require high temperature composite structure (e.g., polyimide) to withstand the resulting temperatures.

Although the tension web, compression frame antenna structure has many potential advantages, sufficient analysis has not been accomplished to validate its feasibility for SPS. When appropriate, future studies of its dynamic characteristics should be accomplished to assess feasibility. The spaceframe should be continued as a baseline until these feasibility studies have been completed.

Alternate Rectenna Phased Arrays. Several rectenna phased array designs have been considered for application to SPS. Figure 6 compares the characteristics of these concepts. The number of elements in the array decrease from top to bottom in this figure. However, as the number of elements decrease, the aperature efficiency decreases. Of the concepts illustrated, the dense array, using stripline interconnections, is easiest to mass produce and install in addition to having a high efficiency. The dense array of stripline interconnected dipoles is the recommended concept.



CONCEPT	NUMBER OF ELEMENTS (9 X 15 M AREA)	DESCRIPTION	COMMENTS
DENSE ARRAY (BILLBOARD)	36044	DIPOLES, $\lambda/2$ SPACING SQUARE CLUSTERS OF 49 ELEMENTS	STRIPLINE INTERCONNECT 0.5% MATCHING LOSS, EDGE EFFECTS } NEEDS STUDY; I^2R LOSS – 0.5% TO 5.5 KM
YAGI ARRAY	9011	λ SPACING, RECTANGULAR CLUSTERS OF 12 ELEMENTS	MUTUAL COUPLING EFFECT NEEDS STUDY
SHORT BACKFIRE ARRAY	2254	2λ SPACING, SQUARE CLUSTERS OF 4 ELEMENTS	BEAMWIDTH SLIGHTLY TOO NARROW NEEDS STUDY
TROUGH	2205	18 PARABOLIC TROUGHS YAGI FEEDS SPACED λ	APERTURE EFFICIENCY <80%
SQUARE PARABOLAS	540	540 PARABOLAS YAGI FED	APERTURE EFFICIENCY <70%

Figure 6. Alternative Rectenna Concepts

Recommended SPS Satellite Concept. As a result of the trade studies, several changes to the GaAs solar array satellite reference concept are recommended. Figure 7 illustrates the recommended satellite concept and Table 4 describes its characteristics. The concept has 3 bays containing GaAs solar arrays and flat reflectors giving CR=2. The microwave antenna is located in the center of the solar array. The efficiency chain for this concept is shown in Figure 8. Because of partial pointing toward the sun as the seasons vary, the efficiency due to seasonal variations is greater than the reference concept which is assumed to remain perpendicular to the orbit plane at all times. Additionally, the output on the ground is 4.61 GW rather than the reference concept 5 GW because of reductions in efficiency in the microwave transmission chain. Sizing of the solar blanket has been altered to reflect these changes. Table 5 summarizes the mass properties for this concept. When compared to the

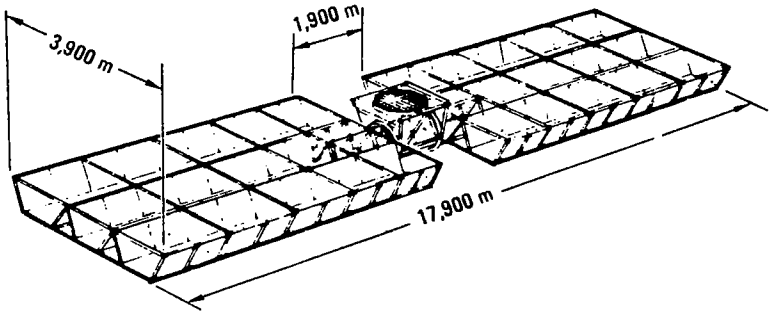


Figure 7 Recommended Satellite Concept

Table 4. Recommended Satellite Concept Description

OVERALL DESCRIPTION

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

SUBSYSTEMS

- POWER CONVERSION
  - GaAlAs SOLAR CELLS
  - CONCENTRATION RATIO = 2
- 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
- STRUCTURE
  - COMPOSITES
  - BEAM MACHINE CONSTRUCTION
- INFORMATION MANAGEMENT
  - DISTRIBUTED

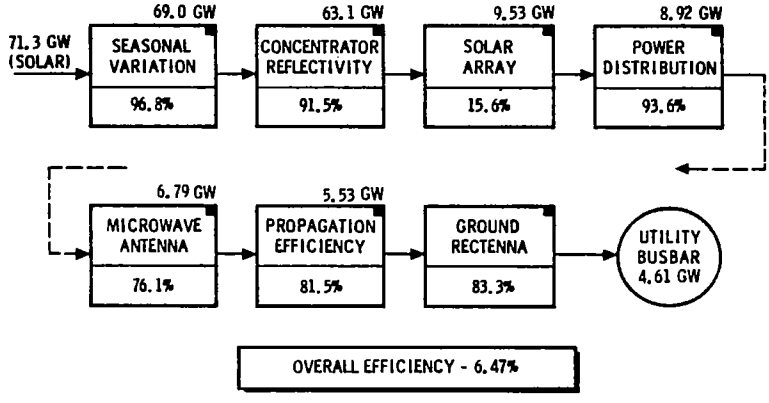


Figure 8. EOL Efficiency Chain for Recommended Concept

Table 5. Recommended Satellite Concept Mass Properties

SUBSYSTEM	MASS (10^6 KG)
COLLECTOR ARRAY	
STRUCTURE AND MECHANISMS	1.122
POWER SOURCE	7.255
POWER DIST. AND CONTROL	0.882
ATTITUDE CONTROL	0.116
INFORMATION MGMT. AND CONTROL	0.050
TOTAL ARRAY (DRY)	(10.025)
ANTENNA SECTION	
STRUCTURE AND MECHANISMS	0.977
THERMAL CONTROL	1.408
MICROWAVE POWER	7.012
POWER DIST. AND CONTROL	4.505
INFORMATION MGMT. AND CONTROL	0.630
TOTAL ANTENNA SECTION (DRY)	(14.532)
TOTAL SATELLITE DRY WEIGHT	24.557
GROWTH (25%)	6.137
TOTAL SATELLITE DRY WEIGHT WITH GROWTH	30.694

reference concept mass, a 3.5×10^6 kg reduction in mass has occurred. Much of this reduction in mass is due to a reduction in solar array mass related to the reduction in power level.

Solid State Microwave Transmission Concepts

The current reference concept uses klystrons for conversion of energy from dc electrical power to microwave radio frequency energy at 2.45 GHz. One of the major concerns of this approach is the reliability of the klystron devices. Solid state amplifier circuits using high efficiency, advanced technology gallium arsenide transistors for dc/RF conversion have been considered as an alternative because of their potential for high reliability. In order to be competative with klystrons, the solid state amplifier circuits and antenna combined efficiencies need to approach the same efficiency as the klystron and antenna combined efficiencies. Two major problems exist for the solid state designs: (1) the temperature of the amplifier base needs to be controlled to about 150°C for efficient and reliable operation and (2) the solid state devices inherently must be operated at low voltages (e.g., 40 volts).

Because of these differences between the klystron and solid state systems, the overall microwave system design may be significantly different. In order to meet the thermal constraints, it is necessary to reduce the maximum power density. This can be accomplished by increasing the antenna area while re-radiating heat from both sides of the antenna. However, as the antenna area increases, the power output must be decreased to satisfy the 23 mW/cm^2 RF energy constraint in the atmosphere to avoid potential microwave interference with the D and F layers of the atmosphere. Such a concept is illustrated in Figure 9. The area of each of 2 antennas is about twice the area of the klystron antenna and each antenna has about half the power output of the klystron antenna. Although the total power output of each satellite system is about 5 GW at the utility interface on the ground, two rectennas of about half the area each of the klystron concept rectennas are needed to collect the energy.

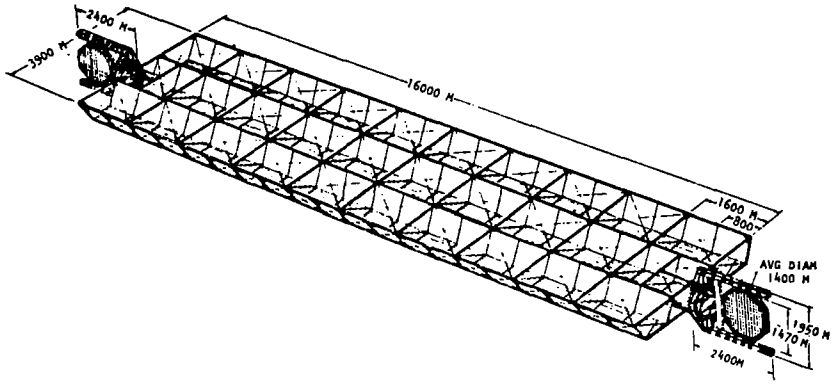


Figure 9. Dual Microwave Antenna Concept

Other approaches still need to be evaluated that solve the thermal problem. They include (1) an antenna which is uniformly illuminated (constant power density per unit area) and (2) an antenna that has evenly distributed solid state power amplifiers but which redistributes the RF energy in the antenna using waveguides to achieve the currently-used Gaussian distribution. Both of these approaches are attempts to achieve a smaller antenna that has higher power than the concept illustrated in Figure 9.

Although the above concepts solve the thermal problem, the problem of power distribution and control, (because of the low voltage requirement) still remains to be solved. Because of the long distances from the solar array to the antennas, conduction at the low voltages required by the amplifiers is not possible. Several compromises need to be studied to arrive at an optimum solution. They include: (1) power distribution at different voltages to the antenna section from the array, increasing in voltage with distance from the antenna section; (2) multiple levels of voltage reduction (e.g., from 20,000 V to 2,000 V and from 2,000 V to 200 V); (3) high power voltage reduction devices on the antenna versus low voltage distance from the devices to the RF power amplifiers; and (4) series/parallel strings of power amplifiers to increase voltage required at the antenna.

All of the solid state microwave concepts described above are similar to the reference concept in overall configuration; i.e., all of the concepts have an antenna containing the dc/RF converters which is separate from the solar array. Another approach to the solution of both the thermal and power distribution problems is to combine the solar array and the antenna. One concept that uses this approach is shown in Figure 10. The solid state power amplifiers in this concept are uniformly distributed on the back of the solar array. The thermal problem is solved because of the low density of the power amplifiers, and the power distribution problem is solved by the back to back location of the power source and the solid state power amplifier. However, since the antenna must be earth oriented it is necessary to direct the sunlight on the solar array using large reflectors. The concept in Figure 10 has a nominal concentration ratio of 2. The large reflector rotates to face the sun and reflects the sunlight onto multiple reflectors that concentrate the solar energy on the solar array. Because the maximum microwave energy must be

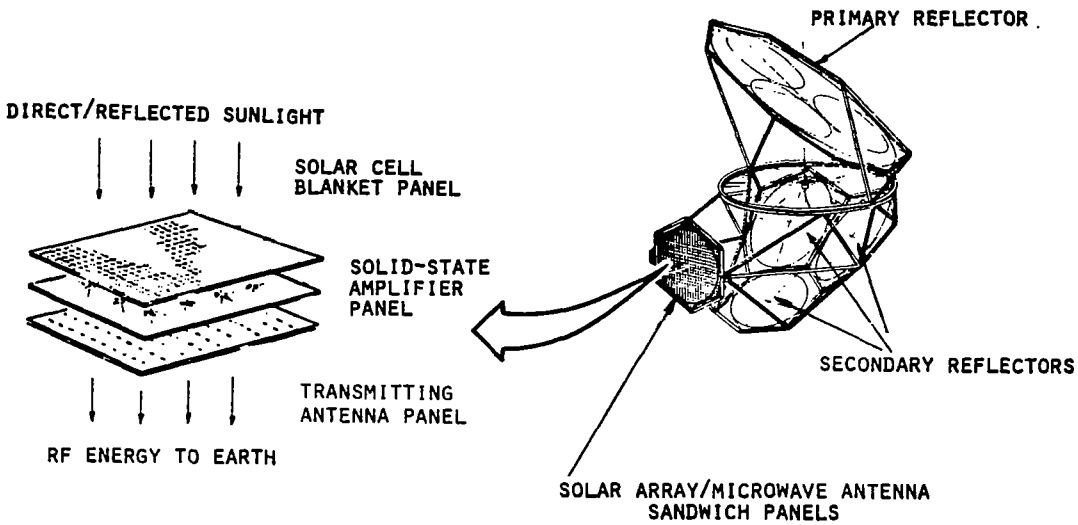


Figure 10. Sandwich Panel Solid State Concept

limited to 23 mW/cm^2 near the earth, this particular concept is limited to 0.816 GW of power at the utility interface due to the large microwave antenna aperture. Despite the relatively low power output, preliminary cost estimates indicate that this concept is competitive with the reference concept. This approach allows use of "sandwich panels", shown in Figure 10 that contain the solar cell blanket, the solid-state amplifier, and the transmitting antenna. This concept requires considerable additional study to conduct an evaluation and comparison with the reference concept and the other solid-state microwave systems previously described. This approach could also be used with klystrons.

In addition to the overall system effort described above, a detailed analysis was conducted to determine optimum power amplifier circuit designs. This study indicated that efficiencies of 82% might be expected for GaAs transistor circuits. This efficiency appears adequate to make the solid-state microwave system competitive with the reference klystron microwave concept.

Laser Transmission Environmental Study

A study was conducted to assess the impact on the environment of laser energy transmission from the satellite to the ground. The laser transmission system is assumed to replace the microwave transmission system. Ground collection and conversion to electrical power can be accomplished by a number of approaches, including photovoltaic cells, tuned optical diodes, heat engines, or thermoelectronic. A current state-of-the-art supersonic flow CO electric discharge laser was used to characterize the laser transmission system, although it was recognized that a viable laser transmission system would require significant technology improvement to satisfy SPS goals.

The following summarizes the results of the environmental impact investigations:

- Global climatic change resulting from the proliferation of laser-SPS systems is highly improbable

- Mesoscale weather modifications at receptor locations will be less significant than such phenomena associated with conventional or nuclear electric power plants of comparable power rating

- Thermal heating of the lower troposphere by the laser beam will promote waste-heat dispersal by vertical mixing, but will also induce severe turbulence which could be hazardous to aircraft intruding into the restricted air zone

- The environmental impact on certain wildlife, especially birds and insects, is uncertain

- Laser-plasma interactions in the ionosphere are insignificant

- Laser-beam perturbation of the plasma chemistry in the mesophere and thermosphere is believed to be of negligible magnitude and consequence; however, confirming research is needed to substantiate this claim

- Serious environmental modifications, such as depletion of the ozone concentration in the stratosphere, are not possible

SPECIAL EMPHASIS STUDIES

Special emphasis studies were concentrated on a definition of satellite, satellite construction base, and rectenna construction. In addition, previous analyses of logistics were updated based on the system study results and further definition of the satellite construction base and the transportation system. The results of these analyses are summarized in the following sections.

Satellite Construction

Satellite construction is assumed to occur entirely at geosynchronous orbit. Two 5 GW satellites are assumed to be built each year in building up a total capability of 60 satellites. The study of satellite construction was focused on determining the functions and the preferred conceptual approach for the satellite construction base (SCB).

Evaluation of Satellite Construction Approaches. Two basic approaches, illustrated in Figure 11 were considered for the SCB: a single-pass facility that constructs all bays simultaneously and a multipass serpentine facility that constructs one bay at a time. These approaches were compared to develop design data, construction functions and timelines, crew functions, and crew size.

The design of the multipass serpentine facility is shown in Figure 12. The construction facility is attached to tracks on a translation platform. The platform consists of three sections attached to one another by sliding guideways which permit lateral movement during repositioning operations.

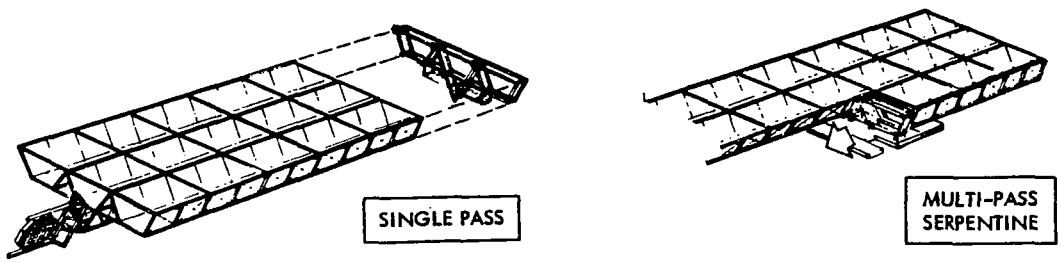
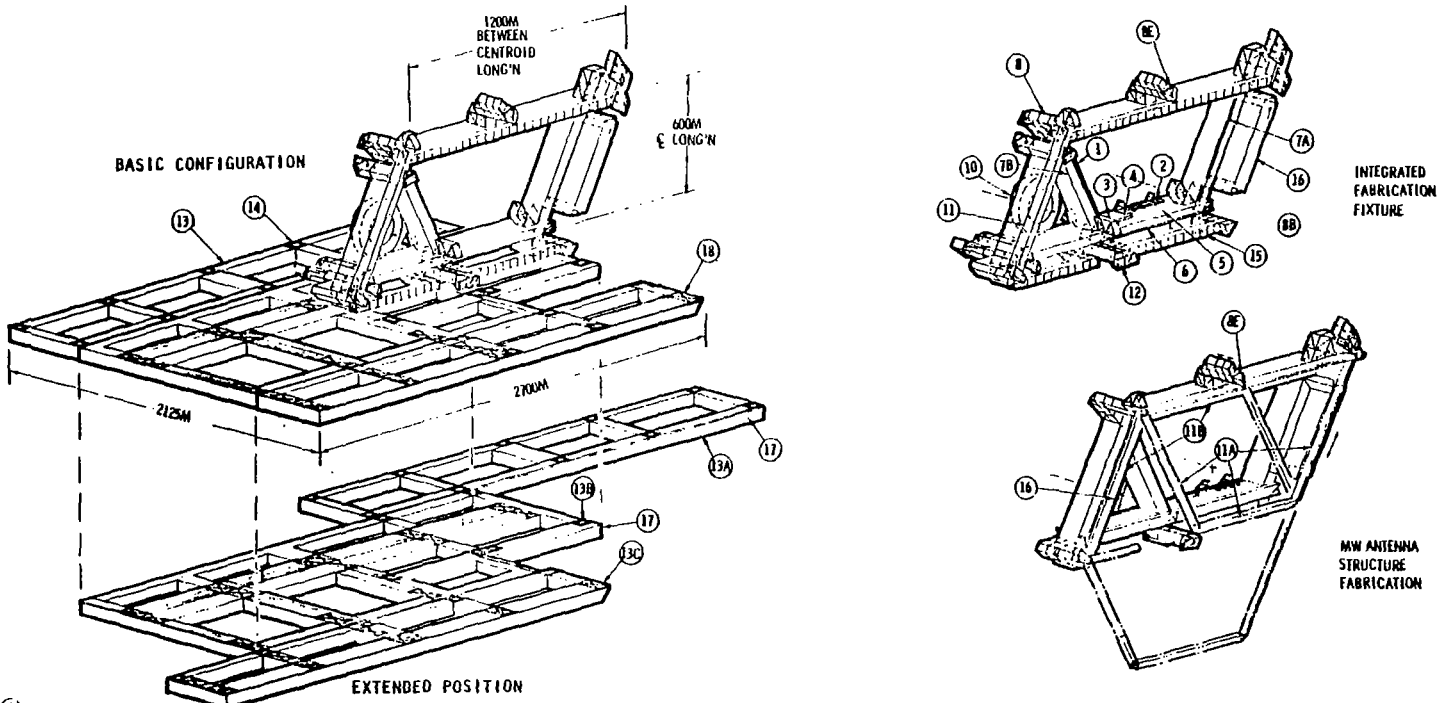


Figure 11. Satellite Construction Approaches

Elevating frame attach fittings are used to secure the platform to the partially completed satellite to permit movement of the facility relative to the satellite. Such a movement is required as each longitudinal bay is completed. Details of the location of the elements of the fabrication facility also are shown in Figure 12. The key to the numbers indicate the elements comprising the facility. All elements of the satellite are constructed in this facility, including the solar array and the microwave antenna. The structure is comprised of 50 m tribeams that are in turn built up from 2 m basic beam elements as shown in Figure 13. More detail on facility functions and design will be presented in a subsequent section.

The single-pass construction facility is shown in Figure 14. This facility does not require a translating platform because it never has to translate laterally relative to the satellite. All of the construction functions occur simultaneously in the longitudinal direction for all three troughs. The solar blankets are installed by means of dispensers which are located along the bottoms of the troughs. The reflector dispensers are located on the diagonals of each trough. The longitudinal tribeams are continuously manufactured in the tribeam facilities. Lateral tribeams are simultaneously manufactured to the proper length and are attached to the longitudinals.

The differences in facility mass, crew sizes, construction equipment, and construction complexity for the serpentine and single pass construction concepts are shown in Table 6. The satellites evaluated consist of three and four trough configurations with either an end-mounted or center-mounted antenna. (The effect of this variation on the construction time, crew size and supporting equipment is negligible.) The relative complexity considers the operations attendant to fixture and platform translation required for serpentine construction as opposed to the single pass concept. The crew sizes reflect average manloading, since the sequence of construction operations (particularly for the single pass concept) permits return of some personnel to earth prior to satellite completion. Support equipment requirements (e.g., tribeam fabricators) vary with the construction concept. For single pass construction, all troughs are completed simultaneously instead of in series. However, the serpentine fixture is required to operate from both sides, which requires two sets of dispensing equipment. The serpentine method results in a smaller crew size, and in general, less supporting equipment. The SCB mass for the two concepts is essentially the same. The



(1) CONSTRUCTION FIXTURE
(2) MAIN SUPPORT FACILITIES & EQUIPMENT
(3) WAREHOUSE
(4) CARGO RECEIVING
(5) POTV DOCKING
(6) SOLAR BLANKET & PDS INST STATION
(7A) 2 REFLECTOR INSTALLATION STATIONS ON UNDERSIDE (+X) OF DIAGONAL
(7B) 2 REFLECTOR INSTALLATION STATIONS, ONE EACH ON +Y & -Y SIDE OF DIAGONAL BRACE
(8) BEAM FAB/INST WORK STATIONS
(8A) LONGERON TRIBEAM FABRICATORS, +Y (3 PLACES (5 PLACES FOR TROUGH 1))
(8B) LONGERON TRIBEAM FABRICATORS, -Y (3 PLACES (5 PLACES FOR TROUGH 1))
(8C) DIAGONAL TRIBEAM FABRICATORS, (2 PLACES (3 PLACES FOR TROUGH 1))
(8D) TRANSVERSE BEAM FABRICATORS (3 PLACES)
(8E) ANTENNA FRAME TRIBEAM FABRICATORS (6 PLACES)
(9) INTRABASE LOGISTICS VEHICLES
(10) ROTATING JOINT ASSEMBLY FIXTURE
(11) ANTENNA FRAME FAB FIXTURE
(11A) LOWER HALF
(11B) UPPER HALF
(12) CONSTRUCTION FIXTURE TRANSLATION CARRIAGE (3 PLACES)
(13) TRANSLATION PLATFORM
(13A) SECTION A
(13B) SECTION B
(13C) SECTION C
(14) ELEVATING FRAME ATTACH FITTING (18 PLACES)
(15) RF ASSY & INST STATION (2 PLACES)
(16) ANTENNA TRANSLATION GUIDEWAYS (2 PLACES)
(17) PLATFORM SLIDING GUIDEWAYS (2 PLACES)
(18) FACILITY TRAVELWAY
(19) INTEGRATED FABRICATION FACILITY

Figure 12. Serpentine Satellite Construction Base (SCB)

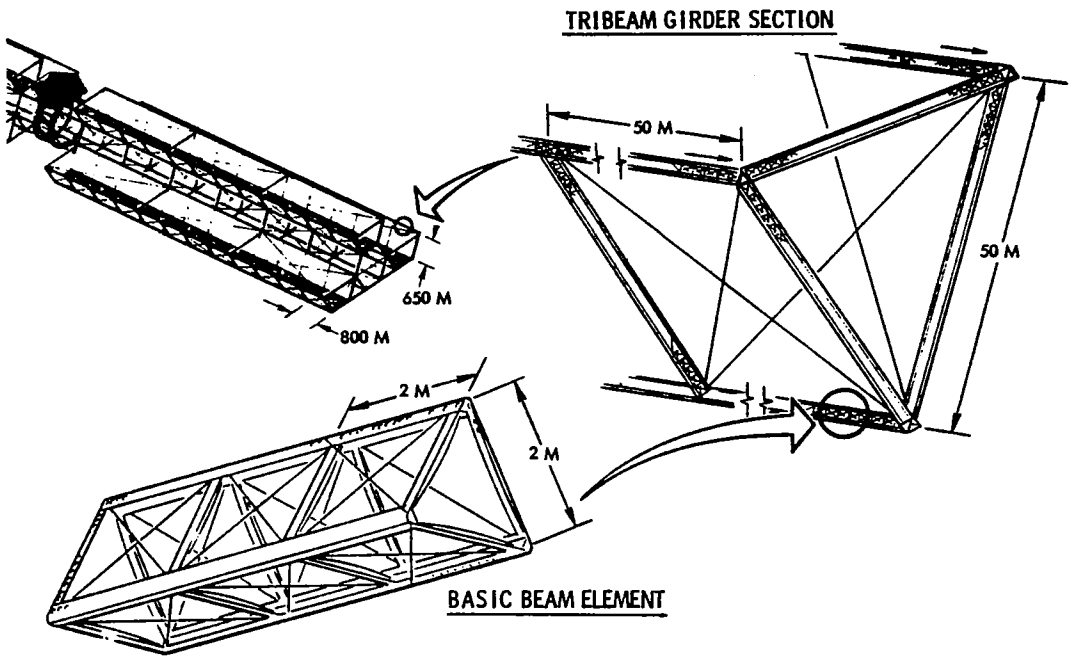


Figure 13. Overall Structure Concept

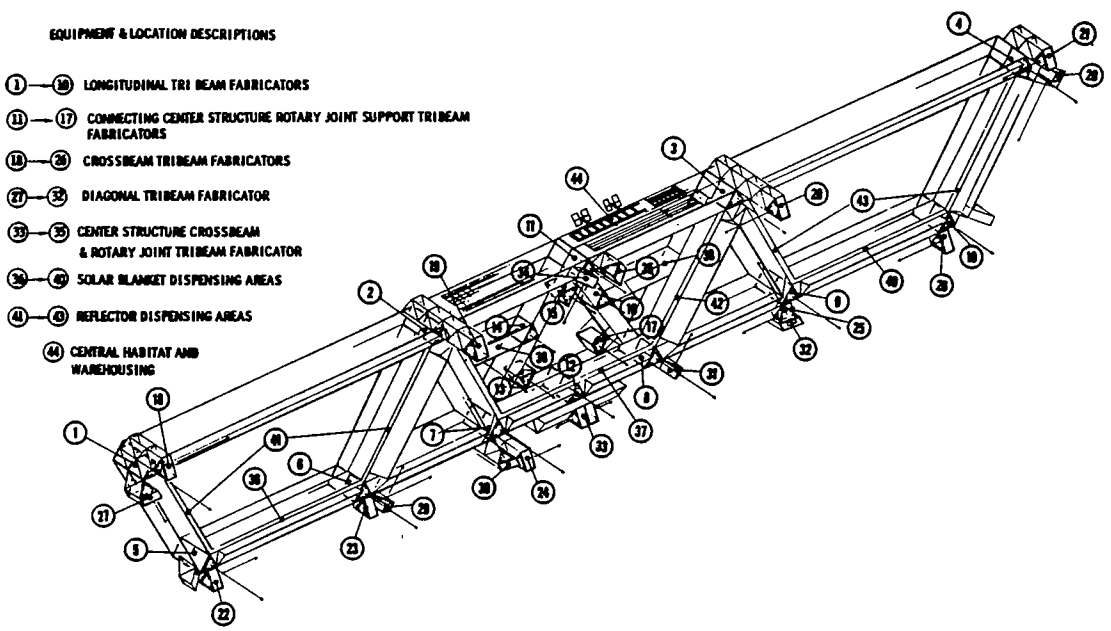


Figure 14. Single-Pass Satellite Construction Base (SCB)

Table 6. Constructability Comparison (180 Day Construction Schedule)

CONSTRUCTION CONCEPT	SATELLITE CONFIGURATION	PASSES	CONST. COMPLEX	CREW SIZE (AVG)	SCB MASS KG x 10^{-6} *	BEAM FABRICATORS		FREE-FLYERS		MANNED MANIP. MODULES	CREW/CARGO LV'S
						SOLAR CONV.	ANTENNA	SOLAR CONV.	ANTENNA		
MULTI-PASS SERPENTINE	FOUR TROUGHS	4	6	266	5.2	22	4	4	6	16	5
	THREE TROUGHS	3	4.5	266	5.2	22	4	4	6	16	5
SINGLE PASS	FOUR TROUGHS	1	1.33	392	6.5	32	4	8	6	64	20
	THREE TROUGHS	1	1	332	5.3	24	4	6	6	48	15

*INCLUDES 25% GROWTH

platform accounts for a large percentage of the serpentine SCB mass. Precursor operations attendant to constructing a platform almost 3 km long in three sections which translate relative to one another are formidable. The sequence of translating these sections and the construction fixture many times during the construction of one satellite involves considerable operational complexity and risk. In addition, the concept involves several sequences of securing and releasing the platform to and from the partially completed satellite structure (2 meter tribeam sections) by means of elevating attach mechanisms. Detailed study will be required to evaluate the feasibility of this operation relative to the stress concentrations involved. For these reasons, the single pass concept is preferred.

Satellite Construction Concept Description. The following provides a more detailed description of the construction concept for an end-mounted space-frame antenna concept using the preferred single-pass construction base concept. First, the overall concept is described followed by a description of the antenna and solar array construction processes. Additional details for center-mounted antenna concepts and for serpentine construction are contained in Volume 5 of this report.

Overall Concept. Figure 15 presents the timeline and sequence of construction functions. Figure 16 illustrates the sequence of events. The construction facility, previously shown in Figure 14 initially constructs the rotary joint. A small, separate facility completes construction of the antenna section. The main construction facility then constructs the solar array section. The timeline used for this sequence assumes that total construction is accomplished in 180 days.

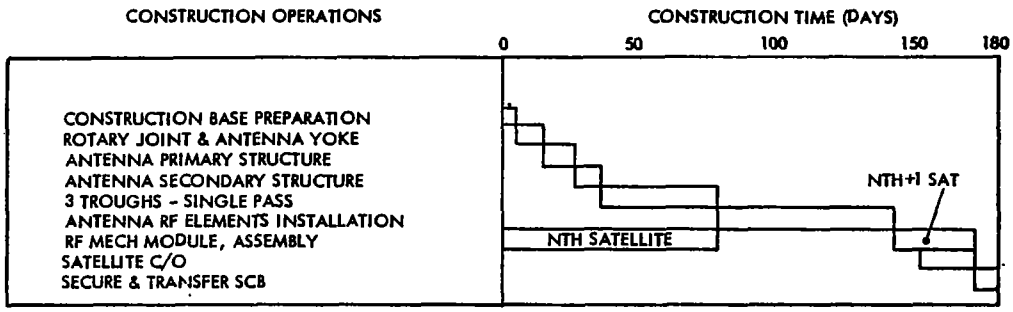


Figure 15. Construction Timeline

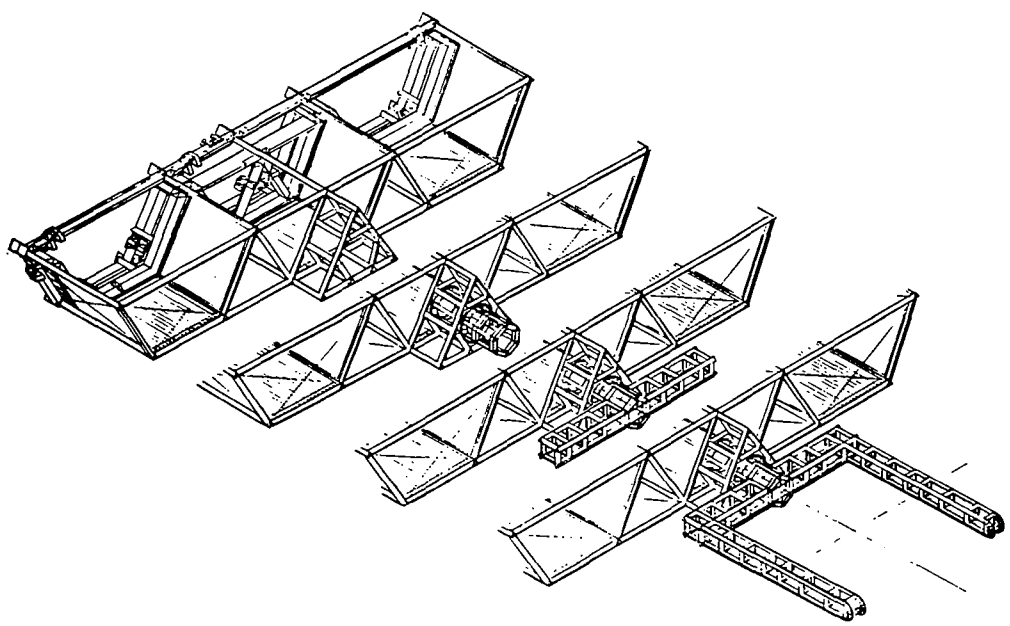


Figure 16. Sequence of Construction Events

Antenna Construction. The sequence of antenna supporting structure construction operations is shown in Figure 17. Initially, the yoke base is constructed in place across the face of the rotary joint utilizing a beam fabricator (or two beam fabricators working in opposite directions) which is free flown from its storage location on the SCB into its initial position and attached to the slip ring structure. Upon completion of the yoke base, the beam fabricator is repositioned to construct each yoke arm as shown. The strengthening ties at the corners are fabricated elsewhere in the facility and moved into place. Following completion of the yoke arms, a beam fabricator is used to construct the gantry utilizing the yoke base as a platform. The gantry is then attached to tracks on the yoke arms. Elevating mechanisms at each end of the gantry provide for moving it within the yoke as required in antenna construction and RF mechanical module installation operations. The elevating mechanisms also provide for moving the gantry clear of the antenna for stowage along the yoke base when not in use. During operations, the gantry is used for antenna maintenance.

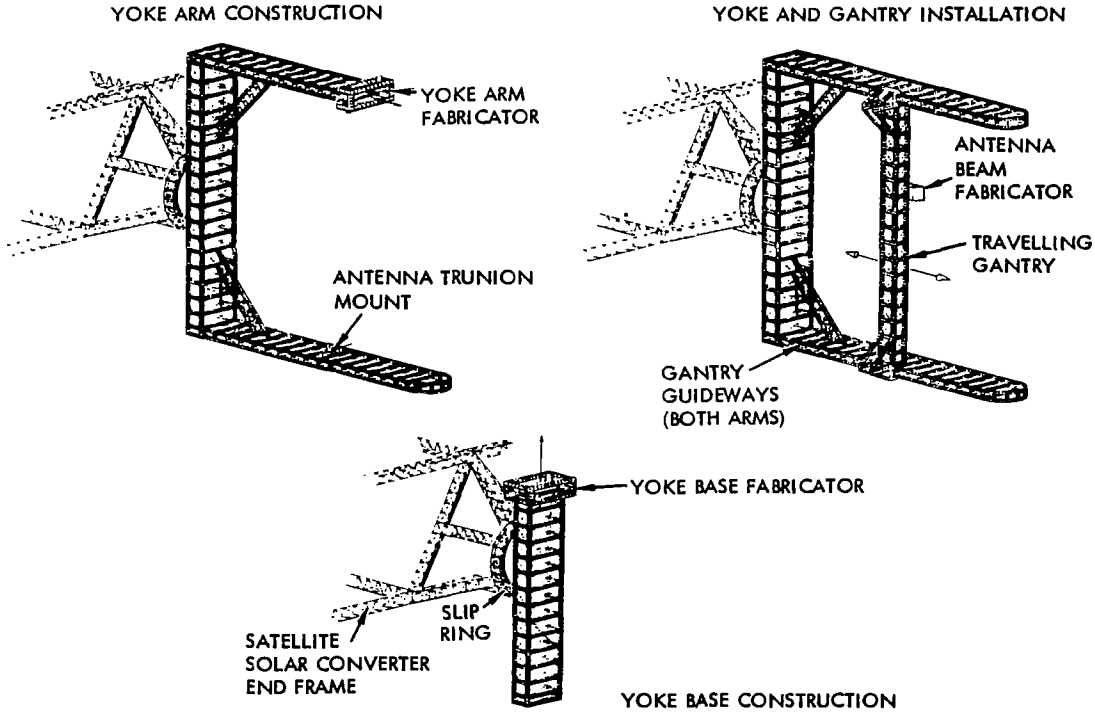


Figure 17. Antenna Supporting Structure Fabrication

The antenna primary structure is constructed by beam fabricators mounted to the lower side of the gantry as shown in Figure 18. Initially, the antenna center beam structure, which attaches to the trunnions, is fabricated and installed in the trunnions which are then locked into position. Following this operation, the gantry-mounted fabricator progresses outward from the center beam, completing one-half of the structure, in successive passes. The

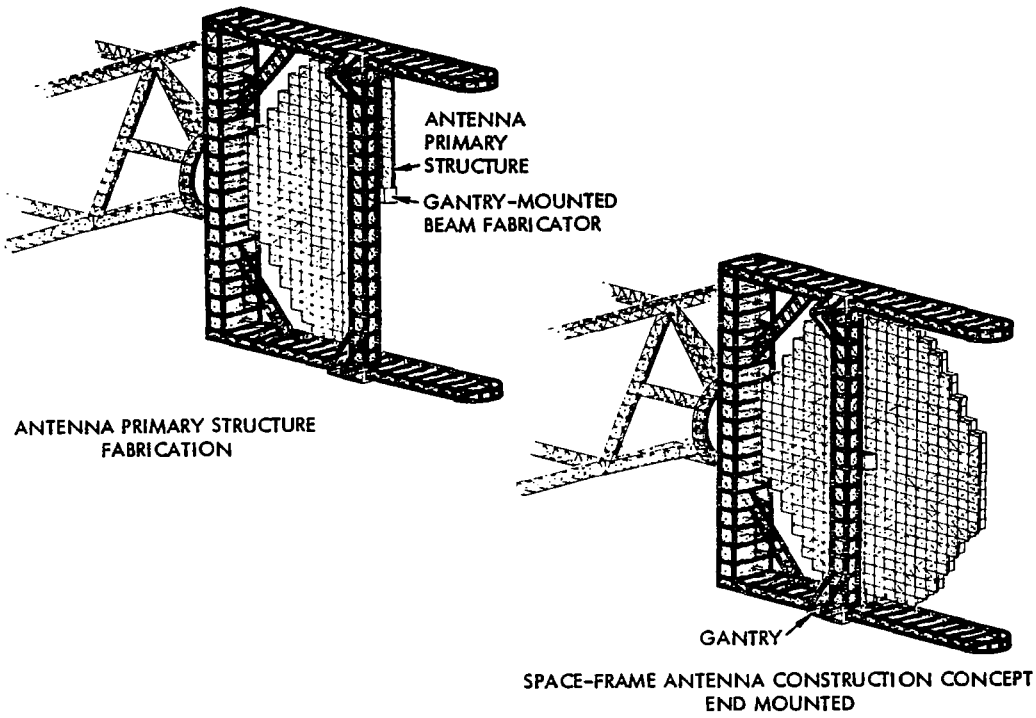


Figure 18. Antenna Primary Structure Fabrication

gantry is then relocated and the fabricator constructs the remaining half of the antenna. After removal of the fabricator, the gantry is used for installation of secondary structure and RF elements.

Solar Array Construction. Figure 19 illustrates the near-completion of one of the three bays of the satellite with a section of the outside reflector panels cut away. It can be seen that the solar blankets are laid out in horizontal strips but that the reflector panels are vertically oriented. The structure of an 800-meter bay is estimated to take one 8-hour shift to fabricate. During this time, the solar blankets are "played out" - from 25-meter rolls - and edge-attached to longitudinal lines of composite materials; the reflectors are unfurled and also loosely constrained by vertical lines. Upon reaching the end of a bay, the construction facility is stopped and, during the next five 8-hour shifts, the cross frame members are attached, the solar blankets are secured and the reflector panels are tensioned.

The reflector panels, measuring 600×800-m, are pleated at 25-m intervals to produce an accordian type fold as shown in Figure 20. They are then rolled along the plane of the end pleat into a roll 25-m long and 1.2-m diameter which is the configuration for transporting into orbit.

When installed, each reflector panel is suspended within the 800-m bay by longitudinal catenaries attached to the upper and lower longerons and by leading and trailing edge catenaries attached to the forward and aft diagonal

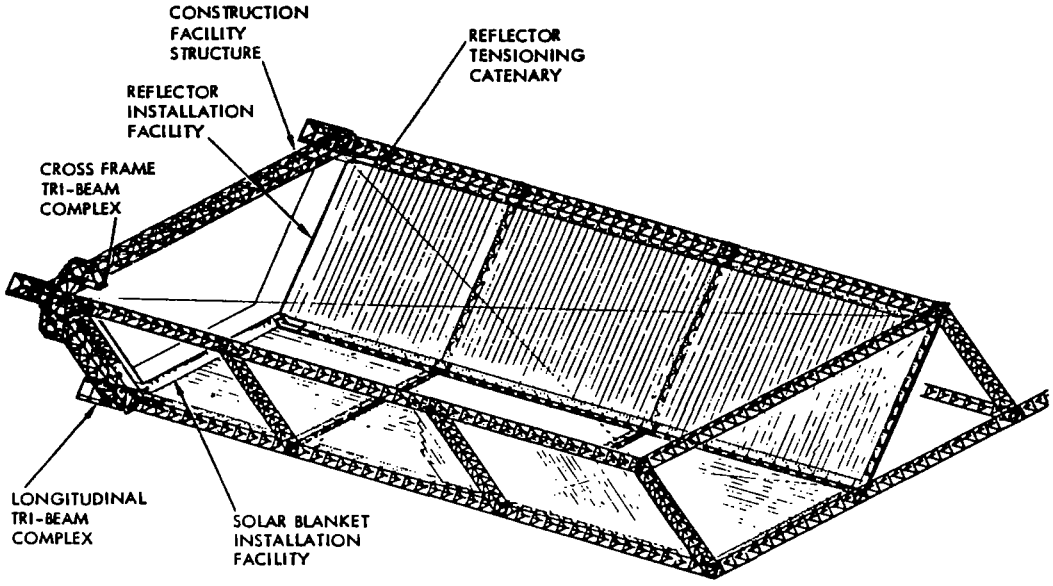


Figure 19. Typical Solar Array Bay Construction

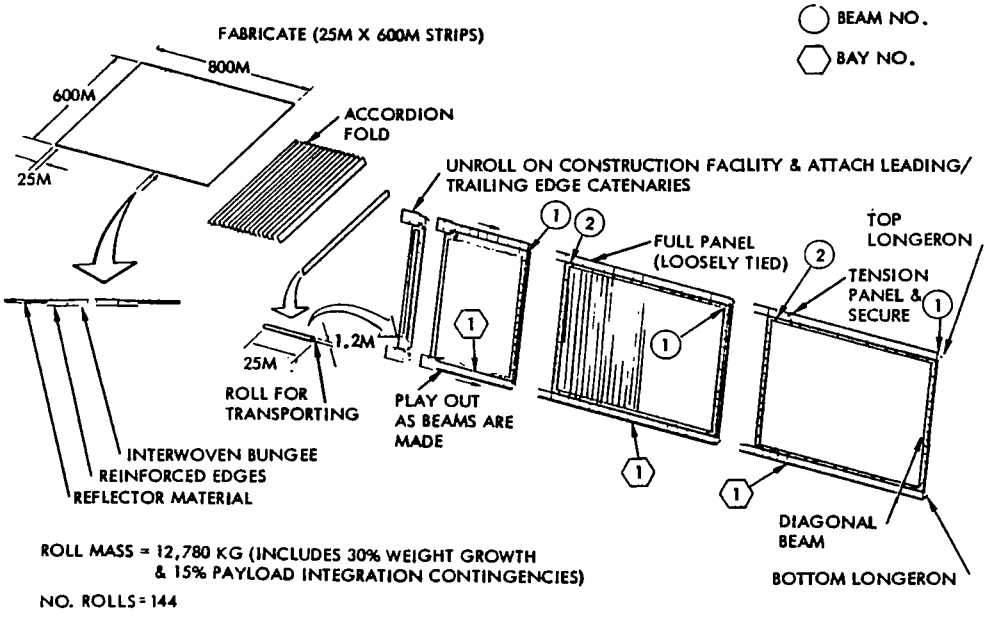


Figure 20. Reflector Packaging and Installation

members of the transverse frames. The catenaries are attached to the trailing and leading diagonal transverse beams and to the longerons. Two panels are required for each 800-m bay of each trough.

Figure 21 shows the installation concept for the solar cell blanket. The solar blanket in each 800 m long bay is a structurally independent installation suspended by side and end catenaries attached to the longerons and cross beams, respectively, and by longitudinal cables stretched between the blanket strips. Each blanket strip is approximately 25 m wide and 750 m long, and is packaged in a 25 m wide roll by 0.6 m in diameter. Each two bays of solar blankets are electrically connected in series, constituting a functional module which produces the required voltage.

Initially the blanket rolls are transported from the SCB warehouse area by a transporter/loader (1) which inserts the rolls into the dispensers (6). The leading edge of the blanket strips, with end catenaries attached, are then threaded through the roller arrangement and attached to the trailing edge of the completed crossbeam. The longitudinal cables to which the side edges of the blanket will be fastened are threaded from the cable dispenser (13) and attached in a similar manner. The longitudinal catenaries are fabricated on the middle deck, fed into the dispensing spindle (15) and then attached to the crossbeam trailing edge.

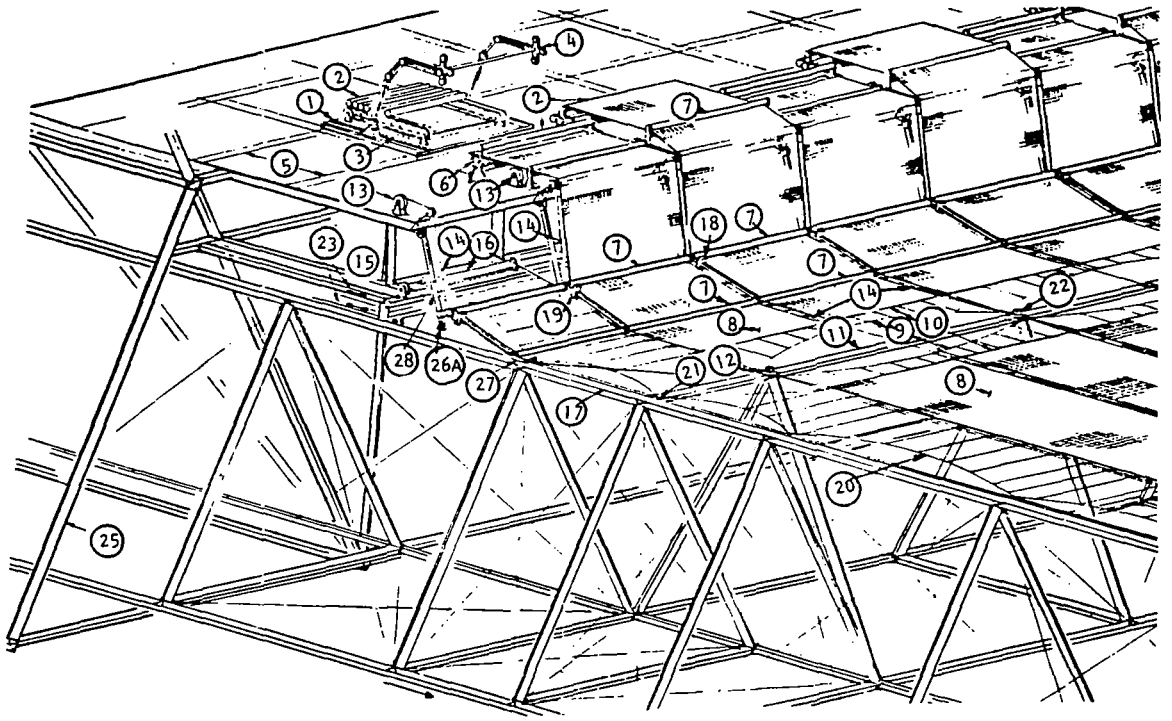
Solar blankets and catenaries are attached to the longitudinal cables by foldover tabs which are applied by automatic fastening equipment. As the crossbeam advances the blanket strips, longitudinal catenaries and cables are payed out. The two outside cables are attached to the longitudinal catenaries, the two longitudinal catenaries to their respective longerons, and the inside edges of adjacent blanket strips to their stabilizing cables. Upon completion of the bay and the next following crossbeam, the trailing edges of the blankets (i.e., the trailing transverse catenaries) and the trailing end of the longitudinal catenaries are attached to the leading edge of that crossbeam. The installation is then tensioned and electrical connections completed.

The primary operations occurring at the upper, middle, and lower deck stations during beam fabrication and solar array installation are identified in Figure 22. The locations of the manned manipulator modules (MMM) required to support the installations also are shown. These modules are mounted on transverse tracks and are spaced so that each module services approximately one-fourth of the 27 installation stations across the span of the crossbeam. Approximately 600 men are required, on the average, to operate the SCB.

Satellite Construction Base Construction

Because of the large size of the SCB, it is necessary to define the approach to its construction starting with the basic space shuttle resources and elements that can be brought up from earth in the shuttle. A detailed study of this process was conducted, including an overview of the total build-up to start the satellite construction process at geosynchronous orbit.

The overall sequence of events is illustrated in Figure 23. The initial step in satellite precursor operations is establishment of a LEO base as shown in the lower left of the figure. Crew and power modules are transported to LEO by Shuttle derivatives and assembled. When the base is fully operational, Shuttle external tanks are delivered and mated to form construction fixtures for SCB construction. Figure 23 shows a completed SCB. Since the more



① S/A BLANKET ROLL TRANSPORTER/LOADER
② S/A BLANKET ROLLS
③ USED ROLL CORES
④ BLANKET ROLL INSTALLER/REMOVER
⑤ TRANSPORTER TRACKS
⑥ S/A BLANKET DISPENSING PINDEL QUAD
⑦ BLANKET STRIP GUIDE ROLLERS
⑧ DEPLOYED SOLAR BLANKET STRIP
⑨ LEADING TRANSVERSE CATENARY
⑩ BLANKET STRIP/TRANSVERSE CATENARY JOINT LINE
⑪ UPPER VERTEX OF SATELLITE (50-M TRIBEAM GIRDER) CROSS BEAM
⑫ TRANSVERSE-CATENARY-TO-CROSS BEAM ATTACH POINT
⑬ LONGITUDINAL CABLE DISPENSER
⑭ LONGITUDINAL CABLE
⑮ LONGITUDINAL CATENARY DISPENSING SPINDEL
⑯ LONGITUDINAL CATENARY ROLL
⑰ UPPER VERTEX OF SATELLITE (50-M TRIBEAM GIRDER) LONGERSON IN BOTTOM CORNER OF TROUGH
⑱ BLANKET-EDGE-TO-CABLE ATTACH MACHINE
⑲ BLANKET-EDGE-TO-LONGITUDINAL CATENARY ATTACH MACHINE
⑳ DEPLOYED LONGITUDINAL CATENARY
㉑ CATENARY-TO-LONGERON ATTACH POINT
㉒ SWITCH GEAR MOUNTED ON CROSS BEAM
㉓ RETRACTING PLATFORM FOR SWITCH GEAR AND SECONDARY FEEDER INSTALLATION
㉔ MAIN FEEDER DISPENSER
㉕ CONSTRUCTION FIXTURE
㉖ TRANSVERSE CATENARY-TO-CROSS BEAM ATTACH MACHINE IN ATTACH POSITION; 26A, NON-ATTACH POSITION
㉗ LONGITUDINAL CATENARY-TO-LONGERON ATTACH MACHINE IN ATTACH POSITION; 27A, NON-ATTACH POSITION
㉘ ATTACH EQUIPMENT TRANSLATING SUPPORT ARM
㉘A TRANSLATING ARM IN CATENARY-TO-CROSS BEAM ATTACH POSITION
㉙ CROSS BEAM (50-M TRIBEAM GIRDER) FABRICATION FACILITY IN BEAM FABRICATION POSITION
㉙A 50-M CROSS BEAM IN FABRICATION POSITION

Figure 21. Solar Array Installation Concept

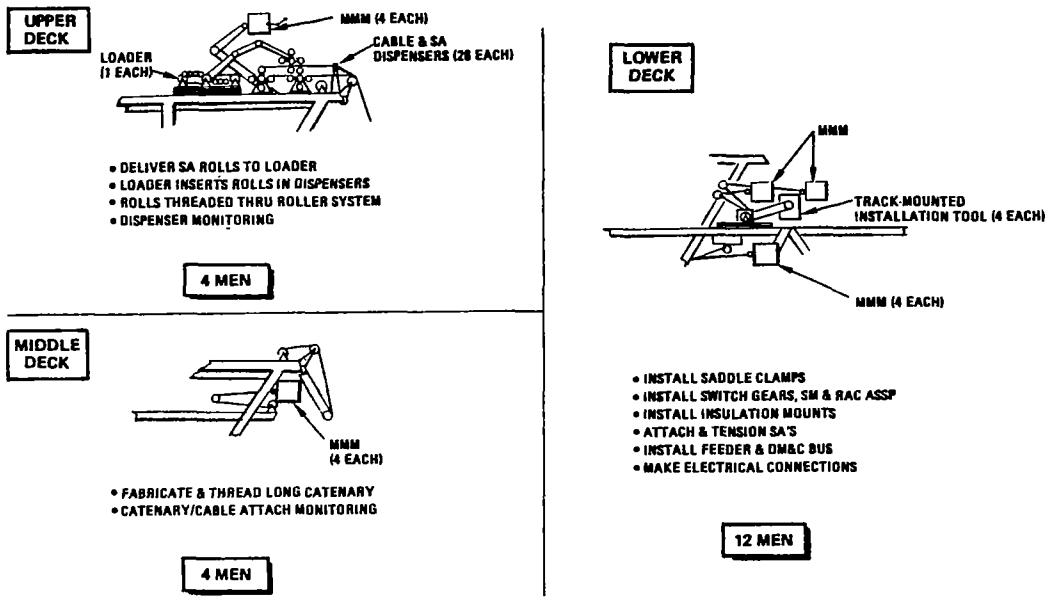


Figure 22. Manned Operations at Solar Array Installation Stations

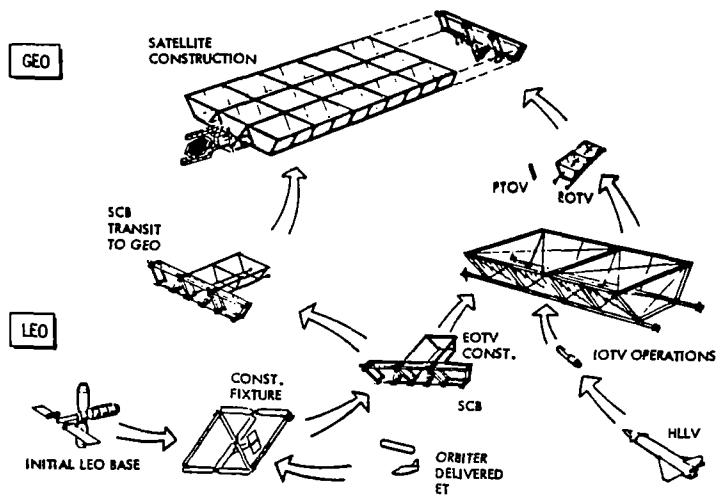


Figure 23. Overall Satellite Construction Scenario

economical HLLV will not be available and since overall plans specify an EOTV test vehicle, it is probable that only the center trough of the SCB would be constructed initially. This trough would be used to fabricate the pilot plant EOTV with antenna. After proof of concept and SPS go-ahead, the remainder of the SCB would be completed, the fleet of EOTV's constructed, and the SCB transferred to GEO, using one or more EOTV's for propulsion and altitude control. Upon reaching GEO, satellite construction would commence, with the logistics support as shown at the right of the figure.

Two basic fabrication facilities are necessary to construct the SCB: a triangular element fabrication facility and a mobile 79 m girder fabrication facility. These facilities are illustrated in Figures 24 and 25.

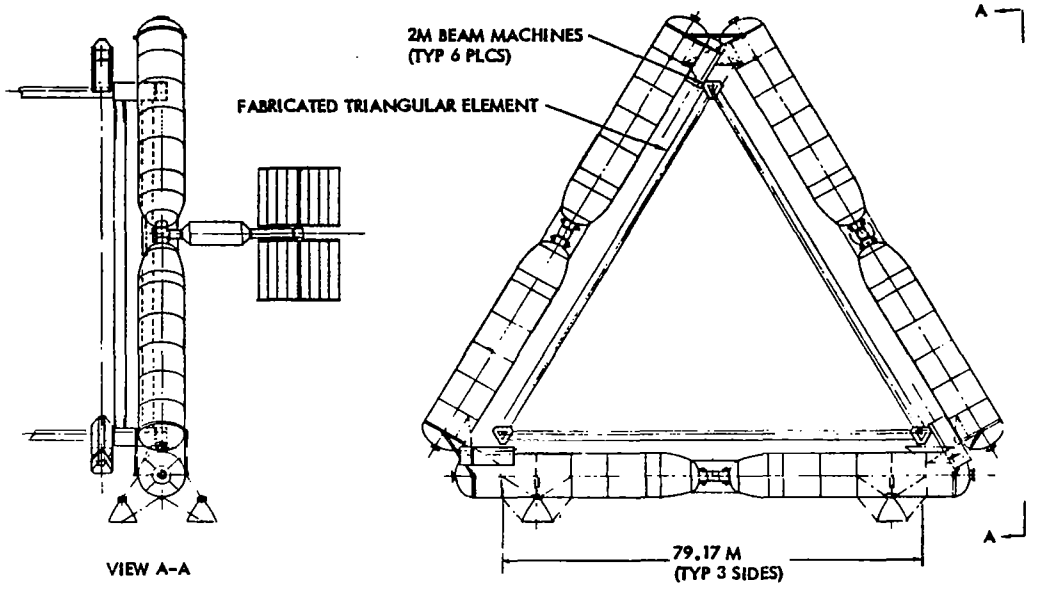


Figure 24. Triangular Element Fabrication Facility

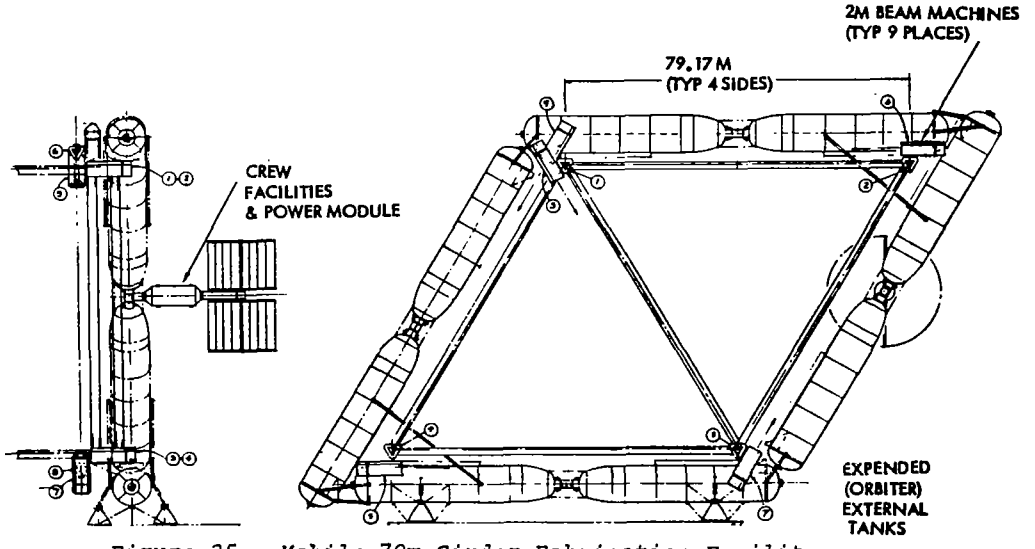


Figure 25. Mobile 79m Girder Fabrication Facility

The triangular element fabrication facility produces the longitudinal and crossbeam pods which will be installed in the SCB for subsequent construction of EOTV and satellite tribeams. It is comprised of six shuttle external tanks (ET's) joined together as shown. The structure which attaches the orbiter to

the aft section of the ET is utilized for joining the ET's and is augmented by prefabricated bracing delivered by the orbiter. A triangular element comprised of 2 meter tribeams is mounted within the triangle formed by the ET's and provides the structure required for mounting the 2 meter beam machines which are used for constructing the outer triangle of the tribeam pod, or fabricator. A total of six beam machines are required; three for longitudinal beams and three for crossbeams. Crew facilities and power module, shown at the left of the figure, provides crew habitat and the electrical power required to operate life support and the beam machines. Reaction control pods attached to the ET's provide the required altitude control.

The primary structure of the SCB consists of a diamond cross section formed by two triangles. A mobile diamond-shaped fixture formed by joining 8 orbiter external tanks is utilized for SCB primary structure fabrication. The beam machines are located at the tips of the structure enclosed by the external tanks. Nine machines are required to construct the four longerons, the four crossbeams and the diagonal beam. A combination crew and power module provides crew facilities and electrical power.

These two basic facilities are used to construct the SCB, which is comprised of primary and secondary structure. Figure 26 shows the SCB primary structure in the final phases of construction. The tribeam facilities have been constructed using the triangular element fabrication facility and the main structure has been fabricated using mobile 79 m girder fabrication facilities. This figure shows the two remaining diagonals being fabricated by mobile girder fabricators. Figure 27 shows construction of the secondary structure which is cantilevered off of the primary structure. In this figure, the central and left portions of the structure are almost complete. The beams comprising the right portion are shown in a partially completed state. When the secondary structure is completed, auxiliary bases are established at the bottom of each trough and the solar array installation equipment is installed.

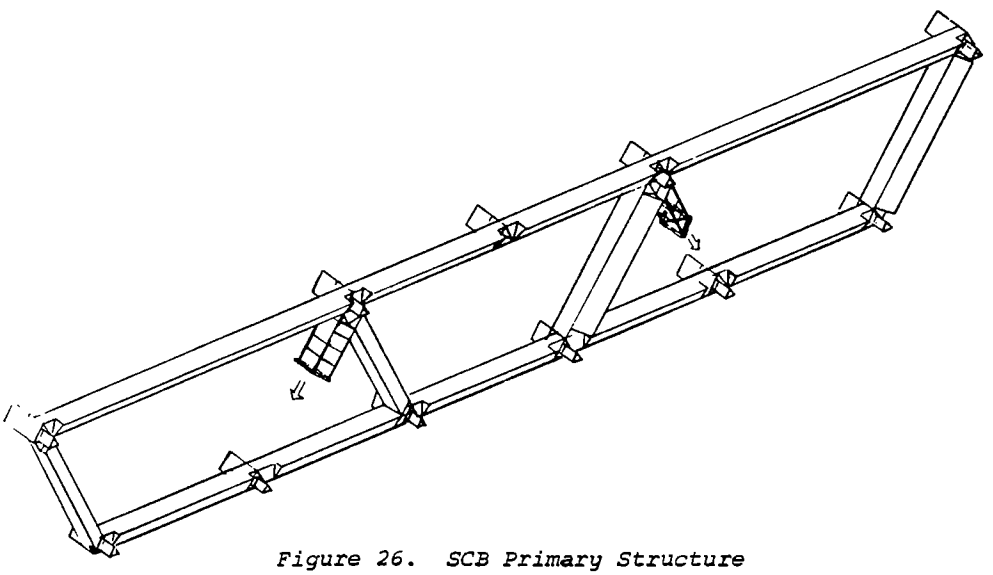


Figure 26. SCB Primary Structure

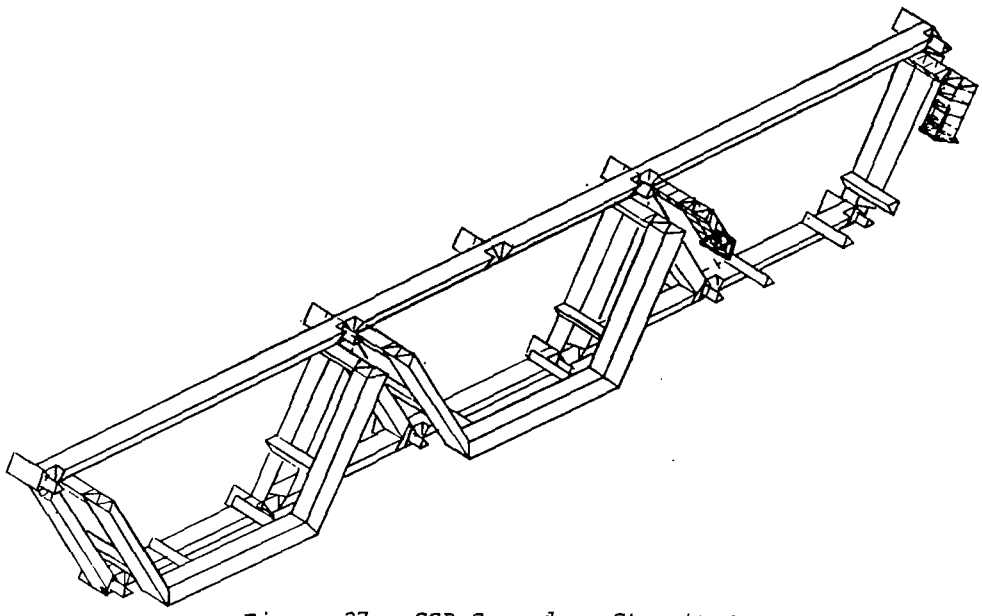


Figure 27. SCB Secondary Structure

Upon completion of the SCB in LEO, construction of the EOTV fleet can commence. Since the EOTV cross section is the same as one trough of the satellite, the SCB is utilized for the EOTV construction as shown in Figure 28. However, it is probable that the SCB would be used initially to construct an EOTV with end-mounted antenna as a test article for proof of concept. As was previously mentioned, it is likely that the SCB will not be completely constructed until after the proof of concept demonstration. Only the center portion would be built for this purpose. When it is fully constructed, the SCB could produce two EOTV's simultaneously as shown in Figure 28.

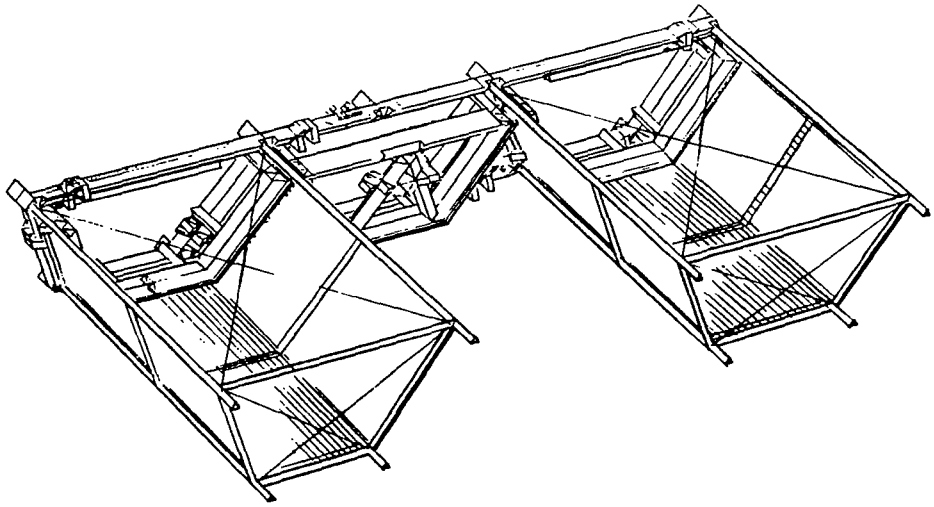


Figure 28. Parallel Fabrication of EOTV's

Following completion of the initial set of EOTV's required to bring cargo to initiate geosynchronous operations, an EOTV would be used to transfer the SCB from LEO to GEO as illustrated in Figure 29. Once in GEO, the SCB would be used to construct the satellites. When replacement EOTV units are needed, the replacement units can be constructed at geosynchronous orbit.

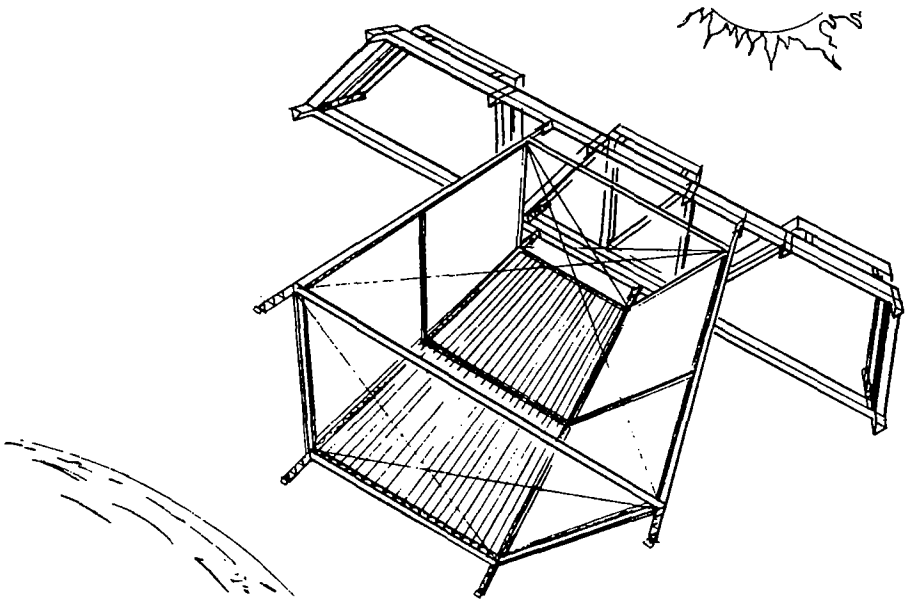


Figure 29. SCB Orbit Transfer Configuration

Rectenna Construction

The rectenna, which is located on the ground, intercepts the incoming microwave energy and transforms the RF energy to dc energy at very high efficiency (83.3%). Figure 30 shows the layout of a typical rectenna site. The portion containing the rectenna panels, shown as the dark elipse, is 10 km by 13 km. A series of power poles carrying 40 kV dc buses are located immediately outside the elipse. Towers carrying 500 kV ac also ring the elipse at a greater distance. Power conversion stations, which are used to convert from 40 kV dc to 500 kV ac are located between the two arrays of power transmission lines. The entire site is fenced in for security.

The eliptical rectenna area contains 1088 rows of rectenna panels which are typically tilted 40 degrees from the horizontal when the rectenna is located at 34° N latitude. A typical rectenna panel system and its supports are shown in Figure 31. The panel, measuring 14.69 m wide by 9.33 m high is comprised of a number of basic rectenna modules, measuring 9.33 m in length by 0.74 m in width, which are attached to a steel supporting structure comprised of horizontal hat sections attached to 4 vertical I-beams. The rectenna module, shown in Figure 32 is a phased array of bow-tie dipoles connected by a stripline. The rectenna modules are delivered to the rectenna site along with the fabricated supporting structure elements. Because of its large size, the rectenna panel is manufactured at the rectenna site. The panels are delivered to a panel installer,

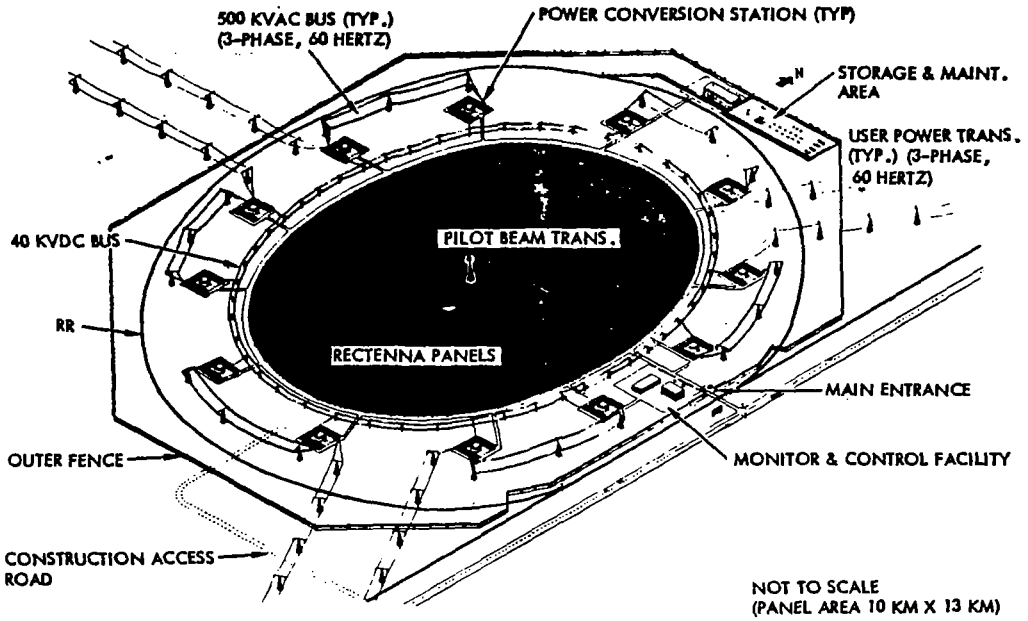


Figure 30. Operational Ground Receiving Facility (Rectenna)

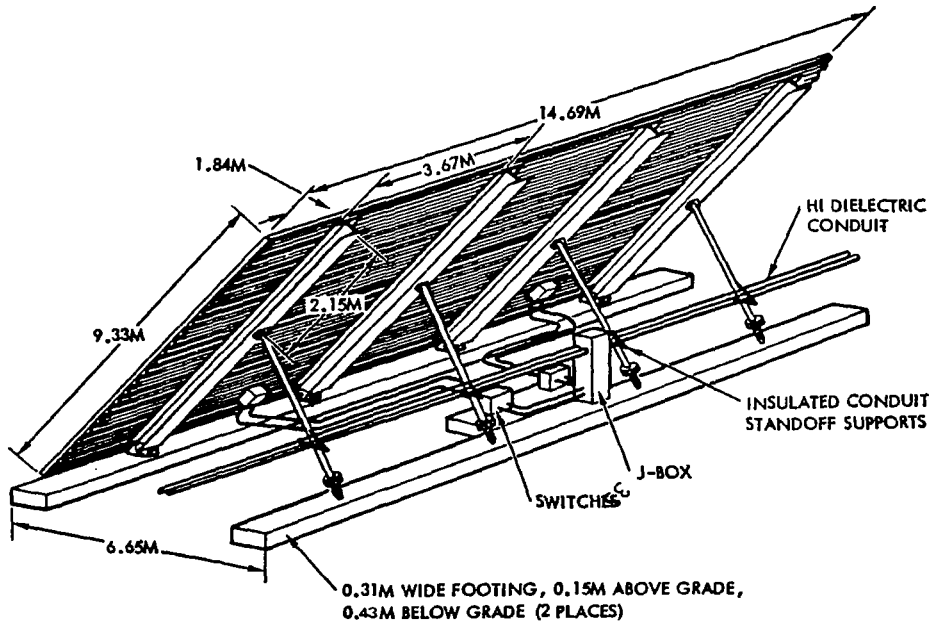


Figure 31. Panel Installation

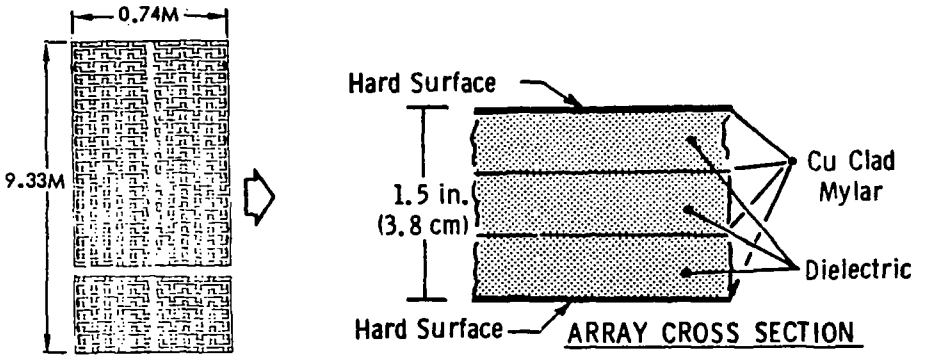


Figure 32. Typical Rectenna Module

shown in Figure 33, by a special-purpose delivery truck. The sequence of panel loading entails (1) elevating the installation machine to permit access by the delivery truck, (2) placement of the delivery truck, (3) securing the installation machine magazine retention mechanism to the panel magazine, (4) elevating the panel magazine to permit the delivery truck to depart, and (5) lowering the bottom panel into position for attachment to the footings. The panels are secured to two continuous concrete footings which are designed for a maximum wind velocity of 90 mi/h. Each panel is secured to the footings at eight locations by fixtures which are imbedded in the concrete during the pouring operation. Mounting attachments which provide for longitudinal and lateral adjustment are secured to the fittings. Screwjacks on each of the rear attach points provide for panel adjustment and alignment. The panel switchgears and feeder lines are mounted above ground behind each panel as shown, although it is recognized that either above or below ground runs for the feeders is feasible.

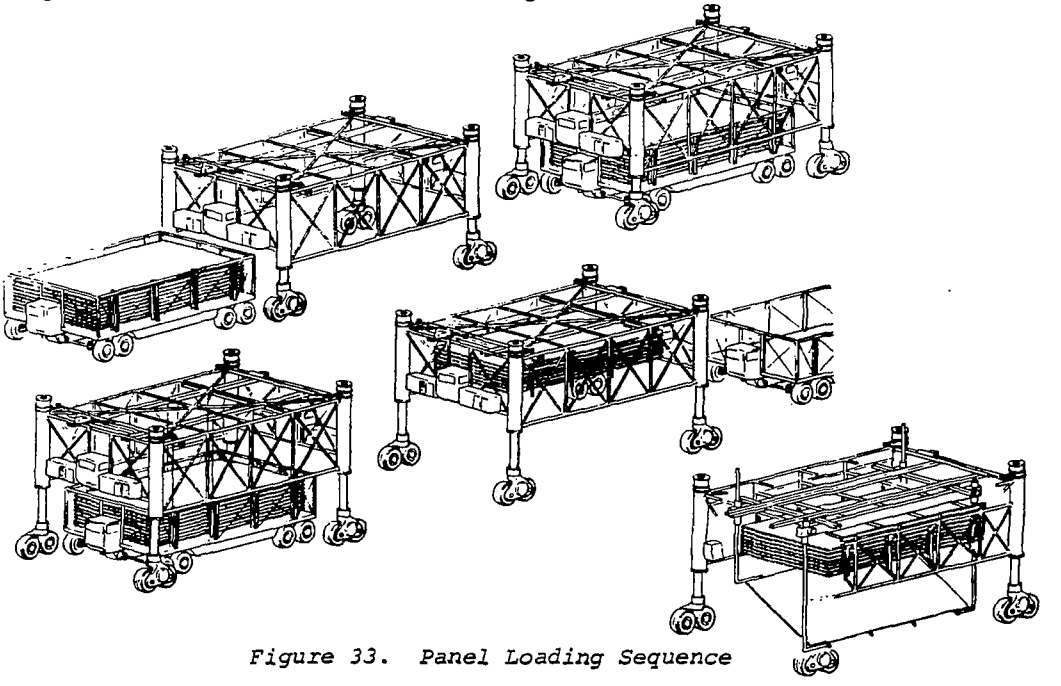


Figure 33. Panel Loading Sequence

Nine major activities involved in rectenna site construction are illustrated in Figure 34. Starting from left to right, the site must be surveyed, utilities and other supporting facilities installed, reference coordinates laid out, and the site cleared and leveled. Following this, more precise grading of the actual panel rows is conducted, footing trenches excavated, concrete poured, and the panels installed. The 40 kV dc and 500 kV ac periphery buses must then be installed, separated by the connecting converter stations.

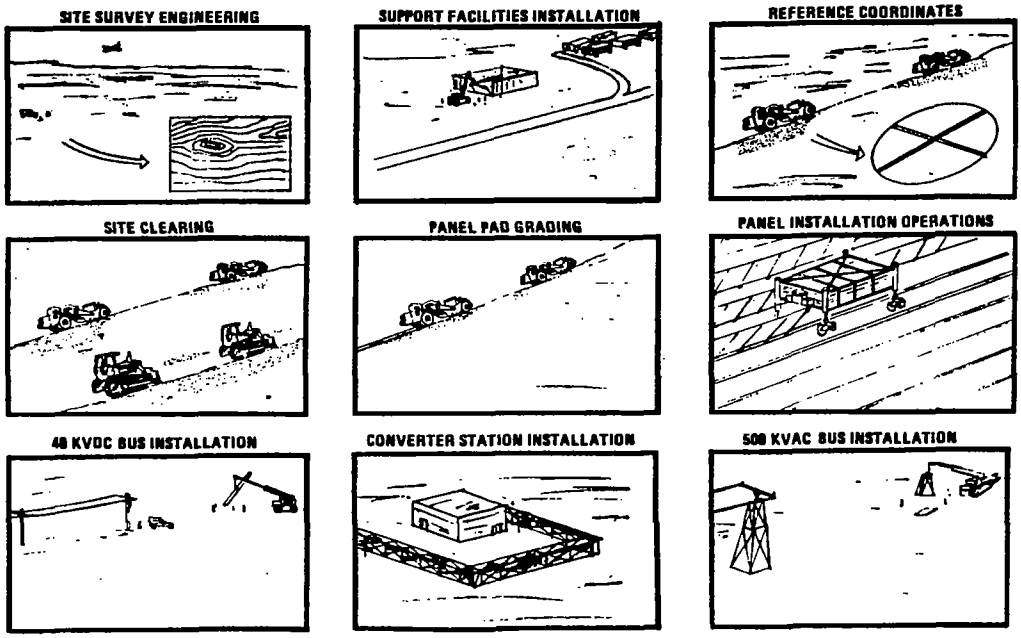


Figure 34. Rectenna Construction Sequence

Approximately 330,000 switchgears, 10^7 meters of feeder cables, miscellaneous junction boxes, and other equipment must be delivered and installed at the panel sites. Tractor/trailor trucks, shown in Figure 35, are used for this purpose and proceed through the panel rows, delivering material at each panel. Additional trucks with reels payout the feeders, which then are installed in conduits and spliced to panel connections by the electrical installation crews. California-Edison data indicate a requirement of 8 man-hours to hookup one panel and form the basis for installation crew sizing.

Construction is predicted to occur over a time span of approximately 15 months. The construction schedule, shown in Figure 36, assumes that site selection already has been made and that land acquisition has been completed. The overall approach, after installation of utilities and support facilities, entails clearing and grading in sections, followed by footing excavation, concrete pouring, and panel installation.

Rectenna mass, crew requirements, and equipment needs are summarized in Table 7. Approximately 85% of the total 1207×10^6 kg attributed to panels is steel. The concrete requirements, approximating the volume of Hoover Dam, are

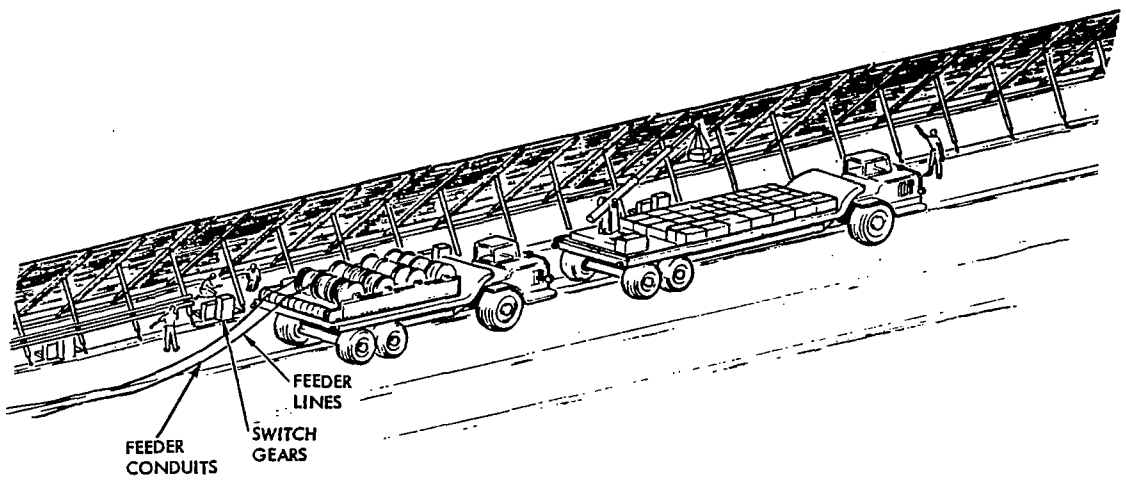


Figure 35. Electrical Installation and Hookup

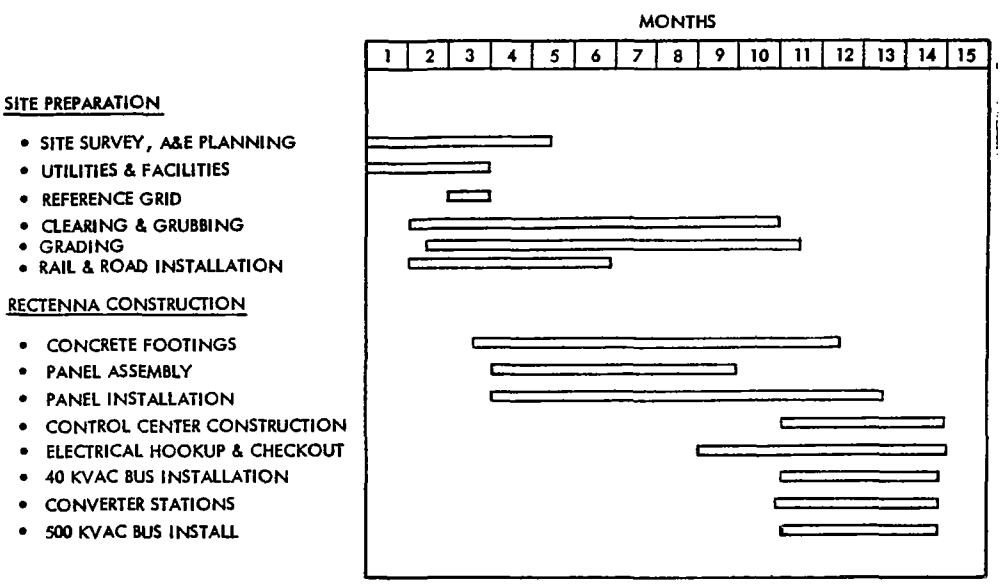


Figure 36. Rectenna Site Construction Schedule

predicated on a 90 mi/h wind directly on all of the panels. Since the panels become self-shielding, more detailed analysis may result in a lowering of this requirement.

Of the equipment, electrical installation trucks (panel trucks) and concrete trucks comprise the greatest numerical requirement. All equipment, with the exception of installers and trucks used to deliver and install panels, is of current design and in service.

Table 7. Construction Summary

• SCHEDULE: 15 MONTHS		
RECTENNA MASS -	PANELS	1207×10^6 kg
	CONCRETE	7176
	FEEDERS	1
	REINFORCE STEEL	51
		8435×10^6 kg
• CREW		
SHIFT SIZE		2474
TOTAL CREW FOR 24 HR/7 DAY OPERATION		9272
• EQUIPMENT		
SCRAPERS/GRADERS		67
DUMP TRUCKS		50
BULLDOZERS		50
CRANES		34
BACK HOES		17
TRACTOR/TRAILER TRUCKS		48
CONCRETE TRUCKS		190
CONCRETE POURING RIGS		10
PANEL INSTALLERS		40
PANEL MAGAZINE TRUCKS		14
ELECTRICAL INSTALLATION TRUCKS		229
MISC. JEEPS, PICKUPS, ETC.		

As a result of the rectenna construction studies, five general categories of problem areas were identified which affect rectenna construction. Site characteristics could impact both crew/equipment requirements and the specified completion schedule. Approval of the environmental impact and other permits have required up to five years lead time for some projects. Site operational control is a necessary element of any undertaking of this size and has not yet been addressed. Lightning protection has been the subject of some study by Rice University, but no definite conclusions have been reached to date on the need for it or the impact on construction if it is needed. Finally, resources (men, equipment, material) for one site are significant and will require considerable advance planning for manpower availability, equipment build-up, and availability of the materials.

Space Logistics

An analysis was conducted to determine approaches to packaging the construction mass for delivery from earth to low earth orbit (LEO) in a heavy lift launch vehicle (HLLV) and from LEO to geosynchronous equatorial orbit (GEO) in an electric orbit transfer vehicle (EOTV). Additionally, a crew module was defined to carry the crew from earth to LEO and from LEO to GEO. The results of this analysis indicated that the HLLV, which carries 227,000 kg of payload, from ground to a 31.6° inclined LEO, can be fully loaded within the volume constraints for all flights. Personnel are carried to orbit in a growth version of the shuttle.

A detailed analysis of the mass flow was conducted and the results of this analysis are summarized in Figure 37, which shows the mass carried to LEO by the HLLV. This mass includes construction, maintenance and POTV and EOTV propellants. It is assumed that 2 SPS's are constructed each year. As shown, the construction mass is the primary mass. Because of the high specific impulse of the EOTV, propellant masses are only 20% of the total mass.

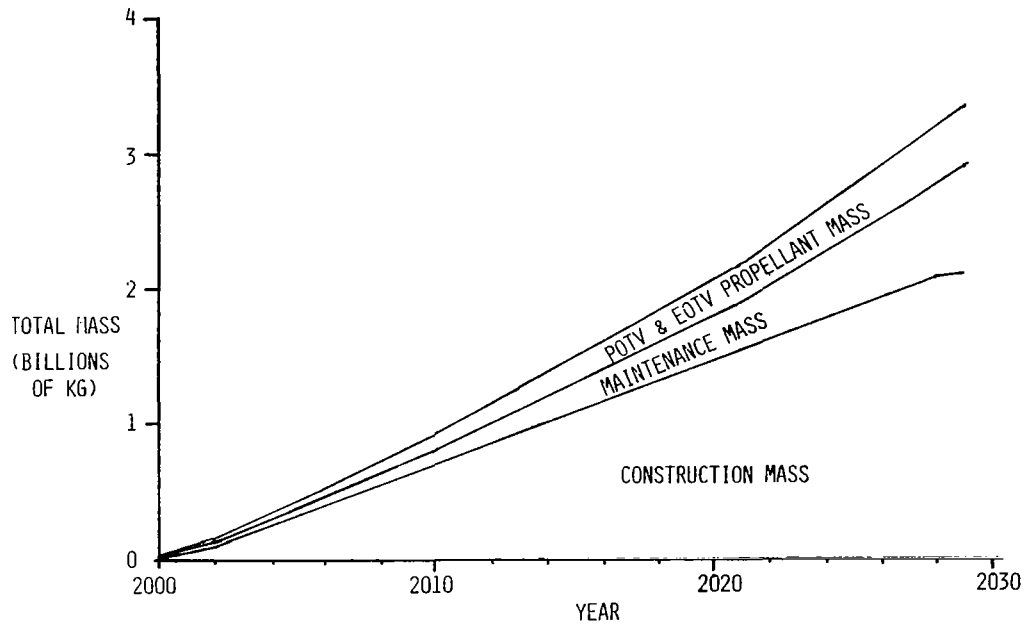


Figure 37. Mass Carried to LEO in HLLV

Crew mass is not included in this mass because the crew is carried to LEO in the shuttle. The construction crew, located at GEO, is composed of 600 men. Additionally, each operational SPS has a 30 man crew at GEO for maintenance. Finally, the LEO base has a 24 man crew. All crew members are rotated at 90-day intervals. The POTV, a LO_2/LH_2 propelled stage, is used to deliver the crew from LEO to GEO.

The construction, maintenance, and propellant masses shown in Figure 37 were used to determine yearly flights for the EOTV and HLLV. Personnel transfer rates were used to determine yearly POTV and growth shuttle flights. These rates are summarized in Table 8.

TRANSPORTATION SYSTEM STUDIES

The overall scenario for SPS space transportation is shown in Figure 38. Eight major elements comprise the transportation system: Shuttle, SPS heavy lift launch vehicle (HLLV), electric orbit transfer vehicle (EOTV), intra-orbit transfer vehicle (IOTV), personnel orbit transfer vehicle (POTV), crew module (CM), LEO propellant depot, and GEO propellant depot. The SPS HLLV is used to bring construction payload, crew expendables, and propellants for the EOTV and POTV. The IOTV is used to carry payloads over short distances; e.g., between the SPS HLLV and the LEO station or EOTV, between the EOTV and the SCB, and between the shuttle orbiter and the POTV. The EOTV carries payload brought up in the HLLV between LEO and GEO. Because of the long flight duration of the EOTV, another vehicle, the POTV, is used to rapidly carry crew members between LEO and GEO. A crew module, capable of carrying 50 crew members, is needed to provide life support during crew transfer. The space shuttle provides transportation of crew, in their crew module, between earth and LEO. All LEO operations occur in a 31.6 degree inclined orbit at an altitude of 487 km.

Table 8. Yearly Space Transportation Rates

CALENDAR YEAR	NUMBER OF FLIGHTS PER YEAR			
	POTV	GROWTH SHUTTLE	EOTV	HLLV
2000	41	45	7.5	200.8
2001	43	47	15.5	410.7
2002	47	51	15.5	413.1
2003	51	55	15.6	415.5
2004	55	59	16.7	442.1
2005	59	63	16.7	443.6
2006	63	67	16.7	446.0
2007	67	71	17.7	474.4
2008	71	75	17.8	475.8
2009	75	79	18.9	503.2
2010	79	83	18.9	505.6
2011	83	87	18.9	508.2
2012	87	91	20.0	535.7
2013	91	95	20.0	537.1
2014	95	99	20.1	540.5
2015	99	103	21.1	567.9
2016	103	107	21.2	569.3
2017	107	111	22.2	595.8
2018	111	115	22.2	598.2
2019	115	119	22.3	599.6
2020	119	123	23.4	628.2
2021	123	127	23.4	629.6
2022	127	131	24.4	635.1
2023	131	135	24.5	659.5
2024	135	139	24.5	660.9
2025	139	143	25.6	689.4
2026	143	147	25.6	691.9
2027	147	151	25.7	694.2
2028	151	155	26.7	720.3
2029	155	159	26.7	722.0
2030	139	141	19.6	535.0
TOTAL	3051	3173	635.6	17049.2

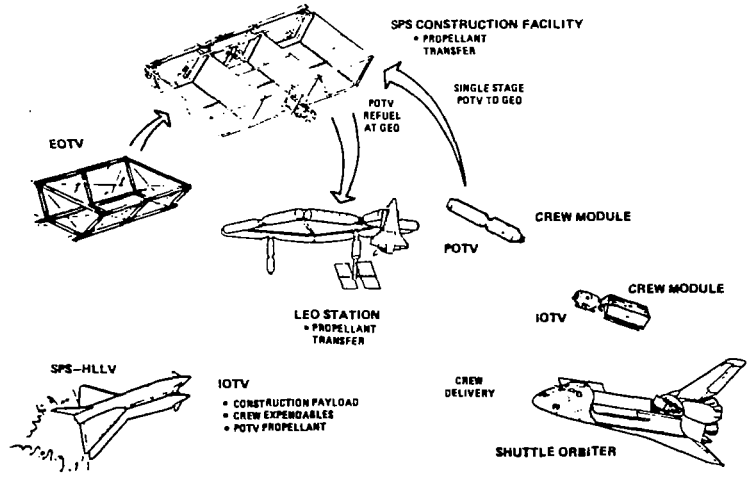


Figure 38. SPS Space Transportation Scenario

The following sections describe the characteristics of the HLLV, EOTV, and POTV (including the crew module).

Heavy Lift Launch Vehicle

The reference concept includes a two-stage, series burn concept that is launched vertically and lands horizontally. In this study, a two-stage concept also was defined, but the stages burn in parallel from take-off to staging. This concept carries 227,000 kg each trip compared to 454,000 kg carried by the reference concept. Table 9 lists the basic ground rules and assumptions used to derive the HLLV design.

Table 9. HLLV Ground Rules and Assumptions

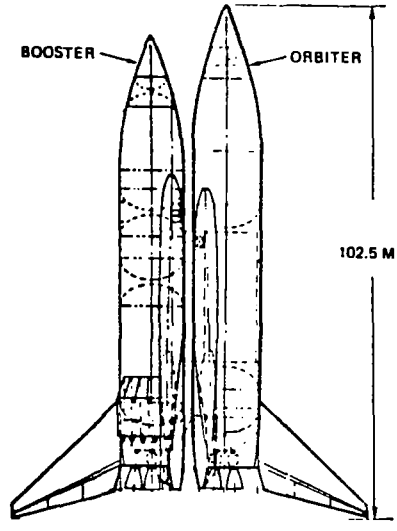
• TWO-STAGE VERTICAL TAKEOFF/HORIZONTAL LANDING (VTO/HL)
• FLY BACK CAPABILITY BOTH STAGES - ABES FIRST STAGE ONLY
• PARALLEL BURN WITH PROPELLANT CROSSFEED
• LOX/RP FIRST STAGE - LOX/LH_2 SECOND STAGE
• HI P_c GAS GENERATOR CYCLE ENGINE - FIRST STAGE [I_s (VAC) = 352 SEC.]
• HI P_c STAGED COMBUSTION ENGINE - SECOND STAGE [I_s (VAC) = 466 SEC.]
• STAGING VELOCITY - HEAT SINK BOOSTER COMPATIBLE
• CIRCA 1990 TECHNOLOGY BASE - BAC/MMC WEIGHT REDUCTION DATA
• ORBITAL PARAMETERS - 487 KM @ 31.6°
• PAYLOAD CAPABILITY - 227×10^3 KG UP/45 KG DOWN
• THRUST/WEIGHT - 1.30 LIFTOFF/3.0 MAX
• 15% WEIGHT GROWTH ALLOWANCE/0.75% ΔV MARGIN

The resulting design and its features are shown in Figure 39. The first stage contains LO_2/RP propellants. The second stage contains LO_2/LH_2 propellants. Both stages burn, similar to the shuttle, from launch through staging. LO_2 and LH_2 propellants are cross-fed from the first stage to the second stage.

A horizontal take-off and landing single stage to orbit concept also is being considered as an alternative to the vertical take-off HLLV's. This concept, shown in Figure 40, uses air-breathing engines for take-off, cruise, and acceleration up to 6,200 ft/s and rocket engines for parallel burn with the air-breather between 6,200 ft/s and 7,200 ft/s and for final injection to orbit. This concept carries 91,000 kg of payload to orbit. Take-off and landing can be accomplished with standard airport runway lengths.

Electric Orbit Transfer Vehicle

Further definition of the EOTV was accomplished. This approach was selected over use of LO_2/LH_2-propelled stages because of the low propellant masses resulting from the high specific impulse possible with electric propulsion. The concept is shown in Figure 41. The structure and dimensions are the same as for a bay section of the satellite. The same SCB can be used for both the satellite and the EOTV. The solar array also is basically the same as the satellite with GaAs solar cells and CR=2. Because of the self-annealing characteristics of the GaAs solar cells, it is expected that the EOTV can pass through the earth radiation belt without significant solar cell radiation



MASS PROPERTIES		
	10^6 KG	10^6 LB
GLOW	7.135	15.73
BLOW	4.831	10.65
WP_1	4.359	9.61
U LOW	2.177	4.80
WP_2	1.579	3.48
PAYLOAD	0.231	0.510

CONCEPT FEATURES

- LOX/RP C.G. CYCLE 1ST STAGE
- LOX/LH_2 (STAGED COMBUSTION) 2ND STAGE
- PROPELLANT CROSSFEED—PARALLEL BURN
- STAGING VELOCITY, 2127 M/S (6978 F/S)
- STAGING ALTITUDE, 55 KM (181,000 FT)

Figure 39. Two-Stage, Parallel Burn HLLV Concept

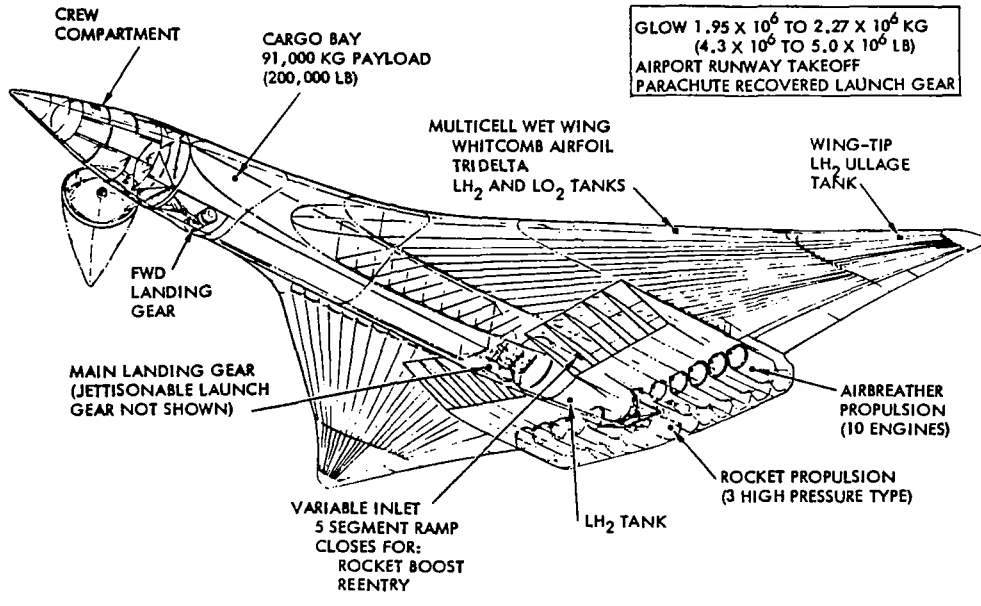


Figure 40. Single-Stage to Orbit HLLV Concept (Star-Raker)

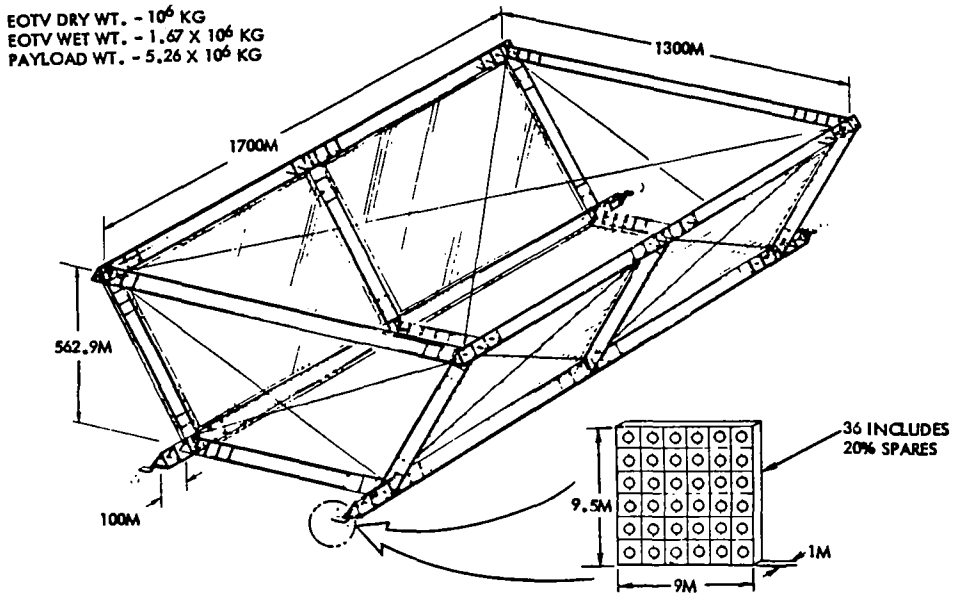


Figure 41. EOTV Configuration

damage. With an outbound payload of 5.26×10^6 kg, the trip time is 100 days. The return trip is accomplished in 22 days with 0.526×10^6 kg of payload (payload containers). Only 0.67×10^6 kg of argon propellant are required each trip. The electric thrusters are located on each corner. These thrusters provide both orbit-raising and attitude control capability. Batteries are used to store energy for attitude control during periods of earth eclipse of the sun, which is frequent while at low earth orbit.

Personnel Orbit Transfer Vehicle

The current reference concept uses a two-stage LO_2/LH_2-propelled concept to carry crew from LEO to GEO. Both stages are recovered in LEO for reuse. A different approach was studied in this contract and is recommended. This approach, shown in Figure 42, uses a single LO_2/LH_2 stage which is fueled from a propellant facility in LEO. All of the propellant in the stage is used during transit from LEO to GEO. The stage is again fueled at GEO for the return trip to LEO. A crew module, carrying 60 passengers, is carried as payload from LEO to GEO and from GEO to LEO. Because of the small size of the stage, it could be carried in a growth version of the shuttle. The crew module is carried to orbit in the shuttle.

PROGRAM DEFINITION

SPS cost and programmatic analyses were completed on the Rockwell reference configuration discussed in this report. Results from contract Exhibits A/B were updated and expanded to define an integrated program for an option of 60 SPS's with an initial IOC in the year 2000. Program definitions were developed for

ground-based exploratory research (1980-1985), program development and initial operations through year 2000, and the commercialization phase ending in year 2030.

A summary schedule that describes these phases is presented in Figure 42. It identifies the ground-based exploratory development activities and key technology programs preceding the 1990 Phase C/D commercialization decision. The 335-MW EOTV precursor pilot plant is shown as an extension of the systems test activity. The 1990 Phase C/D activity will initiate work on all major elements leading to the SCB fabrication, EOTV test article assembly, transfer to GEO, and precursor testing/beam mapping. The growth Shuttle and Shuttle-derived cargo carrier will have an earlier start to transfer the necessary mass to orbit. Subsequent SPS HLLV operations will combine with the Shuttle for full-scale build-up of the first satellite.

Total program costs were developed for DDT&E, production, launch, orbital assembly/construction, ground operations, replacement capital, and operations/maintenance in accordance with the SPS work breakdown structure. These elements are described in Figure 43 for main phases of the SPS program.

The DDT&E phase consists of the one-time effort associated with the design, development, and evaluation of components, subsystems, and systems required for the SPS. DDT&E estimates cover SPS support systems such as space transportation, facilities, and the ground station. Total program development cost through the first SPS is $84.5 billion (DDT&E, $33.4 billion; TFU, $51.1 billion). Satellite DDT&E is $7.9 billion and SPS space transportation DDT&E (including ground support facilities) are estimated at $12.5 billion.

An analysis of TFU costs shows that the largest requirement is for space transportation and ground support facilities. This cost, $22.9 billion (44%), includes an estimate of the initial transportation fleet (HLLV's and OTV's), facilities, and support systems that will have a lifetime capability of building more than one SPS satellite. Space construction and support equipment also fall in this category and represent $8.6 billion of the TFU cost.

Investments per satellite are the cost estimates of an average unit of the total 60-unit program. This average cost of $13.9 billion includes $5.3 billion for the satellite, $3.6 billion for the ground receiving station, and $1.9 billion for space transportation/ground support facilities. The average investment cost per SPS is $3010/kW.

SPS replacement cost and operations/maintenance estimates have been combined into a single figure with an annual cost of $0.2 billion per satellite.

As a secondary objective, planning areas requiring substantial effort during the Phase C/D activity were identified for the various SPS elements. This work concluded in a series of main SPS program plans listed in Table 10. Program schedules and networks, technology/system requirements, and resource considerations are principal items addressed in these program plans. In addition, an analysis of natural resources identified material requirements for the first satellite and ground receiving station requirements needed for the transportation system.

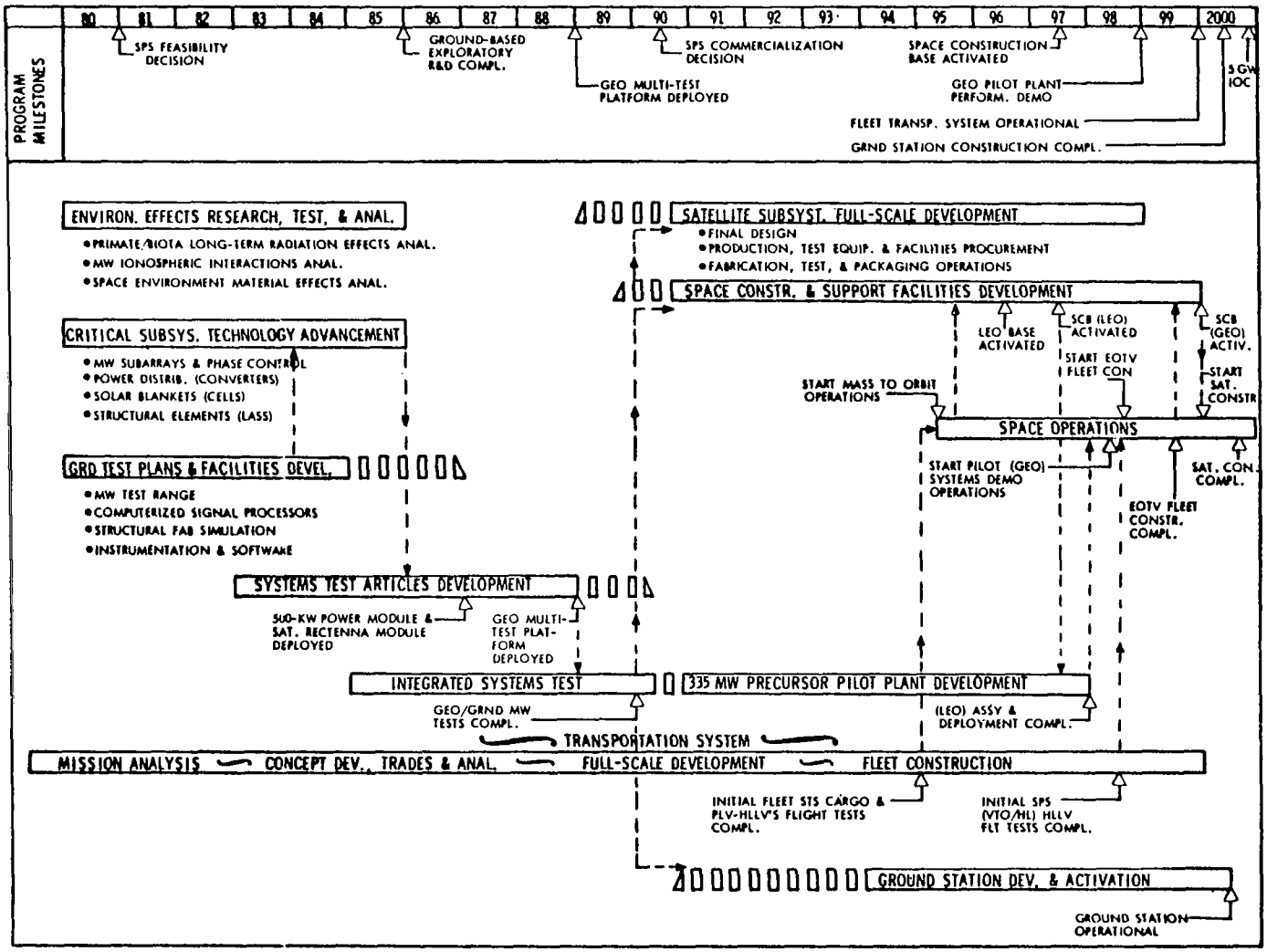


Figure 42. SPS Summary Program Phases and Milestones

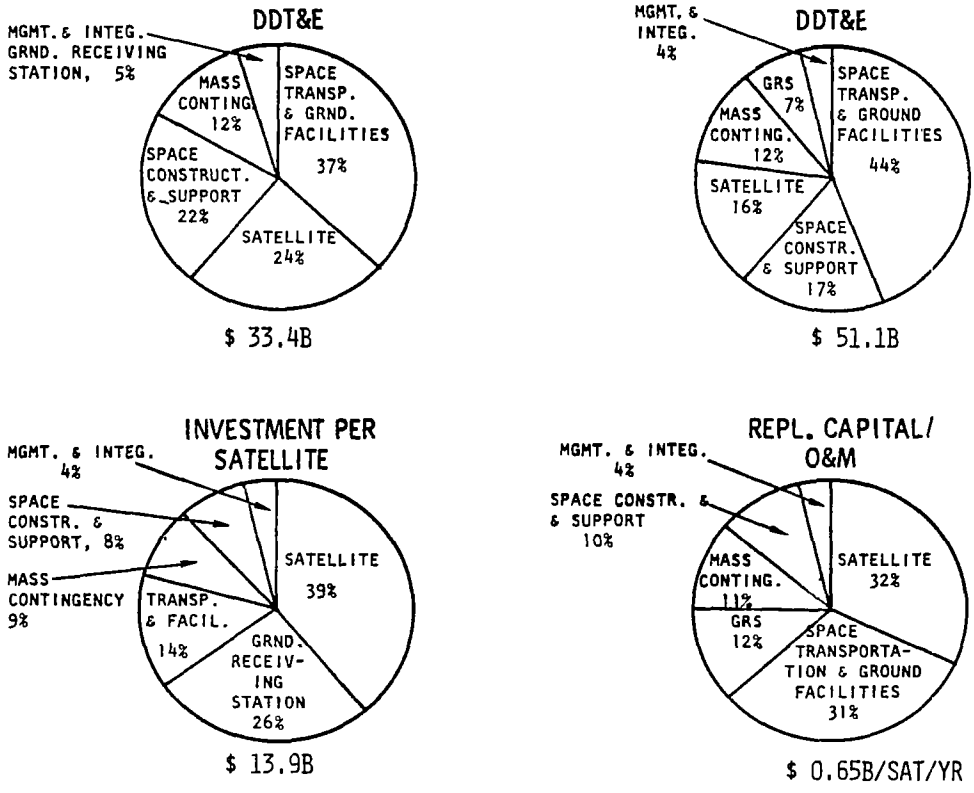


Figure 43. SPS Cost Breakdown

Table 10. SPS Program Plans

• Program Management	• Product Assurance
• Systems Engineering and Integration	• Facilities
• Design and Development	• Ground Operations
• Systems Testing	• Space Operations
• Ground Support Equipment—D&D	• Launch Operations
• Manufacturing	• Specification Tree
	• National Resource Analysis

STUDY LIMITATIONS

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

In addition to the system options that have been studied and defined in this effort, other potential approaches have been proposed. Because of limitations in program funding, an adequate evaluation of all credible concepts can not be conducted. Major emphasis in this study was placed on analysis and definition of the reference concept. Only a very preliminary definition of the solid state microwave concepts has been accomplished. Future effort should concentrate on a thorough definition of the solid state microwave concept.

IMPLICATIONS FOR RESEARCH

A major portion of this contract was devoted to development of a technology plan. The principal elements of the SPS development plan are summarized in Figure 45. Four major elements comprise this plan:

- Microwave Ground-Based Exploratory Research Program
- Key Technology Program (other than microwave)
- SPS Orbital Test Platform Demonstration Program
- Pilot Plant Demonstration Phase

The microwave ground-based exploratory research program provides the seedbed for prototype development of microwave transmission systems. This program will result in key microwave environmental data for evaluation of the microwave transmission system. The key technology program will develop the needed technology in all other SPS technology areas. The orbital test program will result in an end-to-end technology verification of the SPS under operational environmental conditions at geosynchronous orbit. The pilot-plant phase will result in an end-to-end system demonstration of SPS.

The following sections summarize these major activities.

MICROWAVE GROUND-BASED EXPLORATORY RESEARCH PROGRAM

The objective of the program is to conduct technology research in critical areas associated with the SPS microwave system, develop near-prototype hardware, integrate this hardware in an optimum subarray design, conduct integrated tests, and produce performance data for use in the environmental analysis program. A secondary objective is a continuing technology program in the critical areas

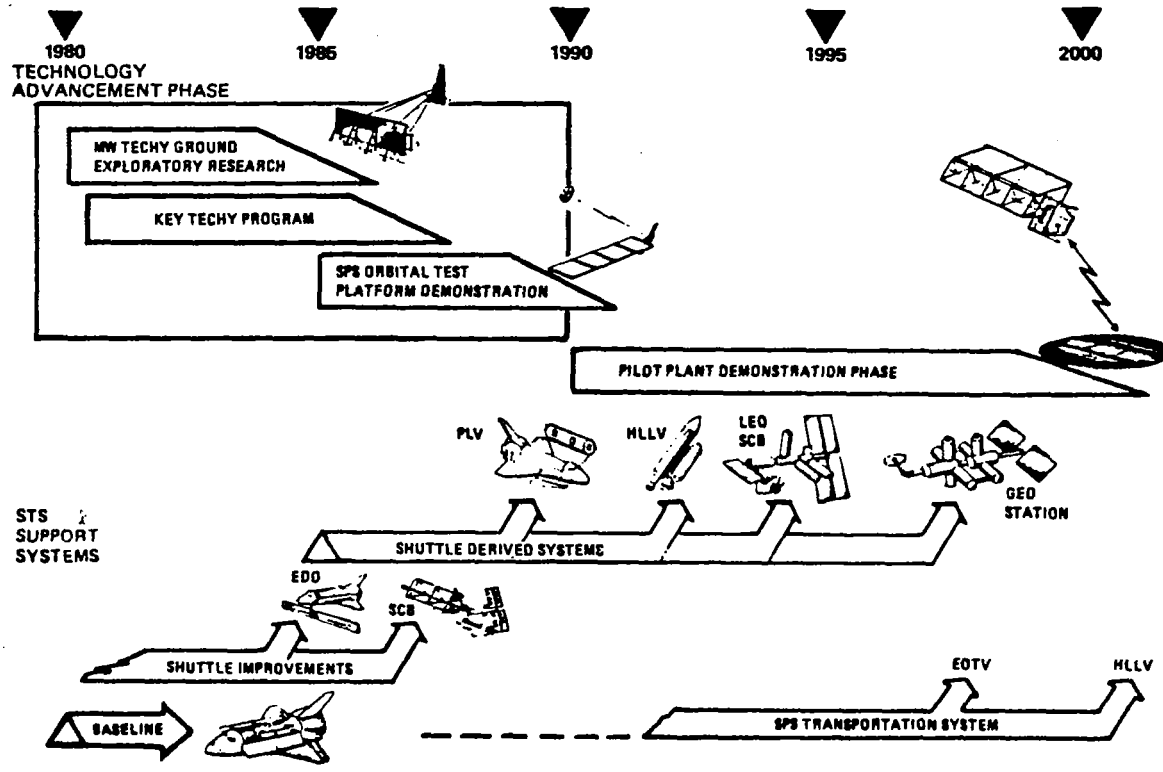


Figure 44. SPS Evolutionary Development Plan Elements

(klystron, phase control, solid state) that will provide progressive development to support the technology advancement program. Development and integrated testing of near-prototype hardware will provide a much stronger data base for economic assessments of the SPS program.

The major elements of the microwave technology (GBER) plan and their interrelationship are shown in Figure 46. The first early microwave power transfer work was accomplished at MSFC in 1969. This was a low power laboratory test and demonstrated concept only. The first significant large RF power transfer was accomplished by JPL in 1975. This test used a large dish antenna and a single power tube. It was a significant demonstration of power transfer but did not simulate the performance of the microwave system as proposed by current SPS system studies. This plan will provide a vehicle for producing prototype performance data through a significant microwave component technology development program. These data can then be used as the data base for the environmental assessment of the microwave system. Uncertainties associated with the predictions of microwave system performance will then be greatly reduced.

The general flow of the GBER program is illustrated in Figure 47. This chart describes a progressive product-oriented development and test program with key milestones.

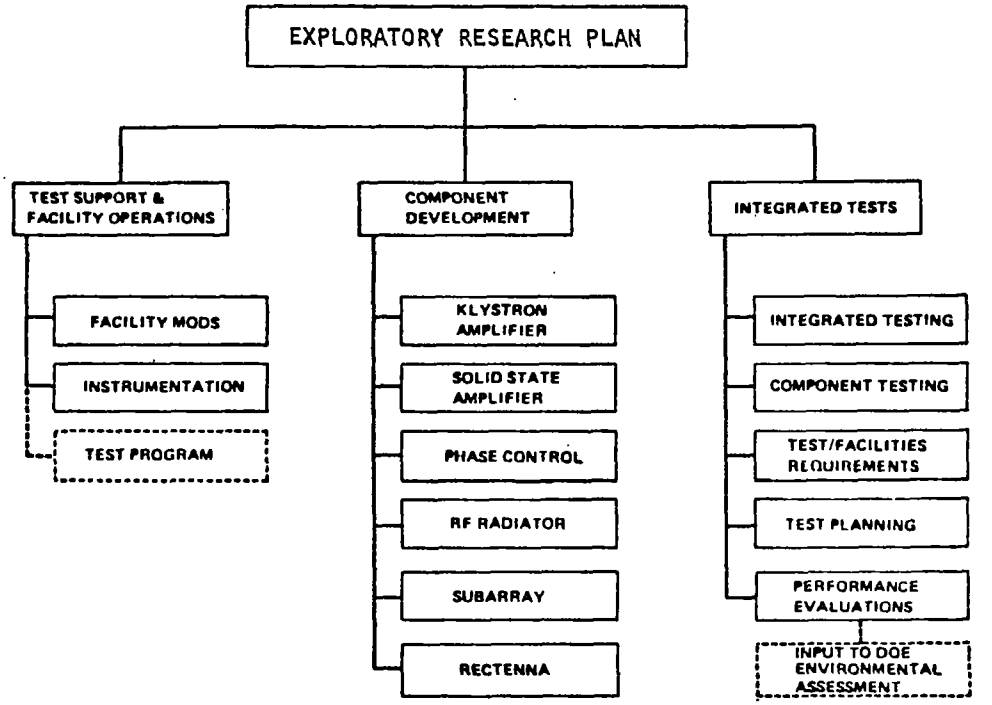


Figure 45. Major Elements of Ground Based Exploratory Research (GBER) Program

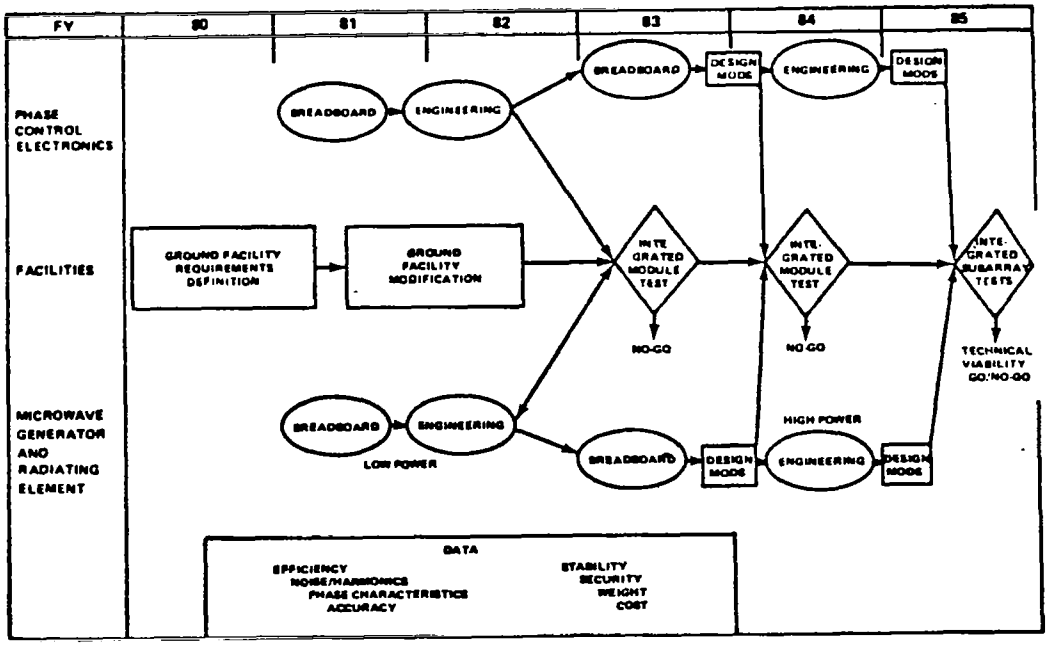


Figure 46. GBER Program Flow Diagram Technical Approach

The GBER plan is divided into three major parts: test support and facility operations, integrated tests, and component development. Component development is further subdivided into klystron amplifier, solid state amplifier, phase control, RF radiator, subarray, and rectenna. Each part contributes to the ultimate objective of determining the performance characteristics of a near prototype SPS subarray.

The integrated test element will provide design requirements for the facility and instrumentation. Integrated testing is subdivided into power module tests, test article tests, and subarray tests. This method provides a step-by-step buildup for an ultimate SPS subarray test and allows key decision points along the way.

The third part of the GBER is component development. This part is important because most of the technology development occurs here. It is the technological progress with key component developments that will ultimately determine the performance characteristics of the near prototypical SPS subarray. Several key elements of the microwave system have been selected for technology investigations.

The GBER program is estimated to require funding of approximately 32 million dollars in the 1980-1985 timeframe. Figure 48 shows the costs by major project element, the anticipated scheduling, and major hardware delivery requirements. Funding begins in 1980 with one million for early development of the various microwave system elements and gradually builds to a peak year (1984) cost of slightly over eight million dollars as the program reaches the system integration and test phase. Thereafter funding levels decrease to that required for an operations and test phase with no more large component buys anticipated.

FY	1980	1981	1982	1983	1984	1985	TOTAL THRU 1985
GROUND TEST FACILITY & INSTRUMENTATION	0.15	0.3	1.5	1.0	0.5	0.5	3.85
INTEGRATED TESTS	0.2	0.2	0.5	0.5	1.0	1.0	3.3
SUBARRAY DEVELOPMENT		0.1	0.4	0.4	0.6	0.6	2.1
PHASE CONTROL (PC)	0.2	0.9	1.0	1.3	1.5	0.5	5.4
SOLID STATE POWER AMPLIFIER (PA)	0.25	1.2	1.5	1.45	0.5	0.5	5.5
KLYSTRON POWER AMPLIFIER (PA)	0.2	1.2	1.5	1.45	1.85* 0.5	0.5	1.85 5.45
MICROWAVE RADIATOR		0.1	0.5	0.7	0.7		2.0
RECTENNA		0.1	0.5	1.0	1.0	0.4	3.0
TOTAL	1.0	4.1	7.4	7.8	8.15	4.0	32.45

*EITHER SS OR KLYSTRON (1984 DECISION)

Figure 47. GBER Program Cost Estimates (Millions of Dollars - 1978)

KEY TECHNOLOGY PROGRAM

The Ground-Based Exploratory Research Program described in the previous section was prepared to evaluate the microwave power transmission system. While the microwave system is considered to be a very critical link in the SPS program, technology areas outside of this link require attention in the 1981-85 time period to answer critical questions and establish credibility of the complete system concept. The Key Technology Program provides a summary of these additional technology studies. The Key Technology Program consists of extended analysis, laboratory development, and ground tests in disciplines other than microwave. In addition, flight experiments and flight project definitions are included. The term "flight experiments" refers to orbital testing of components or elements of a system which can be completed in the 1981-85 period. Flight projects are broader in scope (usually system level activities), are more costly, and are not planned for completion until the 1986-90 period, since they require longer lead times for definition and planning. The flight projects and flight experiments are a part of the SPS Orbital Test Platform Demonstration Program.

During the past and current activities, elements of the SPS program have evolved based on trade results and more detailed refinement of concepts. It is therefore expected that this plan will be continually refined as research proceeds. At present, however, it is believed that this plan encompasses those technology advancements which are needed to build upon past and current activities and provide new technical information on which to establish SPS program credibility and provide information on which to assess SPS program continuation.

The Key Technology Program will be directed toward laboratory development and testing of various elements to determine if the technical and performance assumptions of the earlier studies were valid; to obtain data for needed technical, economic, environmental, and societal assessments; to assess other SPS system/subsystem alternatives; and to conduct limited flight experiments and define flight projects. Key elements requiring such effort include extension of present terrestrial solar cell programs to space applications including processing techniques, annealing, and bonding; extensive computer analysis of large space structures; development and testing of graphite composites and thin-gage aluminum in the various required configurations; simulation and development of concepts and equipment of power distribution for steady state and transient performance; development and testing of space construction techniques for building of structural beams, fastening of structural members, installation of solar arrays and equipment; and development and demonstration of large electric thrusters utilizing argon and associated power processing equipment. Technology to support the HLLV includes airbreathing engines for horizontal takeoff, high chamber pressure rocket engines, high temperature insulation materials, airbreather inlet materials, and variable geometry airbreather inlet techniques.

A top-level summary of the development activities and funding requirements covered in the plan are presented in Figure 48.

KEY TECHNOLOGY AREAS	FY81	FY82	FY83	FY84	FY85	TOTAL
SOLAR ARRAY	2000	3000	3500	3500	3000	15000
	CELL DEV./ANNEALING/ PRODUCTION PROCESSING/ GALLIUM RECOVERY					
POWER DISTRIBUTION	400	800	1500	1200	1000	5000
	COMPUTER SIMULATIONS/ COMPONENT BREADBOARD					
STRUCTURES AND CONTROL	200	900	1300	1300	800	4500
	MODELING & CONTROL TECHNIQUE DEV					
MATERIALS	200	800	1500	1500	1000	5200
	GROUND TEST / DEGRADATION MODEL DEV					
CONSTRUCTION AND ASSEMBLY	700	1300	1700	1500	1000	6500
	GROUND SIMULATIONS/ASSEMBLY TECHNIQUES & EQUIPMENT DEV					
TRANSPORTATION	900	1300	3000	3000	2000	10000
	DEFINITION STUDIES/BOOSTER & ION ENGINE DEV/VEHICLE DESIGN STUDIES					
FLIGHT EXPERIMENTS	2000	5000	7000	8000	6000	28000
	PAYLOAD DEFINITION/KEY SHUTTLE SORTIE FLIGHTS					
FLIGHT PROJECT DEFINITION	800	1200	2500	3000	4500	12000
	PRELIMINARY DEFINITION/PHASE A & B STUDIES					
TOTAL FUNDING (THOUSANDS OF 1978 DOLLARS)	7100	14400	21000	23500	20200	86200

Figure 48. Key Technology Program Summary

SPS ORBITAL TEST PLATFORM DEMONSTRATION PROGRAM

An essential requirement exists for major SPS subsystem test and evaluation at low earth orbit and geosynchronous orbit late in the 1980's. Current NASA planning projects a major SPS subscale test article for LEO-to-LEO microwave testing. This same test platform can be boosted using electric propulsion to GEO to serve as an SPS multi-test platform in both a GEO-to-ground and ground-to-GEO mode (functioning as an inverted test range with the addition of pilot beam electronics).

The GEO multi-test platform would function as the geosynchronous element of a ground-to-GEO inverted microwave test range, as shown in Figure 50. A ground-based, one-kilometer linear transmitting antenna, one power module in width, is proposed for full-scale phase control testing. Full-scale aperture testing is required to verify phase control linearity and array performance prior to commitment of major space antenna construction effort. The pilot-beam element of the orbital system illuminates the ground antenna linear array where the beam is received by the line source retroelectronics which, in turn, phase the line source to return its beam to the satellite. A beam-mapping piggyback subsatellite operates in a free-flying mode and probes the beam pattern by controlled drifting in an east-west pattern.

A GaAs solar array version of the GEO multi-test platform is shown in Figure 51. Because of the GaAs array resistance to natural radiation and its ability to self-anneal radiation damage, transit from LEO to GEO using

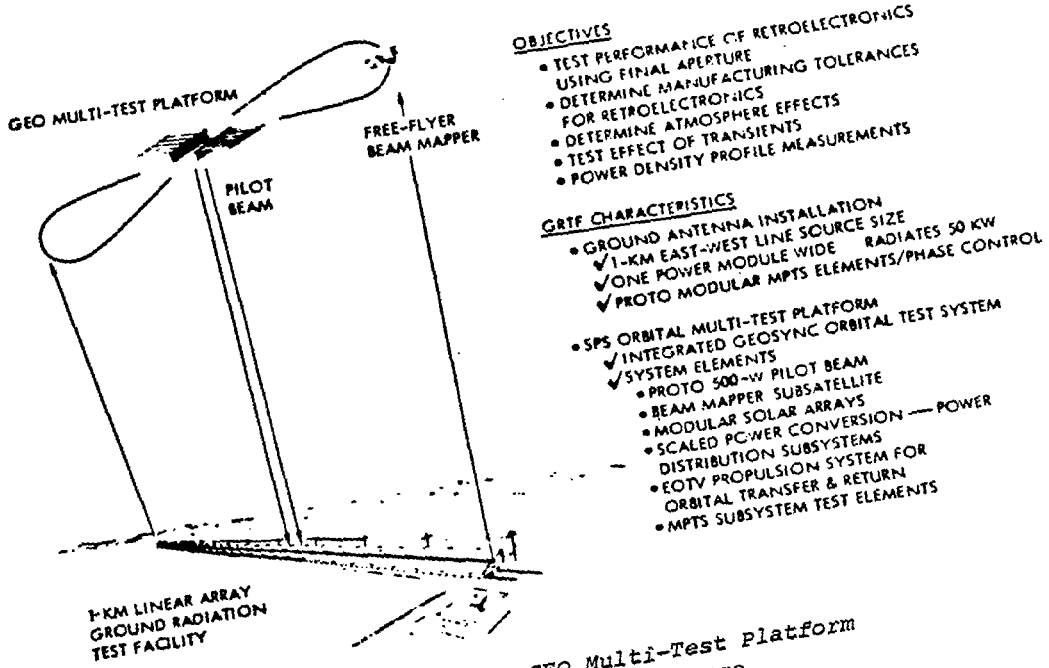


Figure 49. SPS GEO Multi-Test Platform and Inverted Test Range

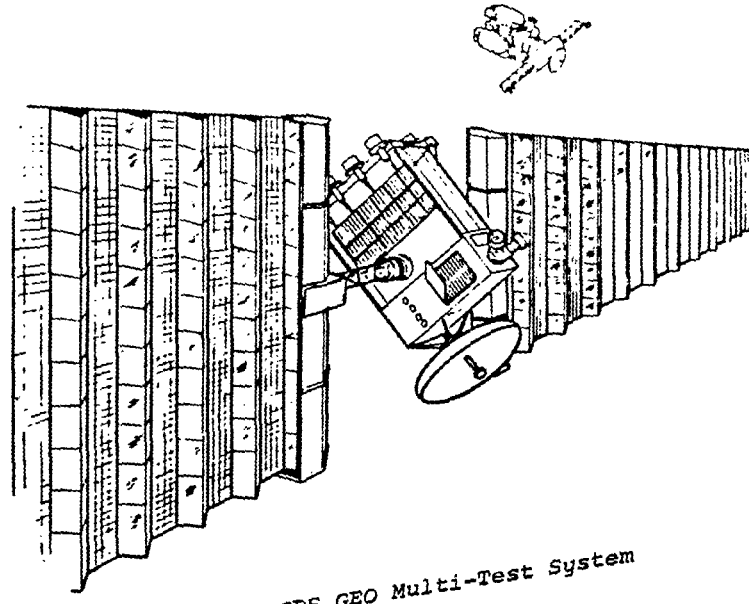


Figure 50. SPS GEO Multi-Test System

self-power in an electric propulsion mode appears feasible. This capability also suggests that such a system could be used as a solar-electric propulsion stage (SEPS) for propulsion of large payloads between earth orbits as well as for providing power during payload operations. For the SPS application, it can be a derivative of a SEPS either as a dedicated modified system or as a hybrid system using a SEPS bus having the SPS multi-test experiments as a payload. Approximately 100 kW of power would be required for the GEO multi-test platform functions.

Other potential routes for development of the SPS multi-test platform include:

- A derivative of the large space structures/large power modules program (LSS/LPM)
- A derivative of power modules using current SEP silicon array technology

The degree to which SPS technical issues are resolved as definition of these systems occurs will have an important influence on their suitability as derivatives.

PILOT PLANT DEMONSTRATION PHASE

Completion of the SPS Technology Advancement phase by 1990 will provide the technical confidence to proceed with the full-scale pilot-plant demonstration phase. The primary objective of this development phase is to demonstrate commercial viability of the SPS system to those utility firms and consortiums that would ultimately capitalize and operate the production system.

The pilot-plant satellite would be constructed in LEO using a Shuttle-derived HLLV for mass transfer and construction support systems. The satellite is transferred to geosynchronous orbit by an electric-propulsion system. The system operates in the same mode as the full-scale satellite by directing a microwave power beam at a total power level of several hundred megawatts to a standard modular segment of the proposed operational ground rectenna. The demonstration/operational period would range from six months to a few years, during which time the SPS elements of the full-scale solar power satellite would be operated in the operational environment. Operational data would provide the quantitative basis for analyses which would support full SPS commercial capability.

The initial step is establishment of a LEO base, previously described, that is capable of constructing a single trough of the satellite. The pilot-plant demonstrator, shown near completion in Figure 52, is sized to the projected EOTV power level of 335 MW at the array. Allowing for radiation degradation and power distribution losses, power to the microwave antenna would be approximately 285 MW. Microwave transmission losses would reduce this value to about 230 MW at the rectenna. This would result in recovery of 8 MW of power for a 7-km-diameter rectenna or 2 MW of power for a 1.75-km-rectenna.

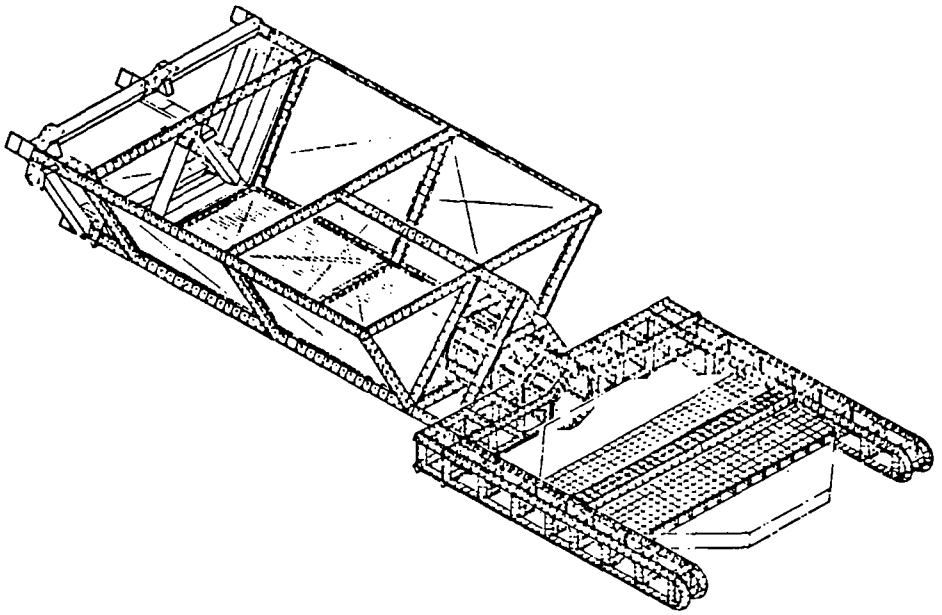


Figure 51. SPS Pilot Plant in Final Phases of Construction

SUGGESTED ADDITIONAL EFFORT

As a result of this study, major areas of future emphasis have been identified for system studies and for near-term technology development.

SYSTEM STUDIES

This study has resulted in an identification of potentially attractive solid-state microwave transmission concepts. Effort in this contract has not yet been sufficient to define these concepts adequately to determine the best approaches and to evaluate them relative to the current reference concept. It is recommended that this effort be continued and heavily emphasized in follow-on system studies.

This contract has resulted in an adequate definition of the electric orbit transfer vehicle and the personnel orbit transfer vehicle. However, transportation costs are most sensitive to the heavy lift launch vehicle operational and fleet costs. Two approaches have been identified for the HLLV; a parallel-burn, two-stage, vertical take-off and horizontal landing concept and a horizontal take-off and landing single-stage to orbit concept. Further definition of these concepts is needed to support launch cost estimates.

The rectenna system installation approach has been defined in this study, but two issues still need to be resolved: lightning protection requirements and their resulting design implications and design analysis and impacts for high wind conditions. These issues can have a significant impact on rectenna installation costs.

TECHNOLOGY DEVELOPMENT

Three primary areas, in addition to the on-going NASA large structures technology development, have been identified for immediate technology development:

- Advanced GaAs solar cell development
- Solid-state device and microwave system development
- Dc-dc converter and switchgear technology

A detailed plan for advanced GaAs solar cell development has been prepared and is contained in Reference 3. This proposed effort includes development and testing of prototype GaAs solar cells with a sapphire substrate, preliminary development of peeled-film technology solar cells, definition of manufacturing methods, and prediction of production rate capability. Testing includes radiation environment effects and solar cell performance measurements.

In order to bring solid state microwave technology to a position competitive with klystron technology, early device (transistor) and power amplifier research is needed. It is recommended that work be immediately initiated on advanced GaAs transistor development and that amplifier circuits be developed using available GaAs transistors. The circuit research will provide a current technology base for amplifier performance and will demonstrate electronic combining of microwave circuits.

No NASA or DOE plan has been identified for early development of high power and voltage dc/dc converters and switchgear that will be needed about 1987 for space technology verification. Although such equipment is in use for ground systems, technology development is needed to improve efficiency at much lower mass.

NASA currently has a program for development of large structures. Current effort appears to be generic and does not have sufficient application to SPS. It is recommended that the program be refocused to provide at least the minimum effort required to support SPS structure definition, evaluation, and ground test, and technology verification effort in the 1985-1990 time period.

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15. Supplementary Notes

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Volume I of Final Report

16. Abstract

This report summarizes Satellite Power System (SPS) concept definition studies (Exhibit C) conducted for the NASA Marshall Space Flight Center. Major areas included system definition, special emphasis studies, transportation system studies, and program definition. System Definition studies resulted in a further definition of the "Reference" system using gallium arsenide solar arrays, analysis of alternative subsystem options for the reference concept, preliminary solid-state microwave concept studies, and an environmental analysis of laser transmission systems. The special emphasis studies concentrated on satellite construction, satellite construction base definition, satellite construction base construction, and rectenna construction. Major emphasis in the transportation studies was put on definition of a two-stage parallel-burn, vertical take-off/horizontal landing concept capable of carrying 230,000 kg of payload. The electric orbit transfer vehicle was defined in greater detail. Program definition included cost analyses and schedule definition.

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