BOEING

Solar Power Satellite System Definition Study

Volume I
Phase 1, Final Report
Executive Summary
D180-25037-1

NASA CR-
160370

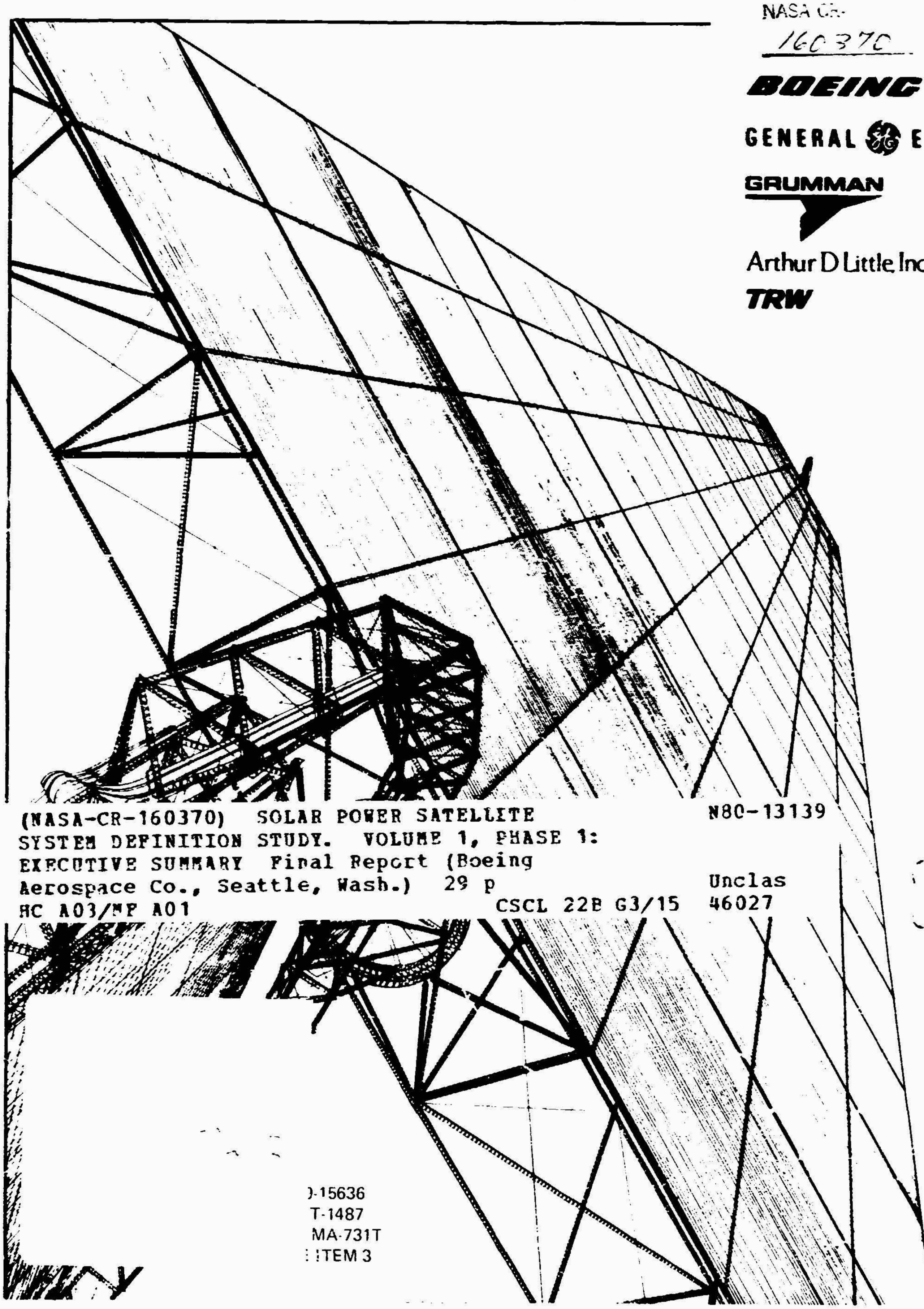
BOEING

GENERAL ELECTRIC

GRUMMAN

Arthur D Little Inc

TRW



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Solar Power Satellite
System Definition Study
Conducted for the NASA Johnson Space Center
Under Contract NAS9-15636

Volume I
PHASE I, FINAL REPORT
Executive Summary
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1.0 INTRODUCTION AND BACKGROUND

1.1 History

Solar power has long been recognized as an ideal source of energy for mankind. It is naturally available and plentiful, does not disturb the environment, e.g., by creation of wastes, and is itself free.

About ten years ago, a way of utilizing solar energy to generate electricity on a 24-hour continuous basis was proposed by Peter Glaser of A. D. Little. His proposal was to place the solar collectors in space, where they can collect sunlight continuously, can readily be aimed at the sun, and where very large collector areas can be obtained with relatively little investment in material resources. Energy collected by these solar power satellites (SPS's) would be transmitted to Earth by electromagnetic means. The original Glaser proposal, and most of the subsequent studies, have assumed the use of radio frequency systems in the microwave frequency range. Recently, the possibility of laser beaming has also been recognized.

The solar power satellite principle is illustrated in figure 1. In a geostationary orbit 36,000 km above the Earth's equator, each SPS would be illuminated by sunlight over 99% of the time and in continuous line-of-sight contact with its ground receiving station. Electrical power produced on the satellite by photovoltaic or heat engine conversion of the sunlight would be converted to electromagnetic energy at high efficiency, and formed into a narrow beam precisely aimed at the SPS ground stations. The ground station receiving antennas would reconvert the energy into electricity for distribution. Solar power satellites are intended to serve as producers of baseload electricity for utility service. SPS's are seen not as a substitute for other solar energy options, but as a complement that would allow solar energy to more completely serve humanity's energy needs.

Dr. Glaser's original proposal was published in 1968 in Science magazine. In 1971 and 1972 a small contractor study team was formed including Arthur D. Little, Grumman, Raytheon and Spectrolab. This team was awarded a study contract

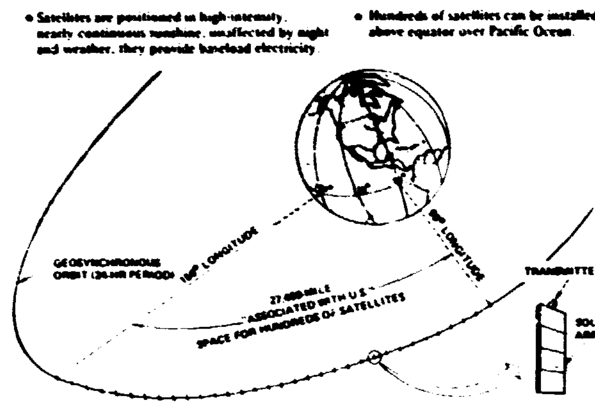


Figure 1. Solar Power Satellites: The Principle

through the NASA Lewis Research Center to investigate basic technical feasibility of the SPS concept. The conclusions of that study were that the system is technically feasible and could provide baseload electricity from solar power for use on Earth. Additional studies and experiments, partly funded by NASA over the period 1973 to 1975, established the feasibility of efficient energy transmission at microwave frequencies. In 1975 a demonstration conducted at JPL transmitted more than 30 kilowatts over a distance greater than a mile with a reception and conversion efficiency of 82 percent.

In the 1975 to 1977 time period, NASA conducted a technical assessment of SPS and began inhouse studies at the Johnson and Marshall Space Centers. The Department of Energy conducted its own assessment; SPS was discussed in congressional hearings. These activities led to development of an SPS Development and Evaluation Program Plan jointly sponsored by DOE and NASA. The principal milestones in this plan are:

Reference System Definition Report, Oct. 1978 (Complete)
Preliminary Program Recommendations, May 1979
Updated Program Recommendations, Jan. 1980
Final Program Recommendations, June 1980

(Also during this period, NASA-funded space transportation system studies indicated that the high traffic volumes required to support an SPS program could lead to cost reductions far below those projected for the space shuttle. The potential for such cost reductions was seen as significant to the economic practicality of SPS.)

As a result, plans were formulated by NASA to conduct solar power satellite system definition studies in 1977 in order to support the first milestone of the DOE/NASA evaluation plan. These would increase by roughly an order of magnitude the degree of depth of design and cost definition for SPS systems. One such study was awarded to Boeing through the Johnson Space Center; the other study was awarded to Rockwell through the Marshall Space Flight Center. These studies created reference system designs including the solar power satellites, ground receiving stations, space transportation systems, space construction systems and other support systems. The results indicated that SPS's could be built by the year 2000 with a likelihood of economic benefit. The principal findings of these studies might be summarized as follows:

1. Examination of energy conversion options led to a preference for silicon photovoltaics in the Boeing study, and gallium arsenide photovoltaics in the Rockwell study. (Both studies suggested thermal engine SPS designs as a hedge against the possibility that expected cost reductions in photovoltaics mass production might not be achieved.) The silicon photovoltaic system offers less risk with a more mature technology but an energy conversion system roughly 40 percent more massive than gallium arsenide.

2. Analyses of the power transmission system confirmed the basic feasibility indicated by the earlier studies and detailed microwave link error analysis confirmed attainability of adequate efficiencies. Integrated power transmission system conceptual designs were developed considering RF, electrical, mechanical, and thermal factors.

3. Space transportation systems were designed to accomplish the SPS transportation operations at acceptable cost.

4. Space construction approaches and construction base designs were developed for construction of 10,000 megawatt SPS's in geosynchronous orbit at a rate of approximately 1 per year.

The principal system elements from that study were the point of departure for the current study. The preferred SPS defined by Boeing is illustrated in figure 2.

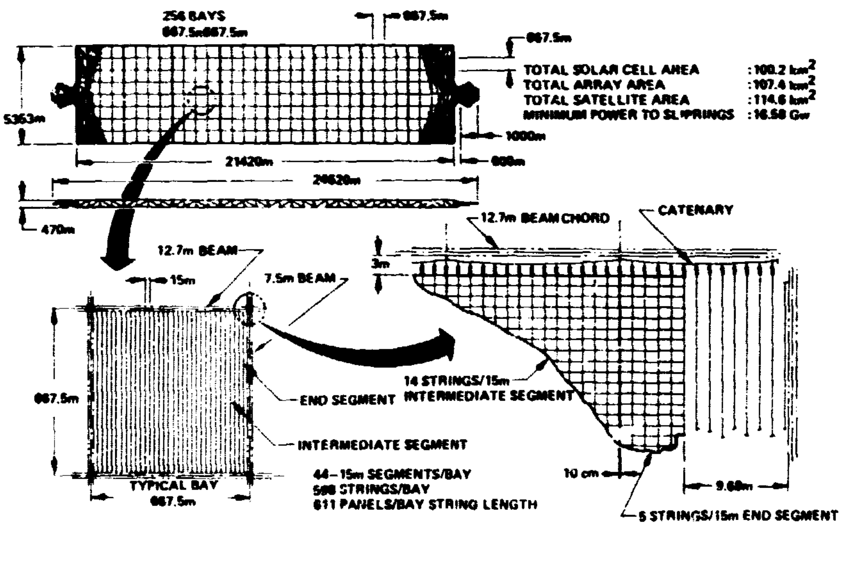


Figure 2. Reference Photovoltaic System Description

1.2 Objectives

The overall intent of the systems definition studies, past and present, may be summarized as follows:

1. Assess the technical feasibility of solar power satellites based on forecasts of technical capability in the various applicable technologies. Select the most appropriate technological paths leading to the most environmentally benign and economically practical systems. Define the areas of high leverage research.

2. Define the characteristics of SPS systems that may be derived if a development were to proceed. Assess performance, cost, operational characteristics, reliability, and the suitability of SPS's as power generators for typical commercial electricity grids.

3. Assess the uncertainties inherent in the system characteristics forecasts, based on technological uncertainties, on cost estimating uncertainties, and on uncertainties that arise from incompleteness in the data base.

4. Define the most economically prudent path to minimizing these uncertainties to the point that confident decisions can be made to proceed or not to proceed with development of this energy system.

The specific objectives of the present study are:

(1) to verify, maintain and update the presently-defined elements of the system,
(2) complete the definition of the total system, and
(3) prepare a series of plans required for technology advancement and SPS program implementation.

Phase I of the present study, reported herewith, has concentrated on the first two objectives. Phase II will emphasize end-to-end operations analyses and the third objective. These objectives and the timing of the study are designed to support the NASA program recommendations in fulfillment of the DOE/NASA evaluation plan.

2.0 STUDY APPROACH AND STUDY TEAM

The JSC/Boeing and MSFC/Rockwell SPS system definition studies of 1977 and early 1978 proceeded largely independently of one another and developed system concepts with a number of significant differences. NASA then developed a reference SPS system description based on NASA inhouse studies as well as on Boeing and Rockwell contract results.

The present study is divided into two phases; the first lasted 7 months and the second will last 9 months. Phase I accomplished additional analyses of the options and issues identified by NASA in developing the reference system report, beginning with a thorough critique of the JSC/Boeing reference system, followed by analyses of options and critique items. The reference design was updated at the end of Phase I. The overall schedule is shown in figure 3.

The Study Contract Team included Boeing as prime contractor and General Electric, Grumman, Arthur D. Little, and TRW as subcontractors. Principal task areas and the study team leaders for each contractor are shown in figure 4.

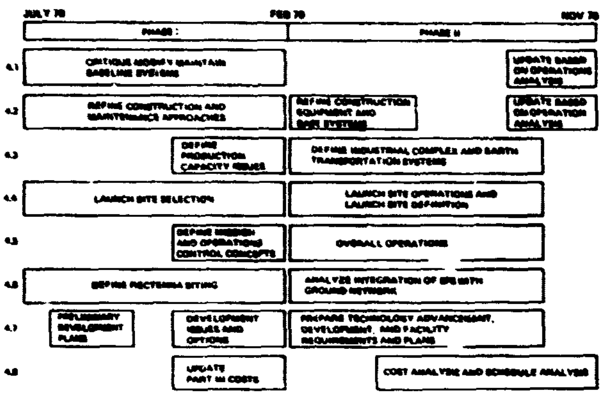


Figure 3. Study Plan Overview

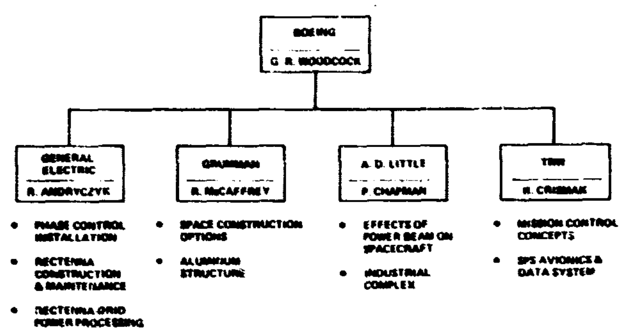


Figure 4. Study Contract Team Organization (Phase I Tasks Shown)

3.0 STUDY RESULTS

The presentation of study results in this executive summary has been grouped under three major headings:

(1) Highlights of Trade Studies and Analyses;
(2) Summary of Updated Baseline;
(3) SPS Development Planning.

The presentation is organized according to the work breakdown structure shown in figure 5.

3.1 Highlights of Trade Studies and Analyses

WBS Item 1.0 Solar Power Satellite Program: Important Critique Results

The critique effort identified and commented on about fifty items. These were grouped into 22 significant concerns for the discussion in Volume II of this report. The four most important are summarized below.

1. Concern was expressed about the long-term suitability and stability of graphite fiber composites in the space environment. The issues raised included creep, micro-cracking, and suitability of thermoplastics for some SPS thermal environments.

2. It was recommended that experimental samples of the lightweight annealable solar array be built and tested to verify annealability as well as survivability of the rest of the array under annealing conditions.

3. Several concerns addressed the high voltages planned for SPS operation. Plasma interactions may occur with the high voltage solar array. In particular, the critique singled out the problem of plasmas produced by the electric thrusters.

   Wear particles may be produced in the slip ring assembly and could "track" high voltage insulators causing arcing and damage to the slip ring assembly or nearby components. A high voltage potential will exist between the structure and the solar arrays and power conductors.

   Concern was also expressed that the power processor high-voltage transformer life may be too short for SPS application due to failures caused by a-c corona within the windings. (This item was addressed and corrected in the Phase I study.)

   Concern was also expressed regarding design of, and selection of materials for, high voltage insulators and cable insulation for use in the space environment.

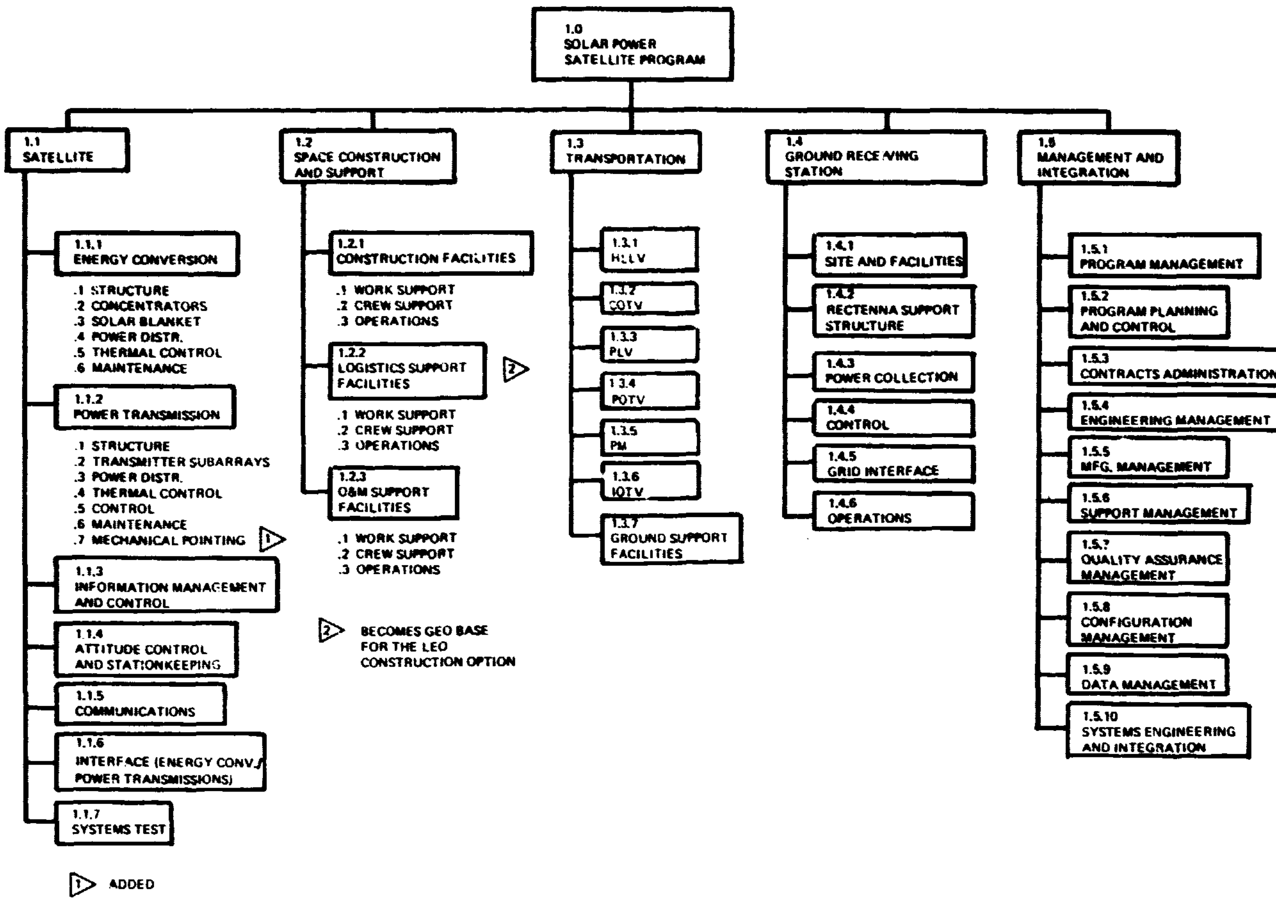


Figure 5. Work Breakdown Structure for SPS

4. The arrangement of the power supply hookup to the klystrons was criticized. Each power processor feeds about 400 klystrons; the potential fault currents that could arise from a high voltage arc at one klystron could involve the entire power supply current. Also, for the klystron power that is provided directly from the solar array busses, a fault could short the entire bus to ground. Electrical and magnetic forces caused by severe transients could cause major mechanical damage to the SPS. A residual concern was also expressed that power supply faults frequently cause failures in other parts of an electronic system.

WBS Item 1.1 Satellite: Size and Configuration Effects

Smaller SPS configurations were compared to the original 10 gigawatt baseline. The first was the present NASA 5 gigawatt baseline with one transmitting antenna. Analysis of the control requirements for this asymmetric configuration determined that because of the overriding importance of solar pressure compensation in the control thrust scheme, no propellant penalties were incurred by the lack of symmetry. Also, no packaging differences have been identified that would arise from dividing the original configuration into two equal halves. Therefore, the only consequence of this alternative to the original baseline is the requirement for more positions in geosynchronous orbit to effect a given total installed generating capacity.

The next alternative was also a five gigawatt system, but the power is divided into two power transmission links each rated at 2½ gigawatts. In order to minimize land use and rectenna costs, it is desirable, when reducing the link power, to increase the transmitter aperture, in turn reducing the receiving station area. This design option, however, has approximately 4 times as many transmitter subarrays as the single-transmitter 5 gigawatt satellite. As a result, it incurs a significant payload packaging problem because of the low packaging density of completely assembled transmitter subarrays. The packaging density situation appears to be much improved through use of a solid state transmitter. In the solid state option all of the active functions are included in a planar sheet only about 2 centimeters thick (including the resonant cavities). Thus, a much higher packaging density per unit of aperture area can be achieved.

The final 2-1/2-gigawatt option, like the second option, results from effectively dividing a symmetric configuration in half. As for the other case, no added penalties were determined for this design option excepting the use of more geosynchronous orbit space.

WBS Item 1.1.1.1 Satellite Energy Conversion Structure

Changing the solar blanket tensioning to uniaxial caused a revision in loads applied to the solar array support structure. The structural bay design was updated to reflect revised load requirements for self-power orbit transfer and solar blanket stretching loads. The structure configuration is shown in figure 6. For the reference case of geosynchronous orbit construction of the SPS the type B beams shown can be changed to type C since orbit transfer loads will not be a consideration. Figure 7 shows the characteristics of the three types of beams.

Evaluation of various structural arrangement options led to the conclusions that a pentahedral truss configuration would be better than the present cubic type (this appears to be true for the transmitter as well). The pentahedral truss retains the square bay shape, has fewer members and types of joints, and would be lighter.

A change to the pentahedral truss will be considered during Phase II. Trade studies conducted in Phase I used the cubic structure as baseline.

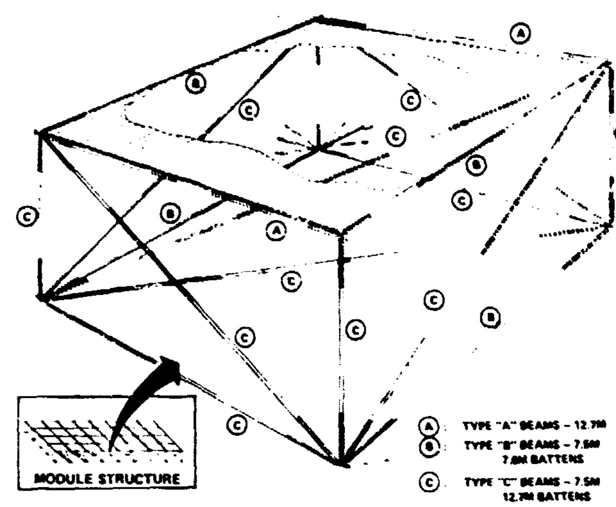
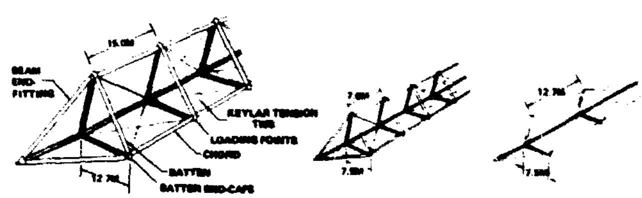


Figure 6. Solar Power Satellite Structural Bay Configuration



ITEM	TYPE A UPPER SURFACE LONGITUDINAL BEAM	TYPE B UPPER AND LOWER SURFACE LATERAL BEAM	TYPE C BEAM USED IN ALL OTHER LOCATIONS
SECTION	CLOSED	OPEN	[illegible]
REF. SIDE LENGTH	30 CM	30CM	[illegible]
MAT'L THICKNESS	0.86 MM	0.71 MM	0.71 MM
EI_x	3.35 E8 N/CM^2	1.80 E8 N/CM^2	1.80 E8 N/CM^2
BEAM WIDTH	12.7M	7.5M	7.5M
BATTEN SPACING	15.0M	7.5M	12.7M
CRITICAL LOAD	17400N (CRIP. CHORD)	10000 N (BUCK. BEAM)	7000 N(BUCK BEAM)
MASS/LENGTH	7.48 KG/M	5.12 KG/M	4.11 KG/M

Figure 7. Solar Power Satellite Structural Update Beam Configurations

An aluminum structure was compared to the low-coefficient-of-expansion (CTE) graphite composites baseline. The following main conclusions resulted:

- Roll formed closed section aluminum structures can be automatically fabricated in orbit;
- Design load requirements for LEO-constructed SPS module can be satisfied. The aluminum design is 23% heavier than composite but may be lower in cost;
- The 10-GW SPS natural frequency with aluminum (AR=4) is 65 times orbital frequency—instead of 100 times;

- The estimated natural frequency appears adequate for satellite control system stability; further analysis needed to verify;
- Based on initial studies, thermal stresses are within the capability of the aluminum design;
- Satellite deflections are within acceptable limits ($\sim 2^{o}$);
- Deflections due to occultations could result in dynamic "ringing" of the entire solar array support structure. Further analysis is needed to evaluate this.

WBS Item 1.1.1.2 Satellite Energy Conversion: Solar Blanket

Effects of array shadowing were investigated. If a segment or section of a long solar cell string is shadowed, it will not generate current. Current flow in the entire string is therefore interrupted. If other strings are connected to the load in parallel with the shadowed string, the difference between their loaded output voltage and the zero-current voltage of the shadowed string, appears as a reverse-bias voltage. The reverse bias voltage, if it is more than a few volts per shadowed solar cell, will destroy the shadowed cells if they are not protected. A small spacecraft flying across the face of an SPS could severely damage an unprotected solar array. Reverse-bias protection is therefore mandatory. The solar blanket panel design was modified to include shunting diodes.

WBS Item 1.1.1.3 Satellite Energy Conversion: Maintenance

A summary of repair and replace requirements for the satellite is presented under WBS Item 1.1.2.6.This section addresses maintenance requirements peculiar to the energy conversion system.

The energy conversion system is designed to be as nearly maintenance-free as possible. Solar cells, blocking and shunting diodes, and attachment and tensioning devices all incorporate enough redundancy to provide a lifetime of more than 30 years. Exceptional maintenance requirements may arise, e.g., in the event of collisions of natural or manmade space objects with the SPS. These will be treated as unscheduled maintenance. Switchgear may require replacement of one or two units annually.

Occasional maintenance of the solar array by annealing to restore output due to damage of the solar cells by solar flare radiation is expected to be necessary. It would be possible to make the solar array maintenance-free with regard to expected radiation by oversizing or providing extra shielding (in the form of thicker coverglasses). Annealing, however, has distinct cost advantages.

It is important to recognize that nearly all of the radiation damage to solar arrays at geosynchronous orbit comes from solar flares, which are a statistical phenomenon. Environment models are used to predict the amount of radiation for which arrays must be designed. The model used by Boeing was originated by the Goddard Space Flight Center. As is typical for such design models, it is roughly a 90% confidence model; an expected-value model would predict less radiation. Use of a conservative model is warranted by the fact that a severe solar flare event will affect all SPS's then in orbit.

Even this conservative model indicates that degradation more than 10% from a single large flare is highly unlikely. Much improvement in the confidence in this result can be expected due to continued accumulation of statistical data from the current solar cycle and with direct observation of proton fluxes in the 2 to 10 MEV range.

The estimated requirements for annealing are clearly sensitive to the model used and the statistical approach adopted. A comparative study of the available data for silicon and gallium arsenide SPS's and solar arrays was conducted. This analysis revealed a significant difference in the environment model used for the Boeing and Rockwell solar blanket degradation analyses. Most of the differences in degradation predicted by the studies is due to differences in environment models. The Rockwell model is less conservative; it would predict that neither a silicon nor a gallium arsenide SPS would be likely to need annealing in 30 years at geosynchronous orbit.

Boeing test data on silicon solar cells are compared in figure 8 with the Rockwell projections for the gallium arsenide solar cell. It is clear that there is no significant degradation difference. Note the difference in proton/electron equivalences between silicon and gallium arsenide. This difference arises because of the difference in mass of the atoms of the two solar cell constituents. Our analysis would predict no significant difference in degradation between the two systems for the same fluence. Since the gallium arsenide solar blanket design has significantly less shielding, we would predict more degradation in the equivalent environment compared to the silicon blanket design.

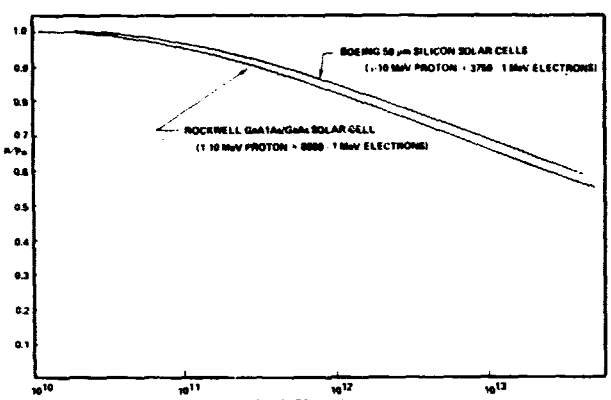


Figure 8. Degradation Comparison For Proton Irradiation

Recent results reported by Hughes show the radiation degradation of gallium arsenide to be a strong function of junction depth; gallium arsenide is reported to degrade less with shallow junctions. Additional radiation degradation testing is needed for both types of solar cells. The possibility that gallium arsenide cells may anneal at relatively low temperatures also needs to be further explored by testing.

Annealing of radiation damage in silicon has been repeatedly demonstrated in the laboratory. Illustrated in figure 9 are the results of oven annealing tests of bare 50 micron silicon solar cells. Several cells were tested with two irradiations and two anneals. All cells tested showed recovery on both anneals.

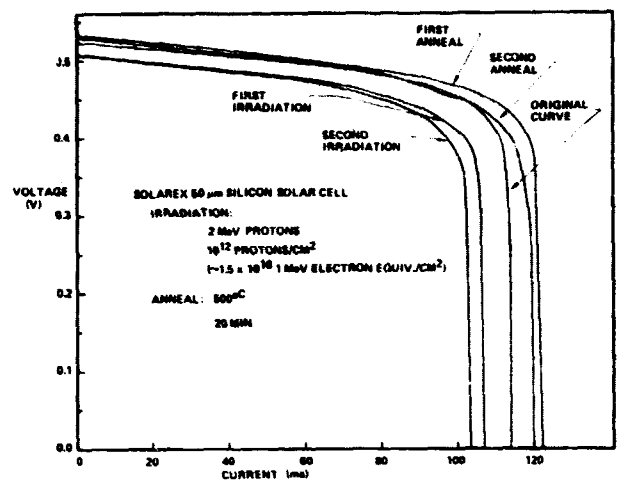


Figure 9. Thermal Annealing of Proton Damage In Silicon: Boeing Test Data

Annealing of the solar blanket on an SPS will require a technique tailored to that purpose, as well as a blanket design compatible with annealing temperatures. Attention has been given to laser directed-energy annealing under this contract. Initial tests of laser annealing of thin solar cells with glass covers were dedicated to measuring thermal response of solar cells to laser energy density. Resulting energy requirements are less than earlier estimates by about a factor of 5 and have been reflected in definition of the reference laser annealing system.

A test program was conducted to further explore the laser annealing of 50-micron solar cells. The original intent was to anneal glass-covered cells but a suitable method of glassing was not found. Ten cells were coated with 75 microns of glass by Schott in Germany using electron-beam evaporation of the glass. The coatings were of poor quality, e.g., full of bubbles, and contained much frozen-in strain. When subjected to annealing temperatures, the coated cells curled up like potato chips and the glass fractured. Attempts at RF sputtering at Boeing yielded glass deposition rates too low to be usable. Ion sputtering was tried on a few cells at Ion Tech. Good quality coatings were produced, but the cells were damaged in handling. Some damaged cells were subjected to annealing temperatures and did not exhibit the mechanical failures of the Schott-coated cells. Ion sputtering merits further investigation, as does electrostatic bonding of glass microsheet.

Laser annealing tests were conducted on nine 50-micron cells. Two were control cells that were not irradiated. These showed no loss in output due to exposure to the laser. One cell was broken in handling. Six cells were successfully tested with results shown in Figure 10. All cells tested showed some recovery. One cell was subjected to two cycles and showed recovery on both cycles. Cells that were moderately degraded appeared to recover more completely than those more severely degraded. Exposure times ranged from two to ten seconds at 500°C. There was some indication that longer exposure was beneficial; compare cell #31 (2 sec) with cell #33 (ten seconds).

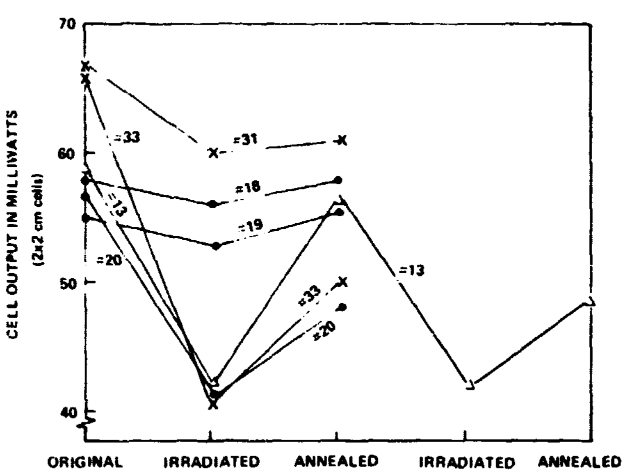


Figure 10 — Laser Annealing Results

These tests achieved moderately successful restoration of output from 50-micron cells after degradation by proton irradiation, under laboratory conditions. Clearly, much additional technology research is needed to develop designs and processes that would bring this technique to the point of suitability for large-scale application. Additional research should investigate a wider range of time-temperature histories and irradiation degradation and should emphasize development of a suitable cell encapsulation technique. Tests should encompass sufficient numbers of cells to enable statistical interpretation of results.

The concept of the SPS annealing system is shown in figure 11. Each laser gimbal would actually have 8-500 watt CO_2 lasers installed. The laser beams would be optically tailored to provide the desired illumination pattern and energy density. The gimbals would be mounted on an overhead gantry that would span the entire bay width; one bay of solar array would be annealed in fifteen meter increments. Solar array strings undergoing annealing will be taken out of service while they are annealed.

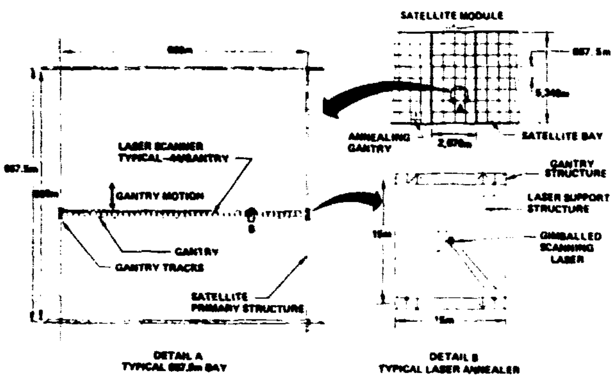


Figure 11. Laser Annealing Concept

WBS Item 1.1.2.1 Satellite Power Transmission Structure

Two analyses were conducted on this subject. The first was an evaluation of the use of aluminum as a structural material for the primary and secondary transmitter structures. Results of a NASTRAN analysis showed that thermal deflections of an aluminum structure would far exceed the required tilt tolerance of 1 to 2 minutes of arc. Therefore, if aluminum were used, the structure would require active thermal deformation compensation.

The second analysis evaluated structure design approach options. Early investigations of the antenna structure developed the tetrahedral truss primary and secondary structure concept. This system provides a maximum of structural efficiency for such an antenna. However, it constrains the subarrays to a non-square system and presents difficulties with respect to maintenance access.

The center illustration in figure 12 represents an attempt to design the antenna structure for maintenance. It provides easy access to subarray repair or replacement and allows square subarrays but is not very efficient structurally and employs tension members. Analysis of this combination indicated a relatively poor stiffness efficiency.

The pentahedral truss appears to offer a good compromise. It maintains good access with good efficiency, eliminates tension members and allows square subarrays. At t'.e beginning of Phase II, the MPTS structure will e revised to a pentahedral truss configuration.

WBS 1.1.2.2 Transmitter Subarrays

Aluminum Subarrays

Aluminum was also investigated for application to the subarray distribution and radiation waveguides. The baseline defined in the earlier study was an aluminum-plated graphite composite waveguide. Significant concerns have been expressed as to its suitability for high power, long life applications where temperature cycling may be a problem.

Aluminum has a high coefficient of thermal expansion compared to the graphite used in the earlier baseline. As a result, due to expected temperature changes, the aluminum waveguides will be significantly detuned resulting in power losses as noted in table 1. The cost equivalent of this efficiency loss is roughly $75 million per 5-gigawatt SPS. Although plated composites are high risk because of potential breaks or delamination of the plating under thermal cycling or high RF power conditions, the cost advantages of a low-coefficient-of-thermal-expansion material justify development of a suitable low-CTE approach.

Table 1. Comparison of Losses for Metal and Composite Waveguide

- AVERAGE STICK = 2.76 METERS
- ΔT = 85°C

	PERCENT POWER LOSS	
	ALUMINUM	COMPOSITE
STICK LENGTH	.67	.02
STICK WIDTH	.42	.12
CROSS GUIDE LENGTH	.17	.02
CROSS GUIDE WIDTH	.11	.03
	1.37%	.19%

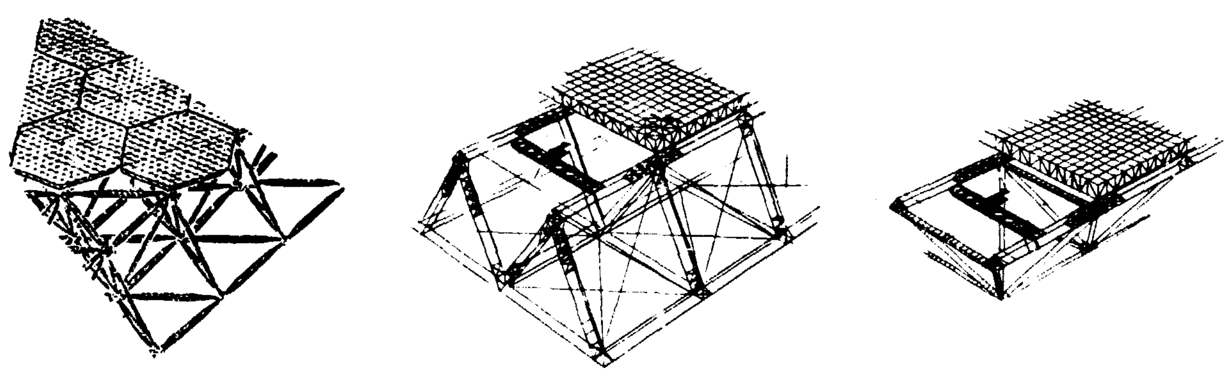


Figure 12. Antenna Structure Options

Solid-State Transmitter

Selection of microwave tubes, e.g., klystrons, for the reference system, has raised issues of power transmitter reliability and maintenance. Extrapolation of current trends in growth of tube life and reliability indicates that a mean-time-between-failure of 25 years is reasonable. Even with this figure, however, repair and replacement of microwave tubes is likely to dominate the maintenance workload for SPS's.

Solid state devices exhibit much better failure statistics. Those shown in figure 13 for gallium arsenide FET's show that at a channel temperature of 135°C, 98% of the devices will still be operating after 30 years. This suggests that a no-maintenance mode of operation may be feasible.

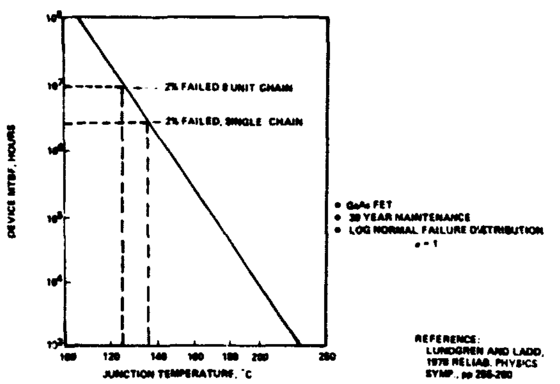


Figure 13. Solid State Device Lifetime

Various devices were considered for this application. GaAs FETs, silicon bipolar transistors and EBS's have the best values of power-added efficiency.

All the two-terminal devices have efficiencies less than 36%, too low for SPS. As noted above in the aluminum waveguide discussion, microwave link efficiency is of great importance in minimizing SPS costs.

Switched-mode amplifiers operate with the device power dissipation time integral (over the operating cycle) minimized as much as possible. This generally requires active device transition times about a factor of ten faster than the RF period. It also generally requires resonant reactive networks which make achieving bandwidths of a tenth or more of the operating frequency (as desired by many communications users) very difficult. In this sense, the narrow bandwidth required by SPS is a real advantage.

Present communications interests in microwave power amplifiers are increased linearity over wide bandwidth, RF output powers equivalent to traveling wave tubes, and longer life than the TWT's. For SPS, efficiency, lifetime, low cost and narrow bandwidth are desired. It is anticipated that with adequate funding the development of high-efficiency switched mode amplifiers for SPS is a low risk. However, SPS research may have to take the initiative because the communications industry can develop and prosper with present DC-RF conversion efficiencies.

The power per device is an important SPS parameter. The number of devices that can be efficiently combined in a module is limited by circuit losses; the power per module determines the RF power density per unit transmitting array area and is directly relatable to overall transmitter power. Silicon bipolar transistors, GaAs FETs and multi-mesa IMPATTs can all handle powers above 10 watts, adequate for SPS application if efficient combining can be accomplished.

GaAs FETs were selected as the preferred DC-RF conversion devices because of higher gain than silicon bipolars, equivalent expected power-added efficiencies, roughly equal power capabilities at 2.5 GHz and much better expected contact metallization reliability. GaAs FETs for SPS application could be fabricated separately and mounted in hybrid fashion or combined with other components on larger GaAs chips in integrated circuits. The latter alternative is preferred because of its expected lower costs in mass production.

A solid state transmitting antenna configuration was synthesized using design criteria for radiating module size developed in previous NASA studies and several circuit and radiator concepts developed in prior proprietary Boeing IR&D work. The basic elements of the solid state transmitting array are .59 x .59 λ (λ = free space wavelength) radiating modules. These are fabricated on 20 mil thick alumina dielectric sheet which is metallized for signal, control and power circuitry. Microstrip techniques are used for combining, filtering, and making antenna elements. Ways have been found to efficiently combine outputs from up to 6 amplifiers. The subarray concept is shown in figure 14

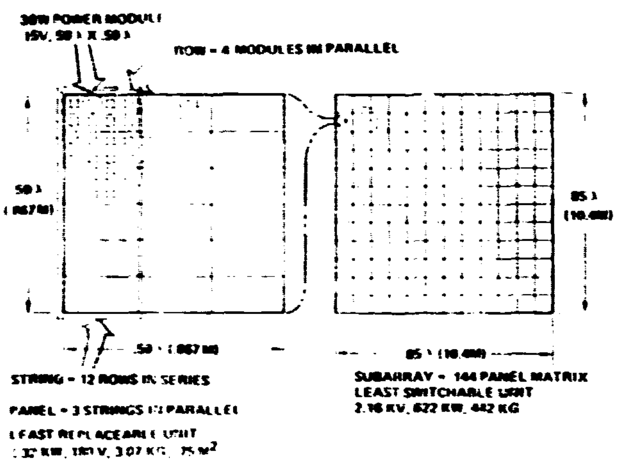


Figure 14. Solid State Subarray Layout

Solid state devices suitable for microwave power amplification operate at voltages on the order of 25 volts. Distribution voltages suitable for SPS application range from 20,000 to 40,000 volts. If it were necessary to process SPS electric power to a voltage of 25 volts, the cost and efficiency of power processing combined with the I^2R losses and conductor mass for such operations might be prohibitive. Therefore, an approach to elimination of power processing is highly desirable. The approach selected employs a series-parallel connection of the microwave power amplifiers (as regards DC power supply) similar to that used for solar cells in generation of the DC power. Aggregate sets of microwave power generators can then be supplied at comparatively high distribution voltages. The minimum-risk option is use of dc/dc converters but this will result in significantly greater SPS mass and cost. AC power distribution may provide a means of minimizing distribution losses and reducing solar array voltage. Mass and cost penalties will be similar to those for full dc/dc processing.

The noise at the power amplifier outputs of the klystron and solid state MPTS options are essentially the same because in a series of amplifiers noise figures of prior stages overwhelm contributions from the following stages. Thus even though a klystron may have a noise figure of 30 db as opposed to approximately 5 db for a solid state amplifier it makes no noticable difference in the system noise figure, if they both have similar front ends. Since the solid state panels have much less area than the comparable klystron modules, the former will spread their noise over a wider solid angle, thereby reducing the ground noise power per unit area.

The solid state transmitter is limited by maximum allowable device temperature to a thermal dissipation of roughly 1.5 kilowatts per square meter. At a conversion efficiency of 80% with a 10 dB Gaussian taper, the thermal constraints and ionosphere power density constraints follow characteristic curves as illustrated in figure 15. As can be seen, the solid state system is constrained to a total power level of approximately 2½ gigawatts with a transmitter aperture of 1.4 kilometers. Thus, this system is well-suited to smaller size, lower power SPS application and in fact may be limited to such.

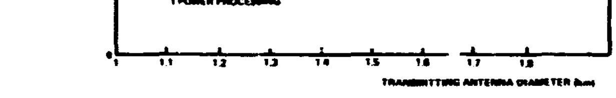


Figure 15. Representative Solid State SPS Costs and Sizing

More elaborate transmitter illumination strategies may allow higher power. The effects of truncating the maximum intensity region of the Gaussian taper as well as the use of reverse-phase rings, merit further investigation.

WBS Item 1.1.2.3 Power Transmitter Power Distribution

Lifetime expectancy for the DC-to-DC converters was analyzed during the critique. This indicated a significant problem with dielectric material life. If the earlier converter were derated to reflect ≥ 20 year life, an increase in mass would be expected. However, a new transformer technology using liquid-cooled transformers provide long life with less mass than the earlier system. Use of a liquid dielectric/coolant avoids the failure mode of corona-induced dielectric flaw growth that limits the life of potted transformers.

WBS Item 1.1.2.4 Power Transmitter Thermal Control

Failure analyses also indicated a problem with the heat pipe cooled klystrons. The difficulty was that the 500°C cooling section would utilize a mercury vapor heat pipe. In the event of a meteoroid puncture or other leak, the liquid metal would be released into the high voltage environment of the transmitter system and lead to arcing damage. Plating of liquid metals on insulators might lead to permanent contamination that would require repair and replacement. Vought Corporation examined a circulating fluid cooling option and found that a mass reduction was possible and that fluid could be selected that would minimize risk of arcing. Their analysis indicates that a circulating fluid system can be made as reliable as the heat pipe system and certainly more reliable than the expected lifetime of the klystrons themselves.

WBS 1.1.2.6 Power Transmitter Maintenance

A general failure analysis was conducted, with principal emphasis on failure rates and their effects on power production. (Some of the failure effects problem areas and their resolutions have been discussed in earlier pages.) The overall analysis is reported here.

A summary of equipment failure rates, updated from Part III results from the earlier study, is presented in table 2. (Expected rates of less than one per year or those that have no effect on power output are not included in the table.)

Table 2. SPS Satellite Failure Summary—10 GW SPS

WBS	NOMENCLATURE	QUANTITY/SPS	FAIL./SPS/YR.
1.1	ENERGY CONVERSION		
1.1.1.1.4	BLANKET TENSIONING DEVICES	337,920	335
1.1.1.3.2	BLANKET MECHANICAL ATTACHMENT	337,920	[illegible]
1.1.1.4.5	CELL STRING BLOCKING DIODES	10,872	7
1.1.2	POWER TRANSMISSION		
1.1.2.2.1	RF/DC CONVERTER MODULE	203,104	7,336
1.1.2.3.2	SWITCHGEAR	912	9
1.1.2.3.3	DC/DC CONVERTER	456	34
1.1.2.3.4	DISCONNECT SWITCHES	912	3
1.1.2.4.2	DC/DC CONVERTER THERMAL CONTROL	456	4
1.1.2.5	PHASE CONTROL	203,500	
1.1.2.5.1	RECEIVERS	[illegible]	4
1.1.2.5.2	DIPLEXERS	203,500	2
1.1.2.5.3	PHASE TRANSMITTERS	220,400	29
1.1.2.5.4	PHASE RECEIVERS	220,400	4
1.1.2.5.5	CONJUGATORS	203,500	33
1.1.2.5.6	CABLING	210,000	25

The annual power loss due to these failures is a function of the number of failures and the power loss per failure. As indicated in figure 16 the principal power loss problem is the DC-to-DC converters followed by klystrons and switchgear. Partial redundancy can be built into the DC-to-DC converters (with a small mass penalty) to minimize this problem.

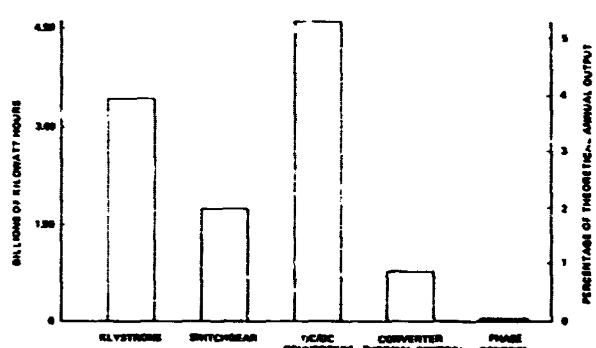


Figure 16. Annual Power Loss due to Failures

WBS Item 1.1.3 Information Management and Control

Telemetry and command requirements were estimated by examining the satellite design and roughly enumerating the instrument points required to determine the satellite state of health and to derive commands in the event of anomalies. For a 5 GW satellite (one MPTS antenna and its related power generation system), the number of measurements totaled nearly 2 million analog, over a million bilevel, and about 70,000 digital. About a half-million commands were identified.

Estimating these requirements necessitated many decisions concerning the component level to which each satellite subsystem will be instrumented and the level to which a command capability will be provided. For the subsystems which are relatively well-defined, this process was accomplished on the existing design. For those subsystems on which very little design information exists, requirements of typical current satellites were extrapolated to the SPS.

The large numbers of telemetry points and commands would represent a heavy workload if all telemetry data were transmitted to the ground. Automatic processing could be done by a distributed processing system on the satellite with processors located near the equipment being monitored and commanded. This approach provides two other advantages: the amount of data transmitted throughout the satellite and to the ground is reduced, and the delay from detection of an anomaly to receipt of a correcting command is reduced. In view of these considerations the on-board processing system was selected.

The design approach provides numerous microprocessors and memories distributed throughout the satellite. These processors are organized into groups, each monitored by a processor that is one of another tier of processors. Tiering continues to a Central Processor Unit which manages the data traffic to and from the ground. The recommended approach employs two systems connected by a limited data link through the slip rings.

The use of fiber optics is recommended for data transmission because of its reduced mass, fault tolerance (because a non-conductor does not propagate faults), wide-band multiplexing capability, immunity to EMI and arc discharges, and available inexpensive materials.

WBS Item 1.1.5 Communications

Analysis of communications system requirements appropriate to the command and data rates described under WBS Item 1.1.3 concluded that an S-band link with dish antennas about 0.6 m diameter would be technically adequate as regards interference from the power link at 2.45 GHz. In the SPS time frame, a higher frequency bank, e.g., X-band, may be a more desirable choice.

WBS Item 1.2 Space Construction and Support

The most economical construction of SPS's, given that many are to be built, will employ a semi-automated construction facility that achieves high crew productivity. The 1977 Boeing study developed a construction facility concept that became known as the "C-clamp." One of the principal objectives of the present study was to develop and evaluate alternatives to the "C-clamp" with the objective of reducing construction base mass, complexity, cost, and reducing construction operations crew size and operating cost.

By the midterm of Phase I the options were narrowed to three preferred systems: the platform-type single-deck, and two- and four-bay end-builders. Figure 17 compares these two types. In the last two months of the study, these three options were compared in more detail. Figure 18 summarizes the results. The mass and cost estimates for the three candidates were within a few percent of one another. Selection of the preferred approach therefore included other criteria.

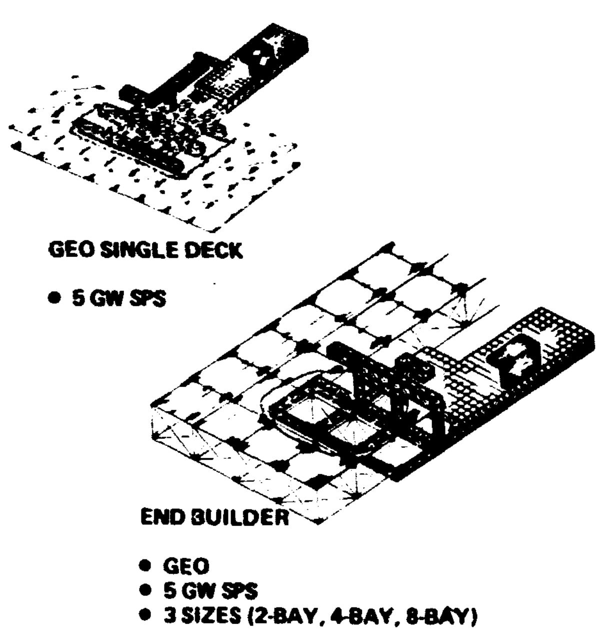


Figure 17. Alternative Construction Concepts

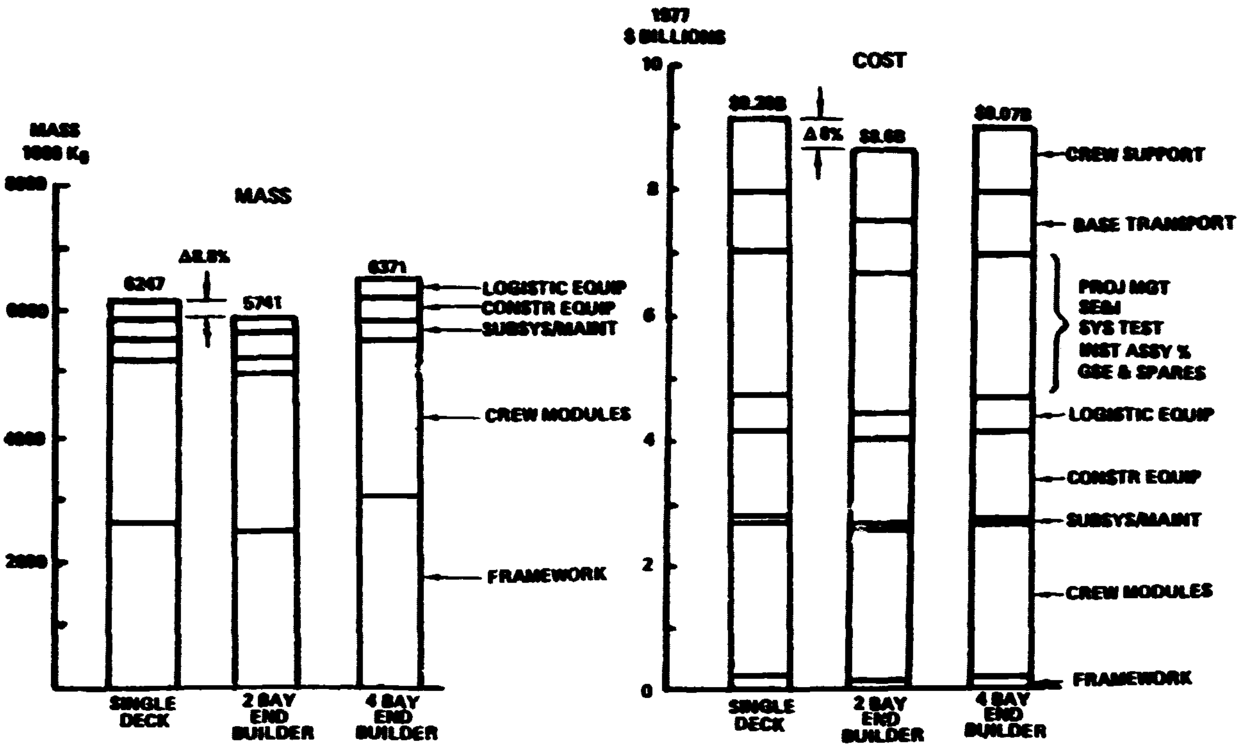


Figure 18. Alternative Construction Concepts Mass and Cost Comparison

Table 3 summarizes the evaluation including qualitative factors. The single-deck facility requires less interdependence of construction operations and is more adaptable to SPS design changes after the base is constructed, but the end-builders have an inherent capability for higher production rates; they represent a higher degree of automation. This supports the view that the cost trends found are valid and are not just estimating variances. The 4-bay end-builder is capable of a significantly higher production rate (for the solar array part of the SPS) than the groundruled 10,000 megawatts ground output equivalent per year. If evaluated for higher production rates, the 4-bay end-builder would undoubtedly prove more economic than the smaller facilities.

Evolutionary increases in degree of automation will be a normal trend of space construction technology. It is our judgment that the platform approach will be well suited to construction of an SPS prototype when some of the processes and equipment will be developmental, and configuration changes may be expected between the prototype and later production units. The four-bay end-builder was selected as the (production) system baseline for the Phase II study.

Table 3. Alternate Construction Concepts Summary

CRITERIA	SINGLE DECK	2-BAY END BUILDER	4-BAY END BUILDER
BASE COST	$9.28B	$8.8B	$9.07B
BASE MASS	6247×10^6 kg	5741×10^6 kg	6371×10^6 kg
CREW SIZE	407	[illegible]	387
OPERATIONS COMPLEXITY	DECOUPLED STRUCTURE ASSY/ SOLAR ARRAY DEPLOY	COUPLED STRUCTURAL ASSY/ SOLAR ARRAY DEPLOY	COUPLED STRUCTURAL ASSY/ SOLAR ARRAY DEPLOY
FLEXIBILITY (AFTER BASE BUILT)			
• HIGHER RATES		FASTER RATE CAPABILITY INHERENT	FASTER RATE CAPABILITY INHERENT
• FRAME DESIGN CHANGES	EASIER TO ADAPT		
• BAY SIZE CHANGE	EASIER TO ADAPT		
DEVELOPMENT RISK	NO SIGNIFICANT DIFFERENCE		

WBS Item 1.3 Transportation

WBS Item 1.3.1 HLLV

The prospect of heavy lift launch vehicle (HLLV) operations at the launch rates needed to support an SPS construction program has raised issues regarding potential environmental effects. The main concerns are atmosphere pollution, and noise and sonic overpressures.

HLLV's will employ clean fuels, methane or kerosene and hydrogen, burned in the rocket engines with oxygen. The quality of fuel consumed by an HLLV fleet will be very small, roughly 0.1% of total combustion fuels (coal and oil) presently burned in the U.S. Thus the gross quantities of pollutants will be negligible. However, the HLLV's will spend a portion of their trajectories in the upper atmosphere and ionosphere. Concern as to possible reduction of the ion density in the ionospheric F-layer had been expressed by a preliminary investigation. Analyses conducted by Boeing indicated that this problem could be minimized by suppressing the trajectory peak altitude to about 100 km. A number of ascent trajectories were simulated using various strategies to minimize trajectory altitude. Results are summarized in figure 19. It was found that the best trajectories had a peak ascent altitude of about 110 kilometers. Trajectories could be suppressed to keep the path below 100 kilometers with a slight performance penalty.

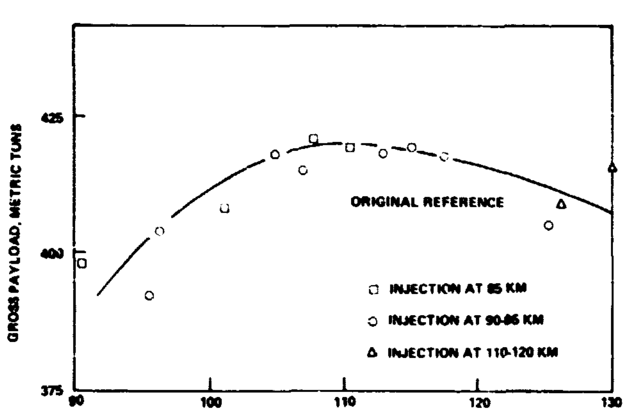


Figure 19. Launch Trajectory Suppression Results

HLLV launch and reentry paths will produce significant sonic overpressures. For a launch site on an eastern seacoast (e.g., KSC), the launch and booster entry overpressures occur over the ocean and are of little concern. Return of the upper stage could result in overpressures up to about 145 pa (3 psf) in the immediate vicinity of the recovery site if no mitigating strategy is used.

Mitigating strategies include (1) transition from high angle of attack to low angle of attack at supersonic speeds to maintain the terminal portion of the trajectory at a higher altitude, and (2) use of a supersonic turn to place the overpressure-generating part of the trajectory over the ocean. These strategies were investigated by trajectory simulations. Results are shown in figure 20.

Figure 20. Supersonic Turn Return Trajectory Can Reduce Overpressures to Less Than 2 psf

WBS Item 1.3.2 Cargo OTV

Electric Orbit Transfer Studies

The preferred orbit-to-orbit transportation concept identified in the 1977 Boeing study was the use of electric propulsion systems to convert SPS modules into powered spacecraft that could transfer themselves to geosynchronous orbit with a trip time of approximately 150 days. A tradeoff study comparing this to construction of SPS at geosynchronous orbit with chemically-fueled

(LO_2/LH_2) orbit transfer vehicles showed a cost saving of roughly \$2 billion per 10,000 megawatt SPS.

During the present Phase I study, an analysis was conducted to evaluate the use of independent electric orbit transfer vehicles to allow the benefits of electric propulsion to be combined with the benefits of geosynchronous orbit construction. The operational concept is illustrated in figure 21. Electric orbit transfer vehicles are constructed in low Earth orbit at a base which also provides staging depot functions. A fleet of approximately 20 electric orbit transfer vehicles conveys SPS payloads to geosynchronous orbit where SPS construction takes place. In order to provide expeditious transfers of crews and supplies, high thrust chemically-propelled orbit transfer vehicles are used to provide this service. The electric orbit transfer vehicles are reused 10 times over a lifetime of several years.

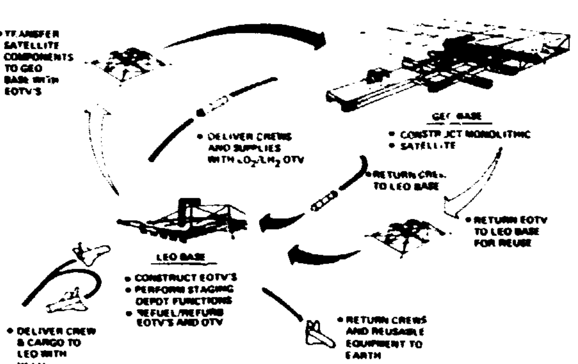


Figure 21. GEO Construction Concept Electric Orbit Transfer Vehicles

As a part of this analysis, improvements were made in the self-power configuration. The most important was in the arrangement of the solar array to be used for orbit transfer. The change improves inertia balancing, reduces the effects of solar blanket stretching loads, and avoids matching degraded solar cell arrays to undegraded arrays in series. Thruster modules were relocated to improve inertia balancing and thrust moment capability. Several propellant tank locations were tried to improve inertia balancing. Location at the center of the module provides the best overall transfer performance. The result of these changes was an improvement in the effective average integrated specific impulse for self-power transfer from approximately 2100 seconds to approximately 3000 seconds. (The electric specific impulse of 7,500 seconds is significantly degraded by the use of chemical thrust during periods of occultation and high gravity gradient torque.)

The independent electric OTV configuration is shown in figure 22. This orbit transfer vehicle is sized to deliver 4,000 metric tons to geosynchronous orbit and return with 200 metric tons. The return payload capability provides for return of packaging equipment and other items from the geosynchronous orbit construction site. Because the electric orbit transfer vehicle is smaller than the SPS modules discussed on the previous page, it suffers comparatively little from performance losses induced by gravity gradients, and achieves an integrated effective specific impulse of 6000 seconds.

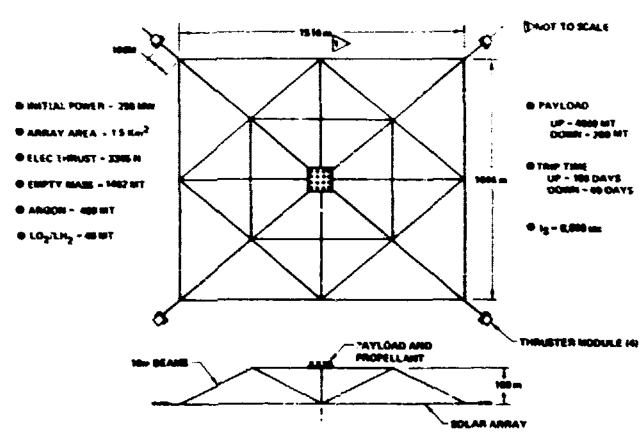


Figure 22. Electric OTV Configuration

A comprehensive cost comparison was developed to evaluate the self-powered electric propulsion option relative to the independent electric orbit transfer vehicle. Differences in costs of construction operations are included. Three options are shown in figure 23: (1) SPS self-transport modules without recovery of the electric propulsion equipment, (2) the same option with use of small electric OTV's to recover the orbit transfer hardware, (3) independent electric orbit transfer vehicles for all orbit-to-orbit cargo transportation with construction of SPS's at geosynchronous orbit.

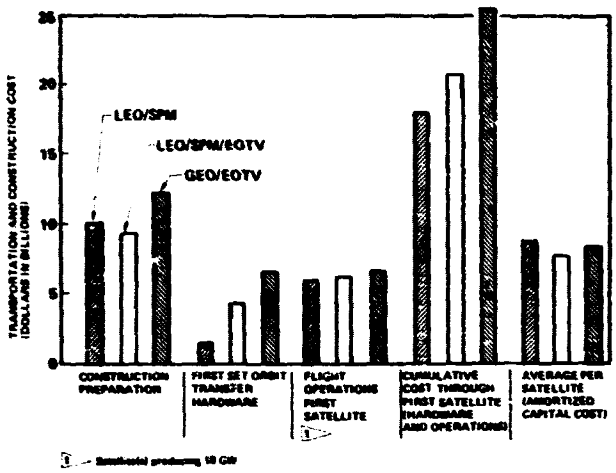


Figure 23. Construction/Transportation Cost Comparison

The bars on the left show the total cost of preparing to carry out the construction operations, including the unit cost of the construction bases and of their transportation. The second set of bars shows the transportation system fleet investment required to establish a production rate of 10,000 megawatts per year. The third set of bars shows the cost of transportation operations for the first year's operation, i.e., construction of two 5,000 megawatts SPS's. The fourth set of bars sums the first three sets showing the total investment through the first year's production operation. The fifth set of bars shows fully amortized costs for the three systems including amortization of all capital investments at an interest rate of 7½%.

The greater capital cost of the independent electric orbit transfer vehicle system is offset by its reduced fuel consumption on a fully amortized basis. However, the difference in front end cost to establish a production rate of 10,000 megawatts per year is approximately $7 billion.

If the independent electric orbit transfer vehicle can be reused many times by successful annealing of its solar blankets, it can provide low cost. If annealing recovery is less complete, the self-power operations which expose solar arrays to the orbit transfer radiation degradation only once, will exhibit lower cost. The independent electric orbit transfer vehicle (with the nominal reuse scenario developed under this study) shows relatively little sensitivity to hardware cost because the cost of the orbit transfer hardware is amortized over several SPS's.

Gallium arsenide solar blankets for the independent electric OTV were also examined. No advantage was found for the use of gallium arsenide in the orbit transfer vehicles under the assumption that silicon was to be used for the satellite systems. Clearly, if gallium arsenide is to be used for the SPS then it makes sense to also use it for the orbit transfer system.

Self-power from low earth orbit construction bases for establishment of SPS's at geosynchronous orbit was recommended as the preferred approach. This preference arose primarily because of the significant difference in front-end cost. It was decided, however, to retain the present NASA baseline of geosynchronous orbit construction for Phase II of the study.

Effects of Ion Jets on the Magnetosphere

Electric orbit transfer operations will consume roughly 10,000 tons of argon per 10,000 megawatts of SPS's emplaced. Although this consumption rate is entirely negligible in terms of resource availability, 10,000 tons of argon represents more than 10^{32} ions and neutrals injected into the Earth's magnetosphere during orbit transfer operations.

A brief investigation of possible effects on the magnetosphere indicated that this is *probably* not an environmental risk. Significant questions remain, and an analytical investigation adequate to give high assurance of no risk will require roughly two years.

Conclusions from the exploratory analysis were as follows:

1. Argon beam from thrusters travel intact for long distances tangential to orbit (at injection angle).

2. Transition from beam to single ion injection into geomagnetic field is a *major unsolved problem in plasma physics.*

3. Below 2.5 earth radii geocentric, all of the beam argon is temporarily captured by the geomagnetic field.

4. Above 2.5 earth radii (10,000 km altitude) most of beam argon escapes in a jet of plasma (86.6 km/sec); a small fraction is peeled off into trapped orbits.

5. A small fraction of the thruster beam charge exchanges at the thruster exit plane and escapes as neutral gas.

6. Inefficiencies in the present thruster systems allow 10-20% of the fuel to escape from the exit plane as thermal (0.1 – 1.0 eV) argon ions and neutrals.

7. At low altitudes (below 1000 km) this thermal argon diffuses back into the upper atmosphere.

8. At higher altitudes this thermal argon populates the magnetosphere.

9. The primary interaction between resident plasma and argon from the thruster is charge exchange between ions and neutrals.

Below 1000 km	$A^+ + 0$ and $A + 0^+$
Above 1000 km	$A^+ + H$ and $A + P^+$

10. The random walk diffusion of neutral and charged species is a *second major unsolved problem*, complicated by the influence of geomagnetic field orbit effects on ions.

WBS Item 3.3 Transportation Ground Support Facilities

Launch Site Selection

The launch site analysis task was motivated by the premise that selection of a low-latitude site would offer significant cost advantages with respect to operations from the Kennedy Space Center, where earth-to-low-orbit space transportation arrives at a 30° inclination orbit. A 30° plane change is required to reach a geosynchronous equatorial orbit. It was presumed that this plane change would incur significant performance penalties relative to a zero-degree or low-inclination low earth orbit. However, with electric propulsion this performance difference in terms of cost is minimal: the principal factor is difference in orbit-to-orbit propellant requirements and electric systems require comparatively little propellant in any case. These potential cost advantages are approximately negated by increased cost of ground transportation to remote sites. Costs of constructing and operating remote sites would be expected to exceed continental U.S. site costs by a factor of 1.5 to 2.

Therefore, the principal motivation for leaving KSC for a remote site will stem from the eventuality of SPS operations outgrowing KSC. Our estimates to date indicate that KSC can handle approximately 10 gigawatts per year of SPS construction.

Remote site possibilities include land-based sites such as the mouth of the Amazon in Brazil and ocean-based sites employing large floating structures such as the western Pacific low latitude sites identified by Jim Akkerman in studies at the Johnson Space Center. Large uncertainties presently exist as to the cost of large floating structures. Further analysis of the floating site option is recommended.

WBS Item 4.0 Ground Receiving Station

Rectenna construction and structural design concepts were developed jointly with the aim of minimizing construction cost. The construction equipment concepts developed were generally similar in sophistication to modern designs for roadbuilding and other field construction equipment, but were tailored to the specific task of rectenna construction. Figure 24 presents a conceptual overview of the rectenna design and construction approach.

A detailed grass-roots cost estimating model was developed and used. This model accounts for materials, capital equipment and labor costs by task and by schedule for each element of the rectenna system. This was necessary because there were no parametric cost estimating methods that are applicable to this problem.

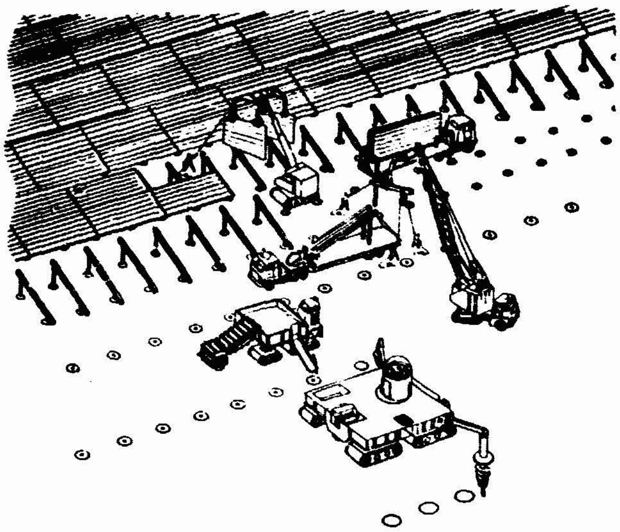
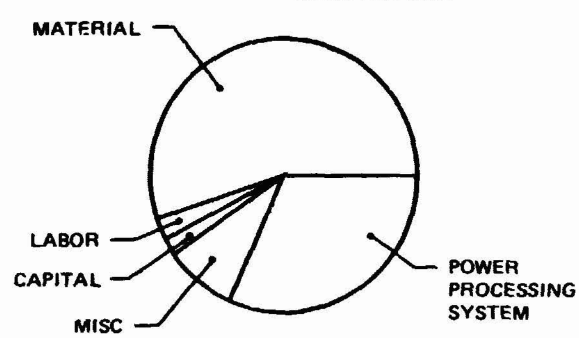


Figure 24. Five GW Rectenna Construction Concept

The cost results of the analysis are summarized in table 4. The construction task was estimated to require 25 months; the cost of the rectenna is nearly $1 billion less than rectenna costs previously estimated by (admittedly inappropriate) parametric methods. The rectenna cost is dominated by materials cost as is evident from the pie chart associated with table 4. Materials quantities are relatively well understood by comparison to equipment costs and labor content. Accordingly, the uncertainty in the presented rectenna cost is judged to be on the order of 15% (one sigma).

Table 4. SPS Ground System Cost (Summary of Major Equipment, Buildings, Material and Labor)

TYPE	SENSITIVITY	TOTAL COST (M$) (1977 DOLLARS)
RECTENNA		
MATERIAL:		
DIODES	4¢/DIODE	298
STEEL IN PANELS	15.8 Kg/m²	349
ALUMINUM BUSBARS (.02" x 0.5")	165,000 METRIC TONS	267
STRUCTURE		
CONCRETE (6 x 10 METER MODULE)	9 METRIC TONS/MODULE	81
STEEL (REINFORCING)	300 Kg/MODULE (100 Kg/ARCH, 3 ARCHES/MODULE)	100
LABOR		50
CAPITAL COST	(TYPICAL MACHINE LIFE IS 5 YEARS, COST TO PROJECT ONLY DURING USE)	40
MISCELLANEOUS		175
	TOTAL RECTENNA COST	1360
GROUND POWER DISTRIBUTION AND TRANSMISSION (PER SPS PHASE III FINAL REVIEW)		630
	TOTAL SPS GROUND SYSTEM COST (EXCLUDING LAND AND DEVELOPMENT COST)	1990



Rectenna Cost Distributions

WBS Item 5.0 Management & Integration

Industrial Infrastructure

Of the several components that require production rates significantly higher than those in present industrial experience, only the solar blankets represent a significant problem. Production rates of SPS hardware are, in general, not high when compared to production rates in major U.S. industries. The solar blankets, however, will require major technological advances in production techniques to meet the production demands of an SPS system.

Arthur D. Little's analysis of the photovoltaic market growth showed that the production rates of solar cells needed for an SPS prototype program are within the range expected for the Department of Energy Terrestrial Silicon Program. Much of the production technology for the terrestrial program will be applicable to SPS. Further in the future, the buildup of production capability to support an SPS production program of 10,000 megawatts per year will require production rates much higher than those for the prototype system.

Mission Control

As a part of the Phase I activity, it was desired to develop a concept for mission control operations to enable studies of mission operations in the Phase II activity. Several concepts were considered. The organization shown in figure 25 was selected for the Phase II analysis..

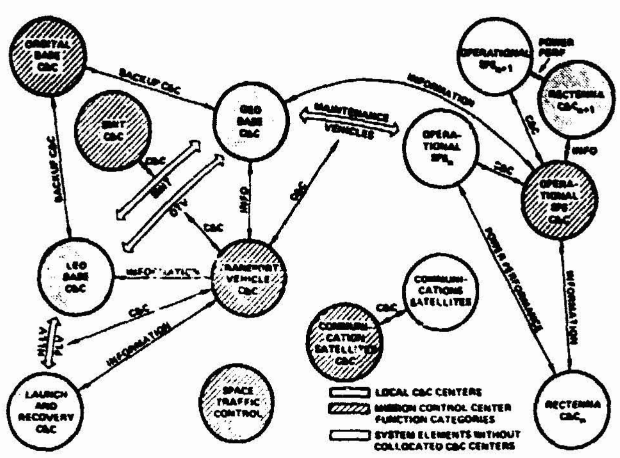


Figure 25. C&C Center Relationships to Major System Elements and To Each Other

3.2 Summary of System Description

WBS Item 1.0 Solar Power Satellite Program

The selected system description is based on a nominal capability to place 10,000 megawatts (ground output nominal generation capacity) of SPS power in orbit per year, in the form of two 5,000 megawatt SPS's.

The SPS efficiency chain was updated to reflect a slight improvement in intersubarray losses, and the orbit transfer compensation factor was deleted from the power budget to reflect geosynchronous-orbit construction. The earlier efficiency chain included a penalty for outages in the klystron power transmitter. These outages are also accounted for in the prediction of SPS plant factor in the maintenance and service analysis. This double bookkeeping has been eliminated. The revised efficiency chain and power budget are shown in table 5.

Table 5. Updated Efficiency and Sizing

	EFFICIENCY	MEGAWATTS PER LINK	
MAIN BUS I^2R	0.994	[illegible]	SOLAR ARRAY OUTPUT
ROTARY JOINT	1.0	[illegible]	
ANTENNA POWER DISTRIBUTION AND PROCESSING	[illegible]	[illegible]	TOTAL INPUT TO ANTENNA
DC-RF CONVERSION	0.85	[illegible]	
WAVEGUIDE I^2R	0.985	[illegible]	TOTAL RF POWER
IDEAL BEAM	[illegible]	6,732	TOTAL RADIATED POWER
INTER-SUBARRAY LOSSES	0.976	[illegible]	
INTRA-SUBARRAY LOSSES	[illegible]	6,341	
ATMOSPHERE LOSSES	0.98	6,221	
INTERCEPT EFFICIENCY	0.96	[illegible]	
RECTENNA RF-DC	0.89	[illegible]	INCIDENT ON RECTENNA
GRID INTERFACING	0.97	[illegible]	
	[illegible]	5,000	NET TO GRID

SOLAR INPUT:	1,353 W/m²
SOLAR-CELL CONVERSION EFFICIENCY (0.173)	234.1
BLANKET FACTORS ([illegible])	221.3
THERMAL DEGRADATION ([illegible])	211.1
ORIENTATION LOSS ([illegible])	[illegible]
APHELION INTENSITY ([illegible])	187.7
NONANNEALABLE RADIATION DEGRATION (0.97)	182.1
REGULATION, AUXILIARY POWER, AND ANNEALING ([illegible])	178
EOL BLANKET OUTPUT	178 W/m²
TOTAL SOLAR-CELL AREA:	[illegible] km²
SOLAR ARRAY OUTPUT	[illegible] MW

WBS Item 1.1 Satellite

The reference 5,000 megawatt system is illustrated in figure 26. The solar blanket is comprised of panel of 50 um silicon solar cells encapsulated in glass front and backside protection as illustrated in figure 27. The solar blanket design was revised to include shunting diodes required to provide shadowing protection. The shadowing protection is provided at the blanket panel level. In the

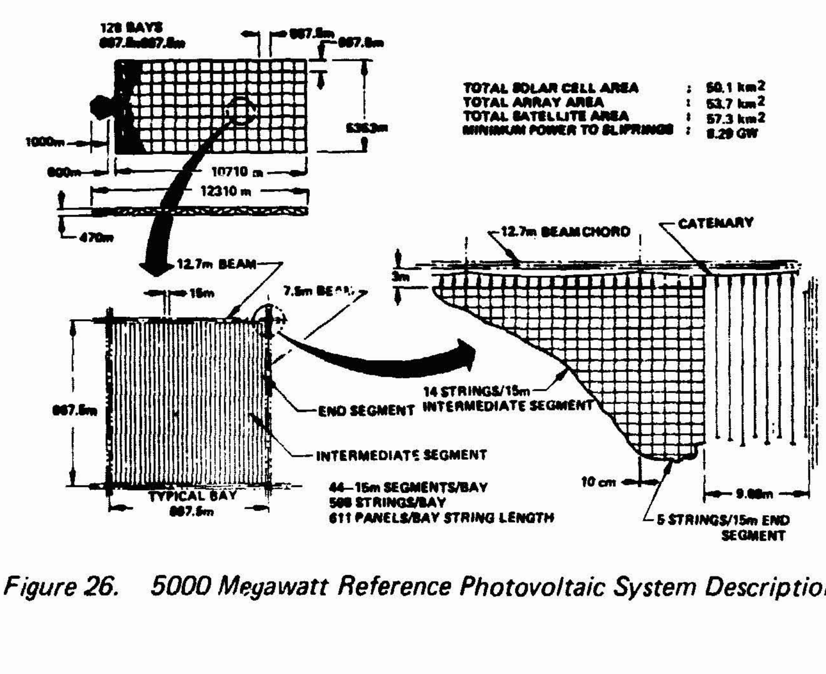


Figure 26. 5000 Megawatt Reference Photovoltaic System Description

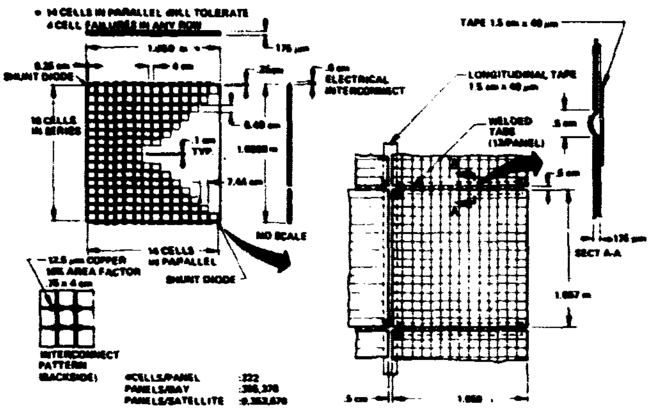


Figure 27. Reference Photovoltaic System Description

event of shadowing or a fault within the blanket, each affected panel is bypassed by the shunting diodes to prevent reverse breakdown failure.

The structure was revised to reflect the loading conditions appropriate to geosynchronous construction. The structure is a hexahedral truss made of graphite composite beams fabricated by beam machines. Solar array support beams are 12.7 meter tribeams with a mass of 7.48 kg per meter length; others are 7.5 meter tribeams of 4 11 kg/m.

Failure effects analyses had indicated that the previous three-bus power distribution configuration could be subjected to very large fault currents in the event of certain types of arcs. Because of this problem, the bus configuration was changed to reflect the use of 10 buses independent of one another.

The power transmitter is shown in figure 28. The transmitter includes primary and secondary structures supporting 7,220 transmitter subarrays and their power processing, distribution, and control equipment. Ten subarray configurations are employed to effect a 9.5 dB, ten-step approximation to a truncated Gaussian illumination taper. Each subarray includes phase control systems, klystron power amplifiers, thermal control, instrumentation, and distribution and radiating waveguides as illustrated in figure 29. The

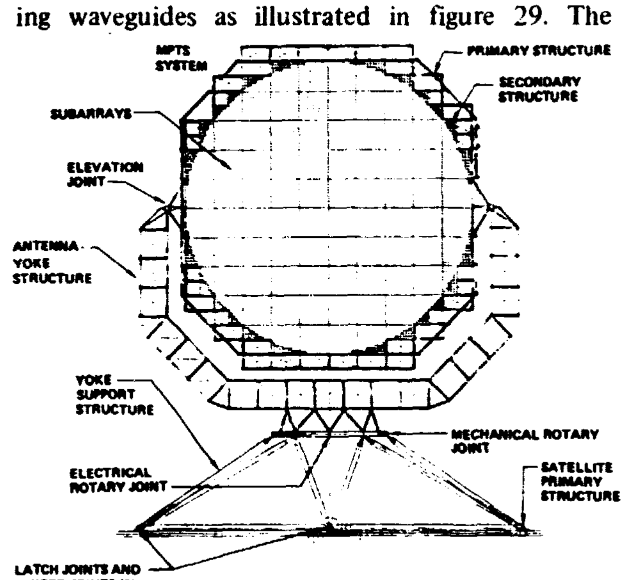


Figure 28. Reference MPTS Structural Approach

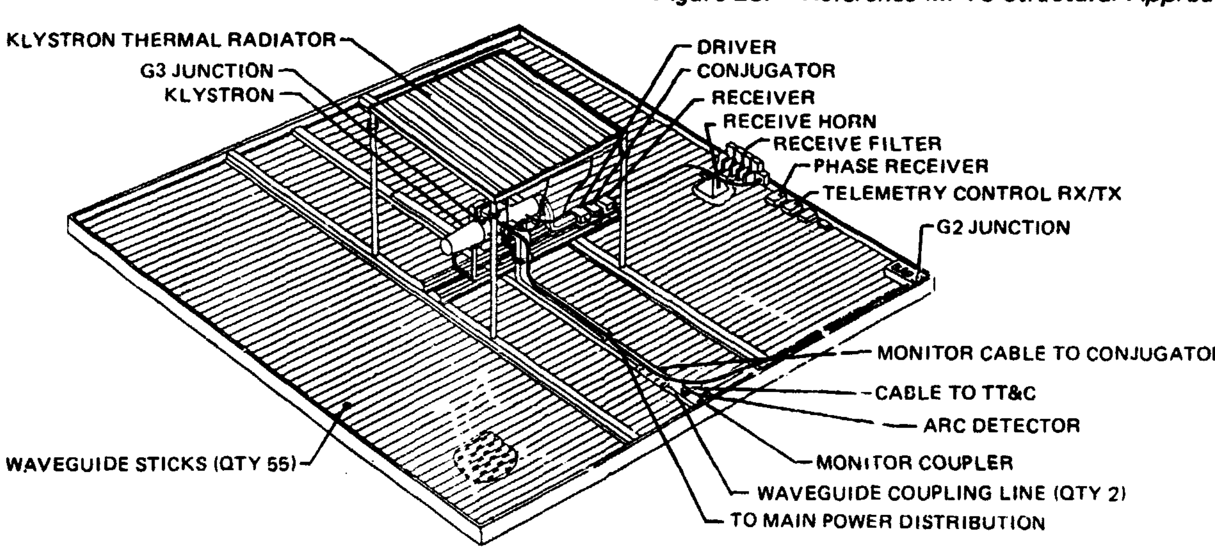


Figure 29. Mechanical Layout of a Typical Klystron Module in the Outer Ring of the Space Antenna

phase control system employs the retrodirective spread-spectrum design developed by LinCom.

WBS Item 1.2 Space Construction and Support

Space construction operations will employ two bases as illustrated in figure 30. The base is low Earth orbit (LEO) will construct and service the independent electric OTV's and function as a staging base to accumulate and transfer payloads from HLLV's to electric OTV's (one OTV will carry ten HLLV payloads) and transfer crews between personnel launch vehicles (PLV's) to personnel orbit transfer vehicles (POTV's).

The SPS construction base will be located in geosynchronous orbit. The selected system is a four-bay end-builder. The main features of this base are summarized in figure 31. The baseline 8 x 16 bay SPS is constructed in two successive passes.

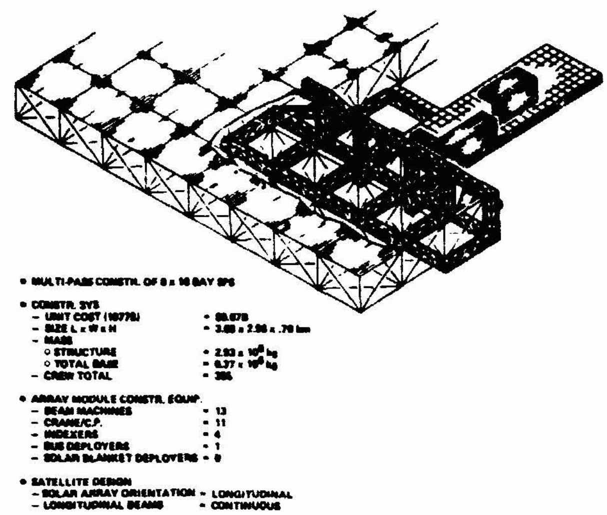


Figure 31. 4 Bay End Builder Base Features

WBS Item 1.3 Space Transportation

The integrated space transportation and operations concept was described earlier in figure 28. The space transportation system consists of the elements summarized in table 6. A budget for annual flights and estimated costs is included in the table.

WBS Item 1.4 Ground Receiving Station

The previous baseline rectenna was changed in structural design to accommodate the construction cost reductions developed by General Electric (discussed earlier). These revisions were summarized on page 19.

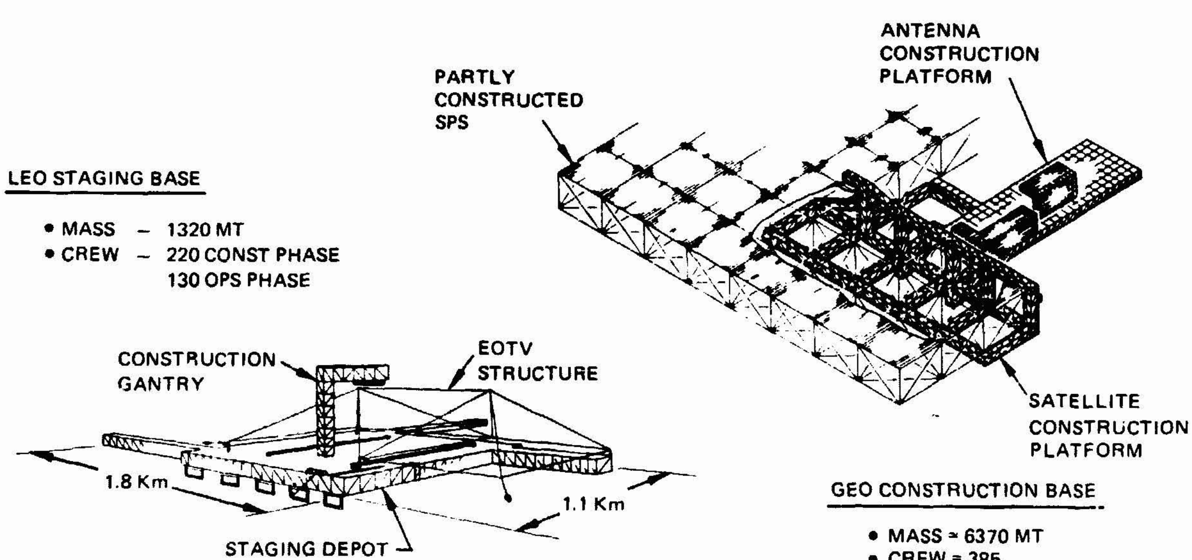
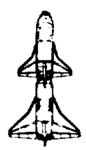
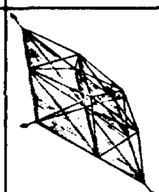
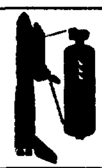
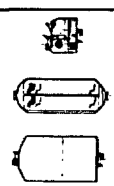


Figure 30. Orbital Bases—GEO Construction

Table 6. Space Transportation Element Summary

WBS NO. AND TRANSPOR–TATION ELEMENT	DESCRIPTION	HLLV FLIGHTS PER YEAR			OTHER FLIGHTS PER YEAR	COST PER FLIGHT	COST PER YEAR	REMARKS
		SPS CARGO	PROPEL-LANT	SUPPLIES				
1.3.1 HLLV (Heavy lift Launch Vehicle)	 • Two-Stage Series-Burn Winged Reusable Rocket, VTOHL • Booster LO_2/LCH_4 (51?8/1709 Tons) • Orbiter LO_2/LH_2 (1976/329 Tons) • Payload Net/Gross (380/420 Tons) • Gross Liftoff Mass (11,000 Tons)	(252)	(64)	(7)	N/A	$ 14M	HLLV Total $4522	Total is 323 flights per year; does not include SPS maintenance operations.
1.3.2 COTV (Cargo Orbit Transfer Vehicle)	 • Silicon Electric OTV, Annealable • Payload up/down 4000/200 Tons • Trip Time up/down 180/40 days • I_{SP} = 8000 sec; Initial power 296 Mw • Thrust 3345 N; Empty mass 1462 Tons • Argon 469 Tons; LO_2/LH_2 46 Tons	252	39	2	27 (Fleet of 23 vehicles)	$ 54M	1458 (COTV) 3528 (HLLV CARGO) 574 (HLLV Prop & Supplies)	85 HLLV Flights are required to launch COTV Fleet; this cost is amortized into COTV cost/flight.
1.3.3 PLV (Personnel Launch Vehicle)	 • Space Shuttle Orbiter and ET with Flyback Booster and 75-passenger personnel transfer module in payload bay. • Gross Liftoff Mass 2715 Tons	N/A	N/A	N/A	38 (Two Boosters and 2 Orbiters)	$ 12M	456	Cost per flight assumes other shuttle traffic as well as SPS support.
1.3.4 POTV (Personnel Orbit Transfer Vehicle)	 • Delivers crews and supplies to GEO base; two-stage reusable vehicle • Propellant LO_2/LH_2 (800 Tons evenly split between two stages) • Empty mass 28 Tons per stage • Thrust-Booster 1800 KN; upper stage 900 KN	N/A	25	N/A	12 (Fleet of 2 vehicles)	$ 3M	36 (POTV) 350 (HLLV Propellant)	HLLV launch of OTV is amortized into cost
1.3.5 PM (Personnel Module)	 • Flight Control Module – Crew = 2, Mass 4 Tons • Passenger Module – 160 passengers Mass 36 Tons • Cargo Module – 96 Tons crew provisions (480 man-months), 15 Tons empty mass	N/A	N/A	5	12 (2 sets of hardware, transported by POTV)	$ 2M	24 (PM) 70 (HLLV Supplies)	The PM files as a payload for the POTV.
							TOTAL 6496	

3.3 SPS Mass and Cost Summaries

Table 7 presents a mass summary for the 5,000 megawatt SPS. The mass is about 3% less than that for the equivalent system at the beginning of the study. The update in the selected system description has also resulted in a revision to the cost estimates. Current values are compared to the value from the 1977 study in table 8, in 1977 dollars. Reasons for significant changes are given in the table. The presentation has been rearranged from earlier results to reflect the current work breakdown structure and separation of indirect cost factors from direct outlays.

Table 7. Baseline Solar Power Satellite Nominal Mass Summary

COMPONENT	MASS (MT)	
1.1.1 ENERGY CONVERSION		27126
1.1.1.1 STRUCTURE	3198	
1.1.1.2 CONCENTRATORS	---	
1.1.1.3 SOLAR BLANKET	2263	
1.1.1.4 POWER DISTRIBUTION & SWITCH GEAR	1213	
1.1.1.6 MAINTENANCE	34	
1.1.2 POWER TRANSMISSION		12253.6
1.1.2.1 STRUCTURE	368.7	
1.1.2.2 TRANSMITTER SUBARRAYS	9493.3	
1.1.2.3 POWER DISTRIBUTION & CONDITIONING	1897.6	
1.1.2.4 THERMAL CONTROL	222.1	
1.1.2.5 PHASE CONTROL	TBD	
1.1.2.6 MAINTENANCE	144	
1.1.2.7 MECHANICAL POINTING	127.9	
1.1.3 INFORMATION MANAGEMENT & CONTROL		3.7
1.1.4 ATTITUDE CONTROL & STATION KEEPING		161.5
1.1.5 COMMUNICATIONS		2.7
1.1.6 INTERFACE (ENERGY CONVERSION/POWER TRANSMISSION)		147.2
SUBTOTAL		39831.7
GROWTH & CONTINGENCY (21%)		8353
TOTAL		48027

Table 8. Projected Unit Cost of One 5-GW SPS (Millions of 1977 Dollars)

WBS	ITEM	COST: POINT OF DEPARTURE (AS 5-GW)	COST: CURRENT	REASON FOR CHANGE
1.1	SATELLITE	3798	3917	
1.1.1	SATELLITE ENERGY CONVERSION	2274	2139	REVISED EFFICIENCY CHAIN; GEO CONSTRUCTION
1.1.2	SATELLITE POWER TRANSMISSION SYSTEM	1227	1263	REDUNDANCY ADDED TO PHASE CONTROL
1.1.3	INFORMATION MGMT & CONTROL	42	42	
1.1.4	ATTITUDE CONTROL & STATION KEEPING	144	144	
1.1.5	COMMUNICATIONS	111	111	
1.1.6	INTERFACE	(INCLUDED IN ENERGY CONV)		
1.2	SPACE CONSTRUCTION AND SUPPORT • DIRECT	554**	218	GEO CONSTRUCTION
	• CAPITAL RECOVERY		420*	
1.3	SPACE TRANSPORTATION • DIRECT	3193**	1802	GEO CONSTRUCTION WITH EOTV; REDUCED SATELLITE MASS
	• CAPITAL RECOVERY		1446*	
1.4	GROUND RECEIVING STATION	2934	2242	NEW ANALYSIS OF RECTENNA DESIGN AND CONSTRUCTION
1.5	MGMT AND INTEGRATION	421	421	
	*INCLUDED IN TOTAL UNDER CAPITAL RECOVERY BELOW			
	TOTAL DIRECT OUTLAYS	**	8600	
	CAPITAL RECOVERY FOR SPACE CONSTRUCTION BASE AND TRANSPORTATION FLEET	–	1866	
	INTEREST DURING CONSTRUCTION	1041	825	2 YEARS CONSTRUCTION TIME @ 7-1/2%
	GROWTH AND CONTINGENCY	1558	1130	EARLIER FIGURE HAD GROWTH APPLIED TWICE TO TRANSPORTATION COST
	PROJECTED TOTAL CAPITAL COST	13,499	12,421	

*INCLUDED IN TOTAL UNDER CAPITAL RECOVERY BELOW
**CAPITAL RECOVERY AND DIRECT WERE NOT SEPARATED IN EARLIER WORK

4.0 SPS PROGRAM EVOLUTION

Analyses of the programmatic structure of an SPS program have resulted in the multi-step approach summarized in table 9. Each step will provide knowledge and technical confidence leading to a program decision to initiate the next step. If the appropriate technical confidence from any step is not achieved, then the approach would be modified or possibly the program terminated if major difficulties were encountered.

The next phase of SPS activities beyond the present evaluation phase will be ground-based exploratory research. Recommended research activities for the beginning of this GBER phase are presented in table 10.

Table 9. SPS Development Phases

STEP	KNOWLEDGE GAINED	TECHNICAL CONFIDENCE	PROGRAM DECISION
EXPLORATORY STUDIES (COMPLETE)	SYSTEMS CONCEPT OPTIONS	THERE ARE NO FIRST-ORDER TECHNICAL OR ECONOMIC BARRIERS TO EVENTUAL SUCCESS	PROCEED WITH SYSTEMS AND EVALUATION STUDIES
SYSTEMS STUDIES	CONCEPTUAL DESIGN CHARACTERIZATIONS OF SELECTED BASELINES, TECHNOLOGY PERFORMANCE OBJECTIVES	DESIGN APPROACHES EXIST THAT CAN PROBABLY ACHIEVE TECHNICAL AND ECONOMIC OBJECTIVES	INITIATE TECHNOLOGY RESEARCH AND CONTINUE EVALUATION STUDIES
TECHNOLOGY RESEARCH	ACTUAL TECHNOLOGY PERFORMANCE	TECHNOLOGY PERFORMANCE SUPPORTS SPS DESIGN APPROACHES	INITIATE ENGINEERING TECHNIQUES DEVELOPMENT
ENGINEERING TECHNIQUES DEVELOPMENT	SU[illegible]S AND SYSTEMS ENG[illegible]G PERFORMANCE; ADEQUATE BASIS FOR SPECIFICATIONS	SPS DESIGN APPROACHES VALIDATED, PREFERRED APPROACHES SELECTED	INITIATE FULL SCALE DEVELOPMENT
FULL SCALE DEVELOPMENT	SPS "WORKS"	SPS CAN BE SUCCESSFULLY COMMERCIALIZED	ENTER COMMERCIAL PRODUCTION

Table 10. Recommendations For First Year of Ground-Based Experimental Research

DISCIPLINE	RESEARCH ITEM
SOLAR ARRAYS	• Begin development of annealable silicon and gallium arsenide arrays. • Improve data base on solar cell/blanket radiation degradation for long-term use. • Begin research and tests on high-voltage array/plasma effects.
THERMAL & FLUID SYSTEMS	• Begin development of heat pipes and circulating systems technology for thermal control of MPTS and power processing systems, including zero-g heat transfer and thermal radiators. • Study and research techniques/technology for in-space assembly and repair of fluid systems. • Begin development of long-life thermal coatings and repair/restore technology. • Update thermal engine SPS evaluation (as part of systems studies).
MICROWAVE POWER TRANSMISSION	• Begin development of high-efficiency low-noise klystrons and magnetrons. • Expand solid state research: Devices, circuits, radiators, thermal control, power supply, and integration. • Begin/extend experimental investigation and evaluation of phase control technologies. • Begin experimental evaluation of rectenna concepts. • Begin laboratory test programs of transmitter subarray integration.
SPS STRUCTURES	• Continue integrated structure and control dynamics analyses. • Begin development of structural verification technology.
MATERIALS & PROCESSES	• Continue/extend critical materials evaluation and accelerated life test technology. • Begin development of high-temperature composites technology for SPS. • Begin development of low-coefficient-of-thermal-expansion RF waveguide technology. • Explore alloys for thermal engines and heat exchangers. • Begin development of bonding and welding technology.
FLIGHT CONTROL SYSTEMS	• Extend/develop control theory and algorithms including active damping. • Perform design study of data and communications systems.
SPACE CONSTRUCTION	• Continue beam builder technology. • Extend crew aids and manipulator technology. • Evaluate and define needs for simulator technology.

Table 10. Recommendations For First Year of Ground-Based Experimental Research (Continued)

DISCIPLINE	RESEARCH ITEM
SPACE TRANSPORTATION	• Begin development of critical high-power electric propulsion technology. • Explore/begin development of reusable LH_2 insulation. • Update SPS transportation system definition (emphasis on HLLV).
SPS POWER DISTRIBUTION	• Evaluate and extend high-voltage insulator technology. • Extend high-voltage lightweight transformer and power processor technology. • Analyze SPS power transients and EMI effects. • Begin technology for SPS power interrupters and circuit breakers. • Begin technology development for high-voltage cables and insulations.
ENVIRONMENT	• In addition to environmental and related research to be conducted by DOE, space plasma effects and spacecraft charging research should be initiated.

Technology verification flight experiments may be needed to support design of a prototype or developmental SPS. Such flight experiments should be sized appropriately to early funding. During the prototype design period, development of production technology will take place. Space operations systems including a prototype production space construction base must be developed in order to support the prototype program. Depending on the size of the prototype, it may be possible to have a late start on the heavy lift launch vehicle to spread out the space vehicle systems development costs.

We have identified the need for an SPS prototype, but there is still a major uncertainty in how large the prototype should be. It seems clear that whatever size prototype is selected, it should provide efficient power transfer. If it is a low power system, it will nonetheless have a large transmitter aperture.

The major funding requirements arise from development from space bases and heavy lift launch vehicles. Some cost deferral options exist to reduce the peak funding. If commercialization proceeds, however, the economic cost of these deferrals tends to exceed their value.