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160540

SOLAR POWER SATELLITE
SYSTEM DEFINITION STUDY

Conducted for the NASA Johnson Space Center

Under Contract NAS9-15636

Volume I

PHASE II, FINAL REPORT

Executive Summary

D180-25461-1

November, 1979

(Rev. A, February, 1980)

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Approved By: G. R. Woodcock
Study Manager

Boeing Aerospace Company
P.O. Box 3999
Seattle, Washington 98124

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SOLAR POWER SATELLITE SYSTEMS DEFINITION STUDY EXECUTIVE SUMMARY

INTRODUCTION

This document is the executive summary report on the Solar Power Satellite System Definition Study, conducted by Boeing, General Electric, Grumman, Arthur D. Little, TRW, and Brown and Root, for NASA-JSC under contract NAS9-15636. This study activity is a part of the joint SPS evaluation initiated in 1977 by the U.S. Department of Energy and NASA and scheduled for completion in June of 1980.

The present study is a separately-contracted continuation of an SPS definition study conducted under contract NAS9-15196 in 1977 and 1978. That study, in turn, stemmed from still earlier efforts. This executive summary begins with a brief review of prior work in order to place the current results in context.

BACKGROUND

Origins of the Idea

Radiant energy from our sun has nurtured the development of life on our planet at least a billion years. The idea of utilizing some of this natural energy for the benefit of humankind, beyond basic life sustenance, has been extant for generations. Civilization arose when primative man developed agriculture, an organized means of utilizing solar energy for food and fiber production. The Greeks toyed with mechanizations . . . they recognized that Hero's Aelopile could be driven by concentrated sunlight. Wind and water power have been used since the beginnings of technological development. Wise architects have long recognized that proper orientation and window configuration in a house could reduce heating costs.

In the late 1800's, a printing press driven by solar-generated steam was exhibited at the Paris Exposition. Solar-heated hot water was in widespread use in Florida during the depression years. (It was later economically displaced by cheap electricity and natural gas). Research into the utilization of solar energy to produce steam for electricity generation was pioneered by the Meinels in the 1950's and 1960's and the power-tower concept was introduced by Hildebrandt about 1972. Photovoltaic cells were an offshoot of the semiconductor technology that began in the 1950's. Photovoltaics have provided electric power to nearly all U.S. spacecraft since the beginnings of the space program.

During these times, solar energy was widely regarded as a subject for eccentric scientists and idealists. Oil was cheap and abundant. The world was generally prosperous. Energy supplies were not a problem. It was into this environment that Dr. Peter Glaser introduced his idea of the solar power satellite (he called it satellite solar power station) in 1968. He had recognized the advantages of solar energy collection in space: (1) higher intensity; (2) dependable supply; (3) vanishingly small design loads for the necessarily large structures; and (4) ease of orienting the solar collector towards the sun. These could be realized if a means of beaming the collected energy to Earth could be found.

In 1962, Peter Kapitza wrote, "It is worth noting that, before electrical engineering was pressed into service by power engineering, it was almost exclusively occupied with electrical communications problems. It is very probable that history will repeat itself: at present, electronics is used mainly in radio-communication, but its future lies in solving major problems in power engineering." Further, the Russian SPS technology reviewer who highlighted Kapitza's view wrote, "In its broad sense, power engineering has always been the base for growth in the material well-being of human society."

Early concepts of wireless power transmission were investigated by Nikola Tesla. His approach was to excite the entire Earth as a resonant capacitor. Later, directed energy transmission was developed by W. C. "Bill" Brown of Raytheon. In the mid-1960's he experimented with helicopters powered by highly directional microwave beams. Glaser's insight was to scale the directed-energy concept up to the transmission of thousands of megawatts of power by a single transmission link, and to consider the case of very large apertures, e.g. 1000 meters, to realize sufficient gain to enable transmission from geosynchronous orbit to Earth.

Peter Glaser's orbital concept for solar energy utilization, unique in its ability to serve baseload electrical generation needs from solar input, was accorded little attention in the energy-rich world of 1968. The little attention it received was mainly devoted to reasons why the solar power satellite idea would not work. Prominent objections were the "impossibility" of efficient energy beaming and the "high cost" of energy for space transportation.

(From the vantage point of today's knowledge, we would reply that (1) a fully coherent electromagnetic energy beam has zero entropy and is ideally capable of 100% efficient energy transfer, and that (2) the idealized orbital energy of a solar power satellite in geosynchronous orbit—16kwh/kg—is equivalent to about one week's output. Hence these issues have to do with attainability of ideals.)

Earlier Studies

In 1972, a technical feasibility study was carried out by a contractor team comprised of Arthur D. Little, Grumman, Raytheon, and Spectrolab, funded by NASA through the Lewis Research Center.

Figure 1 compares the SPS concept from Glaser's original publication in 1968 with the configurations developed by the feasibility study. The latter configuration includes many features found in current configurations, including concentrating solar arrays, a microwave transmitter, and a large space frame truss structure. The study concluded that the SPS was technically feasible and that it could provide baseload (continuous) electric power for utility service.

Boeing began investigating the SPS concept in 1972. Our early studies were very modest in scope, but reached three relevant conclusions:

1) Thermal cycle conversion offers an alternative to photovoltaic conversion. Figure 2 illustrates early thermal-cycle concepts; these did not recognize the importance of gravity gradients or onboard power distribution on configurations designs. In 1972-74 although some investigators, notably Glaser, were forecasting low-cost photovoltaics, the preponderance of expert opinion was that photovoltaics would always be expensive.

2) Space transportation costs per kilogram of payload could come down to about 1/10 to 1/5 of

SPS 2825

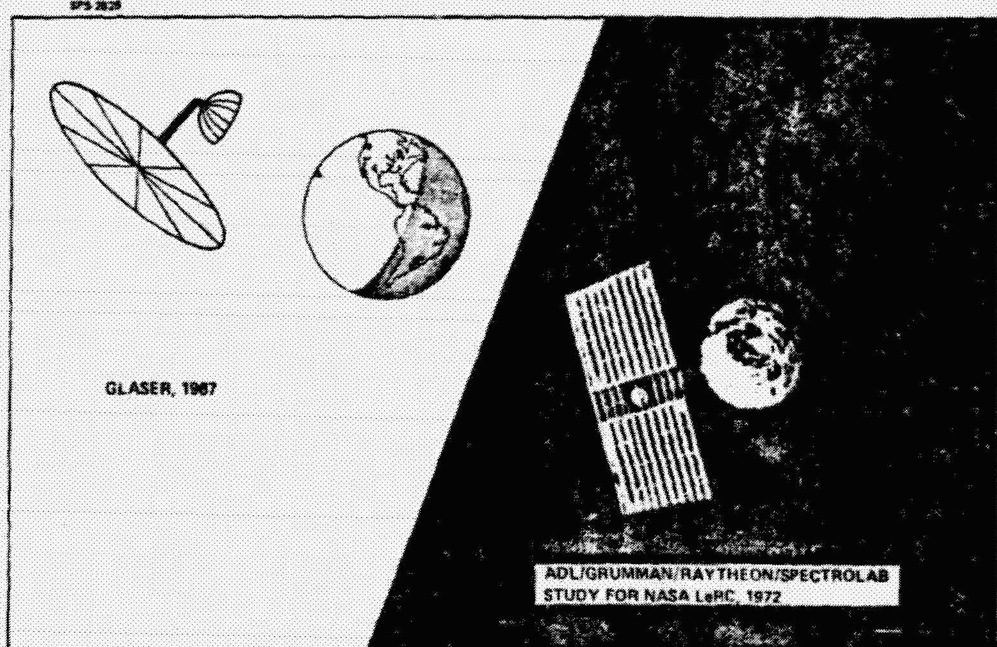
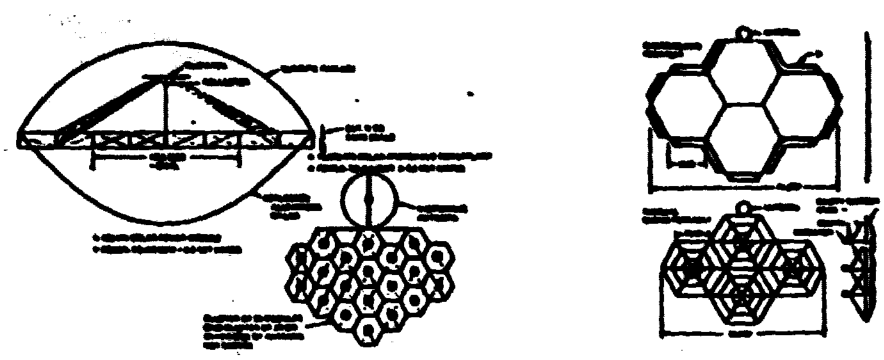


Figure 1 – Early SPS Concepts



SOLAR-BRAYTON POWER SYSTEM CONCEPT* BRAYTON-PHOTOVOLTAIC COMPARISON

*"THEREFORE, WHILE RECOGNIZING THAT SOLAR CELLS MAY ULTIMATELY PROVE TO BE THE BEST SOLUTION, WE EXAMINED THE ALTERNATIVE OF A SOLAR CONCENTRATOR AND HEAT ENGINE."

Figure 2 – Configuration Concepts Circa 1972-4

then-forecast shuttle costs if an SPS-capable transportation system could be developed. This would place much less stringent economic constraints on SPS mass and permit thinking of SPS's becoming economically feasible much earlier than formerly thought.

3) The use of electric propulsion for orbit transfer could have significant cost advantages.

The "energy crisis" of 1973-74 catapulted the concept of solar energy utilization out of the "eccentric scientist" realm into an environment of practical engineering study and experiment. This of course was a change in outlook only and did not reflect any particular technical development. Nearly all of the attention was focused on ground-based means of solar utilization, but interest was also renewed in the SPS idea.

Additional studies and experiments, partly funded by NASA over the period 1973 to 1975, established the feasibility of efficient energy transfer 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.

Figure 3 illustrates comparative evaluations conducted under a 1975 Boeing study of energy conversion alternatives, conducted for MSFC. As a result of these comparisons, nuclear and thermionic options were recommended for de-emphasis because of their relatively high mass. At this point, Rankine energy conversion had not been investigated.

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 the SPS Development and Evaluation Program Plan jointly sponsored by DOE and NASA. The principal milestones in this plan are:

Reference System Definition Report,
October 1978 (Complete)

Preliminary Program Recommendations,
May 1979 (Complete)

Updated Program Recommendations,
January 1980

Final Program Recommendations, June 1980

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

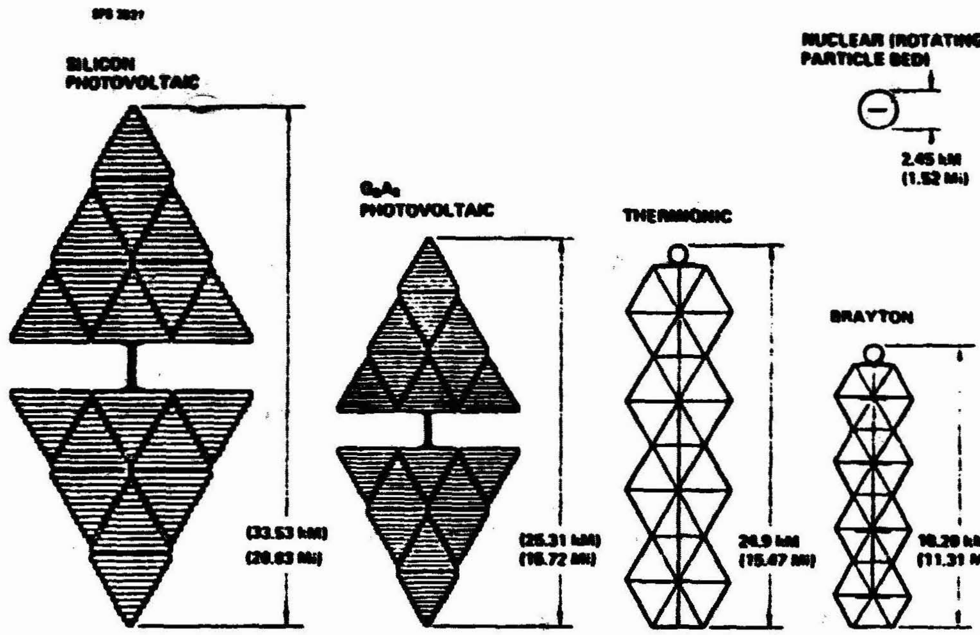


Figure 3 — Comparison of Power Satellite Option Sizes

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.

Figure 4 shows the design evolutions of the principal types of SPS systems and space support systems that developed during the JSC/Boeing-GE study.

The photovoltaic SPS began with the JSC truss configuration at a geometric concentration ratio of 2. This configuration was initially sized for beginning-of-life output capability. It was later resized to allow maintenance of output capability throughout the thirty-year system design life, by periodic array addition. At the completion of part 1 of the study, a total of 10 photovoltaic options had been defined. These included silicon and gallium arsenide energy conversion at concentration ratios 2 and 1 and various power maintenance methods, including periodic annealing. The lowest cost silicon system was selected for continuance into part 2. This system employed no concentration and used in situ annealing of the solar cells for power maintenance. The configuration was further defined during part 2.

The thermal engine analyses began with the Brayton system defined under an earlier contract. Early in the subject study, an analysis of available data on plastic film reflector degradation in the space environment suggested that a 30% degradation might occur. Consequently, the concentrators were enlarged to compensate. The configuration was next divided into 16 modules with trough-shaped concentrators as shown under "constructionized Brayton." During part 1, Rankine and Thermionic systems were also evaluated. Initial evaluations indicated the Rankine system to be more massive than the Brayton system. However, a cycle temperature ratio optimization resulted in a lower overall mass and the Rankine option was selected. Additional design changes introduced at this point eliminated steerable facets from the concentrator by flying the system always exactly facing the sun.

Toward the end of the study, new information became available on plastic film reflectors indicating that degradation would not occur and the final system configuration was, therefore, resized to reflect nondegradation of the concentrator.

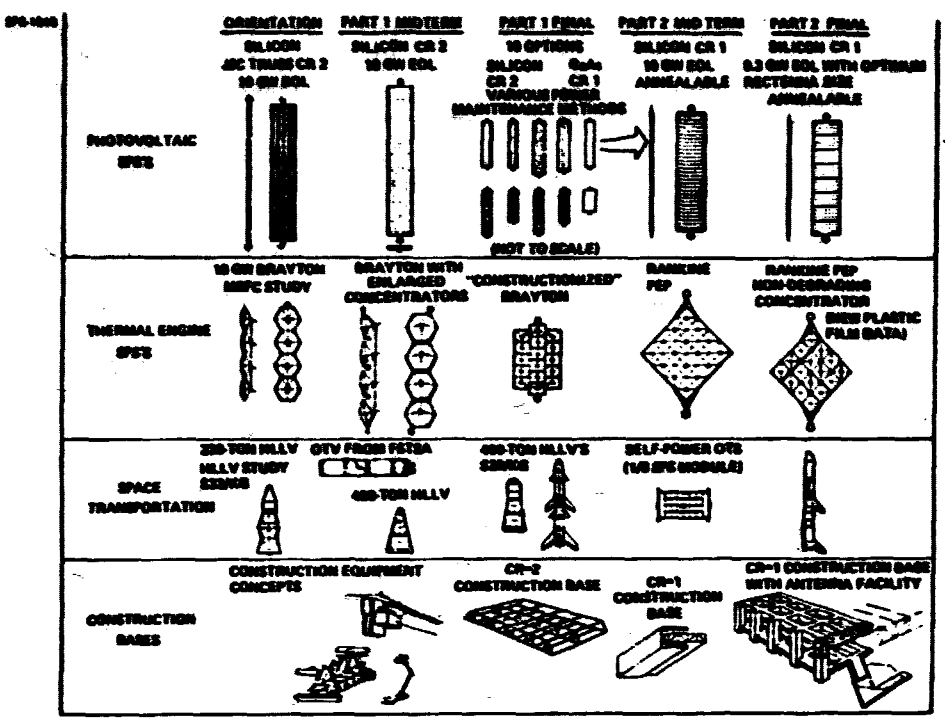


Figure 4 – SPS System Definitions Study Design Evolutions

The principal evolution in space transportation systems was in the launch vehicle. The study began with a 230-ton payload heavy lift launch vehicle defined by an earlier transportation study. It had a large expendable payload shroud. Packaging analyses indicated that higher payload densities could make possible a reusable shroud. Staging optimization studies led to a 400 ton heavy lift launch vehicle that went through the evolution shown. Also, a two-stage winged vehicle option, based on earlier JSC studies, was added. Later, the winged configuration was updated and selected over the ballistic option based on a judgement of less technical risk.

Studies of chemical orbit transfer vehicles included space based and Earth launched options. The orbit transfer option taken from the Future Space Transportation System Analyses study was found to be least cost and was retained. Investigation of the means of moving the SPS hardware itself from low Earth orbit to geosynchronous orbit continued to indicate a significant cost advantage to the self-power concept.

The evolution of construction concepts began with equipment. The initial construction base concept was for the concentration-ratio-2 satellite and included little detail other than overall size and shape. This construction base concept evolved to the illustration shown at the lower right hand corner of the chart. This construction base included capabilities to construct satellite modules and transmitter antennas. Analogous construction base concepts were developed for the thermal engine system, but are not shown.

The principal conclusions reached by the study were as follows:

(1) Silicon was recommended as reference, gallium arsenide as alternate: Silicon was seen as lowest risk, and cost differences were within the uncertainty band;

(2) Rankine was recommended over Brayton: Thermal cycles presented construction and transportation problems when examined in detail; thermal cycles, however, provide a hedge against potential photovoltaics cost problems;

(3) The klystron reference power transmitter design was developed: Detailed error analysis confirmed potential for efficient power transfer;

(4) The winged HLLV was selected over the ballistic option: The transportation cost for either was estimated as \$33/Kg to LEO; the winged option appeared to present less risk;

(5) Electric self-power orbit transfer was selected over LO_2/LH_2 OTV on the basis of lower cost. Independent electric OTV was not investigated;

(6) An end-to-end space construction approach and facility concepts was developed: Construction simplicity was a factor in selecting concentration ratio = 1;

(7) Initial analyses of SPS maintenance and power grid compatibility were conducted: Level-loaded maintenance was selected as more economic than concentrating on equinox periods.

During the summer of 1978, following the study just discussed (and the companion study by Rockwell International for the Marshall Space Flight Center), NASA developed a reference system description published in October 1978. This system description drew data from the Boeing Study, the Rockwell Study, and NASA-Johnson and Marshall Space Flight Center inhouse studies. Principal features of the reference system are as follows: 5,000 megawatt SPS, one transmitter—silicon and gallium arsenide solar cell options; klystron transmitter—magnetron and solid state recognized as potential options; GEO construction with independent electric OTV; two-stage vertical takeoff, horizontal landing rocket HLLV. These decisions were made in parallel with the beginning of the current Boeing study for NASA Johnson Space Center. As these decisions became clear the present study adopted them wherever possible, examined alternatives in certain cases and is now in consonance with the reference system description.

INTRODUCTION TO STUDY RESULTS

Study Team

The present study was initiated in July of 1978, under JSC technical direction. The JSC technical manager was H. Benson. The study team includes Boeing as prime contractor and Arthur D. Little, Brown & Root, General Electric, Grumman, and TRW as subcontractors. The study team leaders for each contractor are named in Figure 5.

SPS System Description Summary

The composite drawing of Figure 6 illustrates the main features of the present reference design silicon-solar-cell SPS. The solar array consists of glass-encapsulated 50-micrometer silicon solar cells suspended in a space frame cubic trusswork of 128 bays, each 667.5 meters square and 470 meters deep. The array area of 49.6 square kilometers generates 8766 megawatts of dc electricity at 44 kv. This electric power is conducted by an arrangement of ten pairs of busses to the slipring where it is transferred to the power transmitter. The transmitter converts the electric power to 6700 megawatts of radiated RF power at 2,450 megahertz. A total of 101,552 high-efficiency klystron power transponders conjugate and

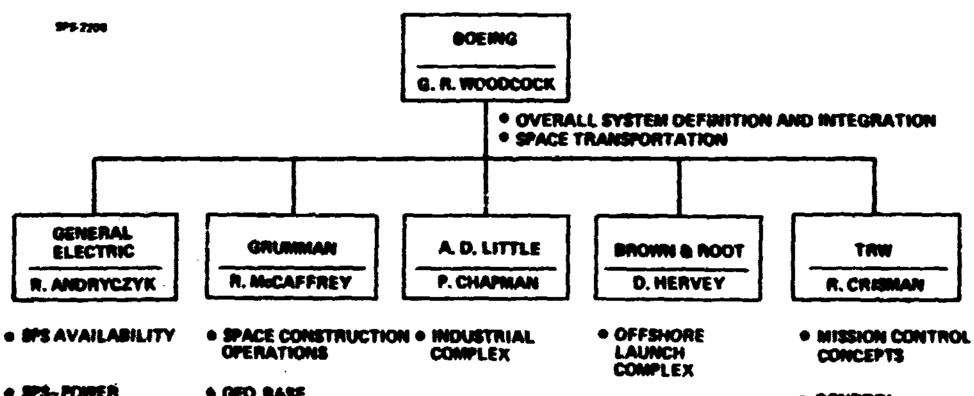


Figure 5 – Study Contract Team Organization

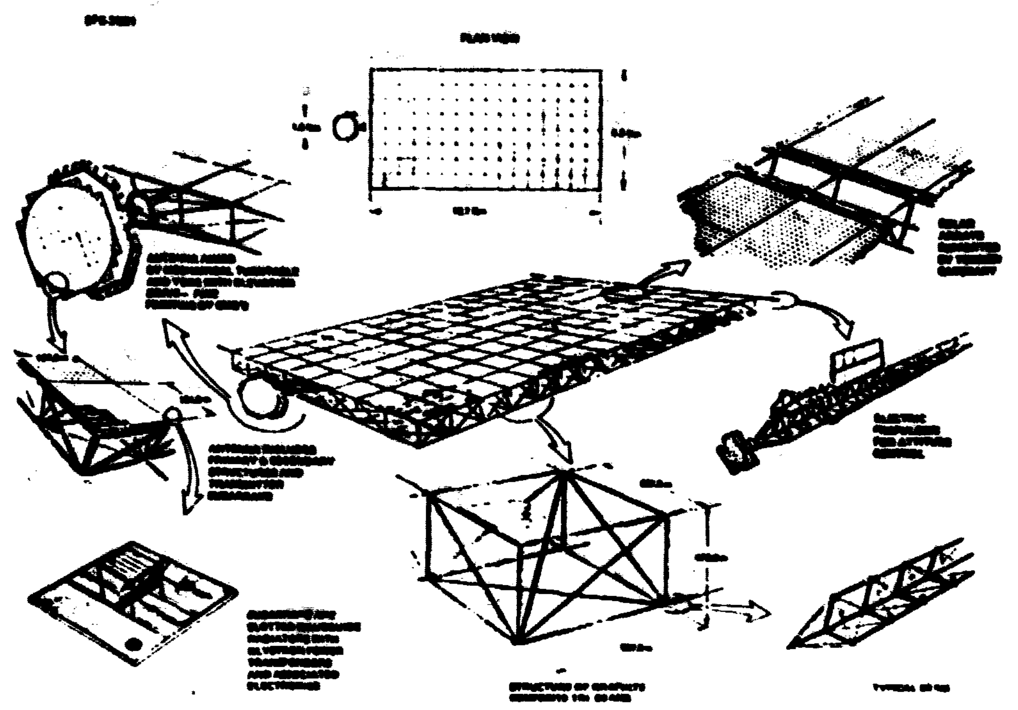


Figure 6 – SPS Silicon Solar Array Reference Design Concept

amplify the uplink phase control signal and return it to Earth as a power beam. Each klystron is individually phase-controlled to maintain precision beam forming and high gain. The SPS solar array is maintained sun-facing by an electric propulsion attitude control system and the transmitter is maintained Earth-facing by a combination of turntable drive coarse pointing and control-moment gyro (CMG) fine pointing.

The complete SPS system includes not only the satellite, but also space construction and support systems: a base in low Earth orbit (LEO base) for construction of electric orbit transfer vehicles (EOTV's) and for service as a space transportation staging and logistics base; a base in geosynchronous orbit (GEO base) that constructs the SPS's and serves as a maintenance support base; and the mobile maintenance systems that visit operating SPS's to provide periodic maintenance. In addition, space transportation provides crew and cargo transportation with four vehicles: Heavy Lift and Personnel Launch Vehicles, and Electric (Cargo) and Personnel Orbit Transfer Vehicles. Finally, on Earth there are SPS receiving stations and the industrial and transportation infrastructure and integrated operations management that support the entire enterprise. The entire system is symbolized by Figure 7.

A further aspect is provided by a timewise slice. The SPS program, beyond the present phase of paper-study evaluation supported by a few exploratory technology investigations, is projected to include five phases as summarized here:

- Research—Evaluate and select SPS technologies; resolve technical, environmental and socio-economic issues;
- Engineering verification—demonstrate conversion of SPS technologies into practical engineering hardware;
- Demonstration—demonstrate end-to-end operational suitability of SPS as a baseload electric power source;
- Investment—create the industrial base to produce SPS generating capabity at 10,000 megawatts/yr;
- Commercial production—install and maintain 300,000 megawatts of SPS generation capacity over 30-year period

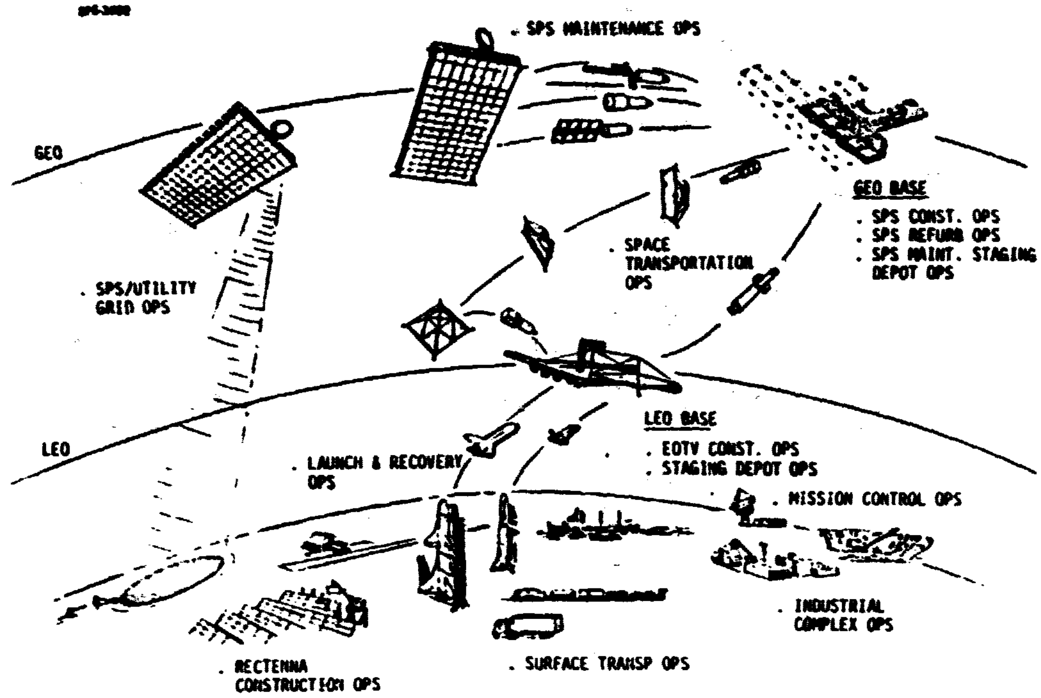


Figure 7 — Integrated SPS Program Operations

STUDY RESULTS

The reference systems concept just described was one study result. It was presented at the outset to provide a frame of reference for the reader.

The study was comprised of eight tasks and was conducted in two phases. The accomplishments and conclusions are summarized in Table 1.

TABLE I

PRINCIPAL STUDY ACCOMPLISHMENTS AND CONCLUSIONS

Task	Phase	Accomplishment	Conclusion
Baseline Critique	I	Developed in-depth critique of baseline	No fundamental flaws but several design deficiencies that should be corrected
	I	Corrected design deficiencies	No significant change in mass, cost, or efficiency
	I	Evaluated electric orbit transfer vehicle in comparison with self-power	Cost & risk differences not decisive; adopted DOE/NASA reference (EOTV)
	II	Defined solid-state SPS option	o Antenna-mounted approach is viable

TABLE I (Continued)

PRINCIPAL STUDY ACCOMPLISHMENTS AND CONCLUSIONS

Task	Phase	Accomplishment	Conclusion
			o Solid-state transmitter optimizes at 2500 megawatts delivered, and is nearly as cost-effective at that power as the Klystron system o Solid-state is sufficiently attractive to merit further analysis & research
	II	Re-analyzed reference design with mass & cost estimates at WBS Level 5/6	o No significant change in mass or cost o Information management and control needs a hierarchical computer network with internal diagnostics and fault correction
Construction and Maintenance	I	Evaluated six construction approach options (Grumman)	Selected 4-bay end-builder as best overall approach
	I	Developed low-cost rectenna construction design and approach (GE)	o Rectenna costs dominated by materal costs o Rectenna costs reduced; $520/KWe (1979 $)
	II	Defined construction base (Grumman)	o Overall approach is sound o Construction crew of 440 for 2 SPS/year o Construction cost is about 10% of SPS cost
	II	Updated & extended maintenance analysis	o Maintenance cost is about 0.3¢/Kwh
Industrial Complex	I	Identified production capacity issues (ADL)	Major issues are: o Photovoltaics o Klystrons o Composite structural materials o Rectennas
	II	Scoped industrial complex needs (ADL)	o Problems are tractable o Ground transportation not a problem
	II	Developed industrial complex cost estimates (ADL/Boeing)	Costs of the required industrial complex are affordable in a context of affordable SPS electricity

TABLE I (Continued)

PRINCIPAL STUDY ACCOMPLISHMENTS AND CONCLUSIONS

Task	Phase	Accomplishment	Conclusion
Launch Complex	I	Evaluated Equatorial Launch	o Found no major performance advantage o Recognized potential need to eventually move from KSC because of traffic level
	I	Defined KSC launch site requirements	o Launch & recovery site costs of added facilities ≈ 5 Billion o KSC capable of handling SPS launch rates up to ~ 10Gw/yr
	II	Developed offshore launch complex concept (Brown & Root)	o It's feasible o Probably least cost way to develop equatorial launch capability
Operations	I/II	Analyzed depressed HLLV trajectories	Trajectories that avoid potential environmental concerns result in less than 10% payload penalty
	II	Developed integrated operations approach and definition	o Operations management not a cost driver o Communications requirements can be met without high costs; need two relay satellites at GEO
SPS/Ground Power Network Integration	I	Examined rectenna siting	o Adequate siting opportunities ex
	I	Updated rectenna description (GE)	o Energy-intensive materials use can be minimized
	I	Updated rectenna/network interconnect	o Rectenna is compatible with either HVAC or HVDC
	II	Updated SPS reliability and availability	Availability ~ 0.92
	II	Assessed SPS LOLP, unit size, control, and reserve margin requirement	o Unit size not a problem o SPS cannot contribute to frequency control unless special synthesis techniques are developed o SPS will not have a major impact on reserve margin requirements

TABLE I (Continued)

PRINCIPAL STUDY ACCOMPLISHMENTS AND CONCLUSIONS

Task	Phase	Accomplishment	Conclusion
Technology Advancement & Development	I/II	Analyzed SPS development	o Identified & characterized 5-phase program structure o 5-phase program facilitates risk management o Overall non-recurring cost is affordable based on projected SPS market; will be repaid by taxes from operating units
Costs & Schedules	I/II	Developed overall non-recurring and recurring costs & schedules	o Costs relatively insensitive to metholodogy details o 18-20 years needed to commercialize SPS
Exploratory Technology	I	Tested Laser Annealing of 50-μm solar cells degraded by proton irradiation	Recovery of about 50% was consistently demonstrated
	II	Tested a fiber-optic phase distribution link at 980 MHz	Received signal much stronger than expected
	II	Additional Exploratory Technology was in progress as of this report date	

The following discussion is keyed to the accomplishments summarized in Table 1.

Critique Summary

The study began with a critique of the 1978 reference design. **The critique concluded that the SPS concept had no fundamental technical flaws, but identified several design deficiencies.** The critique was conducted by an independent panel of technical experts. Roughly 100 critique items were developed, some of an incidental nature. A number of significant items were identified and are summarized in Table 2. Of particular importance were concerns regarding materials and power electronics lifetime, and plasma-high voltage interactions.

In addition to these items, there were certain critique items of an environmental nature. These were previously known and are included in the DOE environmental impact assessment activities. As they are outside the scope of the present systems definition study, they are not included in this description of study results.

Table 2 – Critique Summary

CRITIQUE ITEM	RESOLUTION
SPS Large Unit Size	Examined by GE; not a problem in SPS time frame
Space Debris from Construction Operations	Debris sources not identified; secondary or incidental sources should be worked in Engineeri·g Verification
Long-Term Life of SPS Materials	Research Phase Emphasis
Lack of Definition of Flight Control and Computing Systems	Definition improved in present study
Plasma/High Voltage Interaction Potential	Research Phase Emphasis
Solar Array Performance, Degradation, and Annealing	Initial degradation and annealing tests confirm genera' approach; much emphasis required during research program.
Lifetime of Power Electronics	Design changed to eliminate identified failure mode

Construction Location and Orbit Transfer

As a part of the baseline system task, construction location and orbit transfer options were reviewed. The three concepts compared were: (1) LEO/SPM: construction of the SPS in low Earth orbit and use of self-power to move SPS modules to GEO, as proposed by the earlier Boeing/GE study; (2) LEO/SPM/EOTV: the same with use of EOTV's to return self-power propulsion equipment to LEO for reuse; (3) GEO/EOTV: construction at GEO with use of EOTV's for all cargo orbit transfer. Cost trends with time for the three orbit transfer/construction locations options are shown in Figure 8.

Although a front-end cost advantage was seen for LEO/SPM, the overall trade was too close to call; the DOE/NASA baseline (GEO/EOTV) was retained.

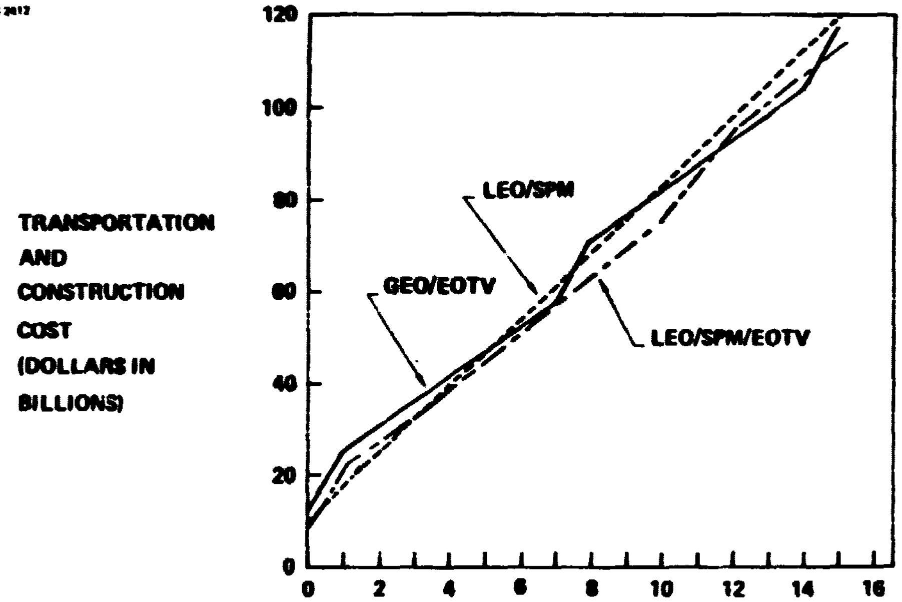


Figure 8 – Cumulative Cost Comparison

Solid State Transmitters

It was concluded that (1) antenna-mounted solid-state transmitters will work; (2) they optimize at 2500 megawatts net ground output; (3) the solid-state approach is about as cost-effective as the Klystron approach at lower power levels and should be researched in the GBED activity.

During Phase I of the study, parametric analyses of solid state SPS's were developed, indicating possible advantages of the solid state approach for power outputs in the 1000-2500 megawatt range. A power combiner module concept was also developed, well-suited for implementation in an SPS similar to the reference configuration.

Early in Phase II the parametric analyses were extended to investigate solid-state "sandwich" configurations. ("Sandwich" configurations employ solar cells and microwave amplifiers in a sandwich back-to-back configuration. Sunlight is concentrated on the array by plastic film reflectors. Sandwich configurations are thermally limited to low powers.) These were compared with separate-antenna options and found to be potentially interesting in the low-power (<1500 megawatts) range but offering no unique advantages, if a solution to the power supply problem for separate-antenna options were developed. The sandwich configurations are mechanically complex and pose worrisome construction issues.

A solid-state reference configuration was created in Phase II. Investigation of series-parallel connections of the solid-state amplifiers as regards dc power supply indicated this to be a promising approach. The solid-state configuration, shown in Figure 9, is similar to the reference configuration with the following major differences:

- The power delivered to the grid is 2500 megawatts rather than 5000 megawatts.
- The array size is 8 x 11 bays rather than 8 x 16 bays.
- The array voltage if 5.5 KV rather than 44 KV. This array voltage provides ±2.2 KV to the transmitter after I^2R drop in the power conductors.
- The transmitter aperture is 1.4 km rather than 1.0 km.

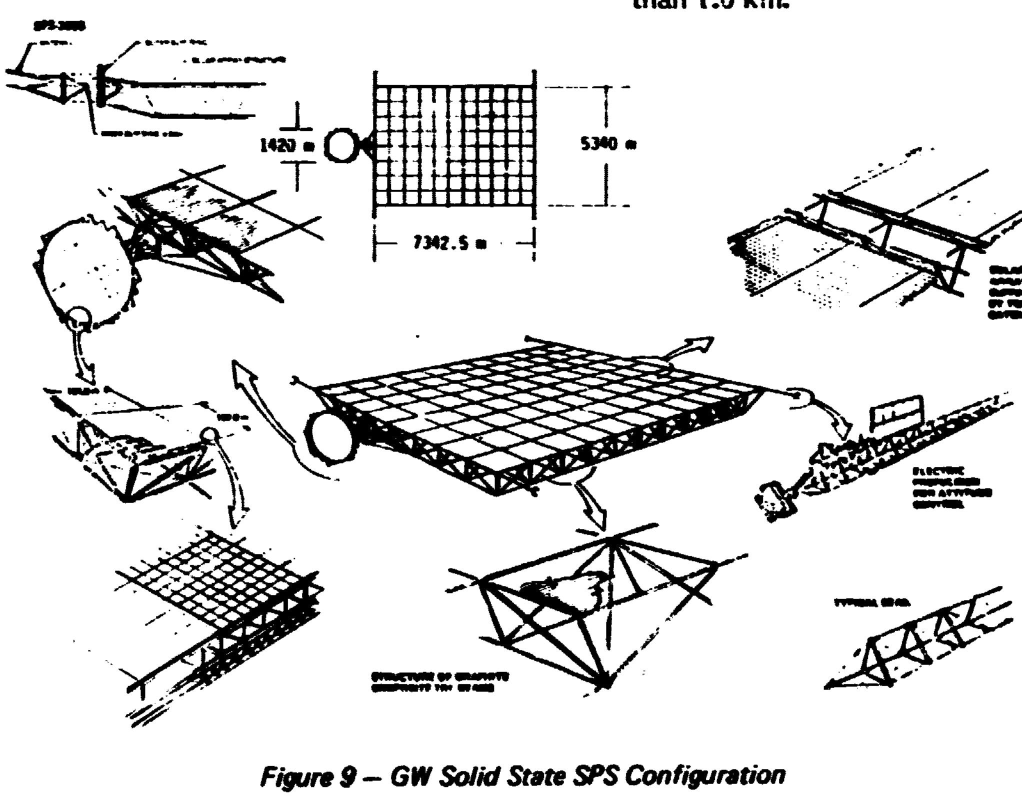


Figure 9 — GW Solid State SPS Configuration

- The transmitter employs gallium arsenide FET's rather than klystrons.

A mass estimate for the solid-state configuration is presented in Table 3. The mass is about 70% of the klystron reference system although the power is only 50%. The comparatively low distribution voltage leads to high distribution losses (thus proportionately more solar array) and a heavy distribution conductor system. Despite comparatively high losses, the direct dc system has less mass and cost than high-voltage systems because the latter require power processors and their associated thermal control.

Future work is expected to reduce the power distribution penalty by achieving higher distribution voltages.

A recurring cost estimate for the solid-state configuration is presented in Table 4. The cost per kilowatt is about 35% greater than for the reference system. As with mass, this arises mainly because of the low distribution voltage.

The cost trend chart, shown in Figure 10, was developed early in Phase II to compare solid-state "sandwich" configurations to the klystron reference systems. These appear to trend very similarly to the reference configurations. The sandwich appears to trend below the baseline only when advanced technologies such as very high efficiency solar cells or selective reflectors are employed. These technologies, however, would also improve the cost and performance of the reference system.

The antenna-mounted solid-state system is also spotted on the chart. It falls slightly above the trend line. Further work on the power distribution problem is expected to move it down to, or slightly below, the trend line. (Note that this chart uses 1977 dollars whereas other results in this report are in 1979 dollars.)

Reference System Definition Update

The reference system update resulted in little change in mass and cost and provided important improvements in design understanding in several areas.

During Phase II, the reference system definition was updated to incorporate correction of design deficiencies and improved definition in some of the subsystem areas. As a part of the system

Table 3 — Solid State SPS Mass Summary

1.1	SPS	35,204	
1.1.1	ENERGY CONVERSION	22,087	
1.1.1.1	STRUCTURE	2,851	Detailed estimate
1.1.1.2	CONCENTRATORS	(0)	Not required
1.1.1.3	SOLAR BLANKETS	14,409	Scaled from reference
1.1.1.4	POWER DISTRIBUTION	4,400	Detailed estimate
1.1.1.5	THERMAL CONTROL	(0)	Allocated to subsystems
1.1.1.6	MAINTENANCE	427	Scaled from reference
1.1.2	POWER TRANSMISSION	6,365	
1.1.2.1	STRUCTURE	460	Scaled from reference
1.1.2.2	TRANSMITTER SUBARRAYS	4,480	Detailed estimate
1.1.2.3	POWER DISTR. & COND.	1,262	Scaled from 1.1.1.4
1.1.2.4	PHASE DISTR.	25	Scaled from reference
1.1.2.5	MAINTENANCE	20	Docking ports only
1.1.2.6	ANTENNA MECH POINTING	118	Scaled by Mass x Area
1.1.3	INFO MGMT & CONTROL	145	Scaled from reference
1.1.4	ATTITUDE CONTROL & STATIONKEEPING	146	Scaled from reference
1.1.5	COMMUNICATIONS	0.2	Same as reference
1.1.6	INTERFACE	113	Est. based on simplification
1.1.7	GROWTH & CONTING. (22%)	6,348	Same % as reference

Table 4 – 2.5 GW Solid State Satellite System Recurring Costs

ITEM	COST ($M)
SATELLITE	3,722
LESS IMPLICIT AMORTIZATION	327
	3,395
CONSTRUCTION AND SUPPORT	664
SPACE TRANSPORTATION	2,154
GROUND TRANSPORTATION	20
RECTENNA	1,290
MISSION CONTROL	10
MGMT AND INTEGRATION	385
MASS GROWTH (17% Net Hardware)	577
TOTAL DIRECT OUTLAY	8,505

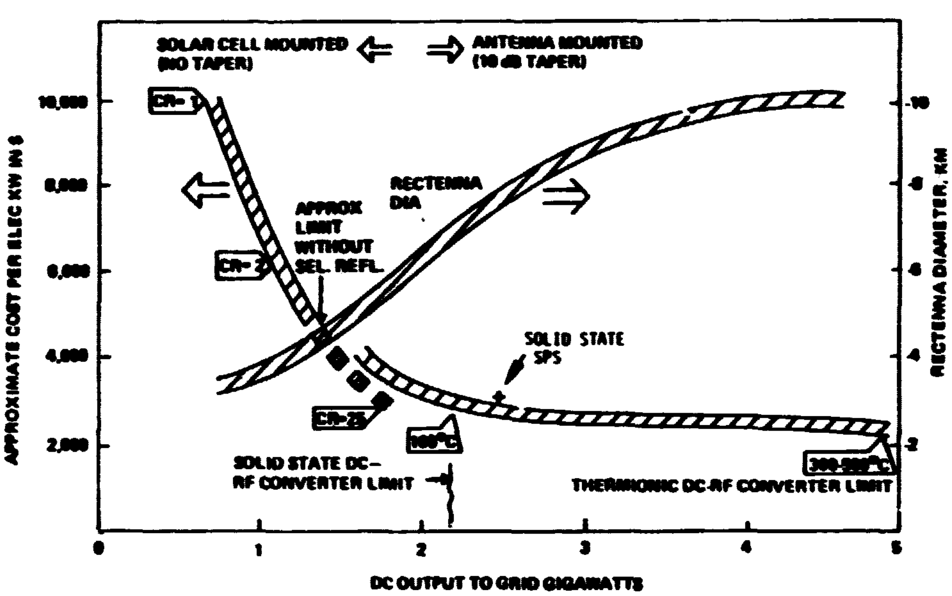


Figure 10 – SPS Cost Trends

definition update, the level of definition was carried to WBS Level 5 on the satellite, with details at Level 6 in most areas. Figure 11 illustrates a typical definition item. The mass of each box and cable was estimated and the mass contribution to each satellite was estimated from the number of each item per satellite.

The updated definition provides additional detail especially in the following areas:

- o Maintenance provisions
- o Phase distribution and subarray control circuits

SPS 3039

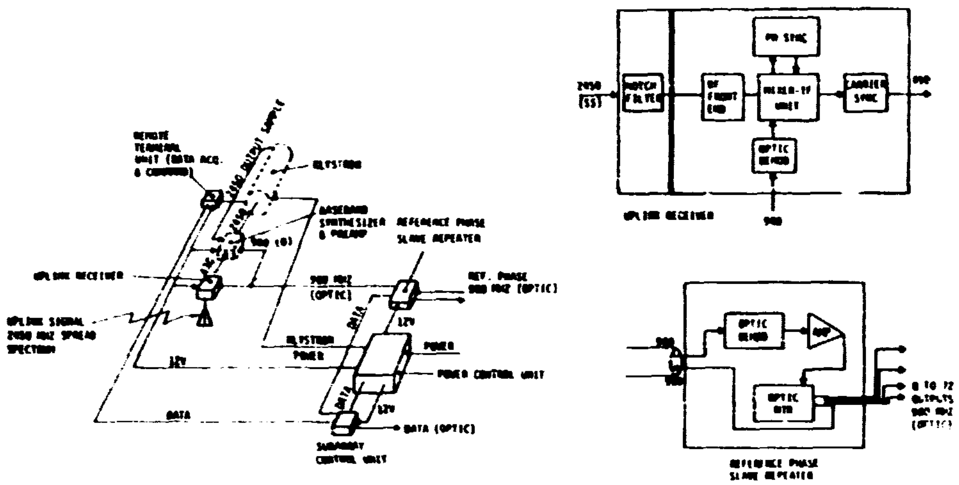


Figure 11 – Typical System Definition at Level 5 (WBS 1.1.2.2.5, Subarray Control Circuits)

o Information management and control

An important change from the earlier definition is that the phase control system was modified by providing an uplink receiver and phase conjugator for each klystron rather than for each subarray. Two benefits result:

o The beam efficiency is improved by about 1%, with attendant value of the order of $100 million, exceeding the cost of the order of $50 million. (The efficiency chain has not been updated from earlier studies as this small improvement is well within the uncertainty band.)

o The grating lobes are reduced in number and intensity, as shown in Figure 12. The strongest grating lobes are reduced from roughly 40 microwatts/cm^2 to less than 2 microwatts/cm^2.

A significant set of conclusions was reached regarding information management and control: (1) The quantity of data to be handled demands a hierarchical computer network with internal diagnostic and fault correction capability; (2) The resulting system should not pose major technical or cost problems in the time frame of interest.

The mass and cost results of the reference system update are tabulated in Tables 5 and 6. Table 5 presents mass and recurring cost elements for the satellite.

Average SPS recurring costs including all WBS elements are summarized in Table 6. The cost estimating method for satellite hardware implicitly includes amortization of factories and equipment, so an appropriate amount has been subtracted here, since these investments were identified as a discrete non-recurring cost included under the investment phase of the program.

Determination of the cost of an SPS to a utility requires specific definition of financial and management scenarios. A representative figure may be obtained by adding back the implicit amortization and then adding 15% for financial costs such as interest during construction; the result is $14.8 billion, just under $3000/KWe in 1979 dollars.

Space Construction

During Phase I, Grumman and Boeing jointly examined a number of construction approaches, the most important illustrated in Figure 13. **The four-bay end-builder was selected as a result of this tradeoff, based on its productivity potential.**

During Phase II, Grumman conducted a definition effort on the geosynchronous orbit (main) construction base. **The results provide a thorough understanding of SPS construction and an adequate basis for space worker health and safety assessments.** Additional definition of the LEO (staging and electric orbit transfer vehicle construction) base was provided by Boeing. An

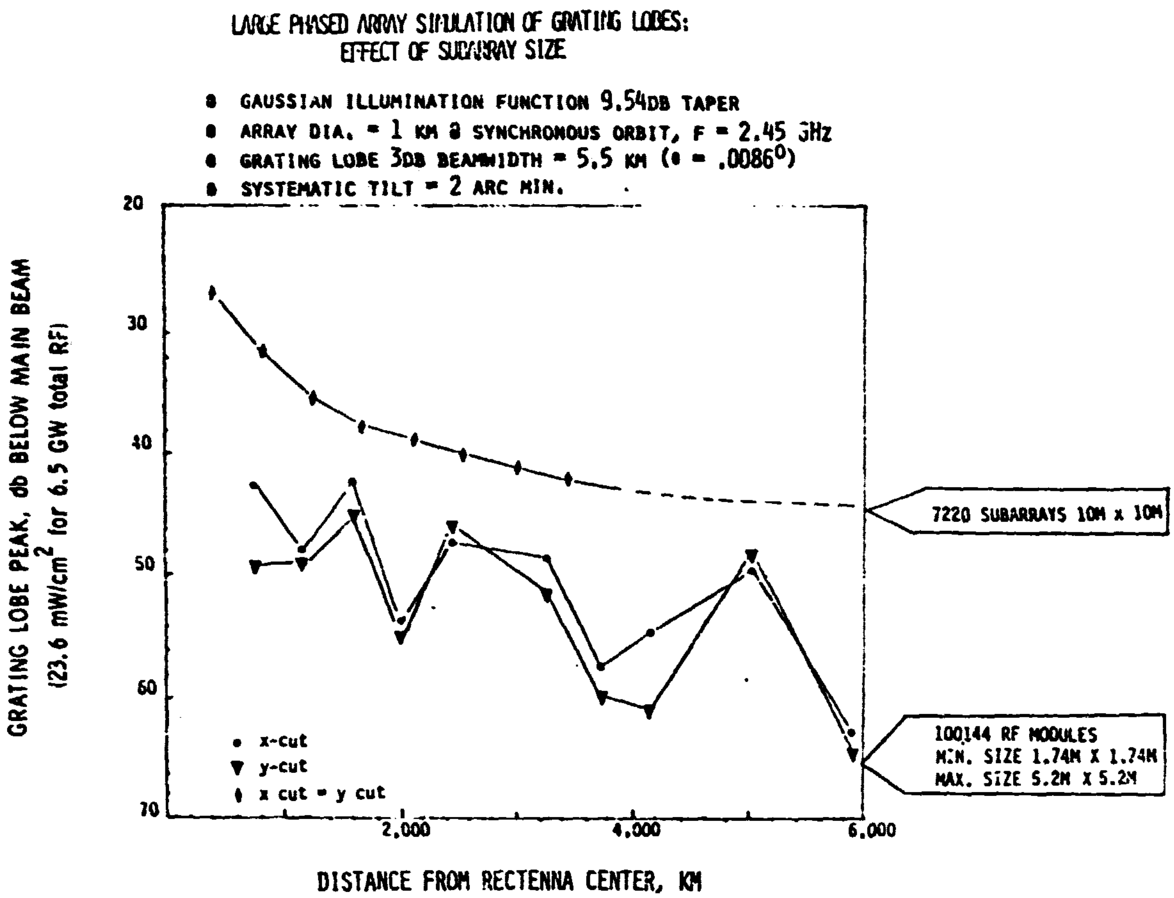


Figure 12 – Large Phased Array Simulation of Grating Lobes: Effect of Subarray Size

Table 5 – SPS Hardware Mass and Cost Summary

	MASS	COST	$/KG
SPS TOTAL	50,984	4,945.9	
ENERGY CONVERSION	27,665.9	2,859.6	
STRUCTURE	4,654	448.2	96
SOLAR BLANKETS	21,144.9	1,987.8	94
POWER DISTRIBUTION	1,246	149.9	120
MAINTENANCE PROVISIONS	621	273.7	440
POWER TRANSMISSION	13,628.9	1,768.7	
STRUCTURE	324.3	25.6	79
SUBARRAYS	10,389.1	889	86
POWER PROC. & DISTR.	2,538.7	324.1	128
PHASE DISTR.	12.3	12.5	1016
MAINTENANCE PROVISIONS	230.2	503.9	2189
ANTENNA MECH POINTING	134.3	13.6	101
INFO MGMT & CONTROL	95.6	48.0	
COMPUTERS	4.5	30.7	6822
CABLING	91.1	17.3	190
ATTITUDE CONTROL & STA. KP.	212.1	160	
HARDWARE	142.1	160	1126
PROPELLANT	70	-	
COMMUNICATIONS	0.18	8	44,000
INTERFACE	235.6	101.6	431
GROWTH ALLOWANCE (22%)	9,146	Carried at Next Level	

Table 6 – SPS Recurring Cost Summary (1979 Dollars)

SPS HARDWARE AS COSTED	4946	
LESS IMPLICIT AMORTIZATION OF INVESTMENT	473 4473	(Half of 10.61% per annum on 8924 M for factories and production equipment)
SPACE TRANSPORTATION	3120	Based on SPS mass with growth'
CONSTRUCTION OPERATIONS	961	Includes 10 support people on the ground per space worker as well as construction base spares
GROUND TRANSPORTATION	35	
RECTENNA	2578	
MISSION CONTROL	10	
PROGRAM MANAGEMENT & INTEGRATION	495	Equivalent to 14,000 direct people
COST ALLOWANCE FOR MASS GROWTH	760	17% of net SPS hardware cost
TOTAL DIRECT OUTLAY	12,432	

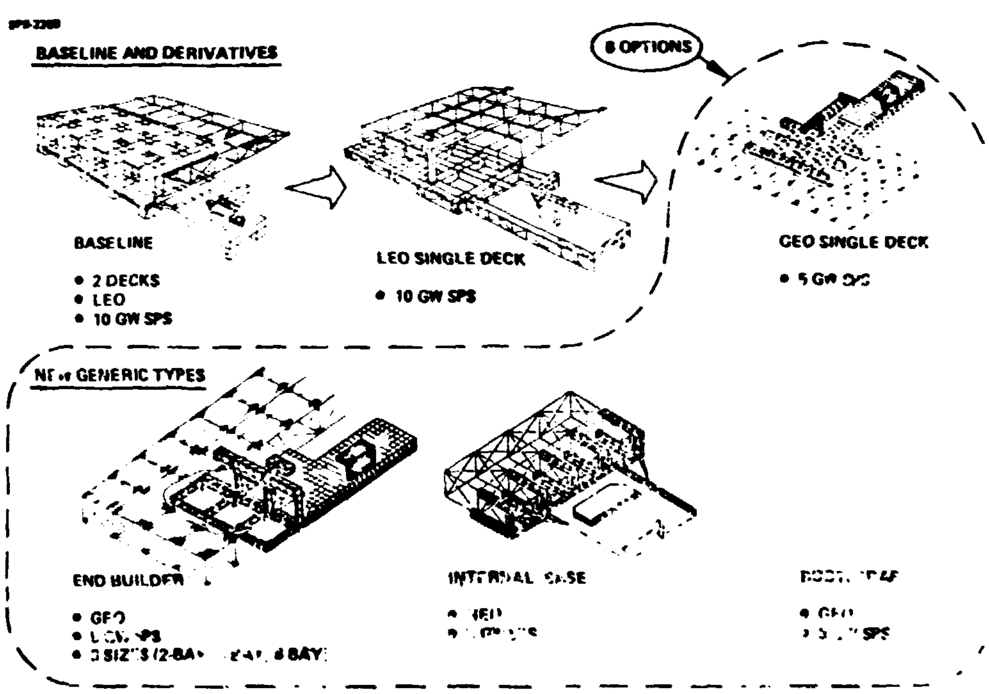


Figure 13 – Alternative Construction Concepts

example of GEO base definition is shown in Figure 14, an illustration of the final stages of yoke/rotary joint construction.

In the first view, the yoke is shown complete positioned ready to receive the antenna. The construction facility is positioned to the left to complete fabrication of the remaining yoke sections.

In the second view of Figure 14, the antenna and yoke have been mated and the yoke, supported entirely by the indexer supports has been separated from the construction facility. The facility is now free to begin fabrication of the rotary joint.

This definition effort led to an update of space construction base costs, masses, and crew complement requirements. These updates are reflected in the system costs presented earlier.

Rectenna Construction

General Electric defined a mechanization and structural concept that reduces rectenna costs from earlier estimates. A pictorial summary of the construction concept is illustrated in Figure 15. The basic support structure is steel-reinforced concrete. This support structure is emplaced by construction equipment employing advanced technology location systems to allow precise location of the footings. Support and rectenna panels are manufactured at the site in portable factory buildings and moved for installation as illustrated. The resulting total rectenna cost, including the rectenna-power pool interface equipment, is $2573 millions in 1979 dollars; this figure is reflected in the costs reported in Table 6.

Concurrently with the Phase II effort, Boeing developed a concept for using rectenna structures as a basis for large-scale controlled-environment agriculture (i.e. a greenhouse). This appears quite feasible and would ameliorate concerns regarding the land use associated with rectenna sites.

Satellite Maintenance

Satellite maintenance analyses concluded that maintenance costs would be roughly 0.3¢/kwh and that failed hardware should be refurbished at the

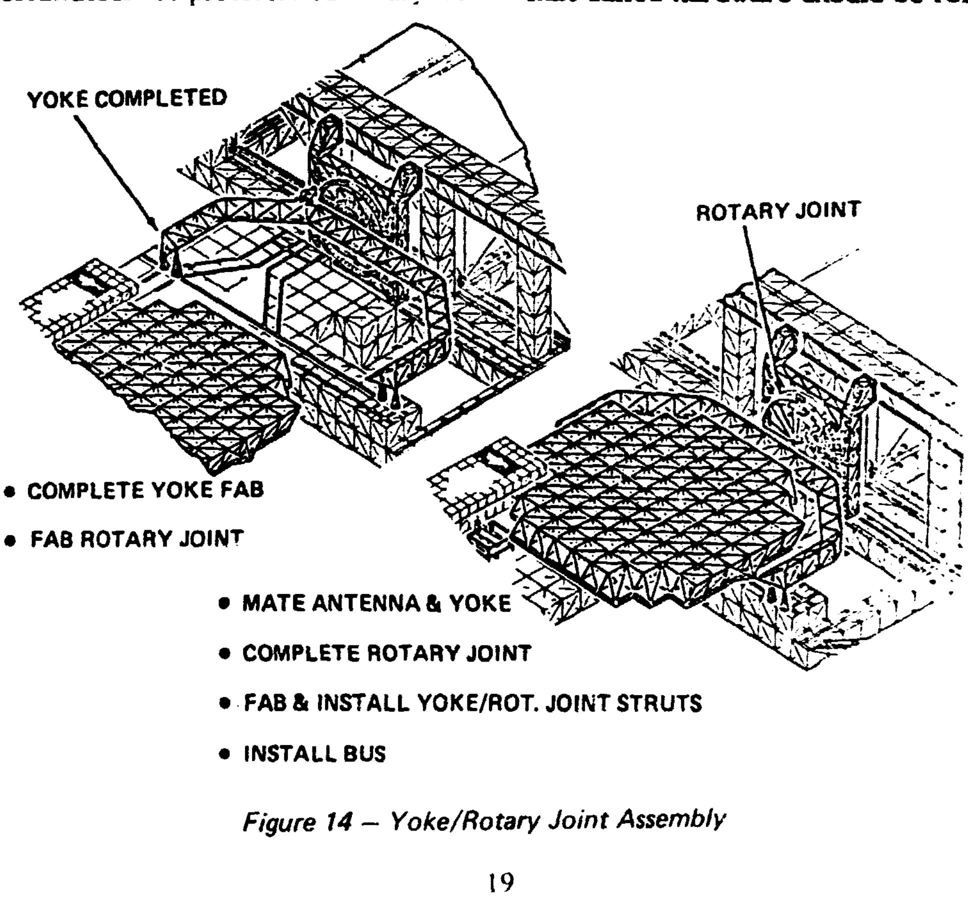


Figure 14 – Yoke/Rotary Joint Assembly

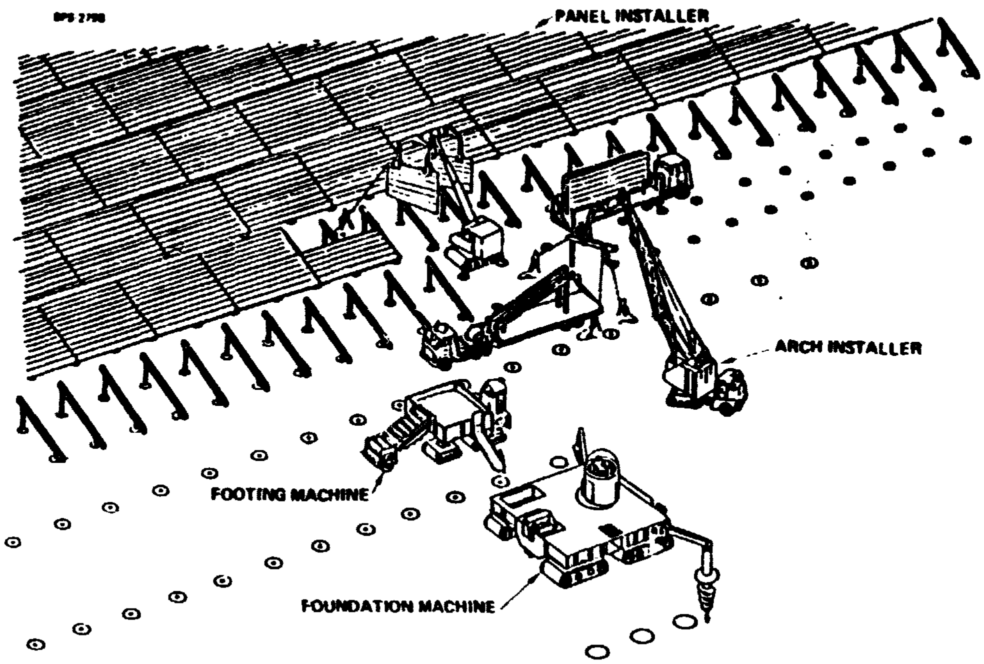


Figure 15 – Five GW Rectenna Construction Concept

GEO Base to the extent practicable. The earlier 1977 study examined maintenance of the klystrons on the power transmitter and did some comparisons of various means of flying and operating maintenance missions. During that study it was assumed that repair of components at the geosynchronous base would require the same size crew as the remove/replace operations at the satellites. During the present study further analyses of the maintenance systems established means of maintenance access for all system components and estimated actual crew counts both for remove/replace operations and for equipment repair operations at the geosynchronous base. Additional definition of installation specifics was required in order to accomplish the maintenance analysis. Illustrated in Figure 16 is a representative access concept for gaining access to power buses and switchgear. The multiple bus power distribution system is accessed by a flying cherrypicker which is a part of the maintenance system.

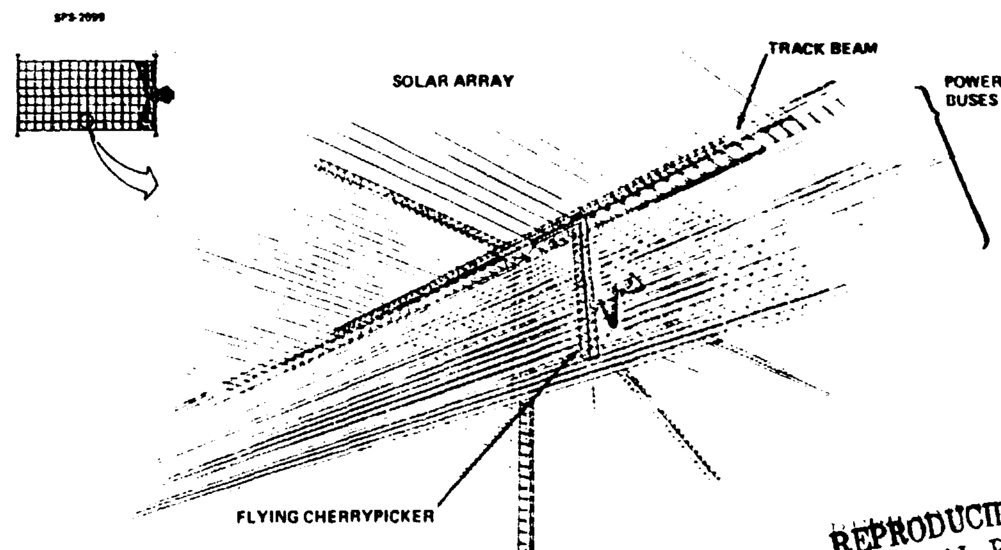


Figure 16 – Main Bus Maintenance Access System

Based on these maintenance access concepts, a complete operations concept was developed. Hardware repair tasks at the GEO base were timelined and manloaded, and overall mainte-nance costs were estimated.

Table 7 summarizes the results of the mainte-nance analysis and indicates the estimated cost of maintenance to be approximately 0.3 cent per kilowatt hour. This cost is categorized in utility language as "operations and maintenance cost." In order to develop the maintenance estimate, a timeslice was taken with 40 SPS's in orbit. This maintenance estimate assumes that each SPS is serviced every six months.

Industrial Infrastructure Needs

Solar array production facilities were identified as the only major challenge in developing the SPS industrial infrastructure.

The ground-based industrial infrastructure required for SPS hardware production was scoped by Arthur D. Little. Investment cost estimates in Table 8 are rough order-of-magnitude. (Most of these investments would be absorbed by the private sector.)

The estimates for solar array production are "upper bound" figures assuming only very moderate technological advance (but extensive automation) compared to today's methods. The figures in Table 8 exclude space transportaiton vehicle launch and recovery facilities and propellant production facilities, described below. Existing ground transportation methods and facilities were found to be adequate.

Propellant production requirements to sustain SPS production at 10,000 megawatts per year are summarized in Table 9. Plant capital cost and energy requirements were derived from a Boeing Commercial Airplane Company study of synthetic fuels for commercial aircraft.

The energy investment in propellants is small. If the electricity requirement is met by coal-fired generation, the total coal consumption approximately doubles. Stated another way, 25,000 tons/day of coal for one year can generate, if used directly, about 2,000 megawatt-years of electricity. Used to produce SPS rocket propellant, the same quantity of coal contributes the transportation energy to generate 300,000 megawatt-years of electricity.

Launch site selection and facilities

The launch site analysis task was motivated by the premise that selection of a low-latitude site would offer significant cost advantages com-

SPS 3098

Table 7 — Maintenance Cost Summary: 40 SPS

ITEM	NUMBER	COST ($M79)	REMARKS
HLLV	80 Flights	936	
PLV	38 "	460	
EOTV	5 "	226	
POTV	36 "	88	
TOTAL TRANSPORTATION OPS		1710	
MAINTENANCE CREW	650	1785	Assumes 10 support people on ground per space worker
SPARES		800	
MISSION CONTROL		20	
TOTAL ANNUAL COST		4315	23rd year of production program

$$\text{O\&M COST} = \frac{4315 \times 10^6}{5 \times 10^6 \text{ KWH} \times 8766 \text{ HR/Y} \times 0.9 \text{ Plant Factor} \times 40 \text{ SPS's}} = 0.27¢/\text{KWH}$$

Table 8 — Industrial Infrastructure Summary SPS Hardware Production

SPS 3099

ITEM	CURRENT CAPACITY	SPS CAPACITY REQUIRED	INVESTMENT COST ($M79)	REMARKS
Solar Array	≈1 MW/YR	18,000 MW/YR	5000	Photovoltaics consume only about 5% of current semiconductor silicon production
Ion Thrusters	Nil	5000 to 10000 units per year	None	Can be absorbed by existing infrastructure
Klystrons	7000/yr	200,000/YR	1500	Present magnetron production is ≈ 2 GW/YR
Rectenna	N/A	2 rectennas/yr	250	Materials consumption small compared to existing productive capacity
Graphite Fibers	150 T/Yr	≈10,000 T/YR	549	About twice projected U.S. capacity in 1993.
Other			1625	Mostly electronics
TOTAL			8924	

Table 9 — Propellant Production Requirements SPS Construction at 10,000 Megawatts/Yr.

SPS [illegible]

	METRIC TONS/YR HLLV	POTV	EOTV	PLV	TOTAL [1] TONS/DAY	PLANT CAPITAL COST $M79	
LO_2	2,671,000	3,722	1,060	57,700	9,000 [2]	650	From Coal [6] and Air
LCH_4	642,600	-0-	-0-	18,700	2,200 [3]	615	
LH_2	123,704	745	353	3,036	420 [4]	500	
ARGON	-0-	-0-	14,400	-0-	47 [5]	-0-	

[1] Capacity required at start of program; includes 20% margin

[2] 1979 U.S. capacity is about 30,000 tons/day

[3] About 0.2% of U.S. Natural Gas Consumption in 1977

[4] Today's capacity is ≈ 100 T/Day

[5] Byproduct of LO_2 Plant

[6] 12,250 T/D coal + 1000 megawatts electric power. Coal use is 0.7% of U.S. '77

pared to operations from the Kennedy Space Center, where earth-to-low-orbit space transportation arrives at a 30° inclination orbit. With a 30° inclination orbit for staging or construction operations, 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, the performance difference is minimal.** (It should be recognized that a significant delta V advantage for equatorial launch exists for chemical orbit transfer to GEO.) 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 options 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. Great uncertainties were identified in the Part I study as to the cost of large floating structures.

As a part of Phase II, Brown & Root developed the concepts shown in Figure 17 for structural support of an offshore launch facility in water depths up to 200 m (650 ft). The facility would include launch and recovery facilities, the latter requiring a 91 x 4572 m (300' x 15,000') runway which dominates support structure costs. The facility would be located off the west coast of South America, roughly 325 km north of the Galapagos Islands. At that location, weather and sea states are unusually mild (the "doldrums").

Since the offshore approach would allow most of the launch and recovery equipment to be installed on the support structure sections as they are built in a shipyard (rather than constructed at a remote site), the savings in equipment installation and checkout and site preparation could more than offset the cost of offshore structures. The major conclusions of the Brown & Root study were as follows:

- **It is technically feasible**
- **Conceptual design to completion will require only six years**
- **Total installed cost estimates were: (1) moored, semi-submersible-$3,005,000,000; (2) stationary, pile-supported-$3,?17,000,000**
- **The runway is a significant cost driver**
- **The concept has real benefits**
- **It is probably the least cost way to provide a large equatorial launch complex**

Launch Trajectories

Depressed launch trajectories were found that will mitigate the environmental concerns relating to the possibility of influences on the upper atmosphere from launch operations. Figure 18 shows the relationship of the current baseline trajectory to the key regions of the upper atmosphere.

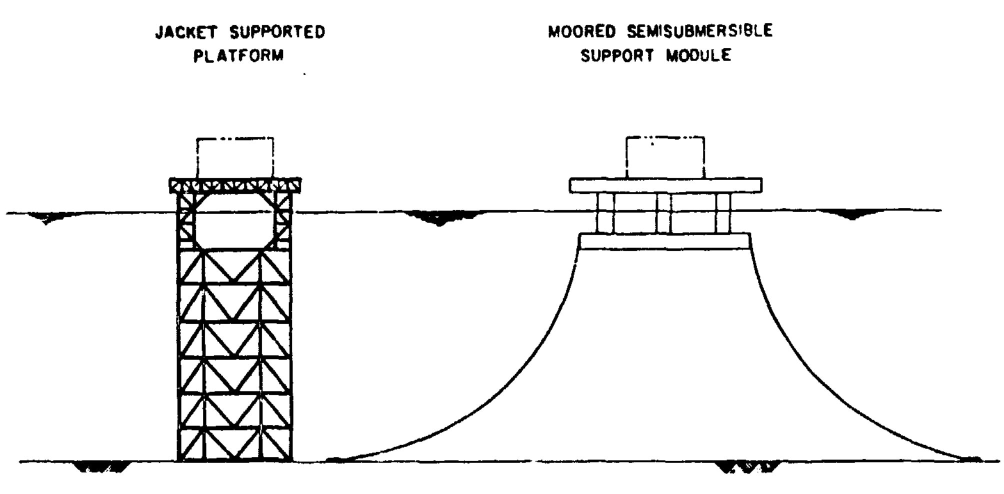


Figure 17 — Brown and Root Offshore Launch Design Concepts

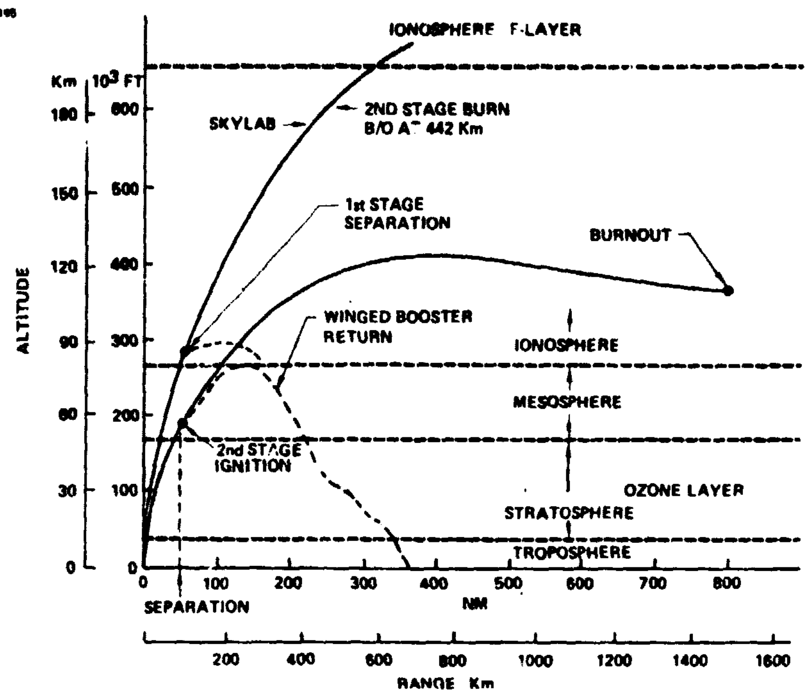


Figure 18 — Reference HLLV Launch Trajectory and Skylab Launch

Some forecasts of ionosphere depletion due to SPS launches have assumed the HLLV trajectory would be like the Skylab trajectory shown, which thrusted directly into the ionosphere F-layer.

The reference HLLV trajectory does not enter the F-layer under mainstage thrust; only the circularization and de-orbit burns occur at that altitude. This reduces the concern about ionosphere depletion by about a factor of five as compared to direct ascent into the ionosphere. Concern still exists because of the potential of hydrogen diffusion upward into the ionosphere. If the trajectory could be suppressed to stay below 100 km (328,000 feet), this concern would be greatly alleviated.

The depressed trajectory shown in Figure 19 was developed during Phase I of the study. It is low enough to keep the rocket effluents in the turbulent mixing regions of the atmosphere, reducing concerns regarding hydrogen diffusion.

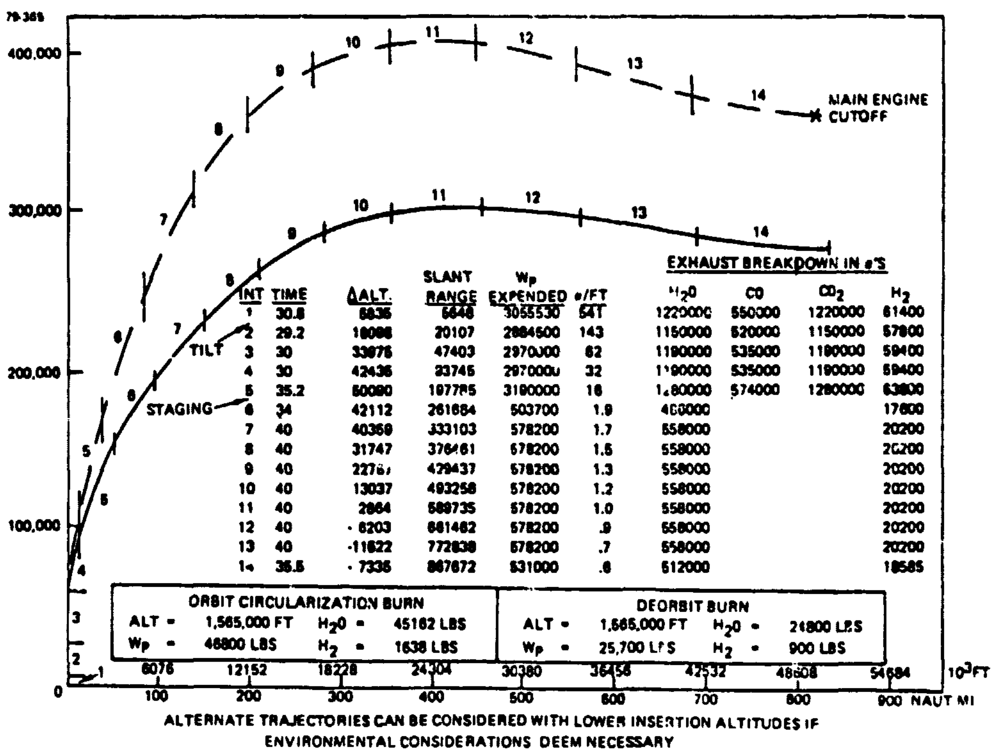
During Phase II, a further concern was expressed that the trajectory developed during Phase I may not be depressed enough. The issue was possible formation of noctilucent clouds (due to H_2O) at about 80 kilometers altitude. It was desired to find a trajectory that would stay below 75 km.

We found that injecting the orbiter at a slight positive (e.g., 2°) path angle has a significant beneficial effect on a highly depressed trajectory: (1) it minimizes post-injection drag losses; (2) it suppresses the pre-injection optimal path; (3) it forces an angle of attack on the orbiter similar to that for entry so that special thermal protection should not be required.

The selected 75-km-or-less trajectory is shown in Figure 20.

In all, about 25 ascent trajectories were simulated using various strategies to minimize trajectory altitude. Results are summarized in Figure 21. 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. Suppression to 75 km incurs about a 10% penalty.

The suppressed trajectories were not fully optimized and no credit was taken for the reduced booster flyback range. Ultimate penalties will be slightly less than indicated.



INT	TIME	ΔALT.	SLANT RANGE	W_p EXPENDED	#/FT	H_2O	CO	CO_2	H_2
1	30.8	6835	5648	3055530	541	1220000	550000	1220000	61400
2	29.2	18086	20107	2884500	143	1150000	520000	1150000	57800
3	30	33876	47403	2970000	62	1190000	535000	1190000	59400
4	30	42436	83745	2970000	32	1190000	535000	1190000	59400
5	35.2	60080	187785	3190000	18	1280000	574000	1280000	63800
6	34	42112	261684	503700	1.9	460000			17600
7	40	40369	333103	578200	1.7	558000			20200
8	40	31747	376461	578200	1.5	558000			20200
9	40	22767	479437	578200	1.3	558000			20200
10	40	13037	493258	578200	1.2	558000			20200
11	40	2864	589735	578200	1.0	558000			20200
12	40	-6203	681482	578200	.9	558000			20200
13	40	-11622	772838	578200	.7	558000			20200
14	36.5	-7336	867872	531000	.6	512000			18585

Figure 19 – SPS Navy Left Launch Vehicle Trajectory and Exhaust Product Data

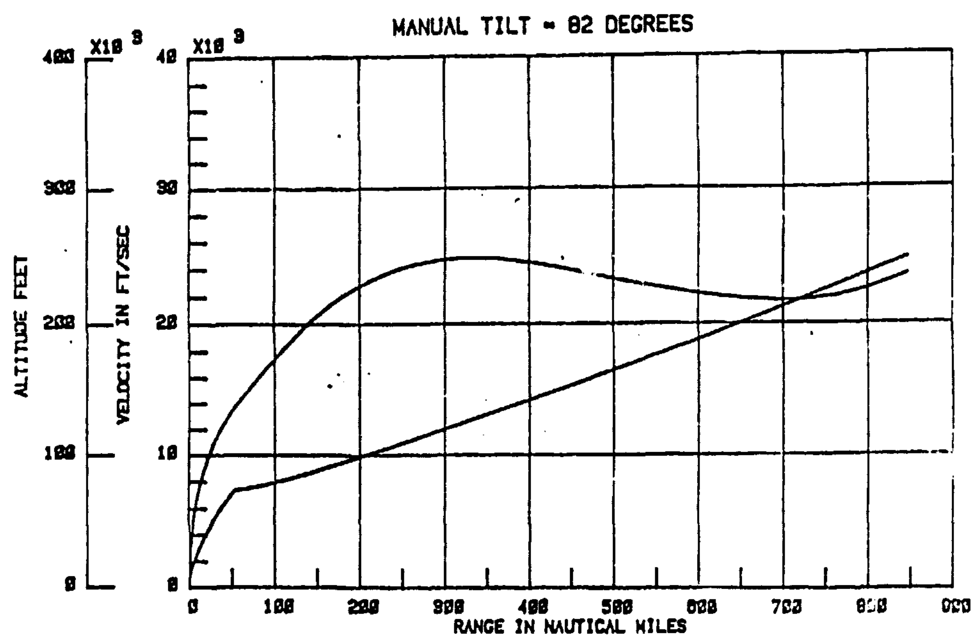


Figure 20 – HLLV Suppressed No. 6

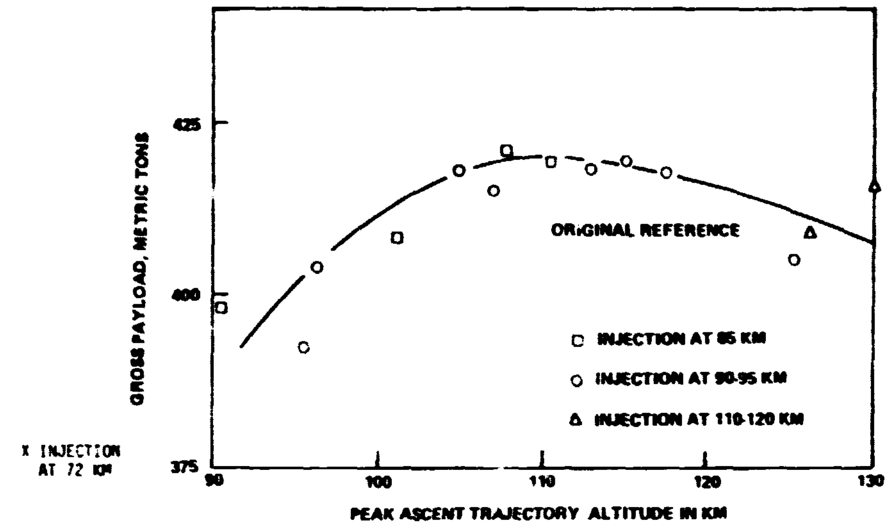


Figure 21 – Launch Trajectory Suppression Results

Operations

Integrated SPS operations were analyzed and plans prepared for each of the twelve operations arenas noted in Figure 22. One of the main outputs of these analyses was the communications requirements matrix shown in Figure 23. (Numbers in the matrix refer to communications requirements fact sheets included in the detailed operations report, Volume III.) **A significant conclusion was reached: operations management will not be a significant contributor to SPS costs.**

Rectenna/Power Pool Compatibility

During Phase I, an investigation of rectenna siting was carried out. The analysis concentrated on the three areas shown in Figure 28, and examined site selection using detailed maps of the areas. **Enough siting opportunities were found to more than satisfy the expected needs of these utility regions for baseload power.**

Some investigators have expressed a viewpoint that SPS receivers can only be sited south of

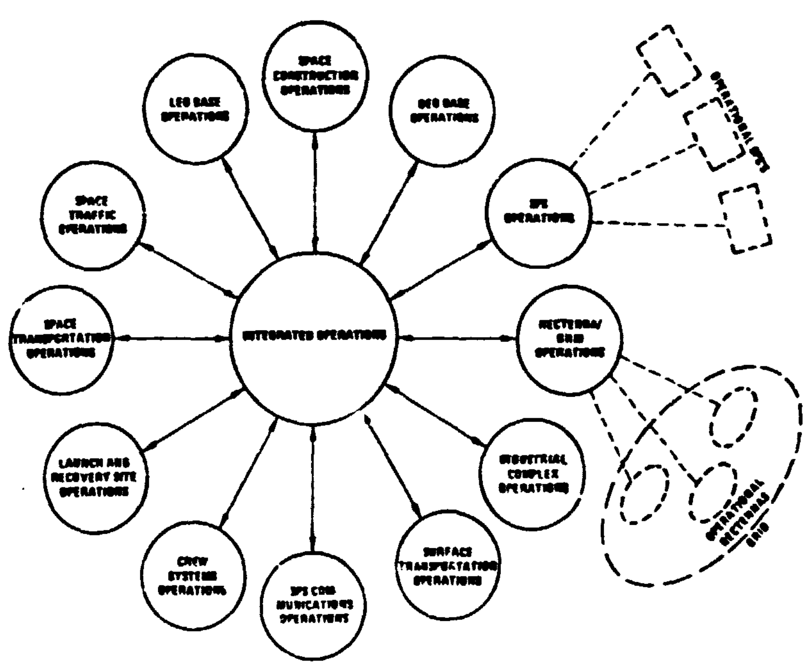


Figure 22 – Integrated Operations Concept

	OCC	LCC	LEO BASE	GEO BASE	MMB	SPS'S	RCC	PLV	HLLV	EOTV	POTV	CARGO TUG	MSS-OTV
OPERATIONS CONTROL CENTER (OCC) (WBS 1.5.1)	X	1	2	3	4	5	6	7	8	9	10	X	11
LAUNCH CONTROL CENTER (LCC) (WBS 1.3.7.5)		X	12	X	X	X	X	13	14	X	X	X	X
LEO BASE (WBS 1.2.2)			X	15	X	X	X	16	17	18	19	20	X
GEO BASE (WBS 1.2.1)				X	21	22	X	X	X	23	24	25	26
MOBILE MAINTENANCE BASE (MMB) (WBS 1.2.3.2)					X	27	X	X	X	X	X	X	28
SOLAR POWER SATELLITES (SPS's) (WBS 1.1)						X	29	X	X	X	X	X	X
RECTENNA CONTROL CENTER (RCC) (WBS 1.4.6)							X	X	X	X	X	X	X
PERSONNEL LAUNCH VEHICLE (PLV) (WBS 1.3.3)								X	30	X	31	32	X
HEAVY LIFT LAUNCH VEHICLE (HLLV) (WBS 1.3.1)									X	X	33	34	X
ELECTRIC ORBIT TRANSFER VEHICLE (EOTV) (WBS 1.3.2)										X	X	35	X
PERSONNEL ORBIT TRANSFER VEHICLE (POTV) (WBS 1.3.4)											X	36	X
CARGO TUG (WBS 1.3.6)												X	37
MAINTENANCE SORTIE SUPPLY OTV (MSS-OTV) (WBS 1.3.3)													X

NUMBERS ARE FACT SHEET NUMBERS
X SIGNIFIES COMMUNICATIONS NOT REQUIRED

Figure 23 – SPS Communications Matrix

SPS-2310

- INVESTIGATION LIMITED TO THREE UTILITY REGIONS:
  - BONNEVILLE POWER ADMINISTRATION (BPA) (PACIFIC NORTHWEST)
  - MID-CONTINENT AREA POWER POOL (MAPP) (NORTH CENTRAL USA)
  - SOUTHERN CALIFORNIA EDISON

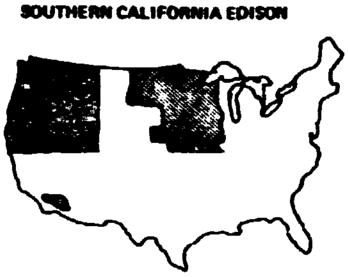


Figure 24 – Siting Investigation Regions

35°N latitude. This apparently arises from a concern over having the incoming power beam nearly parallel to Earth's magnetic field lines. It is possible that this parallel situation could exacerbate ionosphere heating by the beam. If this turns out to be a real problem, it can be alleviated by a longitude offset between the SPS and its ground receiver. **We have not found reason to restrict rectenna siting to a 35° latitude limit.** It is true, of course, that greater land area is required further north, but the rectenna panel area (the main cost contributor) changes little.

Task 5 also forecast SPS power availability based on the failure rate and maintenance analyses.

Available SPS power to utility grid considered random errors, failure modes, scheduled maintenance and eclipse, including shut down and start up times. System planned total outage (down time) is 207.8 hours per year (2.37%).

The description of the rectenna-to-power grid connection approach shown in Figure 25 was developed by General Electric's Utility Systems Engineering Division. The equipment needed to interface an SPS to a utility grid is standard utility engineering state-of-the-art.

General Electric's EUSED Division also examined the operational suitability of SPS for baseload operations and how SPS would be controlled. **They concluded that: (1) the large unit size (2500 to 5000 megawatts) is not a problem for the expected level of utility interconnection and power pool size in the year 2000 and beyond. (2) SPS can load-follow if necessary. A number of ways of varying SPS output were found. (3) Since SPS's do not have rotating inertia, they cannot contribute to frequency control as do rotating generators.** This does not appear to be a problem unless SPS's are more than about 20% of a power

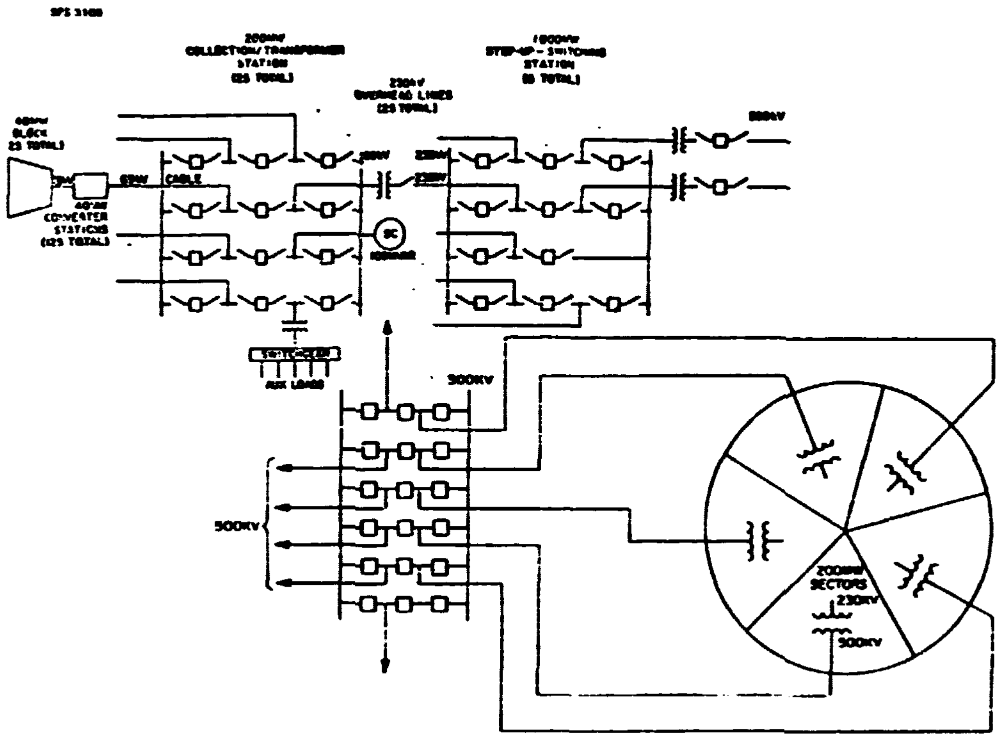


Figure 25 -- Grid Connection Approach

pool's capacity. In situations of high SPS penetration it would be necessary to develop a technique for synthesizing frequency control capability.

Figure 26 shows the power pool control structure recommended by GE.

A sensitivity study was conducted on the effect of SPS's on utility reserve margin requirements. Results are shown in Figure 27. The "mid-term" curve assumes reliability of the SPS as estimated in the maintenance task. The other curves represent progressively worse reliability. Case 4 includes 30% probability of unplanned outage of 1500 megawatts and 3% probability of unplanned complete outage. Planned outages such as eclipse periods do not affect reserve margin requirements.

It was concluded that SPS is not likely to have a major effect on reserve margin requirements.

<u>SPS Research and Development</u>

A multi-phase development approach was formulated. It provides for resolution of issues and control of risk before major development commitments, and a high degree of program flexibility. The entire development activity was scheduled and costed. Main attention was given to the research phase; a detailed planning document was issued in July, 1979, describing research tasks, schedules, and resource requirements. Figure 28 shows the technology demonstration/selection decision schedule derived from that document.

Schedules for later phases were merged with the research schedule, keyed to decision milestones, to yield an end-to-end schedule.

Two major flight projects were identified: an <u>Engineering Verification Test Article</u> and an <u>SPS Demonstrator</u>. The Engineering Verification Test Article concept is shown in Figure 29. It was based on the following major requirements:

- o Test a solar array similar to that planned for SPS at LEO, intermediate altitudes and GEO.
- o Fabricate and test a space structure large enough to demonstrate controllability and dynamic predictability by analysis.

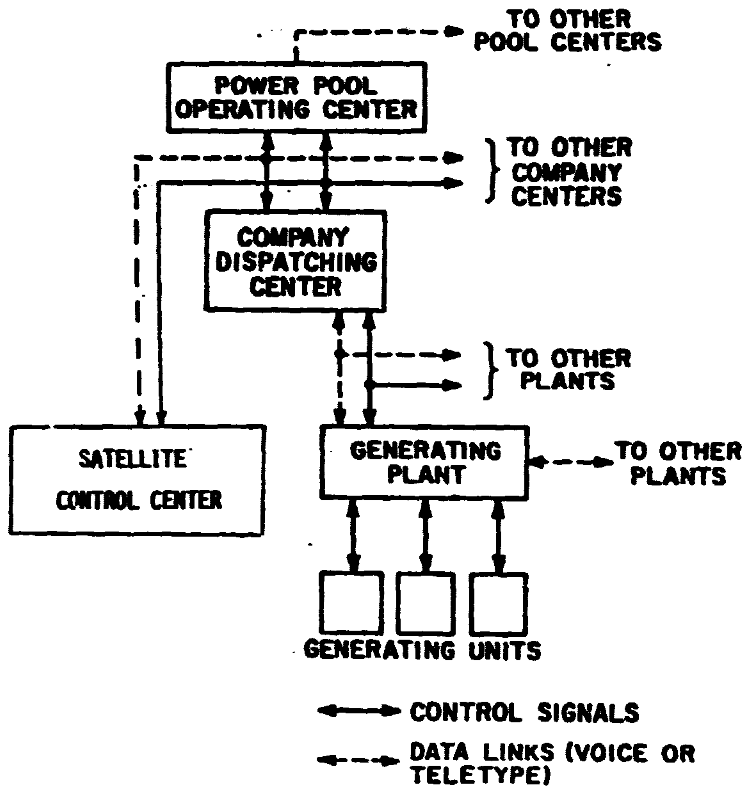


Figure 26 – Utility System Control Structure

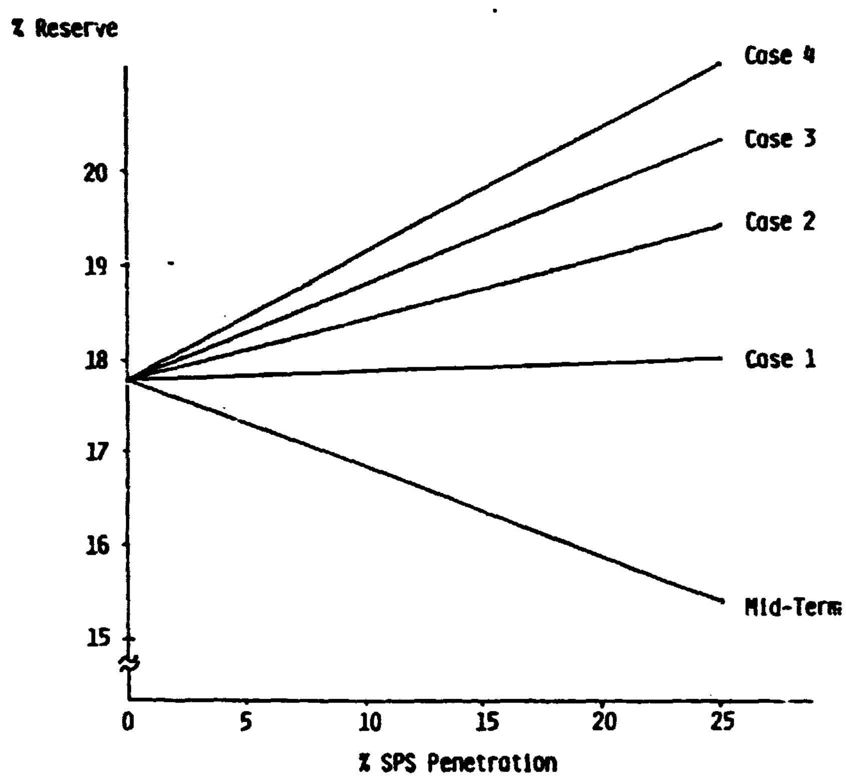


Figure 27 – Utility System Reserve Levels vs SPS Penetration

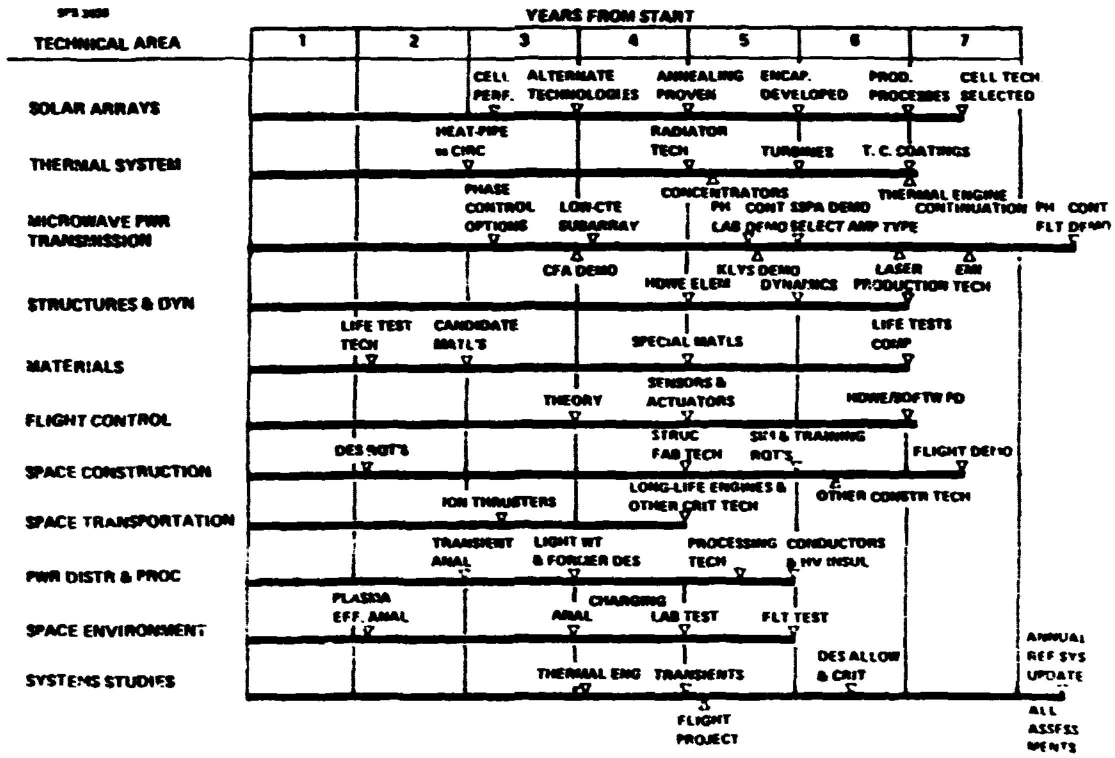


Figure 28 — Research Program Decision Schedule

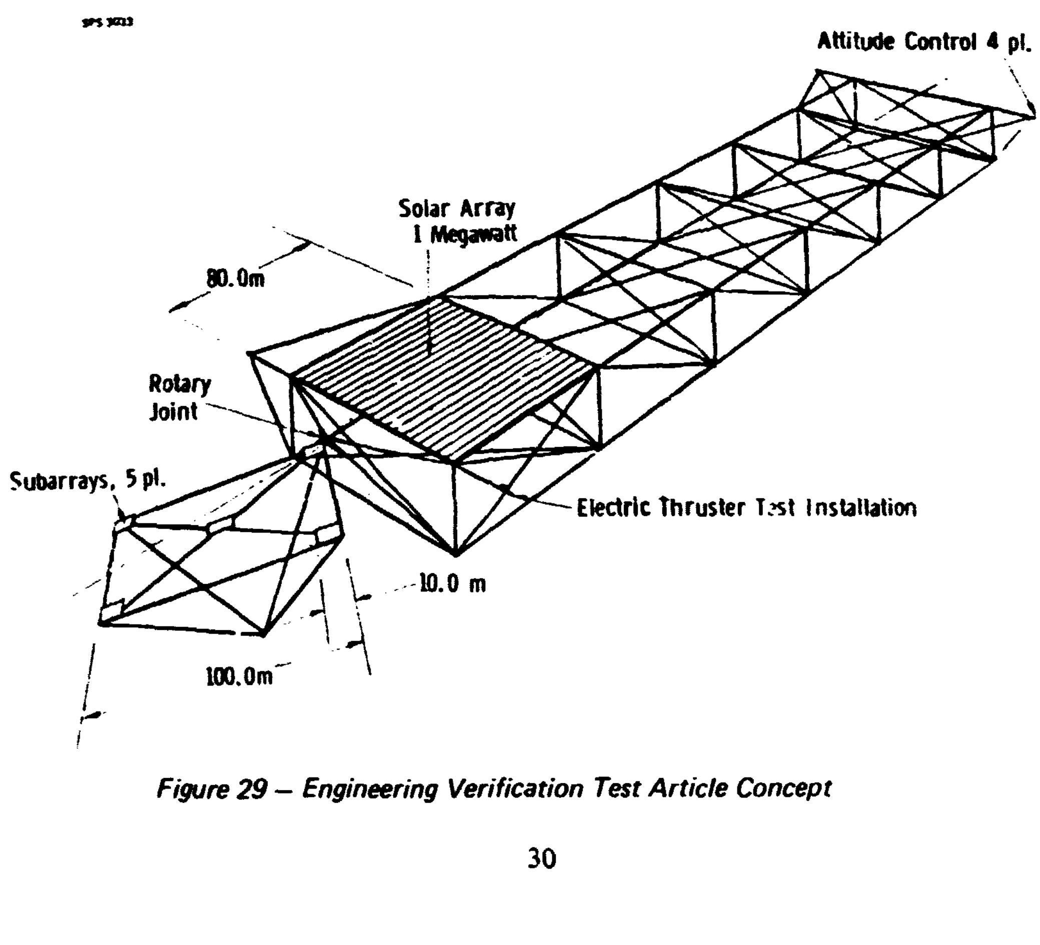


Figure 29 — Engineering Verification Test Article Concept

- o Test Power transmission elements at GEO.
- o Test electric propulsion elements at LEO, GEO, and intermediate altitudes to ascertain plasma and magnetosphere interactions.

The estimated mass for this test article is 40 metric tons.

The principal flight project for the demonstration phase is the pilot-plant-sized SPS shown in Figure 30. It would demonstrate space construction of large structures and power transmitter, EOTV operation, and power transmission from GEO to Earth. The power derived from the rectenna will be 100 to 200 megawatts depending on the rectenna size selected for demonstration.

Cost estimates were made for each element of the program and time-phased to develop the funding projection shown in Figure 31. All elements identified were included, e.g., manned OTV, although many of the items may have other applications.

Items 2 through 6 comprise the engineering verification program. Items 7 through 15 comprise the demonstration program. Items 16 through 24 represent the investment necessary to achieve a production rate of 2 SPS' per year.

In the production phase, the total annual funding will be on the order of 25 billions per year.

The sum of all program elements costs shown here including #1 SPS is 117.4 billions of 1979 dollars.

At the conclusion of the 1977 SPS Systems Definition Study, the estimate of total nonrecurring costs was 84 billions (1977 dollars). Table 10 summarizes the principal differences in the estimates. The most important increases are due to inflation and to elements added to the program to reduce risk, i.e., the earlier program had no demonstration phase.

Technical Issues

Current technical issues were covered in depth in the July Research Planning Report, which recommended a total of 173 research tasks, each aimed at one or more technical issues. A half-dozen major technical issues are summarized in Table 11. As may be seen, although some systems analysis issues remain, most will require conduct of the GBED program. Promising approaches have been developed for resolution of all SPS technical issues, but paper studies will not determine their adequacy. Meaningful further technical progress on SPS requires laboratory research, except in a few areas such as solid state transmitters, laser power transmission, and HLLV options, where further study is warranted.

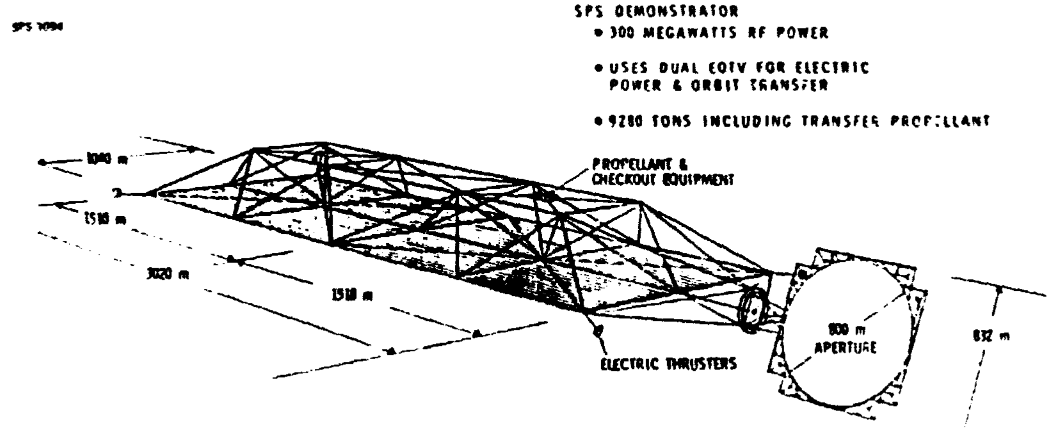


Figure 30 – SPS Demonstration Configuration

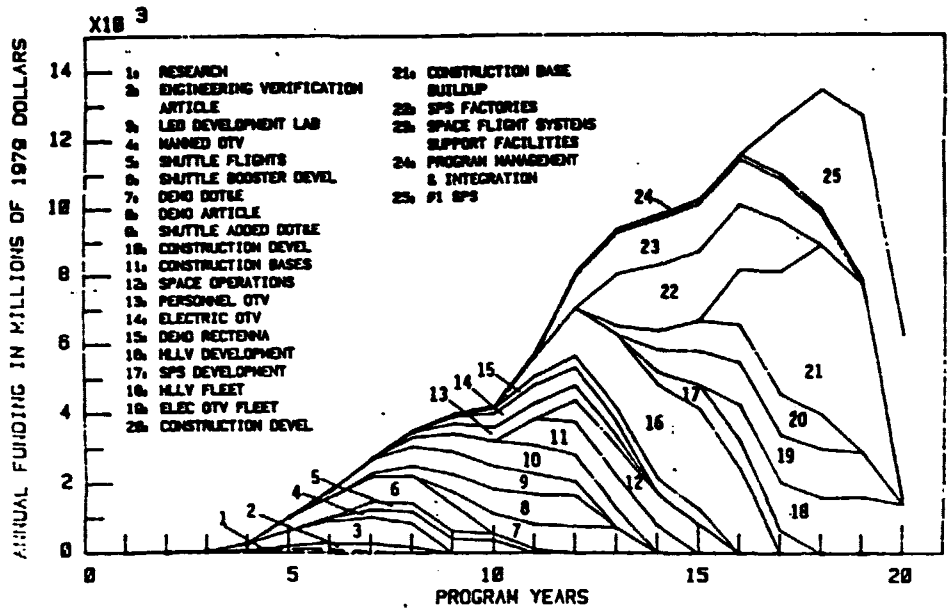


Figure 31 – SPS Total Program Through No. 1

Table 10 – Reasons for Increased Non-Recurring Cost (Values in Billions)

1977 FIGURE	84	
INFLATION	13	
	97	
ADDED ITEMS	(25.7)	
LEO Development Lab	2.7	
Manned OTV	1.4	
Shuttle Booster & Shuttle HLLV	6.7	
SPS Demonstrator	8.1	
EOTV Fleet	6.8	
NEGLECTED ITEMS	(2.7)	
Personnel Module	1.0	
Propellant Production Facilities	1.7	
SMALLER FIRST SPS	-14	
TOTAL	111.4	
INCREASE	6	Mainly HLLV & Construction Bases
	117.4	

Table 11 — SPS Major Technical Issues

ISSUE	MEANS OF RESOLUTION
o HLLV Size and Trajectory Selection	o Analysis of Shuttle-derived and Shuttle-evolved HLLV's; additional trajectory & atmosphere effects analysis
o Array Degradation & Annealing	o Irradiation & Annealing Research (GBED)
o EOTV Performance & Degradation	o Analysis of integrated effects
o Phase Control & Ionosphere Effects	o GBED and satellite experiments
o Technology Selections (e.g., silicon vs GaAs; Long-Life Materials)	o GBED
o Cost Confidence	o GBED & Engineering Verification

Exploratory Technology

Five areas of exploratory technology are under investigation as a part of the present study:

(1) Solar Cell Degradation and Annealing;

(2) Fiber Optic Link Assessment;

(3) Solid-State Transmitter Combiner-Radiator Module;

(4) Radiating Waveguide Antenna Panel Manufacturing tolerances and Uplink Receive Techniques;

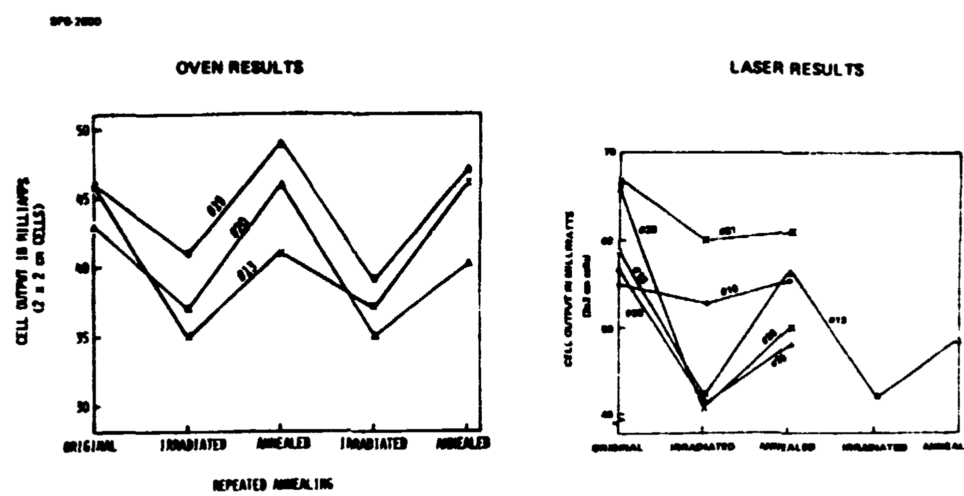
(5) Zero-g and Acceleration Effects on Space Workers (Support to JSC in Houston).

The annealing task was completed early in Phase II of the present study.

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. Thermal bulk annealing of radiation damage in silicon has been repeatedly demonstrated in the laboratory. Attention was given to laser directed-energy annealing under this contract.

A test program was conducted to further explore the laser annealing of glass-encapsulated 50-micron solar 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 ten 50-micron cells. Two were control cells that were not irradiated. These showed no loss in output due to exposure to the laser. Two cells were broken in handling. Six cells were successfully tested. All cells tested without breakage showed some recovery as shown in Figure 32, which compares oven and laser results. 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.



NOTE: THESE WERE ALL BARE CELLS. FURTHER DEVELOPMENT IS NEEDED IN HIGH-TEMPERATURE-COMPATIBLE GLASS ENCAPSULATION.

Figure 32 — Silicon Solar Cell Annealing

The other technology tasks were incomplete as of the date of this report and will be reported at a later date.

CONCLUSIONS

The most important high-level conclusions developed by the present study are:

(1) The reference systems definition is an adequate basis for the GBED program. This is not to say that research should be conducted only on the reference systems—the research should investigate all promising means of resolving SPS technical issues in the most cost-effective manner. The reference systems data base, however, provides an adequate understanding of SPS technologies from which to initiate an effective research program.

(2) Reference design definition carried the level of design detail to greater depth than previous studies. This had little effect on projected system mass and cost. The slight cost increase was mainly due to a bookkeeping change—maintenance provisions installed on the satellite that had earlier been charged to operations and maintenance are now charged to satellite capital cost.

(3) The investigation of a solid-state transmitter for SPS showed the solid-state system to be an attractive option. With expected improvements, it may be the most attractive means of providing an SPS in the 2000-2500 megawatt power range. Rectenna siting studies conducted during the first phase of the present study showed that having an SPS in this power range would allow siting roughly 60% more total capacity.

(4) Concerns regarding the reference electric orbit transfer vehicle make it important to evaluate alternatives. Promising approaches include solar, laser, and arc-heated hydrogen as well as LO_2/LH_2 systems. Examination of laser power transmission from SPS to Earth will also be evaluated in the next phase of study. Possible benefits of laser transmission include much smaller power blocks, e.g., 100 megawatts or less, that could make SPS more attractive to developing countries. A number of challenges exist, including achievement of link efficiencies high enough to make the laser option economically attractive.

(5) Development flight projects for SPS will require some heavy-lift augmentation of the Shuttle, employing modified and adapted Shuttle elements. We should consider continuing this evolution rather than developing a completely new HLLV for the commercialization of SPS. A smaller, Shuttle-evolved HLLV would reduce program nonrecurring cost with only a slight penalty in increased on-orbit assembly work. This approach will be evaluated in the next phase of study.