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SPACE-BASED SOLAR
POWER CONVERSION AND DELIVERY
SYSTEMS STUDY

INTERIM SUMMARY REPORT

Prepared for

The National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, Alabama

Contract No. NAS8-31308

March 31, 1976

MAY 1976
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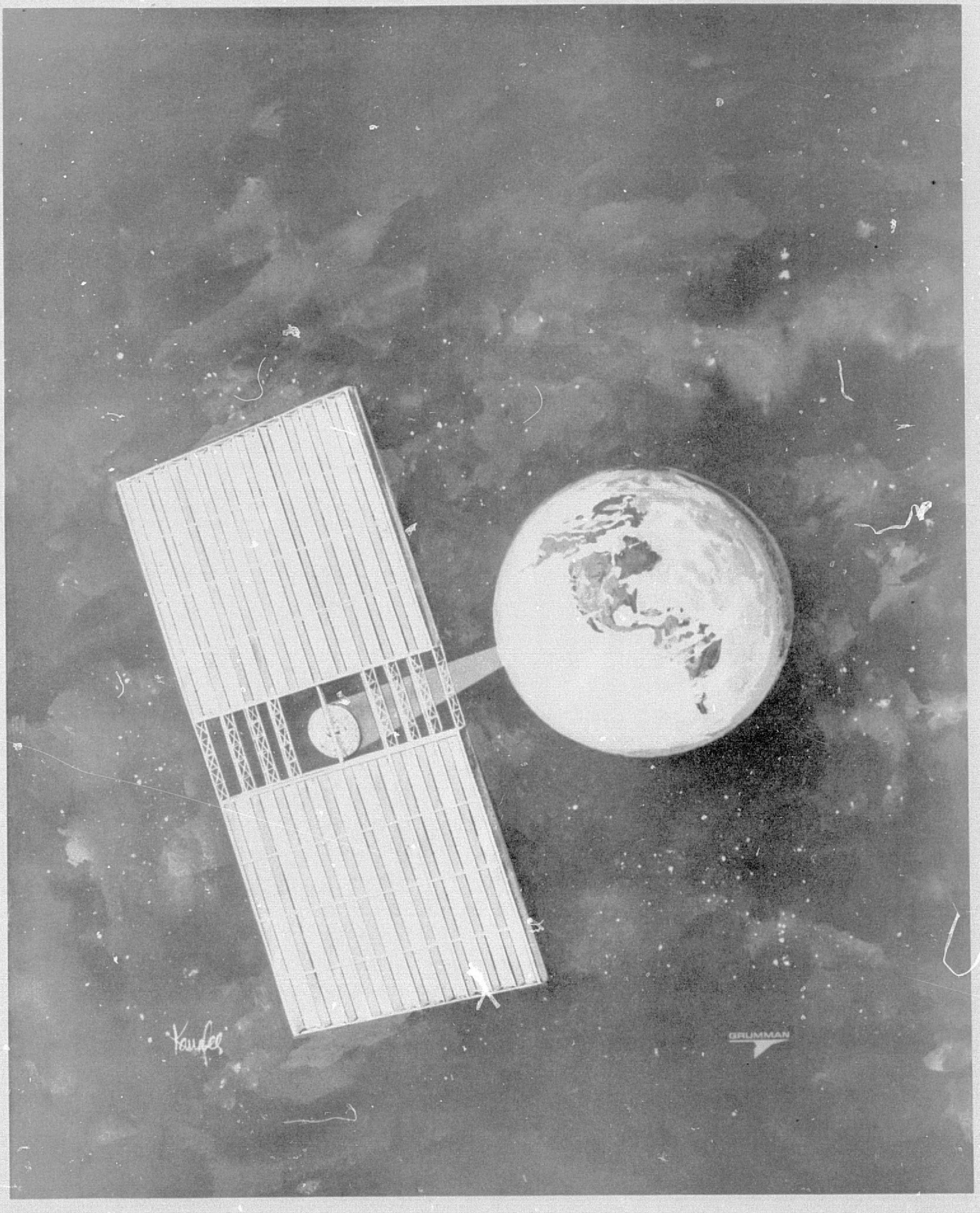
ECONOMICS OPERATIONS RESEARCH SYSTEMS ANALYSIS POLICY STUDIES TECHNOLOGY ASSESSMENT



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NOTE OF TRANSMITTAL

This study on space-based solar power conversion and delivery systems has been prepared for NASA. The George C. Marshall Space Flight Center, under contract NAS8-31308. The prime contractor has been ECON, Inc. whose study management and overall study direction has been under Dr. Edward J. Greenblat. Subcontractors to ECON have been Arthur D. Little, Inc. with Dr. Peter E. Glaser as study manager, Grumman Aerospace Corporation with Mr. C. Allan Nathan as study manager and the Raytheon Company with Mr. Andrew E. Edwards, Jr. as study manager.

Arthur D. Little, Inc. has been responsible for providing cost estimates of present and expected future terrestrial electric power generation and transmission systems. They also provided the framework for the requirements of future environmental assessment studies. The Grumman Aerospace Corporation provided all of the engineering studies on the special requirements and cost estimates for the Satellite Solar Power Station (SSPS) and the Power Relay Satellite (PRS) systems, except for the microwave elements which were performed by the Raytheon Company. ECON, Inc. provided the economic analysis and overall project management.

The following persons are also responsibly associated with the report: Dr. Klaus P. Heiss, Mr. Gregg R. Fawkes and Dr. George A. Hazelrigg, Jr. of ECON, Dr. Bette M. Winer, Dr. Ashok Kalelkar and Dr. John J. Bzura of Arthur D. Little, Mr. Richard L. Kline of Grumman and Mr. Owen E. Maynard of Raytheon. The MSFC COR has been Mr. Walter E. Whitacre of the Payload Studies Office. Mr. Simon V. Manson of the NASA Headquarters Energy Programs Office provided valuable guidance to this project.

Klaus P. Heiss

Klaus P. Heiss
President

Edward J Greenblat

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Study Director

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GRUMMAN
BETHPAGE NEW YORK 11714

March 24, 1976
NSS-LR-76088

Dr. Edward J. Greenblat
900 State Road
Princeton, New Jersey 08540

Dear Ed:

Grumman Aerospace Corporation concurs that this report contains an accurate and thorough presentation of the materials submitted to ECON over the course of this study. Grumman's principal input to ECON is contained in the report, NSS-P-76006, dated March 31, 1976. Grumman has participated in the presentation and review of this report and agrees with its findings and recommendations.

Sincerely,

C Allan Nathan

C. Allan Nathan
Study Manager

CAN/dr

Arthur D. Little, Inc. ACORN PARK · CAMBRIDGE MASSACHUSETTS 02140 · (617) 864-5770

April 2, 1976

Dr. Edward J. Greenblat
Assistant Vice President
ECON, Inc.
900 State Road
Princeton, New Jersey 08540

Dear Dr. Greenblat:

Arthur D. Little, Inc. concurs that this report contains an accurate and thorough presentation of the materials submitted to ECON over the course of this study. Our principal input to ECON is contained in the reports: Review and Analyses of Terrestrial Electric Generation and Transmission Systems; Interface of the SSPS with Electric Power Grids; and Data for Future Impact Assessment of the SSPS, dated October 16, 1975, Case #78127, 78127-1. We have participated in the presentation and review of our contributions to this report and agree to the extent our findings and recommendations have been used.

Sincerely,

Peter E Glaser

Peter E. Glaser
Vice President

kae

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Raytheon concurs that this report contains an accurate and thorough presentation of the materials submitted to ECON over the course of this study. Raytheon's principal input to ECON is contained in the report, ER 75-4390, dated October 31, 1975. Raytheon has participated in the presentation and review of this report and agrees with its findings and recommendations.

O. E. Maynard
Manager Space Systems

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1. INTRODUCTION AND SUMMARY

1.1 Introduction

1.1.1 Purpose of the Study

Even at reduced rates of growth, the demand for electric power is expected to more than triple between now and 1995 and to triple again over the period 1995-2020. Without the development of new power sources and advanced transmission technologies, it may not be possible to supply electric energy at prices that are conducive to generalized economic welfare. Solar power is renewable and its conversion and transmission from space may be advantageous. The goal of this study is to assess the economic merit of space-based photovoltaic systems for power generation and a power relay satellite for power transmission. In this study, satellite solar power generation and transmission systems, as represented by current configurations of the Satellite Solar Power Station (SSPS) and the Power Relay Satellite (PRS), are compared with current and future terrestrial power generation and transmission systems to determine their technical and economic suitability for meeting power demands in the period of 1990 and beyond while meeting ever-increasing environmental and social constraints.

1.1.2 Study Objectives and Scope

The principal objective of this study is to achieve increased understanding of the economic and technical aspects of space-based power generation and transmission systems and to determine whether--or under what circumstances--they may make significant contributions to meeting future energy demands.

Previous studies have defined concepts for the generation and transmission of electrical power from geosynchronous orbit and some demonstrations (i.e., microwave) of the required technology have been made. In funding this study, NASA required the following efforts:

- identification of operational and economic requirements of large, orbiting power conversion and power relay systems
- systems comparisons between synchronous orbit energy-generating systems and terrestrial systems that will be operating in the 1990s and beyond
- preliminary formulation of a framework that can be used for future analyses of the environmental and social impacts of orbital power systems
- definition of near-term research activities which will be required to demonstrate the feasibility and advance the technology needed to achieve launch and operational capabilities of space-based power systems in the 1990 time period.

Of particular interest to NASA has been the identification of key problem areas of operational power systems in orbit and the technologies required to resolve them, development of cost estimates of the required technologies and the identification of the social and environmental impacts arising from the operation of the systems.

By direction, the emphasis of the study has been on the identification and delineation of problem areas and technology requirements rather than on in-depth problem solutions.

1.1.3 Relationship to Other NASA Efforts

Several past and current NASA efforts have been drawn upon in the conduct of this study.

The initial SSPS study, "Feasibility Study of a Satellite Solar Power Station," under contract (NAS3-16804) to NASA Lewis Research Center, was conducted by the contractor team Arthur D. Little, Inc., Grumman Aerospace Corp., The Raytheon Co. and Spectrolab, Inc. [1] and used as a point of departure for the description of the SSPS.

Extensive interface with the work performed under contract to NASA Lewis Research Center (NAS3-17835), "Microwave Power Transmission System Studies" (NASA Report CR-134886) by Raytheon and Grumman, was important in defining transmission system technical and cost characteristics in considerable depth. Additionally, this study served as a guide to the technology development and test programs for the complete SSPS system presented in this study. Cognizance was taken of work performed to date as part of a NASA Lewis/JPL joint program to demonstrate the feasibility of power transmission from space. The receiving-and-rectifying antenna (rectenna) demonstrations by JPL at Goldstone and in the Raytheon Laboratory [2], and the ongoing technology development of the rectenna element into the low power density region for NASA Lewis by Raytheon, were considered for projections of future rectenna efficiencies.

Interface with the effort conducted for NASA MSFC, under contract with the Boeing Company (NAS8-31628) on "Alternate Space-Based Power Generation Systems" was important in establishing common approaches for purposes of comparison.

The evaluation of system concepts for Space Shuttle-derived, Heavy Lift Launch Vehicles (HLLVs), conducted under contract to NASA JSC (NAS9-14710) by Boeing and Grumman, and the Boeing study of "Future Space Transportation System Analysis" [3], had important bearings on transportation considerations.

The work on "Orbital Assembly and Maintenance," conducted under contract NAS9-14379 by The Martin Company [4], has contributed to the understanding of these important areas.

Coordination with parallel efforts on terrestrial power generation and transmission studies, performed for NASA by JPL, provided additional data for comparisons with terrestrial systems [5 and 6].

1.1.4 Major Study Findings

Nine major subprogram areas have been identified which need to be resolved for the development, operation and maintenance of the SSPS. These subprogram areas are as follows:

- Point Design Development
- Systems and Economic Studies
- Microwave Power Technology
- Solar Array Technology
- Large Structures
- Flight Mechanics and Control
- Operations, Manufacturing, Assembly and Maintenance
- Environmental and Other Impacts
- Transportation.

The major economic findings are summarized below. These findings depend upon the resolution of the subprogram areas that have just been listed:

- The SSPS may be cost-effective with respect to terrestrial systems by 1995. Since most terrestrial concepts depend upon nonrenewable energy sources, the economic viability of SSPS may be enhanced relative to terrestrial systems beyond 1995. Given the time period before SSPS may be cost-effective (1995), a decision to enter into a development-to-operations program or large-scale prototype is not economically justifiable at this time. However, given the potential economic benefits of SSPS in the 1995 period, the many concepts that are currently being studied, the new design approaches that are being advanced and the number of possible approaches to development and operations, the study results suggest that a significant study and limited technology program is warranted over the next four-to-five years. The purpose of this program would be to provide reliable information on the economic and technical viability of SSPS.
- SSPS may repay its total $44 billion DDT&E by CY 2013 with less than 60 units, were alternative terrestrial systems generation costs at least 35 mills/kWH. This result requires an SSPS buildup rate that ultimately provides 10 percent or more of United States installed generation capacity.

- The PRS energy transmission concept that has been studied has a decisive economic disadvantage compared to terrestrial systems up to distances of 5,630 km (3,500 nm). Beyond this distance, were it deemed in the national interest to engage in international transmission of power, the PRS appears to have economic advantages over alternative concepts.

The economic results do not indlude the relative social and environmental impacts that would be associated with the systems that were compared. Differences between terrestrial generation systems and the SSPS may be signigicant.

Of particular importance for the economic and technical feasibility of SSPS is a "heavy lift" launch vehicle with a payload to LEO of at least 182,000 kg 400,000 lbs). Finally, it should be noted that risk analyses of the development programs and operations are a required step before any "hard" conclusions may be drawn regarding the economic viability of the systems.

1.2 Summary

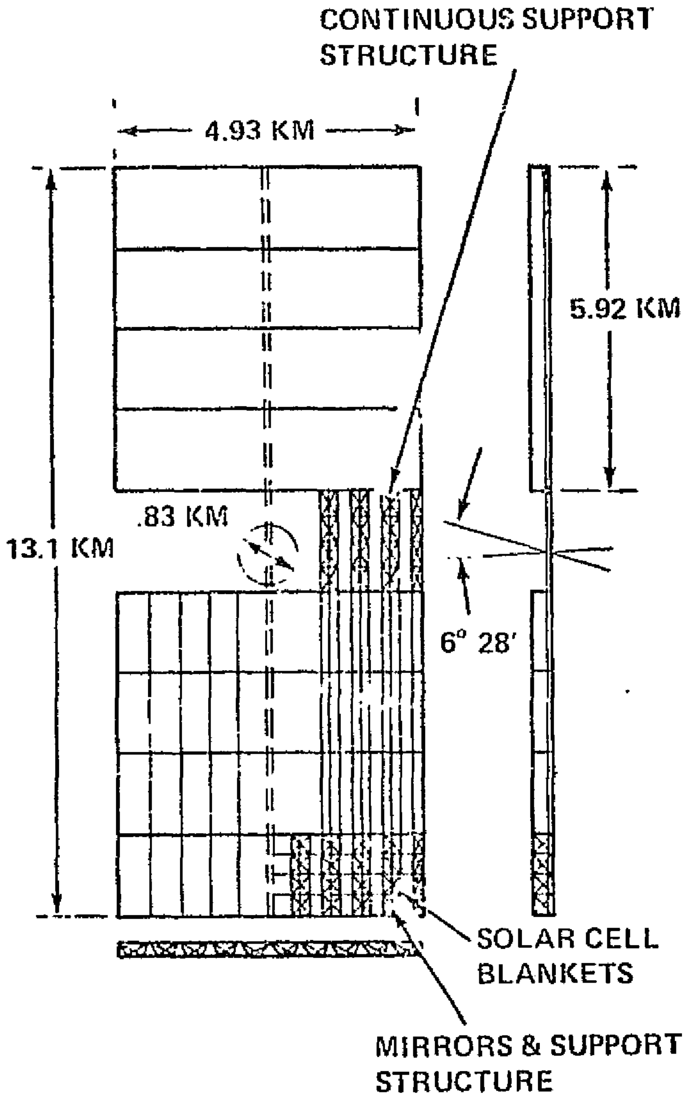
1.2.1 Descriptions of Orbital and Terrestrial Systems

1.2.1.1 Orbital Systems: The Satellite Solar Power Station

The baseline SSPS, illustrated in Figure 1.1, is sized to generate 5,000 MW of rectified power at the output bus of the receiving antenna. This power level was chosen to provide economies of scale while keeping the peak microwave power density in the center of the rectenna to 20 mW/cm^2, a level that is expected to meet anticipated environmental standards. The 20 mW/cm^2 value approaches the anticipated threshold level for affecting changes in the ionsphere. It is noted, however, that the effects of these anticipated changes are unknown.

The satellite's mass in orbit is 18,000,000 kg. An operating frequency of 2.45 GH$_z$ was selected based on considerations of power transmission efficiency, low susceptability to brownouts in rain and minimal potential problems with radio frequency interference. The transmitting antenna is an active planar phased array which uses amplitrons for dc to rf power conversion. The photovoltaic power source generates 8,600 MW of power using an advanced 50-micron thick silicon blanket that has an initial efficiency of 13.7 percent at a solar concentration ratio of two. The overall efficiency from solar blanket busbar to ground station busbar is 58 percent.

The design concept has two large solar cell arrays, each approximately 6 km x 5 km, inter-connected by a carry-through structure of dielectric material. A 0.83 km diameter microwave antenna is located on the centerline between the two arrays and is supported by the central power transmission bus (mast) structure that extends the full length of the power station. The antenna is attached to the mast structure by a joint system which rotates 360 degrees in azimuth (east-west) and ± 8 degrees in elevation (north-south). The solar cell blankets are laid out between channel concentrators stretched over a supporting frame.



- Concept Description

  Collects solar power using photovoltaic converters and transmits power to Earth as microwave power. The microwave power is rectified to dc power at the ground receiving station.

- Characteristics

- Power	5000 MW
- Mass	18.1×10^6 kg
- Size	13.1 x 4.9 km
- Orbit	Geosynchronous
- Life	30 Years
- Operating Frequency	2.45 GH_Z
- dc-to-dc Efficiency	58%
- Solar Array Efficiency	11.3% (13.7% blanket efficiency)

- Costs (1974 Dollars)

- IOC	1990 - 1995
- DDT&E	
- Directly Related	\$20.4B
- Support Programs	\$23.5B
- Unit Costs	\$ 7.6B
- Operating Costs	\$136M/Year

Figure 1.1 The 5,000 MW Satellite Solar Power Station

A 10,000 MW version of the SSPS is illustrated and summarized in Figure 1.2 This version may have desirable scale economies. The 5,000 MW system, however, has served as the baseline throughout the study.

The Power Relay Satellite

The baseline PRS microwave power transmission concept, illustrated in Figure 1.3, is a reflector in synchronous orbit for providing power transfer from a transmitting antenna at one ground location to a ground receiving antenna at a distant location. For reasons similar to those influencing the sizing of the SSPS, the baseline PRS has been sized over a power range of 5,000 to 10,000 MW at the output bus of the ground receiving station. For economic reasons, it is not expected that power densities as low as 20 mW/cm^2 can be maintained.

The transmitting antenna is a phased array with waveguides and converters similar to the SSPS and the receiving ground station is also similar to that of the SSPS. The current concept has transmitting array and rectenna diameters of 10 km and a reflector diameter of 1 km.

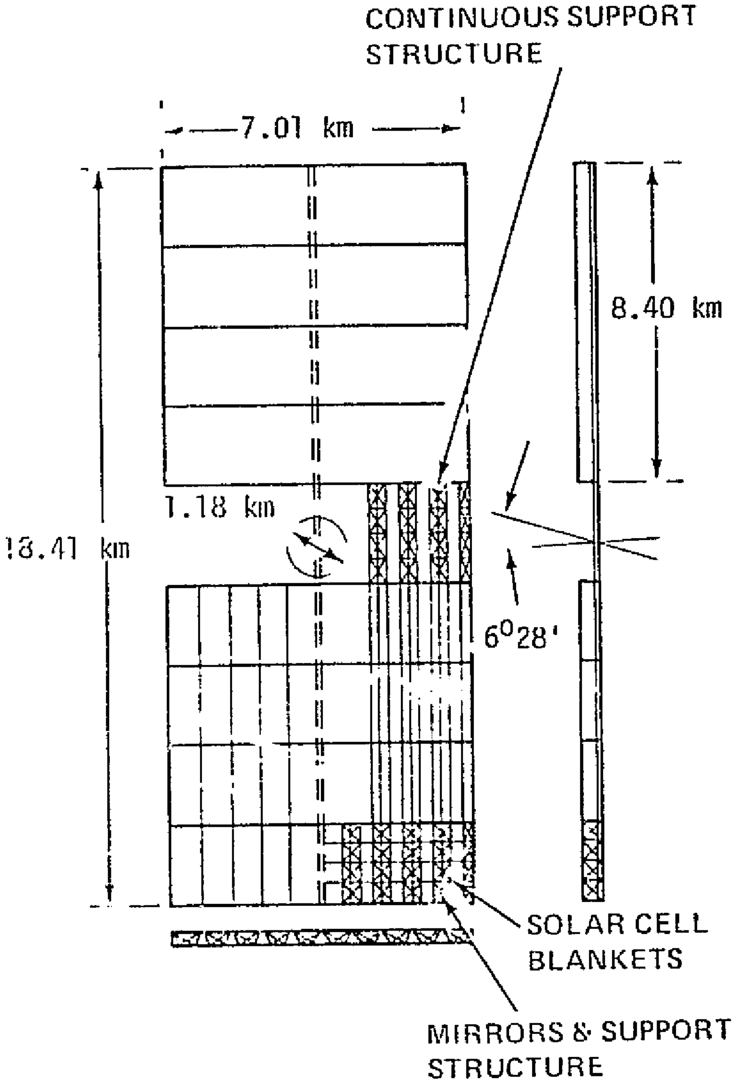
Atmospheric effects and errors at the ground-based transmitting antenna require that it be sectored into subarrays which must be controlled. Control can be accomplished by adaptive control which requires a reference beam sent from the reflector. Alternatively, a sensor matrix at the reflector could provide command control.

The PRS reflector configuration consists of a primary structure that is built up of 108 m x 108 m x 20 m deep bays. Each 108 m module is spanned by a secondary structure which is an 18 m grid of 5 m deep girders. The 18 m substructure provides support for the microwave reflector system. The expected overall efficiency of the system, from input bus of the the transmitting antenna to the output bus of the receiving ground station, is 53 percent.

1.2.1.2 Terrestrial Systems: Power Generation Systems

For the purposes of this study, terrestrial power generation systems have been designated as either "existing" or "future" systems. Although the present form of existing systems may not be installed in the time frame when SSPS could become operational, these systems provide the most reliable data base for the purposes of an economic comparison.

Existing systems include oil-fired and coal-fired fossil fuel plants and light water reactor nuclear (LWR) plants. The technical characteristics of these systems are well-known. The major uncertainties associated with these systems are in the availability and price of fuels for the oil-fired and nuclear systems, the environmental hazards associated with all terrestrial systems and the economic (investment) problems resulting from the social and environmental challenges currently being placed before nuclear systems.



- Concept Description

Collects solar power using photovoltaic converters and transmits power to Earth as microwave power. The microwave power is rectified to dc power at the ground receiving station

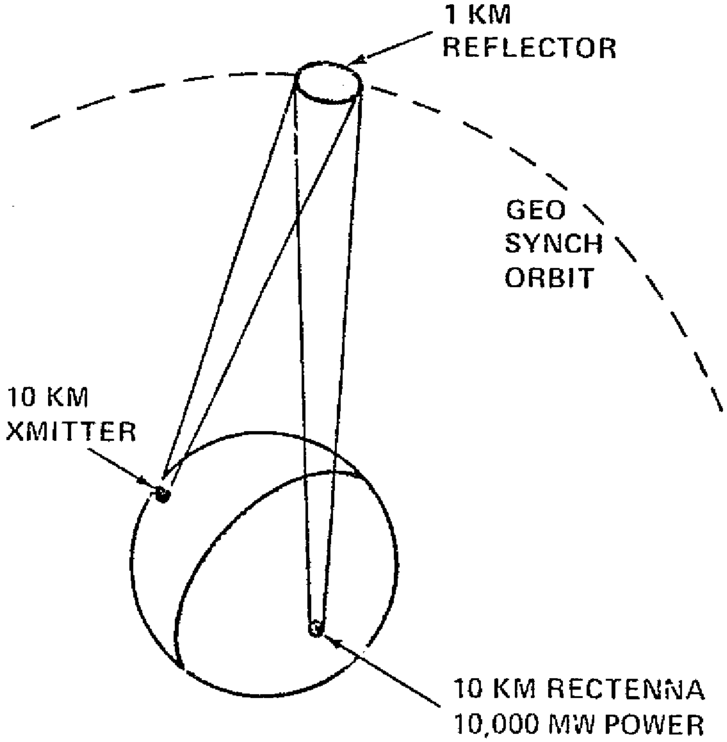
- Characteristics

- Power	10,000 MW
- Mass	34.4×10^6 kg
- Size	18.4 x 7.0 km
- Orbit	Geosynchronous
- Life	30 years
- Operating Frequency	2.45 GHz
- dc-to-dc Efficiency	58%
- Solar Array Efficiency	11.3% (13.7% blanket efficiency)

- Costs (1974 Dollars)

- IOC	1990 - 1995
- DDT&E	
- Directly Related	26.7 B
- Support Programs	23.5 B
- Unit Costs	14.4 B
- Operating Costs	To be determined

Figure 1.2 The 10,000 MW Satellite Solar Power Station



- Concept Description

Transfer large amounts of power over great distances using a microwave transmitter at a ground-based, remotely located power generating plant and reflecting microwave power off a satellite at geosynchronous orbit to a ground-based receiving antenna

- Characteristics

- Power at Rectenna Bus	10,000 MW
- Satellite Mass	0.42×10^6 kg
- Satellite Size	1 km Diameter
- Ground Antenna Size	
- Transmitter	10 km Diameter
- Receiver	10 km Diameter
- Orbit	Geosynchronous
- Life	30 Years
- dc-to-dc Efficiency	53%

- Costs (1974 Dollars)

- IOC	1990 to 1995
- DDT&E	
- Directly Related	\$ 8.6B
- Support Programs	\$13.1B
- Unit Costs	\$ 8.2B
- Operating Costs	\$106M/Year

Figure 1.3 The Power Relay Satellite

The pollution problems and costs associated with the current methods of using coal to directly fire a steam generator have led to the development of several future approaches and processes for using coal either directly (as in the case of fluidized-bed combustion) or after the significant amount of processing required for coal gasification or liquefaction. For this study, enumeration of the costs and system efficiencies associated with future coal processing plants was conducted for: two coal liquefaction techniques (Consol Synthetic Fuel and Solvent Refined Coal), 6 high-BTU coal gasification techniques (Lurgi, Hygas-Electrothermal, Hygas-Steam-Oxygen, Bigas, Synthane, CO_2 Acceptor) and two low-BTU processes (BOM Pressurized, Lurgi). Two future advanced nuclear fission reactor systems considered to be representative of the developing nuclear technology were studied (i.e., the Liquid Metal Fast Breeder Reactor [LMFBR] and the High Temperature Gas-Cooled Reactor [HTGR]).

Power Transmission Systems

In order to compare the PRS transmission concept with terrestrial alternatives, use has been made of available data on representative terrestrial systems in order to design transmission systems that would provide a capability equal to that of the PRS. While these systems provide such a capability, it is unlikely that they would in fact be built.

The categories of terrestrial alternatives studied include transmission via conventional circuits and super conducting transmission lines (all of which are considered to be "existing" systems even though some currently exist only in experimental application), and hydrogen transmission and microwave transmission via waveguides (which are classified as "future" systems).

In order to design the most economic terrestrial power delivery systems that would provide a capability equal to that of the PRS, it was necessary to make the following basic design assumptions:

- Power input--ac electric power would be at the appropriate voltage level.

- Power output--ac electric power would be at the appropriate voltage level.

- All transmission systems would have the capacity required to most economically deliver 5,000 or 10,000 MW. Additional capacity would be added at the source to provide the capability of economically carrying that power which would be lost along the route.

- Designs would be those which were most economical in 1974.

- The cost of the energy lost because of transmission would be based on a 1974 cost of \$0.02/ kWH = \$175 x 10^3/MW-year.
- All transmission systems would be in use 100 percent of the time.
- Overland circuits would range from 3,200 to 8,000 km (2,000 to 5,000 mi) long. This is independent of the great circle distance between the transmitting and receiving points.
- Only transmission capability would be considered. No credit would be given for the potential benefit of energy storage since the PRS does not provide any energy storage option.
- Systems having a transmission efficiency of less than 50 percent would not be considered.

1.2.2 Economic Analysis

For the economic analysis, the SSPS and PRS were compared with terrestrial power generation and transmission systems of equal output capability. Based upon this economic comparison, recommendations have been made regarding the decision to initiate an SSPS development program.

For purposes of decision-making the following decision algorithm was formulated:

- If the SSPS or PRS could be shown to be cost effective, compared with existing systems at todays relative prices (while meeting environmental and social constraints), then there should be little hesitation to go ahead with a positive development-to-operation decision.
- If no future conditions could be identified under which the orbital systems would be cost effective, then the decision to curtail further development is warranted.
- If the orbital systems are not cost effective at today's relative prices but may be cost effective under realistic future conditions, then the decision should be made to proceed with a limited technology program designed to acquire the knowledge for making a later decision.

1.2.2.1 Economic Analysis of Power Generation Systems

Table 1.1 provides an annual cost summary of an operational 5,000 MW SSPS. This summary presents only the recurring unit, operations and maintenance costs and does not include DDT&E. Also, these costs are for a representative operational unit after "learning" has been accomplished. The "serial number" is not specified. With an assumed operational life of 30 years, the busbar cost of energy generated by a 5,000 MW SSPS would be 26.7 mills/kWH. This includes 15.0 mills for capital recovery at a 7.5 percent discount rate, 3.1 mills for maintenance and 8.6 mills for taxes and insurance.

Table 1.2 contains a summary of the major 5,000 MW SSPS unit cost elements. As seen, the satellite hardware accounts for only about 30 percent of the total cost. Transportation is the major cost element (43 percent) and the ground station accounts for 18 percent.

Table 1.3 contains a summary of the development program required for the fabrication, assembly and deployment of a 5,000 MW SSPS. The estimated total DDT&E is $44 billion. Three components have been identified: direct DDT&E, related DDT&E and support programs.

Table 1.1 Annual Cost of an Operational 5,000 MW SSPS

ELEMENT	ANNUAL COST $millions (1974)	USER CHARGE mills/kWH (1974)
• Satellite	657	15.0
• Maintenance	136	3.1
• Taxes, Insurance	377	8.6
TOTAL	1170	26.7

The direct DDT&E programs pertain to those program elements which would not be developed were it not for the decision to develop the SSPS. These total approximately $19.2 billion.

Of much smaller magnitude, $1.3 billion, are the development costs referred to as "related DDT&E." These are developments that are necessary for the realization of an SSPS but might be required by other space programs.

Table 1.2 Five Thousand Megawatt SSPS Unit Cost Summary

ELEMENT	COST $ billions, 1974	PERCENT
o Solar Array	1.798	24.0
Solar Blankets	(1.501)	(20.0)
Array Support Structure	(0.297)	(4.0)
o Transmitting Antenna	0.495	6.5
o Propellents, etc.	*	*
o Fabrication and Assembly Equipment	0.573	7.6
o Transportation	3.278	43.3
Space Shuttle Fleet	(0.240)	(3.2)
HLLV Fleet	(1.074)	(14.2)
Space Shuttle Flights	(0.879)	(11.6)
HLLV Flights	(1.013)	(13.4)
Orbit-to-Orbit Vehicles	(0.072)	(0.0)
o Personnel	0.077	1.0
o Receiving Antenna	1.345	17.8
TOTAL	7.566	100.0

* Cost is negligible, weight has been accounted for in transportation charges.

Table 1.3 SSPS Development Program Costs

DEVELOPMENT PROGRAM	COST $ millions, 1974	PERCENT
• Direct SSPS Development	19176	43.6
Solar Array	(11521)	(26.2)
Structure	(2782)	(6.3)
Reaction Control	(554)	(1.3)
Rotary Joint	(1643)	(3.7)
Microwave Transmission and Reception	(2676)	(6.1)
o Related Development	1292	2.9
• Support Development	23537	53.5
Launch Vehicles	(11626)	(26.4)
Orbit-to-Orbit Transfer	(7478)	(17.0)
Crew Module	(319)	(0.7)
LEO Space Station	(3738)	(8.5)
SO Space Station	(376)	(0.9)
TOTAL DEVELOPMENT	44005	100.0

* Includes 40% for management and a 20% uncertainty factor.

The DDT&E, summarized in Table 1.3, designated "Support Development" are required for the launch, assembly and orbital transfer of the SSPS. Unlike the other technology developments, these are likely to be required--in part or entirety--by other space programs. If the only "customer" for these systems were the SSPS, then the latter should bear the full burden of repaying their development, however, this is not expected to be the case.

As described in the following chapters, at existing relative prices, the SSPS would not be cost effective compared with terrestrial systems but, at expected future relative prices, it may well be cost effective. Figure 1.4 illustrates the comparative economic analysis for an SSPS operational in 1995.

The x-axis (abscissa) contains average values for the cost of electric generation over the 30-year period (1995-2025) in mills/kWH. The y-axis contains the "Economically Justifiable" 5,000 MW SSPS unit cost. The method by which this has been estimated and the rationale for the choice of discount rate is described in Appendix A.

The analysis compares the 5,000 MW SSPS with terrestrial fossil fuel systems. (i.e., oil and coal-fired generation plants).

The line, R, in Figure 1.4 relates the generation cost in mills/kWH of terrestrial coal and oil-fired systems over the period 1995-2025 as indicated on the x-axis. A range of cost estimates resulting from the study performed by University of California - Berkeley for JPL is also shown on the x-axis.

The coal and oil system values are based on three projections of the future:

1. Relative fuel prices[1] remain constant (C_0, O_0)
2. The relative prices of coal increase by 2.6 percent per year, and the relative price of oil increases by 0.67 percent (C_A, O_A)
3. The relative prices of coal and oil increase by 5.0 percent per year (C_B, O_B).

As indicated by the suggested probability distributions, the first projections have a very low expectation. Regarding coal, the cost of production will rise as it becomes necessary to mine deeper veins and provide the expected environmental and human safeguards. Regarding oil, increased scarcity will no doubt raise relative prices. In fact, new oil-fired capability may not be installed by 1995.

The second projection has been adapted from the work of E.A. Hudson and D.W. Jorgenson and is highly regarded in the economic

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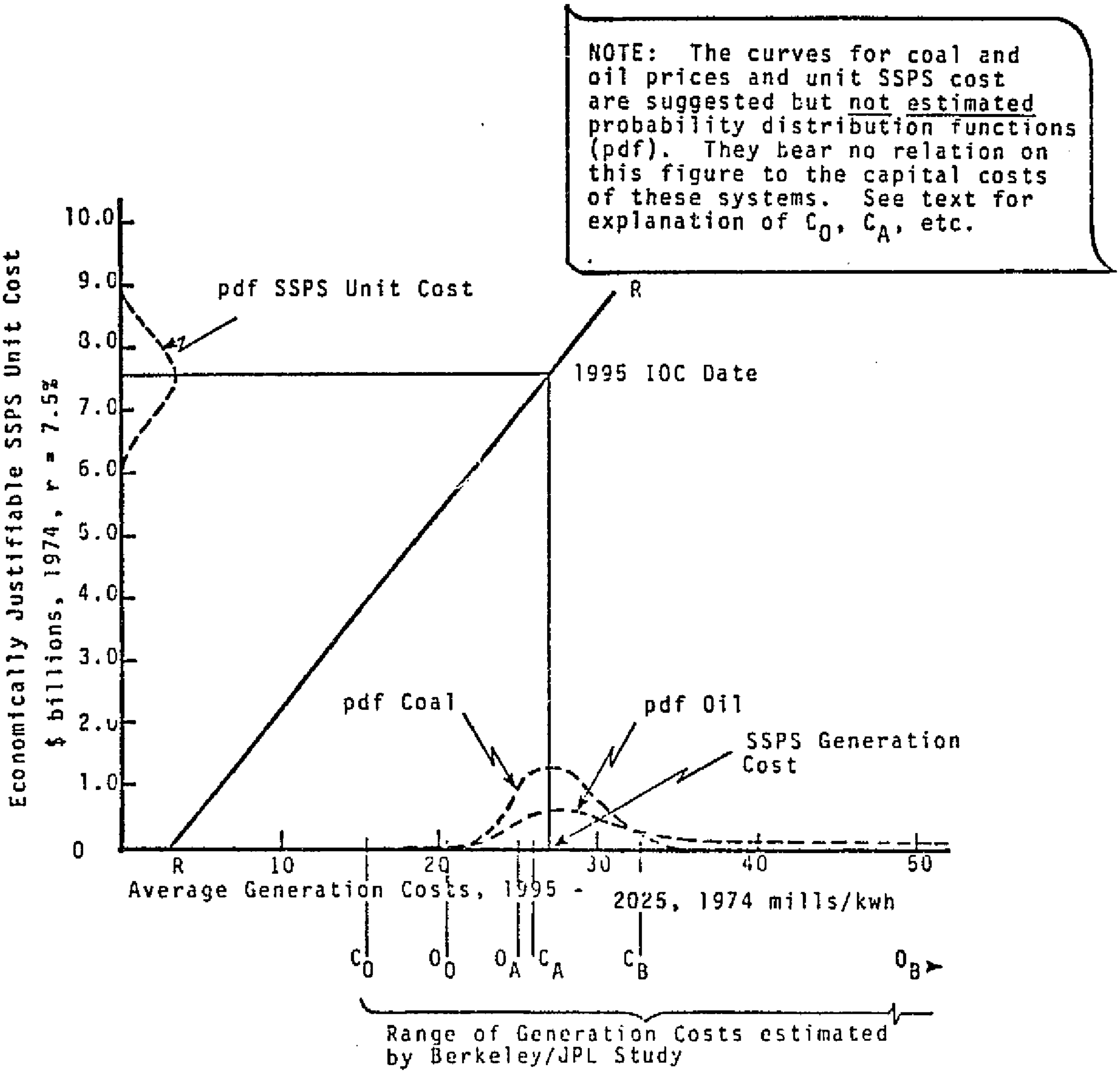
[1] "Relative prices" refer to the price relationship of all goods and services to each other. The usual practice is to consider one good as the baseline and calculate all prices relative to it. Obviously, generalized inflation would not affect relative prices.



NOTE: The curves for coal and oil prices and unit SSPS cost are suggested but not estimated probability distribution functions (pdf). They bear no relation on this figure to the capital costs of these systems. See text for explanation of C_0, C_A, etc.

1.4. Comparative Economic Analysis of a 5,000 MW SSPS Operating Over the Period 1995-2025 energy literature[2]. These estimates were derived from their analysis of a scenario in which the government does not intervene with respect to energy prices.

The third projection has been derived from the Hudson-Jorgenson scenario in which the United States government levies a "BTU" tax of $0.05/million BTU (to encourage fuel conservation), over the period 1975-1980 and $1.35/million BTU over the period 1980-1985[3]. The goal of this action is United States energy independence by 1985.

Based upon projection of the Hudson-Jorgenson estimates of relative price changes to 2025, the typical coal-fired plant would generate electric power at an average price of 25.1 mills/kWH over the period 1995-2025. Were a vigorous policy of energy independence pursued, the average generation price would be about 33 mills/kWH.

The same analysis for oil indicates that the projections of the Hudson-Jorgenson estimates of "no policy change" would not effect the relative standing of oil-fired systems. Were the "energy independence" policy pursued, the price of electric power from oil-fired plants might be driven off the scale.

Based upon these results, there is some expectation--the probability of which is unknown at this time--that the SSPS will be cost effective with respect to fossil fuel systems by 1995. Furthermore, since fossil fuel systems depend upon non-renewable sources of energy, the economic viability of SSPS should be enhanced relative to these beyond 1995.

While every attempt has been made to cost the systems on a consistant basis, one major element of cost has not been addressed: the systems' relative social and environmental impacts. Within this study we have begun to develop a framework for evaluating these impacts. This will, however, require much further study before our level of understanding is adequate for the purpose of decision-making.

A second issue that could impact total systems cost is the relative acceptable distance between population and industrial centers for SSPS rectennas and conventional electric power generators. This is an important determinant of the cost of energy transmission, and

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[2] Hudson, E.A. and D.W. Jorgenson, "U.S. Energy Policy and Economic Growth, 1975-2000," The Bell Journal of Economics and Management Science, Vol. 5, No. 2, Autumn 1974.

[3] It is to be stressed that the 5 percent value is not that of Hudson-Jorgenson. It is our projection of the constant dollar impact estimated in their analysis.

hence, the delivered cost of electric power to the user. Based on current trends in plant siting, it does not seem likely that major energy-intensive industries--such as metals processing--would locate near 5,000 to 10,000 MW nuclear sites. The rectenna site, on the other hand, would appear to be amenable to such activity. These issues, however, await future study.

Finally, it should be noted that the U.S. Energy Research and Development Administration (ERDA) is currently funding research in electric generation technologies such as ocean thermal and solar power towers that are expected to produce energy in the range of 30-50 mills/kWH as well as fusion power, the cost of which is even more difficult to estimate.

Figure 1.5 provides an economic analysis of the payback of the $44 billion development program. The analysis presumes that the total development burden is borne by the SSPS program, an assumption which is not, in our opinion, justified.

One x-axis (abscissa) is "time" in calendar years. A second x-axis indicates the cumulative number of 5,000 MW SSPS units operational at the beginning of the indicated year. The buildup--two per year until 2000, then four per year until 2025--would provide at least 10 percent of the United States incremental generation demand.

The y-axis (ordinate) is generation costs in mills/kWH of alternative (terrestrial) systems. The range of costs resulting from the Berkeley/JPL report is indicated.

The curve P-P is used to parametrically estimate the DDT&E payback as a function of alternative electric generation costs. Its shape depends on the discount rate and the SSPS buildup rate. Its derivation is provided in Appendix A.

If alternative generating systems costs do not exceed 27 mills/kWH--the SSPS estimate--DDT&E would not be repaid. Indeed, the function becomes asymptotic to the x-axis at about 31 mills/kWH, indicating that at least 4 mills/kWH difference between SSPS and terrestrial systems is required to payback the DDT&E. (Again, this presumes that the total DDT&E bill accrues to SSPS.)

As indicated, were the alternative generation cost 35 mills/kWH--point A on the y-axis--the DDT&E would be repaid by CY 2012 with 57 5,000 MW operational SSPS units.

1.2.3 Technology Subprogram Areas

Nine subprogram areas were identified which need to be resolved for the development, operation and maintenance of the SSPS. These were presented in Section 1.1.4. Simultaneous with this effort,

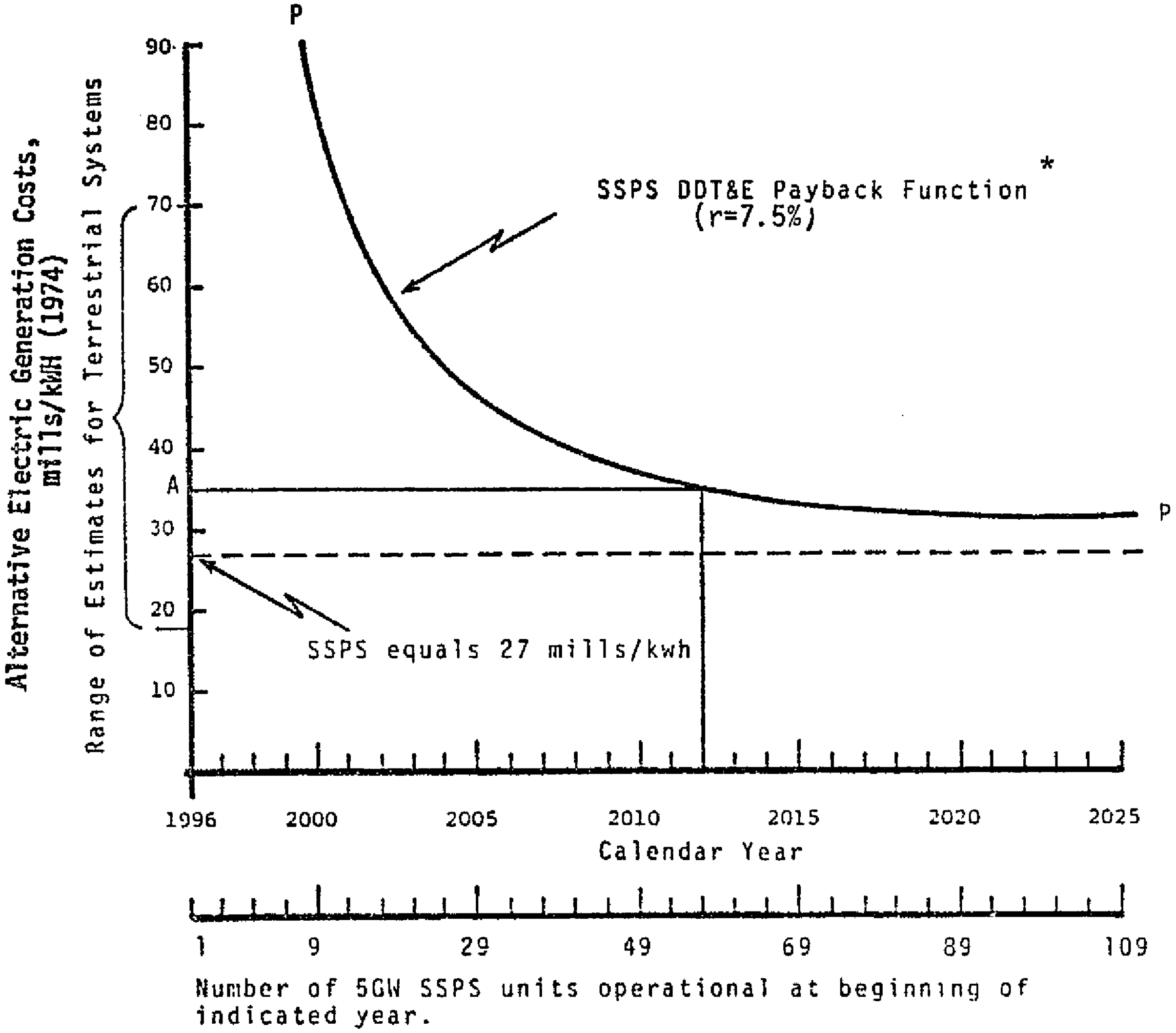

Figure 1.5. Payback Analysis of SSPS Development Programs for a Discount Rate of 7.5 Percent

* Buildup rate equals 2/yr. to CY 2000, 4/yr. to CY 2025.

NASA identified key areas for technology development of the SSPS. Upon review of this effort, it was found that the NASA list of nine subprogram areas was virtually identical in substance to the findings of our study team. It was decided, therefore, to standardize our reporting on the NASA subprogram areas, a listing of which follows:

1. System Definition
2. Power Conversion
3. Microwave Power Transmission
4. Large Structures
5. Operations
6. Transportation
7. Attitude Control & stationkeeping
8. Environmental Effects
9. Orbital Technology Verification.

Selected subprogram areas summarized in this section and the following section, contain a suggested development program for their resolution. More detailed descriptions of these problem areas and proposed resolutions appear in the report.

Power Conversion

- Raw material processes: The process for producing semiconductor grade silicon requires three energy-intensive, high temperature cycles. A single-step process could result in savings of factors from three to five over the price paid today.

- Crystal growth: Three approaches to single-crystal growth are being pursued today. The major problem is to find die materials that can withstand the temperatures of the process while maintaining the efficiency of the solar cell producted. Another problem in this area is to reduce the solar cell thickness to 50 um.

- Solar blanket processes: Current methods for fabricating solar blankets are slow, mostly done by hand. For solar blankets of the size required by SSPS an automated process is required.

- Packaging: The groundrule requirement of 30-year life in a space environment suggests that improvements in solar cell incapsulation are required including increased resistance to radiation damage.

- Solar cell performance: Currently available space-qualified solar cells can achieve beginning-of-life conversion efficiencies of 12-14 percent. For SSPS, a beginning-of-life solar cell efficiency of 18-20 percent is desirable.

- Alternative photovoltaic devices: Although this study has concentrated on silicon solar cells for power conversion, the gallium arsenide and multi-vertical n/n junction cells should be studied further. These devices show high performance at very high concentration ratios.

Microwave Power Transmission[4]

- DC-RF convertors and filters: rf convertors and filters must convert high voltage dc power to rf power with low noise and harmonic content. The design concept used for this study entails the most complex set of mechanical, electrical and thermal technology development problems in the SSPS system. The device must also be capable of being produced at high rates and low cost, and must provide reliable operation over a long period.

- Materials: The most critical and unusual requirements for materials for the SSPS stems from the presence of the exposed cathodes of the rf generators. It is also necessary that structural thermal strain be small so that distortions over the large SSPS dimensions are manageable. Additionally, the waveguide distortions must be small to permit efficient phase front formation.

- Phase control subsystems: Projected phase front control subsystems scatter losses are significant in the microwave transmission efficiency chain. Furthermore, the uncertainty associated with the losses is significant.

- Waveguide: Slotted waveguides interface with rf generators in a high temperature environment. They must distribute the power and emit it uniformly with low losses. The ability to manufacture, fabricate and assemble such waveguides is not certain.

- Attitude control of the transmitting antenna: In this study, attitude pointing control was conceived to be accomplished by mechanical action. The problems associated with this are unprecedented. The requirements are (1) large members of lightweight construction that transmit high power across relative motion interfaces, (2) operations in a space environment with high reliability and safety, (3) low cost, (4) high packaging density for earth launch and then deployment and assembly in space and (5) long life with minimal maintenance.

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[4] See NASA CR-134886, Section 11 for further detail.

- Power transfer: Although the technology for performing this function is essentially known, the large scale of SSPS--in size and power level--is expected to present significant new problems.

- Switch gear: The problem is to make multiple brushes feed multiple sliprings. This will bring the individual switch gear currents close to the threshold where the basic technology is now known. Major advances must be made in packaging for space operations.

Large Structures

The SSPS structure is currently characterized to be thin-walled, of low deployed density, having high surface-to-mass ratio metallic (or possibly composite) elements which can be assembled into open space-frame structural elements. These elements must be assembled into larger space-frames which form a very large (approximately 1 km) antenna and even larger solar arrays. After materials technology development and selection, the problems associated with low thermal inertia, large dimension structures, and traversing the sunlight/shadow terminator at orbital velocities must be resolved.

Operations

- Manufacturing modules: The specific technology for manufacturing modules in space is not known at this time. It is believed, however, that the technology should be relatively straightforward to develop once the basic design and materials have been established for the items to be manufactured in space. The major items for manufacture are structural elements and slotted waveguides for the subarrays.

- Remote manipulators: The specific technology for remote manipulation modules is not known at this time. However, some investigations have been conducted in associated control systems.

Transportation

- Launch vehicles: Although early SSPS development can be achieved with the Space Shuttle or derivatives of the Shuttle, studies indicate that there is a need, for both technical and economic reasons, for a so-called "Heavy Lift Launch Vehicle" with a payload to low earth orbit (LEO) of 182,000 kg (400,000 lbs) or more.

- Orbit-to-Orbit vehicles: A high performance stage is required to transport the SSPS from its LEO (assembly) to synchronous orbit. As of now, the most appealing candidate is ion propulsion since use could be made of the partially extended SSPS solar blanket as a power source. There do exist a number of significant issues for propulsion. These include the development of a large diameter ion thruster, selection of the ion engine propellent and, if it is not desirable to use the SSPS photovoltaic power source, selection and development of an alternative power source.

Attitude Control and Stationkeeping

- Thermal transients: The problem of rapid thermal transients caused by solar eclipsing will occur throughout the life cycle of the SSPS (i.e., during fabrication and assembly, during orbit-to-orbit transfer and during normal operations at synchronous orbit). The extent of the thermal transient problem in each of these phases, however, is not well-known at this time. Therefore, computer programs and experiments for simulations of these conditions should be developed.

- Attitude control of a highly flexible structure: In addition to the thermal transient problems, the problems of maintaining the required attitude control of a large, highly flexible structure such as the SSPS are generally unknown.

- Stationkeeping control problems are expected to grow with increased SSPS populations.

Environmental Effects

SSPS environmental factors that require investigation include the effects of emissions from the space transportation system and possible impacts of the microwave beam. Microwave effects on the ionosphere, RFI and long-term biological/ecological effects require additional study.

1.2.4 Development Programs

This section contains a summarization of near-term programs and long-term developments required for the SSPS. As would be expected, the near-term programs consist mostly of systems studies and critical technology developments in the above-listed areas directed toward the ultimate decision of whether to proceed with SSPS development and, then, the selection of an SSPS configuration, materials, method of assembly, launch and operations. These near-term activities are to be conducted up to the time that the Shuttle may be available for hardware flight testing. In addition. what were regarded to be the required near-term economic studies have been indicated.

1.2.4.1 Economic Studies

- Cost model and data bank that includes total SSPS work breakdown structure (WBS)
  - Probability of costs, performance and schedule
- Identification of operational constraints: environmental and social
- Risk analysis to estimate distribution of total program costs and potential revenues
  - Developmental risks and uncertainties
    - Critical technology paths
    - SSPS size
    - IOC
  - Operational risk analysis
    - Maintenance
    - Transportation
    - Fabrication
    - Assembly
- Commercial investment analysis
  - U.S. market
  - Foreign markets

1.2.4.2 System Definition

A. Select baseline configurations and refine system/subsystem technology assessments

- Photovoltaic, solar thermal and nuclear
- Define baselines to sufficient depth for basis of subsystem studies
  - Transportation, assembly and maintenance
  - Structure and attitude control
  - Power generation, distribution and processing
  - Power transmission
  - Power reception and reconversion
  - Power conditioning for user
- Study configuration alternatives, i.e.,
  - Higher concentration ratios
  - Rotary joint alternatives
  - Large antenna versus multiple antennae

B. Establish framework and develop methods for programmatic analysis

- Define total work breakdown structure (WBS)
- Develop viable alternate program schedules
- Develop cost estimating relationships
- Establish evaluation and assessment criteria
- Develop system modeling tools

C. Perform social benefits/impacts analysis

- Energy payback analysis method
- Quantify environmental impacts

1.2.4.3 Power Conversion

A. Near-term systems studies

- Selection of concentration ratio
    - Introduce active or semi-active cooling
    - Introduce alternate photovoltaic devices into tradeoffs
- Concepts for annealing solar cell
    - Optical and/or chemical

B. Technology developments

- Improve efficiency of silicon cell to 19 percent (AMO; concentration ratio = 1)
- Reduce blanket specific mass to 0.282 kg/m^2
- Reduce cost to \$54/m^2 (ERDA goal for 1985)
    - 3 to 5 reduction in cost for bringing raw materials to semi-conductor grade silicon
    - 10 to 100 reduction in crystal growth costs
    - Automated blanket fabrication processes
    - Improved packaging to achieve 30-year life

1.2.4.4 Microwave Transmission (ref: NAS3-17835)

- DC-RF converters and filters: Provide substantial data related to technical feasibility, efficiency, safety and radio frequency interference
- Materials: Demonstrate cost-effective use of non-metallics in terms of meeting limited distortion requirements for waveguides and structures as well as minimizing impact of other non-metallics on open cathode performance

- Refine stationkeeping technology using low thrust devices
- Materials life testing

- Flight Test
  - Structural fabrication and deployment technology sorties
  - Joint and fastener technology sorties
  - Waveguide fabrication and deployment technology
  - Electronics instalation technology sorties
  - Large subassembly-to-subassembly mating
  - Antenna assembly sorties
  - Rotary joint assembly sorties
  - Conducting central mast assembly
  - Solar array assembly
  - Orbit transfer of large flexible bodies and radiation sensitive material

- Phase control subsystem: Demonstrate phase control steady state accuracy subject to error contributions of dc-rf converters and high power radio frequency environment

- Waveguide: Demonstrate capability of mass producing low mass, distortion-free waveguides that can efficiently operate in a harsh thermal environment

- Biological: Analyze the microwave frequency and power densities being considered for SSPS use

- Antenna attitude control and power transfer: Demonstrate the accuracy and life potential of the antenna rotary joint system - evaluate options in a systems study

- Ionosphere: Measure effects of microwave radiation on ionosphere and determine impacts

- Switch gear: Develop and demonstrate switch gear including protective elements for spaceborne applications (high voltage dc)

- Radio frequency: Investigate radio frequency interference and allocate band to SSPS that would have minimum impact on other users, particularly radio astronomers

- Reliability: Investigate reliability considerations in light of the requirements for millions of amplitrons, billions of diodes, as well as other equipment which must operate with essentially unlimited life or it must be provided for with appropriate redundancy and maintenance

- Other microwave technology requirements: The remaining technology requirements that have been identified in NASA CR-134886, Section 11 are indicated elsewhere

1.2.4.5 Large Structures

A. Near-term systems studies

- Perform configuration trade studies
  - Integrated large structure versus station-kept small structures
  - Structural arrangement impact on concentration ratio selection

    - Design loads - launch through operational phase
    - Thermal loads

- Refine structural analysis tools

    - Math model structure/control interactions
    - Math model thermal dynamic/structural interactions

B. Technology development

- Initiate program to determine long life structural design characteristics of metallic and non-metallic materials

1.2.4.6 Operations

- Assembly system studies

    - Determine cost-effective use of man-in-space assembly
    - Trade off space-fabricated versus ground-fabricated deployable structures
    - Trade off joining and fastening techniques and equipment
    - Trade off LEO versus GEO assembly site

- Assembly concept definitions

    - Design options for remote controlled assembly aids
    - Design options for mobility units
    - Design options for EVA equipments
    - Design options for materials and propellant storage
    - Design concepts for mission control and data acquisition and tracking network

- Other supporting studies

    - Simulation: Manned and remote controlled assembly
    - Analyze maintenace and repair operations

1.2.4.7 Transportation

- Launch systems

    - Tradeoff total system cost to achieve fully recoverable launch vehicle versus more payload and reduced recoverability

  - Evaluate impact of launch site operations on launch vehicle size selection
  - Trade off cost impacts of high packaging density in launch vehicles and space fabrication versus a policy to assemble low density ground-fabricated components in orbit

- Orbit transfer vehicle

  - Study high performance stage alternatives

    - Propulsion systems
    - Power sources
    - Propellants

  - Study potential of large cryogenic propellant tugs

    - One and one-half stage
    - Two stage

1.2.4.8 Attitude Control and Stationkeeping

A. Near-term systems studies

- Define stationkeeping and control requirements during phased assembly in

  - Low earth orbit (LEO)
  - Geosynchronous earth orbit (GEO)

- Define control requirements during transport from LEO to GEO

- Tradeoff actuator type and location

  - Momentum storage
  - Magnetic
  - Solar
  - Dispersed or centrally located impulsive system

- Antenna mechanical pointing system

  - Structural dynamics and mast compliance
  - Sensor and electronics interface with antenna phase front control system
  - Alternatives to rotary joint

B. Technology development

- High performance (I_{sp}=8000 sec) low thrust impulsive system using non-corrosive propellants

1.2.4.9 Environmental

- Quantify impact of land management factors
  - Receiving antenna (10 km)
  - Launch complex
  - Resource extraction and manufacture
- Establish safety standards for radiant power densities
  - At transmitting antenna
  - At receiving antenna (10 or 0.1 mW/cm^2)
  - Communications interference
  - Quantify impact and benefits of waste heat at receiving antenna (10 to 15 percent)
- Quantify safety and control
  - Beam misalignments and slews
  - Re-entry of materials
- Quantify environmental modification factors
  - Transportation system propellants
  - Ionospheric changes
- Standardize methods for energy payback analysis
  - Establish data base

1.2.4.10 Orbital Technology Verification

- Initiate system studies to establish flight demonstration and verification programs
- Refine mission plans and hardware definition for the following Shuttle missions (see also NAS3-17835):
  - Geosynchronous high voltage technology satellite
    - Test microwave converter performance
    - Test phase front control electronics
    - Evaluate high voltage anomalies at GEO using a 20 to 40 kV array

2. STUDY METHODOLOGY AND PRINCIPAL ASSUMPTIONS

The overall study approach is presented in Figure 2.1. Two major parts of the project have been identified: the comparison of orbital and terrestrial systems for (1) power generation and (2) power transmission. In order to perform each major part, it has been necessary to do engineering analyses of the special requirements of orbital systems and economic analyses of orbital and terrestrial systems. An additional study requirement has been to provide the framework for a future social impacts analysis. Due to funding limitations, this work could not be very extensive; however, it should point the direction toward future study activities. A major task of the economic work performed has been to provide a methodology for analysis that is useful to this study, and as well, may be used to compare other studies (present and future) with it. A detailed presentation of this methodology is provided in Appendix A.

All costs have been estimated in constant 1974 dollars. Whereas the effects of inflation are certainly important for estimating current-dollar prices of electricity, it is constant-dollar values that are used for economic comparisons of systems. For present value calculations, costs have been discounted back to 1975. The nominal discount rate used throughout is 7.5 percent. This discount rate, while somewhat lower than the 10 percent figure generally used by the Office of Management and Budget, is somewhat higher than commercially acceptable rates of return for low-risk public utilities investments after the effects of inflation are removed.

A three-phase SSPS development program was assumed for initial analysis: Phase I - a 15 MW (LEO) satellite with an initial operating capability (IOC) in 1985; Phase II - a 1 GW (GEO) SSPS with an IOC in 1990, and Phase III - a 5 GW (GEO) SSPS with a 1995 IOC. The 10 GW SSPS would be subjected to a separate cost/benefit analysis. It is noted that this development plan was formulated to be a "straw man" for this study and the final SSPS development plan is yet to be determined. For the PRS an initial program development plan was assumed that includes: Phase I - a 1 GW demonstration satellite with a 1985 IOC and Phase II - a 10 GW operational satellite with a 1990 IOC.

Four cost elements of the SSPS and terrestrial generating systems have been identified and estimated: capital, fuel, operations and maintenance (O&M) and a "catch all" which accounts for state and federal taxes and insurance. The annual capital recovery (which is converted to the familiar mills/kWH) is a value which, if received each year by the providers of the original capital over the payback period--assumed to be 30 years, yields a present value equal to that of the investment. The single value, 7.5 percent, represents a weighted average of return to debt and equity. Fuel prices reflect projections of today's relative prices. O&M costs have been estimated on the

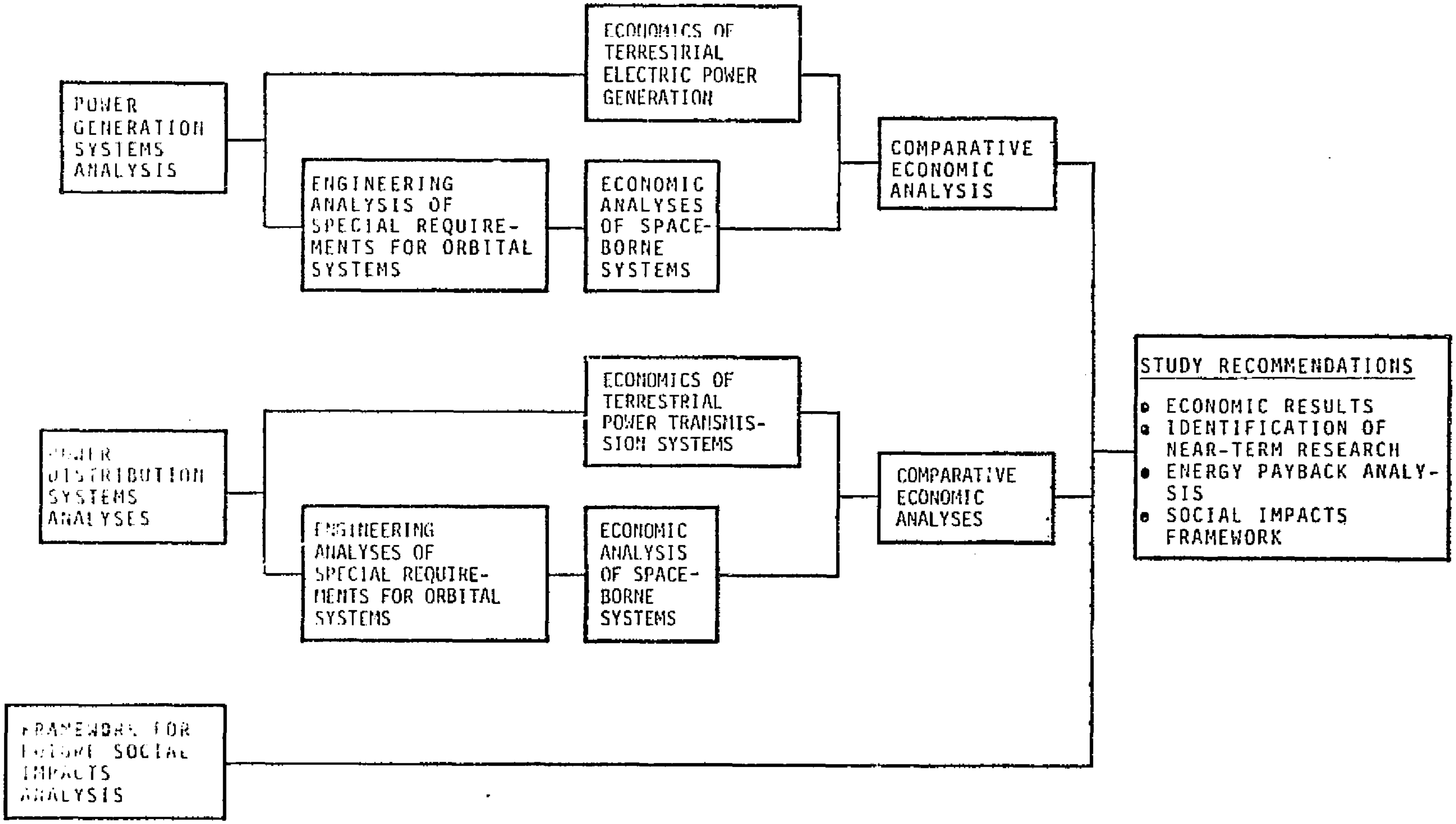


Figure 2.1 Overall Study Methodology

basis of real operating experience--in the case of existing terrestrial systems--on assumptions based on projections of experience--in the case of future terrestrial systems--or on preliminary estimates of mean-time-before-failure (MTBF) in the case of the SSPS. Taxes and insurance are assumed to be 5 percent of adjusted capital investment per year. Again, all of these issues are presented in Appendix A.

For the terrestrial electric transmission systems, cost categories have been identified and estimated for capital (including rights-of-way), transmission losses, O&M and taxes and insurance.

The key technical assumptions are summarized in Table 2.1.

Related assumptions include:

- Assembly operations are Shuttle-based.
- A six-man space station is required for monitoring the satellite and for use as a repair shop and garage for maintenance teleoperators.
- Space station crews are rotated four times per year using a Shuttle and a chemical tug.

Table 2.1 Key Technical Assumptions

	Item	Assumption
I	Large Solar Array	
	a-Blanket Material	Silicon
	b-Blanket Mass	28.2 mg/cm^2
	c-Beginning-of-Life Efficiency at Concentration Ratio = 1 (AMO) (Blanket protected through Van Allen belt)	19%
	d-Radiation Damage	1%/yr
	e-Concentration Ratio	2
II	Large Structure	
	a-Design Life	30 years
	b-Design Loads	Stationkeeping and Gravity Gradients at GEO
	c-Material	Aluminum
	d-Conducting Structure Operating Voltage	40 kV
III	Flight Mechanics and Control	
	a-Orbit	Geosynchronous
	b-Control System Specific Impulse	8,000 sec
	c-Array Pointing Accuracy	1 degree
	d-Antenna Mechanical Pointing Accuracy	1 arc min.
IV	Transporation, Assembly and Maintenance	
	a-15 MW Demonstration	
	• Assembly Orbit	LEO
	• Operating Orbit	LEO
	• Launch System	Shuttle
	b-1 GW Pilot Plant	
	• Assembly Orbit	LEO
	• Operating Orbit	GEO
	• Launch System	Shuttle Derivative
	• Orbit Transfer Vehicle	Large Cryogenic Tug
	c-5 GW Operational Plant	
	• Assembly Orbit	LEO
	• Operating Orbit	GEO
	• Launch System	HLLV
	• Orbit Transfer Vehicle	Advanced Ion
	• Maintenance	Dedicated GEO Space Station
	d-PRS	
	• Assembly Orbit	LEO
	• Operating Orbit	GEO
	• Launch System	Shuttle Derivative
	• Orbit Transfer Vehicle	Large Cryogenic Tug
	• Maintenance	Dedicated GEO Space Station

3. POWER GENERATION SYSTEM ANALYSIS

A space-based power generation concept has been defined that uses large photovoltaic arrays for collecting solar power and transmitting it to Earth using radio frequency (rf) power transmission. This concept is compared with conventional and future Earth-based power generation systems. The SSPS which has been studied since 1968 by a team of companies (Arthur D. Little, Grumman Aerospace, Raytheon and Spectrolab), has been used as the point of departure for refined definition and subsequent comparisons. The terrestrial techniques for baseload power generation used in these comparisons are:

Fossil Fuel

- Coal-fired power generation
- Fluidized-bed coal-fired power generation
- Low-BTU coal-gas-fired generation
- High-BTU coal-gas-fired generation
- Liquefied coal-fired generation
- Oil-fired power generation

Nuclear Fuel

- Light water reactor
- High-temperature gas-cooled reactor
- Breeder reactor.

The data generated for NASA CR-2357 were refined using the results of the Microwave Power Transmission System Studies (MPTS)--NAS3-17835--and the engineering analysis of special requirements performed under this contract (Section 3.1.2.). Special treatment has been given to definition of the major system cost elements, namely, the large solar array, large structure, transportation, assembly, maintenance and the microwave transmission and conversion system.

3.1 Space-Based Concept

The SSPS configuration has gone through an evolution that resulted in the selection of the design concept illustrated in Figure 3.1. This design is used as the basis for technical and economic analysis. The concept is to place large photovoltaic arrays at synchronous orbit to collect solar energy and convert it, on orbit, to electrical power which is then transmitted to the ground using microwaves.

3.1.1 Concept Description

3.1.1.1 Configuration

The baseline SSPS was sized to generate 5 GW of rectified power at the output busbars of the rectenna. This output power level

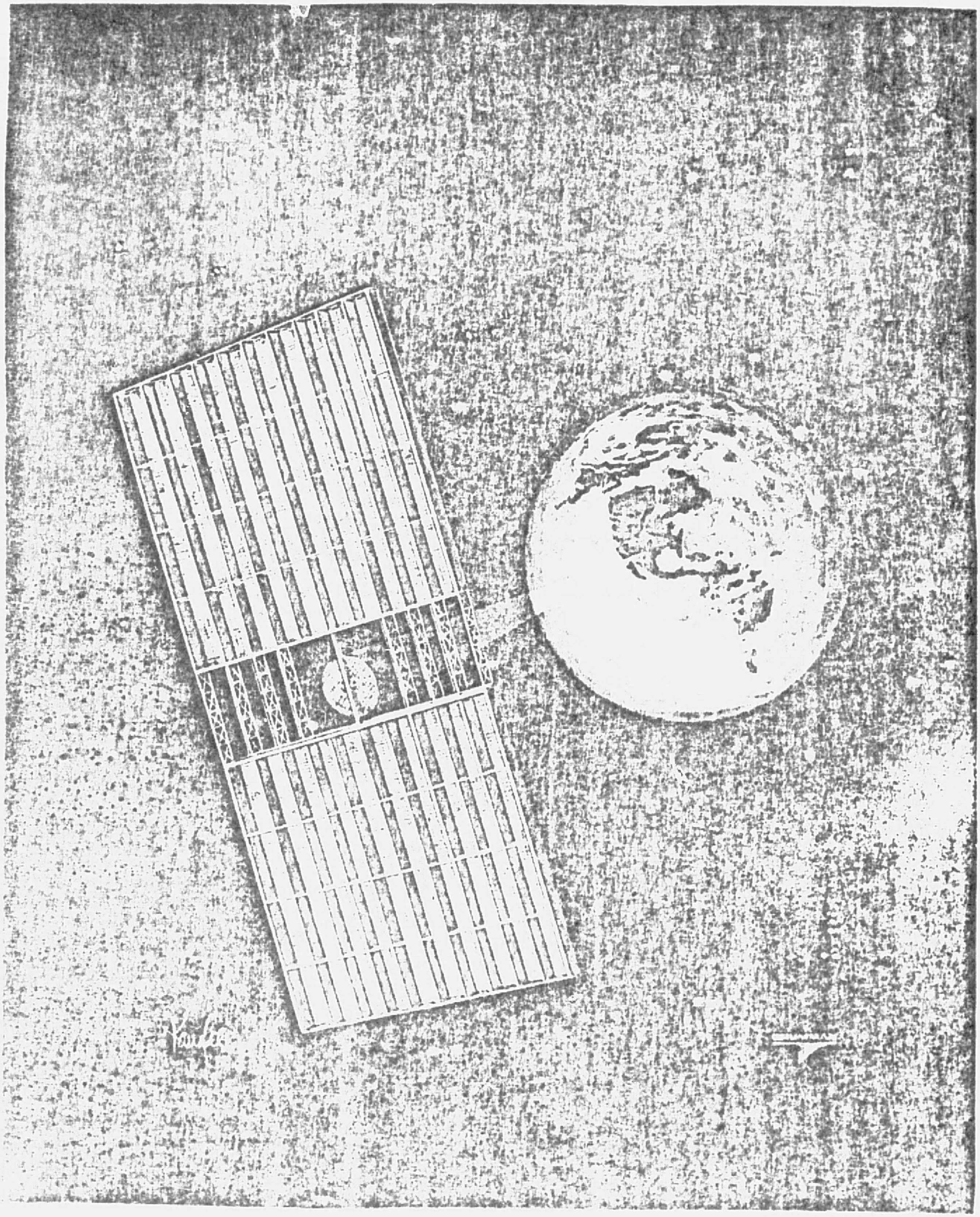


Figure 3.1 Design Concept For a Satellite Solar Power Station

was chosen to provide scale economies subject to the constraint of maintaining the peak microwave power density in the center of the rectenna to 20 mW/cm^2, dropping to 1 mW/cm^2 at the edge and 0.1 mW/cm^2 at the guard ring. An operating frequency of 2.45 GHz was selected based on anticipated power transmission efficiencies, low susceptibility to brownouts in rain and minimal potential problems with radio frequency interference. The transmitting antenna is an active planar phased array that uses amplitrons for dc to rf power conversion. The photovoltaic power source generates 8.62 GW of power using advanced 50 μm thick silicon solar cells that operate at 13.7 percent efficiency (five years into life) at a solar concentration ratio of two. (See Section 3.1.2.1 for a discussion of concentration ratio tradeoffs.)

The design concept, shown in Figure 3.2, has two large photovoltaic solar cell arrays, each 5.92 km x 4 93 km, interconnected by a carry-through structure of dielectric material. The 0.83 km diameter microwave antenna is located on the centerline between the two arrays, and is supported by the central power transmission bus (mast) structure that extends the full length of the power station. The antenna, Figure 3.3, is attached to the mast structure by a joint system, Figure 3.4, that rotates 360 degrees in azimuth (east-west) and ±8 degrees in elevation (north-south). The solar cell blankets are positioned between channel concentrators, consisting of .013 mm (0.5 mill), aluminized Kapton stretched over a supporting frame. The aluminum structure is built up out of an assembly of triangular girders with tension crossbraces. Open-hat cross sections are used to reduce temperature differences across the structural element. Eight transverse structural beams serve as dc power buses to carry high voltage electrical current to the central mast. The coaxial central mast serves as the backbone of the assembly and is sized to transmit power at 40 kV. The microwave power generators operate at 20 kV requiring partitioning or voltage stepdown at the transmitting antenna. The array is stiffened in the region of the microwave power beam using a series of transverse dielectric structural elements.

The solar cell blanket characteristics are summarized in Figure 3.5. The mass-contributing components are the solar cells, radiation shield (FEP Teflon or equivalent), metal interconnectors and the substrate (FEP Teflon or Kapton film laminates). The microwave antenna, Figure 3.3, is constructed in two structural layers. An aluminum primary structure is built up in 108 m x 108 m x 35 m bays using triangular girder members. The primary structure is subdivided on the transmission side into a secondary structure 18 m x 18 m with a 5 m depth to provide pickup points for the waveguide subarrays. A mechanical screw jack system is used to attach the 18 m x 18 m microwave subarrays to the support structure and provides the capability to align the system after assembly. The microwave antenna size may change as a function of relative specific costs between the orbiting antenna and the rectenna. For the purposes of this investigation, a diameter of 0.83 km was chosen with supporting rationale provided in NASA Report CR-134886.

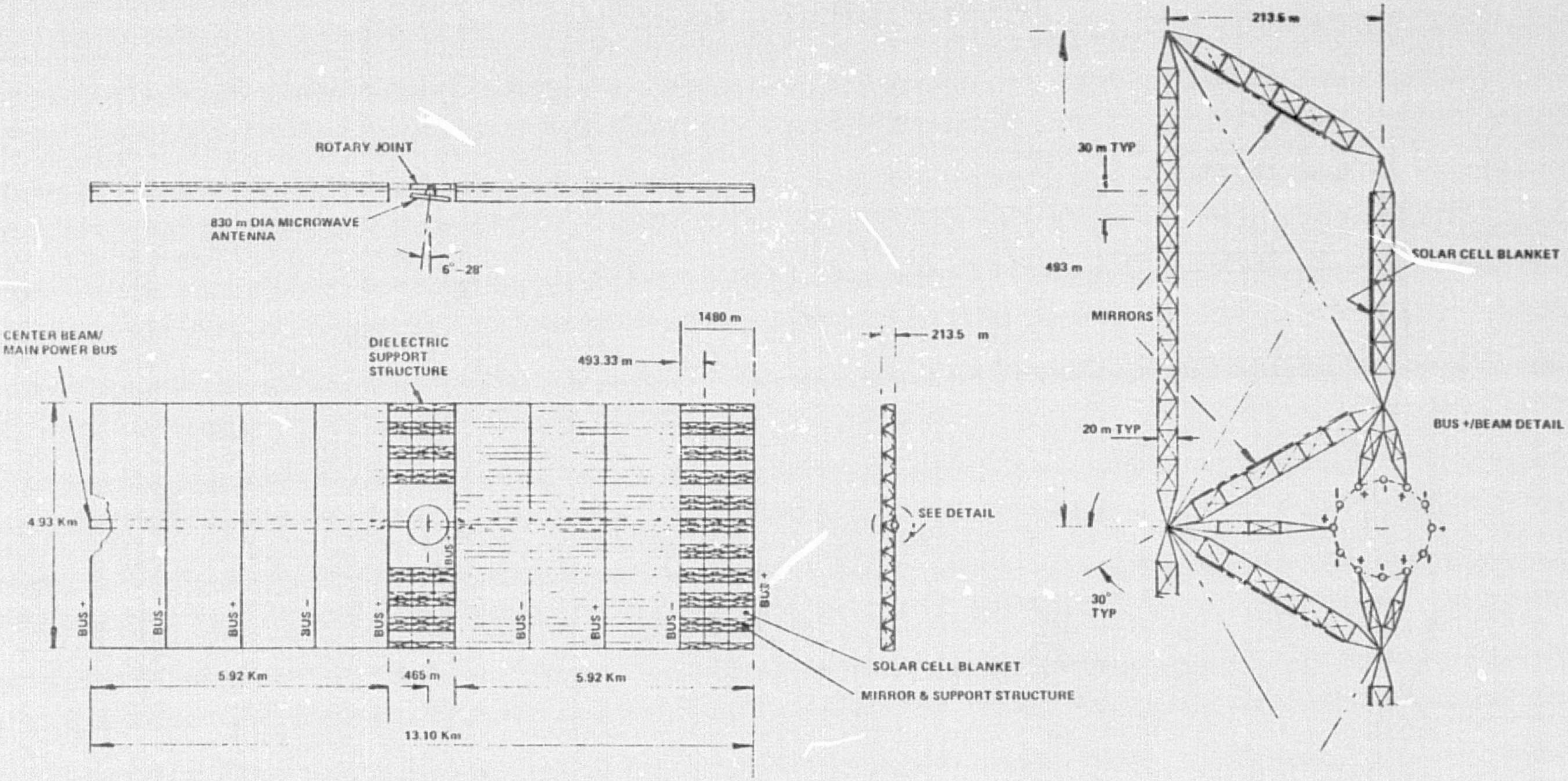


Figure 3.2 SSPS Structural Arrangement

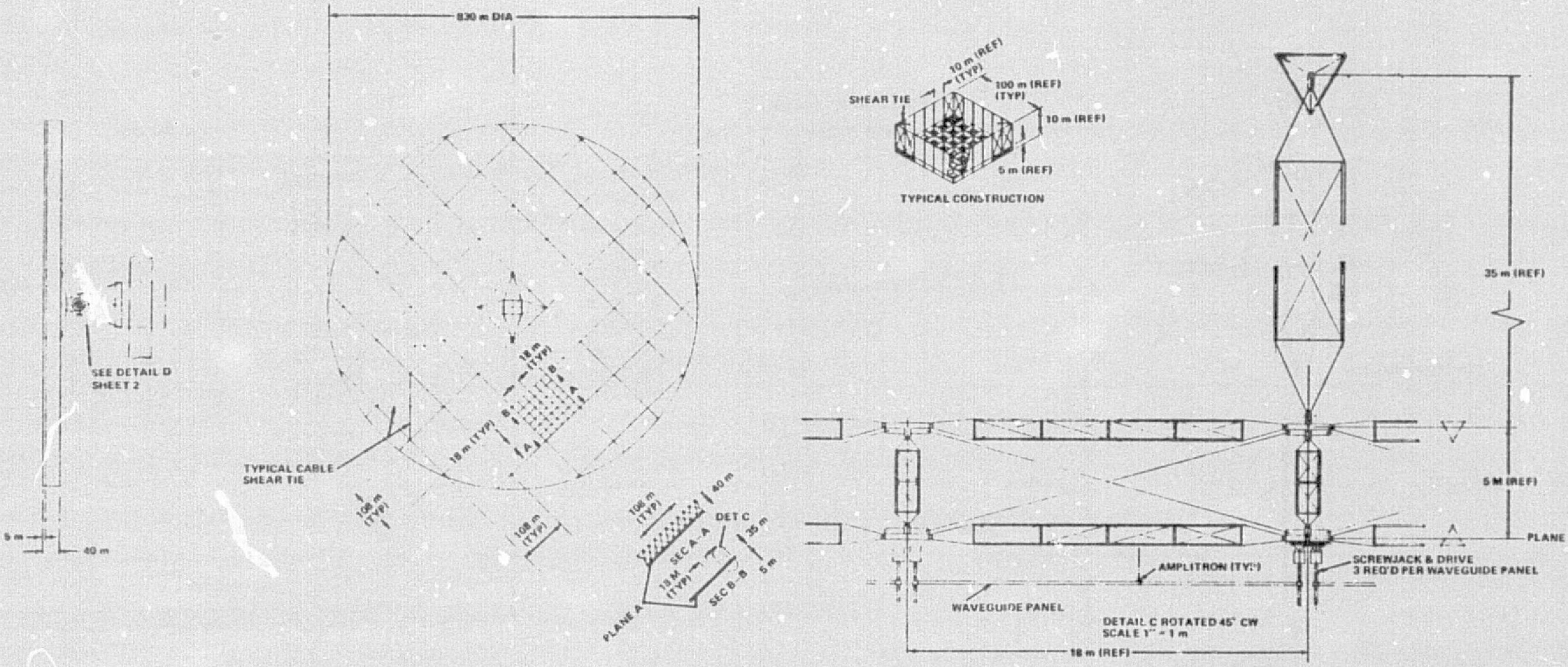


Figure 3.3 Transmitting Antenna

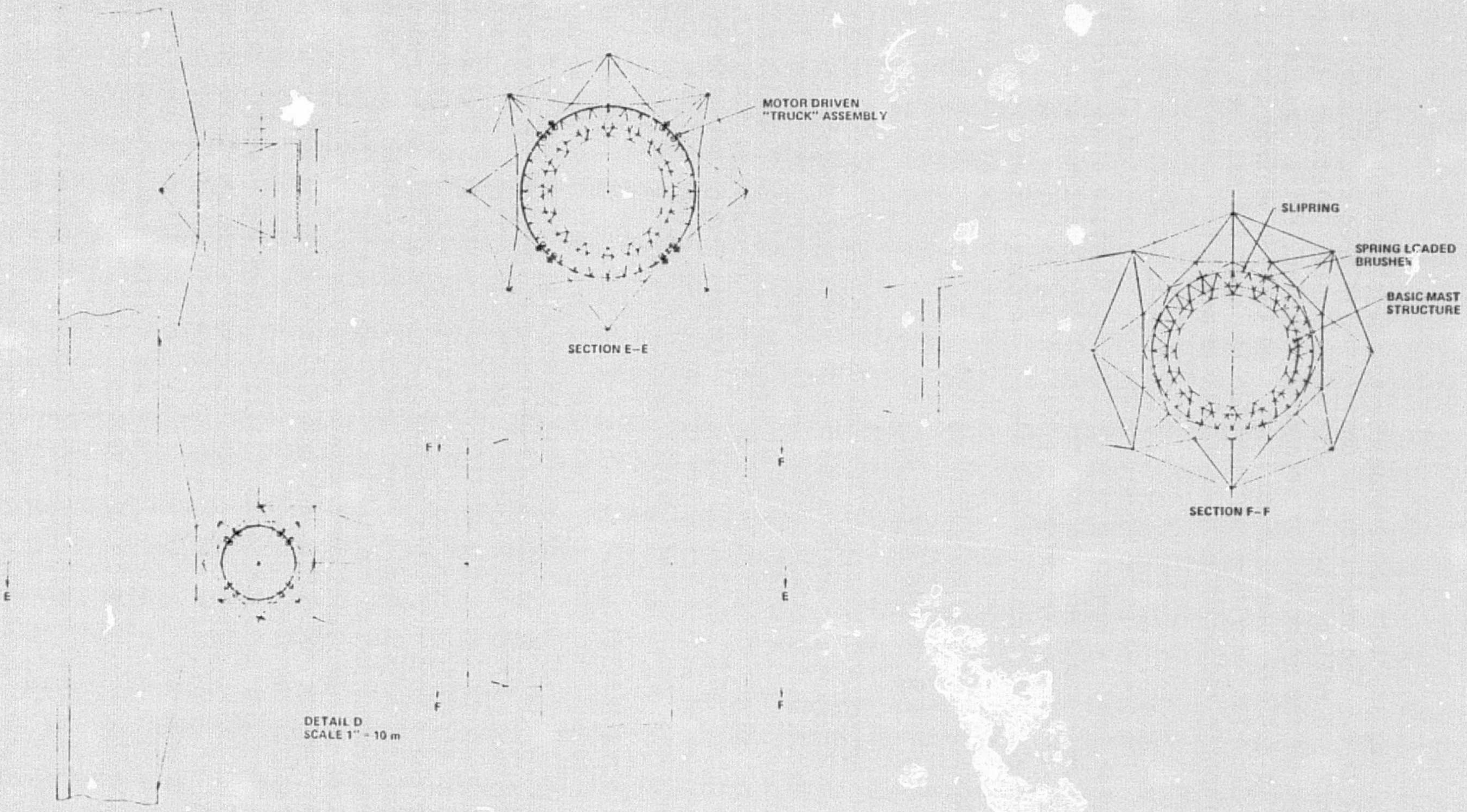


Figure 3.4 Rotary Joint

The dc-to-rf conversion device, baselined for this study, is the amplitron. The amplitron is designed with open construction for low weight and reliability, and with a pure metal (platinum) cathode operating on the principle of secondary emission, rather than a heater, to achieve long cathode life. The tube dc voltage input is 20 kV. Samarium cobalt magnets provide low specific mass and pyrolitic graphite radiators provide a passive means for waste heat rejection.

The ground-based receiving antenna is approximately 11 km in diameter, and is composed of a grid of solid state diode rectifier elements, each combined with an individual dipole antenna and filters. The rectenna panels are oriented normal to the incoming power beam. The dc power is collected at each element in parallel arrays and summed in a series connection to reach voltage levels at which efficient conversion and distribution can be made.

3.1.1.2 System Efficiency

System efficiency is a prime consideration in the design of a space-based power generation plant. An efficiency budget for the SSPS is shown in Table 3.1. Efficiencies have been broken down into three categories: initial, nominal and goal. "Initial" efficiencies are indicative of values appropriate for initial deployment of a demonstration model in the mid-1980s. "Nominal" represents the expected values of efficiencies for an operational plant and the "goal" represents the potential efficiency values for a fully matured system.

The initial solar cell blanket efficiency (9.7 percent at N = 2) is consistent with the near-term design goals for the solar electric propulsion system. The nominal value (13.7 percent at N = 2) is a reasonable projection of the state-of-the-art. Figure 3.6 summarizes the performance of the advanced cell used in this study. A 19 percent efficiency at the beginning of life can be achieved by increases in collection efficiency, decreases in base resistivity and higher doping in the p and n regions. This beginning-of-life efficiency is reduced to 18 percent to take into account unannealed degradation, due to a radiation fluence of 10^{15} e/cm^2 over a 5-year period. The total degradation due to radiation damage over 30 years is 20 percent. Efficiency is further reduced to account for the operating temperature at concentration. No specific efficiency value is indicated for goal because the solar cell technology field is advancing rapidly. Multilayer solar cell concepts, for example, combine the shortwave characteristics of the silicon cell, and have theoretical efficiencies as high as 30 percent. Such advances could be a significant breakthrough for space-based power generation, and would alter and enhance the basic concept design discussed in this report.

A dc-to-rf conversion efficiency of 85 percent for initial deployment is selected since amplitrons have already reached this performance level. Improvement to 90 percent over the next ten to 15 years is believed to be a reasonable projection.

ELEMENT	MASS, mg/cm^2	ACCUM MASS, mg/cm^2	POWER TO RATIO, W/Kg
SOLAR CELL, 50 μm	16.8	16.8	1590
FEP COVER, 25 μm	5.5	22.3	1200
INTERCONNECT Ag MESH	1.4	23.7	1130
SUBSTRATE, KAPTON	1.8	25.5	1050
SUBSTRATE ADHESIVE FEP, 13 μm	2.7	28.2	950

CELL OUTPUT POWER = 26.7 MW/cm^2 AT 27° C. AMO
AT BEGINNING OF LIFE

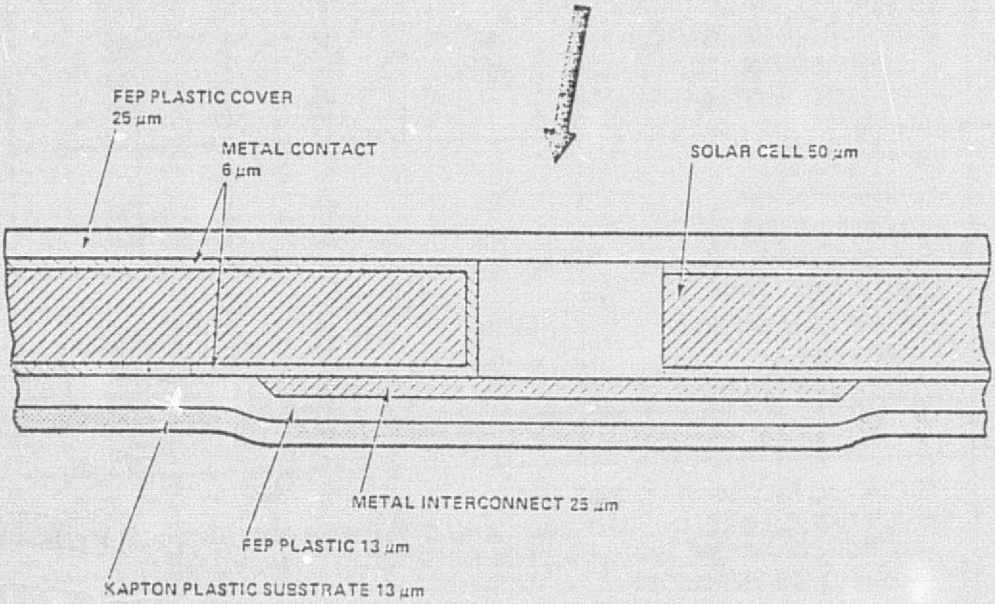


Figure 3.5 Solar Cell Blanket Characteristics

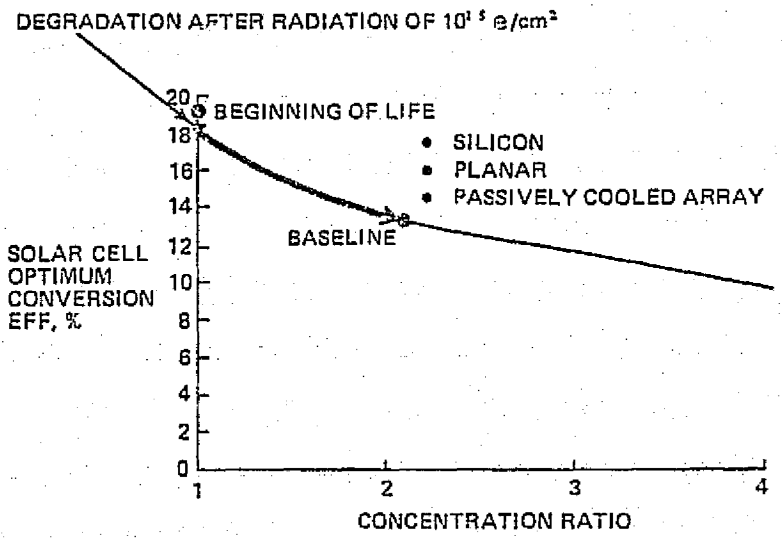
Table 3.1 SSPS Efficiency Budget

	INITIAL	NOMINAL	GOAL
SOLAR ARRAY			
– POINTING	90	90	90
– SOLAR BLANKET	9.7*	13.7*	> 13.7
– POWER DISTRIBUTION	92	92	***
TRANSMITTING ANTENNA			
– POWER DISTRIBUTION	96	96	97
– DC-RF CONVERTER	85	87	90
– PHASE CONTROL	95	96	97
PROPAGATION			
– ATMOSPHERIC	99	99	99
– IONOSPHERIC	100	100	100
RECEIVING ANTENNA			
– BEAM COLLECTION	90-95**	90-95**	90-95
– RECTENNA	84	87	90
– POWER INTERFACE	93	94	95
TOTAL	4.3–4.6	6.6–6.7	> 7.7

*CONCENTRATION RATIO OF TWO

**DEPENDS ON ORBITAL ANTENNA AND GROUND RECTENNA SIZE WITH ASSOCIATED COST, LAND USE, POWER DENSITY TRADEOFF

***SUBJECT TO TRADEOFF



(NOTE:—CELL CONVERSION EFFICIENCY FOR INCIDENT IRRADIANCE VS CONCENTRATION RATIO, FILTER CONFIGURATION OPTIMIZED FOR EACH RATIO, SOLUTION GIVEN FOR OPERATING TEMPERATURE. FLUENCE = 10^{15}e/cm^2 (1 MeV)

REF: SPECTROLAB

Figure 3.6 Solar Cell Efficiency

The wavefront must be electronically controlled to achieve the precision necessary to maintain high efficiency and to control the power distribution on the Earth. The approach to the control of the wavefront is to sector the antenna into numerous subarrays. A study of sensor accuracy potential, mechanical system alignment accuracy and selection of the beam transmitted taper (center to edge) led to the range of phase control efficiencies shown in Table 3.1 which are considered viable.

Beam collection efficiency is a parameter that is selected based on land values, ecological issues and social impacts. The relative size of the transmitting antenna and receiving rectenna, chosen as baseline, depend on relative cost, land use and power density tradeoffs. A level of 90 percent was found as a reasonable value based upon these factors.

3.1.1.3 System Mass

Table 3.2 summarizes the SSPS mass properties at the start and conclusion of this effort. The change in mass from 11.5 x 10^6 kg is due to refined estimates of the microwave subsystem, resulting from

Table 3.2 SSPS Mass Properties

	SPS MASS PROP. AT START OF STUDY		SSPS MASS PROPER . ES RESULTING FROM STUDY			
	5GW; 1 Km DIAMETER ANTENNA		5GW; 0.83 Km DIAMETER ANTENNA MASS		10GW; 1.18 Km DIAMETER ANTENNA MASS	
SUBSYS/COMP	Kg x 10^6	LBM x 10^6	Kg x 10^6	LBM x 10^6	Kg x 10^6	LBM x 10^6
SOLAR ARRAY	(9.57)	(21.1)	(12.30)	(27.29)	(23.98)	(52.8)
• BLANKETS	6.11	13.47	7.83	17.25	15.66	34.49
• CONCENTRATORS	0.93	2.05	1.23	2.71	2.46	5.42
• NON-CONDUCTING STRUCT	1.73	3.81	2.33	5.14	4.58	10.09
• BUSES, SWITCHES	0.23	0.51	0.27	0.59	0.31	0.68
• MAST	0.57	1.26	0.64	1.37	0.97	2.12
MW ANTENNA	(1.89)	(4.16)	(5.55)	(12.22)	(10.74)	(23.66)
• MW TUBES	0.63	1.39	2.33	5.13	4.66	10.26
• POWER DIST	0.03	0.07	0.54	1.19	0.72	1.59
• PHASE CONTROL ELECT	0.28	0.61	0.13	0.29	0.28	0.62
• WAVEGUIDES	0.70	1.54	2.31	5.09	4.60	10.13
• STRUCTURE	0.25	0.55	0.14	0.31	0128	0.62
• CONTOUR CONTROL	–	–	0.10	0.22	0.20	0.44
ROTARY JOINT			(0.17)	(0.37)	(0.20)	(0.43)
• MECHANISM	–	–	0.066	0.14	0.093	0.20
• STRUCTURE	–	–	0.106	0.23	0.106	0.23
CONTROL SYSTEM	(.02)	(.04)	(0.036)	(.079)	(0.055)	(0.121)
• ACTUATORS			0.012	0.026	0.015	0.033
• PROPELLANT/YR			0.024	0.053	0.040	0.088
TOTAL SYSTEM	11.48	25.30	18.06	39.75	34.38	77.01

- MAJOR CHANGES IN CONFIGURATION
  - REFINED ESTIMATE OF ANTENNA MASS FROM MPTS STUDIES NAS 3-17835
  - REFINED ESTIMATE OF MICROWAVE EFFICIENCY CHAIN INCREASES POWER SOURCE SIZE

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

Raytheon's MPTS studies (NAS3-17835), and refined estimates of structural mass. The largest increases are in the microwave tubes and waveguides. The refined estimates of the microwave efficiency chain is the dominant factor in the increase of the solar array mass. The array structure mass changed, due to refined structural analysis performed in this study which indicated the need for improved column stability of the main longitudinal beams.

The solar array represents 67 percent of the satellite mass with the solar blankets the major contributor at 7.83×10^6 kg. The transmitting antenna contributes 31 percent to the satellite mass. The major mass elements in the antenna are the amplitrons (2.33×10^6 kg) and the waveguides (2.1×10^6 kg).

The solar cell blankets are of advanced design with an efficiency of 13.7 percent at a concentration ratio (N) of 2. The specific mass of the array blankets is 0.282 kg/m^2, they are approximately 50 μm thick, and are made up of individual 5 cm x 8 cm cells that operate at a Vmp voltage of 0.6 V and a current of 2.5 amp.

There are approximately 1.4×10^6 amplitrons in the transmitting antenna, each having a mass of 1.618 kg and providing an rf power added of 5,000 W. The major mass contributors to the dc-rf convertor are the anode and cathode waste heat radiators, contributing 1.071 kg to the total device's mass.

The slotted waveguide subarrays are 18 m x 18 m, each of mass 1,383 kg. The waveguides in this baseline design are aluminum with a wall thickness of 0.5 mm. To keep power loss due to thermal deflection below 1 percent, aluminum waveguides must be less than 5 m in length. Therefore, a third level of structure must be added to shorten the span of the waveguide. An alternate solution to the problem is to use composites.

Included in Table 3.2 is a mass breakdown for a 10 GW system. The 10 GW SSPS mass increases 94 percent to 34.4×10^6 kg, over the 5 GW system, thus obtaining a slight economy of scale. The overall dimensions of the 10 GW satellite increase to 7.0 x 18.3 km over the 5 GW version, while the antenna diameter grows from 0.83 km to 1.2 km. The change in antenna size is made to limit peak power at the center.

3.1.2 Engineering Analysis of Special Requirements for the Satellite Solar Power Station

This section defines system requirements, alternate design concepts to satisfy these requirements, and reports analyses on key performance, cost and development issues associated with each concept in the following major areas:

- Large solar arrays
- Large structures

- Flight mechanics and control
- Transportation, assembly and maintenance
- Microwave transmission
- Safety of large structures.

Emphasis has been placed on identifying operational and economic requirements for the orbiting system and defining near-term research activities that will be required to assure feasibility, development, launch and operational capabilities in the post-1990 time frame.

3.1.2.1 Large Solar Arrays

The solar array comprises between 60 and 70 percent of the satellite mass and, for a comparative analysis, it must be defined with care to avoid highly pessimistic or optimistic results. This study has considered a broad range of performance, mass and cost parameters.

Configuration Tradeoffs

An important system tradeoff is an evaluation of the relationships between concentration ratio, system mass, complexity and cost. A preliminary analysis of the interrelationships is shown in Figure 3.7. The effects of concentration and the configuration approach on structural mass is also shown. For this analysis, the efficiency of solar cells with concentration was assumed constant. (Note: The added mass of the thermal control system to provide constant cell efficiency with concentration ratio is not included.) The following summarizes the pertinent trends of this tradeoff.

- A passively-cooled silicon blanket array tends to show minimum structural mass at a concentration ratio of:
  - two to three for front-lighted designs
  - six to ten for a two-dimensional, back-lighted design
  - greater than 100 for a three-dimensional, back-lighted design.

Other photovoltaic materials and configuration concepts should be evaluated in an overall study of concentration ratios. The multilayer aluminum gallium arsenide (Al-GaAs/GaAs) cell has been given the most attention in the past few years, and recent laboratory data show these cells to have high efficiency at high concentration ratios and to be less susceptible to radiation degradation. Estimates of Al-GaAs/GaAs performance in air mass zero (AMO) are shown in Figure 3.8. A comparison with the expected silicon performance is included.

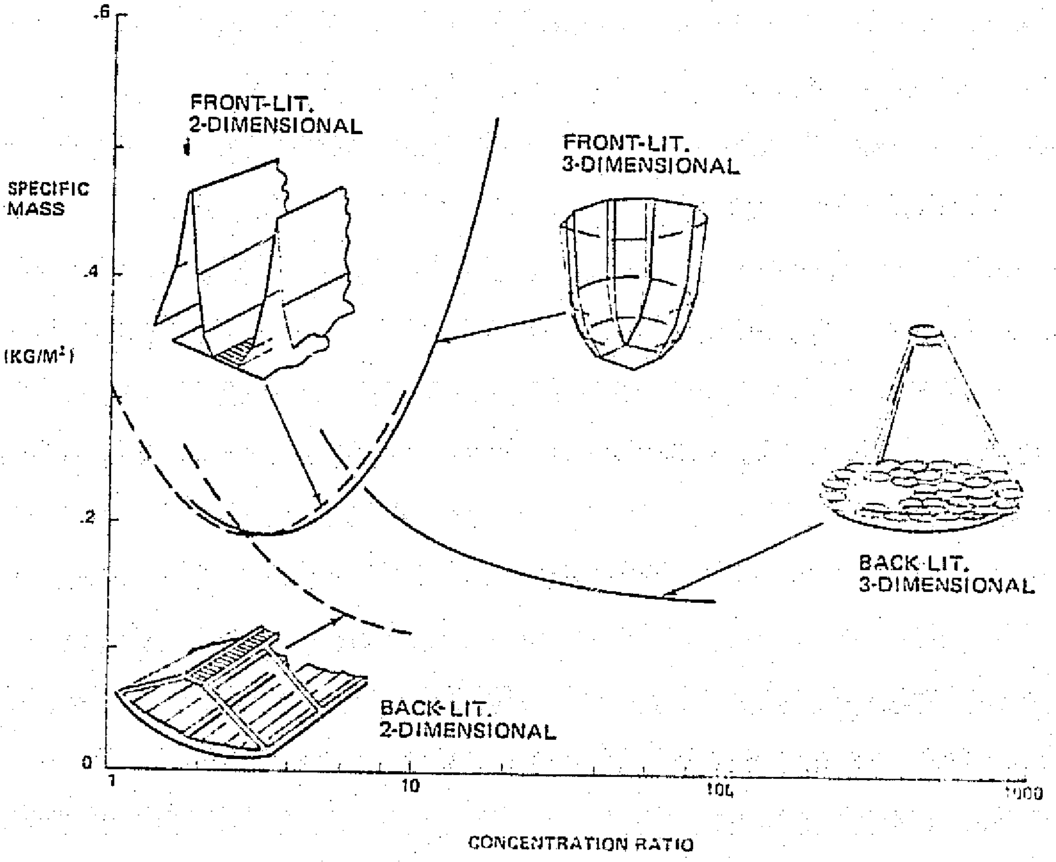


Figure 3.7 Specific Mass Variation With Concentration Ratio

Figure 3.9 shows the solar array mass dependence on concentration. The Al-GaAs/GaAs configuration has the potential to achieve lower mass than the projected silicon blanket at concentration ratios between six and ten. These are front-lighted designs using flat mirror surfaces. At higher concentrations, back-lighted designs become less massive. Therefore, a sensitivity to the assumed structural mass trends is also presented.

For purposes of comparison, Figure 3.10 shows the mass dependence on concentration ratio of two front-lit silicon cell arrays for solar cell thicknesses of 50 μm and 100 μm. These data include the effects of solar cell efficiency degradation with increased concentration, using the silicon cell performance data shown in Figure 3.9. Both the four-mirror and two-mirror concentrator configuration exhibit minimum mass at a concentration ratio slightly above two.

Configuration Sensitivity Studies

Satellite mass sensitivity to variations in solar cell efficiency, microwave efficiency, solar blanket mass and system ground output power is shown in Figure 3.11 for the two-dimensional front-lit design. A 10 percent variation in solar cell efficiency will vary solar array mass 1.2 x 10^6 kg while a 10 percent variation in microwave efficiency varies solar array 1 x 10^6 kg. The 100 μm solar cell results in a solar array that is 2.2 x 10^6 kg more massive than its 50 μm counterpart. Current designs are between 150 and 200 μm thickness. However, laboratory-produced cells of 50 μm (Spectrolab) have been manufactured and tested.

Figure 3.12 presents the cost trends of solar cells in the context of a more general solar array design/cost trade. Solar array costs are shown plotted against variations in solar blanket costs, solar blanket mass efficiency and transportation-assembly costs. The solid line represents the nominal SSPS goal for efficiency (13.7 percent at N = 2), specific mass 0.282 kg/m^2 and transportation-assembly cost of $217/kg. The dashed line shows the effect of an increase in transportation-assembly costs to $1000/kg; while the dashed-dot line represents near-term technology solar blanket specific mass 0.525 kg/m^2 and an efficiency of 9.7 percent at N = 2, with a transportation cost of $217/kg.

The estimated cost spread for the operational SSPS solar blanket, shown in Figure 3.12, was compared with historical data in Figure 3.13. A production learning curve was established using actual experience on the initial 2 x 2 cm cell and the 2 x 6 cm cell produced for the Apollo telescope mount (Skylab). This established a 75 percent learning curve for solar blanket costs using conventional fabrication techniques. The high-cost estimate, $150/$m^2$, for the operational SSPS falls on this trend line.

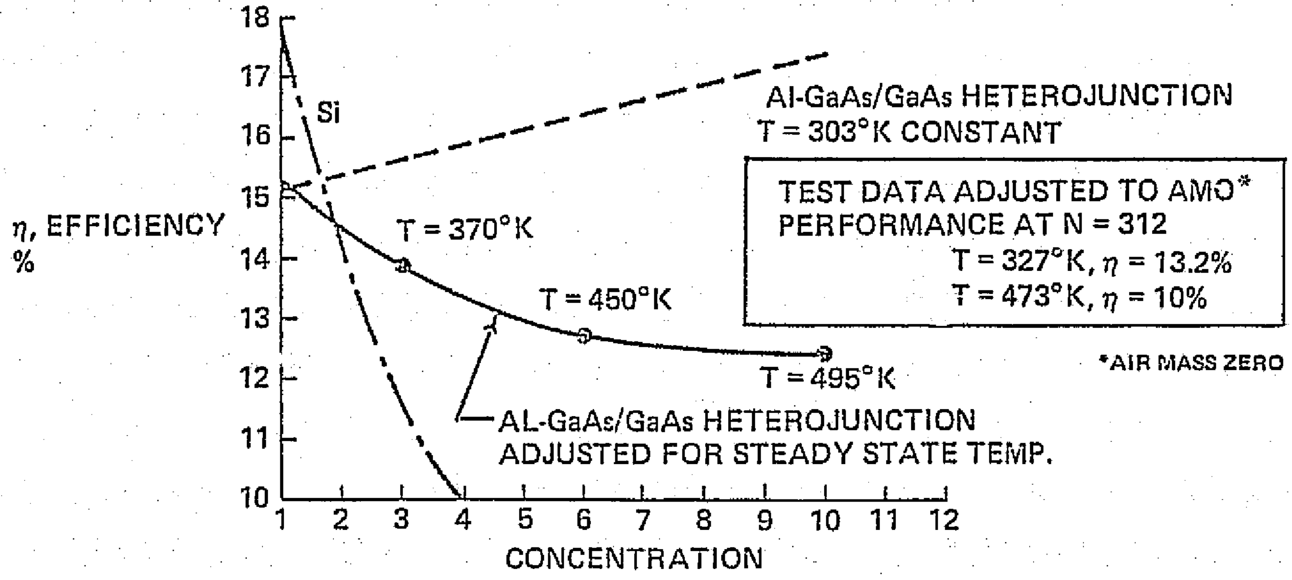


Figure 3.8 Estimated Al-GaAs/GaAs Performance (AMO)

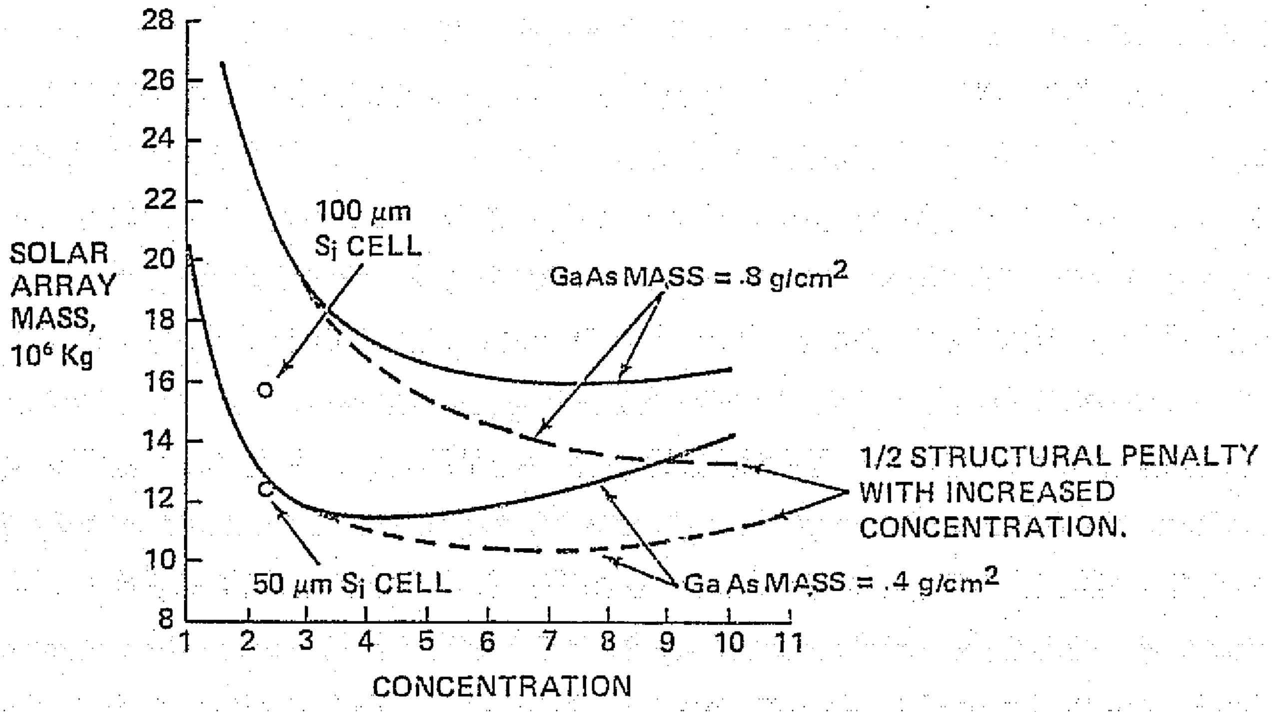


Figure 3.9 Estimated Solar Array Mass

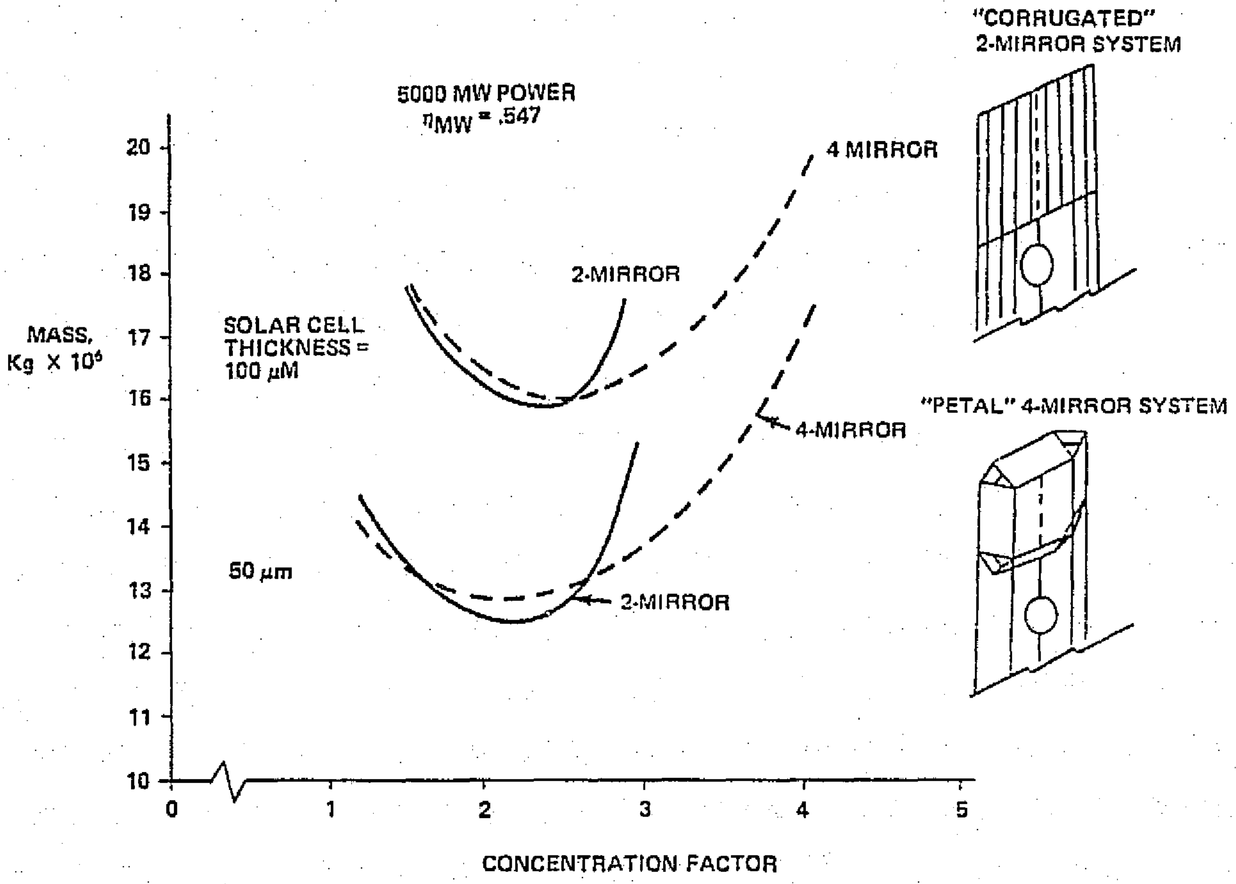


Figure 3.10 Solar Array Configuration Mass Comparison

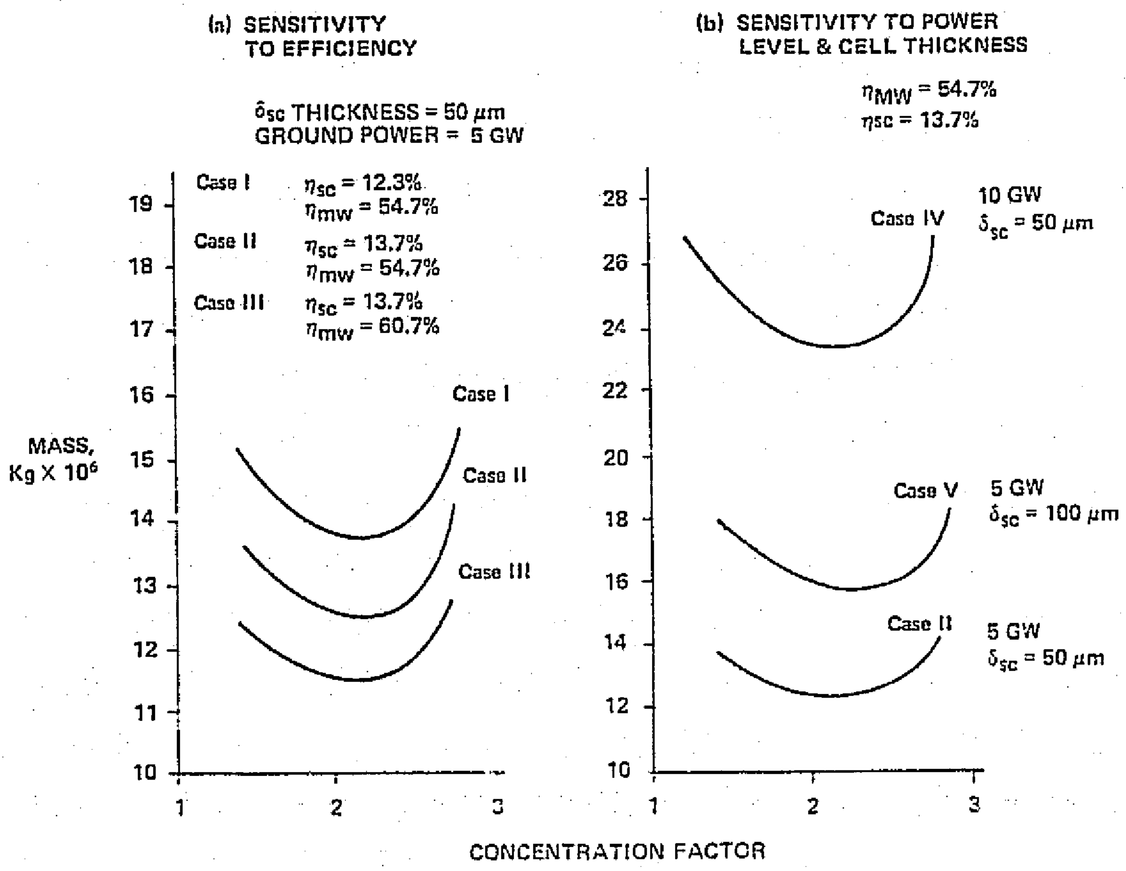


Figure 3.11 Solar Array Mass Sensitivity, Two-Mirror Corrugated Configuration

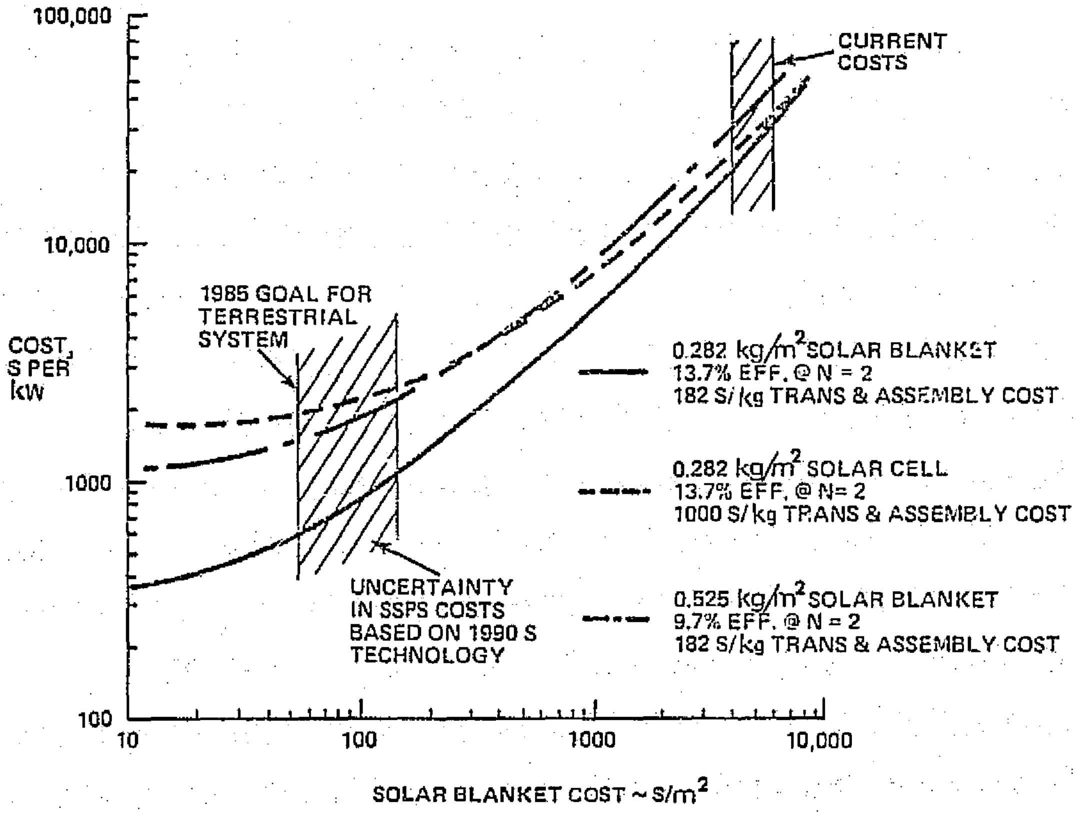


Figure 3.12 Solar Array Design Cost Trade

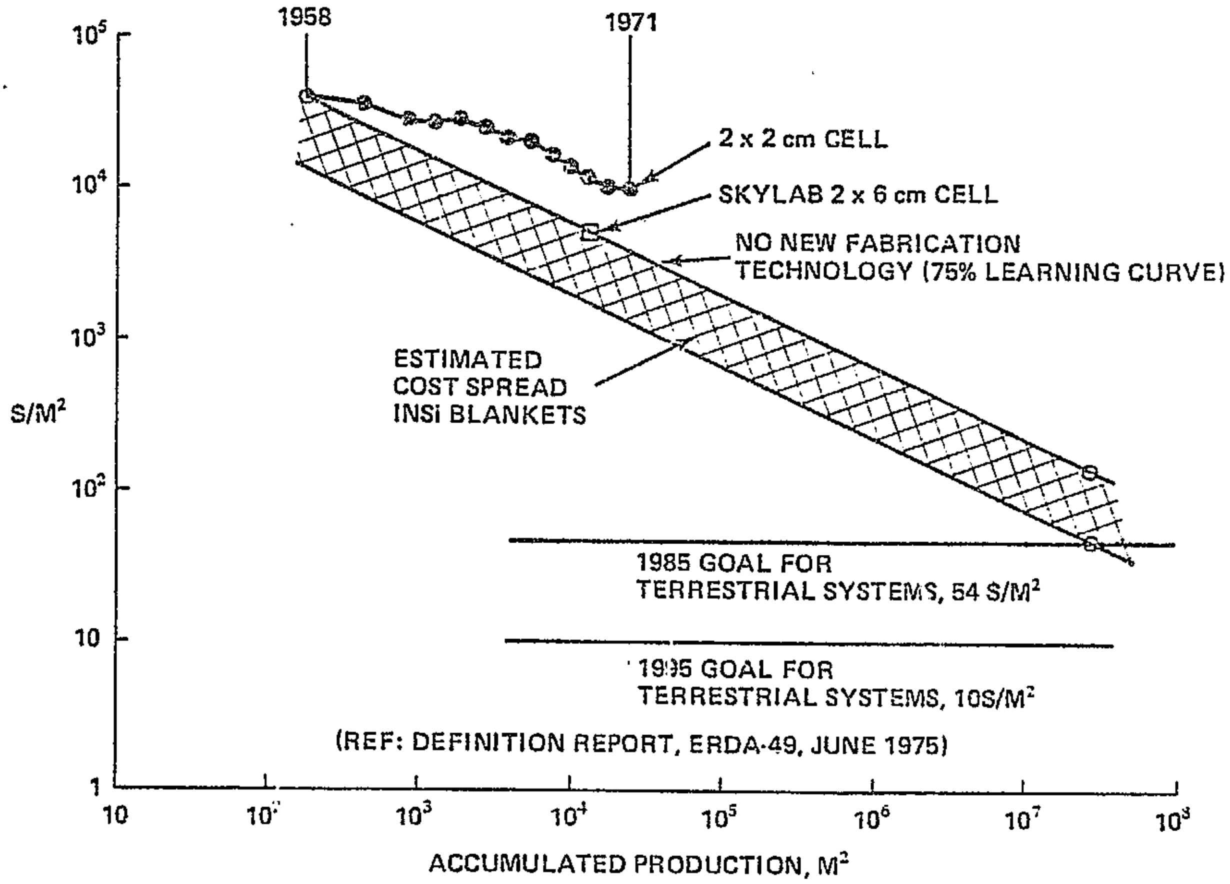


Figure 3.13 Projected Silicon Solar Cell Costs

Technology improvements in fabrication techniques which would reduce the cost of today's blankets from \$7000/m^2 to \$1200/m^2 could be adequate to achieve the \$54/m^2 goal for SSPS over the production run required. If SSPS were the only program contributing to the increased blanket production, the first unit cost would be \$2.5 x 10^9 or an average \$91/m^2. This assumes that no substantial terrestrial solar blanket market develops. However, the estimated technology expenditures to reduce solar cell costs to less than \$54/m^2 is \$300 x 10^6 (See Chapter 6) up to 1985. The technology path to reduced unit cost appears to be economically more efficient than depending wholly on production increases.

Conclusions

The following points summarize the conclusions of the large solar array engineering analysis:

- A solar blanket cost range of \$54/m^2 to \$150/m^2 is reasonable. The lower value is consistent with the ERDA goal for terrestrial arrays and the \$150/m^2 is consistent with today's space-qualified blanket fabrication techniques for quantity production in excess of 20 x 10^6 m^2 of array. The following cost reduction programs should be pursued:

  1. Raw silicon to semi-conductor quality - Three high temperature cycles are presently used whereas one might be possible. Alternatives to the use of an expensive trichlorosilane process in the purification step should be sought.

  2. Single-crystal manufacture - Cost reduction factors of five-to-100 can be achieved using a continuous crystal growth technique (EFG). The key problem here is finding die materials that withstand the process temperatures without interaction with silicon.

  3. Process technology - Automation for junction formation, contacts integration, etching, encapsulating, etc., including automatic testing.

- A beginning-of-life silicon solar cell efficiency of between 13 and 18 percent is a reasonable span for assessment of SSPS feasibility. The lower efficiencies can be achieved with current technology using a cell of 150 µm-to-200 µm thick. The upper level of efficiency can be achieved with the following technology advances:

  - Increase in collection efficiency (small effect)

- Decrease base resistivity to 0.01 ohm-cm
- Higher doping in p and n regions

- Improvement in radiation damage resistance and annealing is key to SSPS feasibility. A problem with low resistivity cells is that they have a tendency to degrade in the presence of radiation. Annealing methods, using lithium doped cells or optical/thermal techniques, might be pursued.

3.1.2.2 Large Structures

The objectives of the study of large structures were to:

- evaluate the SSPS two-dimensional, front-lighted structural design
- estimate member sizes based on design requirements for the operational environment
- establish estimates for the nonconductive and conductive structural masses of the array
- establish structural mass estimates of the antenna.

Solar Array Structure

Figures 3.14, 3.15 and 3.16 show the general structural configuration of the SSPS vehicle. The basic structure of each solar array (5.92 km x 4.93 km) consists of 20 m-deep x 493 m-long cap members. Shear stiffness is provided by cross-bracing cables. The large diameter (100 m) coaxial mast transmission bus which carries power to the microwave antenna is located on the solar array centerline. The mast member sizes are based on power transmission requirements; the mast is also considered part of the primary structure and is included in the analyses. The primary chordwise structural members are located at X630, X2109, X3588, X4565 and X5865. As shown in the drawing, these members are made up of 246.5 m x 20 m truss girders and 493 m and 20 m girders. All the lower members (at - Z213.5 m) of these chordwise trusses are power conductors carrying electrical power to the main bus or mast. These members are also considered structurally effective. At each interval within the 1479 m bays, additional chordwise members are added which reduce the column length of the longitudinal members. Analysis of these members, for combined compression loads and bendings moments induced by blanket pretension loads, indicated the requirement of additional supports for the 1479 m longitudinals.

Each primary member (246.5 m x 20 m or 493 m x 20 m) consists of three 1.5 m truss girder cap members stiffened by the same size truss girder spaced at 30 m and cross-braced cables. The 1.5 m truss

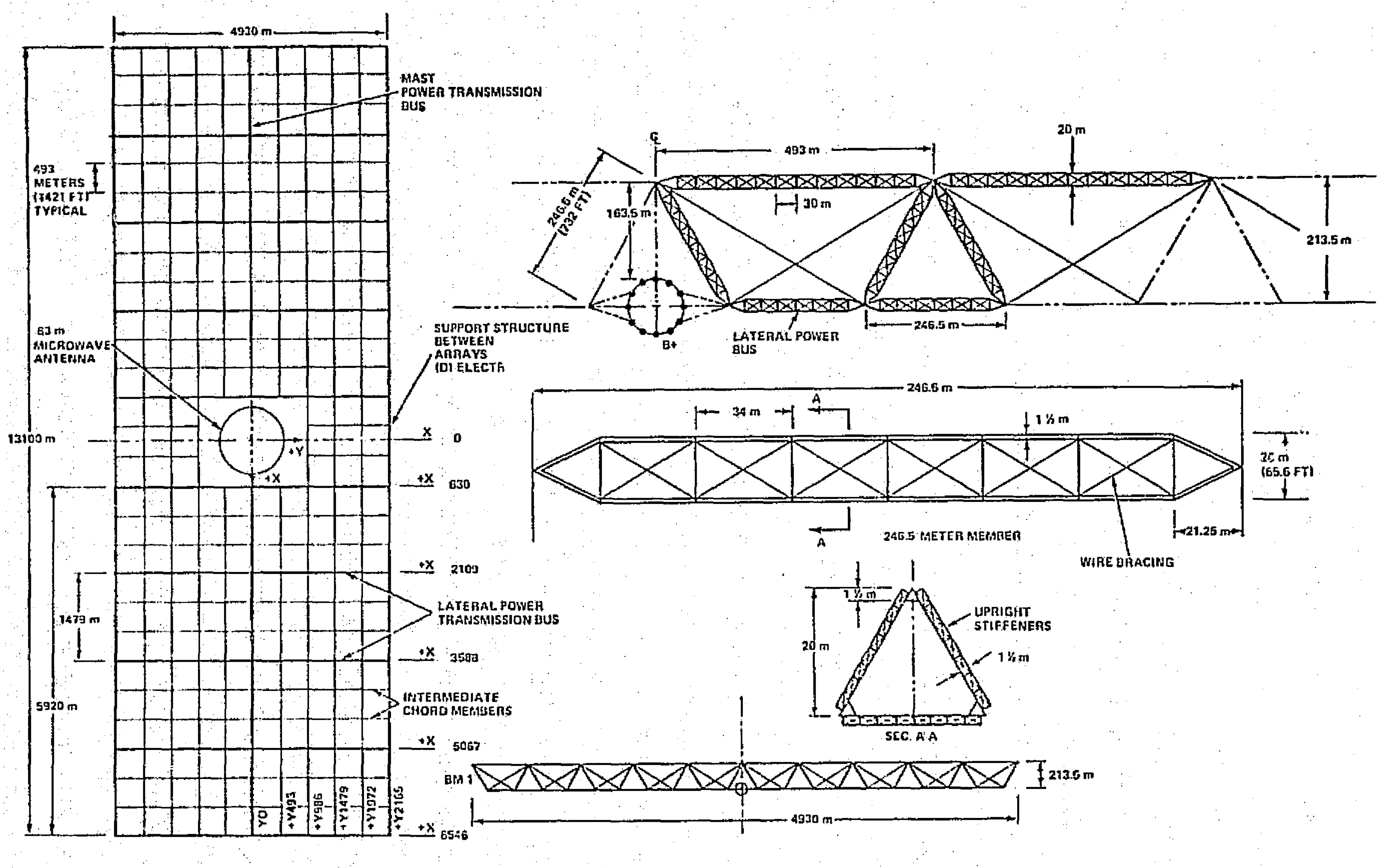


Figure 3.14 SSPS Structural Arrangement

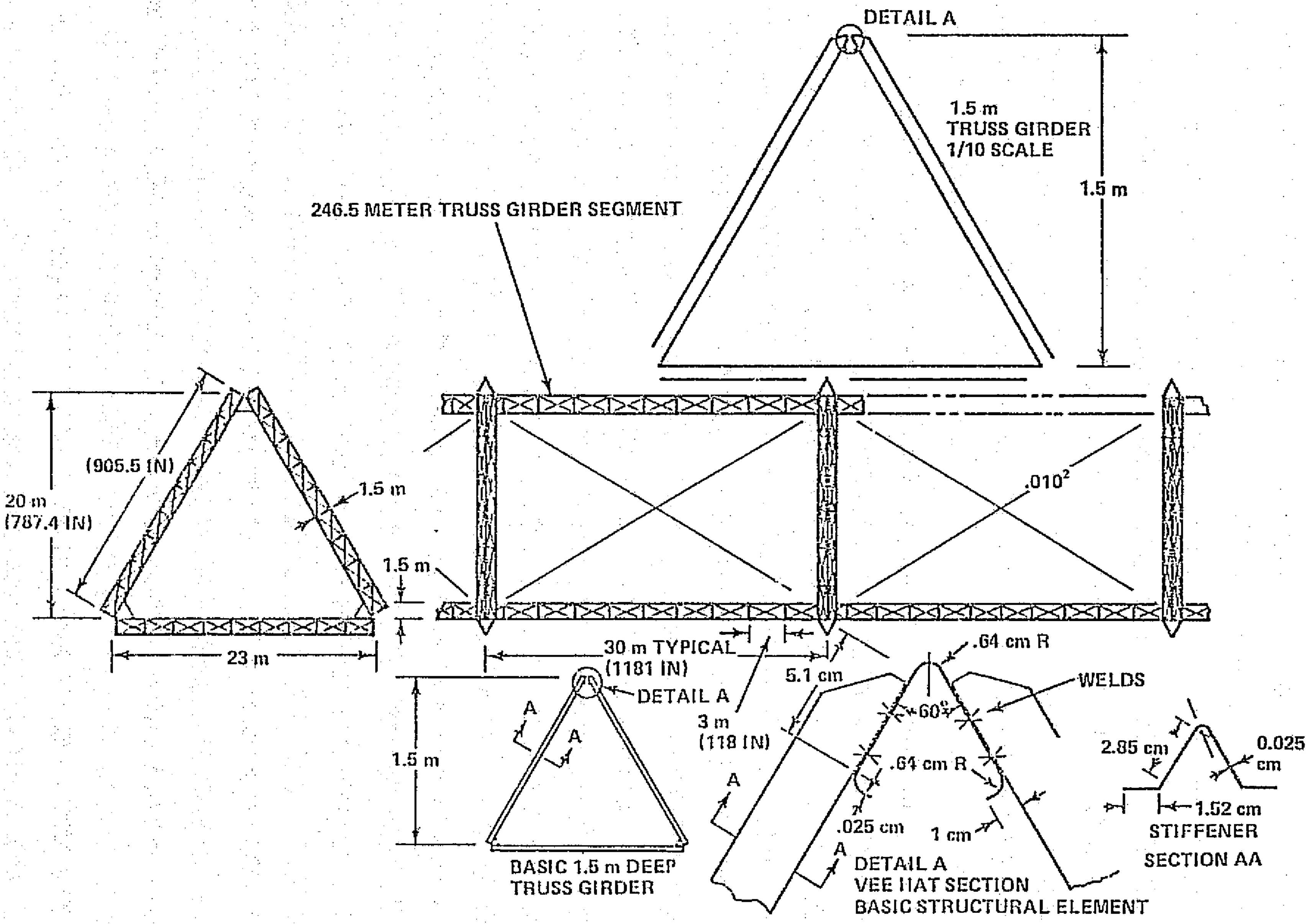


Figure 3.15 SSPS Structural Members

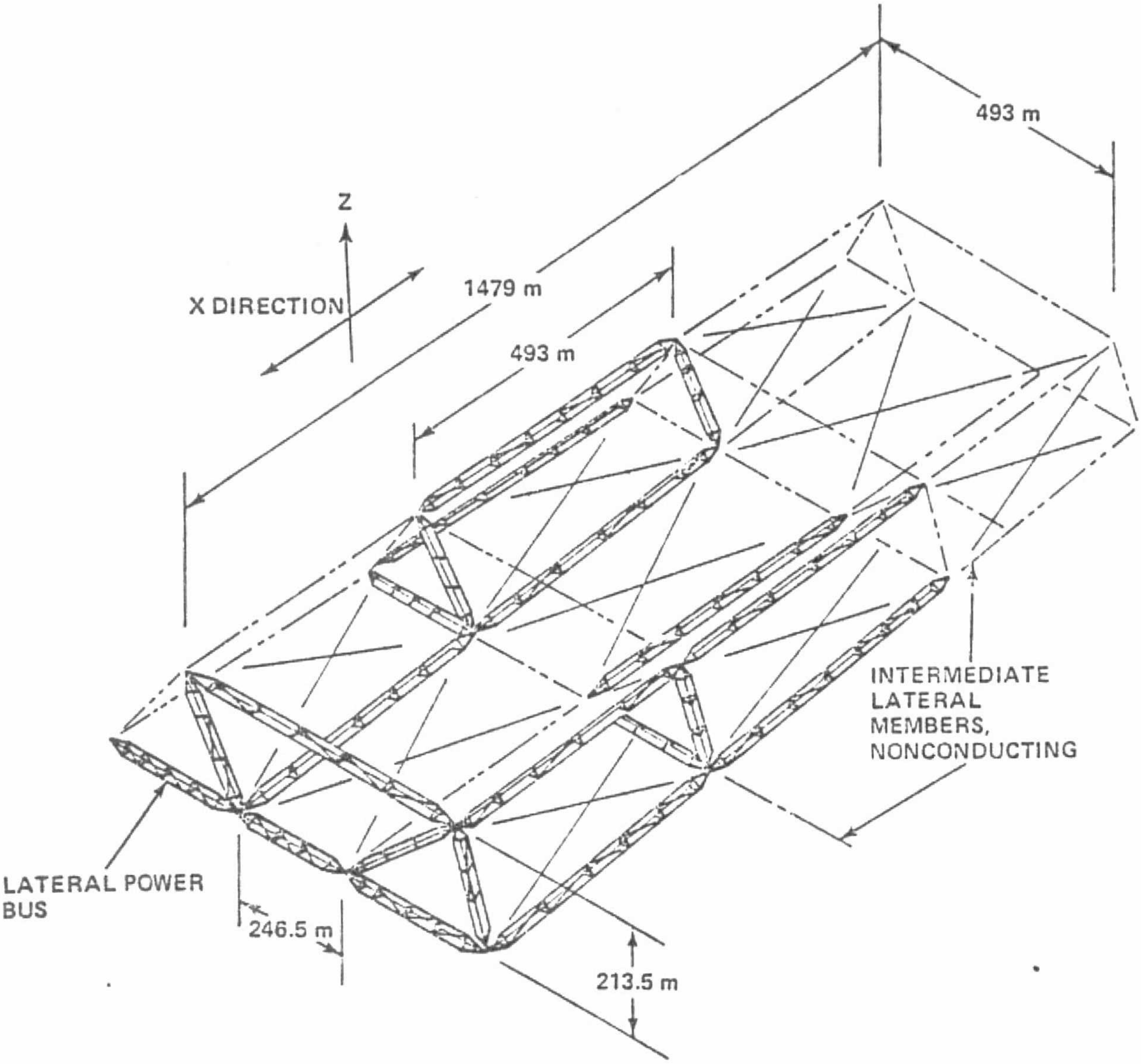


Figure 3.16 SSPS Structural Assembly of 1,749 m Segment

girder is the basic structural member; it consists of the basic structural element vee hat section, 0.025 cm thick, as shown in the figure. The material selected for the basic element in this study is 5052 in the "zero" condition and is roll formed into the vee hat section. Since the material is work-hardenable, the estimated final condition is 5052-H32.

Stiffness and Natural Frequency - A preliminary estimate of the stiffness and natural frequency of the SSPS was calculated using beam theory. For purposes of this study, the beam simulation resulted in a moment of inertia distribution curve as shown in Figure 3.17.

Nonconducting Structural Weights - Figure 3.18 summarizes the solar array structural arrangement and weights. The primary structural element is a truss girder built up from roll-formed modified vee hat sections with bent up stabilizing angles at the outstanding legs. The basic structural member was designed as a 1.5 m deep truss girder.

The structural members are designed for a limit control force at each array tip of 2980 N times a factor of safety of 1.50. A peak 605 N ultimate compression load was used to size the aluminum cross-section.

Pretension forces in the mirrors and solar blankets were combined with the axial compression load to assess the beam column strength of the 493 m longitudinals. The total mass of all nonconducting structures was calculated at 2.3 x 10^6 kg.

Conducting Structure - Because of the large amount of conducting material required to collect the electrical power generated by the solar blankets and transmit it to the microwave antenna, the bus material has been integrated into the structure. A mass optimization computer program was used to determine the power distribution system. Figures 3.19 and 3.20 show the electric current flow for a typical system. The efficiency is 92 percent at an operating temperature of 38°C dropping to 91 percent at a temperature of 149°C.

Table 3.3 summarizes the mass and cross-section of the conducting structure. Switches are assumed to be 30 percent of the lateral bus mass, yielding a total buses/switches mass of 0.27 x 10^6 kg.

Transmitting Antenna Structure - The microwave power transmission system (MPTS) is 0.83 km in diameter x 40 m deep. The antenna is assembled in two rectangular grid structural layers. The primary structure is built-up in 108 m x 108 m x 35 m bays using triangular girder compression members 18 m long x 3 m deep. The secondary structure is used as a support point for the waveguide subarrays and is built-up in 18 m x 18 m x 5 m bays. The total antenna structure/mechanical system mass is 412,000 kg (cf. Table 3.4) using aluminum.

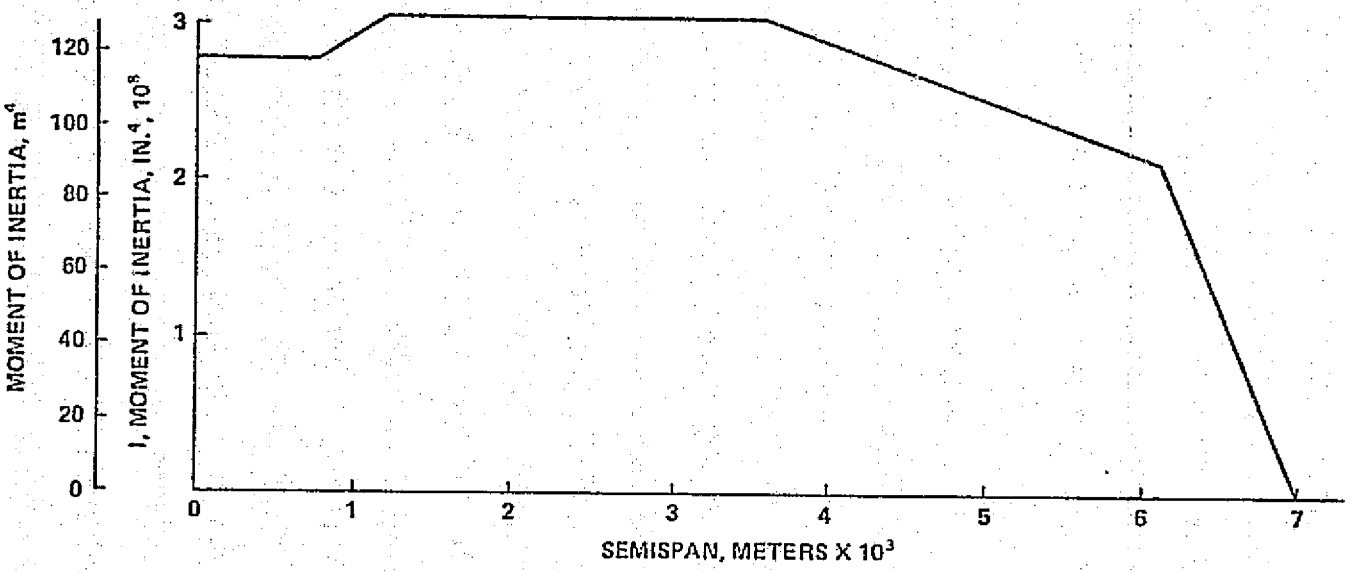
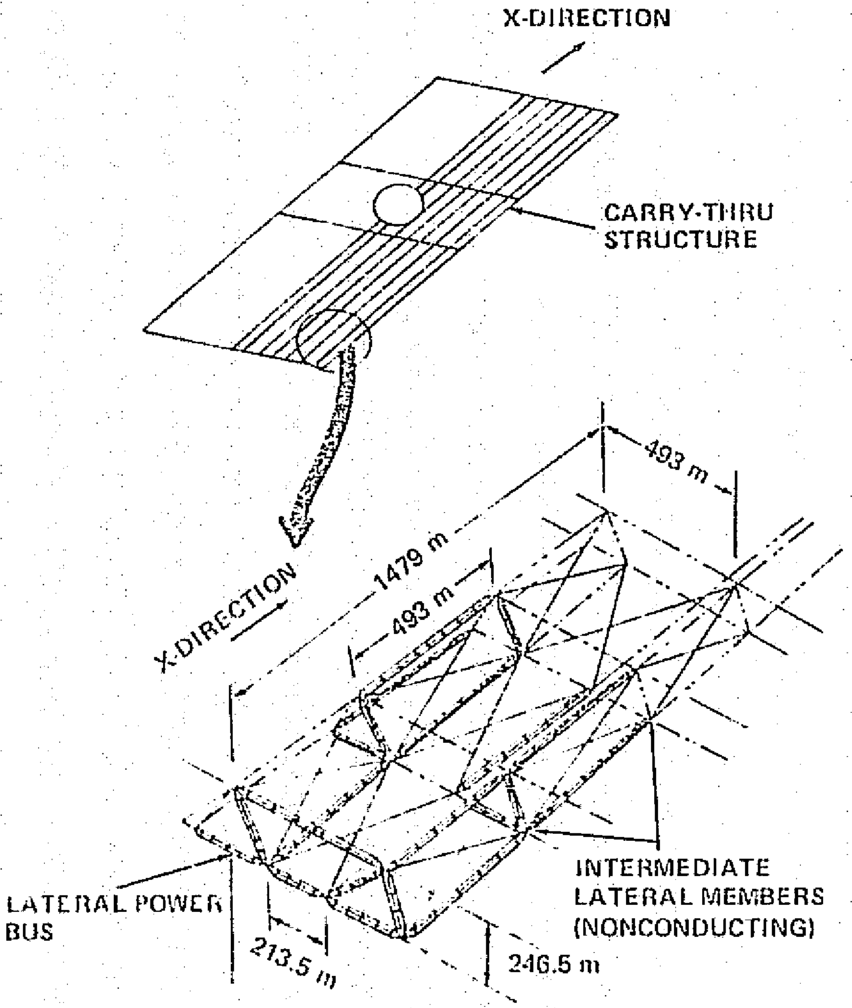


Figure 3.17 Configuration Moment of Inertia



ARRAY

MEMBER	NUMBER	WGT/MEMBER LB	WGT LB X 10^6	MASS 10^6 KG
CHORDWISE MEMBERS (ALUMINUM) (1.676 X 10^6 LB)				
2465 m	520	1503	0.782	.355
493 m	260	3009	0.782	.355
213.5 m	52	1362	0.071	.032
163.5 m	39	1042	0.041	.019
LONGITUDINAL MEMBERS (ALUMINUM) (2.383 X 10^6 LB)				
493 m	792	3009	2.383	1.082
CARRY THROUGH STRUCTURE (GLASS) (0.33 X 10^6 LB)				
CHORDWISE MEMBERS				
246.5 m	24	1503	0.036	.016
493 m	12	3009	0.036	.016
213.5 m	8	1362	0.011	.005
LONGITUDINALS				
493 m	72	3009	0.217	.099
BRACING			0.043	.020
SUBTOTAL			4.689	2.129
10% NONOPTIMUM FACTOR			0.465	0.211
TOTAL			5.154	2.340

Figure 3.18 Solar Array Nonconducting Structure

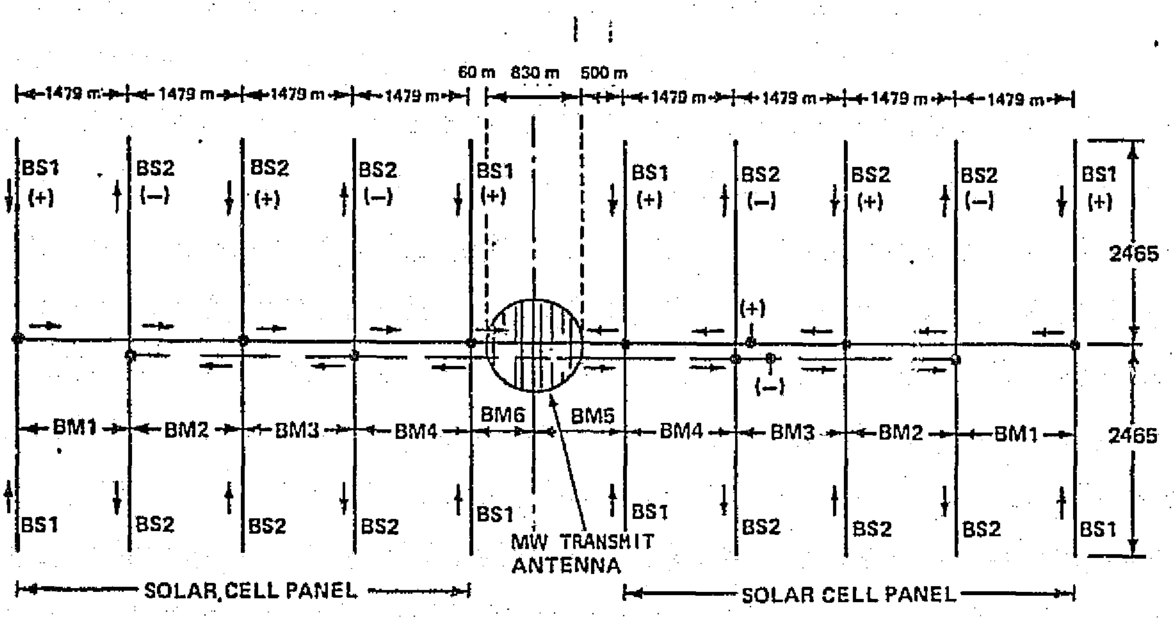


Figure 3.19 SSPS Conducting Structure Electrical Buses Grid Configuration

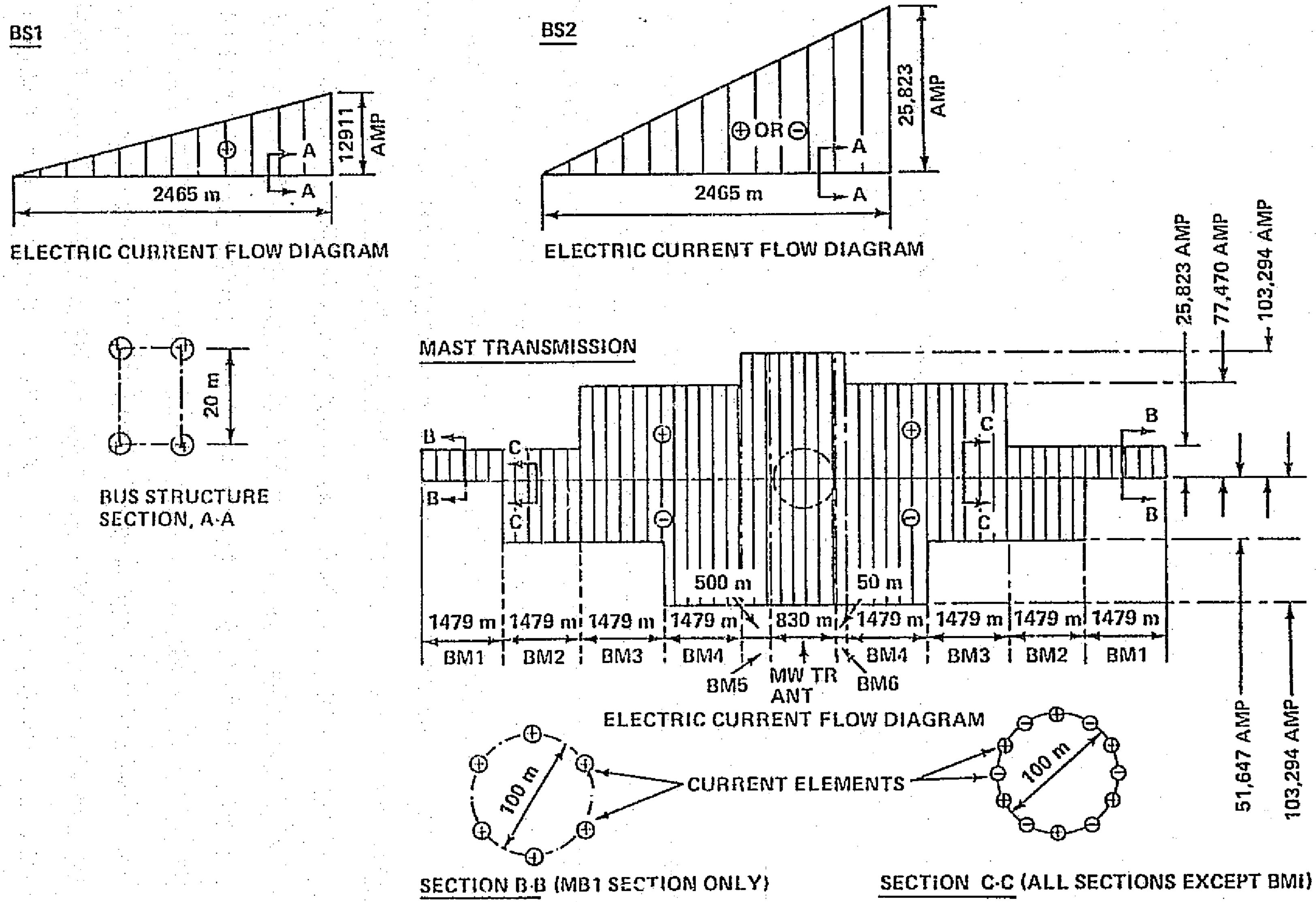


Figure 3.20 SSPS Conducting Structure - Solar Array and Mast Transmission Electric Buses Dimensions Electric Current Flow

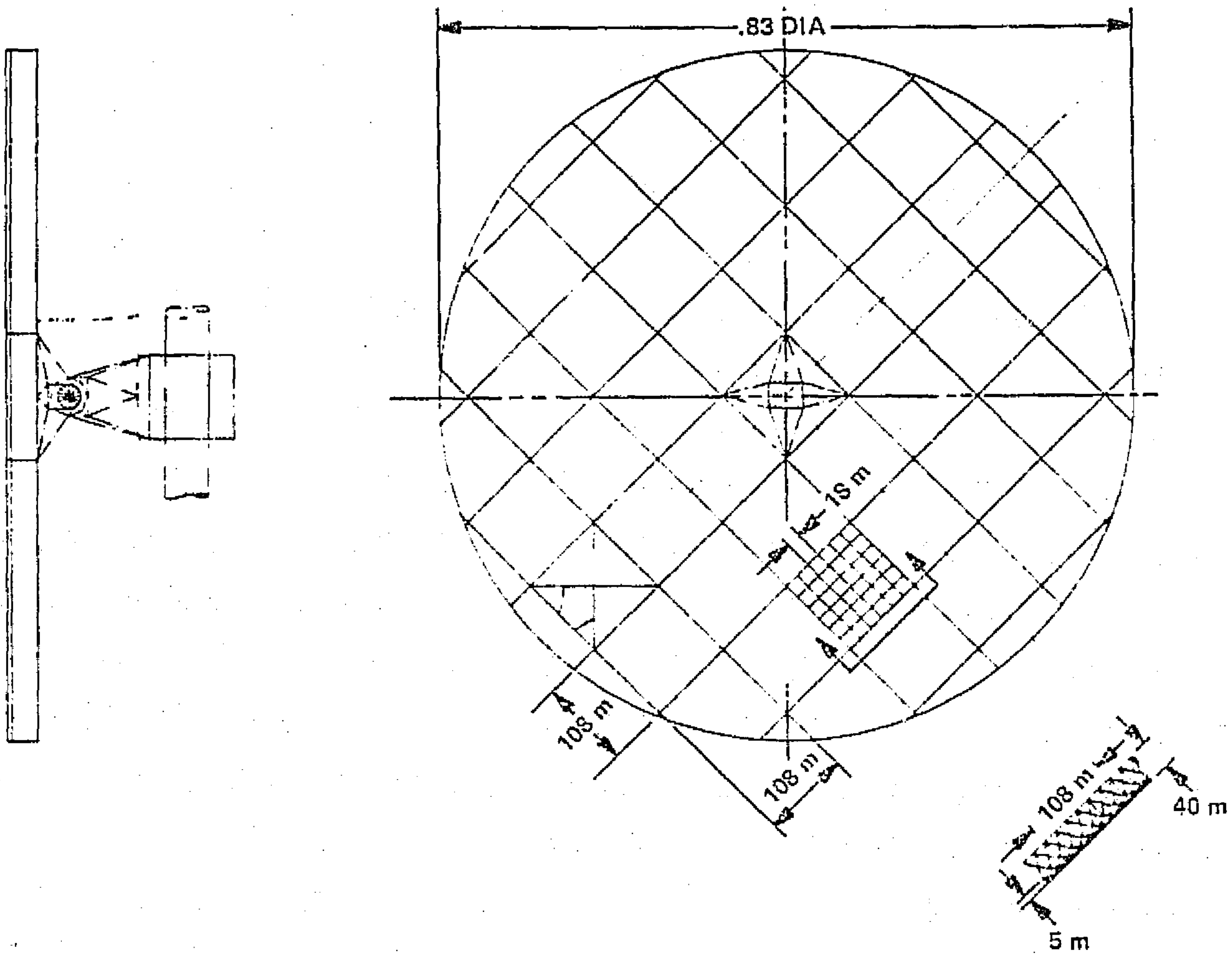
Table 3.3 Conducting Structure Mass

MAST MASS

MAST SEGMENT	LENGTH cm x 10^5	CROSS-SECTION cm^2	MASS, Kg. x 10^6
BM1	3.0	39.6	.033
BM2+	3.0	39.6	.033
BM2-	3.0	79.2	.066
BM3+	3.0	118.2	.098
BM3-	3.0	79.2	.066
BM4+	3.0	118.2	.098
BM4-	3.0	158.4	.132
BM5+	0.55	158.4	.024
BM5-	0.55	158.4	.024
BM5+	0.78	158.4	.034
BM6-	0.78	158.4	.034
		TOTAL	0.642

LATERAL BUS WEIGHT

BUS MEMBER	LENGTH cm x 10^5	OPT CROSS-SECTION, cm^2	NO. OF MEMBERS	MASS, x 10^6
BS1	2465	10.3	10	.073
BS2	2465	21.6	10	.143
			TOTAL	.221



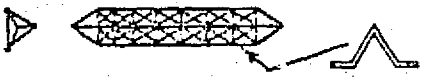
		ALUMINUM (2024-t6)	
• TEMP, °K		450	
• MODULES OF ELASTICITY, N/cm^2		6.2×10^6	
• DENSITY, g/cm^3		2.80	
• THICKNESS RANGE, cm		0.038 TO 0.102	
• MASS	LB	(10^3)	KG
SUBARRAY PRI. STRUCT.	207		94
SUBARRAY SEC. STRUCT.	70		32
ANT. SUPPORT STRUCT.	233		106
YOKE & MECHANISMS	146		66
COATINGS	31		14
AMPLITRON SUPPORT			
CONTOUR CONTROL ACTUATORS	185		84
AMPLITRON ATTACH STRUCT	35		16
TOTAL	907		412

Table 3.4 Antenna Structural Arrangement

A thermal analysis of the transmitting antenna resulted in the following:

- A triangular open section was best suited for the beam caps, resulting in the lowest temperature and temperature difference (See Figure 3.21).
- The 35 m long vertical members restrict the maximum waste heat power density at the center of the antenna to 3,800 W/m^2 for aluminum construction and 8,100 W/m^2 graphite/polyimide construction.
- The temperature difference between the upper and lower cap members (35 m apart) is approximately 5±°K in the center and 16 ± 3°K at the edges.

The temperature profiles along the horizontal structural triangular girder were evaluated for various orbital positions during the equinoxes and solstices. Figure 3.22 presents the expected variation in thermal gradients between primary and secondary structural caps. The average primary structure thermal gradient is approximately 5°K at the center of the antenna. The expected variation in this difference is ± 1°K.

The vertical columns of the structure have the same view of the antenna surface and space and consequently, cannot be easily configured with coatings, insulation or geometry selection to minimize peak temperatures of the material. Figure 3.23 shows the maximum waste heat flux that will be experienced by the vertical columns for microwave convertor efficiencies of 85 percent and 70 percent. Limitations as to the taper of the distribution (e.g., the db drop of power density at the antenna's center relative to its edge) must be imposed depending upon the structural material selected. A near uniform distribution must be used if the structure is aluminum or graphite/epoxy (70 percent converter efficiency). Because of the potential limitations that the structure could place on the layout of the microwave converters, the chosen material may be graphite, polyimide, steel or titanium. Selection of graphite/polyimide would be compatible with a desirable 5:1 db taper for the convertor Gaussian distribution.

3.1.2.3 Flight Mechanics and Control

The objectives of the flight mechanics and control effort have been to establish engineering requirements for stationkeeping, positioning and attitude control of the SSPS.

The flight mechanics and control studies were performed on an 11.8 x 10^6 kg SSPS, the baseline configuration at the start of the study. Propellant expenditure is 2 x 10^{-3} times configuration mass, at I_{sp} = 8,000 sec.

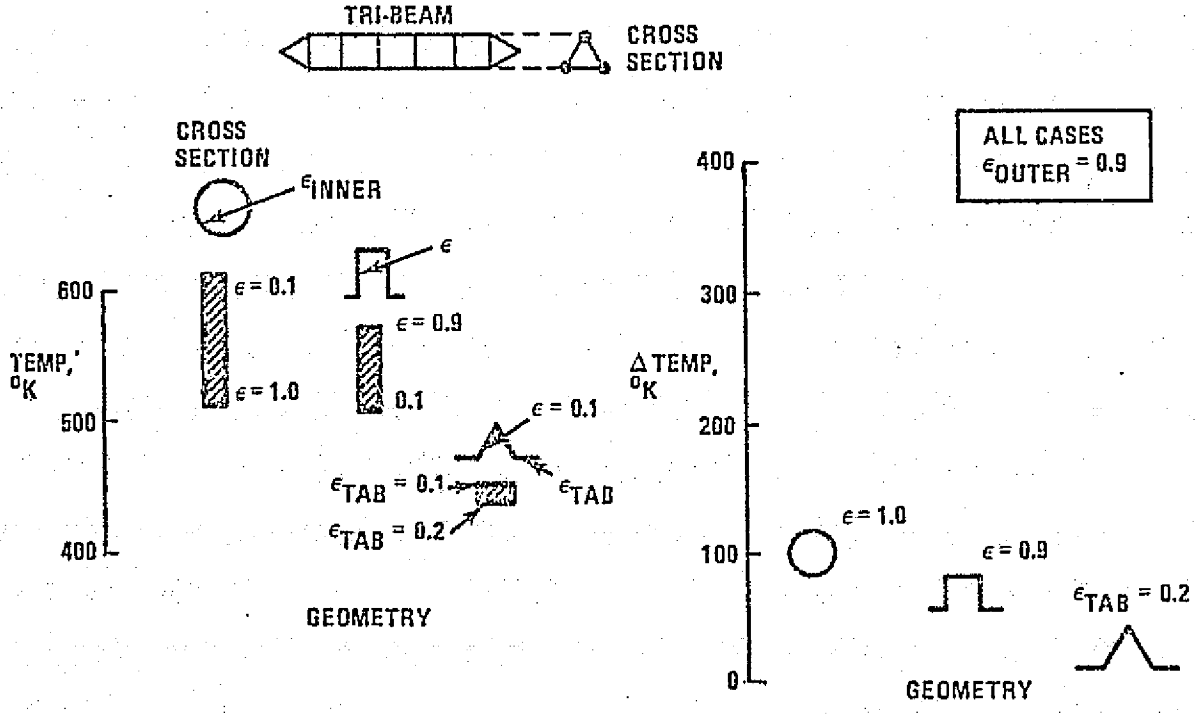


Figure 3.21 Comparison of Maximum Temperature and Temperature Differences

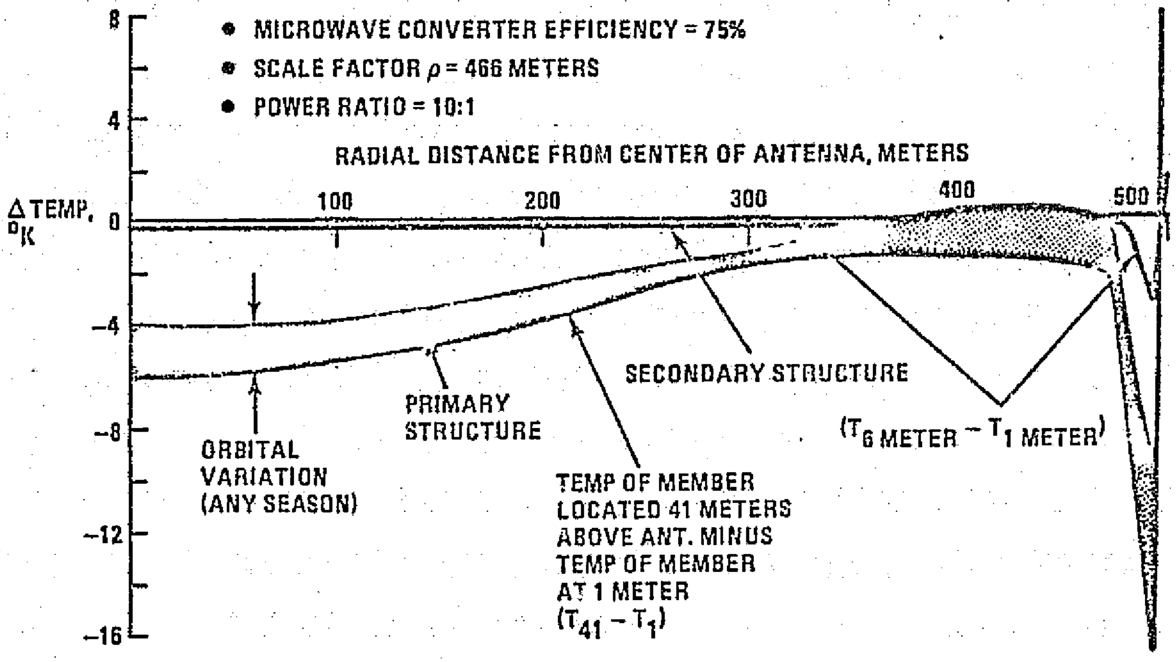


Figure 3.22 Temperature Difference Between Beam Cap Members Located Different Distances Above Antenna Surface

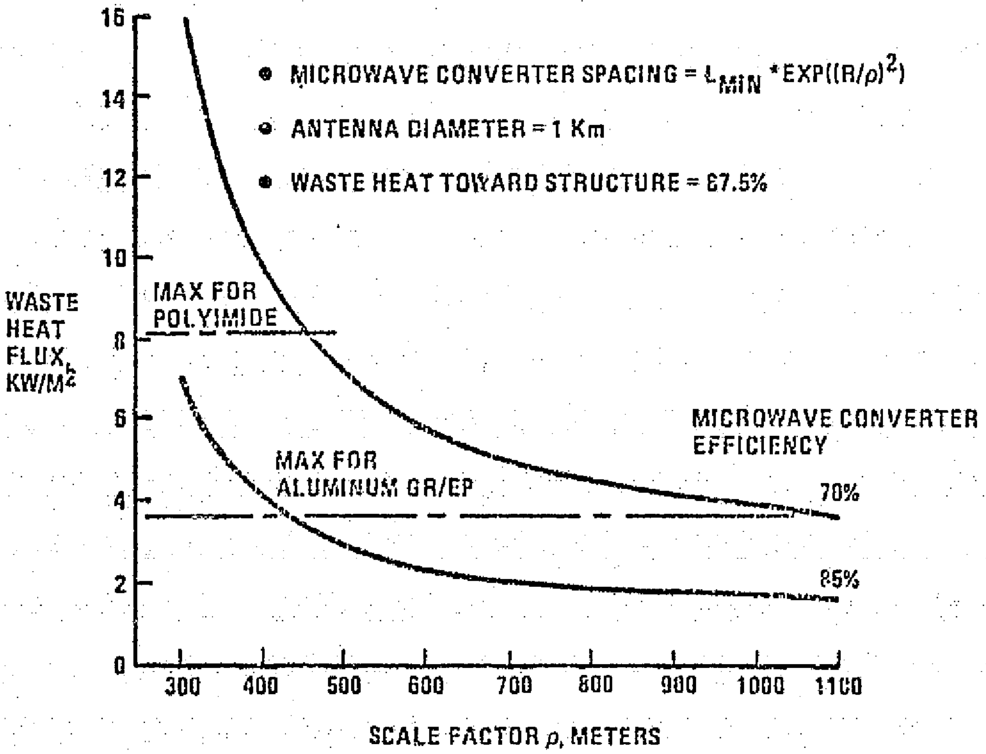


Figure 3.23 Waste Heat Flux at Center of Antenna as Function of Scale Factor

Analysis of SSPS stationkeeping requirements has shown the following:

- SSPS stationkeeping propellant requirements are approximately 9,750 kg per year using ion propulsion (I_{sp} = 8,000 sec)
- North-South drift has more impact on overall microwave transmission efficiency than longitudinal drift for the rectenna latitude of 40°N, representative of service for the Northeast,
- Solar pressure is the dominant perturbing force: analysis shows that this perturbing force is most economically dealt with by continuously controlling orbital period and by not correcting for eccentricity drift.

SSPS attidude control system studies have found the following:

- gravity gradient torques are the dominant attitude disturbance to the spacecraft, requiring 8 x 10^9 N-m-sec momentum from the control system daily
- transients from the antenna rotary joint control system, used for antenna pointing, size the array roll thrusters (40 N engines mounted at the extreme of the array)
- mechanical steering of the solar array to point toward the sun for the entire year could result in a 10^6 kg decrease in system mass. This approach, however, would result in a complex mechanical system which could result in significant reliability problems.

Table 3.5 summarizes the yearly propellant expenditure for the SSPS assuming argon-ion thrusters (I_{sp} = 8,000 sec). Two levels of expenditure are shown. The first level assumes that eccentricity drift due to solar pressure is not corrected. This is reasonable if the number of SSPSs at geosynchronous orbit servicing the United States is less than 15. Beyond this number eccentricity control is required thereby increasing propellant consumption.

Orbit Keeping

There are four major influences on the SSPS causing it to drift from its nominal orbital location. These are:

- longitudinal drift - the ellipticity of the earth causes the SSPS to seek out Earth's minor axis
- Inclination drift - the interaction of the sun and moon's gravitation causes the orbit to regress so that its inclination changes with respect to the equator

Table 3.5 SSPS Propellant Requirements,
Isp = 8,000 sec

	LBM/YR	KG/YR
STATIONKEEPING		
• LONGITUDE DRIFT	1,600	726
• INCLINATION DRIFT	14,700	6,673
• SOLAR PRESSURE		
– ALTITUDE DRIFT	5,100	2,316
– ELLIPTICITY DRIFT	0 (32,784)*	0 (14,883)*
• MICROWAVE PRESSURE	68	31
SUBTOTAL	21,470 (54,252)*	9,745 (24,628)*
ATTITUDE CONTROL		
• GRAVITY GRADIENT	30,408	13,804
• ANTENNA CONTROL	162	73.7
• SOLAR PRESSURE	870	394
• MICROWAVE PRESSURE	292	134
SUBTOTAL	31,732	14,404
TOTAL	53,202 (85,986)*	24,149 (39,032)*

*REQUIREMENT AFTER 15 SSPS ARE PLACED IN ORBIT TO SERVICE THE UNITED STATES.

- Major axis and eccentricity drift - solar pressure distorts the orbit from circular to elliptical and back again over a 1-year period; in addition, there is a change in major axis which increases the orbital period and then restores it nominally over the same elapsed time

- Microwave pressure - the electromagnetic field at the aperture of the slotted array causes a "rebound" pressure on the antenna.

The stationkeeping propellant required to continuously correct longitudinal drift is shown in Figure 3.24 for an 11.4 x 10^6 kg SSPS. The worst-case SSPS positions, 106°W, 75°W, 15°E and 105°E longitude, can be maintained with approximately 681 kg/yr of propellant. The use of a cold gas system, I_{sp} = 200 sec, would require about 27,240 kg/yr. A continuous engine thrust level of approximately 2.2 N would be required to maintain longitude.

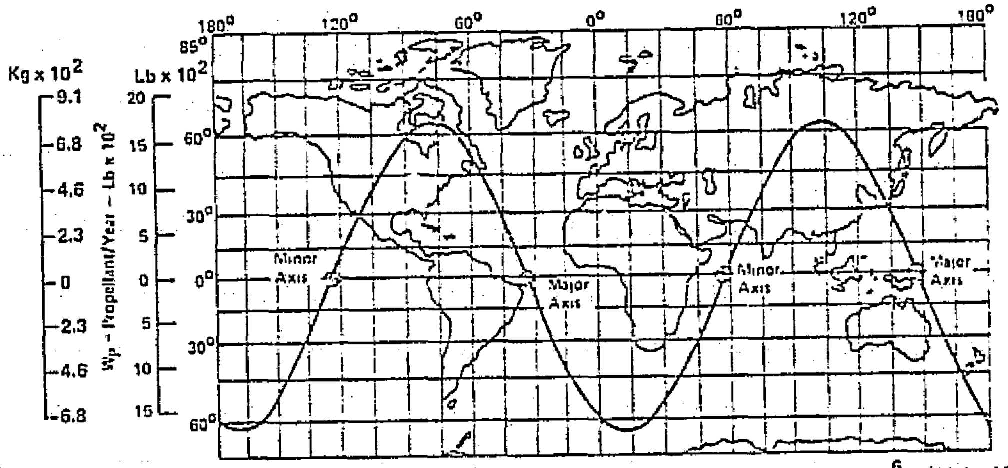
Figure 3.25 shows the time history of inclination drift for various initial orbit conditions. A unique set of orbital parameters with an inclination of -7.5 degrees results in a stable orbit that does not require propellants for orbit maintenance. This orbit, however, produces a figure-eight ground track causing a 16-degree variation in the rectenna-to-satellite line-of-sight for a rectenna located in the Northeast. Angular motions of this type have two undesirable effects when the satellite is in the southern half of its orbital swing:

- the path through the atmosphere is increased, decreasing efficiency by 1.5 percent

- the ground pattern of the microwave beam elongates in the north-south direction, requiring a larger rectenna to capture an equivalent amount of power (e.g., 15 percent in area to account for beam variations if the -7.5-degree inclination orbit is used).

Figure 3.26 shows the SSPS propellant requirements for continuous correction of inclination drift. A propellant expenditure of about 6,674 kg/yr is required to maintain an equatorial orbit using ion propulsion at a specific impulse of 8,000 sec.

The effect of solar pressure is twofold. First, it changes the major axis, hence, orbital period and, second, it changes eccentri- If the change in period goes unchecked, the SSPS will <u>precess</u> at a rate of approximately 3.5 degrees per day. A propellant expenditure of 2,135 kg/yr is required to offset this satellite motion. The propellant required to correct the ellipticity has been calculated at 1.59 x 10^5 kg/yr. This propellant quantity assumes that an opposing force of 200-to-300 N is continuously applied to offset the solar force. The effect of ellipticity on overall system performance, however, is not significant, provided the 24-hour orbit period is maintained. Ellipticity causes an apparent



SSPS wt 25 x 10^6 lb (11.4 x 10^6 kg)
Propellant I_{SP} 0000 Sec
(Continuous Thrust)

Figure 3.24 Longitudinal Drift Propellant Requirements/Year

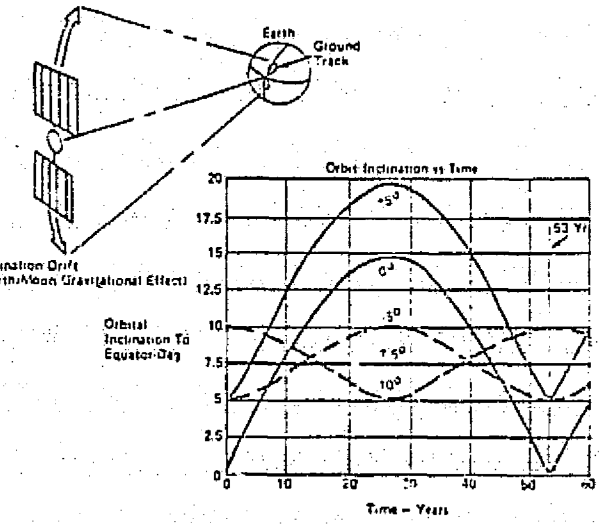


Figure 3.25 Inclination Drift Characteristics

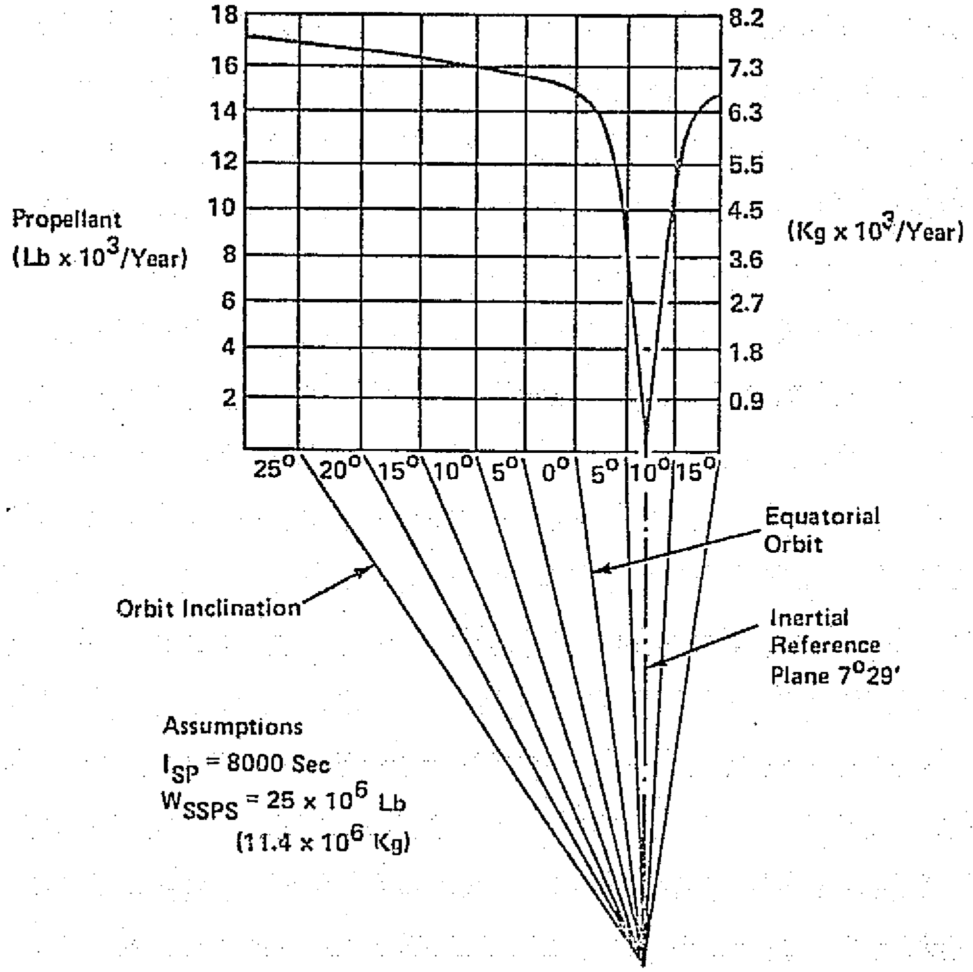


Figure 3.26 Inclination Drift Propellant Requirements

longitudinal drift to an observer on the ground. The satellite will "lead" or "lag" the rectenna location by 3.5 degrees during the course of one day.

A constant radial microwave pressure force of 17.8 N (4 lbs) is exerted on the transmitting antenna. This force is for 10 GW of power into the microwave convertors. A radial acceleration affects orbit eccentricity with only small perturbations to the orbit period. A force of 17.8 N will cause ±1.8 km altitude perturbation over a period of 80 days. The economical approach to controlling this perturbation is to perform an apogee/perigee correction every two months, rather than applying a continuous, opposing, radial thrust of 17.8 N (4 lbs). The yearly propellant requirement performing periodic horizontal thrust correction would be 31 kg.

Spacecraft Attitude Control

The groundrules and assumptions are:

- SSPS is in equatorial synchronous orbit
- The solar array vector normal is pointed to within ±1 degree of the projection of the sum vector on the equatorial plane.

Figure 3.27 defines the axis system used in calculating disturbance torques. The spacecraft's longitudinal axis, the x-axis is normal to the orbital plane. The y- and z-axes lie in the orbital plane (equatorial plane). The sun line is in the x-z plane with a yearly oscillation about the y-axis of ±23.5 degrees.

Disturbance Torques

Torques on the satellite result from the following sources:

- aerodynamic
- gravity gradient
- solar pressure
- magnetic
- microwave pressure
- rotary joint friction.

At an altitude of 35,800 km (19,330 nm) the atmospheric density is equivalent to the plasma proton density, 3.46×10^{-24} kg/m^3 (3×10^{-22} slug/ft^3), which results in a dynamic pressure of 7.3×10^{-14} N/m^2. The resulting aerodynamic force on the SSPS is only 22.4×10^{-6}N (5×10^{-6} lbf) which produces an insignificantly small disturbance torque on the nearly symmetric SSPS shape.

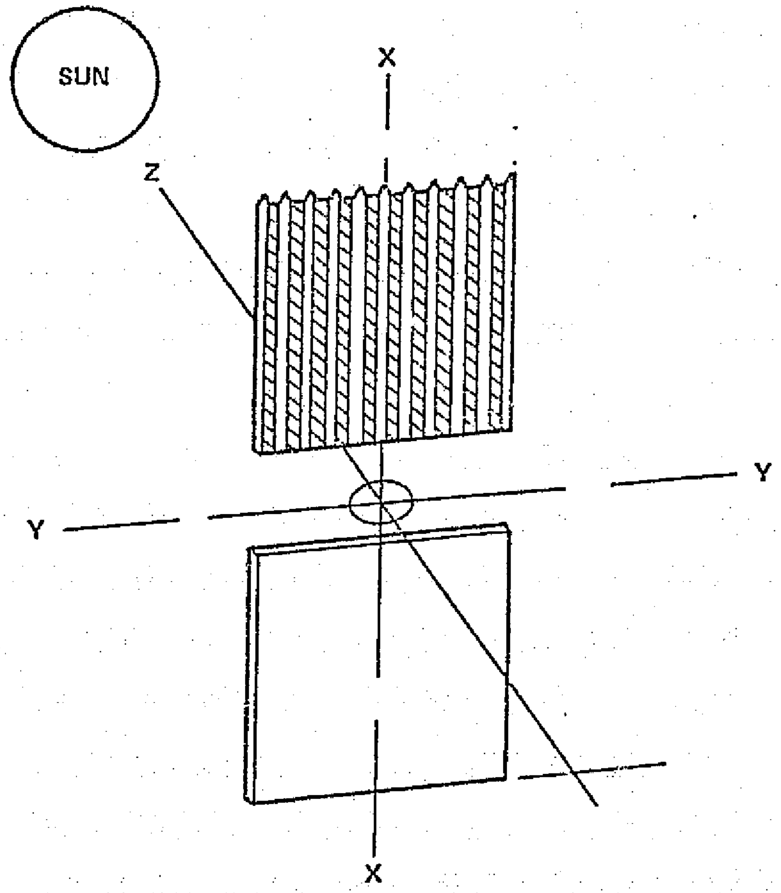


Figure 3.27 Axis System

Solar radiation pressures have a much larger effect. The cg-to-cp distance for y-axis-induced torque is 25 m, due to the offset of the microwave antenna. The x-axis torque is induced by off-nominal steering angles which cause a slightly different force on the corrugated mirror system.

Careful design of the solar blanket power distribution system will minimize the effects of magnetic-induced torques. If each unit of the magnetic field has opposite polarity to an adjacent current loop, the net magnetic torque is relatively small, i.e., 4.5×10^{-5} N.

An estimate of the force created by the radiation of electromagnetic power from the microwave antenna has been computed assuming a total input power of 10^{10} w. The total force normal to the antenna is not expected to exceed 17.8 N. This force produces a sinusoidal y- and z-axes torque, with a peak amplitude of 2,955 N-m at a period of 24 hours.

The gravity gradient torques acting on the SSPS will be at least an order of magnitude larger than the torques discussed above. These torque magnitudes are:

T_y = 33,200 N-m/deg offset

T_z = 29,700 N-m/deg offset

$T_x = 1.1 \times 10^5 \sin \omega_0 t$, N-m ($\omega_0$ = orbital rate, rad/sec;
t = time, sec)

A rotary joint is used to mechanically point the microwave antenna at the ground-based rectenna. The antenna-to-array relative motion requires 360 degrees of travel each day. Sliprings are used to transfer power across the joint. Contact pressures between the brushes and rotary joint ring will vary between 27,500 N/m^2 and 68,940 N/m^2 (4 and 10 psi) for optimum power transfer. At an assumed system voltage of 20 kV and a brush current rate of 7.75×10^4 A/m^2 a brush area of 6.45 m^2 is required to transfer 10 GW of power. The total normal force of 4.45×10^5 N is exerted on the slipring. At a coefficient of rolling friction of 0.1 and a central mast diameter of 50 m, 1.02×10^6 N-m of torque is induced on the spacecraft.

Table 3.6 summarizes the disturbance torque discussed above. The largest torques are induced by the slipring, antenna control system and gravity gradients. All other induced torques are small and can be neglected.

3.1.2.4 Transportation, Assembly and Maintenance

The cost of transportation, assembly and maintenance is the most significant variable in establishing the economic competitiveness of the SSPS. The objective of this section is to outline approaches to SSPS transportation and assembly and to bound expected costs.

Table 3.6 Control System Performance

CONTROL SYSTEM CHARACTERISTICS
- DAMPING = 0.5
- FREQUENCY = STRUCT FREQ/10

	AXIS TORQUE (N·m)		
TORQUE DISTURBANCE	(ROLL) X	(PITCH) Y	(YAW) Z
SOLAR PRESSURE	136	5,500	0
MW PRESSURE (PEAK)	0	2,955	2,955
GRAVITY GRADIENT	110,000	33,900	29,700
ANTENNA CONTROL	1,020,000	0	0
SUM	1,130,136	41,655	32,655

If SSPS electrical unit charge rates are to be kept low enough to be competitive with ground-based power generation the increment of the unit charge rate attributed to the transportation of materials to low earth orbit (LEO) should not exceed 20 to 30 percent of the total or approximately 4 to 5 mills/kWH. Using 4 to 5 mills/kWH as a cost target, the study has identified the following trends:

- An operations cost between $10 and $20 million per flight is considered viable and adequate to achieve cost-competitive space-based power, provided payload capability to LEO of greater than 180,000 kg can be achieved in an advanced launch system.

- Launch site operations may be a key issue in selecting launch system size. The larger the vehicle the fewer launches per day, and requirement for fewer launch opportunities.

Cost of transporting the SSPS from LEO to geosynchronous altitude is a strong driver in the selection of the assembly altitude. Candidate orbit-to-orbit transportation systems have been evaluated and indicate an incremental unit charge rate of 0.9 mills/kWH ($26/kg) can be achieved if major assemblies are fabricated in LEO and ion propulsion is used to transport the assemblies (or major subassemblies) to geosynchronous orbit.

Assessment of assembly operations performed in this study have indicated the following:

- Assembly using ground-based remote control tends to be lower in cost than manned space-based control of assembly operations.

- Assembly rates of better than 14 kg/H, costs for space stations to accomodate assembly crews of less than $10 million/man (amortized over five SSPS units) and low-cost approach for resupply and recycling of crews are required if manned space-based control of assembly is to be cost-effective.

- Assembly at geosynchronous orbit using remote controlled techniques would be cost-effective at assembly rates greater than 5 kg/H.

Preliminary analysis of SSPS maintenance requirements have identified the following key issues:

- A detailed study which trades off the cost of repair versus the loss of revenue, if no repair is performed, is needed to establish reliability goals and maintenance support approaches.

- The major maintenance cost-driver tends to be the control system (electric propulsion units).

- Proper layout of the solar blanket circuitry and microwave tube feed system could result in a near maintenance-free design.

- A maintenance approach which shares man-rated equipment between many power stations is needed to reduce the impact of initial investment for maintenance support equipment.

Transportation to Low Earth Orbit

The matrix of potential launch systems is shown in Figure 3.28. These launch systems span a range of design approaches which vary from the use of the current Shuttle to the development of a fully reusable LOX/Hydrogen, Heavy Lift Launch Vehicle (HLLV) with a 182,000 kg payload capacity to LEO.

The candidate launch systems have been compared in terms of their contribution to the unit charge rate to power users following a methodology developed for this study. A discount rate of 7.5 percent was used in this assessment. Costs include those required for operations, initial fleet purchase and fleet replacement.

The effects of launch system cost and payload potential on unit charge rate are shown parametrically in Figure 3.29. Superimposed on the figure are the four launch system options. Included is the span of operating costs which reflect the potential level of recoverability of hardware on the Space Shuttle derivative, Flyback Shuttle/Saturn Derivative and Flyback HLLV second stage. It becomes apparent that recoverability--specifically the feasibility of second stage propulsion and avionics reuse--is as strong a cost-driver as payload performance.

The combined effect of operations cost and fleet cost reflect the same trend as shown in Figure 3.30. The uncertainty of reuse of second stage components could preclude achieving the highly desirable $40 to $100/kg launch system costs for SSPS.

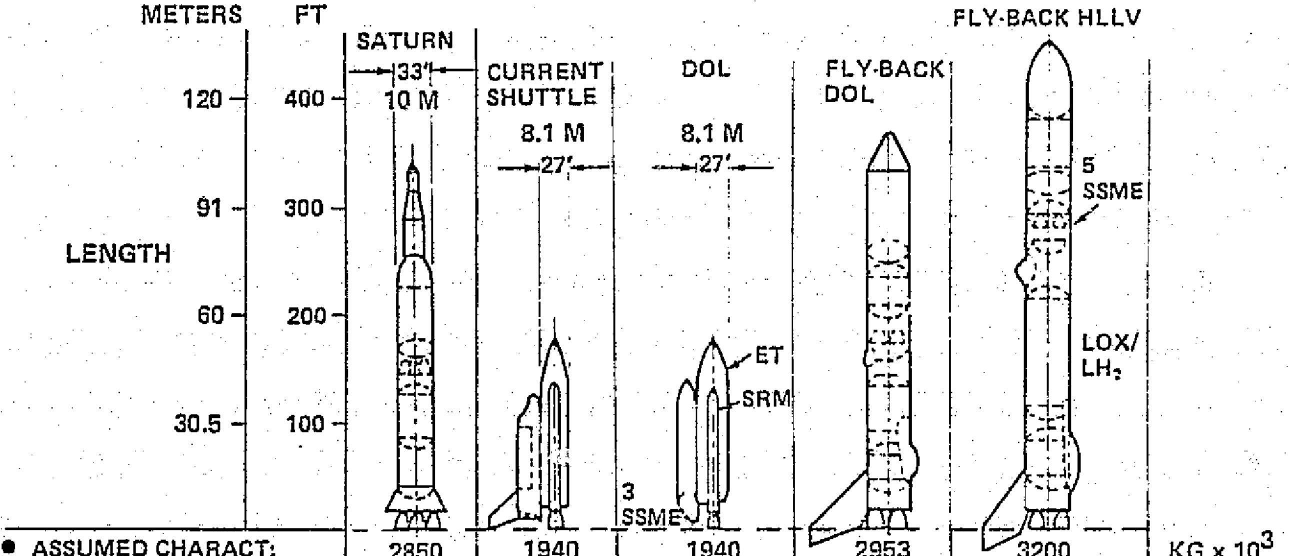
Orbit-to-Orbit Transportation

The cost of transporting the SSPS from LEO to geosynchronous altitude is a strong driver in the selection of the assembly altitude. This section addresses candidate orbit-to-orbit transportation system approaches, assuming that assembly is performed at the following altitudes:

- low earth orbit 463 km (250 n.m.)

- 12,970 km (7,000 n.m.)

02



	SATURN	CURRENT SHUTTLE	DOL	FLY-BACK DOL	FLY-BACK HLLV	
● ASSUMED CHARACT:	2850	1940	1940	2953	3200	KG x 10^3
– GROSS L/O WT, KLB	6367	4207	4207	6530	7012	
– PAYLOAD TO LEO, KLB	270	65	160	195	400	
● COST SPAN	123	29.5	73	88.5	183	KG x 10^3
– UNIT, SM	N/A	200 – 300	150 – 250	350 – 450	600 – 900	
– COST/FLIGHT, SM	300	10.5	13 – 35	8 – 30	9 – 35	
– S/LB (EXCLUDING		352	180 – 483	101 – 338	51 – 194	S/I G
FLEET COSTS & DDT&E)		161	82 – 219	46 – 154	23 – 88	

Figure 3.28 Typical Candidate Launch Systems

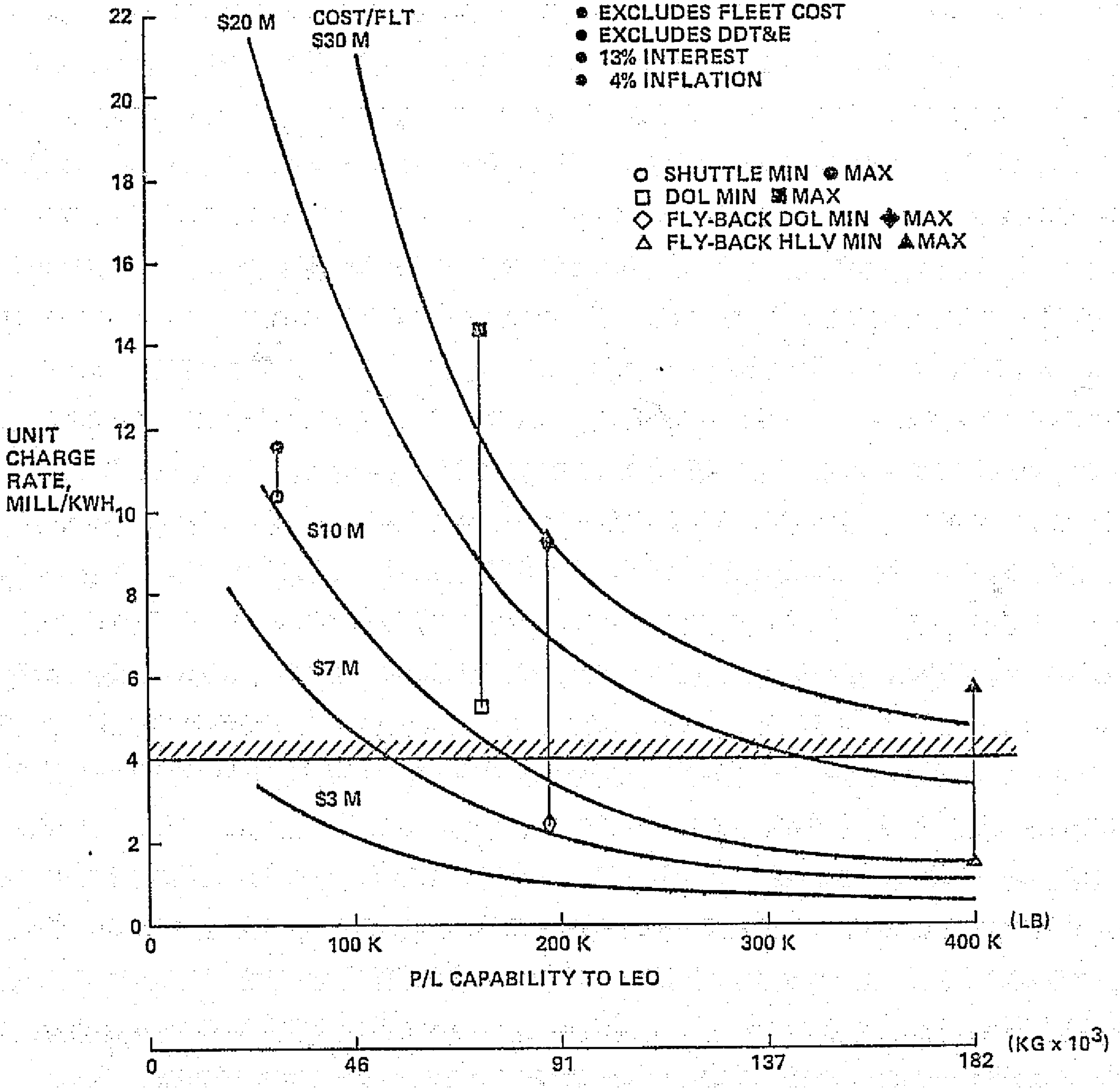


Figure 3.29 User Cost for Transportation to LEO

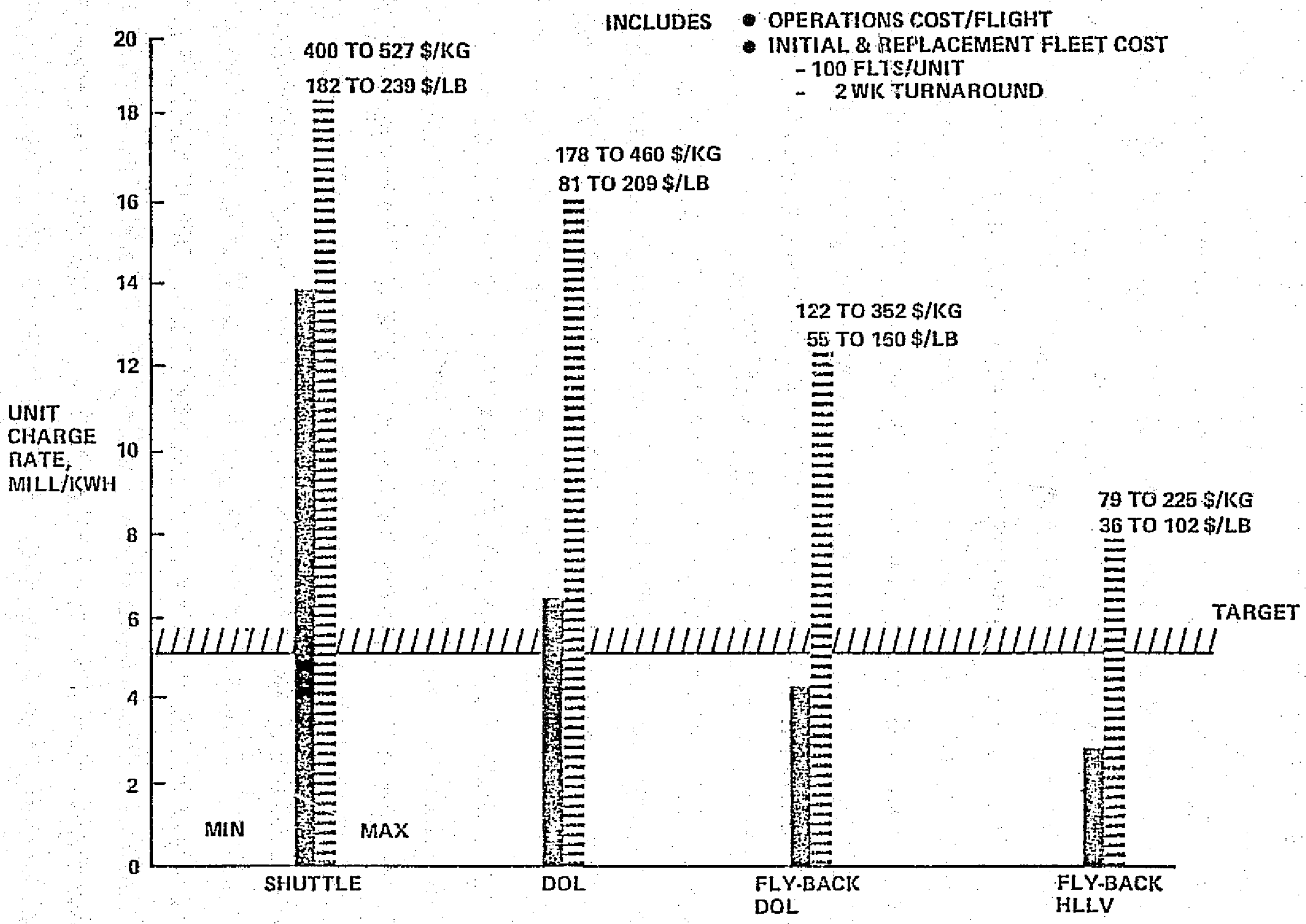


Figure 3.30 Launch System Comparison

- Geosynchronous orbit.

The assessment of these options (Figure 3.31) indicates that an incremental charge rate of 0.9 mills/kwh can be achieved if assembly is performed in LEO and ion propulsion (solar or nuclear) is used to transport the assembled SSPS to geosynchronous orbit. This corresponds to a \$26/kg for orbit-to-orbit transportation. If assembly is performed at 13 x 10^3 km (7,000 n.m.) using large chemical stages to transport materials from LEO and ion propulsion to transport the assembled SSPS to geosynchronous altitude, the orbit-to-orbit transportation cost would run \$246/kg. The use of a large nuclear stage to transport materials from LEO to a geosynchronous assembly site would result in a cost of \$280/kg.

Assembly

Fabrication and Packaging - A key to obtaining cost-competitive space-generated power is to optimize the level of ground prefabrication versus the corresponding level of orbital assembly for each major component of the SSPS. Two methods were investigated for assembling the SSPS antenna structure. In Method I, prefabricated beams are assumed to be manufactured on the ground, tightly packaged in the Shuttle payload bay and deployed in orbit. Method II assumes that ground personnel prepare flat stock with appropriate coatings for processing in an automatic manufacturing module in space.

Of the total 521,364 kg (1,147,000 lb) of antenna mechanical elements, 310,000 kg (682,000 lb) were structure built up from basic triangular girders. The available Shuttle payload volume used in these preliminary studies was the full 4.5 m diameter by the 18.3 m length. The payload capability assumed was 29,510 kg to an assembly site located in 28.5 degrees inclined orbit at an altitude not greater than 463 km A packaging density greater than 97.8 kg/m^3 had to be achieved to take full advantage of the Shuttle (higher packaging density would be required if pallets and payload attachment factors were considered).

Assembly of structural members on the ground (Method I) required that these members be stowed in a folded or compressed manner to achieve as high a density as possible. A survey of existing stowable structural members was made and indicated that these devices can be categorized into three broad areas. One was the folded girder designs and the others were the telescoping and STEM-type tubular designs. An analysis of the STEM-type versus the girder indicated that the girder construction is significantly lighter than the larger diameter STEM-type tubular. The STEM devices were dropped from further consideration in the Method I assembly plan.

Typical astromast characteristics are shown in Table 3.6. Packaging densities (without deployment cannister) vary from 64 to 257 kg/m^3. A check of the beam design efficiency (weight of deployable structure/mass of an ideal structure with same end loads)

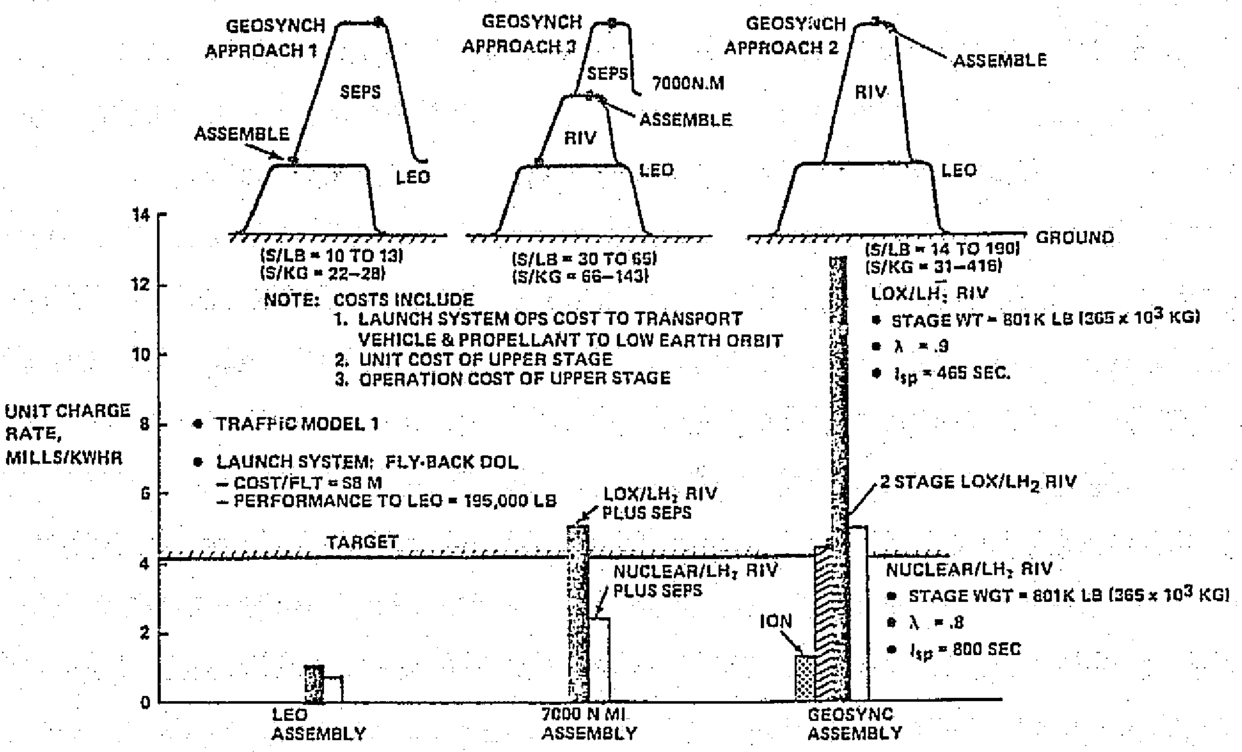


Figure 3.31 Concept Comparison, Orbit-to-Orbit Transportation

indicates that these devices are overdesigned by a factor of two-to-three, due to mechanism mass and, perhaps, geometry constraints imposed on the packaging arrangement. A packaging study of these (astromast) devices for the microwave antenna indicated a significant reduction in packaging density. For the beam geometrics used in the antenna, packaging densities of only about 2-4 kg/m^3 could be achieved. Therefore, a range in equivalent packaging densities (accounting for a nonoptimization factor for mass and orbiter packaging) of from eight to 80 kg/m^3 appeared feasible and was used for the Method I structural concept in the comparison analysis.

Complete fabrication and assembly of the members in orbit, Method II, could achieve 100 percent Shuttle load factor by transporting flat stock to the fabrication/assembly site. This concept requires a free-flying or space station supported "factory." A preliminary operations analysis of this process has tentatively established a rate of assembly of 190 kg/hr. The operations include: 1) feed and roll-form three longeron sections between intercostals, 2) feed and roll-form intercostals, 3) clamp and spot weld, 4) weave tension wire, and 5) align members using tension wires and collimator.

Table 3.7 is a comparison of the two methods studied for the antenna. The manufacture of the triangular girder in space, Method II, resulted in fewer Shuttle flights. The support equipment required for both methods was found to be similar. Both required mechanisms in orbit. The prepackaged beams would require a deployment cannister while the manufacturing module is required in Method II.

Method of Assembly

The major issue to be answered, before cost-effective SSPS assembly can be achieved, involves determining the degree of on-orbit manned participation in the assembly operation. In an effort to bound the problem, the following extremes in basic approach to assembly have been considered:

- remote assembly using teleoperators controlled from the ground
- EVA assembly.

The first requirement in this assessment is to establish an estimate for production rate. The assembly of a common component of the antenna structure using remote controlled operations was analyzed, and it was estimated that the structure could be assembled at a rate of between 3.2 and 5.9 kg/r using teleoperators. A similar assessment of assembly using men in an EVA mode was made. Structural assembly rates using the EVA approach were estimated to be somewhat higher, between 8.1 and 11.4 kg/m-r.

Table 3.7 State-of-Art Astromast Characteristics

VARIABLE	A	B	C	D	E	F
MAST DIAM. (IN.) (M)	13.4 (0.34)	4 (0.1)	6 (0.15)	10 (0.25)	20 (0.51)	8 (0.2)
MAST LENGTH (FT) (M)	40 (12.2)	15 (4.51)	8 (2.4)	100 (30.5)	84 (25.5)	10 (3.05)
APPROX. WEIGHT						
MAST (LB) (KG)	46 (21)	0.30 (0.14)	2.0 (0.91)	20 (9.1)	214 (97)	1.3 (0.59)
CANISTER (LB) (KG)	128 (58.2)		20 (9.1)	30 (13.5)	186 (84.5)	
PACKAGE DENSITY (LB/FT^3) (KG/M^3)	3.7 (59.4)	6.1 (97.5)	4.5 (72)	8.7 (139)	15.7 (252)	9.9 (158)
BENDING STIFFNESS (LB-IN.^{2} x 10^{-6} (KG/M^2)	77 (262)	0.12 (0.4)	0.70 (2.37)	5.5 (18.7)	280 (955)	2.02 (6.95)
BENDING STRENGTH (IN-LB) (N-M)	7,800 (881.4)	25 (2.83)	80 (1.0)	460 (52)	36,000 (4,068)	200 (22.6)

Table 3.8 Structural Fabrication Option Comparison

	METHOD I	METHOD II
• OPERATION		
– ON-GROUND	ASSEMBLE ARTICULATED BEAMS	PRE-PROCESS FLAT STOCK
– IN-ORBIT	DEPLOY	AUTO MANUFACTURE
• PACKAGING DENSITY	1 TO 5 LB/FT^3 (16 TO 80 KG/M^3)	> 6 LB/FT^3 (96 KG/M^3)
• NUMBER SHUTTLE FLIGHTS TO DELIVER STRUCTURE	6 TO 12	10
• MAJOR SUPPORT EQUIPMENT IN-ORBIT	• NONE TO 1 SPACE STATION (6 MAN) • DEPLOYMENT DEVICE	• 0 TO 1 SPACE STATION (6-MAN) • 1 FAB MODULE
• FLIGHTS TO DEPLOY EQUIPMENT	0 TO 11(2)	0 TO 12(2)
• FLIGHTS TO SUPPORT EQUIPMENT & MEN(1)	0 TO 1	0 TO 1

NOTES:
1. RECYCLE CREW & CONSUMABLES
2. REQUIRED IF SPACE STATION IS INCLUDED IN SCENARIO

Assessment of the entire SSPS assembly would require significantly more depth of definition of each satellite component to detail assembly flows and operations. Therefore, a parametric analysis was performed on the driver elements in the two basic assembly approaches. The major cost-drivers for remote controlled assembly, shown in Figure 3.32, are assembly rate, teleoperator consumables rate and the number of manned maintenance/monitor facilities required. A remote controlled assembly approach can achieve acceptable costs (2 to 4 mills/kWH) at a production rate of 2 kg/H if consumables usage is kept low.

Figure 3.33 relates the major cost-driver for space-based, man-controlled assembly operations to the contribution that final assembly makes to the unit charge rate. The major drivers are assembly rate, the cost of space stations (assumes 10-year life) and the cost to recycle crews. To achieve reasonable cost levels, production rates in excess of 11 kg/H are required along with low cost space stations ($16 million/man) and transport modes that can recycle large numbers of crew members in one flight.

Figure 3.34 presents a comparison of cost between assembly at low altitude and at geosynchronous altitude for a remote controlled approach. The Shuttle, used as the manned maintenance/monitor facility in low orbit, is replaced by a six-man geosynchronous orbit space station. The appropriate manned tug was added to the geosynchronous assembly site scenario. Assembly at geosynchronous orbit tends to double assembly cost, though at assembly rates greater than 4.5 kg/H acceptable cost can be achieved.

Maintenance

As assessment of the SSPS was performed to determine the need for maintenance and to identify the subsystems requiring major technology efforts to enhance reliability.

SSPS Recurring Costs - Tables 3.9 through 3.11 list the definition of the Lowest Replaceable Unit (LRU) for the solar array, the microwave antenna, the rotary joint and the array control system.

Included are estimates of the failure rates and the corresponding number of LRUs replaced over the power station's 30-year life. The recurring maintenance cost for the array is estimated at $3.99 million/yr while the cost to maintain the antenna is $0.99 million/H. The control system, mainly the ion engines for pointing of the array and antenna rotary joint, requires the most maintenance, $39.10 million/H.

Maintenance Support Costs - The nonrecurring (excluding development costs) and the recurring costs for maintenance support have been analyzed assuming the following scenario:

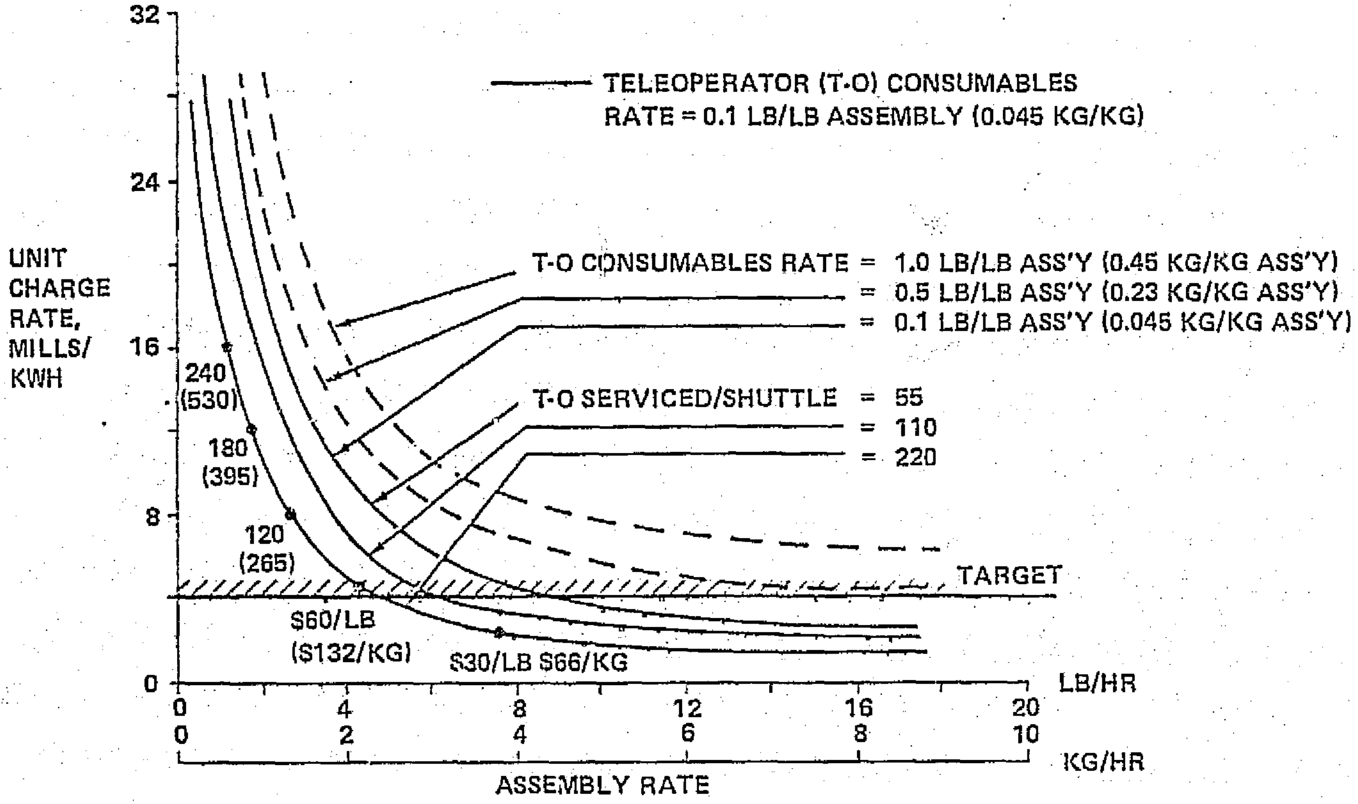


Figure 3.32 Assembly Cost, Remote Control From Ground (Low Altitude Assembly Site)

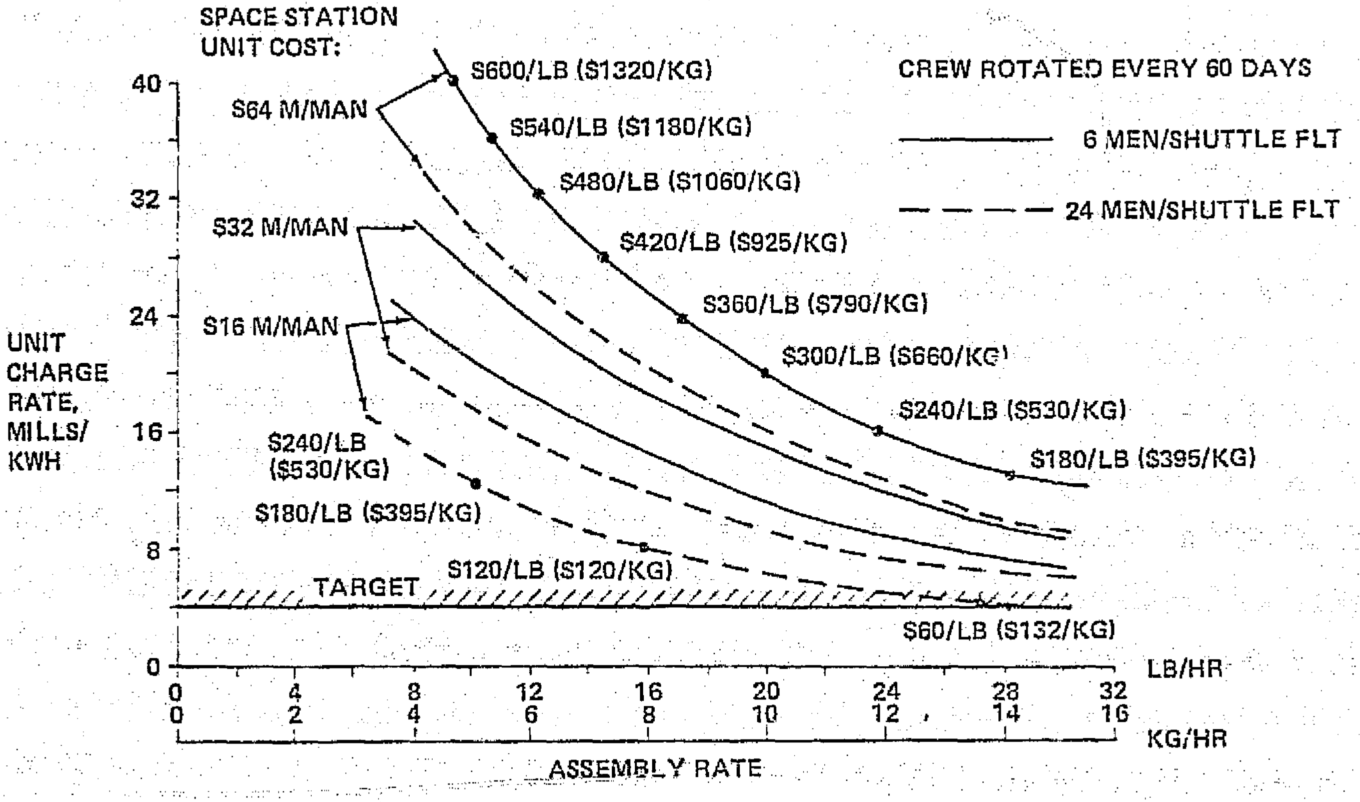


Figure 3.33 Assembly Cost, Manned Operations in Orbit (Low Altitude Assembly Site)

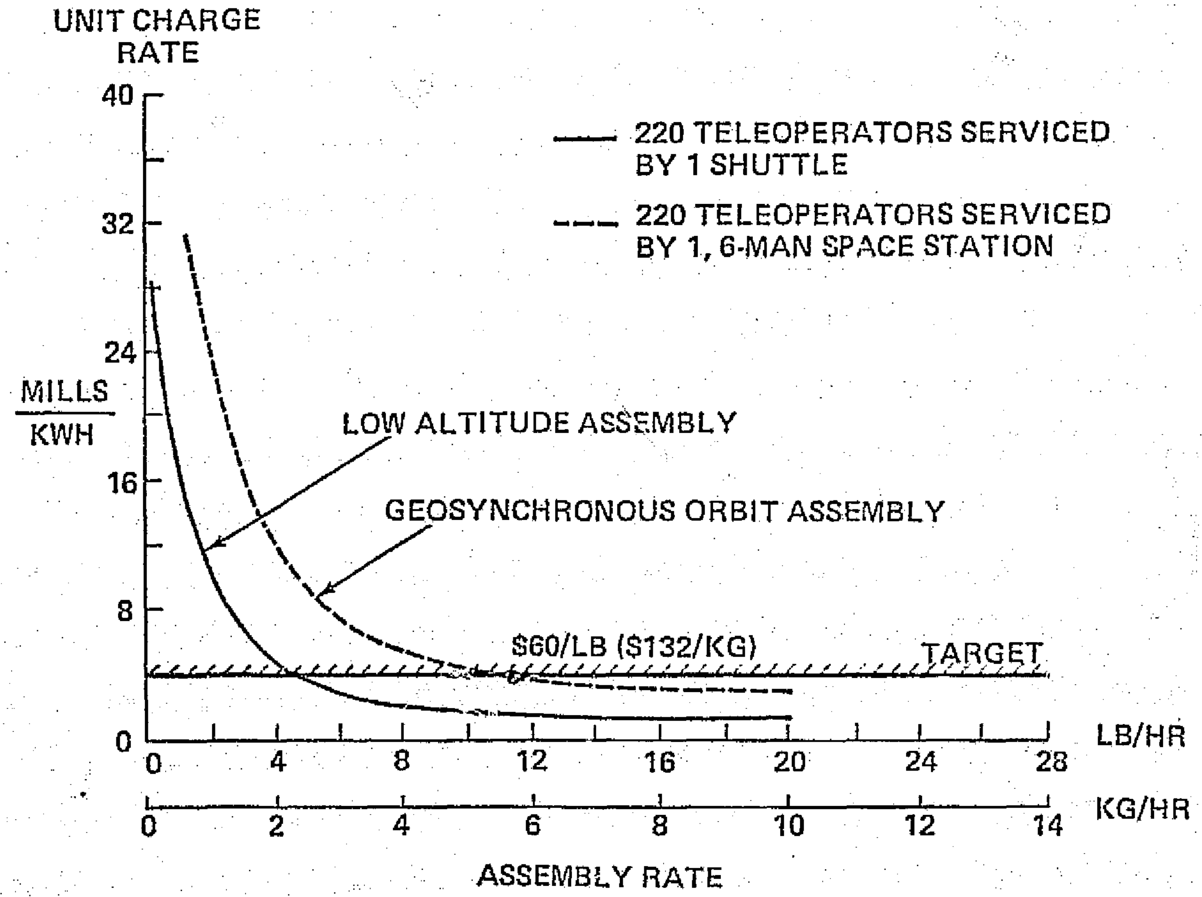


Figure 3.34 Assembly Cost, Remote Controlled Assembly

Table 3.9 Solar Array Maintenance Cost

ELEMENT	LRU DESCRIPTION	LRU WT, Kg	LRU FAILURES OVER 30 YRS	COST OVER 30 YRS, $M	AVG PER YR, $M
1. BLANKET	80-1670 x 207m MODULES	97,484	1	41.90	1.40
2. CONCENTRATOR	160-1670 x 207m MODULES	768	1	0.23	0.01
3. NONCONDUCT STRUCT.	TO DESIGN	—	—	—	—
4. BUSES	400 m	26,000	1	8.29	0.28
5. SWITCHES	59 BLOCKING DIODES/BLANKET LRU	97,484	1	41.90	1.40
6. MAST	6(+), 6(-) BUSES/PANEL	85,000	1	27.12	0.9
			TOTAL MILLS/KWH =		$3.99 M 9.1/YR

ASSUMPTIONS:

1. BLANKET – CELL OPEN CIRCUIT FAILURE = 2.6×10^{-4}/YR. THE PROBABILITY OF 5.6% LRU POWER LOSS OVER 30 YRS IS LESS THAN 10^{-99}. ONE LRU REPLACEMENT ASSUMED OVER 30 YRS.
2. CONCENTRATOR – MIRROR FAILURE LESS LIKELY THAN BLANKET FAILURE. ONE LRU REPLACEMENT ASSUMED OVER 30 YRS.
3. NONCONDUCTING STRUCTURE – ASSUMED NOT TO FAIL.
4. BUSES – BUS/CONNECTOR FAILURE RATE (OAO) = 10^{-9} F/YR. ONE LRU REPLACEMENT ASSUMED OVER 30 YEARS.
5. SWITCHES – BLOCKING DIODE FAILURE RATE (OAO) = 10^{-7} F/YR. ASSUMES ONE BLANKET LRU REPLACED BECAUSE OF DIODE FAILURE.
6. MAST – SAME AS FOR BUSES.

Table 3.10 Microwave Antenna Maintenance Cost

ELEMENT	LRU DESCRIPTION	LRU KG	LRU FAILURES OVER 30 YRS.	COST OVER 30 YRS, SM	AVG PER YR, SM
1 MW TUBE	1670 – 18 x 18 m SUBARRAY	3017	4	5.73	0.19
2 POWER DIST	18 x 18 m SUBARRAY	3017	1	1.43	0.05
3 COMMAND ELECTRONICS	1670 UNITS	467	3%	20.56	0.65
4 TRANS. ANTENNA (EXCLUDE TUBES)	1670 – 18 x 18 m SUBARRAY	3107	1	1.43	0.05
5 STRUCTURE	TO DESIGN	–	–	–	–
6 CONTOUR CONTROL	6680 UNITS	22	1404	0.35	0.01
				TOTALS MILLS/KWH	0.99 0.02/YR

ASSUMPTIONS:

1. MW TUBE – MTBF = 1.14 x 10^{6} HRS PROJECTED (NO MOVING PARTS, NO SEALS & LOW TEMPERATURE CATHODE).
2. POWER DIST – HIGHLY REDUNDANT SYSTEM EXPECTED TO MEET 30-YR LIFE REQ MT. ONE SUBARRAY FAILURE ASSUMED.
3. COMMAND ELECTRONICS – 30-YR LIFE ACHIEVED WITH HIGH LEVEL OF REDUNDANCY 3% FAILURE ASSUMED.
4. TRANS. ANTENNA – WAVEGUIDES CONSIDERED STRUCTURE WITH LOW FAILURE RATE. ONE SUBARRAY FAILURE ASSUMED.
5. STRUCTURE – ASSUMED NOT TO FAIL.
6. CONTOUR CONTROL – FAILURE RATE = 0.8 F/10^{6} (1% DUTY FACTOR) FOR BRUSHLESS DC MOTOR OPERATING AT 500°C.

Table 3.11 Rotary Joint & Array Control System

ELEMENT	LRU DESCRIPTION	LRU KG	LRU FAILURES OVER 30 YRS.	COST OVER 30 YRS, SM	AVG COST YR, SM
ROTARY JOINT					
• SLIPRING	24 BRUSHES, 4 SLIPRINGS				
– BRUSH		10	72	0.24	0.01
– SLIPRING		63	12	0.26	0.01
• DRIVE	8 BRUSHLESS MOTORS/GEAR TRAIN UNITS (4 ACTIVE, 4 STANDBY)				
– MOTOR/GEARS		1,367	24	11.0	0.37
– LIM		1,086			
CONTROL SYSTEM					
• ACTUATORS	64 ELECTRIC ENGINES	203	640	1,010	33
• PROPELLANT	24,000 Kg/YR	–	–	–	5.7
				TOTAL MILLS/KWH	39.09 0.9/YR

ASSUMPTIONS

1. 1. SLIPRING – PREVIOUS SPACE STATION STUDIES INDICATE MTBF = 10 YRS WITHIN REACH.
2. DRIVE – SAME AS SLIPRING.
3. ACTUATORS – CURRENT ESTIMATES PLACE ION ENGINE FAILURE RATE AT 3800 F/10^6 HR. ASSUME ORDER MAGNITUDE IMPROVEMENT AND A 10% DUTY FACTOR. COST ASSUMES $7500/KG. FOR ENGINE & POWER CONDITIONING.

- A six-man space station is required for monitoring the satellite and for use as a repair shop and garage for maintenance teleoperators
- Maintenance is performed using ground-controlled teleoperators
- Space station crews are rotated four times per year, using the Shuttle and a chemical tug
- A HLLV/Ion stage (Payload = 181,600 kg to LEO) is used to initially place the space station and to resupply the station once each year.

Table 3.12 summarizes the cost impact of using the assumed maintenance support scenario.

3.1.2.5 Microwave Transmission

The MPTS for the SSPS has been studied and reported on in detail by Raytheon in NAS CR-134886, under contract NAS3-17835 to Lewis Research Center. In the current study, information was generated on the development program beyond early flight testing and available technical information was summarized in a form useful for the comparisons with ground-based systems. Most of the following information is taken from that report and presented here for ready reference.

The transmitting antenna for a 5 GW SSPS is an active planar phased array of 0.83 km minimum diameter and with a mass of 5.7×10^6 kg when constructed of aluminum and when using amplitrons for dc-to-rf power conversion. Graphite composites are alternate choices for material and klystrons are an alternate choice for convertors. The transmitting antenna consists of 18 m x 18 m slotted waveguide sub-arrays that are electronically controlled to direct the power beam at the ground receiving antenna with an rms error of only 10 m. The sub-arrays use groups of 5 kw amplitrons in series to convert input dc power to microwave power. The receiving and rectifying antenna (rectenna) is an array about 11 km in diameter, consisting of dipole elements each connected to a solid state diode that converts microwave power back to dc power.

An operating frequency of 2.45 GHz in the United States industrial band results in near optimum efficiency, avoids brownouts in rain and should have minimal problems in radio frequency interference and allocation. A 5 GW ground power output keeps the peak microwave power density in the center of the beam on Earth at 17 mW/cm^2 for a 0.83 km transmitting antenna.

High efficiency requirements dictate the band of microwave frequencies that can be considered. The effect of molecular absorption, shown in Figure 3.35, limits frequencies to less than 10 GHz. This limit reduces further if brownouts in light rain (5 mm/hr)

Table 3.12 Maintenance Support Cost

NONRECURRING (EXCLUDES DEVELOPMENT)	
• SPACE BASE	
– HARDWARE	$490 M
– TRANSPORT	8 M
• MANIPULATOR MODULES	
– 50 UNITS	400 M
– TRANSPORT	1 M
• MISSION CONTROL FACILITY	20 M
	$919 M
RECURRING/YR	
• CREW ROTATION (4 FLIGHTS)	
– SHUTTLE FLIGHTS	$ 42 M
– SHUTTLE AMORTIZATION	1.8 M
– TUG FLIGHTS	4.0 M
– TUG AMORTIZATION	0.6 M
– CREW TRANSPORT MODULE	4 M
– CREW TRANSPORT MODULE AMORTIZATION	0.7 M
• RESUPPLY CREW & MANIPULATOR CONSUMER	
– HLLV (1/YR)	9 M
– AMORTIZATION	6 M
– ION STAGE	1 M
– AMORTIZATION	4.6 M
• MISSION CONTROL	
– PERSONNEL (320)	14 M/YR
	$ 87.7 M

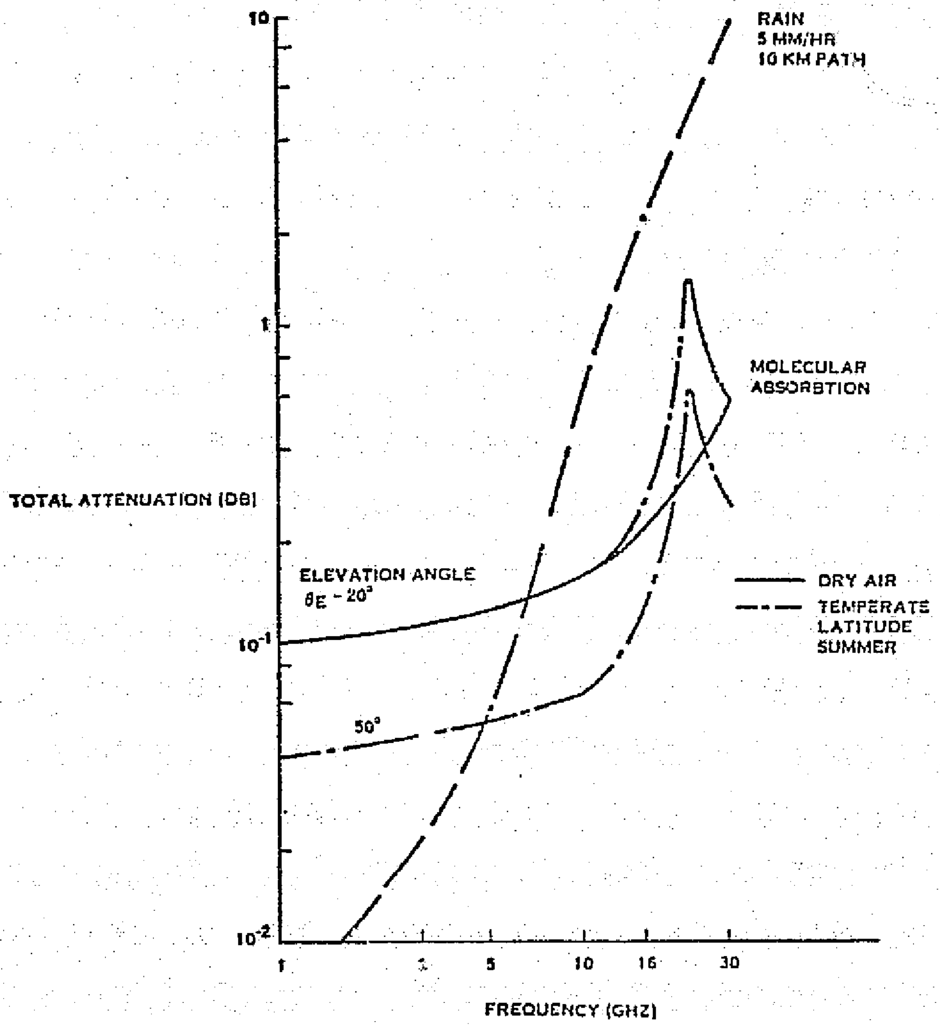


Figure 3.35: Transmission Efficiency - Molecular Absorption and Rain

are to be excluded, and the avoidance of brownouts in heavy rain and severe thunderstorms, for which attenuations are shown in Figure 3.36, would place an upper limit not far above 3 GHz. Severe rain conditions are experienced, even in desert locations that are prime candidates for the ground receiving antenna.

It was concluded that the MPTS should operate at a frequency of 2.45 GHz in the United States industrial band, and recommended that a ground output power level of 5 GW be selected for a nominal design. The reasons for this are that economy of scale is essentially reached at this level and peak ground power density is maintained at a relatively low level. The amplitron-aluminum configuration is selected for cost estimates although a graphite composite material selection remains a candidate, and a klystron is a potential candidate for the dc-rf convertor. These options are shown in Table 3.13.

The maximum power density at the center of the receiving rectenna may be the factor that limits the maximum power generation capacity of the SSPS. Figure 3.37 is a comparison of microwave transmission characteristics for a 5 GW and 10 GW system and two transmitter diameters. The amplitrons on the transmitting antenna are layed out in a stepped approximation to a Gaussian distribution on the antenna surface. The taper ratio between the peak power density at the center and the edge is indicative of the shape of this layout. The 5 db taper is less densely packaged at the center than the 10 db taper design. The resulting maximum power density on the ground indicates that a 5 GW system may be more acceptable than the 10 GW option. A value of 20 mW/cm^2 was estimated to be a threshold above which ionospheric changes could be expected at the 2.45 GHz operating frequency. This factor and the fact that the biological level limit in the United States is 10 mW/cm^2 makes it prudent to anticipate the 5 GW SSPS option.

Efficiency and safety needs dictate that a closed loop form of control be implemented for phase front or beam formation. Two approaches, adaptive and command, have been formulated and are illustrated in Figure 3.38. The command system uses a matrix of sensors at the ground antenna to determine the received power beam center and shape. A processor then develops commands which are routed to the sub-arrays over the telecommunications link. This approach has limited resolution, but nevertheless, it is anticipated that antenna thermal distortions, a major source of error, can be accurately modeled and suitable command algorithms developed. In any event, it will serve as a system monitor and as a safety override function.

A potentially more accurate scheme calls for a reference beam to be transmitted from the center of the ground antenna. This is sensed at each sub-array and at a reference sub-array in the antenna center. The latter transmits the reference to the sub-array over a calibrated coaxial cable at which point it is compared with the incoming beam. A difference in phase between these signals is interpreted as a displacement of the sub-arrays from the nominal

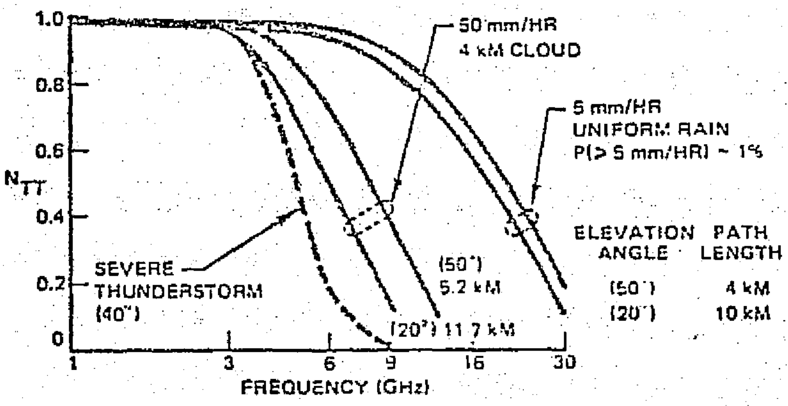


Figure 3.36: Transmission Efficiency - Molecular Absorption and Rain

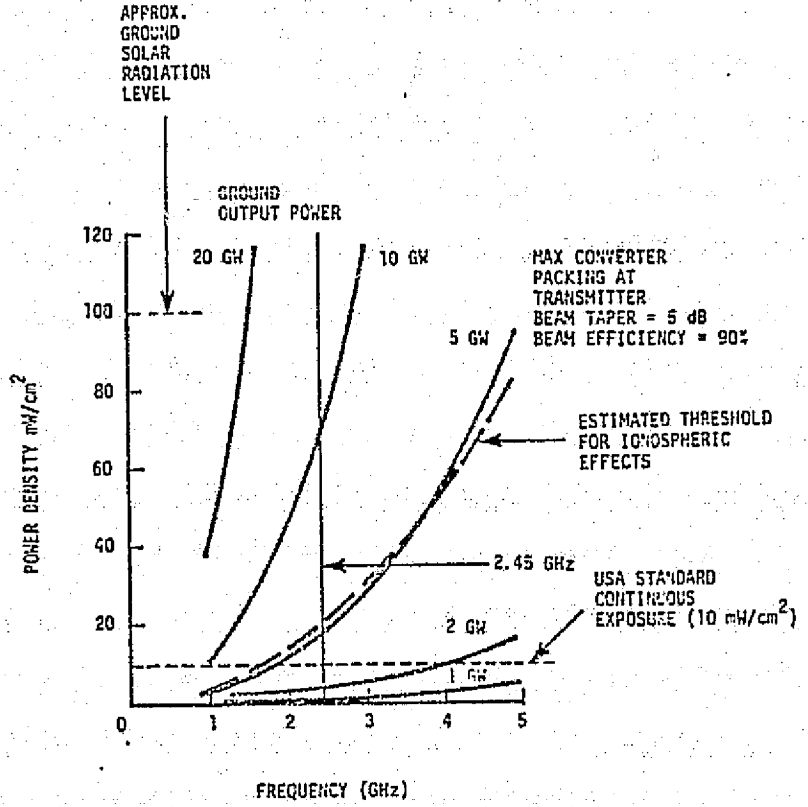


Figure 3.37: Peak Ground Power Density Versus Frequency

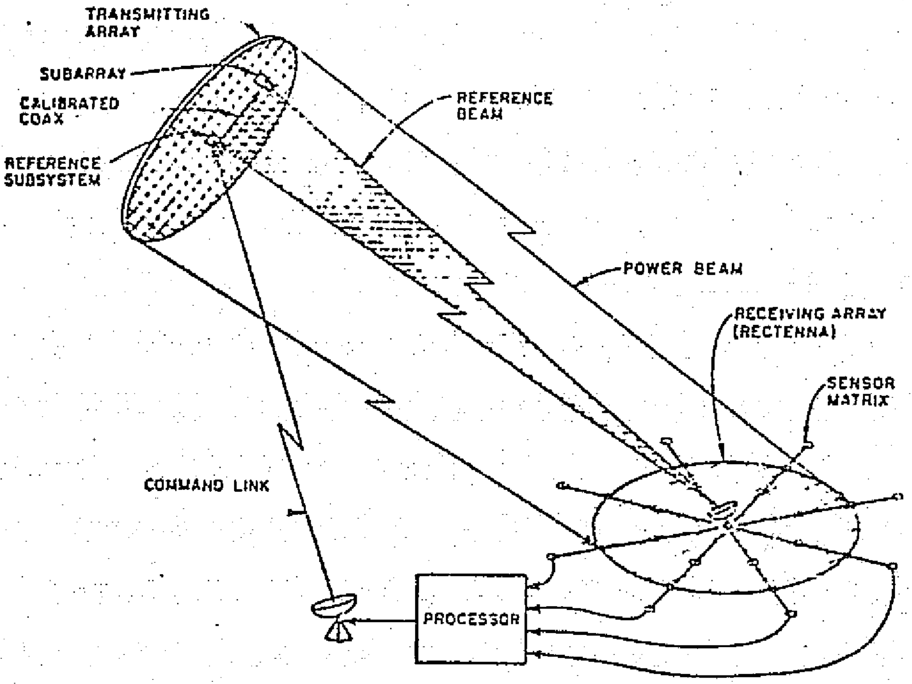


Figure 3.38: Command and Adaptive Phase Front Control Concepts

Table 3.13 Comparison of 5 GW Systems

TAPER = 5 dB
Beam Efficiency = 90%

POWER SOURCE - 1.5 kg/kw
-500$/kg
Transportation Assembly-300$/kg

DC-RF Converter	Structure & Waveguide Material	DC-RF Converter Mass x 10^4 kg	Transmitting Antenna Total Mass x 10^4 kg	MPTS $/kw	SPS $/kw
Amplitron	Aluminum	2.6	6.2	700	2300
	Graphite	2.6	5.0	700	2300
Klystron	Aluminum	7.3	12.5	1100	2800
	Graphite	7.3	10.8	1100	2800

reference plane due, for example, to thermal distortion of the structure. A shift is applied to the phase of that part of the transmitted beam so that the total phase front results in efficient beam launching to point toward and focus on the rectenna.

The rectenna, covering an area of about 100 km^2, is composed of inclined panels which are tilted to normality with the incoming power beam. The accuracy of construction is not critical since the individual rectenna elements have broad dipole gain patterns. For the same reason, the phase front can be distorted by the atmosphere or ionosphere without appreciably affecting efficiency. The ground plane is open metal construction for low cost and low wind resistance. Sealing of the rectenna elements within a protective tube is suggested as a means to achieve economical environment compatibility. Principal concern regarding weather phenomena is the potential damage from large hailstones. This factor must be considered in site selection.

3.1.2.6 Safety of Large Structure

A safety analysis has been performed for the mission phases associated with constructing and servicing the SSPS. Phases range from Earth launch to the final salvage efforts at the termination of expected service life. Potentially hazardous situations were identified in virtually all phases. Of the approximately 30 natural and induced hazards which can conceivably influence project success, eight were examined to a depth commensurate with a preliminary analysis. Of major significance, design of the existing astronaut pressure suit may seriously limit his external activities unless design changes are considered.

The analysis was performed assuming assembly operations are Shuttle-based. Future studies should include assessment of the impact of space station and the HLLV. Further studies are required to resolve questions which evolved during the course of this analysis, as well as those natural and induced hazards which were not examined. Table 3.14 provides an overview of astronaut participation in each of the 15 mission/task phases.

The examination was limited to the following natural and induced hazards: temperature, sunlight/darkness, collision with structural members, electrical shock, rotating machinery, structural failure, pressure suit design and fragmentation of pressure vessels. Meteorite damage, ambient radiation and solar events require in-depth investigation.

3.1.3 Program Planning and Cost

3.1.3.1 Work Breakdown Structure and Program Schedule

A preliminary SSPS Work Breakdown Structure (WBS) and program schedule have been compiled to establish a "strawman" for programmatic analysis. A 3-step development program, Figure 3.39, was utilized.

Table 3.14 Overview of Manned Participation

SPACE-BASED SOLAR POWER

PHASE	FUNCTION	CREW INVOLVEMENT	POTENTIAL SAFETY HAZARDS	SIM. REQ'D	SUPPORT EQUIP. REQ'D	SPECIAL PCDR's REQ'D
LAUNCH	RESTRAIN SUPPORT MONITOR	NONE NONE MONITOR	PACKAGING FAILURES CAUSE COMPONENT DAM'G DOUBLE FAIL: E.G. COMM.LOSS.& SYS. FAILURE			
ORBITAL C/O	P/L DOORS OPEN	INITIATE	JAMMED DOOR			X
	RMS DEPLOY	OPERATE	NONE			
	REMOVE PROTECT. SHELL/DEPLOY	OPERATE	TIGHT SPACE DURING REMOVAL FROM P/L BAY SHROUD - HIGH DAMAGE POTENTIAL			X
P/L ORBITAL RETRIEVAL	INSTALL/RETURN ITEMS	MONITOR/ VERIFY	EVA COLLISION	X		X
	P/L DOORS CLOSED	INITIATE	JAMMED DOOR			X
SEGMENT ASSEMBLY (EARTH MFR'D.)	UNFOLD	INITIATE	CONTACT SHUTTLE/SHROUD			X
	RIGIDIZE	NONE				
	STABILIZE FREE	INITIATE INITIATE	FAILED JET(S), FUEL LOSS, TUMBLING, CONTACT VEHICLE EVA		X	X X
ORBITAL FABRICATION	STOCK LOAD	MONITOR	PACKAGING FAILURE CAUSES EQUIP. DAMAGE/ EVA CONTACT	X	X	X
	FABRICATE	MONITOR	MATERIAL BREAKAGE/EVA CONTACT	X	X	X
	REMOVE ASS'Y	OPERATE	JAMMED MANIPULATOR	X	X	X
	STRUCT. TEST	MONITOR	NONE			X
	STOCK UNLOAD	MONITOR	NONE			X
ASSEMBLY STORAGE	RMS DEPLOY	OPERATE/EVA	COLLISION/HIGH DAMAGE POTENTIAL DUE TO JET(S) FAILURE TO CUT OFF	X X	X	X
	RMS REMOVE	OPERATE/EVA	EVA CONTACT	X		X
STORAGE RETRIEVAL	RMS INSTALL/ FREE/ STABILIZE	OPERATE/EVA	EVA CONTACT HIGH DAMAGE POTENTIAL	X	X	X
			FAILED JET(S), FUEL LOSS AND SYSTEM FAILURE			X
			SUNLIGHT/DARKNESS ERRORS			X
TRANSPORT SEGMENTS	STABILIZE THRUST	NONE	FAILED JET(S), FUEL LOSS			X
		INITIATE	THRUST EARLY/LATE CONTACT OTHER VEHICLE			X X

Table 3.14 Overview of Manned Participation (Cont'd)

SPACE BASED SOLAR POWER

PHASE	FUNCTION	CREW INVOLVEMENT	POTENTIAL SAFETY HAZARDS	SIM. REQD.	SUPPORT EQUIP. REQD.	SPECIAL PCDR's REQD.
ROTARY JOINT ASSEMBLY	ORIENT SECURE	OPERATE/EVA	EVA/STRUCTURE COLLISION - HIGH DAMAGE POTENTIAL	X	X	X
	OPERATE	INITIATE	EVA IRRADIATION EVA TETHER BREAKS	X	X	X
ANTENNA SEGMENT TO SEGMENT ASSEMBLY	STABILIZE	NONE	FAILED JET(S), FUEL LOSS			
	ORIENT	OPERATE/EVA	EVA TETHER BREAKS	X	X	X
	DOCK	OPERATE/EVA	EVA CRUSHED BETWEEN SEGMENTS	X	X	X
	LATCH	AUTO/VERIFY	PREMATURE LATCH & NEED FOR REDOCK SUNLIGHT/DARKNESS EXTREMES	X	X	X
	RIGGING	MONITOR	CABLE OVERLOAD		X	X
ACTIVATE ASSEMBLIES INDIVIDUALLY	CHECKOUT	NONE				
	INITIATE	NONE				
	OPERATE	INITIATE	EVA IRRADIATION	X	X	X
PRE-OPERATION	FINAL ALIGNMENT	MONITOR AUTO/VERIFY	EVA COLLISION COMM. LOSS	X	X	X
	CLEAR EQUIP.	AUTO/VERIFY	EVA COLLISION			
ACTIVATE ANTENNA	CHECKOUT	MONITOR	ELECTRICAL SHORTS			X
	OPERATE	INITITAE	MICROWAVE LEAKAGE			X
SCHEDULED MAINTENANCE CYCLE	R/R ARRAY COMPONENTS	OPERATE/EVA	EVA TETHER BREAKS			X
			ELECTRICAL SHORTS			X
	ORBITAL DECAY CORRECTION		TEMPERATURE, SUNLIGHT/DARKNESS EXTREMES			X
UNSCHEDULED MAINTENANCE	R/R ARRAY COMPONENTS	EVA	STRUCTURAL FAILURE	X	X	X
			MICROWAVE LEAKAGE		X	X
			ELECTRICAL SHORTS			X
	R/R DAMAGED GIRDER(S)	EVA	ELECTRICAL SHORTS			
			SUNLIGHT/DARKNESS EXTREMES			X

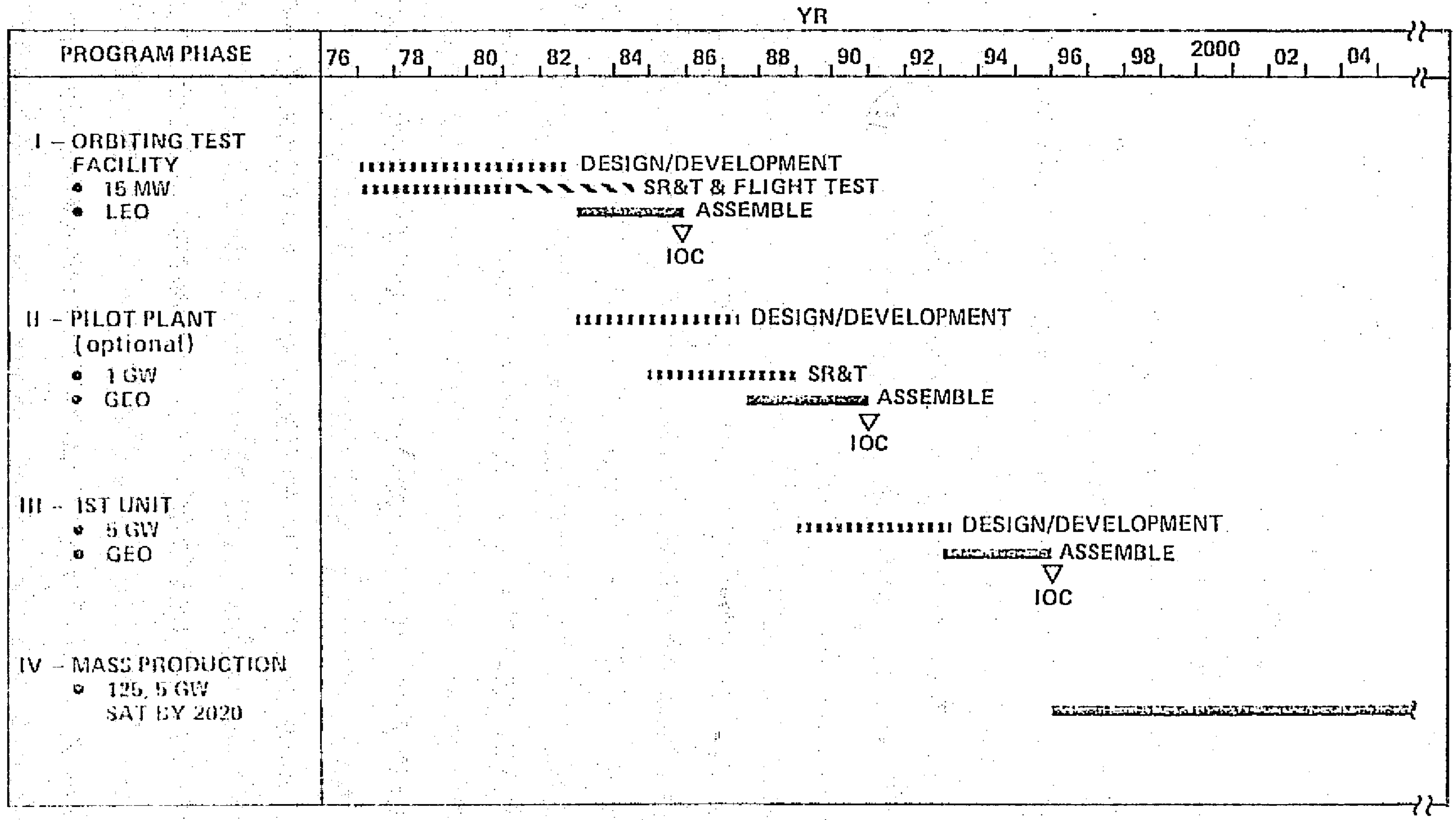


Figure 3.39 Program Schedule Baselined for Preliminary SSPS Cost

A small LEO process development and test facility was planned for deployment in 1985. A geosynchronous-stationed, 1 GW pilot plant option was scheduled with a 1990 IOC and a full capability plant (5 GW) scheduled for 1995. The 1 GW plant decision would be based on its economic merit, i.e., the total development cost with it opposed to without it. This special analysis will be done as part of additional work to be performed by the study team.

Figure 3.40 is the WBS used as the roadmap for cost accounting and program planning. There are 11 Level-2 elements identified:

- project management
- system engineering and integration
- transportation
- assembly
- on-orbit assembly support equipment
- transportation and assembly ground support equipment
- LEO development and test satellite program
- pilot plant [optional]
- operational plant
- system maintenance
- facilities.

Appendix B delineates the definition of each WBS element in the form of a dictionary. Included in Appendix B are the program schedules and cost estimates for each WBS element.

3.1.3.2 Cost Analysis

This section is comprised of two parts. The first provides the nominal costs of an operational 5 GW SSPS. The second part provides the DDT&E programs necessary for the system's development. All costs are based upon the SSPS program plan presented in Section 3.1.3.1 and the cost-element details presented in Appendix B.

3.1.3.2.1 Satellite Solar Power Station

Table 3.15 provides a nominal cost summary of an operational 5 GW SSPS. With an assumed operational life of 30 years the power cost would be 26.7 mills/kWH. This includes 15.0 mills for capital recovery at 7.5 percent rate of return, 3.1 mills for maintenance and 8.6 mills for taxes and insurance.

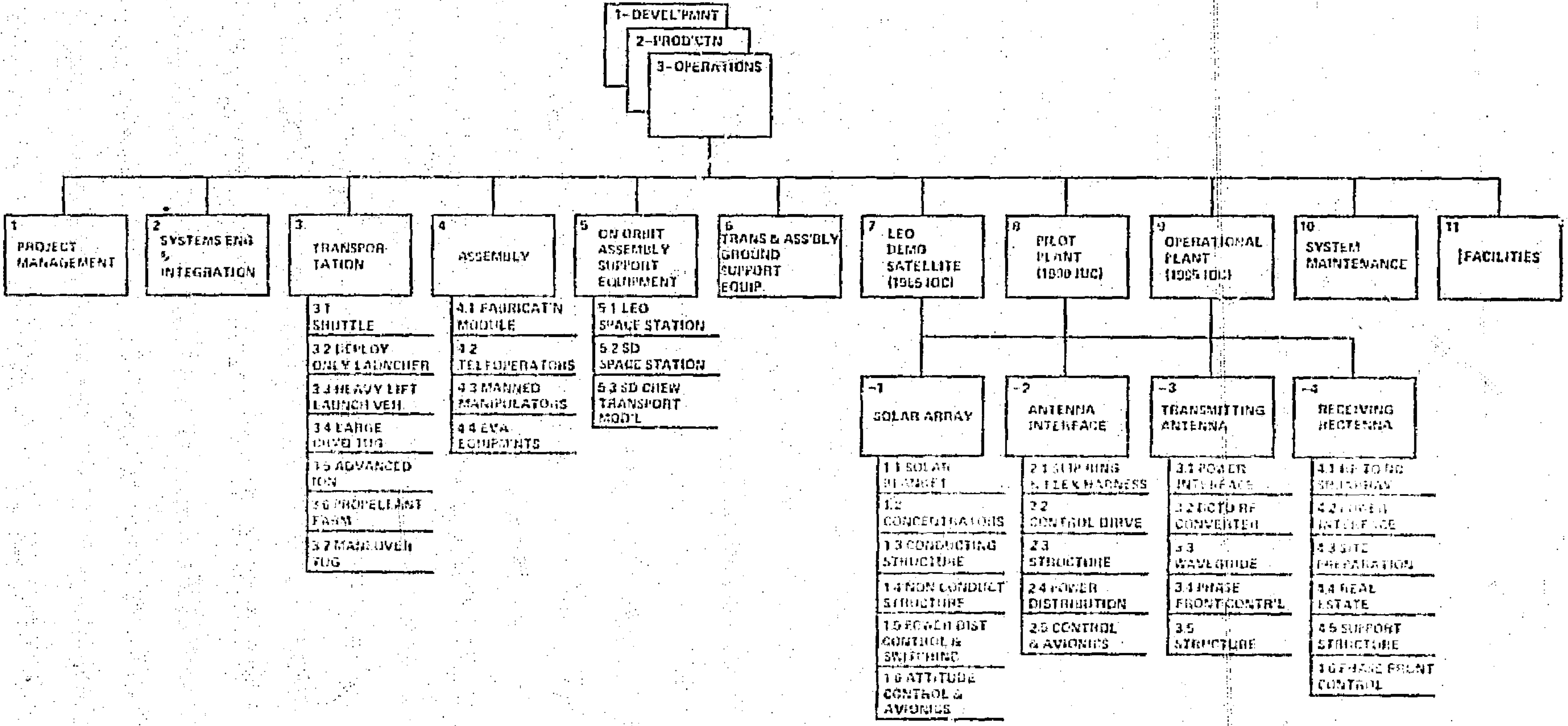


Figure 3.40 Work Breakdown Structure

Table 3.16 contains a summary of the 5 GW SSPS Satellite nominal cost elements. As seen, the satellite's hardware accounts for only about 30 percent of its cost. Transportation is the major cost element (43.2 percent), and the rectenna accounts for 18 percent.

Table 3.17 contains the detailed cost summary of the elements that comprise the capital investment component (satellite and receiving antenna) of the 5 GW SSPS. As noted above, a relatively minor proportion of the total cost is represented by "space hardware" (31 percent), the rest consisting of the equipment required for orbital fabrication and assembly, transportation and the rectenna.

The costs of fabrication and assembly equipment as well as high energy stages (for transport of equipment and personnel from LEO to SEO) have been amortized over five SSPS units. It has been assumed that five SSPS units can be fabricated and assembled over a 10-year period, and the amortization formula repays the original capital with interest (7.5 percent) with equal annual payments. The launch vehicle fleet, space shuttles and HLLV have been costed in a similar manner but in these cases the amortization is based upon use-life of 100 flights and a 2-week turn-around. Assuming that the launch vehicle fleet will be dedicated to the SSPS program, there exists a "cushion" of extra flights that would incur only operations costs. The three HLLVs are capable of 156 flights in a 2-year period and the two space shuttles are capable of 104 flights. One hundred twelve HLLV flights and 76 shuttle flights are estimated to be required for each SSPS, or 56 and 38 per year, respectively. With 2-week turn-around the fleets are capable of 78 and 52 flights annually, respectively, allowing 22 and 14 additional flights, respectively. This result allows for sizeable growth in the activity level of launches or reduction in the average launch vehicle load factor (to 75 percent) without significant cost impact.

As given above, the fleet was costed assuming a 100-use life and this resulted in $1.31 billion (2.6 mills/kwh). Were the use-life 150 flights, the charges would be $0.94 billion, were the use-life 200 flights, $0.75 billion, were the use-life 500 flights, $0.43 billion.

3.1.3.2.2 SSPS DDT&E Programs

Tables 3.18 and 3.19 contain cost estimates of the development program required for the fabrication, assembly and deployment of a 5 GW SSPS. Three components have been identified: Direct DDT&E, related DDT&E and support programs.

The direct DDT&E programs pertain to those program elements which would <u>not</u> be developed were it not for the decision to develop the SSPS. These total approximately $19.3 billion, and the costs are distributed over the three phases of the program plan. The heaviest funding requirements occur over the period 1986 through 1990. The development costs in this period could provide for the installation

Table 3.15 Annual ROM Cost of an Operational 5 GW SSPS

Element	Annual Cost $Millions, (1974)	User Charge Mills/kWH (1974)
• Satellite	657	15.0
• Maintenance	136	3.1
• Taxes, Insurance	377	8.6
TOTAL	1156	26.7

Table 3.16 Five GW SSPS Unit Cost Summary, Satellite

Element	Cost $Millions, (1974)	Percent
• Solar Array	1.826	24.0
Solar Blankets	(1.529)	(20.1)
• Transmitting Antenna	0.495	6.5
• Propellants and Misc. Supplies	*	*
• Fabrication and Assembly Equip.	0.573	7.5
• Transportation	3.278	43.2
Space Shuttle Fleet	(0.240)	(3.2)
HLLV Fleet	(1.074)	(14.1)
Space Shuttle Flights	(0.879)	(11.6)
HLLV Flights	(1.013)	(13.3)
Other	(0.072)	(0.9)
• Personnel	0.077	1.0
• Receiving Antenna	1.345	17.7
TOTAL	7.594	100.0

* Cost is negligible, weight has been accounted for in Transportation Charges.

Table 3.17 Five GW Operational SSPS Unit Cost

System Components	Mass $\times 10^6$ kg	Design Variable	Specific Cost (Dollars, 1974)	Unit Cost ($Billions 1974)
Satellite				2.293
• Solar Array	12.3			1.826
• Blankets	(7.83)	27.8 km^2	54/m^2	1.501
• Concentrators	(1.23)	61.1 km^2	1.1/m^2	.067
• Structure	2.23	2.23×10^6 kg	81/kg	.180
• Mast	0.64	0.64×10^6 kg	81/kg	.050
• Buses, Switches	(0.27)			
• Transmitting antenna	5.72	5×10^6 kw[1,2]	99/kw	.495
• Power Distribution	(0.54)		(18/kw)	.090
• Phase Front Control	(0.13)		(26/kw)	.130
• Waveguide	(2.31)		(14/xw)	.070
• DC-RF Convertors	(2.33)		(26/kw)	.130
• Structure	(0.41)		(15/kw)	.075
Supplies	2.53			
• Cryo Propellants	(.981)			NEG
• Ion Propellants	(.772)			NEG
• S/S Resupply	(.772)			NEG
Equipment				.573
• 12 LEO Space Stations[3]	(.920)			.217
• 1 SEO Space Station	(.076)			.062
• Assembly Equipment[3]				
- Manned Manipulators	(.023)			.038
- Teleoperators	(.039)			
- EVA Equipment	(.018)			.089
• Fabrication Module[3]	(.016)			.015
• Crew Module[3]	(.012)			.007
• Orbit Maintenance, Module[3]	(.002)			.005
Transportation				3.278
• Launch Vehicle Fleet[4]				1.314
• Space Shuttles		2 for 2 years	$\$60 \times 10^6$/yr	.240
• HLLV's		3 for 2 years	$\$179 \times 10^6$/yr	1.074
• Large CRYO Tug[3]				.009
• Support Tugs[3]				.008
• Advanced ION Stage[3]				.055
• HLLV Flights			$\$9 \times 10^6$/flt	1.013
• Satellite		99		.891
• Supplies		13		.117
• Equipment[3]		17		.005
• Shuttle Flights			$\$12 \times 10^6$/flt	0.879
• Crew Rotation		72		.864
• Teleoperator Equipment		3		.011
• Crew Module		1		.004
Personnel		1711 Man Yrs	$\$45 \times 10^3$/yr	.077
Receiving Antenna		5×10^6 kw[1,2]		1.345
• Real Estate				.095
• Site Preparation				.040
• Support Structure				.570
• RF-DC Sub-arrays				.380
• Power Interface				.235
• Phase Front Control				.025
TOTAL SSPS Mass/Cost	18.06			7.566 (5)

[1] Net power output at the busbar.

[2] Efficiency losses have been accounted for.

[3] Amortized over five SSPS units.

[4] 100 flight use-life was assumed.

[5] Equivalent to $1513/kw or 15.04 mills/kwh.

[6] Satellite mass.

Table 3.18 SSPS Direct and Related Development Programs, $Millions (1974)

Development Item	EXPENDITURE PERIOD 1981-1985	1986-1990	1991-1995	Total
DIRECT				
• Solar Array	1108	2453	3104	6665
• Rotary Joint	383	446	149	978
• Transmitting Antenna	616	464	260	1340
• Receiving Antenna	75	1610	403	2088
• 15 MW Demo Sat	427			427
Subtotal	2609	4973	3916	11071
• Management, S&I (@ 40%)	1044	1989	1566	4566
Subtotal	3653	6962	5482	15981
• 20% Uncertainty Factor	731	1392	1096	3196
Subtotal Direct	4384	8354	6579	19319
RELATED				
• Assembly Equipment	410			
• Logistics Equipment	44			
• Maintenance Equipment		44		
• Fabrication Module	271			
Subtotal	725	44		769
• Management, S&I (@ 40%)	290	18		308
Subtotal	1015	62		1077
• 20% Uncertainty Factor	203	12		215
Subtotal Related	1218	74		1292
TOTAL	5602 (3394)	8428 (3557)	6579 (1931)	20609 (8882)

NOTE: ( ) Indicates 1975 present value, r = 7.5%.

Table 3.19 Support Programs, $Millions (1974)

Technology Development	IOC Year		TOTAL
	1986	1992	
• LEO Transport			
- Shuttle Derivative	380		380
- Heavy Lift Launch Vehicle		6540	6540
• SO Transport			
- Large Cryo Tug	166		166
- Advanced Ion Stage		3847	3847
- Propellant Depot	223		223
- Tug for Depot	215		215
• SO Crew Training Module	190		190
• LEO Space Station	2225		2225
• SO Space Station	224		224
Subtotal	3623	10387	14010
• Management, S&I (@ 40%)	1449	4155	5604
Subtotal	5072	14542	19614
• 20% Uncertainty	1014	2908	3993
TOTAL	6086 (2570)	17450 (5130)	23536 (7701)

NOTE: ( ) Indicates 1975 present value, r =7.5%.

of a 1 GW pilot plant in synchronous orbit. The purpose of this plant would be to provide a final decision point on the technical and economic feasibility of an operational plant. The unit cost of this pilot plant might be approximately $16 billion, allowing for management and uncertainty as provided in Tables 3.18 and 3.19. A major component of the pilot plant's cost would be transportation. This is because the HLLV and ion orbit-transfer stages are not expected to be developed until 1990. The plant would not be strictly a development item since it is expected that some of the unit cost could be offset by revenues from the sale of power. The decision to install the 1 GW plant should be based upon its economic merit. This is a task that will be performed in continued efforts of the study team.

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Of smaller magnitude are the development costs referred to as, "related DDT&E." These are developments that are necessary for the realization of an SSPS but <u>might</u> be required by other space programs as well. It is not unreasonable to anticipate that other programs will require the development of assembly, logistics and maintenance equipment. These developments require relatively small funding amounting to approximately $1.1 billion through the first operational SSPS unit. In total, the direct and related costs are equal to $20.5 billion.

The DDT&E designated "support programs" are required for the launch, assembly and orbital transfer of the SSPS. Unlike the other technology developments, these are likely to be required--in part or entirety--by other space programs. If the only "customer" for these systems were the SSPS, then the latter should bear the full burden of repaying their development but one would not expect this to be the case.

It is more likely that other space programs will require these systems but that the SSPS will have specific requirements of a technical or programmatic nature. In this case, the SSPS should bear the economic burden caused by its specific requirements.

3.2 Terrestrial Power Generation System

Studies of the economic feasibility of the SSPS concept must be made in comparison with terrestrial power generation systems currently in use or likely to be in use before the year 2000. This section provides, first, a description of the nine systems used for this comparison and second, a summary of their cost and operation characteristics.

3.2.1 System Descriptions

Oil-fired, coal-fired and light water reactor power generation systems produce most of the electrical energy currently consumed. The characteristics of these systems are well known, with the only major revisions anticipated being the addition of pollution control equipment. For the purposes of this study these systems have been classified "existing systems."

In addition, six systems (for which experimental or prototype data exist in the literature) have been included representing power generation approaches which might be employed during the next 25 years and these have been classified "future systems." They include fluidized-bed coal consumption, coal gasification and liquefaction, the breeder reactor and the gas-cooled reactor.

Other potentially competitive systems would include the several approaches to fusion; however, they are not yet feasible and their economic factors are not understood. The void associated with difficulties in their development, and with material, as well as social limitations associated with those listed above, is the market in which the space-based systems must compete.

3.2.1.1 Existing Systems

Coal-Fired Power Generation

While coal is the most abundant fossil fuel in the United States, it is difficult to transport and causes considerable waste disposal and pollution control problems. In fact, the waste disposal problem is increased with increasing pollution control: in addition to a somewhat larger volume of fly ash, the lime slurry used to remove sulfur emissions from the flue gas must also be disposed of, posing a significant pollution problem.

Although environmentally unregulated coal-fired plants are not likely to exist after 1985, the characteristics for both regulated and unregulated plants have been summarized in the Section 3.2.2.

Oil-Fired Power Generation

The uncertain future cost of and availability of low-sulfur oil makes it unlikely that oil-fired generation will be as common in the time frame 1985-2000 as it is now. For completeness, it was necessary to consider the costs of oil-fired generation in this study. The environmentally unregulated plant uses and discharges heated water directly into the water source. The environmentally regulated plant uses a dry cooling tower to remove the waste heat, and therefore avoids thermal pollution.

Light Water Reactor

In this study, the term Light-Water Reactor (LWR) refers to both the boiling water reactor (BWR) and the pressurized water reactor (PWR) systems. The cost and the efficiencies associated with these two systems are very similar and have been combined in Section 3.2.2. The only difference between the environmentally regulated and unregulated units is the inclusion of dry cooling towers.

3.2.1.2 Future Systems

The pollution problems and costs associated with using coal to directly fire a steam generator have led to the development of several entirely different approaches and processes for using coal either directly (fluidized-bed combustion) or after a significant amount of processing. Extensive processing is required for coal gasification or liquefaction; a detailed consideration of the costs and inefficiencies associated with processing plants was conducted for the following processes: two liquefaction processes (Consol Synthetic Fuel and Solvent Refined Coal); six high-BTU coal gasification (Lurgi, Hygas-Electrothermal, Hygas-Steam-Oxygen, Bigas, Synthane and CO_2 Acceptor); and two low-BTU processes (BOM Pressurized and Lurgi). Conservative cost estimates were drawn from these data for use in Section 3.2.2.

Also, the efficiencies and amount of solid wastes associated with each process will vary with the type of coal. The values presented are those for a national average type of coal with average characteristics.

Two other nuclear reactor systems are considered as representative of the developing nuclear technology: the Liquid Metal-Fast Breeder Reactor (LMFBR) and the High temperature Gas Cooled Reactor (HTGR).

Fluidized-Bed Combustion

In fluidized-bed combustion, sulfur and pollutants are removed during the combustion process by burning coal in the presence of a sulfur acceptor such as limestone.

Both atmospheric and pressurized fluidized-bed combustion power plants are being developed. The atmospheric systems would be used primarily for intermediate-load plants and for retrofitting existing coal-fired generators. The pressurized fluidized-bed boiler system could be used very effectively to meet baseload requirements.

The amount of solid wastes associated with this type of plant is significantly less than the solid wastes associated with the environmentally controlled coal unit. This is because of the use of a regenerative sulfur-control system.

Low-BTU Coal Gasification

The low-BTU coal gasification/power generation system involves a two-stage process in which coal is converted to a low-BTU ($\approx$ 200 BTU/scf) gas close to the mine and then shipped via pipeline to the power plant where it can be used to power a highly efficient ($\approx$ 40 percent), combined cycle generator (waste heat from the gas turbine is used as the heat source for a steam cycle).

No costs or efficiencies have been estimated for transporting the gas via pipeline because of the uncertainty about the required transmission distance.

High-BTU Coal Gasification

The high-BTU coal gasification/power generation system is a two-stage process in which coal is converted to a high-BTU (≈ 900 BTU/scf) gas close to the coal mine and then shipped via pipeline to a combined cycle power plant.

Coal Liquefaction

The coal liquefaction/power generation system is a two-stage process in which coal is converted to a liquid close to the coal mine and then shipped by pipeline to the power plant type normally fueled by oil. No costs or efficiencies have been estimated for transporting the liquid because of uncertainty in the transmission distance.

Liquid Metal Fast Breeder Reactor (LMFBR)

The basic difference between the LMFBR and the LWR is that the LMFBR can potentially generate all its fuel requirements from U-238 and eventually require no U-235. A greater amount of the energy potentially available in the U-235 in the original breeder fuel can be used because much more of the U-238 is converted to plutonium, itself a fuel. However, the environmental concerns surrounding the use of and the possible effects of a nuclear accident have raised some serious questions about the future of the LMFBR program.

High-Temperature Gas-Cooled Reactor (HTGR)

The HTGR is a helium-cooled advanced reactor which operates on the uranium-thorium fuel cycle. Highly enriched uranium (93.5 percent U-235) is used in combination with Thorium 232 in a graphite matrix core. Uranium 233 is formed when the Thorium 232 captures a neutron. The thorium and the U-233 can be easily separated by chemical means, and the U-233 can be used to fabricate new fuel elements. Much less plutonium is formed.

3.2.2 Costs of Terrestrial Systems

The operating characteristics and capital cost estimates summarized in Table 3.20 have been derived from the literature on each of the generation systems used here for comparison. They are "representative" numbers for each type of system, acknowledging that significant cost variations occur from one site to another.

The components of the total "cost at the busbar" include the costs of: capital; operation and maintenance; fuel; and taxes, insurance and depreciation (an annual charge of 5 percent of the capital

Table 3.20 Cost Estimates for Terrestrial Power Generation Plants
(1974$; Discount Rate = 7.5%)

Plant Type	Direct Coal-Fired	Direct Oil-Fired	Fluidized-Bed Coal-Fired	Low-BTU Coal-Gas Fired	High-BTU Coal-Gas Fired	Liquefied-Coal Fired	Light Water Reactor	High-Temperature Gas-Cooled Reactor	Liquid Metal Fast Breeder Reactor
Mature Plant Availability Factor	.75	.75	.75	.8	.8	.75	.8	.75	.75
Lead Time(1)									
Preconstruction	2.5	2.5	2.5	-	-	-	5	5	5
Construction	4	3.5	3	4(5)	4(5)	4(5)	6	4	6
Heat Rate(2)									
Environmentally Unregulated	8,960	8,962	-	-	-	-	10,200	-	-
Environmentally Regulated	9,558	9,053	9,614	11,590 (BOM Pres)	15,050 (Synthane)	13,790 (average)	10,300	8,740	8,650
Solid Waste(3)									
Environmentally Unregulated (lbs./kWH)	0.091	-	-	-	-	-	1.94	-	-
Environmentally Regulated (lbs./kWH)	0.279	-	.105	.120	.157	.116	1.94	1.09	-
Capital Cost (1974$/kW)									
Environmentally Unregulated	274	240	-	-	-	-	342	-	-
Environmentally Regulated	330	253	258	236	340	445 (average)	363(6)	380	477
Cost of Capital(4) (1974 mills/kWH)	4.8	3.6	3.6	3.2	4.6	6.6	5.3	5.5	7.4
O and M Cost(4) (1974 mills/kWH)	2.1	0.7	1.3	2.4	2.3	3.6	1.2	1.3	1.9
Fuel Cost(4)	6.3	14.5	6.1	7.6	10.4	9.0	2.9	5.0	-
Taxes and Insurance (1974 mills/kWH)	2.5	1.9	2.1	1.7	2.4	3.5	2.6	2.9	3.6
BUSBAR Cost (1974 mills/kWH)	15.7	20.7	13.1	14.9	19.7	22.7	12.0	14.7	12.9

(1) Capital Expenditures assumed to occur in uniform increments during construction phase (See Economic Methodology).

(2) Cost of operating pollution control equipment reflected in heat rate, not O and M cost.

(3) Cost of solid waste disposal not included in total BUSBAR cost.

(4) For environmentally regulated plants only (See Appendix A, Section A.2)

(5) Data not available; conservative assumption made for purposes of economic analysis.

(6) The method of analysis used by utility companies (6% inflation, 10% discount rates) yields an equivalent cost of $951/kW for this plant in 1985 dollars (See Appendix A).

investment). The fuel and O&M costs are taken from the literature; the method for determining the cost of capital as a user charge is described in Appendix A (to wit, determining the equivalent annuity over the 30-year plant lifetime at a 7.5 percent discount rate to repay the capital expenditures made in equal increments during the construction phase). All cost estimates are expressed in 1974 dollars.

3.3 Economic Analysis of SSPS and Development Programs

3.3.1 Comparative Economic Analysis

The purpose of this section is to economically compare the current estimate for an operational 5 GW SSPS with terrestrial systems generating an equivalent output. This comparison is performed to determine the potential economic viability of the SSPS concept. Based upon this analysis, recommendations may be made regarding the decision to enter into an SSPS development program. (cf. Section 1.1.4.)

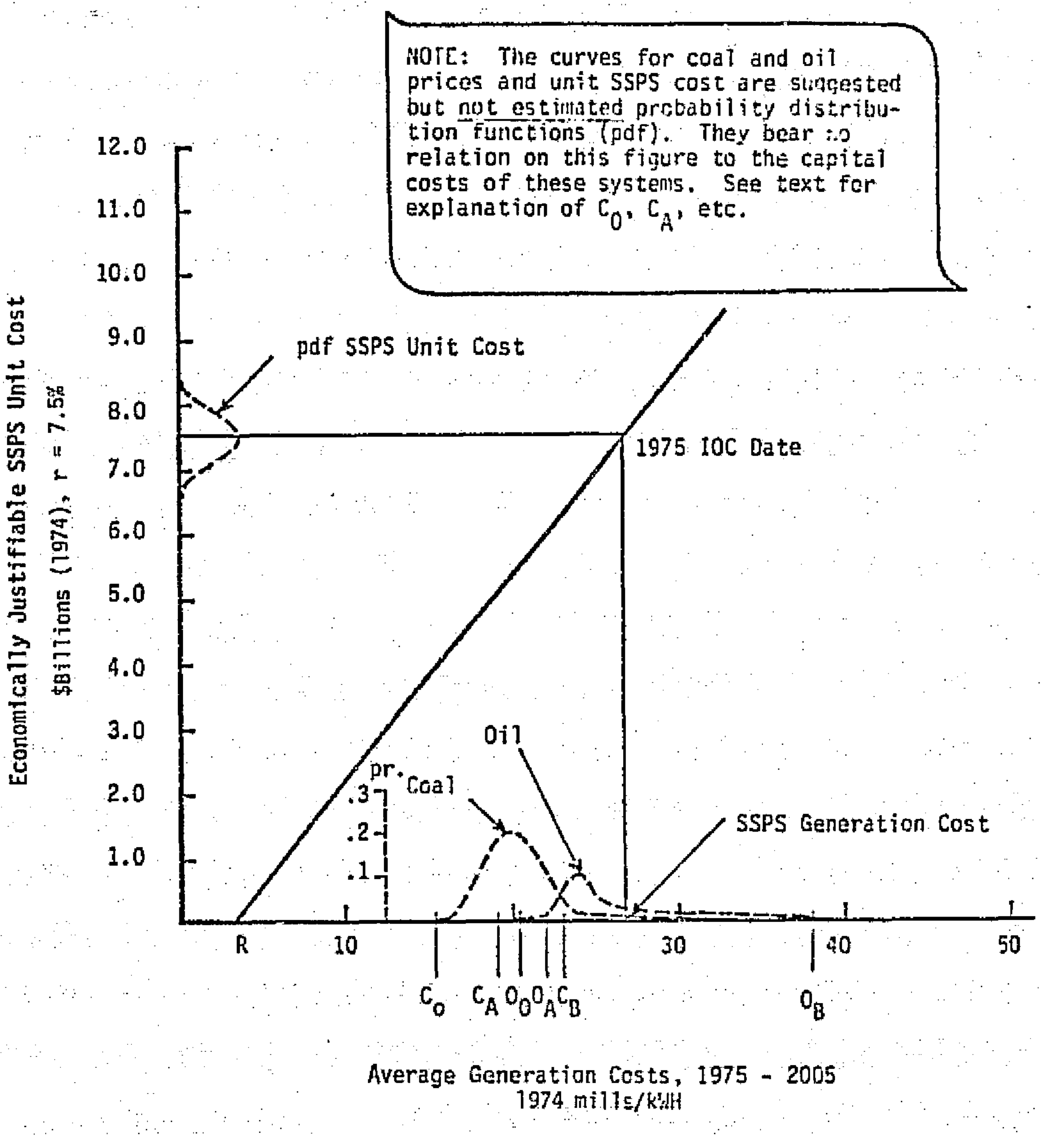
For purposes of decision-making the following decision algorithm was formulated:

- If the SSPS could be shown to be cost effective, compared with existing systems at today's relative prices (while meeting environmental and social constraints), then there should be little hesitation to go ahead with a positive development-to-operation decision.
- If no future conditions could be identified under which the orbital system would be cost effective, then the decision to curtail further development is warranted.
- If the SSPS is not cost effective at today's relative prices but may be cost effective under realistic future conditions, then the decision should be made to proceed with a limited technology program designed to acquire the knowledge for making a later decision.

The analysis compares the 5 GW SSPS with existing terrestrial fossil fuel systems, i.e., oil- and coal-fired generation plants. Of the terrestrial systems, the most realistic alternative is believed to be the "coal option," for which supply is known to exist in large quantity.

Figure 3.41 provides a framework for an ecomonic comparison of a 5 GW SSPS with terrestrial electric generation systems, were the SSPS installed in 1975.

This is the first economic comparison to be made, and it asks the question: How do the power generation systems compare now, based on projections of 1974 constant dollar prices over 30 years?



NOTE: The curves for coal and oil prices and unit SSPS cost are suggested but not estimated probability distribution functions (pdf). They bear no relation on this figure to the capital costs of these systems. See text for explanation of C_0, C_A, etc.

Figure 3.41 Comparative Economic Analysis of a 5 GW SSPS Operating Over the Period, 1975-2005

The x-axis shows average values for the cost of electric generation over the 30-year period, 1975-2005 in 1974 mills/kwh. The y-axis contains the "Economically Justifiable" 5GW SSPS unit cost, evaluated at a 7.5 percent discount rate. The methodology by which this has been estimated is documented in Appendix A.

The line, R, in Figure 3.41 relates the generation-cost values on the x-axis to justifiable unit cost on the y-axis using the approach described in Appendix A. The estimated average electric generation cost in mills/kWH of two terrestrial systems, coal- and oil-fired, over the period 1975-2005 is indicated on the x-axis. The curves that are associated with each of the systems are suggested probability distribution functions (pdf). These express the likelihood that the cost values for each of the fossil fuel systems are attained.

These values are based on three projections of the future:

1. Relative fuel prices remain constant over the 30-year period beginning in 1975, (C_O, O_O)
2. The relative price of coal increases by 2.6 percent per year over the 30-year period and the relative price of oil increased by 0.67 percent (C_A, O_A)
3. The relative prices of coal and oil increase 5.0 percent per year (C_B, O_B).

As indicated by the assigned probability values, the first projection, constant relative prices, is viewed to be most <u>unlikely</u>. Regarding coal, the cost of production will rise as it becomes necessary to mine deeper veins and provide the expected environmental and human safeguards. Regarding oil, increased scarcity will no doubt raise <u>relative</u> prices.

The second projection has been taken from the work of E.A. Hudson and D.W. Jorgenson, which is regarded with esteem in the energy economic literature.[1] These estimates were derived from their analysis of a scenario in which the government <u>does not intervene</u> with respect to energy prices.

The third projection has been derived from the Hudson-Jorgenson scenario in which the U.S. government levies a "BTU" tax of $.05/million BTU over the period 1975-1980, and $1.35/million BTU

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[1] Hudson, E.A. and D.W. Jorgenson, "U.S. Energy Policy and Economic Growth, 1975-2000," The Bell Journal of Economics and Management Science (Vol. 5, No. 2) Autumn 1974.

over the period 1980-1985.[2] The goal of this action is United States energy independence by the year 1985.

Figure 3.42 illustrates the history of the relative price changes in (1) all fuels and related products and power, (2) coal, and (3) crude petroleum with respect to the wholesale price index (WPI). As shown, from World War II to 1973, these indices--with the exception of coal after 1969--maintained constant relative prices. Coal prices rose sharply due to increased costs necessitated by new environmental standards. After zero relative price change they jumped sharply upward, no doubt in response to the precipitous rise in oil prices. The future trend of relative fuel prices is <u>not</u> expected to follow the experience of 1973-1975. Rather it is expected that they will fall within the range covered by the above three cases, i.e., 0-5 percent per year, with the exception that the higher end of the range is more likely.

Figure 3.41 compares the SSPS with the terrestrial systems if the SSPS were to be operational in 1975. The average generation prices over the operational life (30 years) of the coal- and oil-fired plants are given as a function of the growth rate in fuel prices. If relative prices of coal were to remain constant throughout the period, the average generation price would be 15.7 mills/kWH. This is represented by the point C_0 on the x-axis. The case of 2.6 percent per year increase in coal prices (resulting in an average of 18.8 mills/kWH) is indicated by C_A; and the 5 percent per annum increase in fuel prices (an average of 23.4 mills/kWH) is indicated by C_B. As indicated by the suggested-but-not-estimated probability distributions in Figure 3.41 the "no-growth in relative prices" case is expected to be unlikely; and the expectation is that the government will undertake a <u>rational energy policy</u>. Whether this takes the exact form of a "BTU tax," is not known. In any event the impact of a rational policy will serve to raise the relative prices of fuels.

The corresponding values for oil are indicated by O_0 (20.7 mills/kWH), O_A (22.2 mills/kWH) and O_B (38.3 mills/kWH).

As illustrated in Figure 3.41, were a 5 GW SSPS to be installed today, it would not be competitive with fossil fuel plants, especially the coal-fired systems. There exists some expectation, however, that were an "Energy Independence" policy pursued by federal government, oil prices might rise such that SSPS would break even with oil-fired systems.

The above analysis was repeated for the installation of a 5 GW SSPS in 1995, the nominal IOC used for this study. This is presented in Figure 3.43.

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[2] It is to be stressed that the 5 percent value is not that of Hudson and Jorgenson. It is an approximation of the constant dollar impact of their analyzed policy.

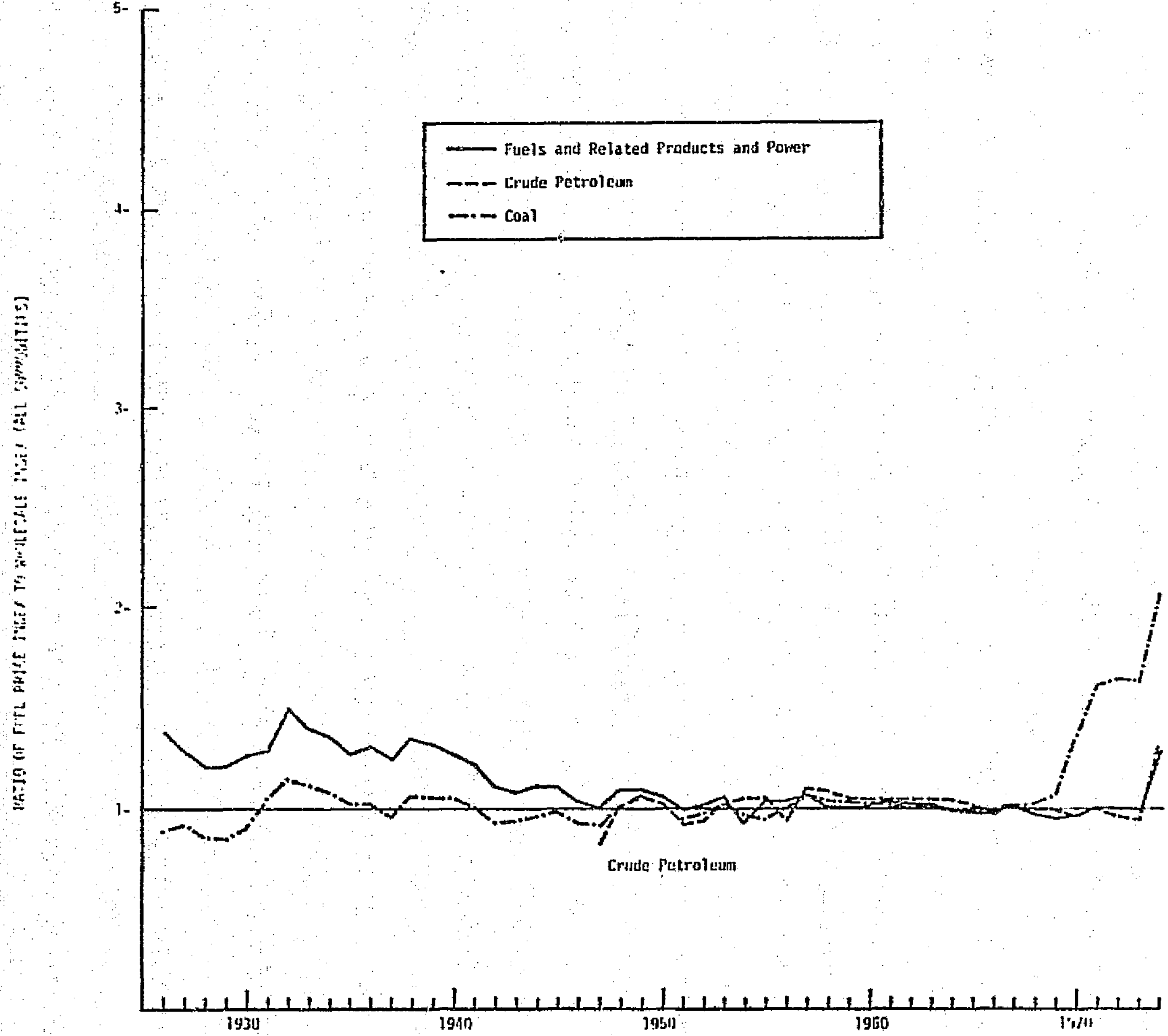
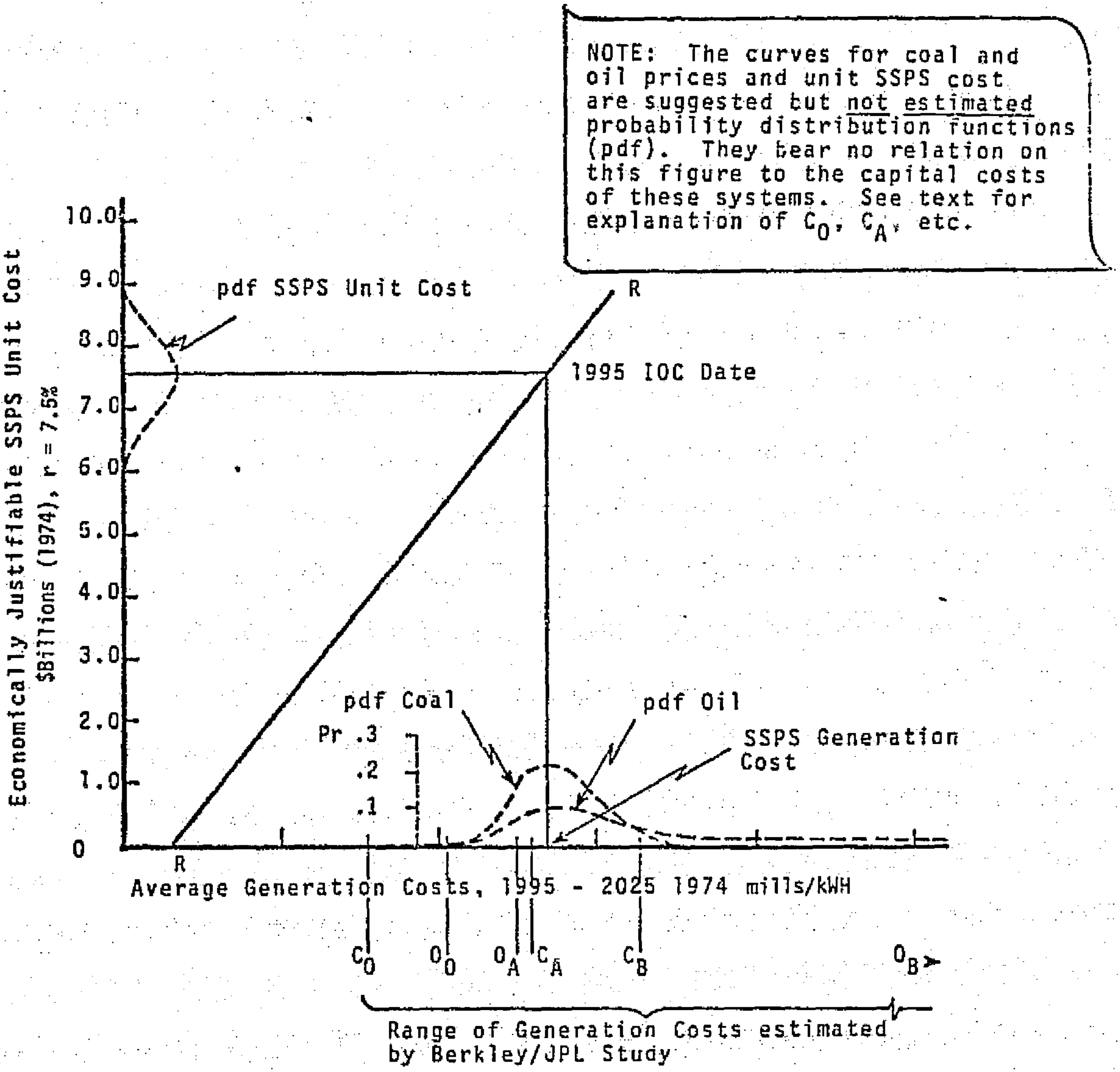


Figure 3.42 The History of Relative Fuel Prices



NOTE: The curves for coal and oil prices and unit SSPS cost are suggested but not estimated probability distribution functions (pdf). They bear no relation on this figure to the capital costs of these systems. See text for explanation of C_0, C_A, etc.

Figure 3.43 Comparative Economic Analysis of a 5,000 MW SSPS Operating Over the Period, 1995-2025

Based upon projection of the Hudson-Jorgenson estimates of relative price changes to the year 2025, the coal-fired plant would generate electric power at an average price of 25.1 mills/kWH at the busbar over the period 1995-2025. Were a vigorous policy of energy independence pursued the average generation price would be about 33 mills/kWH.

The same analysis for oil indicates that the projections of the Hudson-Jorgenson estimates of "no policy change" would not affect the relative standing of oil-fired systems. Were the "energy independence" policy pursued, the price of electric power from oil-fired plants might be driven off the scale.

Based upon these results, the SSPS is expected to be cost-effective with respect to fossil fuel systems by 1995. Furthermore, since fossil fuel systems depend upon <u>nonrenewable</u> sources of energy, the economic viability of SSPS may be <u>enhanced relative</u> to these <u>beyond</u> 1995.

While every attempt has been made to cost the systems on a consistent basis, one major element of cost has not been addressed: the systems' relative <u>social and environmental impacts</u>. Within this study we have begun to develop a framework for evaluating these impacts. This will, however, require much further study before our level of understanding is adequate for the purpose of decision-making.

A second issue that could impact total systems' cost is the relative permissable distance from population and industrial centers for SSPS rectennas and conventional electric power generators. This is an important determinant of the cost of energy transmission. Whereas it does not seem likely that major energy-intensive industries--such as metals processing--would locate near 5-10 GW nuclear sites, the rectenna site would appear to be amenable to such activity. These issues, however, await future study.

Finally it should be noted that the U.S. Energy Research and Development Administration (ERDA) is currently funding research in electric generation technologies such as ocean thermal and solar power towers that would produce energy in the range of 30-50 mills/kWH as well as fusion power, the cost of which is even more difficult to estimate.

3.3.2 Economic Analysis of SSPS Technology Development Programs

It is useful for an economic analysis to view the SSPS as a chain of efficiency conversions, from solar power conversion to delivery of 5 GW of electric power at the busbar. Table 3.21 below provides this efficiency chain with the nominal efficiencies that have been used throughout the study. By "nominal" efficiencies we mean those that are believed to be achievable for the 5 GW SSPS with a 1995 IOC.

Table 3.21 SSPS Subsystem Efficiency Chain

SSPS Subsystem	Nominal Efficiency		Power In (MW)	Power Out (MW)	1974$/kw (Out)	kg/kw (Out)
Solar Blanket (N=2)	.137					
		.126	67901	8558	207.53	1.318
'ower Distribution	.920					
Ant. Power Distribution	.960		8558	8216	10.95	0.125
DC-RF Conversion	.870		8216	7148	18.19	0.622
Phase Control	.960		7148	6862	18.94	0.036
Propagation	.990		6862	6793	NA	NA
Beam Collection	.900		6793	6114	119.40	NA
Rectenna	.870		6114	5319	71.44	NA
Power Interface	.940		5319	5000	47.50	NA

As shown in the table, about 8.6 million kW of electric power must be produced by the solar array (with a concentration ratio of two) in order to provide 5 million kW at the ground busbar. For the purpose of economic analysis, the specific costs of the individual SSPS subsystems have been estimated as a function of the $/kW actual output.

Table 3.22 contains values representing 10 percent reductions from the nominal efficiencies provided in Table 3.21, and the efficiency values if their potential is eventually realized. Table 3.23 contains estimates of the cost impact on a 5 GW SSPS if either the 10 percent reductions in the subsystem efficiency values or the realization of the potential efficiency values occurs. It was assumed that if there were a reduction in efficiency it would not be offset by gains in efficiencies elsewhere in the system but by increased size of all of the SSPS elements upstream of the offending element.

As might be expected, the greatest cost sensitivity to efficiency variations is to potential efficiency losses at the receiving antenna. Were the efficiency of the rectenna or power interface reduced, the power level of the entire SSPS would have to be raised in order to maintain 5 GW at the busbar. As shown in Table 3.23 a 10 percent reduction in the nominal efficiency of the power interface would increase the SSPS unit cost $728 million which is equivalent to 1.4 mills/kWH.

As shown there are benefits to the realization of the "potential efficiencies," but these are not as potentially significant as the impacts of reduced efficiency. It should be emphasized however, that we do not presume that the realization of the indicated values for efficiency losses and gains are equally probable. Estimates of these values and their distribution require more extensive analysis than has been possible in this study.

Not included in Table 3.23, but very important to the economics of SSPS, is the sensitivity to the specific costs of the solar blanket. For this study we have used $\$54/m^2$, this is equivalent to almost 3 mills/kWH. Every 10 percent increase in the specific cost of the solar blanket will have a .3 mill/kWH impact, which is less than the cost impact due to the 10 percent subsystem efficiency reductions in Table 3.23. By another calculation it may be estimated that the cost impact of a 10 percent increase in the mass of the solar blanket would increase the SSPS unit cost about .1 mill/kWH. Given these results, it is suggested that in the near term, concern should be focused on the problems of subsystem efficiencies as well as solar blanket specific cost and mass.

Table 3.22 Data for Sensitivity Analyses

SSPS Subsystem	Efficiencies		
	Nominal	10% Reduction	Potential
Solar Blanket	.137	.123	(3)
Power Distribution	.920	.828	(3)
Ant. Power Distribution	.960	.864	.970
DC-RF Convertor	.870	.783	.900
Phase Control	.960	.864	.970
Propagation	.990	.990(1)	.990(1)
Beam Collection	.900 - .950	.810(2)	.900(2)
Rectenna	.870	.783	.900
Power Interface	.940	.846	.950

(1) Constant.

(2) Low value assumed initially--prior to required in-depth analysis of environmental and land-use impact.

(3) To be determined.

Table 3.23 SSPS Subsystem Sensitivity Analysis

SSPS Subsystem	Cost Sensitivity ($Millions, 1974)	
	10% Reduction	Goal*
Solar Blanket	269 (.52)	**
Power Distribution	269 (.52)	**
Ant. Power Distribution	286 (.55)	26 (.05)
DC-RF Conversion	392 (.76)	101 (.20)
Phase Control	409 (.79)	35 (.07)
Beam Collection	580 (1.12)	178 (.35)***
Rectenna	685 (1.32)	154 (.30)
Power Interface	728 (1.4)	51 (.10)

* If "Goals" were realized throughout (nominal Beam Collection) savings are equal to $365 x 10^6, or 0.71 mills/kWH. If 10% reduction in efficiencies were realized throughout SSPS unit cost rise use by more than $30 x 10^9.

** Goal is to be determined.

*** Depending on acceptance environmental and land use determination. Equivalent additional land rental equal to $15 x 10^6/year for 30 years.

NOTE: ( ) Indicates equivalence in mills/kWH.

Figure 3.44 provides an economic analysis of the payback of the $44 billion development program.[3] The analysis presumes that the total development burden is borne by the SSPS program, an assumption which is not, in our opinion, justified.

One x-axis (abscissa) is "time" in calendar years. A second x-axis indicates the cumulative number of 5,000 MW SSPS units operational at the beginning of the indicated year. The buildup--two per year until 2000, then four per year until 2025--would provide at least 10 percent of the United States incremental generation demand.

The y-axis (ordinate) is generation costs in mills/kWH of alternative (terrestrial) systems. The range of cross resulting from the Berkley/JPL report is indicated.

The curve P-P is used to parametrically estimate the DDT&E payback as a function of alternative electric generation costs. Its shape depends on the discount rate and the SSPS buildup rate. Its derivation is provided in Appendix A.

Were alternative generating systems' cost not to exceed 27 mills/kWH--the SSPS estimate--DDT&E would not be repaid. Indeed, the function becomes asymptotic to the x-axis at about 31 mills/kwh, indicating that at least 4 mills/kWH difference between SSPS and terrestrial systems is required to payback the DDT&E (again, this presumes that the total DDT&E bill accrues to SSPS).

As indicated, were the alternative generation cost 35 mills/kWH--point A on the y-axis-the DDT&E would be repaid by CY 2012 with 57 5,000 megawatt operational SSPS units.

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[3] The $44 billion does not include the unit cost of 1 GW pilot plant which could be $16 billion. The technology development required for the 1 GW pilot plant, however, is included in the $44 billion estimate. These or similar developments would be required even if the decision were made not to install the 1 GW pilot plant. The pilot plant would be expected to offset some of its cost with revenues from the sale of power. Its net costs and benefits will be subject to a separate analysis.

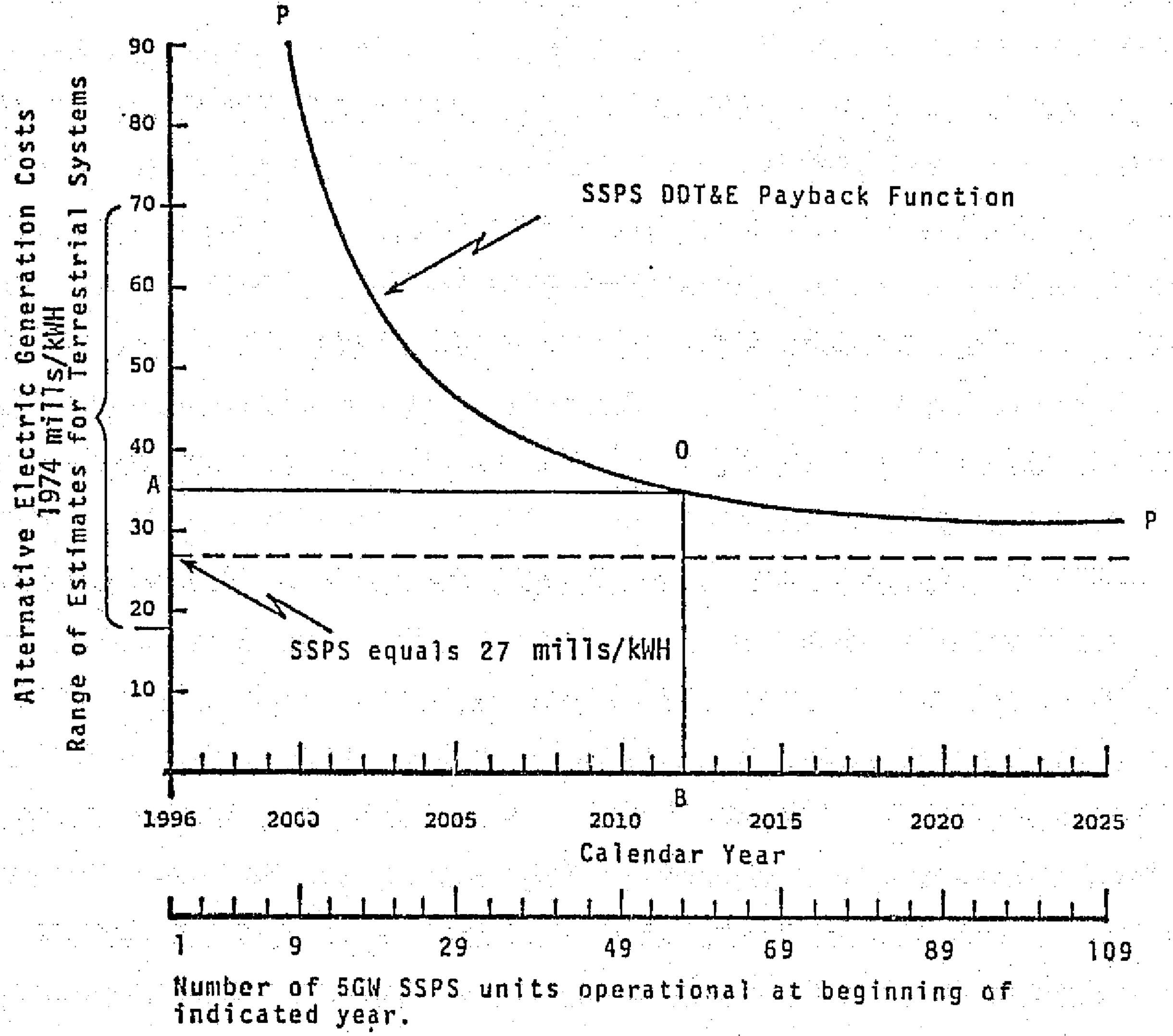

Figure 3.44 Payback Analysis of SSPS Development Programs (r=7.5%)

4. POWER DISTRIBUTION SYSTEM ANALYSIS

The Power Relay Satellite (PRS) has been proposed as a method for transmitting large amounts of electric power 3,200 km or more across land and up to 11,500 km across water. To assess the viability of the PRS concept, a comparison has been made with the following terrestrial power transmission system alternates:

- Electric power transmission via conventional circuits
- Super conducting power transmission lines
- Hydroden transmission
- Microwave transmission via waveguide.

4.1 The Power Relay Satellite

4.1.1 Concept Description

4.1.1.1 Configuration

The Power Relay Satellite (PRS) Microwave Power Transmission concept, as shown in Figure 4.1 , consists of a reflector in synchronous orbit to provide power transfer from a transmitting antenna at one ground location to a ground receiving antenna at a distant location. The transmitting antenna is a phased array with slotted waveguides and converters similar to the SSPS but larger, and operating in the terrestrial environment. The receiving antenna is a rectenna similar to that used in the SSPS. If ground power densitites are to be in the vicinity of 20 mW/cm^2, the transmitting array and rectenna should be 10 km in diameter and the reflector should be 1 km in diameter for 5 GW to 10 GW systems.

Atmospheric effects and errors at the ground-based transmitting array require that it be sectored into subarrays with each phase controlled as in the SSPS. Adaptive control techniques to correct this problem require a reference beam sent from the reflector at a frequency displaced from the power frequency. A sensor matrix at the reflector could provide the necessary command control capability.

The dispersive effects of the atmosphere cause a relative loss in gain and, hence, efficiency, of a ground antenna as its dimensions increase. However, time constants for atmospheric turbulence are relatively long, so that sectoring of the antenna into subarrays with command or adaptive phase control, using the reflector satellite reference, can reduce this effect to some degree, depending upon subarray dimensions. The maximum subarray dimension for this purpose is approximately 100 m.

The PRS reflector configuration, shown in Figure 4.2 consists of a primary structure approximately 1 km in diameter constructed of 25 meter deep truss girders spaced at 108 m. Each 103 m module is spanned by an 13 m grid of 5 m depth girders. Electrically driven screwjacks are mounted at the four corners of the reflector subarray. The primary

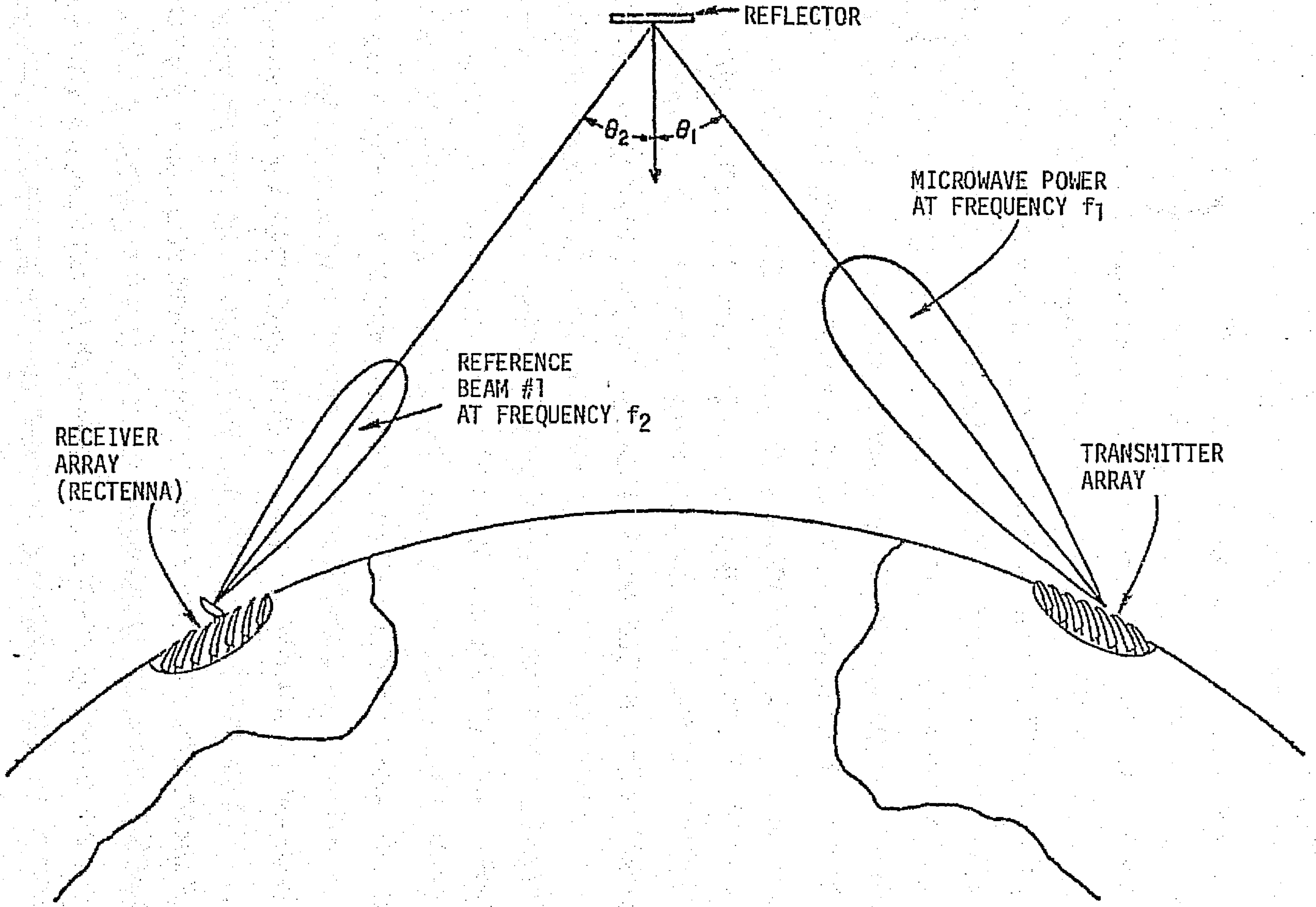

Figure 4.1 PRS Concept

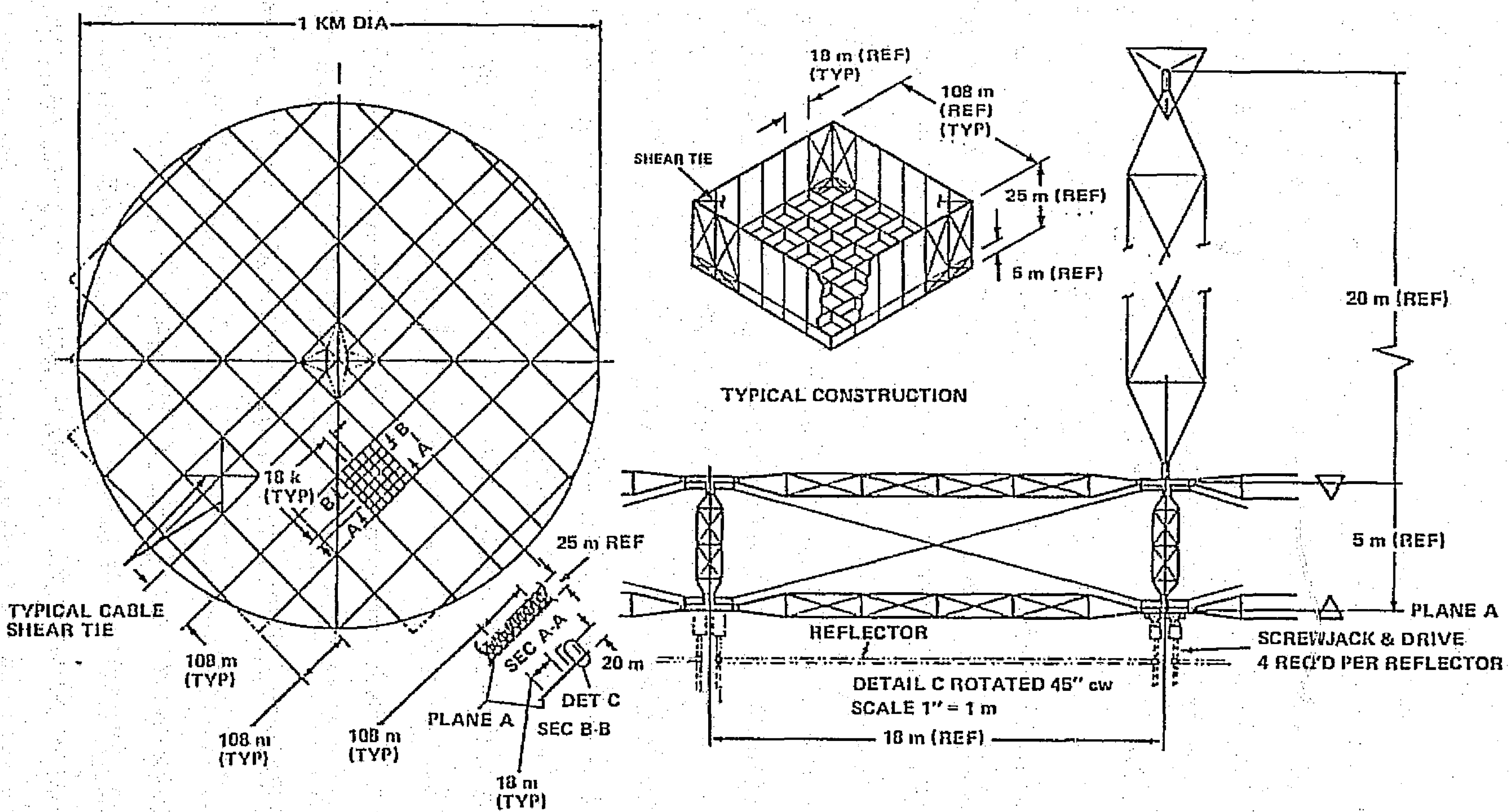

Figure 4.2 Configuration of a 1 km Diameter Power Relay Station

structure is built up of 108 m x 108 m x 20 m deep bays. The upper cap is a triangular truss girder 108 m long by 3 m deep. The material used is a graphite epoxy composite. The secondary structure, which forms the lower cap of the primary bending structure, is 5 m deep with bays of 18 m x 18 m. This 18 m square substructure spans the 108 m bays and provides supports for the microwave reflector system.

4.1.1.2 System Efficiency

The PRS efficiency budget in Table 4.1 reflects the additional efficiency losses (relative to an SSPS) due to the path from the reflector to the receiving antenna. The SSPS requires transmission only from the satellite to the receiving ground station. A 95 percent beam collection was used for the up-and down-legs. Ionospheric loss of 2 percent for the two-way path is due to diurnal Faraday rotation effects using a linearly polarized rectenna. This could be eliminated with a dual polarized rectenna if shown to be economical. As derived in Table 4.1, a 53 percent efficiency is taken to be the nominal PRS value.

Transmission losses increase with lower elevation angles. The effect is greater for rain conditions, as shown for a one-way (up or down link) path in Figure 4.3 . Elevation angles below 20 degrees should be avoided since land area use becomes excessive at small elevation angles. This limits SSPS to about 60 degrees latitude for the rectenna, and limits the PRS ground installations to lower latitudes depending upon the longitudinal difference between rectenna and transmitter. Maximum PRS transmission distance with one satellite would be 7,200 km due to the earth's curvature.

4.1.1.3 Mass Properties

Table 4.2 summarizes the PRS on-orbit mass properties. The structure accounts for 64 percent of the total mass and the control subsystem contributes the remaining 36 percent. The major single mass contributor is the phase control electronics (0.131×10^6 kg). This subsystem includes the rate gyros, interferometers and interface electronics to point and stabilize each reflector subarray, in addition to generating an integrated attitude and stabilization signal to the overall satellite control system. The breakdown is as follows for each 18 m x 18 m subarray:

Item	Mass
Digital Subsystem	10 kg
Instrumentation Subsystem	10
Interferometer Subsystem	34
	54 kg

Equipment is dual redundant for reliability. The Digital Subsystem accepts, commands and controls the subarray. The Instrumentation Subsystem measures and reports temperatures, strain, status, etc. The Interferometer Subsystem determines attitude for the angular positioning of the subarrays. This is needed in addition for position control to maintain efficiency.

Table 4.1 Microwave Power Transmission System Efficiency Budget for PRS

Item	Initial, %	Nominal, %	Goal, %
TRANSMITTING ANTENNA			
Power Interface	94	94	95
DC-RF Converter	85	87	90
Phase Control	95	96	97
PROPAGATION			
Atmospheric (2-way)	98	98	98
Ionospheric (2-way)	98	98	98
REFLECTOR			
Beam Collection	95	95	95
Ohmic Losses	99	99	99
Phase Control	95	96	97
RECEIVING ANTENNA			
Beam Collection	95	95	95
Rectenna	84	87	90
Power Interface	93	94	95
	48	53	59

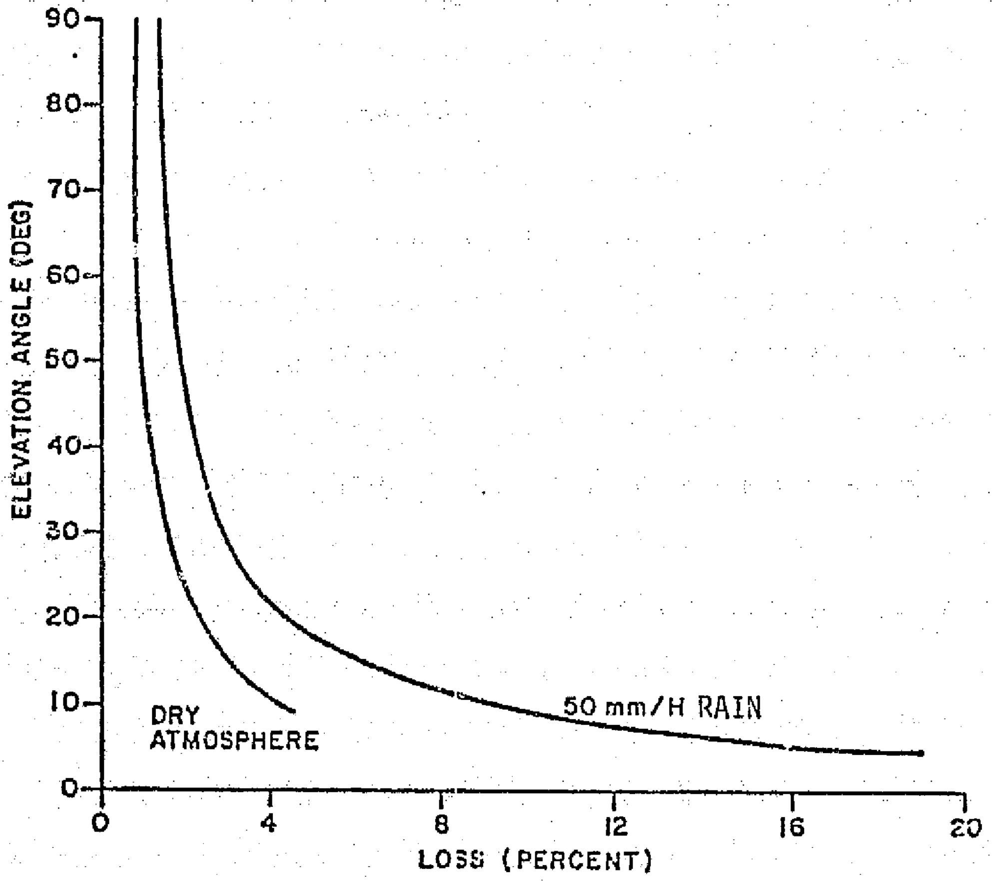

Figure 4.3 Transmission Loss for Two Atmospheric Conditions Versus Elevation Angle

Table 4.2 PRS Mass Properties

SUBSYSTEM/COMPONENT	MASS	
	kg x 10^6	LBM x 10^6
STRUCTURE	(0.270)	
• Primary Structure	0.0935	0.206
• Secondary Structure	0.0298	0.062
• Coatings & Insulation	0.0220	0.048
• Frame Structure	0.0793	0.175
• Wire Mesh	0.0456	0.100
CONTROL	(0.149)	
• Contour Control	0.0122	0.027
• Phase Control Electronics	0.1310	0.289
• Altitude Control	0.0060	0.013
TOTAL	0.4194	0.920

4.1.2 Engineering Analysis of Special Requirements for the Power Relay System

This section summarizes the analysis of engineering requirements for the PRS in the following areas:

- Antennas and Rectennas
- Reflectors
- Flight Mechanics and Control
- Microwave Power Generation
- Ground Safety

4.1.2.1 Antennas and Rectennas

The Power Relay Satellite (PRS) Microwave Power Transmission concept uses a reflector in synchronous orbit to provide power transfer from a transmitting antenna at one ground location to a ground receiving and rectifying antenna at a distant location. The transmitting antenna is a phased array radiating through slotted waveguides and the receiving antenna is a rectenna similar to that used for SSPS.

Examples of transmission links are an Arizona-Japan for overseas power relay and Arizona-Pennsylvania for domestic power relay. Coordinates and elevation angles are given in Table 4.3. It is seen that an Arizona-Japan link for PRS represents a near maximum transmission distance with low elevation angles. The satellite is located midway to keep both elevation angles above 20 degrees. The comparable link in the eastward direction would be Arizona-Spain. A contrasting link with much shorter ground distance and higher elevation angles is Arizona-Pennsylvania.

Figure 4.4 illustrates how the transmitting antenna size (and reflector size) is determined by the power density of its center, aperture illumination taper and total power transmitted. The latter depends upon receiving antenna output power and system efficiency. For the evaluation of environmental/biological effects, the key parameter is peak power density at the transmitting antenna. This is due to the receiving antenna's having the same diameter but lower power because of system efficiency losses. The beam taper of 10 dB is a good first choice for a 95 percent beam collection efficiency since it results in relatively small reflector dimensions.

The cost trends for the PRS, illustrated in Figure 4.5 for a 5 GW case (plotted as functions of peak power density at the transmitting antenna), confirm what could be expected from Figure 4.4 There is a tradeoff between the transmitting antenna cost and the reflector cost. The totals for a range of ground power outputs in Figure 4.6 show that capital cost decreases with increasing total power output and, depending upon the power output, decrease with peak ground power density.

The environmental/biological levels shown in Figure 4.6 make it clear that the economics of the PRS drive the acceptance of greater environmental risk in going to higher power densities than the SSPS.

Table 4.3 PRS Site Examples

	Ground Transmitter	Satellite Longitude	Rectenna
PRS-1 (Arizona-Japan)	Latitude 33°00'N Longitude 113°30'W Elev. Angle 20°	167°00'W	Latitude 36°00'N Longitude 220°0'W Elev. Angle 20°
PRS-2 (Arizona-Penna)	Elev. Angle 52°	113°30'W	Latitude 41°30'N Longitude 78°30'W Elev. Angle 31°

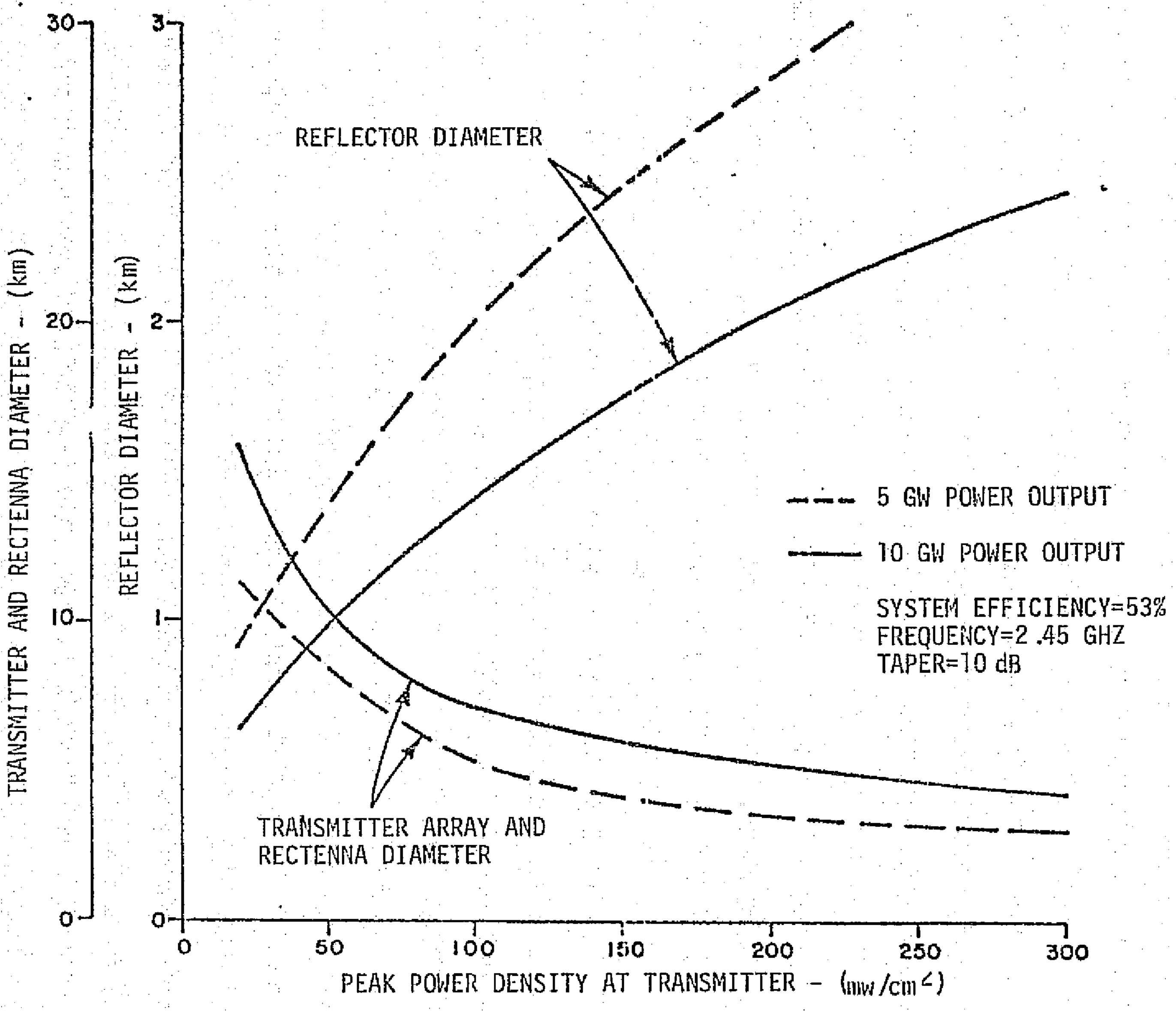

Figure 4.4 PRS Dimension Versus Peak Power Density at Transmitter

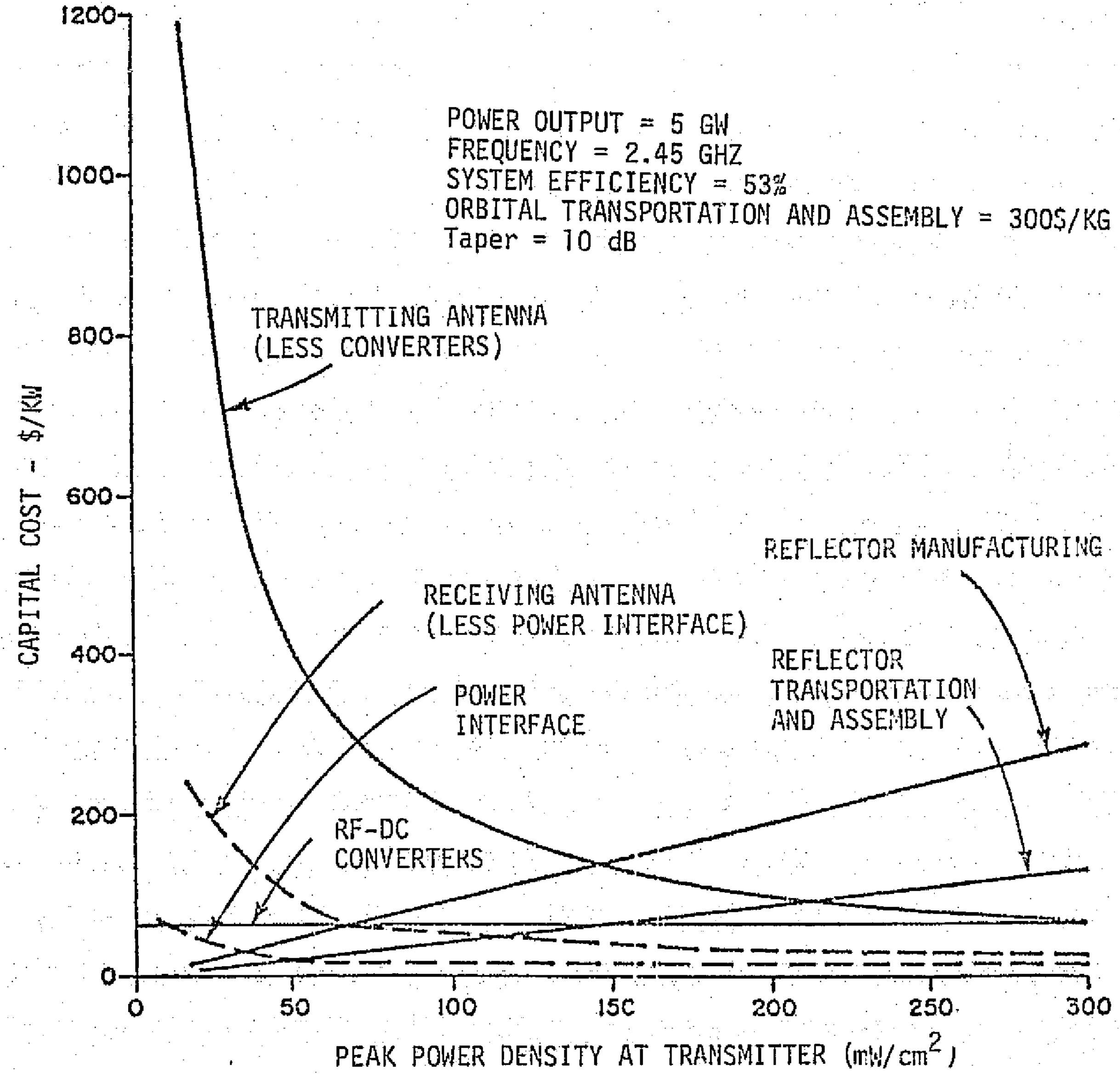

Figure 4.5 PRS Cost Elements Vs. Peak Power Density at Transmitter

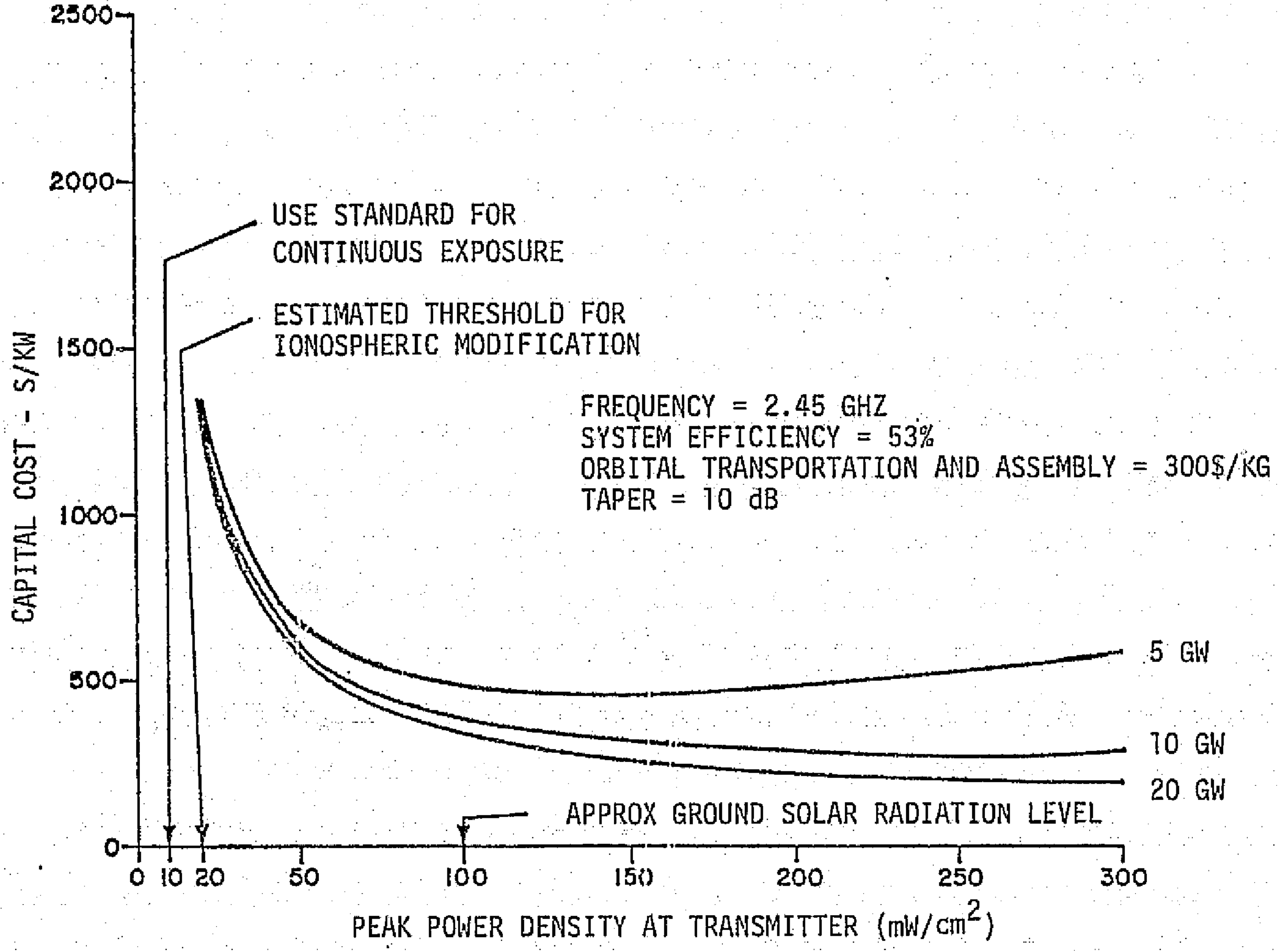

Figure 4.6 PRS Cost for Various Power Outputs

Figures 4. 7, 4.8 and 4.9 illustrate that the basic cost trends noted above are relatively insensitive to assumptions on equipment manufacturing cost, orbital transportation and assembly costs, and system efficiency. The transportation and assembly cost is a relatively minor factor in this example.

A PRS design point was selected at a peak power density of 50 mW/cm^2 for 5 GW and 10 GW systems because this is at the "knee" of the total cost curve. Lower power densities imply great risk of cost escalation due to the steepness of the cost curve in that area; and higher power densities increase the biological/environmental risk without a commensurate reduction in cost.

4.1.2.2 Reflectors

Reflector surface distortion and attitude control errors greater than 0.5 arc sec are corrected by mechanical adjustment of subreflectors analogous to the subarrays of the transmitter, as shown in Figure 4.10. The sum of phases of the uplink power beam and a ground reference signal launched from the rectenna is determined, and this is compared with a sum reference signal sensed at the center of the reflector and sent to the subreflector. Command control capability is based on a ground sensor power matrix as for the SSPS. The reference signal is at frequency f_2 to distinguish it from the power beam at frequency f_1 and from the reflector-to-transmitter reference signal f_3, noted in Figure 4.10.

The structural concept for the SSPS transmitting antenna is a rectangular grid-girder with aluminum or graphite composite materials, and the basic subarray building block is 18 m x 18 m. The same concept could be used for the PRS reflector. Subarrays can be taken as 18 m x 18 m, as in the case of the SSPS, on the assumption that the sizing cost tradeoff is comparable to the SSPS, i.e., reflector mechanical errors have doubled the effect, but dc-rf converter-produced errors are absent (taken into account at the ground transmitting antenna).

The 18 m x 18 m reflector modules, (Figure 4.11), consist of a framework supported by screwjacks at the corners and a wire mesh reflector surface attached by springs to the framework. The frame is fabricated using graphite composite. The wire mesh reflector is 0.15 mm diameter aluminum wire with a spacing between wires of 2 mm. The wire mesh has an equivalent uniaxial thickness of 0.0088 mm.

To achieve a surface roughness of less than 5 mm across the reflector subarray (for efficient microwave performance) the wire mesh is pretensioned to compensate for a continuous microwave radiation pressure of 55 N and a temperature variation between 366°K and 116°K. The subarray support frame is fabricated in graphite composite and can maintain a deflection of less than 5 mm over the 18 m length for temperature difference between caps of less than 29°K.

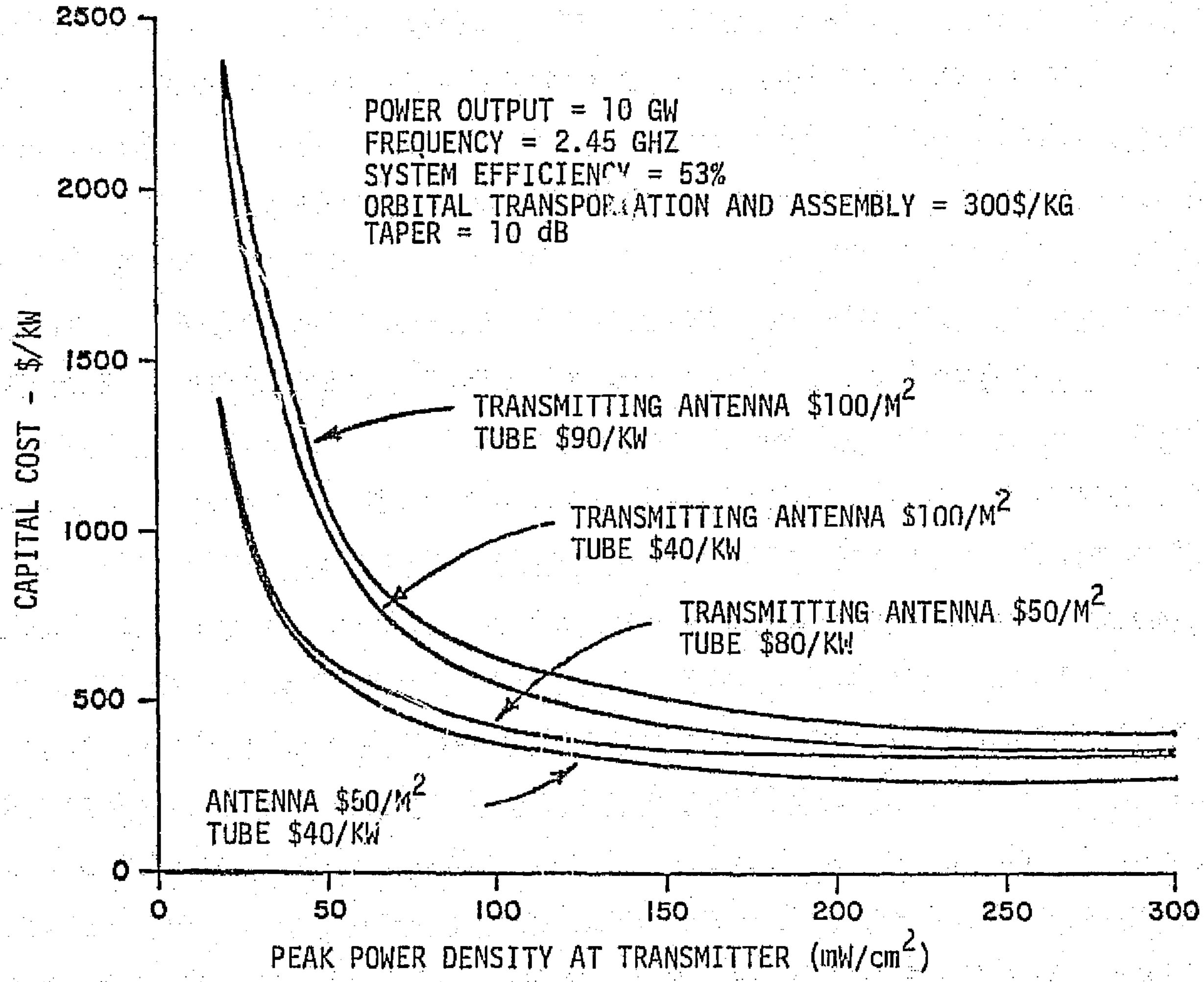

Figure 4.7 PRS Cost for Several Transmitter Cost Factors

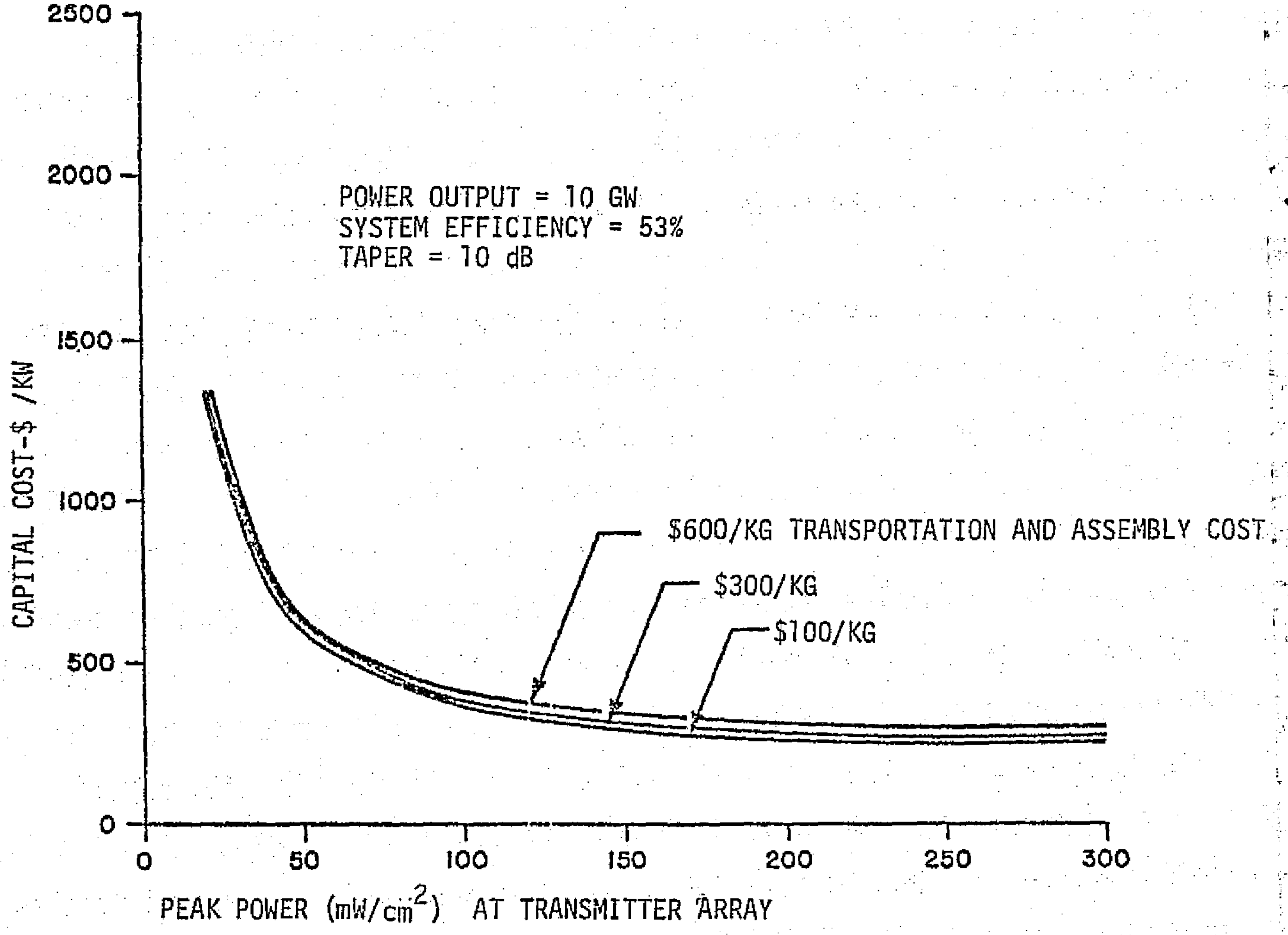

Figure 4.8 PRS Cost for Several Transportation/Assembly Cost Factors

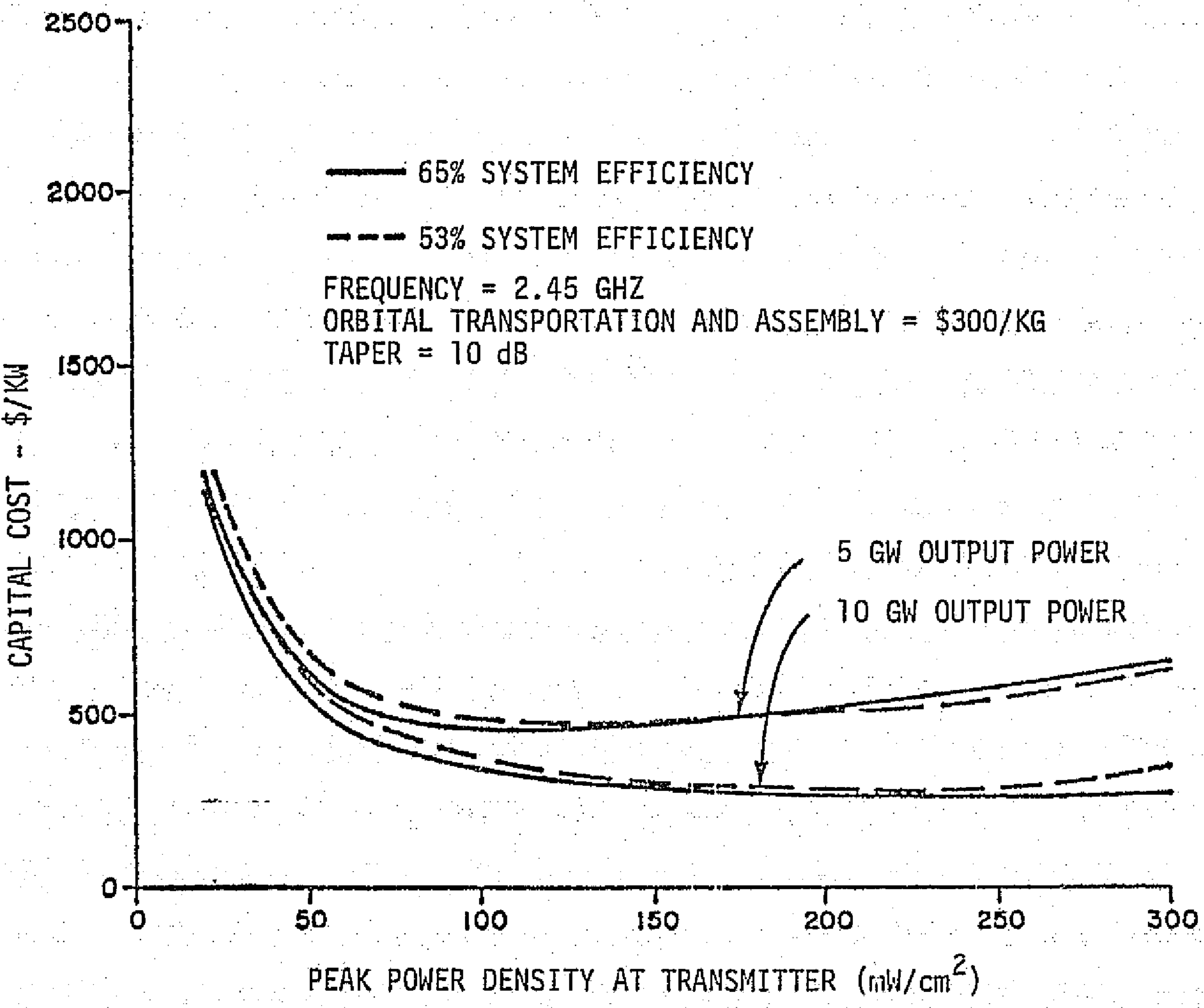

Figure 4.9 PRS Cost and System Efficiency

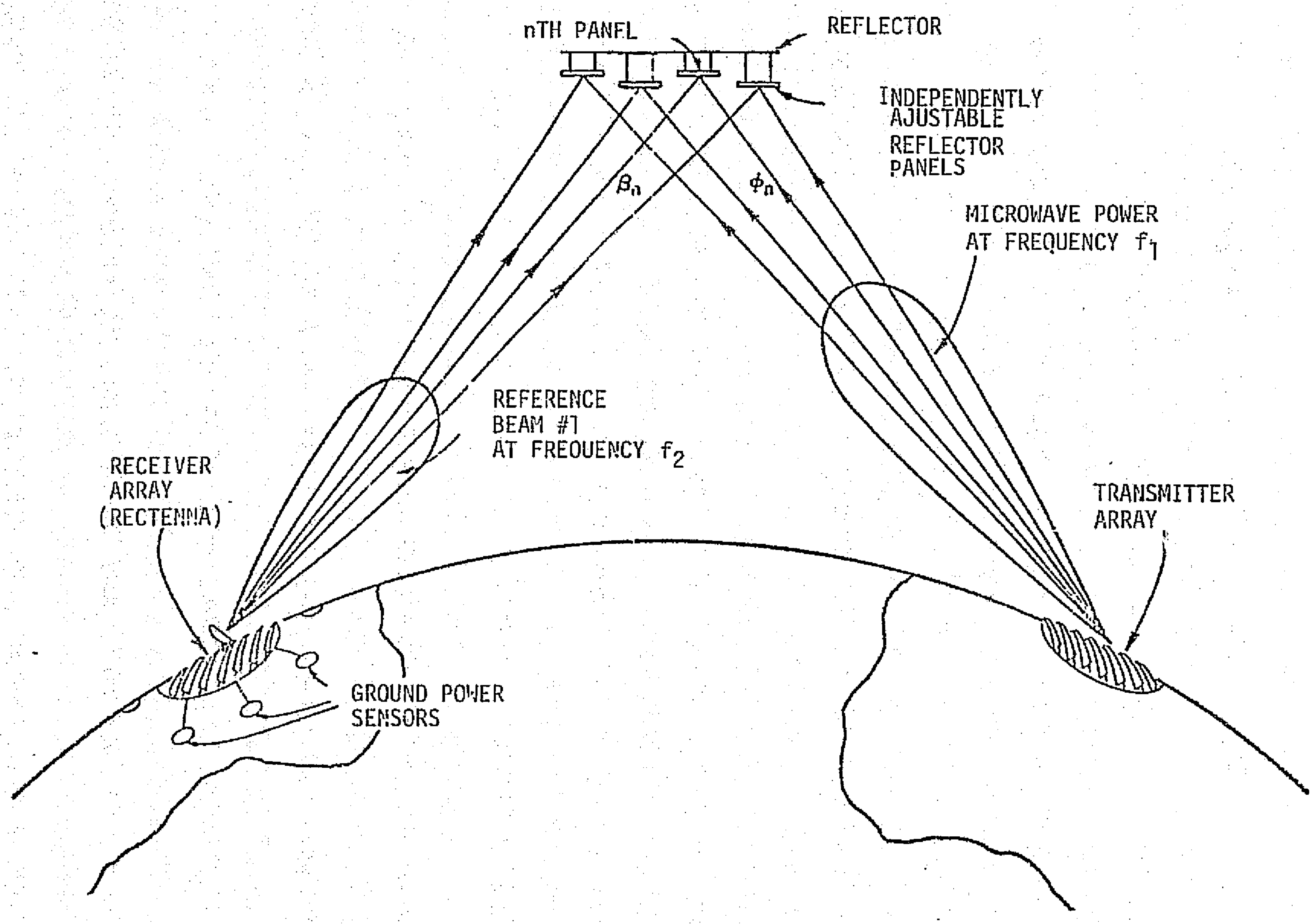

Figure 4.10 PRS Reflector Phase Control

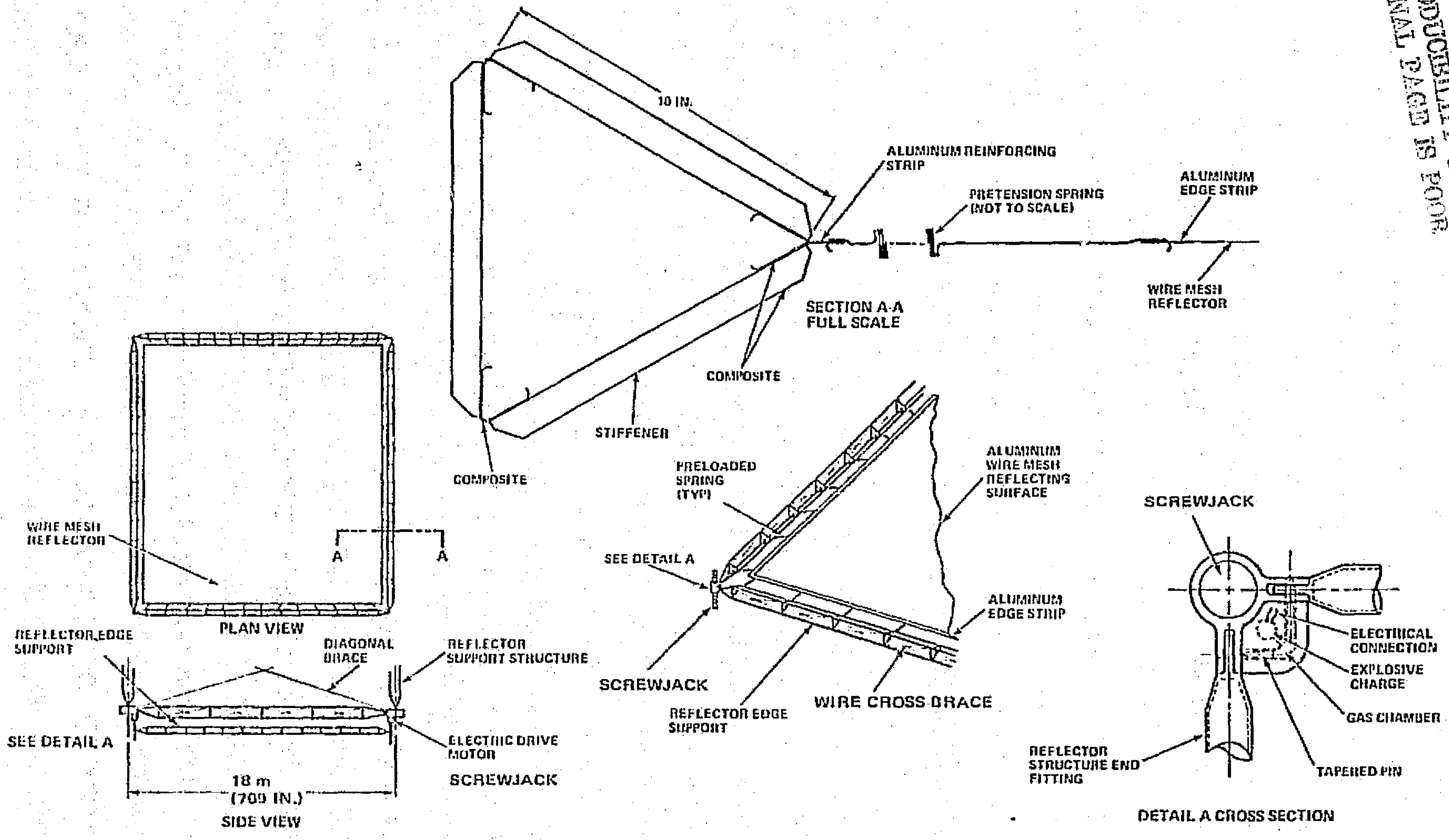

Figure 4.11 Power Relay Satellite Reflector Module, 18 m x 18 m

The relative vertical displacement of all reflector subarrays must be maintained to within a fraction of a wavelength. This may be accomplished through the use of the mechanical screwjack control system. The feasibility of achieving this fine a mechanical control over the entire satellite is suspect and requires considerable dynamic/control analysis depth to determine concept feasibility.

4.1.2.3 Flight Mechanics and Control

An assessment of PRS stationkeeping requirements indicates that yearly propellant requirements are modest, 812 kg/yr using electric propulsion and 29,000 kg/yr using a cold gas system. Satellite orbit position should be maintained to within ± 10 km of the nominal location in order to keep transmitted beam steering tolerance below 1 arc minute.

The dominant attitude disturbance torque is gravity gradient requiring 73 kg/yr (I_{sp} = 8,000 sec) for correction. Unlike the SSPS which be placed in a favorable orientation to minimize gravity gradient effects, the PRS continually points in such a direction as to cause an offset of principal axes relative to the vertical.

A major PRS stationkeeping and control issue is the selection of a power source for electric propulsion control units. A tradeoff is required to determine if it would be more cost-effective to use a cold gas system (I_{sp} = 200 sec) which uses 31,940 kg/yr of propellant. The costs of the power source, electric engines, etc., could be more than those associated with the yearly resupply of propellants using the lower performance systems.

A dynamics analysis which couples the spacecraft attitude and stationkeeping control system with the structure and reflector contour control is needed to determine concept feasibility. Unlike the SSPS transmitting antenna where active electronic phase control can compensate for structural/mechanical control system errors, the PRS system must be maintained to extremely tight alignment through mechanical means only, with electronic phase control techniques limited to indications of error.

Stationkeeping Requirements

Table 4.4 summarizes the PRS stationkeeping requirements for two locations, 167°W and 113.5°W longitude. The first location is used for transmitting power from a source in the southwest to a receiver in Japan. The second location transmits from the southwest to transmission to the continental United States Northeast.

The most severe perturbation is the microwave pressure. The 15 N force requires 118 m/sec delta-V for correction daily with an apogee/perigee maneuver. The next dominant perturbation is from sun/moon gravity, 46 m/sec-yr. Solar pressure perturbations require 0.24 m/sec for attitude control and 18 m/sec per year for eccentricity control; 4.5 m/sec per year is required for longitudinal control at the mid-pacific location and 2.4 m/sec per year at the southwest location, 113.5°W longitude.

Propellant Requirements

Table 4.5 summarizes the PRS stationkeeping propellant requirements for two orbit positions (167°W and 113.5°W) and two propulsion system specific impulses (8,000 sec and 200 sec). The difference in propellant requirement for the two orbit positions is small, indicating that the PRS will not be constrained from servicing any ground locations due to propellant factors. The difference in propellant for an ion propulsion system (8,000 sec I_{sp}) is better than an order of magnitude lower than a cold gas system. However, 29,000 kg for the cold gas system is not unreasonable and should be considered further.

Impact of Stationkeeping Accuracy on Microwave Performance

The factors covering the interrelationships between stationkeeping accuracy and microwave (MW) transmission efficiency for SSPS apply to the satellite-to-ground leg of the PRS mission. North-south drift (inclination drift) was found to have a significant impact on system efficiency and, therefore, is to be controlled. On the other hand, the longitudinal cyclic motion resulting from uncontrolled eccentricity drift would not seriously effect MW performance. In analyzing PRS stationkeeping propellant requirements, Table 4.5, the quantity allocated to eccentricity control, can be removed based on the down-leg MW performance sensitivities.

The impact of eccentricity drift on MW performance from the transmitting antenna on the ground to the satellite is not clear-cut. This assessment requires analysis of the MW performance degradation with increased electronic steering angles to the transmitted beam needed to track the satellite. We do know, however, from the Raytheon MPTS studies that MW performance drops off considerably beyond a steering angle of 1 arc minute (equivalent to an orbit position accuracy of 10^2km. The PRS eccentricity drift caused by solar pressure would require at least 1 arc minute of transmitted beam steering. Therefore, it is recommended that eccentricity drift be controlled on the PRS.

Attitude Control

The dominant disturbance torque which contributes to the PRS propellant requirements is gravity gradient (Table 4.6). Unlike the SSPS, the PRS must remain at a fixed attitude off-set from the local vertical causing a continuous torque bias on the system. This offset requires approximately 0.18 N (0.04 lb) of continuous thrust for attitude control. The effects of microwave and solar pressure on attitude control requirements are significantly lower than that of gravity gradients.

4.1.2.4 Microwave Power Generations

The dc-rf converters discussed in Section 3.1.2.5 are candidates to meet the requirements for the ground transmitting antenna for the PRS. The appropriate 5 kW amplitron and the 48 kW klystron parameters are given in Tables 4.7 (a and b) and 4.8 (a and b) in which it is seen that the amplitron

Table 4.4 PRS Stationkeeping Delta-V m/sec, (ft/sec)

	LONGITUDE	
	167°W	113.5°W
LONGITUDINAL DRIFT	4.7 (15.5)	2.5 (8.2)
INCLINATION DRIFT	46.0 (151.5)	46.0 (151.5)
ALTITUDE DRIFT	0.3 (0.849)	0.3 (0.849)
ECCENTRICITY DRIFT	17.9 (58.7)	17.9 (58.7)
MW PRESSURE	117.8 (386.5)	117.8 (386.5)
TOTAL	186.8 (613)	184.6 (605.7)

Table 4.5 Annual PRS Stationkeeping Propellant, kg/yr (lb/yr)

DRIFT TERM	LONGITUDE			
	167°W		113.5°W	
	I_{SP} SEC		I_{SP} SEC	
	8,000	200	8,000	200
LONGITUDINAL	20.5 (45.3)	820 (1,808)	10.8 (23.9)	434 (957)
INCLINATION	200.8 (442.3)	7,940 (17,490)	200.8 (442.3)	7,940 (17,490)
ALTITUDE	1.1 (2.5)	45 (99)	1.1 (2.5)	45 (99)
ECCENTRICITY	77.8 (171.4)	310 (683)	77.8 (171.4)	310 (683)
MW PRESSURE	511.7 (1,127	19,893 (43,818)	511.7 (1,127)	19,893 (43,818)
TOTAL	811.9 (1,788.5)	29,009 (63,898)	802 (1,767.1)	28,623 (63,047)

Table 4.6 Total Annual PRS Propellant Requirements, (Including Attitude Control) kg/yr (lb/yr) at 167°W

	I_{SP} = 8,000 SEC	I_{SP} = 200 SEC
STATION KEEPING		
LONGITUDINAL DRIFT	20.5 (45.3)	820 (1,808)
INCLINATION DRIFT	200.8 (442.3)	7,940 (17,490)
SOLAR PRESSURE		
– ALTITUDE	1.1 (2.5	45 (99)
– ECCENTRICITY	77.8 (171.4)	310 (683)
MICROWAVE PRESSURE	511.7 (1,127)	19,893 (43,818)
SUBTOTAL	811.9 (1,788.5)	29,009 (63,898)
ATTITUDE CONTROL		
GRAVITY GRADIENT	73 (161.4)	2,932 (6,457.6)
TOTAL	885.3 (1949.9)	31,941 (70,355.6)

cost and efficiency advantages over the klystron recommend it for inclusion in the PRS system.

The amplitron may be cooled by air or by liquid but it is assumed the net cost per tube will be similar to that given in Table 4.7a. It must be closed in the conventional manner to retain high vacuum in this application, whereas the SSPS version can be off-jacketed to save mass and enhance reliability. The PRS must be designed for tube replacement recognizing that failures in the seal will occur. A replacement rate of 1 percent per year was assumed in the operations and maintenance estimate.

The amplitrons are arranged in series sections, and in each of the subarrays their phase is controlled by the adaptive or command approaches. Noise output is reduced by the filter which produces some loss in efficiency as noted in Table 4.7b.

4.1.2.5 Ground Safety

The two concerns for ground safety relative to the MPTS are (1) the high voltage used for power distribution and (2) the microwave power density. The voltages at the receiving antenna reach a level of 66 kV at about 5,000 inverter points in the 100 km^{2}area. The rectenna element voltages are small, but these are subsequently collected to a 1 kV level for inversion to ac at the 66 kV level for either distribution to a power grid or conversion to a higher voltage for ground power transmission. The 1 kV level can be dangerous to maintenance personnel. The situation would be similar at the transmitting antenna where high voltage is distributed and converted to dc at a minimum level of 20 kV for the amplitron converters. The safety measures for protection against medium and high voltage are relatively common in the power industry, and application to the PRS should be straightforward.

The safety aspects of the microwave power beam are different from SSPS. The nominal peak level at the transmitting antenna has been selected for PRS at 50 mW/cm^2. This is to be compared with the United States' standard of 10 mW/cm^2 for continuous exposure. The density at the receiving antenna is 20 mW/cm^2. Other nations have set lower continuous exposure limits.

Safety measures would include: shielding of maintenance personnel; excluding air space and/or providing aircraft with warning devices to insure a fly-through of minimal duration; and providing for a safety ring around the receiving antenna. In the case of the receiving antennae, the cost model includes purchase of land out to a distance where the power density is 0.1 mW/cm^2. This occurs at about twice the normal radius and, therefore, requires about four times the area. Yet, this consideration is a small factor in the total PRS cost. Continuous sites would not require this extra land.

Table 4.7a MPTS 5kW Amplitron Parameters

ANODE	108 GRAMS
ANODE RADIATOR	1000
CATHODE	9
CATHODE RADIATOR	71
MAGNET	260
POLES	100
INPUT AND OUTPUT	40
MOTOR AND DRIVE	30
	1618 GRAMS – 3.56 LB
SPECIFIC MASS	0.33 g/W
SPECIFIC COST	0.018 S/W

Table 4.7b MPTS 5kW Amplitron Power Budget

RF POWER ADDED	5000 WATTS
ANODE ELECTRON BOMBARDMENT	371
ANODE CIRCUIT LOSSES	177
CATHODE DISSIPATION	199
DC INPUT POWER	5747 WATTS
GROSS EFFICIENCY	87%
OUTPUT FILTER DISSIPATION	125 WATTS
NET EFFICIENCY	85%

Table 4.8a MPTS 48 kW Klystron Parameters

ELECTRICAL	
VOLTAGE	38.9 KV
CIRCUIT	1.54 A
GAIN	31 dB
MICROPERVEANCE	0.2
WEIGHTS	
MAGNET PLUS POLE PIECES	16300 GRAMS
TUBE	32374
TOTAL	48674 GRAMS
SPECIFIC MASS	1.01 g/W
COST	
SPECIFIC COST	0.039 S/W

Table 4.8b MPTS 48 kW Klystron Power Budget

OUTPUT POWER	48362 WATTS
OUTPUT CAVITY LOSSES	
SKIN LOSSES	2038
INTERCEPTION	384
OTHER INTERCEPTION	461
HEATER POWER	60
SOLENOID	1000
COLLECTOR DISSIPATION	8755
TOTAL BEAM POWER	60000 WATTS
OTHER POWER	1060
TOTAL INPUT	61060 WATTS
NET EFFICIENCY	79.2%

The probability of beam wander can be kept negligible using the command control scheme. Also, it is not possible to produce higher power densities elsewhere as a result of failures. Failures can increase the sidelobe levels substantially, but simulation of failures on the SSPS showed the level would probably increase to no greater than 1/10 to 1/100 of the mid-beam intensity. There is a natural safety feature in that failures tend to both defocus the beam and reduce the available power. Thus, the principal concern should be movement of a well-focused beam outside of the protected area for substantial amounts of time.

4.2 Terrestrial Power Transmission Systems

4.2.1 System Description

The Power Relay Satellite (PRS) has been proposed as a method for transmitting large amounts of electric power 3,200 km or more across land and up to 11,500 km across water. To assess the economic viability of the PRS concept, it is necessary to know the minimum costs associated with transmitting this power using terrestrial alternatives. This section provides basic descriptions of the terrestrial alternatives. Their costs are summarized in the following section.

It should be kept in mind that the type of power transmission represented by the PRS is unlike any type of power transmission system in use or envisioned by the electric power utilities today. The transmission would be over extremely long distances, with no possibility of tapping off power at an intermediate point, should it be economically desirable. The system would deliver its power 100 percent of the time and would have extremely high losses with no possibility of changing the losses by changing the load. The PRS would be a "one-way" transmission system which could deliver power from one point to another point without being able to reverse the power flow, because the receiving and transmitting antennas would be quite different.

In order to compare the PRS system with terrestrial alternatives, use has been made of available data on representative terrestrial alternatives to design transmission systems which would perform in a like manner, but which would never be built under any forseeable circumstances.

The categories of alternatives considered include electric power transmission via conventional circuits and super conducting transmission lines (all of the above will be considered as "existing systems," even though some exist currently only in experimental application); and hydrogen transmission and microwave transmission via waveguide (which will be classified as "future systems").

In order to design the most economical terrestrial power delivery systems that would perform in a manner similar to that of the PRS, it was necessary to make the following basic design assumptions:

- Power input-ac electric power would be at the appropriate voltage level.
- Power output-ac electric power would be at the appropriate voltage level.
- All transmission systems would have the capacity required to most economically deliver 5 or 10 GW. Additional capacity would be added at the source to provided the capability of economically carrying that power which would be lost along the route.
- Designs would be those which were most economical in 1974.
- The cost of the energy lost because of transmission would be based on a 1974 cost of $0.02/kWH = $175 x 10^3 /MW-year.
- All transmission systems would be in use 100 percent of the time.
- Overland circuits would be anywhere from 3,200 km to 8,500 km long. This is independent of the great circle distance between the transmitting and receiving points.
- Only transmission systems would be considered. No credit would be given for the potential benefit of energy storage. The PRS does not provide any energy storage option in and of itself.
- Systems having a transmission efficiency of less than 50 percent would not be considered.

The power into and delivered by all systems was taken to be ac electric power at the appropriate voltage. It is necessary to explicitly state this assumption because many of the terrestrial systems do have energy in some other form along some part of the transmission path. While some of these other energy forms (e.g., hydrogen gas) may be more desirable than the ac electric power to meet other energy markets, the PRS will be delivering ac power.

The systems presented and designed in this study are one-way transmission systems. It is inherent in the transmission process that power will be lost along the way and the magnitude of these losses must be included in the system design. In order to minimize the capital costs of the equipment, each portion of each system has been designed to have only the required economic capacity at that particular location. The output capacity has been assumed to be 5 GW or 10 GW for all systems.

The costs developed in this study apply only to power transmission in one direction. The costs of transmission in the other direction, when this is physically possible, will be significantly different.

The maximum power capacity of any conventional circuit is determined primarily by the voltage and conductor heating; heating caused by the resistive losses in each conductor. For overhead lines, the conductors are bare and the surrounding air is both the coolant and the insulator. The maximum allowable conductor temperature is determined by thermal expansion of the conductor and the resulting sag of the catenary. This maximum temperature determines the maximum conductor current and the power transmission capacity of the circuit. The capacity of underground cables is more strictly limited, as they must rely on the thermal characteristics of the surrounding soil to remove the waste heat. An underground cable can be destroyed if run in an overloaded condition because the soil's thermal capacity can decrease if the soil temperature increases.

The capacity of conventional circuits can be increased by increasing the diameter of the conductor; this reduces the resistance and thereby reduces the losses. However, there is a practical limit to the effectiveness of this approach. This limit is determined by the conductor density and mechanical strength, tower spacing, etc. For both overhead and underground lines, the penalty paid for increasing capacity in this manner is increased capital cost.

An approach that can be used for increasing the capacity of underground cables is to provide a method of dissipating the heat other than the natural thermal conduction of the surrounding soil. If a fluid or gas is circulated past the cable and then mechanically cooled, the required thermal conduction in the soil is significantly reduced. The penalty that must be paid is a small increase in the capital costs and a large increase in the operating costs. These are the forced-cooled cables. One example of a forced-cooled system has been included as part of this study.

When conventional circuits are used over short transmission distances, the voltage variation along the line is small and the circuits are designed to accommodate voltages somewhat higher than the nominal level. When transmission losses of 50% are allowed, the voltage variations along the route are very high. To prevent the voltage from exceeding the circuit maximum, the analysis was done by fixing the voltage at the sending end and the power at the receiving end. The voltage at the receiving end was assumed to fall as much as necessary, given the other parameters.

Regarding the ac circuits, whenever it was necessary to interrupt the circuits (i.e., to remove an unnecessary circuit) a transformer was used to boost the voltage backup to the design level on all circuits. This was not possible with dc circuits.

4.2.1.1 Existing Systems

AC Power Transmission

The reactive elements in transmission lines have limited the usefulness of ac power transmission for transmitting power over really long distances. Unless reactive compensation is added to the circuit along the way, the power factor[1] at the point of delivery will decrease and approach zero. When the power delivered is assumed to be fixed, and the voltage allowed to drop, the current in each conductor must increase as the power factor decreases (transmission distances increase) and the losses in the line would increase inordinately. Ac power transmission systems could not be used for transmitting power over 3,200 km with less than 50 percent losses if it were not possible to keep the power factor close to 1.

The primary reactive component in overhead lines is inductance. In order to control the effect of this inductance, it is necessary to add large capacitors in series with the line. Since the inductance is distributed evenly along the line, adding capacitance evenly along the line could maintain a constant power factor ideally set at one. This approach, however, is uneconomical. For this study, therefore, the compensating capacitors were assumed to be lumped together every 850 km and to be capable of keeping the power factor at any one point between 0.85 and one.

The usefulness of dc power transmission compared to ac is limited by the ease with which high-voltage ac power can be produced and transmitted using low-cost, efficient transformers. While the cost of dc lines is considerably lower than that of ac lines with the same capacity, the cost of producing the high-voltage dc power by connecting dc generators in series is prohibitive. Direct current transmission, therefore, has had to await the development of high-voltage ac/dc rectification and inversion equipment.

The first rectifier system was installed in Sweden in 1954. Twenty years later, only 10 dc transmission systems are in operation, in all probability because of the high cost of converter stations. For transmission distances on the order of 3,200 km, however, the cost of converter stations could be easily balanced by the significantly reduced cost of the transmission line (overhead and underground).

DC-Superconducting Cables

The reduction and eventual disappearance of the electrical resistance of a metal as its temperature is reduced appears to offer a means of reducing the operating costs for transmission lines and increasing the capacity. A superconducting metal is one in which the electrical

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[1] Power factor = (power in the line) /(I x V) in the line.

resistance becomes zero below a certain transition temperature. The energy losses due to transmission in these materials would result primarily from the energy required to refrigerate and keep the system below the transition temperature.

The cost estimates for a dc superconducting cable that were used in this study are those estimates produced by General Electric for the Los Alamos Scientific Laboratory, adjusted to 1974 prices. Of all the cost estimates available for these types of systems, only those provided by General Electric were consistant with the detailed engineering cost estimates done for the Linde Corporation for comparable portions of an ac superconducting system.

4.2.1.2 Future Systems

Microwave Transmission by Closed Waveguide

One of the methods considered as an alternative to conventional transmission lines for purposes of comparison to the PRS is microwave transmission. This approach involves the conversion of the powerplant generator output into radio frequency (rf) power, the transmission of this rf power along an appropriate waveguide system, and finally, its reconversion into ac power for distribution.

The most practical technique for transmission along the Earth's surface relies on closed waveguides, i.e., hollow tubes in which the electromagnetic field is completely enclosed by conducting walls. The most important design parameters are the following: waveguide dimensions, operating frequency, power-handling capability, transmission losses; and mode situation.

Designs using four different modes were examined; the characteristics of the resulting transmission lines are summarized in Table 4.9. Of particular importance is the calculation of the distance by which a 50 percent loss has occurred ("3 dB loss length"). As one of the criteria to be applied in this portion of the study indicates that no system is to be considered which has losses greater than 50 percent, terrestrial microwave transmission via closed waveguide cannot be considered competitive with other transmission systems discussed in this section over the specified distances of 3,200 to 8,000 km. (2,000 to 5,000 mi).

Another alternative means of transmitting electric power involves the use of hydrogen as a link between an electric power source and an electric distribution system. Whereas a thorough review was made during this study of hydrogen transmission both by pipeline over land and by supertanker over oceans, it rapidly became clear that the use of hydrogen for electrical transmission would not be economically attractive. The principal reason is due to the high cost and inefficiencies of the systems needed to convert electricity to hydrogen and hydrogen to electricity.

Table 4.9 Transmission Line Design Comparison

Mode	Waveguide Size (m)	Dimension Tolerance (cm)*	Operating Frequency	Power Capacity GWe	Loss (W/m at 1 GWe)	3-dB Loss Length (km)
TE_{10}	35.2 x 17.5	± 5.1	6.9 MHz	2,400	374	1235
TE_{10}	6.1 x 6.1	± 1.3	37 MHz	154	3478	196
TE_{01}	3.0(diam)	S: ± .01 D&E: ± 2.5	1 GHz	30	374	1835
TE_{01}	1.8(diam)	S: ± .01 D&E: ± .03	3 GHz	10	374	196

*Straightness Tolerance(s) is per 30.3 m. Diameter and Ellipticity (D&E) Tolerances are per 15.2 m.

For an electricity → hydrogen → electricity system, the hydrogen would probably be produced by utilizing the output of a nuclear powerplant with a water electrolyzing system. Small plants currently run at 75-80 percent efficiency at approximately $167/kW, and are projected to achieve 100 percent efficiency by 1990 at $70/kW.

Alternative methods of producing hydrogen exist, and these include thermolysis of water at 3000°C and the reforming of hydrocarbons. Only the latter seems to be practicable within the 1990 time-frame.

The other crucial link in the electricity hydrogen → electricity chain is the reconversion of hydrogen to electricity. If the hydrogen is burned as fuel in a conventional power station, the overall efficiency is at best 40 percent. The only alternative currently available is the fuel cell which exhibits typical efficiencies from 43-49 percent and a capital cost of $350/kW. Anticipated advancements are expected to improve the efficiency to 52-59 percent and reduce the capital cost to $175/kW. Even if conversion is assumed to have an efficiency of 50 percent, the cost of the delivered energy will be at least double the cost of energy at the input. In addition, the capital costs of the fuel cell the electrolyzer and the converter stations have to be borne by the system for an economic evaluation.

A similar cycle for transportation of liquid hydrogen by tanker, Figure 4.12, suffers from the same problems as transportation of hydrogen gas by pipeline: it is inefficient and expensive. This approach to electric power transportation could be seriously considered only if no other fuel could be transported and used for on-site generation.

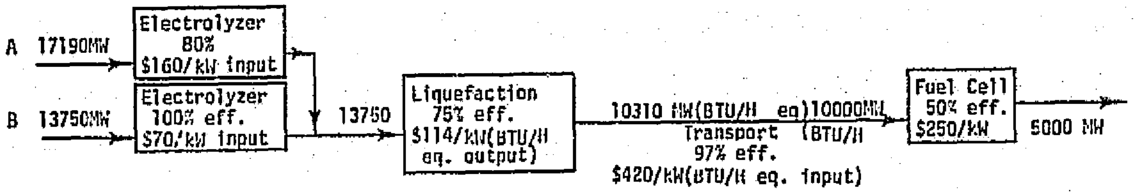

Figure 4.12 Transport of Liquified Hydrogen by Tanker - San Diego to Tokyo

4.2.2 Economics of Terrestrial Systems

The costs of the transmission systems described in the previous section have been calculated in a consistent mills/kWH user charge format (as a function of transmission distance) for comparison with the PRS.

Conventional Transmission Systems

There is no single cost per circuit or single effective resistance/circuit-km for any particular system. The resistance/circuit-km can be reduced (within limits), but only with a corresponding increase in capital costs. Designing the optimum system requires knowing the detailed relationship between the capital costs and resistance and a specific transmission route. Since these data are not generally available, it was necessary to use a representative capital cost and representative effective resistance per circuit-km for each system considered.

The capital costs and effective resistances/circuit-km that were used in this part of the study have been garnered from a variety of sources published in various years. The costs have all been adjusted to 1974 dollars using the Handy-Whitman Index and the resulting values then compared to each other to make sure they were reasonable and consistent. These values represent the best estimate of the costs that can be made given the limitations of this study.

The total transmission costs for all the terrestrial systems are not sensitive to the cost of the land required for the right-of-way (ROW). The ROW costs have been included as part of the capital costs of the various conventional transmission systems and assumed to average $1000/acre--low for flat land near cities and high for mountainous or desert terrain. This is equivalent to about $11,200/circuit-km for the 765-kV ac overhead line, just 3.6 percent of the total costs of the circuit.

The cost of delivering energy is the sum of the fixed costs of and the operating costs of the system used. The systems had to be designed to minimize this sum. However, the operating costs and the fixed costs are related. The higher the loading of each transmission circuit, the fewer the circuits required to deliver the same amount of power and the lower the capital costs and thereby the fixed costs. On the other hand, the higher the loading of the circuit (except the superconducting power transmission line), the higher the percentage of power that is lost and this loss must be paid for (2¢/kWH).

Each transmission system was designed to achieve minimum total cost, while not exceeding a 50 percent transmission loss. It was necessary to do this type of economic analysis for each of the candidate transmission systems. However, as a result of the high capital costs for underground systems, the minimums for the naturally-cooled underground systems always occur when the circuit is loaded above the thermal limit. For that reason, extra underground circuits are added only when it is necessary to carry more power than the existing circuit can physically accommodate. A minimum does exist for the forced-cooled conventional underground systems. The fixed cost rate assumed for the purposes of this calculation was 0.15.

Transmission costs for nine conventional systems have been estimated by ECON and are summarized in Figure 4.13. This figure will serve as the basis for comparison to the PRS (Section 4.3).

Hydrogen Transmission

The cost of transmission by pipeline compares unfavorably with the ± 400 kV dc overhead line. In addition, one of the basic design parameters was that no system would be considered if the transmission losses were greater than 100 percent of the delivered energy. Hydrogen transmission clearly does not qualify for overland transmission; however, cost estimates for LH_2 transport by tanker have been included in Figure 4.12 for the purpose of comparison of international energy transfer costs.

4.3 Comparative Economic Analysis of Orbital and Terrestrial Electric Transmission Systems

The PRS system in its current configuration has been compared with terrestrial electric transmission systems that currently exist or that might exist in the 1990-2020 time-frame. Transmission costs for PRS systems with output powers ranging from 5 to 10 GW have been compared with terrestrial systems delivering comparable outputs. This comparison is summarized in Figure 4.12.

The PRS would provide less costly energy transmission than current or projected underground cables, and would be less costly after 5,600 km than the current 765 kV ac overhead lines. It offers higher costs than currently existing ± 400 kV dc overhead lines or several other systems already in limited application (such as the dc superconducting cable) or those expected to be utilized (such as the ± 800 kV dc overhead line). The relatively higher costs of the PRS is the result of both high capital costs and unavoidably high transmission losses. Specifically, at an output level of 10 GW the cost of the PRS transmission losses, calculated at a representative generation cost of 20 mills/kWH, are almost 50 percent greater than the capital costs.

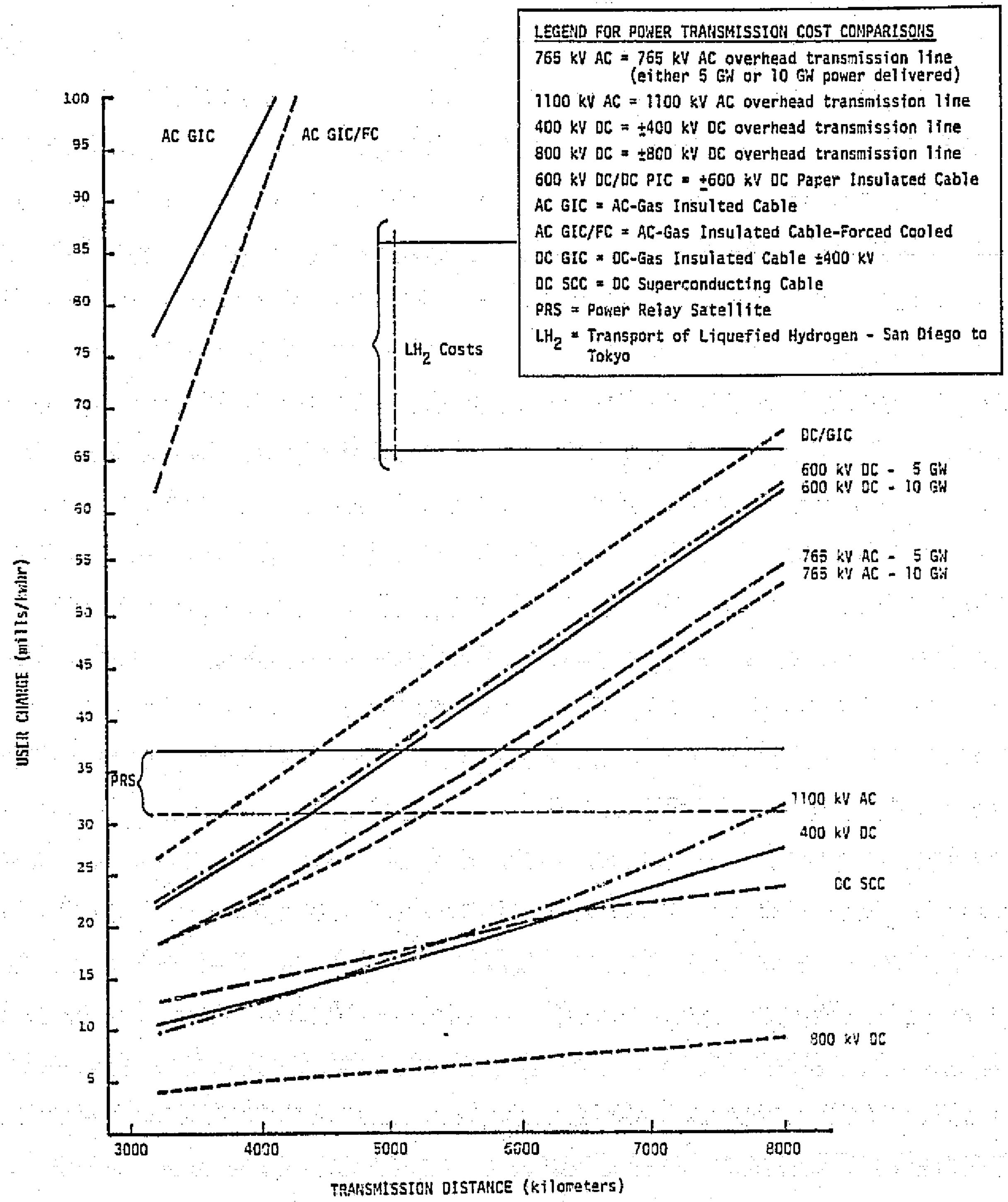

Figure 4.12 Power Transmission Cost Comparisons

highest practicable limits. If there existed the political requirement for large intercontinental energy transfers, the PRS seems to be economically superior to bulk energy transport *via* liquid hydrogen.

5. SOCIAL IMPACTS

5.1 Environmental Impact Analysis

The actual impact assessment task performed under this study was very modest and is viewed as a preliminary examination of data needs for a future impact assessment. The objective of the task was to identify the type of data in terms of input system variables and environmental considerations which must be developed and provided for the conduct of a future impact assessment. The primary factors requiring study were:

- Land Management Factors
  - Receiving Antenna
  - Launch Complex
  - Resource Extraction and Manufacturing
- Radiant Energy Densities
- Waste Heat
- Safety and Control
- Environmental Modification Factors

5.1.1 Land Management Factors

5.1.1.1 The Receiving Antenna

The receiving antenna is expected to be the largest (in area occupied) subsystem of SSPS from a terrestrial point of view. The actual antenna itself, the receiving control station, the conversion system, a part of the transmission system and enough land area for protective purposes will require a land area of over three hundred square kilometers for a 5 GW station. (The rectenna itself is 100 km^2). This area constitutes a substantial committment of land area that might otherwise be deployed for alternate uses. The extent to which part of the rectenna site might be shared with other users should be studied. Competing (or joint) demands for the chosen receiving antenna site may include the use of the land for farming, recreational purposes, industrial development, conservation, maintenance of drainage planes or other weather control purposes, urban development and residential housing.

Other land management impacts which may result from the receiving antenna location include indirect effects such as increased industrialization in the vicinity of the site and the associated shifts in demographic patterns. These impacts will have to be examined in relation to the capability of the surroundings to sustain such growth.

Finally, whereas tidal marshes and coastal wetlands are not suitable for antenna siting because of their importance in the ecological chain of sea life including offshore fisheries, offshore siting on the ocean surface appears to be a feasible alternative. The impacts of confining a small percent of ocean surface areas solely for the antenna do not appear prohibitive.

5.1.1.2 The Launch Complex

Many of the factors that control land management impacts associated with the receiving antenna are also pertinent to an analysis of the impacts associated with the launch complex siting. It is expected that the launch complex will occupy a land area much smaller than a receiving antenna site and whereas the receiving antenna is mated with only one satellite power station, the launch complex, if properly planned, will service several SSPS systems. In attempting to choose the location for the launch complex factors needing evaluation will include alternate land uses, location of land with respect to transportation systems, location with respect to proximity to source of SSPS components, the effect of land use on development of nearby land (i.e., growth of communities and industries to support the complex), and the ability of the surrounding natural resources to support the expected population growth attributable to the complex.

5.1.1.3 Resource Extraction and Manufacturing

Aside from the launch complex and the receiving antenna sites, the production and maintenance of the SSPS will require substantial committment of land resource in terms of mining, extraction, fabrication, manufacture and transportation of components that comprise the SSPS system. Each system will require certain resources (such as aluminum). Whenever an irreversible or irretrievable committment of resources is projected a detailed anlaysis of availability and competitive uses of the resources should proceed any final decision regarding the resource use.

5.1.2 Radiant Power Densities

The microwave beam and its impacts need careful evaluation. The orbital transmitting and the ground receiving antennae parameters determine the power density distribution in the microwave beam. The impacts associated with this power transmission are those due to the interaction of the beam with the ionosphere, atmosphere and the receiving antenna. In the lower atmosphere and in the vicinity of the receiving antenna the prime environmental impacts will be caused by the effect of the beam on human organisms, plants, birds, aircraft, weather patterns and disturbances in communications.

In the close vicinity of the satellite the peak microwave power density may exceed 2170 mW/cm^2. More work is needed in assessing the effect of prolonged radiation at such densities at GEO altitudes. Within the ionosphere itself some emission in the radio frequency range is possible and the microwave beam could adversely affect high frequency communication systems locally as well as low frequency navigational systems currently in use. Communication systems utilizing frequencies below that utilized by the SSPS (2,450 MHz) will have to utilize filters to screen out disturbances whereas systems operating as frequencies greater than that utilized by the SSPSwill need to filter the harmonics generated by the microwave beam. Some consideration will have to be given8to the problem facing radio-astronomers. They will effectively be prevented from "pointing" toward the satellite. Fortunately, the H_2 and OH radiation lines will not be interfered with and will be available to the astronomers. A detailed impact assessment will require more information than is currently available on the effects of prolonged microwave radiation through the Earth's upper and lower atmosphere.

The impact of radiant power densities can only be approximately estimated at this time. The effects on birds exposed to microwave power flux densities within the beam at the receiving antenna and the effects on aircraft flying through the beam are projected to be a potential concern and should be determined experimentally. Radio frequency interference by the fundamental microwave frequency and its harmonics turn on and shutdown sequences, random background power, and other superfluous signals resulting from specific design approaches are also a potential concern and a detailed impact evaluation will require that rf interference with other communication channels be carefully controlled.

5.1.3 Waste Heat

Waste heat will be generated by the SSPS system during launch operations, orbital energy collection and conversion and at the receiving antenna. The primary terrestrial impact will be due to waste heat generation at the receiving antenna where, due to the inefficiency of dipole rectification, about 10-15 percent of the rectified microwave power could be released as waste heat. This is substantially less than the waste heat released from conventional power production methods based on thermodynamic cycles.

In evaluating the potential adverse impacts of waste heat generation at the receiving antenna, considerations must be given to the effects of waste heat on the local flora and fauna and on local weather modification due to "heat island" effects. Although albedo control of the receiving antenna components and structure would have the effect of rejecting, on the average, a larger fraction of the incoming solar radiation as compared with the incoming microwave radiation--thereby permitting control over the net energy interchange--a potential problem does exist. Solar radiation is cyclical with a 24-hour period and the microwave radiation would be continuous. The effects of continuous heat rejection on the local flora and fauna as well as weather conditions may vary greatly from those due to cyclical heat rejection even though the average energy in each case may be equivalent.

5.1.4 Safety and Control

In recent years, safety has become a major issue in determining the fate of several energy-related projects. Typical examples of this are conventional nuclear reactors, fast breeder reactors and liquefied natural gas storage projects. Such projects, as the ones mentioned above, are designed and built with safety as one of the prime objectives in mind. On a probabilistic basis, the chances of a major accident involving say a nuclear reactor are very remote. However, although the chances are remote, a rare accident may result in consequences of catastrophic proportions. The public at large does not fully appreciate the many subtleties of safety systems, construction techniques and control systems but can fully comprehend an analysis dealing with the consequences of an accident.

It would appear that the SSPS will be closely scrutinized for safety by the public and that safety and risks may emerge as the most important impact issues. The SSPS will have to be carefully designed with sufficient redundancy in the key safety related-systems that it can be quantitatively shown that the probability of a major accident (loss of control) are extremely remote and that the failure modes are essentially "fail-safe" and will not result in catastrophic consequences.

The current design philosophy of the SSPS is based on maintaining close control and communication between the orbital and ground systems as a primary safety system. This requires that the orbital microwave beam directional system and the phase control be locked into the receiving antenna by means of pilot signal beamed from the Earth-based satellite control station. Such action would preclude the deviation of the microwave beam beyond allowable limits. In case of system failure, the microwave beam phase control cannot be achieved and the beam demodulates and spreads out such that beam density received at ground level would approximate current communciations signal levels and be acceptably low.

5.1.5 Environmental Modification Factors

Several subsystems of the SSPS will, as a result of normal operation, modify the environment by their operation. The degree of environmental modification (or environmental insult) will depend on what actions are taken to minimize the deleterious effects of the subsystems The important SSPS subsystem requiring potential environmental modification considerations include the shuttle operations, transfer from LEO to GEO, orbit keeping, maintenance operations, microwave transmission and the receiving antenna operation.

The transfer of the partially assembled SSPS from LEO to GEO is currently envisioned as being accomplished by the deployment of an advanced electrical propulsion system. Mercury or cesium may be utilized as the working fluid in such systems although argon is a more likely choice The impact of ionic metal discharge at orbital altitudes remains to be evaluated. The frequency and quantity of ionic discharge and its reaction with the environment will need to be established to complete the impact evaluation in this category.

Orbit keeping and maintenance operations will also require some propellant discharge at GEO altitudes. Argon, mercury and/or cesium are contemplated as potential candidate propellants. Once again, frequency, quantity, and interaction with the environment will need to be specified to assess the degree of environmental modification achieved to judge whether it is considered acceptable.

The effect of long-term local transmission of a microwave power beam through the ionosphere remains an unknown. It is expected that because of the rather low power densities involved in the beam the degree of permanent environmental modification will be small. This impact category should be evaluated experimentally before declaring the detailed assessment "complete."

5.2 SSPS Energy Payback

In an environmental impacts analysis of the photovoltaic-powered SSPS, it is enlightening to consider the relationship between the total energy used to manufacture and deploy the system relative to the energy generated by the system. This section summarizes these energy relationships for the on orbit elements of the SSPS, namely, the photovoltaic solar array, the transmitting antenna and the transportation systems to place the satellite at the operational location. A similar assessment of the ground-based element (the rectenna) is required to determine total system energy economics. A significant advancement in the technology permitting realistic definition of the materials and production processes for the rectenna must be conducted before meaningful energy costs can be determined. It is considered important however, to complete the analysis for those sections where the materials and processes are well known.

The payback period for the on-orbit elements of the SSPS is 1.6 years. Table 5.1 summarizes the energy contributions for the major system elements including transportation, materials processing and overhead for facilities operation. These data were compiled for a 5000 MW system using the results of processing-energy requirements for SSPS materials (other than the solar blankets and transportation energy requirements for Shuttle) in recent studies by Battelle. Solar cell blanket energy for manufacture is a projection of requirements from today's processes based on data generated by industry (Spectrolab, Centralab and Tyco) as well as NASA agencies.

The major contributors to SSPS energy requirements are the manufacture of the photovoltaic blankets and the transportation of equipment and materials to low earth orbit. Ninety-seven percent of the energy needs are used by these two elements of the system.

The processes and energy requirements for manufacturing a silicon solar blanket are listed in Table 5.2 using current technology and projected technologies. Since the power output of a solar cell is a function of surface area, each fabrication process is presented in terms of watt-hours per square centimeter of cell.

Table 5.1 Satellite Energy Payback Analysis

ITEM	MASS KG X 10^6	UNIT ENERGY REQ'MT	FACILITY ENERGY REQ'MT	TOTAL KWH x 10^6	COMMENTS
SATELLITE					
• SOLAR BLANKET	7.83	2473 KWH/KG (69.7 WHR/CM^2)	447 KWH/KG (12.6 WHR/CM^2)	22,863	(1) 18 x 10^6 KG SATELLITE PLUS 5.3 x 10^6 KG SUPPORT EQUIP. (2) 1.2 x 10^6 KG MERCURY PROPELLANT* (3) 1,990 KWH/KG OF PAYLOAD TO LOW EARTH ORBIT (4) INCLUDED IN 1,990 KWH/KG
• ALUMINUM	5.89	90 KWH/KG	135 KWH/KG	1,325	
• GRAPHITE RADIATORS	1.55	51 KWH/KG	128 KWH/KG	277	
• COPPER	0.65	36 KWH/KG	54 KWH/KG	58.5	
• KAPTON	1.23	58 KWH/KG	87 KWH/KG	178	
• OTHER	0.85	15 KWH/KG	23	32.3	
TRANSPORTATION					
• TO LOW EARTH ORBIT	23.3(1)	1,990 KWH/KG(3)	N/A(4)	45,574	*CURRENT DESIGN USES ARGON
• TO GEOSYNCHRONOUS ORBIT	1.2(2)	126 KWH/KG	189 KWH/KG	378	
			TOTAL	70,685.8	

Table 5.2 Solar Cell Blanket Manufacture Energy Requirements

	CURRENT, WATT-HRS/ CM^2		PROJECTION WATT-HRS/ CM^2	
● RAW MATERIALS PROCESS	(244)	(304)		(60)
– SiO_2 – Si	4.0			
– Si – $SiHCl_3$	70.0			
– $SiHCl_3$ – Si	230.0			
● SOLAR CELL BLANKET PROCESS		(97)		(9.7)
– CRYSTAL GROWTH	17		1.7	
– SLICING	6		.6	
– LAP & POLISH	8		.8	
– DIFFUSE	15		1.5	
– EVAPORATE METAL	12		1.2	
– EVAPORATE A-R	3		.3	
– SINTER	6	.6	.6	
– SOLDER	5		.5	
– TEST	25		2.5	
● FACILITY		(149)		(12.6)
– AIR CONDITIONING	60		5	
– LIGHTING	44		4	
– FUME SCRUBBER	12		1	
– GENERAL SERVICE	15		1	
– BACKUP	8		.7	
– MISC	10		.9	
● TOTAL		(550)		(82.3)

Requirements for producing semi-conductor grade silicon is the largest energy-intensive process. A three-step process is used today. Silicon dioxide is mixed with carbon and heated to produce metallurgical grade silicon. Purification follows by converting silicon to trichlorosilane which is the decomposed to yield semiconductor grade silicon. The energy requirements for these steps have been estimated at 304 WH/cm^2.

Cost of energy for producing semi-conductor grade silicon is a significant proportion of the cost of the product. Current goals of the producers (i.e., Dow, Corning, Monsanto, etc.) are to reduce these costs to $10/kg by replacing the three-step process with a single step. Twenty promising reaction processes are actively being investigated. To achieve their goal, the energy needed cannot exceed 30 WH/cm^2. A conservative 60 WH/cm^2 is used in these SSPS estimates as the projection for future system processes.

The energy requirements for fabricating the current solar cell blanket were provided by several manufacturers who established energy use by looking at their equipment power levels, the run process time and the number of cells produced. The estimates provided by the manufacturers varied considerably and, where reasonable, conservative estimates were used in this assessment. The total solar cell blanket process requires approximately 97 WH/cm^2.

The "projected" requirement assumes that process energy can be reduced by a factor of 10. Tyco's EFG (edge-fed growth) process technology efforts, for example, already reduced the crystal gorwth step requirements by ten. Automation in the remaining steps should reduce waste, significantly increase production volume and decrease energy requirements.

The facility's energy requirements for lighting, air conditioning, etc. were taken from estimates by Centralab, which assumes 2 x 10^6, 4 cm^2 cells are produced annually. The projected estimate assume that the annual plant energy service requirements will not vary but production for an equivalent floor space will increase by a factor of better than ten.

Current studies of Shuttle energy requirements has established an estimate of 430 x 10^9 BTU/Flt including energy required to produce the propellants and airframe, and to support the launch facilities. This equates to 4815 kWH/kg of mass to low earth orbit . A deploy-only derivative of the Shuttle could increase payload to low earth orbit by a factor of 2.5 without increasing the amount of propellants or the extent of facilities used. Therefore, 1926 kWH/kg was used in the transportation estimates for the SSPS.

If no improvements in solar blanket technologies or launch operations take place, the payback period for the SSPS would increase to six years.

The study of energy economics is an issue requiring considerably more effort than was applied under this contract. Energy economics is a relatively new consideration in system tradeoffs and lacks the data base and agreed-upon methodology to arrive at meaningful conclusions. These efforts should be expanded in the near future.

It is recognized that the rectenna also contributes to the energy input to the SSPS system but this contribution has not been included in the above analysis.

6. IMPLICATIONS FOR TECHNOLOGY DEVELOPMENT

This section summarizes the technology issues needing funding to insure development of the space-based power generation options in the post 1990 time frame. Included are assessments of the technology risk, technology background and recommended technology programs in the following key areas:

- point design development
- systems and economic studies
- microwave power technology
- solar array technology
- large structures including manufacturing, assembly, maintenance and control
- environmental and other impacts.

The technology status and development risk of major technical areas have been assessed using the format adopted in the "Microwave Power Transmission System Studies," NAS3-17835. This provides continuity of highly related efforts.

A risk rating, using the levels 1 through 5 shown in Table 6.1, provides a backdrop for delineating the status of technology. Each key area is addressed and technology programs and objectives suggested.

6.1 Point Design Development

The present (photovoltaic) baseline design--as well as others not included in this study--should be studied further. Special considerations should be given to satellite design as this will provide the basis for tradeoff studies and eventual subsystem optimization (from the technical and economic viewpoints).

Point design analysis of the solar array should project future states of technology, i.e., 1980, 1985 and 1990, as these are likely to be key decision points in the SSPS decision process.

A point design for the current "front-lit" concentration approach should be compared with a "back-lit" design to help identify the cost-effective configuration.

Point design studies of structural arrangements should compare the relatively standard approaches used in this study with approaches that make maximum use of tension supports. An integral part of these

Table 6.1 Technology and Hardware Development Risk Rating Definition

		RISK RATING				
		1	2	3	4	5
		IN USE	IN DEVELOPMENT	ON THE TECHNOLOGY FRONTIER	CONCEPTUAL	INVENTION
STATUS ANTICIPATED WITH: a) SPECIFIC MPTS-FUNDED PROGRAM b) OTHER KNOWN PROGRAMS	TECHNOLOGY	FULLY DEVELOPED	PARTLY DEVELOPED	KNOWN BUT NOT DEVELOPED	NOT KNOWN, CHANCE OF IT BECOMING KNOWN IN TIME FOR MPTS IS GOOD	NOT KNOWN, CHANCE OF IT BECOMING KNOWN IN TIME FOR MPTS IS POOR
	HARDWARE	OFF-THE-SHELF ITEM OR PROTOTYPE AVAILABLE HAVING REQUIRED FUNCTION, PERFORMANCE & PACKAGING	FUNCTIONALLY EQUIVALENT HARDWARE IN USE (OPERATIONAL)	FUNCTIONALLY EQUIVALENT HARDWARE IN DEVELOPMENT	NO HARDWARE IN USE OR DEVELOPMENT BUT DEVELOPMENT IS PROBABLE	HARDWARE WILL NOT BE AVAILABLE UNLESS A BREAKTHROUGH OR INVENTION IS DEVELOPED
PROBABILITY OF DEVELOPMENT COMPLETION WITHIN SCHEDULE AND COST		CERTAIN (ALREADY EXIST)	VERY HIGH	HIGH	LOW	VERY LOW

structural studies should be the point design development of the power distribution system, including selection of ac or dc transmission and the system power level.

Point design options of the control system should consider both centrally located actuators and distributed actuators. These point designs should be used in detailed structural dynamics assessments.

6.2 Systems and Economic Studies

Systems and economic studies should be directed to two major areas, (1) the potential national (and world) economic benefits that may accrue from satellite power stations (SPS) and (2) the selection of the cost-effective SPS system.

Studies that would provide information in the first area include:

- Analysis of the market (demand) for SPS-provided electric power. Because the major proportion of SPS generation costs are capital-related (88 percent), and because the SPS plants are expected to operate at very high plant factors (95 percent), electric power cost (to the busbar) may be forecasted with relatively high accuracy over a 20- to 30-year period. The possibility raises the potential for the offering of long-term power contracts to power-intensive users. The consequences of this are only speculative at this point, but may include, the restructuring of production to capture cost advantages that may accrue from long-term power contracts, location of industry near ground station sites, and favorable environmental effects which may accrue from higher proportions of electrical sources of power.
- The 95 percent plant factor of SSPS (and presumably other forms of satellite power generation) may allow for a restructuring of the supply elements of electric power generation. Currently there exist baseload plants, peaking plants, reserve peaking plants and standby reserve plants. Certainly, this is largely explained by the diurnal demand for power, but to some extent it is a requirement imposed by the system's reliability. The very high reliability of SPS plants coupled with the possibility that through pricing policies the diurnal demand might be altered (i.e., distributed more evenly throughout the day), the power supply structure might be altered in a cost-saving way.

Studies that are required to determine the most cost-effective variant of SPS include:

- The development of a cost model that includes the total SPS work breakdown structure and allows for the specification and estimation of probabilities of costs, performance and schedules.

- Risk analysis to estimate the distribution of total program costs and potential revenues. This includes the analysis of development, production and operational aspects of the PRS program alternatives.

- Insofar as alternative PRS approaches may involve different social and environmental risks, these potential constraints should be studied.

- For SSPS, future solar cell costs and technical characteristics are among the key uncertainties. Therefore, a separate programmatic and risk analysis of solar cell development should be performed.

6.3 Microwave Power Technology

The technical issues for the microwave power transmission systems (MPTS) were developed through a risk assessment of all elements of the concept as they impact the MPTS portions, and these were ranked in an estimated order of importance. For the 24 items in risk rating category 4 the issues presented in Table 6.2 specifically relate to the impact on the microwave portion.

Table 6.3 is a summary of cost estimates for the ground-based development program which would advance technology to a level suitable for the 1985 demonstration satellite. The technology issues have been broken down into four tasks. The first task encompasses those technologies associated with microwave transmission and conversion and is focused through a phased ground test program. The second task consists of the design, analysis, and test of a prototype rotary joint of sufficient size for proof of concept. The third task utilizes Arecibo to test high microwave power density impact on the lower altitude layers of the ionosphere. The fourth task is a detailed examination of radio frequency allocation issues and the selection of a frequency band for space-based power generation.

6.4 Solar Array Technology

Major system considerations are the cost, mass and efficiency of the solar cell blanket. Methods to achieve the goals needed for a cost-effective SSPS have been identified. Needed is an active solar cell development program that concentrates on a low cost fabrication and efficiency improvement for the single-crystal silicon cell for the prime program path, and an active research and proof of concept program for alternate photovoltaic devices for a backup program path.

Table 6.2 Microwave Technology Requirements

ITEM	TECHNOLOGY RISK ASSESSMENT		COMMENTS
	RATING	RANKING	
DC-RF Converters & Filters	4	1	BACKGROUND: Pre-amplifier amplifier & filters convert the high voltage DC power to RF power having low noise and harmonic content. There are at 0.1 to 1.5 million identical devices in one system. This is the highest single contributor to dissipation loss (15 to 19%) with the amplifier contributing 90% of that dissipation. The simplest design concept still results in the most complex mechanical, electrical and thermal set of technology development problems in the system. This combines with requirements for the development of a high production rate at low cost, resulting in reliable operation over a long life. What the noise & harmonic characteristics for the converters are and how they will act in cascade are not known. Filter requirements are to be determined. Ability to develop all the parts, interface them with each other and with the slotted array and operate them with full control and stability constitutes a high development risk and requires the longest lead time in an ambitious development program. TECHNICAL OBJECTIVES: Provide substantial data relating to technical feasibility, efficiency, safety and radio frequency interference.
Materials	4	2	BACKGROUND: Most critical and unusual requirements for materials in this application relate to the presence of the exposed cathodes for the RF generators. In addition, it is desirable that structural thermal strain be small so that distortions over the large dimensions are manageable. The waveguide distortions must be small to permit efficient phase front formation. The waveguide deployed configuration result in low packaging density so that it is desirable to form the low density configuration on orbit out of material packaged for high density launch. Before meaningful technology development can begin relating to fabrication, manufacture and assembly. It is necessary to determine the applicability of the non-metallic materials in particular as they relate to potential contamination of the open cathodes of the RF generators. Due to the critical interaction of materials with structures, waveguides and RF generators, the materials development risk rating should be a strong 4. TECHNICAL OBJECTIVES: Demonstrate cost effective use of non-metallic in terms of meeting distortion free waveguide and minimum impact on open cathodes performance.
Phase Control Subsystems	4	3	BACKGROUND: Phase front control subsystems projected scatter losses (2 to 6%) are second only to the microwave array losses (19 to 25%) in the microwave power transmission efficiency chain. The uncertainty associated with limiting losses to this value is significant. Phase control, being essential to beam pointing as well as focusing, must be shown to be reliable for power user and safety purposes. Risk rating should then be a strong 4. TECHNICAL OBJECTIVES: Demonstrate phase control steady state accuracy subject to error contributions of DC-RF converters and high power radio frequency environment.

Table 6.2 Microwave Technology Requirements (cont'd)

ITEM	TECHNOLOGY RISK ASSESSMENT		COMMENTS
	RATING	RANKING	
Waveguide	4+	4	**BACKGROUND:** Slotted waveguides interface with the RF generators in a high temperature environment. They must distribute the power and emit it uniformly with low losses. They represent a large % of the weight and are conceived to be of .020" wall thickness in aluminum of possibly non metallic composite layups with metallic coating. The ability to manufacture, fabricate and assemble such waveguides is not certain. To provide proper interfacing with RF generators, to limit distortion so as to operate satisfactorily as a subarray of slotted waveguides, and to do so within estimated cost and schedule constitutes high development risk. Risk rating should therefore be a strong 4+; however, significant materials technology development and selection must precede in depth technology investigations. **TECHNICAL OBJECTIVES:** Demonstrate capability of mass producing light weight, distortion free waveguides that can efficiently operate in a harsh thermal environment.
Biological	4	5	**BACKGROUND:** The CW microwave frequency and power densities to be investigated are rather well established. Effects to be anticipated in the sites yet to be selected are functions of ambient condition and the life forms peculiar to the region and those that are in transit. Most certainly areas like the desert southwest of the U.S. would be leading contenders so that effects on plants and animals should be investigated. Detailed investigations building on these conducted for more general purposes must be conducted to assure complete understanding of long-term and transient effects and to provide the basis for securing national and international agreement on frequency allocations, intensities and exposure limits. Development risk rating should be 4. **TECHNICAL OBJECTIVES:** Demonstrate safety of microwave frequency and power densities being considered for SSPS use.
Attitude Control	4	6	**BACKGROUND:** Control of antenna pointing conceived to be accomplished by mechanical action between the antenna and main mast as well as between the ends of the main mast and the solar array primary structure in the vicinity of the slip rings. These are very large members, of light weight construction, having to transmit unprecedented power across the relative motion interfaces, to operate in the space environment, with high reliability and safety, at low cost, packaged for high density earth launch, deployed or assembled in space, for a very long time with limited operations and maintenance attention. The actuators to establish the motion, the moving joints and the moving or flexing conductors are the largest and most complex machinery employed in the photovoltaic powered station and will be the subject of most critical operations and maintenance analyses in order to design the machinery to be essentially maintenance-free. Nevertheless it must be designed to permit maintenance under most adverse conditions of damage and environment. Development risk rating should be 4. **TECHNICAL OBJECTIVES:** Demonstrate the accuracy and life potential of the microwave mechanical pointing system.

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Table 6.2 Microwave Technology Requirements (cont'd)

ITEM	TECHNOLOGY RISK ASSESSMENT		COMMENTS
	RATING	RANKING	
Ionosphere	4	7	BACKGROUND: Effects of the ionosphere on the phase control link are not known definitively, however existing data and analysis indicate that they are probably insignificantly small at the frequencies and power densities being considered. The effects on the ionosphere induced by the microwave power beam are believed to be small. However, from the point of view of other users of the ionosphere and its participation in natural processes there may yet be limits imposed on the power density. The theoretical approaches to doing this are known but the limits that may, yet be imposed are unknown. Development risk rating should be 4. TECHNICAL OBJECTIVES: Measure effects of microwave radiation on the ionosphere and determine social impact.
Power Transfer	4	8	BACKGROUND: The electrical power transfer function, at this large size and power level across flexing and rotating joints, cannot be separated from the mechanical and attitude control functions entirely. Although the technology for performing the functions is basically known, the large scale will present significant new problems. Development risk rating should be 4. TECHNICAL OBJECTIVES: Select power best power transfer design for SSPS and demonstrate performance.
Switch Gear	4	9	BACKGROUND: Switch gear had been conceived assuming multiple brushes from high voltage DC source transferred power to a single slip ring. Extraordinarily high currents in the switch gear resulted and would be the subject of a high risk (4+) technology development program. Decision has now been made to make the multiple brushes feed multiple sliprings, bringing the individual switch gear currents close to the region where the basic technology is known and the major advances would be in packaging for space operations. Risk rating should then be 4. Some aspects of the packaging technology having to do largely with size are not known, which leads to a risk rating of 4. TECHNICAL OBJECTIVES: Develop and demonstrate switch gear including protective elements for spaceborne applications.

Table 6.2 Microwave Technology Requirements (cont'd)

ITEM	TECHNOLOGY RISK ASSESSMENT		COMMENTS
	RATING	RANKING	
Radio Frequency	4	10	BACKGROUND: Radio frequency and bandwidth allocation is normally a long process involving national and international technology and socio-economic considerations. It will take 2 to 4 years of DC-RF converters' and filters' technology development to mature the concept and make available meaningful data. Convincing the national and international community involved that gigawatts of power beamed from space at an allocated frequency with a specified narrow bandwidth will not in fact result in significant interference requires a positive approach that is yet to be defined. When it is shown convincingly that power from space would (a) be a significant answer to the national and international future power needs and (b) permit frequency allocation and bandwidth to be defined without significant interference outside the band; then securing high priority for frequency allocation will be a normal process. The appropriate risk rating is 4. TECHNICAL OBJECTIVES: Investigate radio frequency interference and allocate band to SSPS that would have minimum impact on other users, particularly Radio Astronomy.

Table 6.3 Microwave Technology Resource Requirements, $ millions (1975)

TASK	Calendar Year										COMMENTS
	76	77	78	79	80	81	82	83	84	85	
1 • DC-RF CONVERTERS & FILTERS	.5	.6	.4	.4	.4	.4					
• PHASE CONTROL	.4	.4	.3	.2	.2						
• WAVEGUIDE	.4	.4	.4	.4	.4	.2					
• SWITCH GEAR	.4	.4	.3	.2	.2						
• GROUND TEST (INCLUDE BIO TESTS)	2.4	2.5	2.2	3.3	5.3	7.0					
2 • ATTITUDE CONTROL	.3	1.0	2.0	2.0	.4	.4					
• POWER TRANSFER	.2	2.0	3.0	6.0	1.0	.4					
3 IONOSPHERE	← 11 →										REQUIRES MODIFICATION OF ARECIBO
4 RADIO FREQUENCY	.3	.3	.3								
TOTAL	6.3	9.4	10.7	14.3	9.7	10					

Table 6.4 summarizes the key technical areas with their associated risk rating and ranking for developing a low-mass, low-cost, highly efficient solar cell blanket for SSPS. The technology risks are rated in the categories outlined in Table 6.1. The rankings of the priority for the association technology programs are based on the status (risk) and the economic impact the technology improvement would have on the program.

Some of the technology issues identified in Table 6.4 are already being pursued by industry and ERDA. In ranking priorities, those technology programs that NASA might support are given higher rank. For example, cost improvements for processing raw materials to semi-conductor grade silicon is alreading being actively pursued by industry. Also, ERDA is supporting development of the EFG crystal growth process development. NASA might augment this program to insure that efficiency levels and quality control levels needed for a space-based array are met.

Table 6.5 is an overview of recommended technology development expenditures assuming that SSPS goals should be met in the mid-1980s for assurance of a 1995 operational plant IOC. These suggestions are in agreement with those recommended for terrestrial applications outlined in the "Workshop Proceedings for Photovoltaic Conversion of Solar Energy for Terrestrial Applications," held October 1973. NASA expenditures in Tasks 1 and 2 should be minimal. The unique requirements for space qualified solar cells warrants NASA expenditures in Tasks 3 through 5 at the same levels recommended for terrestrial applications.

Issues Requiring Further Systems Study

Solar concentration is shown to reduce SSPS cost. Lightweight mirror design concepts and their implementation are needed. New filter designs for concentrators will help improve solar cell life and performance. If high concentration is used, techniques for fabricating lightweight structure and contour control are needed.

The SSPS will generate high-voltage power in a relatively stable thermal environment, but must maintain performance during a 30-year exposure to ultraviolet radiation as well as particulate radiation. The objective is 6 percent degradation over five years. Improvements in environment resistance can be achieved by improved material, radiation spectral tailoring, high-voltage plasma protection, meteorite hardening and improved annealing techniques.

Multi-megawatt solar power generation requires switching protection at high voltage and current. Development of high-voltage switches and blocking devices are needed. Circuit design must consider induced magnetic moments to reduce effects on the overall spacecraft control. High voltage also leads to corona formation that reduces component life. The power distribution system design

Table 6.4 Large Solar Array Technology Requirements

ITEM	TECHNOLOGY RISK ASSESSMENT		COMMENTS
	RATING	RANKING	
1. Raw Material Process	3	4	BACKGROUND: The initial process in fabricating solar blankets requires three energy intensive high temperature cycles. A single step process could result in savings of 3 to 5 over the $60/kg to $80/kg price paid today. Trichlorosilane used in the process is a large contributor to both energy use and cost. Alternates to this process should be pursued. Presently, Dow Corporation is researching more economical goals for producing semiconductor grade silicon. Dow is actively investigating 20 promising chemical reactions with the goal to reduce the cost to $10/kg. TECHNOLOGY OBJECTIVES: Achieve a 3 to 5 reduction in cost for bringing raw mate to semiconductor grade silicon.
2. Crystal Growth	2	5	BACKGROUND: Three approaches to single-crystal growth being pursued today are: 1) Czochralski; 2) WEB and 3) EFG. The Czochralski method is characterized by large amounts of waste materials and is projected to achieve at most a factor of 2 savings in cost. WEB process could be sealed up in crystal growth speed and geometry with the potential of achieving a factor of 5 reduction in cost. The EFG process shows the promise for the most significant cost reductions (a factor of 10 to 100). The major problems are to find die materials that can withstand the temperatures of the process and you maintain the efficiency of the solar cell produced. The current process work being performed by TYCO fabricates a silicon ribbon 100 μ thick approaching the 50 μ SSPS requirement. TECHNOLOGY OBJECTIVES: Develop the EFG process to the point where 50 μ silicon ribbon can be produced with 100% crystal and cell yield. WEB process should be continued as a program backup.
3. Blanket Processes	4	2	BACKGROUND: Current methods for fabricating solar blankets is a slow, mostly hand-made process. A continuous process is indicated. An automated process that includes function formation, installs contacts, performs etching, etc. is basically an engineering problem. A pilot plant and verification program is needed. TECHNOLOGY OBJECTIVES: Formulate alternate concepts for blanket processing and demonstrate most promising techniques.
4. Packaging	3	5	BACKGROUND: The requirement for 30 year life in a space environment suggests that improvements in cell encapsulation would be required. Materials technology that improves the thermal and radiation resistance of the cell must be developed and included in the overall automated fabrication of the blanket. TECHNOLOGY OBJECTIVES: Develop new materials that improve cell efficiency and radiation resistance. Incorporate advanced encapsulation approach into the continuous cell fabrication process.

Table 6.4 Large Solar Array Technology Requirements (cont'd)

ITEM	TECHNOLOGY RISK ASSESSMENT		COMMENTS
	RATING	RANKING	
5. Solar Cell Performance Improvement	4	1	BACKGROUND: Current industry space qualified solar cells can achieve beginning of life conversion efficiencies of 12 to 14%. A program that strives to improve these efficiency levels to 18 to 20% (AMO) is required. This goal can be achieved through increases in fill factor, short-circuit current, and open-circuit voltage. It would be desirable to decrease resistivity of the bulk silicon to 0.01 ohm-cm. Lower resistivity gives higher open-circuit voltage. Increased short-circuit current could be achieved by antireflective coatings that match across the cell spectrum. The major issue is to achieve these efficiency improvements in a mass produced light-weight solar cell blanket. TECHNOLOGY OBJECTIVES: Improve solar cell conversion efficiency to 19% (AMO) and maintain this efficiency in a mass produced light-weight solar cell blanket.
6. Alternate Photovoltaic Devices	4	3	BACKGROUND: Investigations into alternate photovoltaic conversion devices are showing a great deal of promise. Of particular interest is the Gallium Arsenside Al GaAs/GaAs heterojunction cell. These devices shown high performance at concentration (12% AMO at a concentration ratio of 300). An active research and proof of concept program on alternate devices to the silicon cell should be pursued. TECHNOLOGY OBJECTIVES: To identify and develop at least one new photovoltaic conversion device that can serve as an alternate to the silicon.

Table 6.5 Large Solar Array Technology Resource Requirement
$M Terrestrial/($M Space)

TASK	76	77	78	79	80	81	82	83	84	85	COMMENT
	TECHNOLOGY ←				→ PROOF OF CONCEPT						
1. REDUCE RAW MATERIAL PROCESS COST	0.8 (0.1)	1 (0.2)	1.5 (0.3)	2 (0.5)	← 50 → ← (1) →						AUGMENT INDUSTRY/ERDA EFFORT
2. REDUCE CRYSTAL GROWTH PROCESS	2.5 (0.5)	4 (1.0)	3.5 (1.0)	5 (2.0)	← 30 → ← (3) →						AUGMENT INDUSTRY/ERDA EFFORT
3. BLANKET PROCESS	2.5 (2.5)	2.5 (2.5)	3 (3)	4 (4)	5 (5)	← 80 → ← (3) →					NASA SUPPORT SPACE-BASED BLANKET PROCESS DEVELOPMENT
4. PERFORMANCE IMPROVEMENT	4 (4)	4.5 (4.5)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)	5	5	NASA SUPPORT SPACE-BASED BLANKET IMPROVEMENT
5. ALTERNATE PHOTOVOLTAIC DEVICES	3 (3)	3 (3)	3 (3)	4 (3)	5 (5)	5 (5)	5 (5)	5 (5)	5	5	NASA SUPPORT SPACE-BASED ALTERNATES
TOTAL	12.8 (10.1)	15 (11.2)	16 (12.3)	20 (14.5)	← 220 → ← (37) →						

must address long transmission distances on SSPS. A key trade is to determine the extent to which the conducting buses can also be used as structure. A tradeoff between ease of assembly, cost, mass, reliability and electrical efficiency should be addressed.

A systems study summarized in Figure 6.1 should be performed to delineate a technology development program that establishes realistic goals in a phased program. The objective of this study would be to determine the primary and backup paths for the demonstration satellite's solar blanket.

The tasks in the systems study have the following outputs:

Task 1: Configuration Concept Design/Selection

- Candidate concept designs for the solar array using various levels of concentration and solar cell type
- Structural thermal evaluation of the array including the solar blanket itself.

Task 2: Programmatics

- Evaluation of the costs of each candidate array
- A ranking of program options with final selection of the primary and backup program path
- Technology program schedule and performance goals.

Task 3: Operations

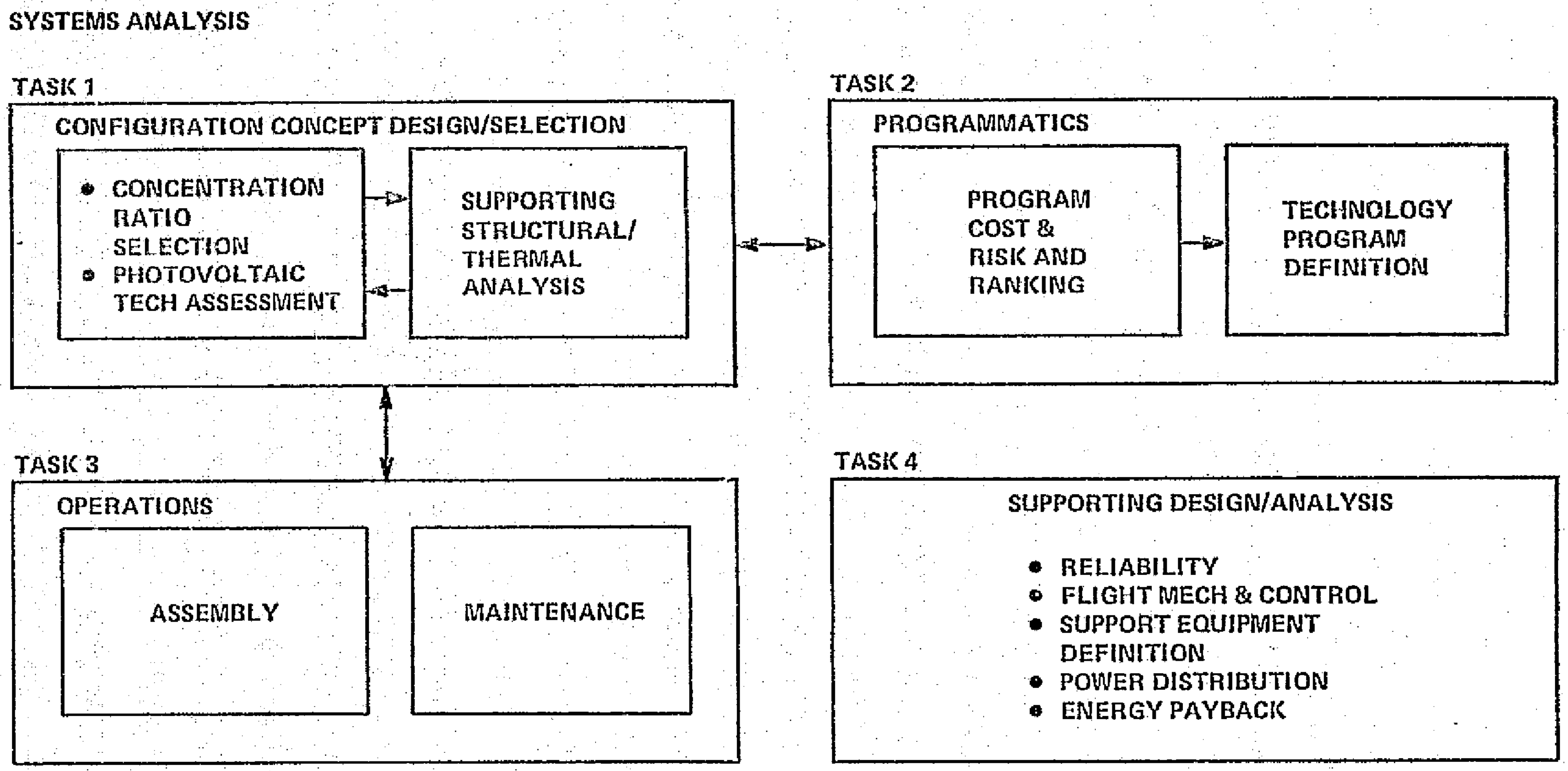
- Identification and evaluation of solar blanket assembly and maintenance operations
- Mission plan for Shuttle sortie demonstration flights.

Task 4: Supporting Design/Analysis

- Documentation of those efforts on assembly support equipment designs, power distribution interfaces, etc., needed to support the systems study.

6.5 Large Structures - Manufacturing, Assembly, Maintenance and Control

The development of necessary technologies for deployment of large structures in space requires a broad range of investigation including evaluation of materials characteristics, unique structural designs that are lightweight and capable of being tightly packaged for launch and development of low cost space assembly equipments and techniques. Table 6.6 is a top level summary of these issues.



TECHNOLOGY PROGRAMS

- EFFICIENCY IMPROVEMENT (14% → 19%)
- WEIGHT REDUCTION (.525 → .282 KG/M^2)
- COST REDUCTION (→ 54 \$/M^2)
- LIFE INCREASE (→ 30 YRS, 6% DEGRADATION IN 5 YRS)
- HIGH-VOLTAGE CIRCUIT CONTROL (40 KV ~ 8% LOSS)

Figure 6.1 Large Solar Array Program Phase A Study

Table 6.6 Structures Technology Requirements

ITEM	TECHNOLOGY RISK ASSESSMENT		COMMENTS
	RATING	RANKING	
Structure	4	1	BACKGROUND: Structure is characterized as being thin wall, low deployed density, high surface-to-mass ratio, metallic or possibly composite elements assembled into open space frame structural elements which in turn are assembled into yet larger space frames forming very large (approx. 1 km) antenna and even larger solar arrays. After materials technology development and selection, the new problems associated with low thermal inertia large dimension structures traversing the sunlight/shadow terminator at orbital velocities must be resolved. The resulting basic design, recognizing high launch packaging density limitations must be fabricated on orbit to achieve the final low density deployed configuration. How this should be done is not known and development risk rating should be considered as a firm four. TECHNICAL OBJECTIVES: Develop basic structural element with thickness of 0.02 inches (0.005 m) and less using aluminum and composites commensurate with required ground-based and/or space-based manufacturing and assembly techniques.
Manufacturing Modules	4	2	BACKGROUND: The specific technology for manufacturing modules is not known at this time, but should be relatively straightforward to develop once the basic design and materials have been established for the items to be manufactured in space. The major items are structural elements (open space frame structures) and slotted waveguides for the subarrays. Materials technology must be understood first and then engineering efforts for relatively automated manufacture must begin. Several iterations are probably required so the development must be paced to assure a reliable economic process. Development risk rating should be a firm 4. TECHNICAL OBJECTIVES: Develop modules for on-orbit manufacturing of waveguides and structure.
Remote Manipulators	4	3	BACKGROUND: The specific technology for remote manipulation modules is not known at this time. However, some investigations have been conducted in associated control systems. The development of these particular remote manipulators should begin after the hardware to be maneuvered and joined has been defined. The control links will probably be through TDRS so capabilities and limitations may begin earlier. Development risk rating should be a firm 4. TECHNICAL OBJECTIVES: Develop remote manipulator modules for the assembly, installation, removal, replacement, maintenance and operations in space.

Table 6.7 is an estimate of the near-term resource requirements needed to implement structural technology efforts. These technologies have been categorized under two broad tasks. The first is structural design and analysis which will provide the base upon which the design efforts for the demonstration satellite will build. The second task will design, build and test through simulation and verification programs, assembly/fabrication equipments and techniques.

Issues Requiring Further Systems Study

1. Static and Dynamic Structural Response to Thermal and Load Environments

The orbital load conditions which may design the structure are solar pressure, gravity gradient control torques and orbital station keeping control torques and orbital station-keeping control forces. The dynamic responses of the large, flexible lightweight space structure to these disturbances require assessment to obtain a stress-time history over the 30-year service life.

A significant contribution to the thermal stress/distortion is the induced thermal gradients resulting from the eclipse of the SSPS by the Earth's shadow. The SSPS experiences eclipse during a 45-day period at the vernal and autumnal equinoxes. The time in the Earth shadow varies from 0 to 72 minutes. As the satellite enters the shadow, the temperature decrease in the thin structural members will be rapid. Thus, the vehicle will experience significant thermal gradients. As the satellite exits the shadow, the thermal excitations will reverse. The entire thermal exposure cycle can induce low frequency oscillations in the entire flexible vehicle. The effects of these oscillations on the overall system require assessment.

To study the control of a flexible structure in a gravity-gradient field, it is necessary to accurately determine the difference between the gravity force and the orbital centrifugal force at each mass point. In many existing computer programs these effects are computed and then subtracted; however, the effects are nearly equal, and it is the small difference which is of consequence. This procedure is considered too inaccurate to be of value. To improve the procedure, the gravity and orbital centrifugal effects should be expanded in a series, analytically subtracted, and programmed in a general time-history structural program.

It is likely that the attitude control jets will excite a number of high-frequency vibration modes as well as the lower-frequency and rigid-body modes. These combined

Table 6.7 Structural Technology Resource Requirements

TASK	76	77	78	79	80	81	82	83	84	85
	PRELIMINARY DESIGN				←→	DESIGN DEMO SATELLITE				
1. STRUCTURE										
• CONFIGURATION	.5	.5	1.0	1.0						
• STRUCTURAL & CONTROL ANALYSIS	.3	.7	1.0	1.6						
• THERMAL	.3	.7	1.0	1.0						
• STRUCTURAL ELEMENT DESIGN & FABRICATION	.7	1.0	2.0	3.5						
2. ASSEMBLY & OPERATIONS	2.0	3.5	7.0	10.0						
TOTAL	3.8	6.4	12	17.1						

motions may result in waves which emanate from each jet and damp out as they proceed through the structure. To accurately predict the dynamic behavior of the structure, it appears that an unusually large number of modes will be required; thus, the computer time and storage requirements would be excessive. For these reasons a study is recommended to determine more effective dynamic-analysis methods for large flexible space structures. The improved techniques developed in this study will also provide increased confidence in the ability of the control system to achieve the required stability.

A suggested near term effort, that follows the logic shown in Figure 6.2 would identify the extent of control system/structural dynamics problems by starting with a relatively small structural model and building up to a point of confidence in the simulation. The task outputs would be:

Task 1: Structural design for an SSPS array, antenna and rotary joint with members sized for operational load, transport loads and thermal induced loads.

Task 2: Structural dynamics model of array rotary joint and antenna in addition to model characteristics needed in a control analysis simulation.

Task 3: Design and assessment of alternate control system designs for the solar array rotary joint and antenna subarray mechanical pointing system.

Task 4: Design and analysis of an SSPS stationkeeping system.

Task 5: Verification simulation of combined effect of control system and structural dynamics.

2. Manufacturing and Assembly Techniques

The capability to fabricate and assemble large structures in space is a key issue. The design fabrication, assembly and transportation of the large space structure presents many significant problems requiring advances in the state-of-the-art of the related structural, materials, manufacturing and assembly technologies. The manufacturing and assembly techniques studies under this contract were based on the use of an automatic fabrication module. The module automatically fabricates and assembles the major structural components from raw stock in low earth orbit.

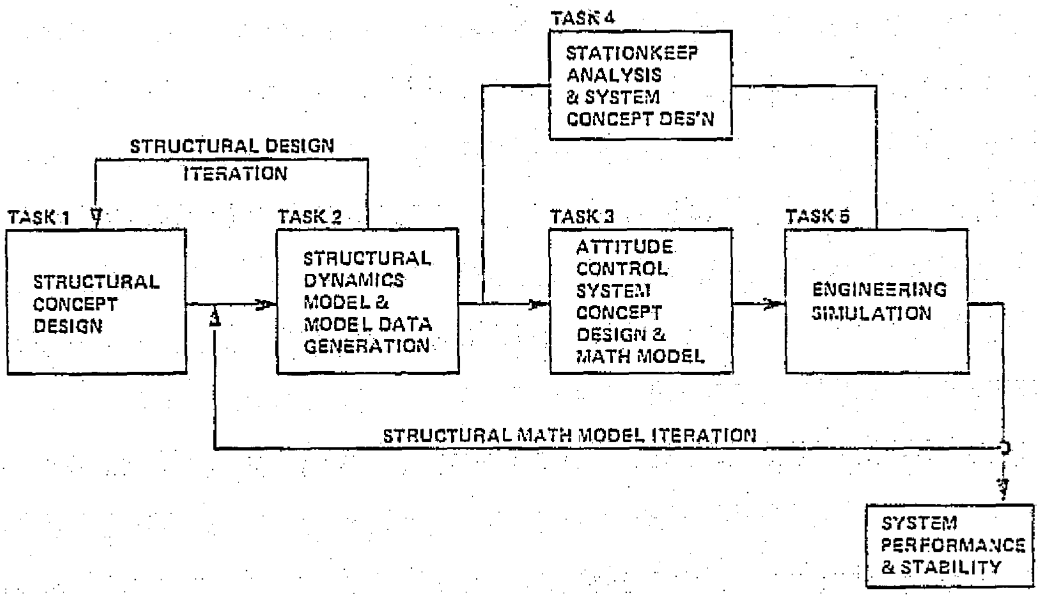


Figure 6.2 Near-Term Structural Systems Study

It is recommended that the above be studied together with alternate methods of manufacture and assembly to establish the most effective and lightest configuration.

The manufacturing modules roll-form the basic structural elements which are assembled and welded into the progressively larger components. Investigations should be made to assess the use of other materials such as kevlar composites, graphite/epoxy composites, beryllium alloys, titanium alloys and various other aluminum alloys. These materials evaluations should be coupled with the use of other structural shapes and configurations to obtain a more realistic trade study of mass, cost and complexity.

3. Structural Verification Techniques

It is recommended that investigations be carried out to evolve methods for verifying the structural integrity of the SSPS vehicle. The application of ground test techniques currently in use are obviously infeasible. It is proposed that ground test techniques for scale models which are structrually and dynamically similar be developed. This procedure will provide verification of analysis methods. A second phase of this activity would be to design, fabricate and flight test an instrumented model of reasonable scale.

4. Maintenance

Additional system level studies are required to delineate technical issues and programs for maintenance operations. The failure rates assumed in the maintenance assessment in this study are soft at best. The failure rate for solar cells for example is based on OAO where careful selection of high quality components was the rule. On SSPS, mass production of solar blankets may preclude achieving as high a reliability. If the open-circuit failure rate for an individual solar cell increases an order of magnitude (2.63×10^{-3}/yr), 7.8 percent of the blanket LRU will fail in 30 years, requiring at least one replacement of the entire array ($112 M/yr) over the life of the satellite. A trend might also be demonstrated for the microwave components; however, the assumed redundancy and amplitron tolerance to malfunction may provide significant relief. An across-the-board reliability assessment of the SSPS is needed to more precisely determine maintenance cost.

The 5.6 percent power degradation level before lowest replaceable unit (LRU) replacement used to determine maintenance cost is driven by the assumed cost to repair (238 $/kg). If transportation and maintenance cost double, the point where cost of repair equals expected loss in revenue will also double. A study that more precisely evaluates the tradeoff between loss in revenue and the cost to repair is needed for each major satellite component. Amortization of support equipment costs for various approaches to maintenance should be included in the analysis.

The initial investment for maintenance support equipment, which assumes that one 6-man space station is allocated to each SSPS, appears to be excessive for the amount of maintenance predicted. Modifications to the maintenance scenario assumed should be reevaluated. Perhaps the space base and teleoperators assigned to each SSPS could be used to service several satellites, thus reducing considerably the cost to each unit. A second option would eliminate the use of multiple, manned-space stations. An on-orbit maintenance "depot" facility would house spares and teleoperators and the manned transport vehicle would be of sufficient size to allow maintenance of support equipments and other functions requiring manned participation. In this manner, the costs for the man-rated equipments could be shared by many power stations. Additional study is needed to determine the most cost-effective approach.

6.6 Transportation

Transportation costs are potentially the most significant element in determining the costs of the SSPS. Transportation costs vary as a function of the lift capability of the launch system and the orbit inclination at which assembly is performed. The technology base for developing the launch vehicle is in-hand. Early SSPS development can be achieved with the Shuttle or derivatives of the Shuttle. Studies are already underway that are evaluating conceptual designs for heavy lift launch vehicles with payloads to low earth orbit of 183,000 kg (400,000 lb) or greater. The orbit transfer stage, which will transport the SSPS totally assembled or as large assembled modules to geosynchronous orbit, require more technology development if cost goals are to be met. Near-term system studies are required to delineate the requirements and cost impact of transportation options.

Figure 6.3 shows the relationship between orbit-to-orbit stage characteristics, launch system performance, and electric power incremental unit charge rate. A high performance gas core reactor or ion stage would be required for cost-effectiveness. The ion propulsion or other high performance propulsion systems appear to offer the lowest cost approach for orbit-to-orbit transport of material. The following is a list of significant issues for ion propulsion:

1. Development of a large diameter thruster. Current engine development (LeRC) has concentrated on a 30 cm thruster. An extension of the ion thruster diameter to 1 meter

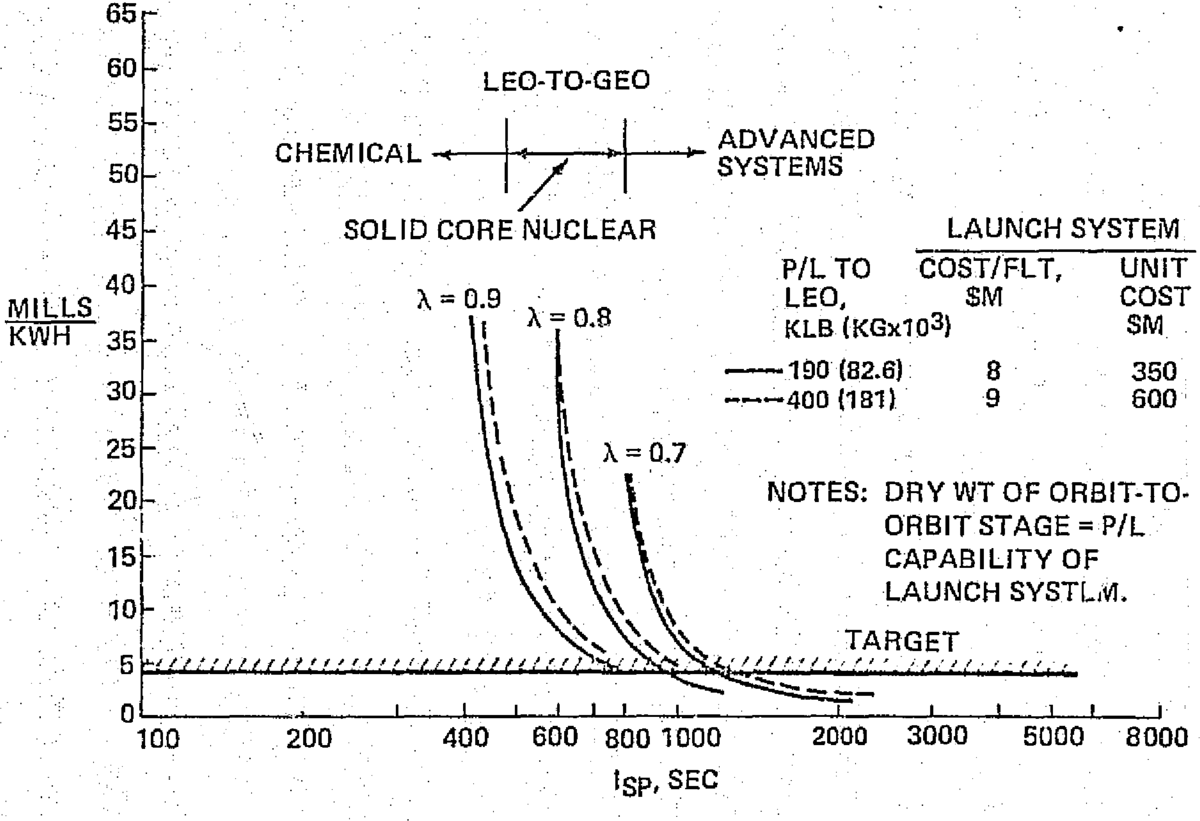


Figure 6.3 Orbit-To-Orbit Transport Costs

seems within technical feasibility. The grid material of the engine will be the limit to the size of these devices. As the thruster operates, the grids distort thermally varying the spacing between the grids.

2. Selection and development of the power source. The major concern is that the stage must transport materials through the Van Allen Belts. The silicon photovoltaic power source may not be the best approach when performance degradation of the cell due to radiation while in the belts is more precisely taken into account. Other power sources, such as nuclear or solar thermal, could readily get around the radiation problem but would introduce other technology problems. What is needed is an across-the-board system study of all options to better identify the more attractive approaches.

3. Selection of the propellant. Most current technology development has concentrated on mercury propellants. Use of this material on a scale needed for the SSPS may not be acceptable in terms of the potential contamination to SSPS sensitive devices as the microwave converters and solar cells. As in the case with selection of the power source, an across-the-board systems study of the propellant options is needed to clarify technology requirements.

6.7 Environmental Impact Analysis

As in the case with any project that may significantly affect the human environment, all components of the SSPS and more generally, SPS, systems should be subjected to a thorough evaluation of the impact on the environment. In planning the SSPS (or SPS) program,[1] this task should not be treated lightly for it is the issue of environmental impact that has delayed construction of conventional nuclear reactors, and liquefied natural gas storage projects, and was an emotional issue in the United States supersonic transport program.

Because of the magnitude of the SSPS (SPS) program, detailed environmental impact assessments (EIA) and environmental impact statements (EIS) must be prepared for the major components and subsystems of the SSPS (SPS). These assessments in aggregate will comprise the assessment of the SSPS (SPS) and will be used when comparing the impact of the SSPS (SPS) with the impact of alternative power systems. Among the major components and subsystems of SSPS are the launch and landing facilities for shuttle vehicles, the receiving antenna complexes, the

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[1] This study has been limited to the SSPS concept of satellite power generation. Other systems are being studied and whichever version of satellite power station (SPS) is selected must be subjected to rigorous environmental analysis.

corridors in the atmosphere through which microwave energy will be beamed from orbiting satellites, the orbiting solar array and microwave transmission systems, the terrestrial power grid, facilities dedicated to the manufacture of components of the system, and all of the SSPS support facilities. Other variants of SPS such as solar thermal and nuclear will have some unique characteristics regarding environmental impact. There is, however, much commonality among these systems.

The National Environmental Policy Act of 1969 (NEPA) and the Council of Environmental Quality (CEQ) guidelines clearly state the procedures whereby projects are subjected to environmental review. The environmental impact assessment/statement (EIA/EIS) level of analysis must be in conformance with these requirements. In broad outlines the EIA/EIS format for all subsystems of SSPS will require:

Description of the SSPS (SPS) System. Each subsystem project must include a general project description, and descriptions of the construction phase, the operation phase and the eventual abandonment phase. The general project description should include the nature of the action, the location and the purpose of the action as it relates to the total SSPS (SPS) system.

Description of the Existing Environment. The physical, biotic, and human environments at and in the vicinity of the proposed project site must be thoroughly documented prior to the initiation of the project. The description of the existing environment includes such factors as real estate availability and tax structure, availability of utilities and transportation, labor force, living and recreational conditions, baseline environmental data, zoning laws, building codes and required permits, and a justification for the particular choice of site for the proposed SSPS subsystem.

Environmental Effects. A thorough description of the environmental effects that are specific to the subsystem locational environment interaction is the most important part of the EIA/EIS analysis and it involves a synthesis of the project description and the description of the environment without the proposed project. Impacts on the physical, biotic and human environments must be studied in a level of detail appropriate to the subsystem magnitude and operational mode.

Alternatives to the Proposed Project. All reasonable alternatives to the SSPS (SPS) must be evaluated from an environmental point of view so that choice in the course of action can be made. The alternative of taking no action or postponing the action must be considered. This comparison of alternative systems will not be made at the component level of the SSPS (SPS) but at the aggregate level because of the magnitude of the SSPS (SPS) and the long time period during which it will be developed. The discussion of alternative techniques for power generation will continue as a general topic amongst policy makers for many years. It is obvious that the discussion of alternatives to the SSPS (SPS) will be subject to criticism by all parties who are adversely affected by the action since they will be biased towards any alternative action which avoids impacting them in either an environmental or economic sense.

Other Effects. In addition to the above four major areas of EIA/EIS analysis, the CEQ guidelines currently require that additional points be addressed. Some of these points are very important in the planning phases of SSPS (SPS). Briefly these include:

- adverse environmental effects which cannot be avoided
- relationships between short-term uses of man's environment and the maintenance and enhancement of long-term productivity
- any irreversible or irretrievable commitments of resources that would be involved in the proposed action
- an indication of what other interests and considerations of federal policy are thought to offset the adverse environmental effect of the proposed action.

The comprehensiveness and objectivity of environmental impact assessments are crucial to the success of any project. Review of impact statements by public agencies and by the courts is often focused primarily on how the analysis meets the terms of the law and the attendant regulation. The actual substance of the report, although important, is often less an issue than the completeness and objectivity of the analysis. Further, a thorough assessment provides an objective framework within which the project can be considered by the public.

Preparation of an EIA/EIS for the SSPS is presently several years away because the program is still in the planning and feasibility stages. However, there are a number of environmental assessments that should be undertaken during the early stages of such a large and important program. An environmental definition study phase should be initiated immediately to:

1. Examine the environmental regulations applicable to all subsystems of the SSPS operation in order to ensure compliance with the law and expedite SSPS realization.
2. Identify those technical areas where long lead-time environmental studies should be initiated in order to establish baseline data required for the support of the environmental impact assessment. Most notable among these is the effect of microwave radiation upon fauna, flora, and the land, water and atmosphere.

3. Identify the resources that must be allocated to development of the SSPS. Included in this assessment should be land management factors, total energy requirements for system construction, resource factors for long-term operation and maintenance, and other factors which represent an irreversible and irretrievable commitment of resources.

4. Identify the unavoidable adverse effects on the environment.

5. Identify technical and institutional obstacles to the successful completion of the SSPS program in order that they may be overcome.

Considering the importance of the SSPS (SPS) program, a multi-man-year effort will be required of a team that has expertise in biology, the physical sciences, social sciences, engineering, environmental affairs and risk analysis, as well as a thorough familiarity with the technical and operational details of the SSPS (or SPS).

Appendix A: Economic Methodology

A.1 Introduction

The materials presented herein were developed for this study over the period February through June 1975, and represent an important project activity of ECON, Inc. Some earlier results have already been disseminated [10, 11 and 12].

The purpose of this appendix is to present a detailed review of the economic concepts and analytical constructions used in this report. The objective is twofold:

- to provide the reader with the means to verify the study's results and substitute alternative input data and assumptions if desired, and
- to provide a reconciliation of the approaches used in this study with those of other energy-economics studies.

The basis for the first objective is clear. Regarding the second objective, it is all too often that due to the lack of complete information and inconsistency of approaches among energy-economics studies, comparisons are impossible. In this appendix, the minimum information required to make interstudy comparisons is established.

The following topics are addressed:

- Methodology for Comparative Economic Analysis of Electric Generation Systems (A.1)
- Computation of the Present Value of Capital and the Equivalent Annuity (A.2)
- Reconciliation of Alternative Approaches for Computing the Present Value of Capital and Equivalent Annuity (A.3)
- Computation of Economically Justifiable SSPS Unit Cost (A.4)
- DDT&E Payback Analysis (A.5).

A.2 Methodology for Comparative Economic Analysis of Electric Generation Systems

Figure A.1 illustrates the cash flow profile of a representative electric power generation system. The cash flows required for the construction of the system are represented by the values, \$110 x 10^6 per year (C_t) over the period 1991 to 1995. The capital payback (A_t) is represented by the values, \$41.7 x 10^6 per year over the 30-year operational life of the system.

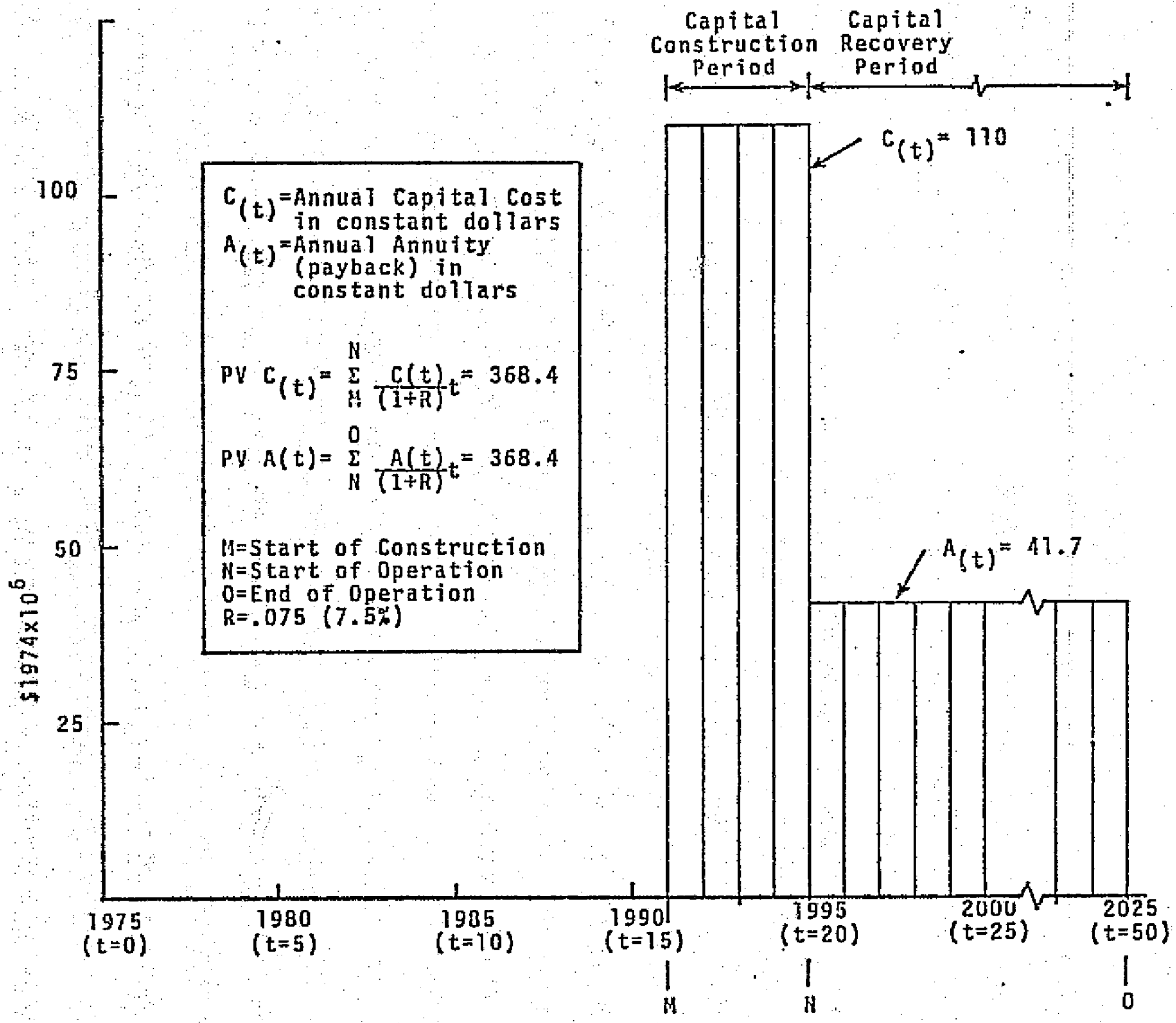

Figure A.1 Electric Generation System Cash Flow Profile

In the example shown, the constant dollar cost of the plant is $440 per kilowatt and these costs are distributed equally over the 4-year construction period.[1] According to the formula provided for computation of present value, the (1975) present value of the cost of capital is $368.40. The capital recovery payment (annuity over the 30-year operational period of the plant) is a value such that its (1975) present value equals that of the present value of the capital. Thus, at the stipulated discount rate, 7.5 percent, the annuity (A_t) is a cash flow received by the providers of capital to the utilities (lenders and equity owners) such that they (in 1975) are indifferent to holding $368.40 or receiving a annuity of $41.70 per year over the period 1995 through 2025. This present value concept is expanded below with the use of Figure A.2 which provides an additional example.

Assume that a particular technology subsystem of the SSPS were estimated to cost $380 million and that the costs of development would be expended--evenly--over the period 1985 through 1990. All expenditures would be paid out at the beginning of each year, i.e., $76 million would be expended at the beginning of each year for five years. Using the formula provided in Figure A.1, the present value of this expenditure is computed to be $161 million. This is the value which is economically equivalent in 1975 to $360 million expended in the way assumed, i.e., five equal payments. That is, a "rational" economic being would be economically indifferent between having a bank balance of $161 million (in 1975) and receiving $76 million per year for five years starting at the beginning of 1985.

As illustrated in Figure A.2, a $380 million DDT&E expenditure could be financed with an initial bank balance of $161 million starting in 1975. The present value, $161 million, is a function of (1) the discount rate, (2) the year that the expenditure begins, and (3) the expenditure pattern. Higher interest rates and/or an earlier expenditure start would reduce the present value, and vice-versa.

As shown in Figure A.2, $161 million put in the "bank" would compound at an annual rate of 7.5 percent to $325 million at the beginning of 1985 when the first "withdrawal" of $76 million is made. This would reduce the "bank balance" which would, in turn, increase by the interest received over the year; and then another $76 million payment would be made, and so on. After the last $76 million payment, the balance would be reduced to zero.

The computed value of A, the economically equivalent annuity, is a function of the parameters shown, i.e., M, the date of the beginning of construction, N the date of the beginning of operation, O the end of operation and R, the discount rate. The most sensitive paramenter is R--

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[1] The assumption of equal distribution of costs over the construction period is only for purposes of example. Certainly, the present value of capital may be computed under any distribution of outlays.

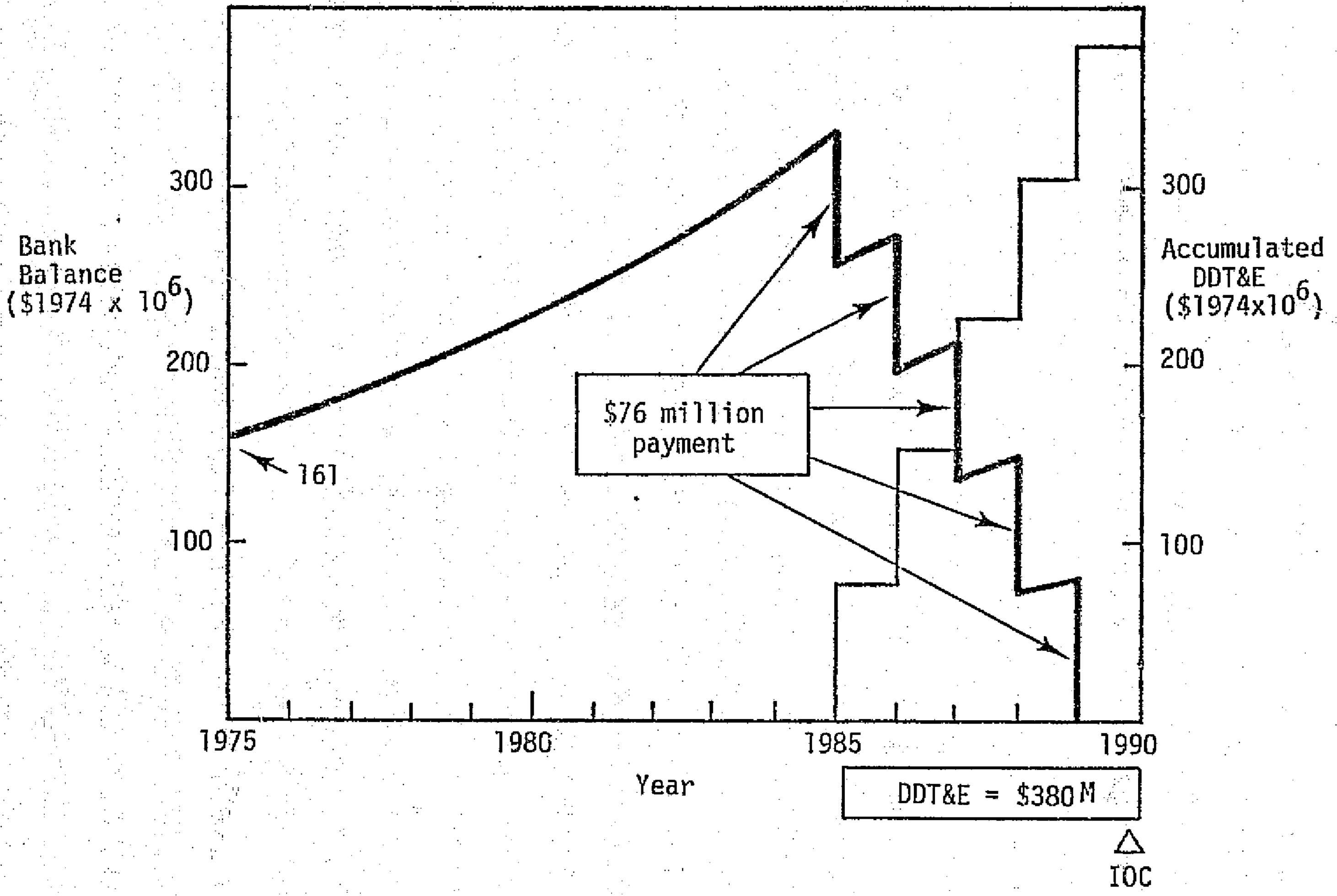

Figure A.2 Percent Value Rationale, R=7.5%

the higher the value of R the greater the annuity must be to yield an eqivalent economic value, and vice-versa.

To the value of A must then be added the "recurring" costs of the electrical generation system, i.e., values for taxes and insurance, operations and maintenance and, in the case of the terrestrial systems, fuels.

A major point to be emphasized is that "constant dollars" not "current dollars" measure the economic cost of a project. Unless it can be shown that there will be differential inflation among the cost components of a plant, the correct approach is to use constant dollars.

While the recent experience has, indeed, evidenced a higher rate of inflation for fuels than other generating systems' cost components, the historical data show that over the long-run, relative price changes in these categories have been essentially equal. It is assumed, therefore, that the recent dramatic (differential) inflation in fuels will be a short-run phenomenon, and by the time period in which the SSPS or terrestrial systems would be constructed (around 1995) the relative prices will have readjusted themselves to their long-run historical relationships. The issue is that we do not know what the rate of differential inflation may be over the next 20 years, and it is deemed preferable to make the neutral assumption--which, again, is in line with the historical trend--that over the long-run the relative rate of inflation among the cost components will be approximately equal. On the other hand, to the extent that it is believed that we may expect differential changes in the real economic cost, i.e., relative prices of fuels, etc., these should be introduced into the analysis.

The discount rate chosen for this study, 7.5 percent, is economically conservative with respect to the SSPS. This rate has the effect of placing a relative cost burden on the SSPS, since it is the most capital intensive of the systems being compared. Other studies[2] have indicated a required real average rate of return (between equity and debt capital) for the future funding of electric utilities to be about 5 percent. We have elected to use a higher discount rate for two reasons: one, to introduce a risk factor for uncertainties in the development and operations in the SSPS system and two, to reflect the idea that SSPS--at least in its earliest stages--may be a mixed public/private enterprise. Currently, a discount rate of 10 percent is being used to evaluate public projects. The 7.5 percent used would represent, therefore, an averaging between the real rate of return that is required by a commercial venture (5 percent) and that which is expected to accrue to purely public ventures (10 percent).

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[2] U.S. Federal Energy Administration, Project Independence Blueprint Final Task Force Report - Finance, November 1974.

The Aerospace Corporation, Power Plant Economic Model, Program Description/User's Guide (ATR-74[7417-16]-1), June 1974.

Hass, J.E., E.J. Mitchell and B.K. Stone, Financing the Energy Industry, Cambridge: Ballinger Publishing Company, 1974.

A.3 Computation of the Present Value of Capital and the Equivalent Annuity

Figure A.3 contains a summary of the methodology used for computing the present value of capital and the (economically) equivalent annuity. The numbers in parenthesis represent the step-numbers identified in the figure.

The "constant-dollar cost" measured in units of dollars per kilowatt (1) is divided by the "mature plant availability factor" (2). This equals the "adjusted constant dollar cost" measured in dollars per kilowatt (3). This value, divided by the "length of the construction period" measured in years (4) equals the "adjusted constant dollar cost" of capital per year measured in dollars per kilowatt (5). This value and others (the discount rate [R] and the number of compounding periods per year [N]) as given in (6) are inputted to an equation (7) to compute the "present value of capital" at t=0 (8). This result and the other parameters in (9) may be inputted into an equation (10) which computes a value for the annuity that must be adjusted to account for the waiting (construction) period. This adjustment is done with the value generated in (11). This yields the equivalent annuity (PMT*) whose dimensions are dollars per kilowatt per year. This value if received annually over the payback period would yield a present value equal to the present value of the capital. If a result in units of "mills per kilowatt hour" is desirable, the next step is to divide the result in (12) by the constant, 8.76, given in (13). This equals (14) the annuity value in mills per kilowatt hour.

As indicated in Figure A.3, the parameter PMT is the value obtained in (5), Y is equal to the construction period in years given in (4), N is equal to one (the number of compoundings per year) and R is the discount rate. In (9) the parameter, PV, is the result obtained from (8), X is equal to the payback period (assumed to be 30 years), N is equal to one and R is equal to 7.5 percent. The value, 8.76, given in (13) is the well-known conversion factor used to adjust dollars per kilowatt year into mills per kilowatt hour.

A.4 Reconciliation of Alternative Approaches for Computing the Present Value of Capital and Equivalent Annuity

Figure A.4 illustrates a reconciliation between various approaches that are used for determining the present value of capital and the equivalent annuity. As will be shown, they yield the same economic results.

Method I is the approach used throughout this study. The example given is for a direct coal-fired plant operating at a (mature) plant availability factor of .75. As provided in the previous section, the adjusted capital costs for an environmentally controlled system, is $440 per kilowatt. As illustrated in Figure A.4, the capital costs are assumed to be distributed equally over the construction period, i.e., $110 per kilowatt, per year. The costs are then discounted back to the start of the construction period, t=0. The present value at t=0 given a 7.5 percent discount rate equals

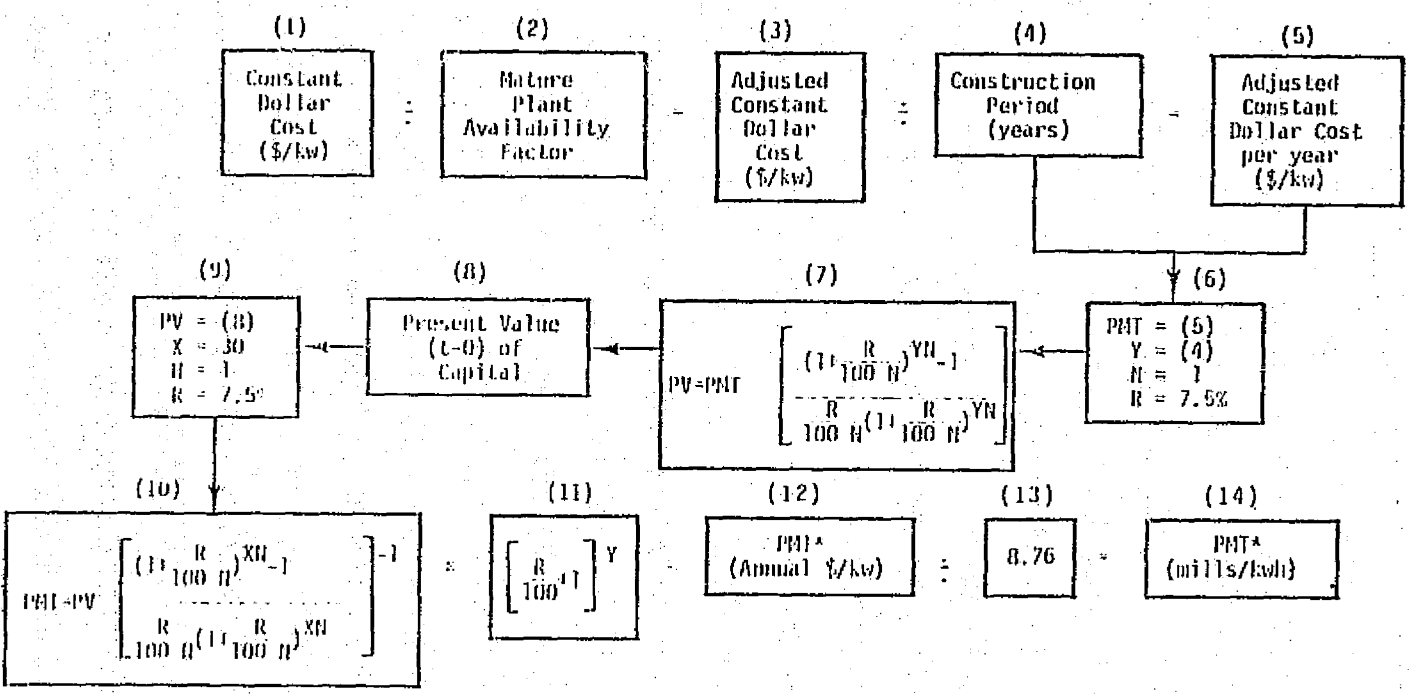
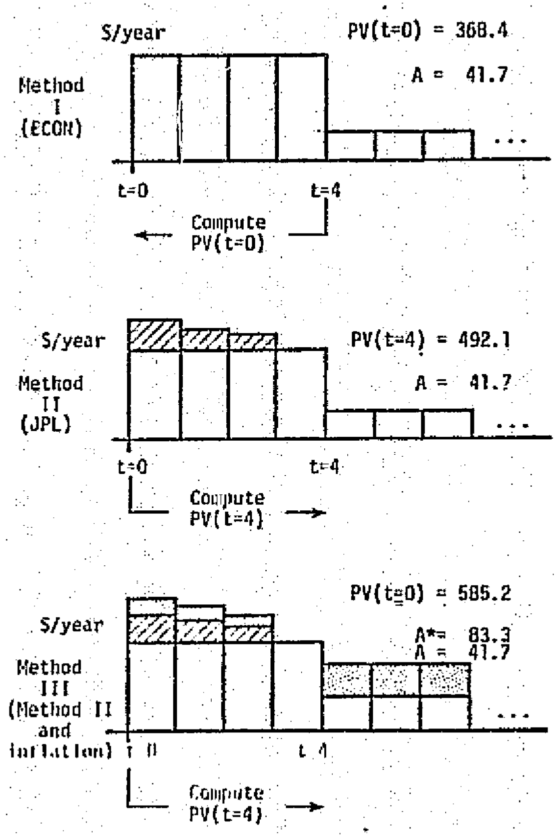


Figure A.3 Methodology for Determining the Present Value of Capital and Equivalent Annuity



PV(t) Present Value of Capital, time equals t
A*= Equivalent Annuity with Inflation Component
A = Equivalent Annuity in Constant Dollars

CAPITAL COST CONSTANT $	ESCALATION (6%) DURING CONSTRUCTION	INTEREST (7.5%) DURING CONSTRUCTION	TOTAL CONSTRUCTION COST
440.0	-	-	440.0
440.0	-	92.1	492.1
440.0	41.2	104.0	585.2

Figure A.4 Reconciliation of Alternative Approaches
(Costs in Units of $/kW)

$368.40 per kilowatt. The equivalent annuity over the operational period equals $41.7 per year or 4.8 mills/kwh.

According to Method II (which is the approach that JPL has chosen[3]), the present value calculations are evaluated at t=4, the end of the construction period. According to this approach, the present value of the capital would be $492.1 per kilowatt. The numerical difference in present value between Method II and Method I is represented by the shaded area in the illustration for Method II, and this is usually referred to as "interest incurred during construction." The equivalent annuity evaluated at t=4 is $41.7 per year, the same as Method I, and hence, the approaches used by ECON and JPL yield identical results.

The reason that the numerical results for the equivalent annuity are equal in approaches I and II is explained as follows: In Method I the present value of capital outlays is calculated at t=0 and revenues do not accrue until after t=4. Thus, there is a period of waiting (varying for each dose of capital outlay) before revenues accrue to pay back the capital expenditure. In Method II there is no waiting period, revenues are received in the period immediately following t=4, the reference date for which the present value of capital outlays has been computed.

Method III is Method II plus a factor provided for inflation during the construction period. As seen, the capital cost in constant dollars is the same. There is, additionally, an escalation factor--assumed for the example to be 6 percent per year--that would raise the total capital costs by $41.2 per kilowatt. Added to this is the interest accrued during construction, and considering inflation, this would be $104.0 per kilowatt. Total capital cost evaluated at t=4 is $585.2 per kilowatt. In order to compute the equivalent annuity, the "nominal interest rate" of 13.9 percent is used. This is the product of the real interest rate, 7.5 percent and the inflation rate, 6 percent (1.075 x 1.06 = 1.1395). Thus, under this approach with a 6 percent per year inflation assumed to be sustained throughout the 30-year payback period, it requires $83.3 per year (9.5 mills/kwh) to generate revenues with a present value equal to that of the capital, and provide for a real rate of return of 7.5 percent or $41.7 per year in constant dollars.

Each of these methods are economically equivalent. Although the numerical results may differ, each evaluates the systems to cost the same amount in terms of economic resources.

A.5 Computation of Economically Justifiable SSPS Unit Cost

Figure A.5 provides the methodology used for computing the "economically justifiable" unit cost of a 5,000 MW SSPS.

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[3] Doane, J.W. and R.P. O'Toole, "Baseline Economic Analysis for Solar and Conventional Central Power Plants," Jet Propulsion Laboratory Engineering Memorandum, September 3, 1975.

The first input in Figure A.5 is a value for electric generation costs (in mills per kilowatt hour) of an alternative (competing) system, item (1). This value must then be scaled up to the annual revenues at a level of 5,000 MW. The scaling factor is given in (2). This equals the annual revenues from the generation of 5,000 MW per year, and it is this revenue which serves as the basis for the computation of the SSPS allowable unit cost.

Before the capital can be repaid, the SSPS has to pay its maintenance costs, calculated to be $136 million per year (See Section 3.1.3.2.1) and taxes and insurance which are assumed to be 32.2 percent of the revenues. The use of this latter constant requires an explanation.

According to our working assumption, annual taxes and insurance are equal to 5 percent of capital. This is in line with a "rule-of-thumb" which is currently used for terrestrial plants. We cannot, however, use the 5 percent constant in this exercise, since it is the capital itself that we are trying to estimate. To eliminate this problem, a "trick" has been devised. This is to assume that the cost for taxes and insurance would be incurred in the same proportion to revenues as computed with the original SSPS unit cost estimate (cf. p. 107). Hence, when we first estimated the capital costs of SSPS to be $7.6 billion, using the 5 percent constant, the value for taxes and insurance was estimated to be $377 million per year. Summing the annual cost of capital ($657 million per year), the value for maintenance ($136 million per year), and $377 million per year, the total annual SSPS cost was $1170 million per year. The proportion of annual costs for taxes and insurance is 32.2 percent of the total.

Subtracting the value for taxes and insurance and operations and maintenance from the annual revenues, a value may be obtained for the maximum economically justifiable annual revenues for repayment of the SSPS unit cost. This value is designated as the parameter, "PMT", and with the other parameters shown in (7) are inputted into the equation (8) to obtain the economically justifiable present value (at t=0) of the unit cost (9). In order to convert the present values into undiscounted dollars, the result in (9) is inputted along with the parameters given in (10) into the equation shown in (11). This provides a value for the economically justifiable annual construction cost of the SSPS. To obtain the total economically justifiable unit cost, this result is multiplied by the value of the parameter "X" given in (10) which is the length of the construction period--in years. The product of the result in (11) and (12) is the economically justifiable (5,000 MW) SSPS unit cost given in (13).

A.6 DDT&E Payback Analysis

The methodology for performing SSPS DDT&E Payback Analysis is illustrated in Figure A.6. Inputs to the analysis are the SSPS buildup profile (1) and the present value of the SSPS DDT&E (2). Although the exact date to which the DDT&E is discounted is arbitrary, it is, in this example, 1975.

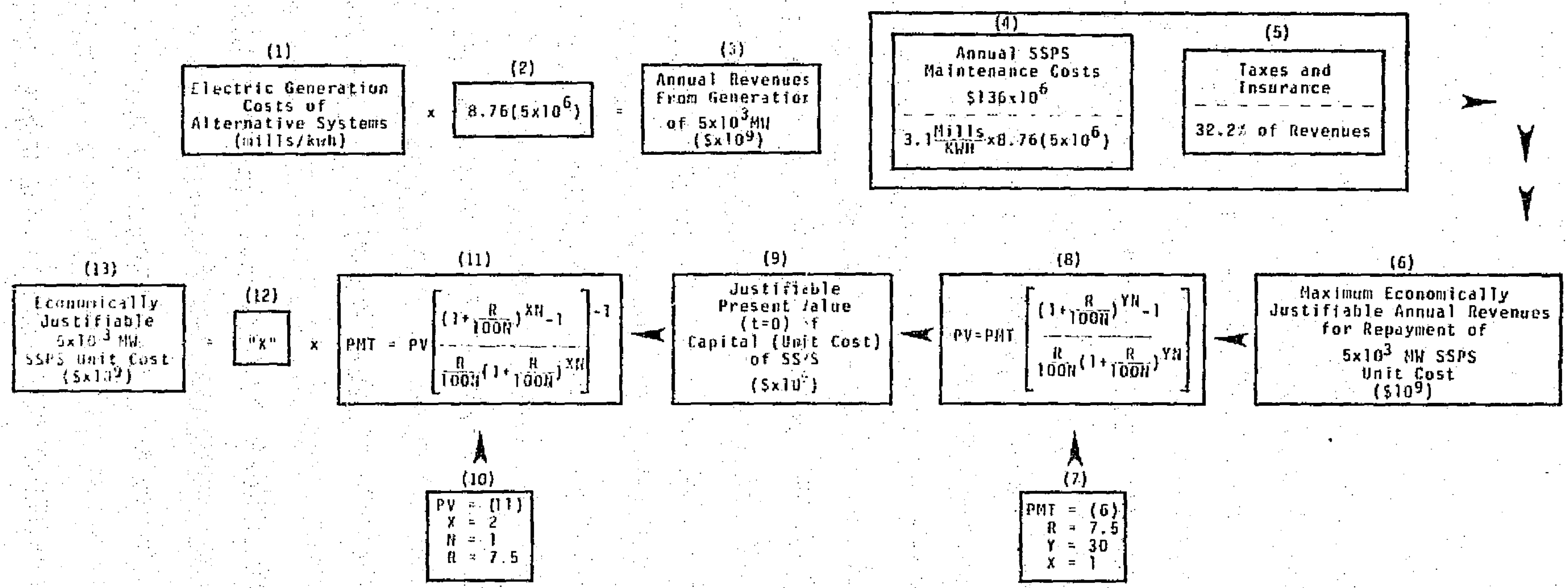

Figure A.5 Methodology for Computing the Economically Justifiable Unit Cost of a 5,000 MW SSPS

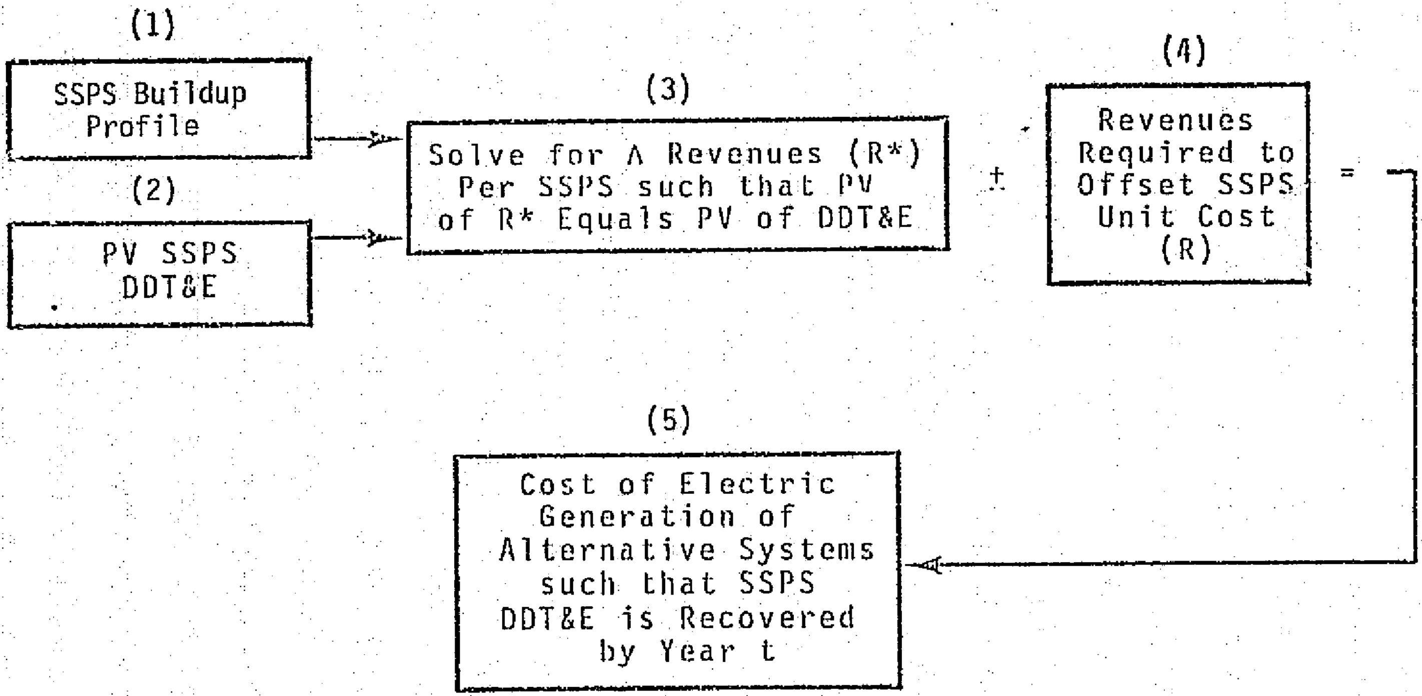

Figure A.6 Methodology for SSPS DDT&E Payback Analysis

The SSPS buildup profile has been originally presented in Section and is given again as Figure A.7. As indicated in Figure A.7 with an initial operational capability (IOC) of (end of) 1995, by the (end of) 1996 there would have been one SSPS revenue-year. According to the build-up profile there would be a build-up rate of two SSPS per year until 2000, and after that, four per year through 2025. The cumulative number of 5 GW operational units at the end of a given year, t, would be as indicated in Figure A.7.

The second input to the analysis is the present value of the SSPS DDT&E (2). This value (provided on pages 109 and 110) in undiscounted values is $44 billion.

The next step (3) is to solve for "Delta Revenues" (R*) per SSPS such that the (1975) present value of R* equals the (1975) present value of the DDT&E. Examples of the calculations of R* for 1996, 1997 and 1998 are provided in Table A.1.

Table A.1 contains examples of the method for computing the SSPS DDT&E Payback Function.

By (end of) 1996, t--which for purposes of discounting back to 1975--is valued at "21." There is one SSPS operating for one year. To solve for R*, the present value of R* is set equal to the present value of the SSPS DDT&E. The computed value is, of course, a relatively large value, and we would not expect that a single operational SSPS could ever repay the DDT&E. In 1977 (t+1) there would have been one SSPS operating for two years and three SSPSs operating for one year (the original SSPS would be operating for two years and the two additional SSPSs with a 1996 IOC would have been operating for one year). The method would be to solve for an R* such that its present value would be equal to the present value of the DDT&E. In 1998 (t+2) there would be one SSPS operating for three years, three SSPSs operating for two years and five SSPSs operating for one year, and so on.

As indicated in Figure A.7, the values of the DDT&E Payback Function do not begin to fall into a reasonable "range" until about 2005 when 29 SSPSs will have been operating for at least one year, leading to a value of R* of about 20 mills per kilowatt hour.

As stated in the report, the DDT&E Payback Function becomes asymptotic to the x axis as the alternative electric generation costs approach 27 mills per kilowatt hour. This is explained by the discounting phenomenon which reduces the present value of future revenues.

To the value of R* is added the unit SSPS costs shown in (4) as (R) and has been estimated to be 26.7 mills per kilowatt hour. R*--which is a unique, interest rate-dependent value--is added to the value, R, which is constant, and the result is given in Figure A.6 as (5), the cost of electric generation of alternative system such that the SSPS DDT&E is recovered by year t. This is the ordinate of Figure A.7. The reason that the ordinate and the result in (5) is given as the cost of alternative

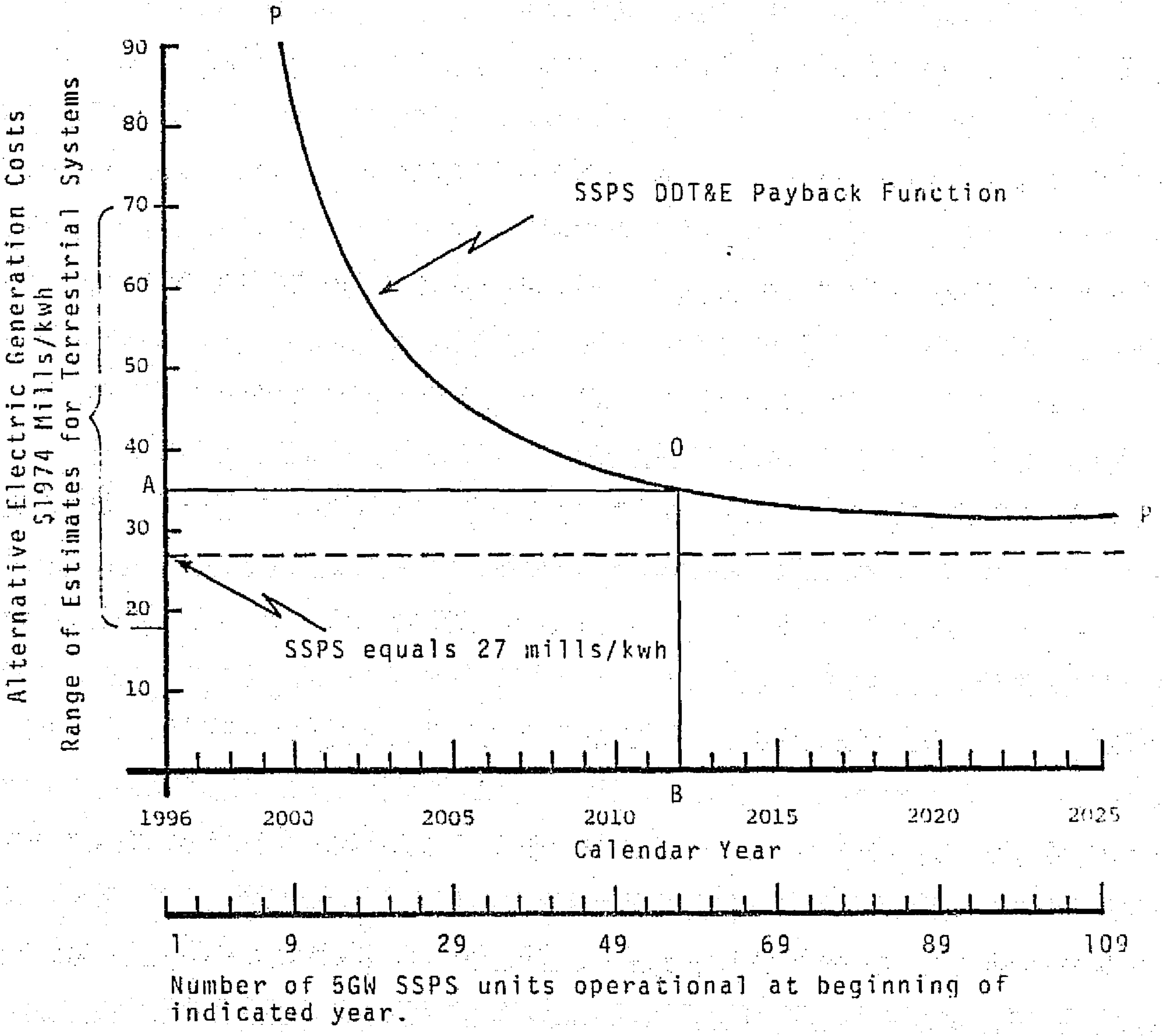

Figure A.7 Payback Analysis of SSPS Development Programs (r=7.5%)

Table A.1 Method for Estimating the SSPS DDT&E Payback Function

(END OF) YEAR	SSPS BUILD-UP SCENARIO	SOLUTION FOR $(R^*)^1$: ANNUAL REVENUES PER OPERATIONAL 5×10^3 MW SSPS[2]
1996(t)	1 SSPS operating for 1 year	$(1975)PV = \$16.5\times10^9 = \frac{R^*}{(1+r)^t}$
1997(t+1)	1 SSPS operating for 2 years 3 SSPS operating for 1 year	$(1975)PV = \$16.5\times10^9 = \frac{R^*}{(1+r)^t} + \frac{3R^*}{(1+r)^{t+1}}$
1998(t+2)	1 SSPS operating for 3 years 3 SSPS operating for 2 years 5 SSPS operating for 1 year	$(1975)PV = \$16.5\times10^9 = \frac{R^*}{(1+r)^t} + \frac{3R^*}{(1+r)^{t+1}} + \frac{5R^*}{(1+r)^{t+2}}$
...	...	...
2025(t+29)	1 SSPS operating for 30 years 3 SSPS operating for 29 years ... 109 SSPS operating for 1 year	$(1975)PV = \$16.5\times10^9 = \frac{R^*}{(1+r)^t} + \frac{3R^*}{(1+r)^{t+1}} + \ldots + \frac{109R^*}{(1+r)^{t+29}}$

1. R*=Required annual revenues per SSPS in year t+N for DDT&E recovery.
   To convert to mills per kilowatt hour, divide result by: $8.76(5.10^6)$.
2. $r = .075$ (7.5%), $t=21$

generation systems, is that we assume that SSPS would not be used if there were alternative systems available that would provide equal generation capabilities and electric power at lower cost.

APPENDIX B: WORK BREAKDOWN STRUCTURES SSPS AND PRS SYSTEMS

B.1 Satellite Solar Power Station

B.1.1 Work Breakdown Structure and Program Schedule

A preliminary SSPS Work Breakdown Structure (WBS) and program schedule have been compiled to establish a "strawman" for programmatic analysis. A three-step program (cf. 103). Figure 3.40 was utilized. A small LEO Process Development and Test Facility was planned for deployment in 1985. A geosynchronous-stationed 1 GW pilot plant might be scheduled with a 1900 IOC, depending upon its economic merit, and a full capability plant (5 GW) is scheduled for 1995.

Figure B.1 is the WBS used as the roadmap for cost accounting and program planning. There are 11 Level-2 elements identified:

- Project Management
- System Engineering and Integration
- Transportation
- Assembly
- On-Orbit Assembly Support Equipment
- Transportation and Assembly Ground Support Equipments
- LEO Development and Test Satellite Program
- Pilot Plant
- Operational Plant
- System Maintenance
- Facilities.

Project Management (-01)

This element of work accounts for the technical and administrative planning, organization, direction, coordination, control and approval mechanisms to accomplish overall program objectives.

System Engineering and Integration (-02)

This element includes all the necessary engineering and systems management efforts needed to achieve an integrated program. It includes engineering management, systems engineering, design engineering, support engineering and the assurance technologies, namely, reliability, quality assurance maintainability, safety, environmental protection as well as impact and assessment.

Transportation (-03)

This element includes the development, production and operation of all systems that transport materials, equipment and personnel from launch through deployment at the designated mission orbit. Figure B.2 is a program schedule for the transportation elements used in the programmatic analysis of the SSPS and includes the following elements:

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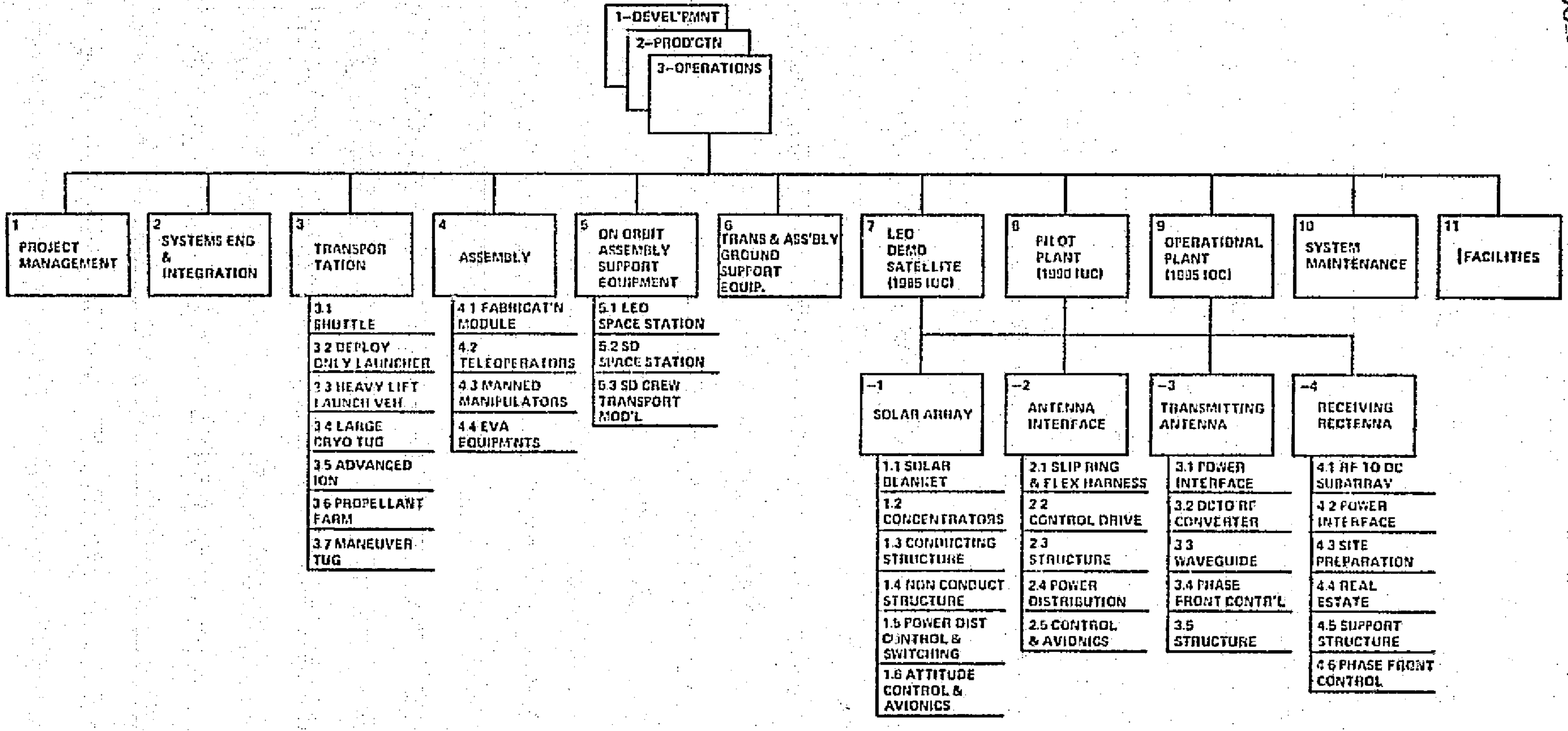


Figure B.1 Work breakdown Structure

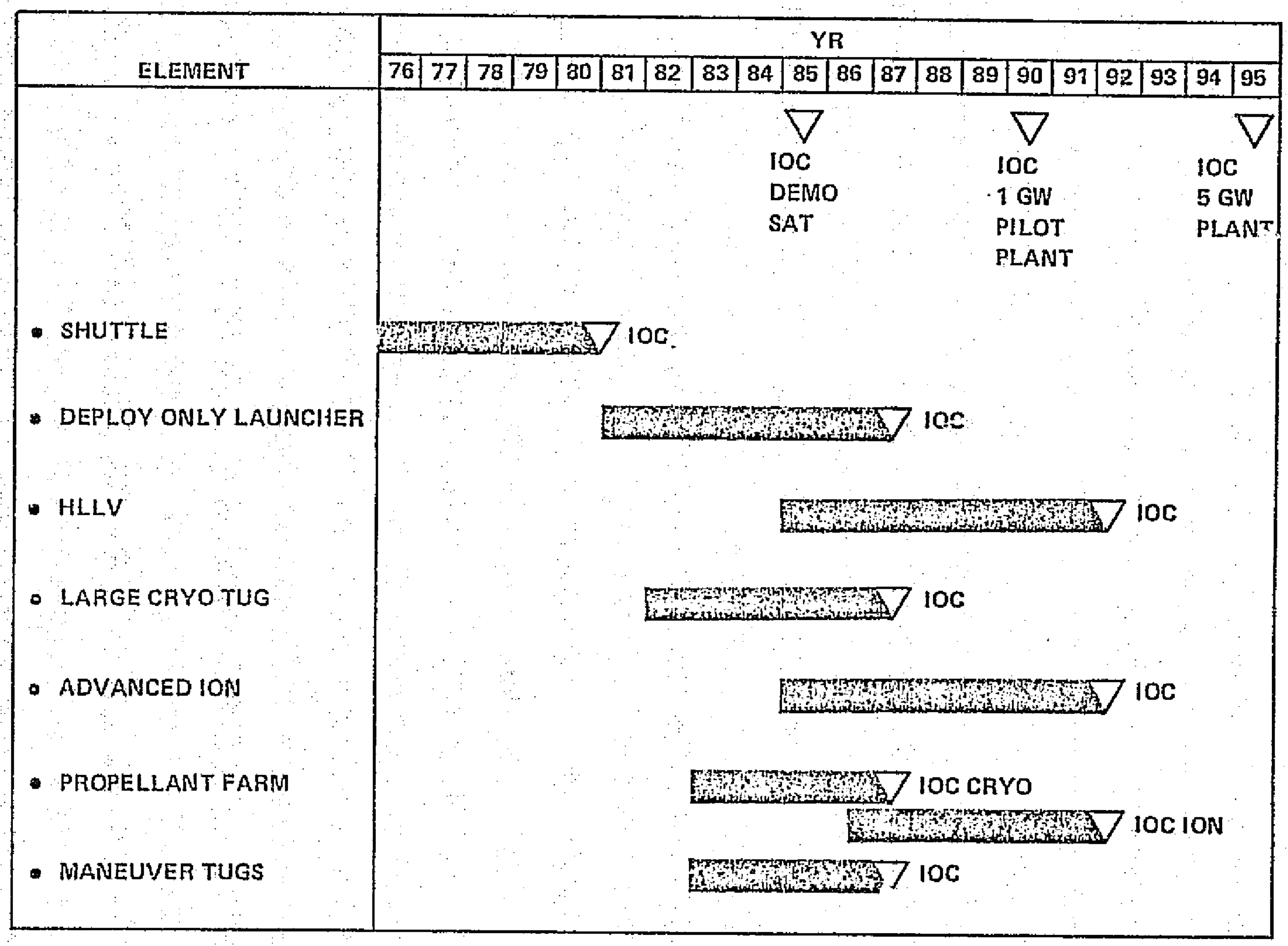


Figure B.2 Transportation System Development Schedule

(- 03-1) Shuttle (IOC 1981)

(- 03-2) Deploy Only Launcher (IOC 1987) - A derivative of shuttle using External Tank, Solid Rockets and a payload shroud which is integrated with a propulsion package of SSME's. This launch system is fully recoverable with a payload to low earth orbit of 72,640 kg (160,000 lb).

(- 03-3) HLLV (IOC 1992) - New Heavy Lift Launch Vehicle, fully recoverable with 181,600 kg (400,000 lb) payload to Low Earth Orbit.

(- 03-4) Large Cryo Tug (IOC 1987) - An orbit transfer vehicle for transporting materials, equipments and personnel between low earth orbit and geosynchronous. The vehicle baselined for this study is a derivative of the external tank and SSME. It requires in-orbit refueling.

(- 03-5) Advanced Ion (IOC 1992) - A large high performance stage with the capability to transport assembled SSPS from LEO to geosynchronous orbit.

(- 03-6) Propellant Farm (IOC 1987) - A set of propellant storage tanks and support equipment for storing and transferring propellants for the Large Cryo Tug and Advanced Ion Stage.

(- 03-7) Maneuver Tug (IOC 1987) - A Tug used to maneuver and transport large equipments, materials, propellants, etc. in the vicinity of the assembly site and propellant farm.

Assembly (-04)

This WBS element includes all equipment required in the assembly operation for the fabrication, joining and integration of the SSPS. Figure B.3 is a development schedule for the equipment included under this WBS element. This element includes:

(- 04-1) Fabrication Modules (IOC 1983) - A highly automated device that fabricates structural beams in orbit.

(- 04-2) Teleoperators (IOC 1983) - A remotely controlled module used to assemble structure, microwave components, solar blankets, etc.

(- 04-3) Manned Manipulators (IOC 1983) - A manned-rated maneuvering vehicle with manipulator arms used in assembly.

(- 04-4) EVA Equipment (IOC 1983) - Space suits and equipment for an EVA mode of assembly.

(- 04-5) Logistics Equipments (IOC 1983) - A small Tug used to move equipment, materials and personnel in the vicinity of the assembly site.

On-Orbit Assembly Support Modules and Equipment (-05)

Equipment needed in support of assembly operations. This includes space stations, Shuttle ancillary equipment and crew transport modules. Figure B.4 is a schedule for the deployment of these equipment. The following summarizes the Level-3 WBS elements:

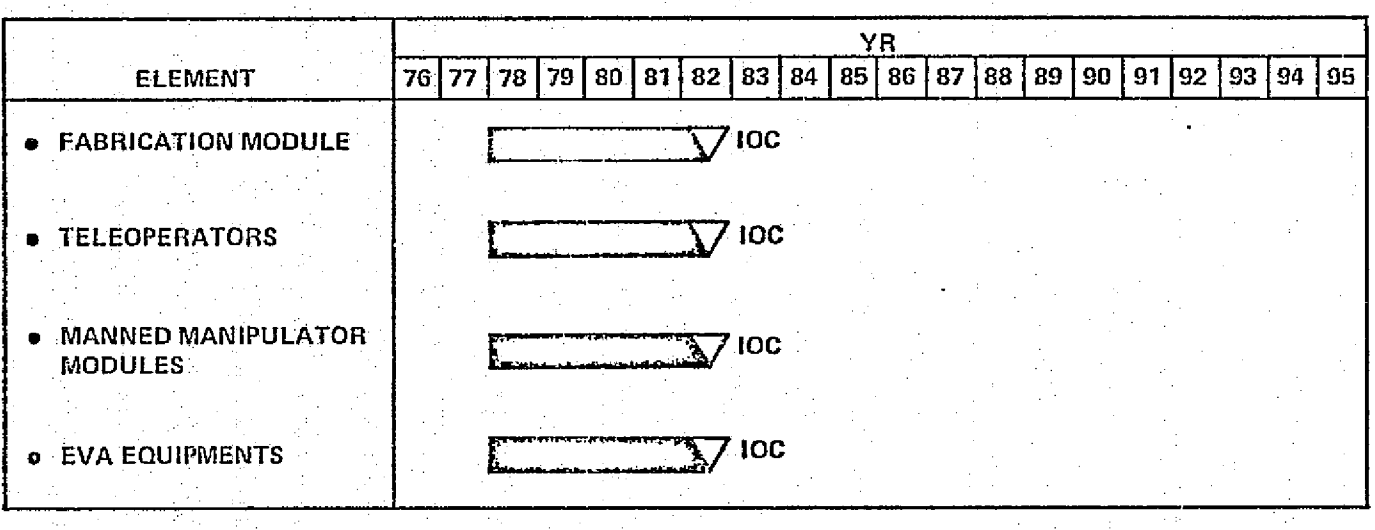


Figure B.3 Development Schedule - Assembly

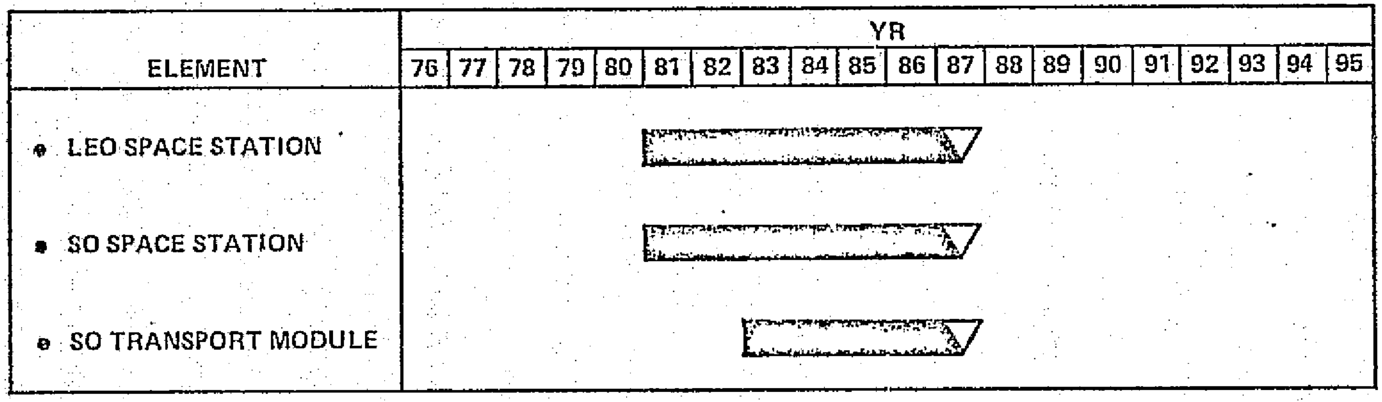


Figure B.4 Development Schedule - On-Orbit Assembly Support Equipment

(- 05-1) LEO Space Station (IOC 1987) - A modular, 6-man space station used to house the assembly crew, maintenance facilities, large elements work area (hangar), and assembly equipment in low earth orbit.

(- 05-2) SO Space Station (IOC 1987) - A modular, 6-man space station to perform functions similar to those for LEO Space Station but on geosynchronous orbit.

(- 05-3) SO Transfer Module (IOC 1987) - A crew transport module used to house crews for transport between LEO and synchronous orbit.

Transport and Assembly Ground Support Equipment (IOC 1983, 1987 and 1992) (-06)

The ground equipment required to support launch and mission operations including development of communications centers and networks. This WBS element has not been included in the programmatic analyses because more depth of definition of the satellite, assembly equipment and operations is required to define this WBS element to sufficient depth for costing. In the interim, this is considered to be included in the 20 percent task factor applied for cost uncertainty.

LEO Development and Test Satellite (IOC 1985) (-07)

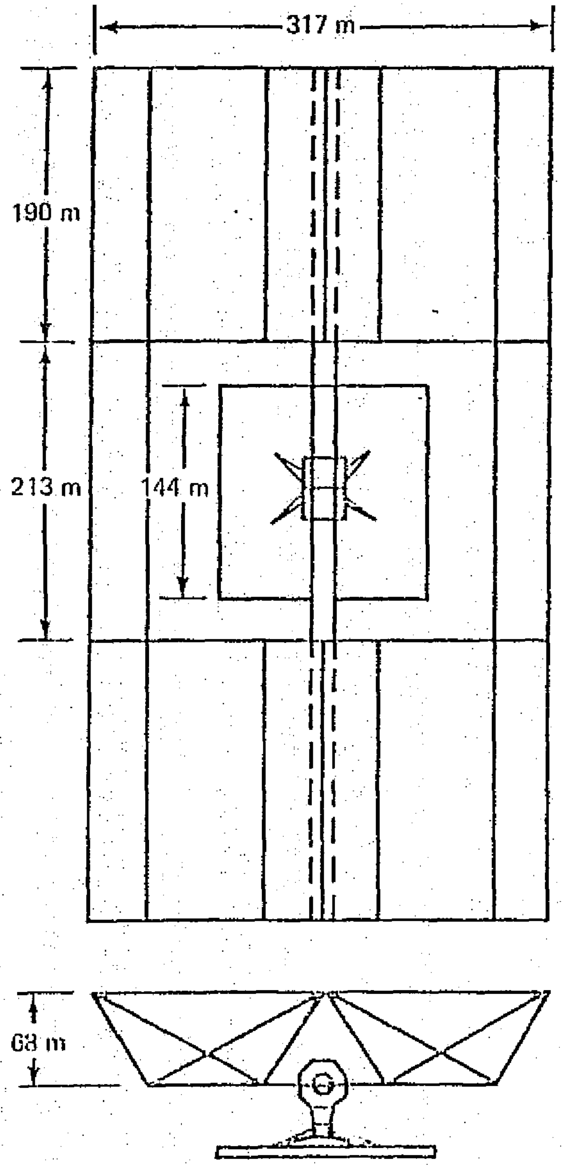
Figure B.5 is a conceptual design for a 15 MW (transmitting antenna output power) demonstration and test satellite. The solar array is layed-out at a concentration ratio of two. The silicon solar cell blanket efficiency was established using the projected efficiency for the SEPS array (12%) and then degrading efficiency for the operating temperature at a concentration ratio of two. A power distribution system efficiency of 82 percent was utilized to compute the array output power.

The array mass estimates used the projected SEPS solar blanket masses (0.525 kg/m^2) and the 0.5 mil aluminized Kapton masses projected for the 1995 mirror system. The mass per unit length of structure for the 1995 satellite was used to establish the non-conducting structural masses. The column lengths for this design are approximately the same as the 1995 system. The mass of the conducting structure and central mast are sized by electrical requirements in the 1995 system; but are sized by structural requirements in this system. The rotary joint is scaled down (1/10 size) from the 1995 system. The total mass of the satellite is 228,343 kg (503,148 lb).

The 1985 development and test satellite is assumed to be a development spacecraft placed in low earth orbit by the Shuttle. The final configuration is envisioned to be assembled through a series of sortie technology flights started as early as 1981. Figure B.6 is a preliminary mission schedule leading to deployment of the demonstration and test satellite.

The first Sortie mission evaluates different methods for deploying and fabricating structural elements. Options for assembly operation of the basic structural beam are demonstrated in Mission 2 and 3. Waveguide

12 mw OUTPUT POWER



CHARACTERISTICS

- SOLAR BLANKET
  - CONCENTRATION RATIO = 2
  - CELL EFFICIENCY = 9.7%
  - POWER DISTRIBUTION EFFICIENCY = 92%
- MICROWAVE CONVERSION EFFICIENCY = 82%

WEIGHTS (228,343 KG)

ARRAY
- BLANKET = 39,571 KG (0.525 KG/M^2)
- CONCENTRATOR = 3,014 KG (0.02 KG/M^2)
- NONCONDUCT. STRUCT. = 16,692 KG (2.76 KG/M LENGTH)
- CONDUCT. STRUCT. = 2,633 KG (2.76 KG/M LENGTH)
- MAST = 1,049 KG (2.76 KG/M LENGTH)

SUBTOTAL = 62,966 KG

ROTARY JOINT = 12,670 KG (1/10 WT OPS SYST)

ANTENNA
- STRUCTURE = 9,083 KG (.43 kg/m^2)
- CONTOUR CONTROL = 3,648 KG (.38 kg/m^2)
- POWER DISTRIBUTION = 10,648 KG (RAYTHEON EST)
- CONTROL ELECT = 5,632 KG (RAYTHEON EST)
- TUBES = 2,848 KG (RAYTHEON EST)
- WAVEGUIDE = 95,296 KG (RAYTHEON EST)

SUBTOTAL = 127,155 KG

Figure B.5 Demonstration and Test Satellite

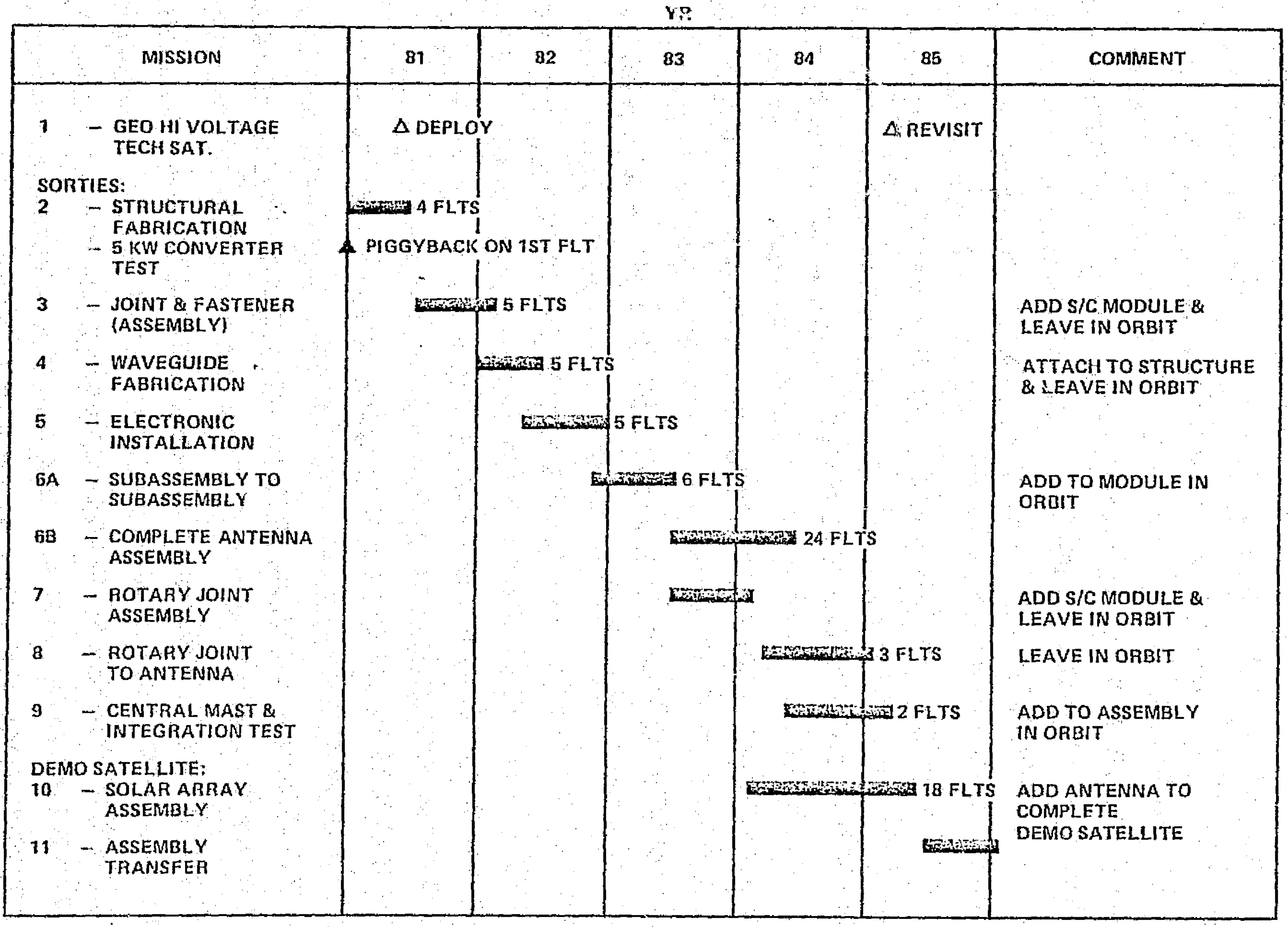
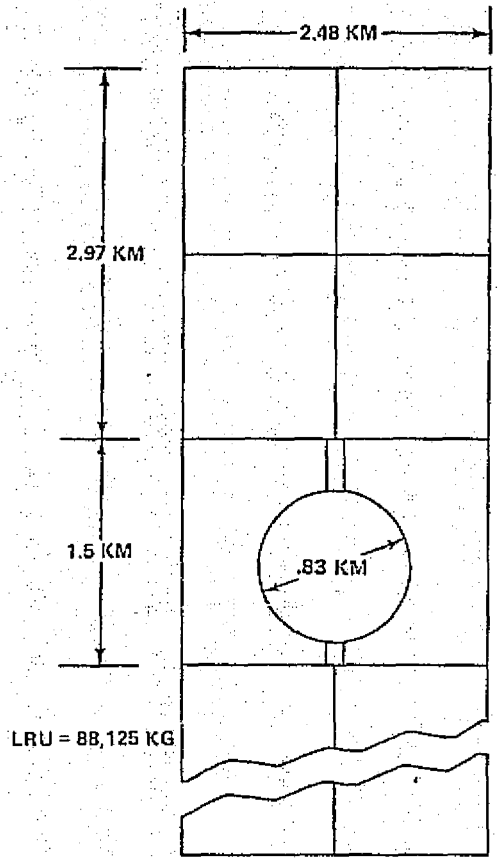


Figure B.6 Mission Schedule



CHARACTERISTICS

- SOLAR BLANKET
  - CONCENTRATION RATIO = 2
  - CELL EFFICIENCY = 11%
  - POWER DISTRIBUTION EFFICIENCY = 92%
- MICROWAVE CONVERSION EFFICIENCY ≈ 57% RECTIFIED AT GROUND

WEIGHTS

ARRAY	KG X 10^6	COMMENT
• BLANKET =	2.82	(7.04 KM^2) (0.4 KG/M^2)
• CONCENTRATOR =	0.31	(15.4 KM^2) (.02 KG/M^2)
• NONCONDUCT STRUCT =	0.61	(18.5 KM^2) (0.033 KG/M^2)
• CONDUCTING STRUCT =	0.07	(18.5 KM^2) (0.004 KG/M^2)
• MAST =	0.38	(7.4 KM) (0.052 KG/KM)
	4.19	
ROTARY JOINT	0.20	(SAME AS 1995 SYSTEM)
MW ANTENNA	3.94	(SAME AS 1995 SYSTEM WITH REDUCE # OF TUBES)
TOTAL	8.33	(8.23 x 10^6 Kg)

Figure B.7 Pilot Plant (1990) 1 GW Ground Power

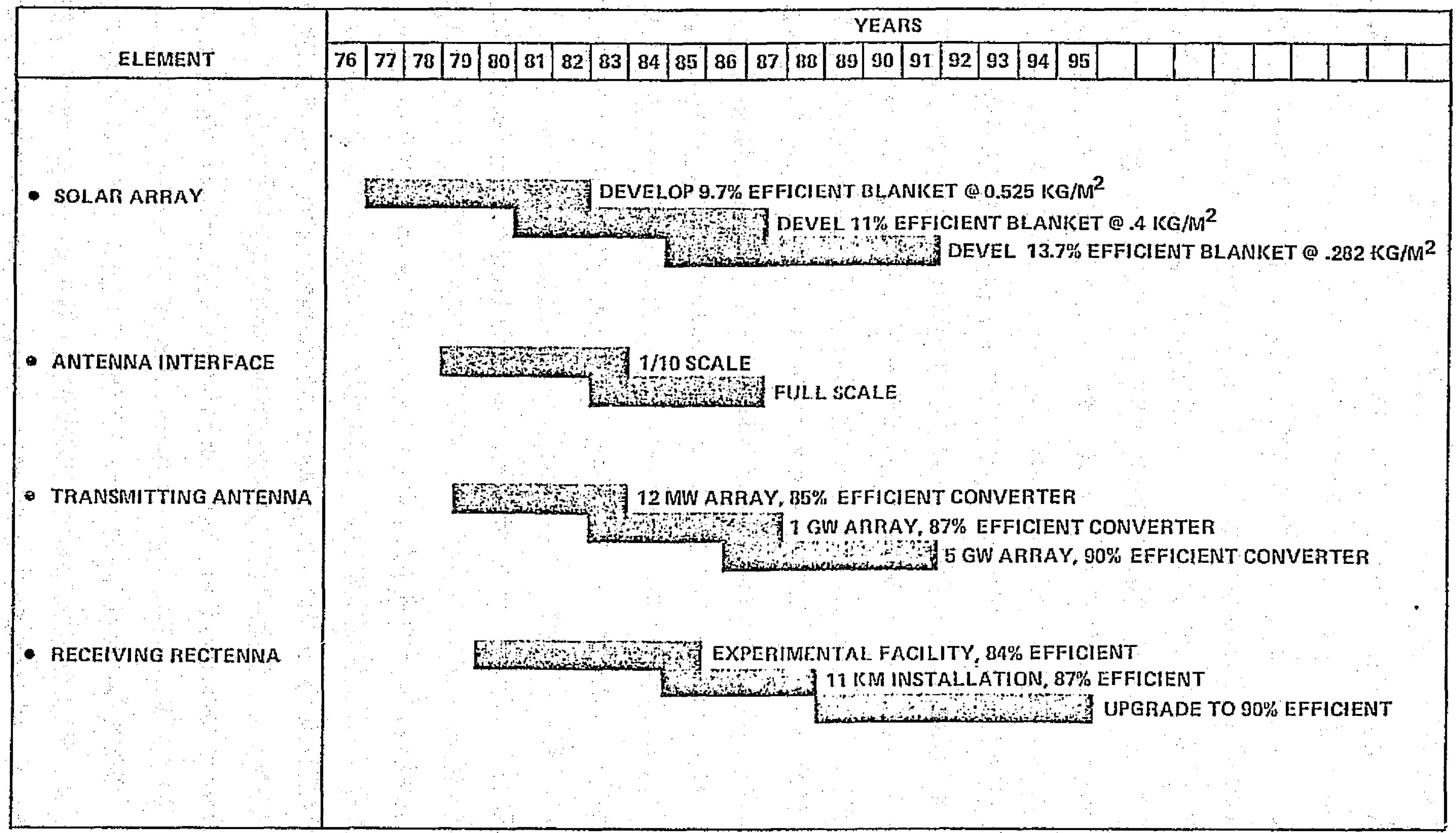


Figure B.8 SSPS Development Schedule Key Milestones deployment and/or fabrication is addressed in Mission 4; while installation of the microwave components and electronics integration is addressed in Mission 5. Mission 6 is a series of flights that builds on the single 18 x 18 m subarray, left in orbit in Mission 5, up to the desired antenna size for the Demonstration Satellite. Missions 7 and 8 assemble the Rotary Joint and interface it with the Antenna. Mission 9 assembles the central mast and joins it to the rotary joint. Mission 10 assembles the solar array and installs the microwave antenna to complete the assembly of the demonstration satellite. Mission 11 transfers the assembled satellite to its operational orbit.

Pilot Plant (IOC 1990) (-080)

Figure B.7 is a conceptual design of a 1 GW, ground-output pilot plant for operation in 1990 at geosynchronous altitude. Whether this 1 GW plant should be built depends upon its economic merit. The assumptions used to size the configuration are included. The total system mass is 8.33×10^6 kg. The transmitting antenna on this configuration is the same size as that for the 1995 SSPS; however, it is assumed to transmit ≈ operational power level.

Operational Plant (IOC 1995) (-09)

The operational plant is a 5 GW facility which utilizes an advanced solar blanket and the same antenna size as the 1990 facility with full complement of rf generators. A system description of this plant can be found in Section 3.1.1. Figure B.8 is a schedule of key development for each Level III WBS element. The following summarizes the subdivision of work:

(- 09-01) Solar Array: A large photovoltaic array operated at 2:1 concentration with the following elements:
    (-01.1) Solar Blankets
    (-01.2) Concentrators
    (-01.3) Conducting Structure
    (-01.4) Non-Conducting Structure
    (-01.5) Power Distribution, Control and Switching
    (-01.6) Attitude Control and Avionics
(- 09-02) Antenna Interface: A large diameter rotary joint for fine pointing the antenna and transferring power with the following elements:
    (-02.1) Slip Rings and Flex Harness
    (-02.2) Control Drive
    (-02.3) Structure
    (-02.4) Power Distribution
    (-02.5) Control and Avionics
(- 09-03) Transmitting Antenna: A large phased array that utilizes slotted waveguides and crossfield amplifiers. The following elements are included:
    (-03.1) Power Interface
    (-03.2) dc to rf Converter
    (-03.3) Slotted Waveguide
    (-03.4) Phase Front Control
    (-03.5) Support Structure

(- 09-04) Rectenna: A large solid state receiving and rectifying antenna for conversion of rf power to dc electric. The following cost elements are included:

(-04.1) RF-DC Subarrays
(-04.2) Power Interface
(-04.3) Site Preparation
(-04.4) Real Estate
(-04.5) Support Structure
(-04.6) Phase Front Control.

Systems Maintenance (-10)

This includes those equipments for on-orbit maintenance of the satellite, and the cost of spares and the equipments necessary to maintain spares. The cost of the on-orbit equipments and spares have been included in the cost estimates. The cost of the ground equipments and the ground spares have not been included in the cost estimates of Section 3.1.3.2.1. It is assumed to be covered in the 20 percent cost uncertainty allotment.

Facilities (-11)

This WBS element includes the facilities required for support operations and the manufacture of the major hardware elements of the satellite. Cost estimates for facilities have not been included in the overall program assessment in this preliminary study. These are assumed to be covered in the 20 percent cost uncertainty allotment.

B.1.2 Cost Estimates

Cost estimates for the SSPS program have been made using existing cost estimating relationship (CER's). The Koelle model (presented at the International Academy of Astronautics, October 14, 1972) was used to establish development and unit production estimates for the transportation systems, and support equipments. The aerospace "Spacecraft System Cost Model", augmented with the Koelle model trends as a function of "new technology" required in the program, was used to estimate the SSPS subsystem development cost.

Table B.1 is a compilation of cost estimates for the SSPS program. Costs are listed by WBS element.

Estimates of the SSPS subsystem costs required an extensive extrapolation from the existing data base. Considerable "grass roots" estimating based on detailed engineering definition of the subsystem should be performed to refine the estimates presented here.

The major subsystem development cost is the solar array where costs vary as a function of system power level and weight. Development costs for a 10 GW operational plant solar array could increase as much as $1 billion over that for a 5 GW system.

Table B.1 System Cost Estimate

WBS NO.	WBS IDENTIFICATION	IUC	LEVEL 1 WBS ELEMENTS			COMMENTS
			1–DEVELOPMENT	2–PRODUCTION	3–OPERATIONS	
–01	PROJECT MANAGEMENT					40% OF TOTAL COST OF WBS ELEMENTS 02 THRU –11
–02	SYST ENG & INTEGRATION					
–03	TRANSPORTATION					
–03–01	SHUTTLE	1981	N/A	$ 200 M/UNIT	$12M/FLT	
–03–02	DEPLOY ONLY LAUNCHER	1987	$ 380 M	150 M/UNIT	$13M/FLT	
–03–03	HLLV	1992	6,540 M	400 M/UNIT	$9M/FLT	
–03–04	LARGE CRYO TUG	1987	166 M	15 M/UNIT	$1M/FLT	
–03–05	ADVANCED ION	1992	3,847 M	190 M/UNIT	$1M/FLT	
–03–06	PROPELLANT FARM	1987	223 M	16 M/UNIT		
–03–0	MANEUVER TUG	1987	215 M	2.6 M/UNIT		
–04	ASSEMBLY					
–04–01	FABRICATION MODULES	1983	$ 271 M	$ 12 M/UNIT		
–04–02	TELEOPERATORS	1983	19 M	2.5 M/UNIT		
–04–03	MANNED MANIPULATORS	1983	365 M	11 M/UNIT		
–04–04	EVA EQUIPMENT	1983	20 M	1.5 M/UNIT		
–04–05	LOGISTICS EQUIPMENT	1983	44 M	2.5 M/UNIT		
–05	ON-ORBIT ASSEMBLY SUPPORT EQUIPMENT					
–05–01	LEO SPACE STATION	1987	$2,225 M	$ 62 M/MAN		
–05–02	SO SPACE STATION	1987	224 M	62 M/MAN		
–05–03	SO TRANSFER VEHICLE	1987	190 M	23 M/MAN		
–06	TRANSPORT & ASSEMBLY GROUND SUPPORT EQUIPMENT		TBD	TBD		INCLUDE IN UNCERTAINTY FACTOR
–07	LEO DEMO SATELLITE	1985	$1,108 M	3,461 S/KW	1376 S/KG(1)	(1) ASSEMBLY OPERATIONS
–07–01	SOLAR ARRAY		1,108 M	3,461 S/KW		
–07–02	ANTENNA INTERFACE		383 M	2,670 S/KW		
–07–03	TRANSMIT ANTENNA		610 M	386 S/KW		
–07–04	RECEIVING RECTENNA		59 M	1,099 S/KW		

Table B.1 System Cost Estimate (Cont'd)

WBS NO.	WBS IDENTIFICATION	IOC	LEVEL 1 WBS ELEMENTS 1–DEVELOPMENT	2–PRODUCTION	3–OPERATIONS	COMMENTS
–08	PILOT PLANT	1990			1086 \$/KG(2)	(2) TRANSPORTATION & ASSEMBLY OPERATIONS
–08–01	SOLAR ARRAY		\$2,453 M	765 \$/KW		
–08–02	ANTENNA INTERFACE		446 M	105 \$/KW		
–08–03	TRANSMIT ANTENNA		320 M	144 \$/KW		
–08–04	RECEIVING RECTENNA		1,218 M	392 \$/KW		
–09	OPERATIONAL PLANT	1995			180 \$/KG(2)	(3) INCLUDED IN CONDUCTING STRUCTURE ESTIMATE
–09–01	SOLAR ARRAY	1995	\$3,104 M			
–09–01.1	SOLAR BLANKET			55 \$/M^2		
–09–01.2	CONCENTRATORS			1.1 \$/M^2		
–09–01.3	CONDUCTING STRUCTURE			81 \$/KG		
–09–01.4	NONCONDUCTING STRUCTURE			81 \$/KG		
–09–01.5	PWR DIST CONT'L & SWITCH			(3)		
–09–01.6	ATT'D CONTR'L & AVIONICS			\$2.1 M/THRUSTER		
–09–02	ANTENNA INTERFACE	1995	\$ 149 M	18 \$/KW		
–09–03	TRANSMIT ANTENNA	1995	\$ 260 M			
–09–03.1	POWER INTERFACE			18 \$/KW		
–09–03.2	DC TO RF CONVERTER			26 \$/KW		
–09–03.3	WAVEGUIDE			14 \$/KW		
–09–03.4	PHASE FRONT CONTROL			26 \$/KW		
–09–03.5	SUPPORT STRUCTURE			15 \$/KW		
–09–04	RECEIVING RECTENNA	1995	\$ 403 M			
–09–04.1	RF TO DC SUBARRAY			76 \$/KW		
–09–04.2	POWER INTERFACE			47 \$/KW		
–09–04.3	SITE PREPARATION			8 \$/KW		
–09–04.4	REAL ESTATE			19 \$/KW		
–09–04.5	SUPPORT STRUCTURE			114 \$/KW		
–09–04.6	PHASE FRONT CONTROL			5 \$/KW		

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Table B.1 System Cost Estimate (Cont'd)

WBS NO.	WBS IDENTIFICATION	IOC	LEVEL 1 WBS ELEMENTS			COMMENTS
			1–DEVELOPMENT	2–PRODUCTION	3–OPERATIONS	
–10	SYSTEM MAINTENANCE					(4) SEE SECTION 4.1.2.4
–10–01	LEO DEMO	1985	TBD	TBD	TBD	
–10–02	PILOT PLANT	1990	TBD	TBD	TBD	
–10–03	OPERATIONAL PLANT	1995		$919 M(4)/SSPS	$87.7 M/YR(4)	
–10–03.1	SOLAR ARRAY				42.7 /YR(4)	
–10–03.2	ANTENNA INTERFACE				0.4 M/YR(4)	
–10–03.3	TRANSMIT ANTENNA				1 M/YR(4)	
–10–03.4	RECEIVING RECTENNA				4.6 M/YR	
–11	FACILITIES		TBD	TBD	TBD	

Cost sensitivity studies indicate that the SSPS rotary joint with its associated control system could be a major development cost driver. To limit maintenance cost (Section 3.1.2.4), the design life of the rotary joint and control system is of major importance. These development cost estimates assumed a rotary joint and control system design life of five years. If the design life were increased to 30 years, development costs for the first full scale rotary joint (used in the 1990 Pilot Plant, if built) could run as high as $1 billion.

The cost estimates for structure are considered to be low. The CER's used to establish these estimates are based on a history of spacecraft launched as a single unit. The added complexity of space assembly on the design and development of the structure could impact the costs considerably.

Eighty-five percent of development costs for supporting systems is spent to develop three major systems. The major support system development cost is for the Heavy Lift Launch Vehicle with DDT&E of over $6 billion. The Advanced Ion propulsion stage is estimated to cost in excess of $3.5 billion while the Space Station is estimated at slightly above $2 billion.

B.2 Power Relay Satellite

B.2.1 Work Breakdown Structure and Program Schedule

A "strawman" PRS Work Breakdown Structure (WBS) and program schedule has been formulated to support programmatic studies. A two-step program was utilized. A geosynchronous demonstration satellite was scheduled for 1985 requiring the development of a Low Earth Orbit and Synchronous Orbit space station over the next ten years. A refined version of the demonstration system was scheduled for 1990.

All elements of the WBS outlined for the SSPS in Section B.1 apply with the exception of elements (-07) LEO Demonstration Satellite (-08) Pilot Plant and (-09) Operational Plant. Figure B.9 is a WBS replacement and used for accounting PRS costs.

The 1 GW system for 1985 is assumed to be assembled and transported using the following major elements:

- Shuttle (IOC 1981)
- Full Capability Tug (IOC 1983)
- LEO Space Station (IOC 1983)
- SO Space Station (IOC 1983).

The 1990 system, rated at 10 GW, is assumed for purposes of the "strawman" plan to be assembled and transported using the major elements:

- Deploy Only Launch (IOC 1987)
- Large Cryo Tugs (IOC 1987)
- LEO Space Station (IOC 1983)
- SO Space Station (IOC 1983)

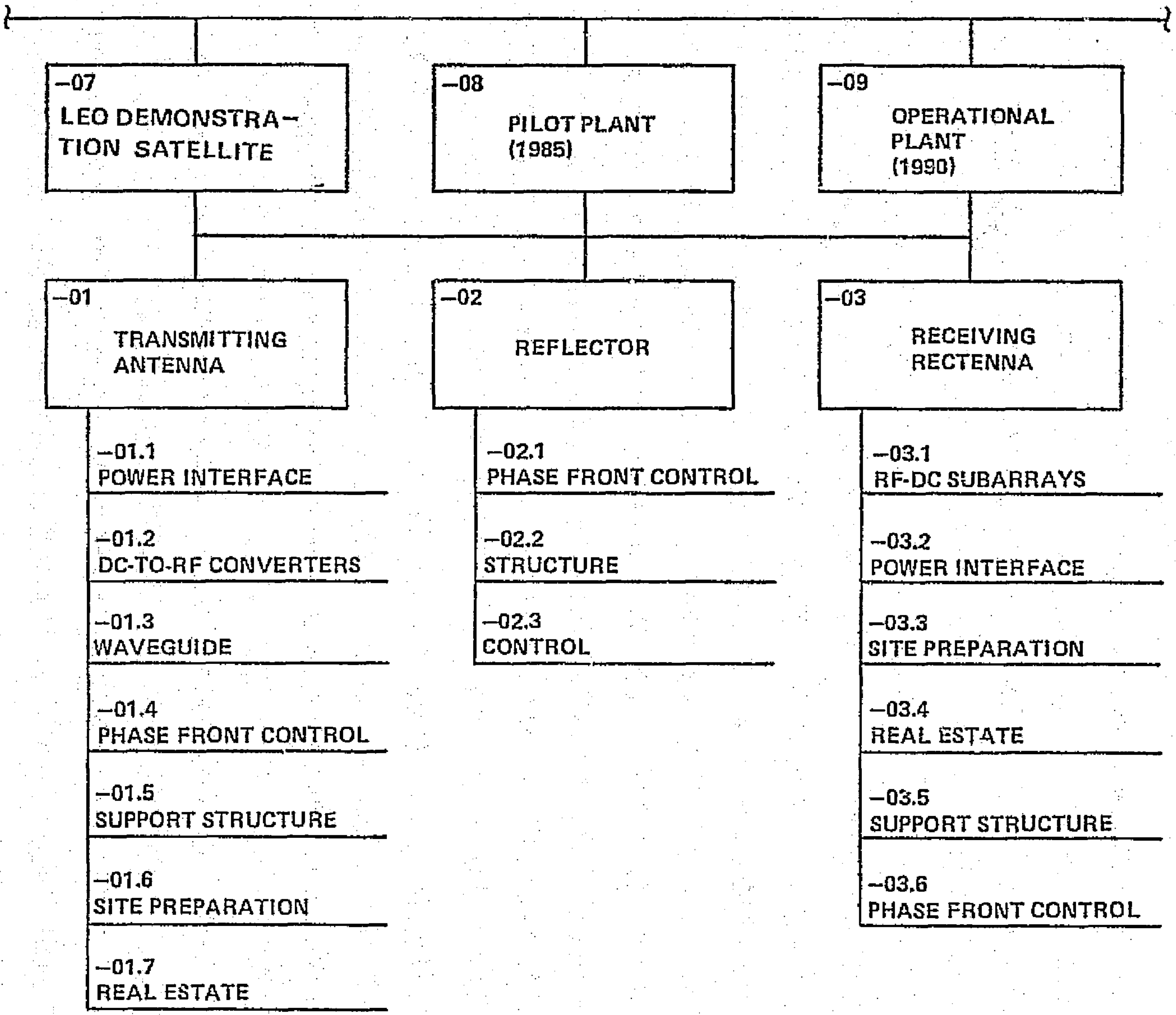

Figure B.9 Delta Work Breakdown Structure

B.2.2 PRS Cost Estimates

Table B.2 contains a compilation of costs using the same relationships used in the SSPS estimates. The cost to develop a full scale (1 km) reflector and place it into geosynchronous orbit using a Full Capability Tug (P/L to SO $\leq$ 5000 kg) appears to be excessive. The development plan that solves the assembly technology problems with a small low earth orbit demonstration satellite should be a lower cost approach. The use of Shuttle derivatives (i.e., DOL and Large Cryo Tug) significantly reduces transportation and assembly costs. The requirement for an HLLV and advanced ion stage still must be evaluated, though the relatively small mass to orbit for the PRS reflector may not justify the development of these advanced systems.

The dominant cost for the transmitter is the slotted waveguide which must cover an area of almost 100 km^2 with a precisely dimensioned surface. The receiving antenna costs are the same as those used in the SSPS estimates.

The transmitter and receiving antenna maintenance costs are based on the assumption of 1 percent per year replacement on hardware and the following personnel (at each site):

Control - Monitor Crew	10/shift x 3 = 20
Maintenance Crew	8/shift x 3 = 24
Support Personnel	2/shift x 3 = 6
	60

The important repairable items for the transmitting antenna are:

Wavequides	\$ 35 x 10^6 (taken as 10% repairable)
Phase Control	\$ 20 x 10^6
DC-RF Converters	\$330 x 10^6
Power Interface	\$410 x 10^6

For the receiving antenna, these are:

Support Structure	\$ 23 x 10^6 (taken as 50% repairable)
RF-DC Subarray	\$ 31 x 10^6
Power Interface	\$ 47 x 10^6
Phase Front Control	\$ 3 x 10^6

The yearly costs are then:

PRS Transmitting Antenna O and M

Equipment	\$795 x 10^6 x 0.01 =	\$7.95 x 10^6/year
Personnel	60MY/yr x \$60K/yr =	\$3.60 x 10^6/year
TOTAL		\$11.55 x 10^6/year

Table B.2 PRS System Cost Estimates

WBS NO.	WBS IDENTIFICATION	IOC	LEVEL 1 WBS ELEMENTS			COMMENTS
			1–DEVELOPMENT	2–PRODUCTION	3–OPERATIONS	
–08	PILOT PLANT	1985			3624 $/KG(1)	(1) TRANSPORTATION & ASSEMBLY – SHUTTLE – FULL CAPABILITY TUG – LEO & SO SPACE STATIONS
–08–01	TRANSMITTING ANTENNA		$1140 M	N/A		
–08–02	REFLECTOR		1521 M			
–08–03	RECEIVING RECTENNA		317 M			
–09	OPERATIONAL PLANT	1990				
–09–01	TRANSMITTING ANTENNA		$980 M		$11.6 M/YR	MAINTENANCE
–09–01.1	POWER INTERFACE			41 $/KW		
–09–01.2	DC-TO-RF CONVERTERS			33 $/KW		
–09–01.3	WAVEGUIDE			354 $/KW		
–09–01.4	PHASE FRONT CONTROL			2 $/KW		
–09–01.5	SUPPORT STRUCTURE			36 $/KW		
–09–01.6	SITE PREPARATION			14 $/KW		
–09–01.7	REAL ESTATE			8 $/KW		
–09–02	REFLECTOR		$30 M		1086 $/KG	TRANSPORTATION & ASSEMBLY
–09–02.1	PHASE FRONT CONTROL			16.3 $/KW	$90 M/YR	MAINTENANCE
–09–02.2	STRUCTURE			94 $/KG		
–09–02.3	CONTROL			$2.8 M/UNIT		
–09–03	RECEIVING RECTENNA		$280 M		$4.6 M/YR	MAINTENANCE
–09–03.1	RF-DC SUBARRAY			76 $/KW		
–09–03.2	POWER INTERFACE			47 $/KW		
–09–03.3	SITE PREPARATION			8 $/KW		
–09–03.4	REAL ESTATE			19 $/KW		
–09–03.5	SUPPORT STRUCTURE			114 $/KW		
–09–03.6	PHASE FRONT CONTROL			5 $/KW		

PRS Receiving Antenna O&M

Equipment	\$104 x 10^6 x 0.01 =	\$1.04 x 10^6/year
Personnel	60MY/yr x \$60K/yr =	\$3.60 x 10^6/year
TOTAL		\$4.64 x 10^6/year

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GLOSSARY OF TECHNICAL UNITS AND ABBREVIATIONS

ac	alternating current
AMO	air mass zero
amp, (A)	amperes
BTU	British Thermal Unit
cm	centimeter (10^{-2} meters)
dB	decibel
dc	direct current
e/cm^2	electrons per square centimeter
g, (gm)	gram (10^{-3} kilograms)
GHz	gigahertz (10^9 cycles per second)
GW	gigawatt (10^9 watts)
η	efficiency (decimal fraction)
I	electrical current
I_{xy}	moment of inertia ($kg-m^2$)
I_{sp}	specific impulse (seconds)
kg	kilogram (2.2046 pounds mass)
km	kilometer (10^3 meters)
kW	kilowatt (10^3 watts)
kWH	kilowatt-hours
m	meter (3.2808 feet)
micron, (μm)	millionth (10^{-6}) of a meter
MHz	megahertz (10^6 cycles per second)

mm	millimeter (10^{-3} meter)
MW	megawatt (10^{6} watt)--except in Chapter 4 where it is used to denote "microwave"
mW	milliwatt (10^{-3} watt)
N	newtons (1N=0.2248 pounds force)
nm	nautical mile(s)
psi	pounds per square inch
rf	radio frequency
RFI	radio frequency interference
solar flux	1353 megawatts per square kilometer
scf	standard cubic foot

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