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SPACE-BASED SOLAR POWER CONVERSION AND DELIVERY SYSTEMS STUDY

SECOND INTERIM REPORT
VOLUME I

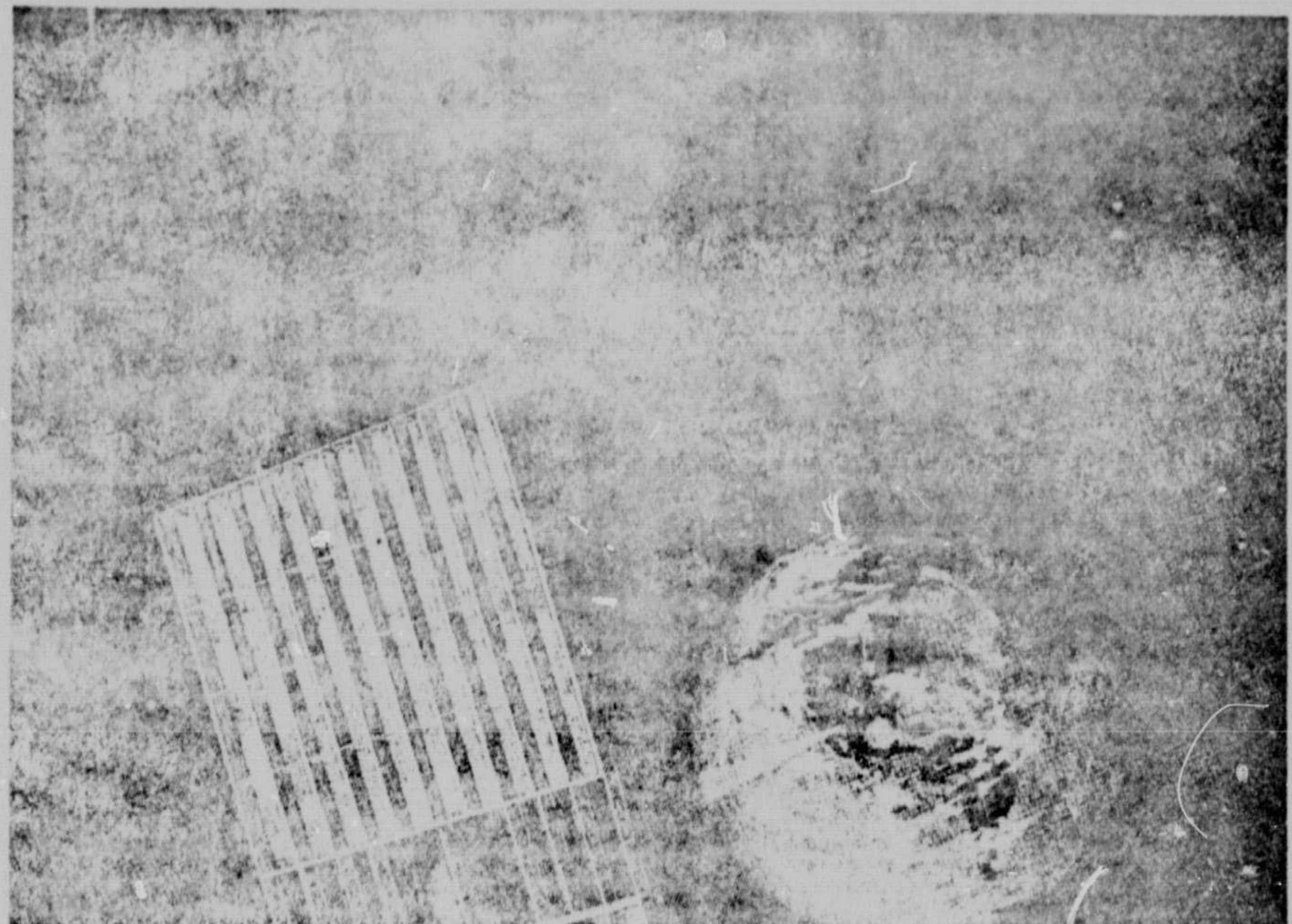
EXECUTIVE SUMMARY

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER

Under
Contract No. NAS8-31308

June 30, 1976

ECONOMICS OPERATIONS RESEARCH SYSTEMS ANALYSIS POLICY STUDIES TECHNOLOGY ASSESSMENT



ABSTRACT

This study of space-based solar power conversion and delivery systems was initiated by NASA, George C. Marshall Space Flight Center, on February 1, 1975, with ECON, Inc. as prime contractor and with Grumman Aerospace Corporation, Arthur D. Little, Inc. and Raytheon Company as subcontractors to ECON. The initial study effort ended November 30, 1975, and resulted in an interim report released March 31, 1976. This phase of the study examined potential concepts for a photovoltaic satellite solar power system, focusing on power levels of 5000 MW and 10,000 MW, and a power relay satellite, and studied certain aspects of the economics of these systems. The conclusions of the first study phase are that, given appropriate technological advances and continued increases in the real cost of generating electrical power by terrestrial systems, satellite solar power systems might become economically viable by the mid-to-late 1990s and that it is unlikely that the power relay satellite will become economically viable at any time over the study period - through 2025.

The second study phase, conducted during the period February 1 to June 30, 1976, examined in greater depth the technical and economic aspects of satellite solar power systems with a focus on the current configuration 5000 MW system. The technical studies, documented in this report, include analyses of the orbital system structures, control and stationkeeping, and the formulation of program plans and costs for input to the economic analyses. The economic analyses centered about the development and use of a risk analysis model for a system cost assessment, identification of critical issues and technologies, and to provide information for programmatic decision making. Also, a preliminary economic examination of some utility interface issues was conducted. This phase of study has resulted in the major conclusions that, under the present state-of-knowledge, it might be possible to formulate a program plan for the development of a satellite solar power system that can be economically justified, and that the key area of technological uncertainty is the productivity of man in space, that is, man's ability to fabricate and assemble large structures in space.

NOTE OF TRANSMITTAL

The economic and engineering analyses of space-based solar power systems developed and reported in this summary volume and the accompanying detailed volumes have been prepared for NASA, George C. Marshall Space Flight Center, under Contract No. NAS8-31308. ECON study manager for this effort during the period 1 February to 30 June, 1976, has been Dr. George A. Hazelrigg, Jr. Also during this period, the Grumman Aerospace Corporation has been under subcontract to ECON to provide the engineering analysis. The Grumman study manager for this study phase has been Mr. Rudolph J. Adornato. The Grumman contributions to the total study effort are documented in Section 3 of this volume and in Volume II of this report. These sections are included verbatim as received from Grumman.

The materials included in this report comprise three volumes: Volume I, Executive Summary; Volume II, Engineering Analysis of Orbital Systems; and Volume III, Economic Analysis of Space-Based Solar Systems. The data presented in these volumes represents additions to, and an update of, the Space-Based Power Conversion and Delivery Systems Study, Interim Summary Report, March 31, 1976.

ECON recognizes the assistance of Dr. Edward J. Greenblat and Mr. Gregg R. Fawkes of ECON in the preparation of this report, and the guidance of Dr. Peter E. Glaser and Dr. Bette M. Winer of Arthur D. Little, Inc., and Mr. Owen E. Maynard of Raytheon. The MSFC COR has been Mr. Walter E. Whitacre of the Payload Studies Offices.

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1. INTRODUCTION

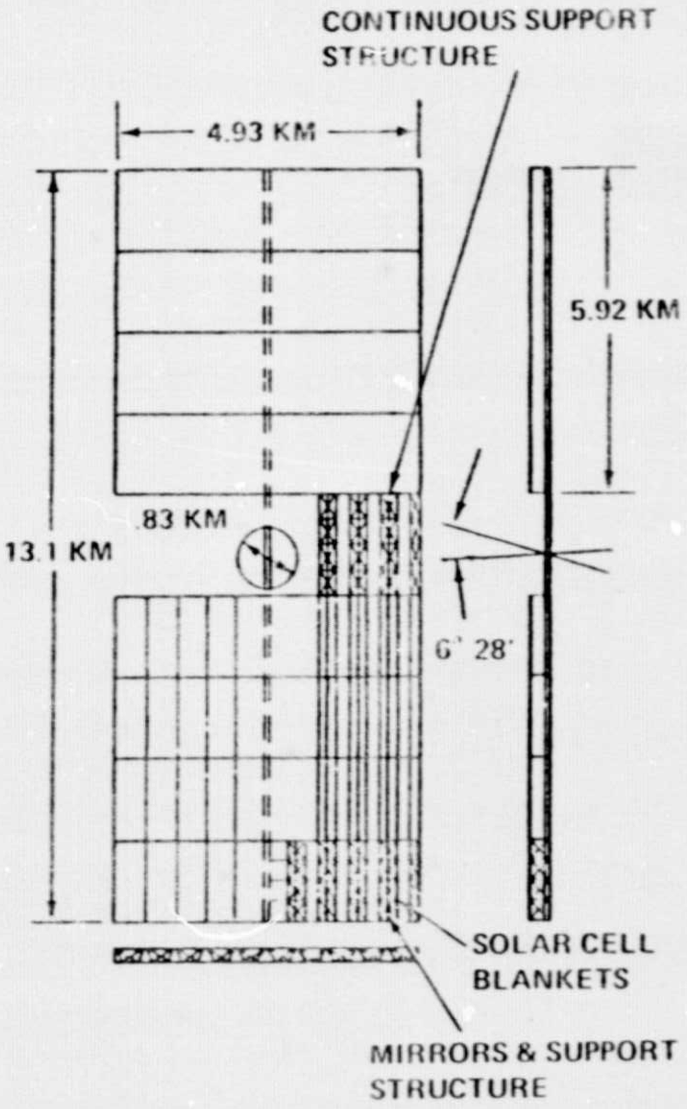
Even at reduced rates of growth, the demand for electric power is expected to more than triple between now and 1995 and to triple again over the period 1995-2020. Without the development of new power sources and advanced transmission technologies, it may not be possible to supply electric energy at prices 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 to assess the technology developments necessary in order to make these systems economically viable.

1.1 Study Objectives and Scope

The principal objective of this study is to achieve increased understanding of the economic and technical aspects of space-based solar power systems and to determine whether, or under what circumstances, a program to develop a capability for space-based solar power systems can be economically justified.

Previous studies have defined concepts for the generation and transmission of electrical power from geosynchronous orbit and some demonstrations of the required technologies have been made. The current configuration photovoltaic system analyzed during this phase of study is shown in Figure 1.1. In funding this phase of study, NASA requested the following efforts:

1. Additional engineering studies of the current configuration focusing in the following areas:
    - orbital system structures
    - control and stationkeeping analysis
    - flight mechanics and orbit transfer stresses
2. An analysis of alternative program plans focusing on the economics of low earth orbit and geosynchronous orbit test satellites.
3. An identification of critical issues and technologies relevant to the construction and operation of a photovoltaic satellite solar power system.
4. A preliminary identification and analysis of utility interface issues and problems.



- 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.

- Approximate Characteristics

- Power	5000 MW (begining of sixth year of operation)
- 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)

Figure 1.1 The Current Configuration 5,000 MW Satellite Solar Power Station

Of particular interest during this phase of study has been the continued refinement of cost estimates and costing methodologies. To satisfy these objectives, a significant part of the study effort was devoted to the development and use of cost and cost-risk analysis computer models. These models are used to combine economic and technical data in order to provide information for programmatic decision making.

The study effort reported herein has been conducted over the period 1 February to 30 June, 1976. The economic results obtained during this study period are new and are based upon many assumptions and judgements that could not be fully substantiated within the resources available for this study. They are, thus, subject to review and update and should be interpreted accordingly.

1.2 Major Study Findings

The major findings of this study phase are summarized below. They are discussed in somewhat more detail in Sections 2 and 3 of this volume. Detailed documentation of the technical work performed is given in Volume II and of the economic work in Volume III of this report.

- The assembled current configuration space-based solar power system (SSPS) is structurally compatible with aerodynamic orbit operations, with thrusting forces during transport to geosynchronous orbit, and with stationkeeping maneuvering.
- SSPS controllability performance of one degree for solar array pointing and one arc-minute for microwave antenna earth-pointing is achievable.
- The baseline structural configuration is incompatible with thermally-induced internal loads during both sunlight and earth shadowing conditions.
- An annual ΔV of 225 m/sec is required for stationkeeping the SSPS to within longitudinal and lateral drift allowances. Approximately 14,000 .445 N thrusters are required for three-axis translation
- A methodology has been developed for comparing alternative program plans. This methodology was applied to three preliminary program plans, one calling for direct development of an SSPS and two others making use of low earth orbit and geosynchronous orbit test satellite subprograms at power levels of 15MW and 500-1000MW respectively. Of the three specific alternatives compared, the direct development program was found to be economically preferred. From the results of this analysis, it is recommended that test satellite subprograms using smaller test satellites be given consideration.

- The critical technology areas with respect to the economic viability of an SSPS lie in two major areas, the productivity of man in space and solar cell technology. Of these, the ability of man to fabricate and assemble large structures in space is the major cost and risk driving element, dominating all other cost and risk elements.

- A preliminary decision tree analysis concludes that, under the present state-of-knowledge, it might be possible to formulate a high (80 percent) confidence level decision making program plan with a positive net expected value. Such a program plan could be economically justified.

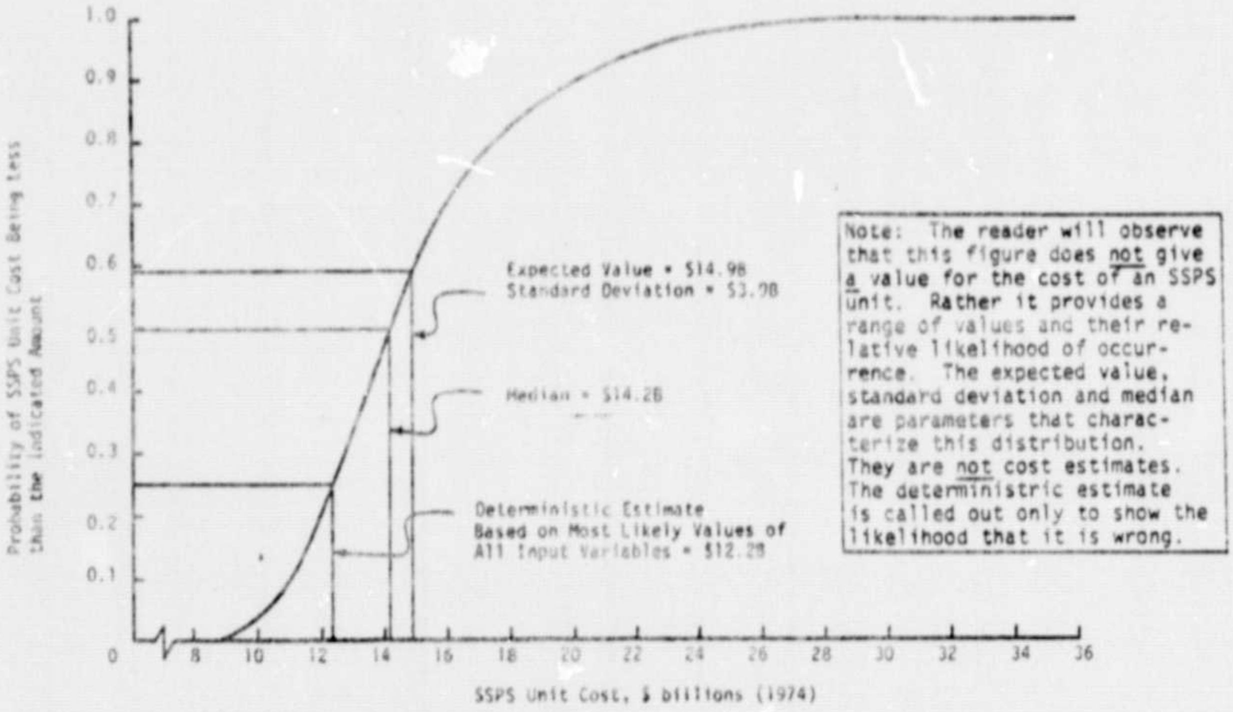
2. SUMMARY OF ECONOMIC ANALYSES

This section summarizes the major results of the economic analyses conducted during the study period February 1 to June 30, 1976, relevant to the current configuration SSPS. These studies focused on the development of a risk analysis model for measuring cost-risks at various points in time in an SSPS development program, and the use of the risk analysis results for programmatic decision making, programmatic risk analysis and identification of critical technologies. In addition, this study includes a brief analysis of some issues relevant to the utilities interface. The results presented in this section should be viewed as preliminary and tentative, and are subject to update and refinement upon review and continued analysis.

2.1 Cost and Risk Analysis Results

A risk analysis model was developed to analyze the cost and risk associated with the second SSPS unit. The cost components included in the analysis are the unit production costs (for satellite and ground station) and the operation and maintenance costs. The analysis focuses on the second unit as the first "production" unit. Unit production costs of the first unit are treated as a part of the development program insofar as the first unit may be a prototype or may be constructed using various techniques, for example, growth from smaller satellites, that are not representative of the construction of later units.

In keeping with the notion that SSPS cost estimating represents forecasting the future, and that, in general, such forecasts cannot be precise, the results of the risk analysis are probability distributions of costs as shown in Figure 2.1 for unit production costs and Figure 2.2 for annual operation and maintenance costs, rather than point estimates. These distributions are a reflection of the present state-of-knowledge of the technologies required for an SSPS upon the current configuration SSPS. That is, they pertain strictly to the current configuration as depicted in Section 1, Figure 1.1, and are the result of projections of the state-of-the-art of the technologies needed to produce the second unit SSPS, in the proposed current configuration, and the uncertainties associated with these state-of-the-art projections. To produce these distributions, SSPS unit production and operation and maintenance cost models were developed. These models require some 150 input variables which describe the various technical and cost parameters of the system. The cost models determine unit production and operation and maintenance costs as a function of the input variables. Then, the state-of-knowledge relevant to each variable was assessed. The state-of-knowledge is expressed as a probability distribution on each variable showing the range of possible values that the variable could take on and the relative likelihood of any particular value within the range occurring.



Note: The reader will observe that this figure does <u>not</u> give <u>a</u> value for the cost of an SSPS unit. Rather it provides a range of values and their relative likelihood of occurrence. The expected value, standard deviation and median are parameters that characterize this distribution. They are <u>not</u> cost estimates. The deterministic estimate is called out only to show the likelihood that it is wrong.

Figure 2.1 Cumulative Distribution Function of SSPS Unit Cost

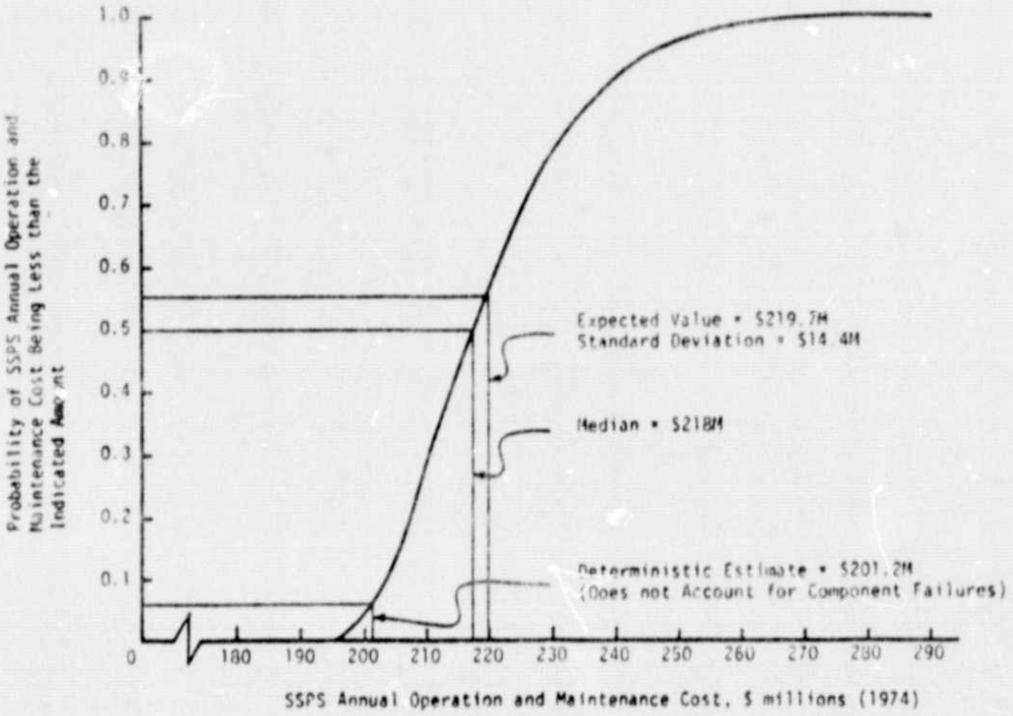


Figure 2.2 Cumulative Distribution Function of SSPS Operation and Maintenance Cost

The cost distributions shown were subsequently generated using a Monte Carlo analysis that repetitively samples the input variable distributions and, from each "sample" of input data, obtains the necessary cost data. These data are accumulated over 400 to 1000 passes through the cost model and form the distributions shown.

Figure 2.1 indicates that the cost of producing the second SSPS unit may range from about \$8 billion (1974) to about \$35 billion (1974). That is, uncertainties in technology growth and development in the period between the present and the time when the second unit could be produced, combined with the present engineering uncertainties associated with the current configuration, limit the accuracy of SSPS cost estimates to the range and characteristics shown. A similar interpretation may be given to Figure 2.2. The cost data shown in Figures 2.1 and 2.2 differ from cost data generated in earlier phases of this study effort in that earlier study phases addressed potential technology capabilities and requirements and provided system cost data based upon desired and/or required technology capabilities whereas the results shown here assess the probability that these technology developments will, in fact, occur within time and funding limitations.

The results shown in Figures 2.1 and 2.2 can be combined with the following assumptions in order to determine the probability that, given the present state-of-knowledge, the second unit could be built and operated with a positive net present value:

1. The SSPS unit availability factor is 0.95. That is, it is producing power 95 percent of the time. This includes power outages due to solar eclipses near the equinoxes.
2. The power output of the SSPS unit decreases by one percent per year due to degradation of various components.
3. The lifetime of the SSPS unit is 30 years.
4. The capital investment in the SSPS unit is made in one lump-sum payment two years prior to the initial operation date of the SSPS unit.
5. The real price of power at the rectenna busbar (1974 dollars) increases at the rate of one percent per year.
6. No charge is made for taxes and insurance.
7. Present value computations use a discount rate of 7.5 percent.

The probability distribution of net present value of the second unit is shown as a function of the price of power at the rectenna busbar on the first day of operation in Figure 2.3. If the price of power at the busbar on the first day of operation is 30 mills/kWh (1974),

Figure 2.3 indicates that there is about a 21 percent chance (about one in five) that the second unit will be economically viable.

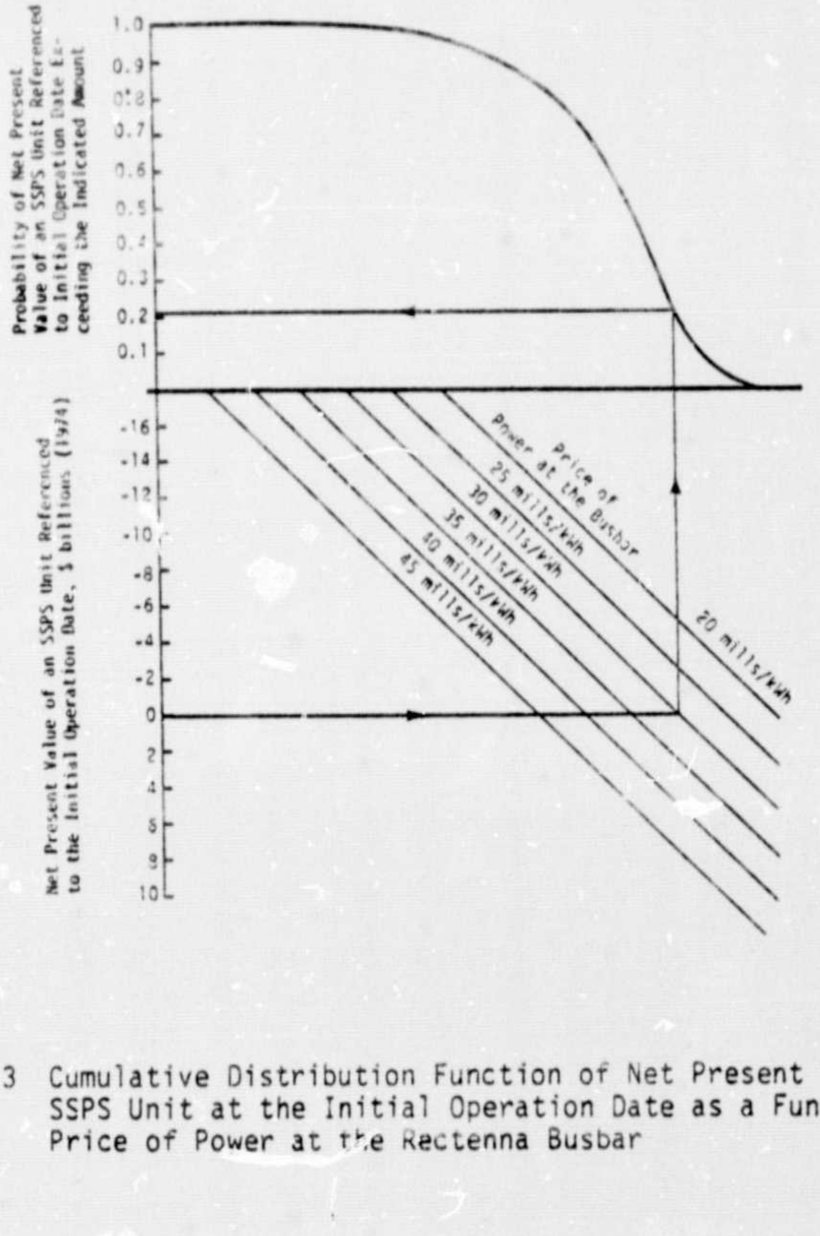


Figure 2.3 Cumulative Distribution Function of Net Present Value of an SSPS Unit at the Initial Operation Date as a Function of Price of Power at the Rectenna Busbar

2.2 Critical Technologies

The critical component in making a decision to proceed with an SSPS development program is the economic viability of the current (or subsequent) SSPS configuration. Thus, using the risk analysis model, the technologies critical to the economically successful production of a current configuration SSPS are identified in terms of their contribution to the cost and risk of SSPS unit production as follows. First, the risk profile of the current configuration SSPS was established as described above. Then from the list of inputs to the risk analysis model, 56 potentially significant technology items were identified. Each of these variables has associated with it a state-of-knowledge that is described by a probability density function ranging from a minimum value to a maximum value. (Based on today's knowledge, there is probability zero that a parameter will lie outside the range so described. Furthermore, the probability density function has its maximum value at the most likely value of a parameter.) The assessment of critical technologies focuses on the minimum, maximum and most likely values of each significant input variable. The effect of removing uncertainty in each of these variables was investigated by setting the range over which each variable may vary to zero, one-by-one, first to the minimum value, then the most likely value and then the maximum value. That is, the effect of removing uncertainty in each variable was investigated over the full range of values which, by today's state-of-knowledge, each variable may take on. For example, to determine the contribution to cost and risk of the cost of the solar array blanket per unit area, that cost is input to the risk model as a deterministic value, first at its minimum value, then at its most likely value and, last, at its maximum value, holding all other inputs the same as they were in the basic risk analysis. The key results of the exercise are shown in Figure 2.4. The technologies that potentially have the most impact on the cost and risk include:

- solar cell efficiency
- specific mass of the solar blanket
- fraction of satellite assembled by man
- rate of manned assembly
- rate of remote assembly
- low earth orbit space station unit cost
- solar array blanket specific cost.

It is interesting to note that these critical technologies encompass only two general areas, uncertainties associated with the solar arrays, that is, solar array costs, mass and performance, and uncertainties associated with the assembly of large systems in space. This figure clearly shows the driving technology to be the rate of manned assembly--that is, the productivity of man in space is the major cost and risk driver for the current configuration SSPS. Since this conclusion could substantially affect future SSPS development programs, it is recommended that it be subjected to a careful review before being fully accepted. It must be emphasized again that these results derive from subjective assessments of the state-of-knowledge relative to the current configuration SSPS and are subject to variability upon review. However, there is little doubt that the productivity of man in space is an area of uncertainty that needs to be dealt with sooner rather than later.

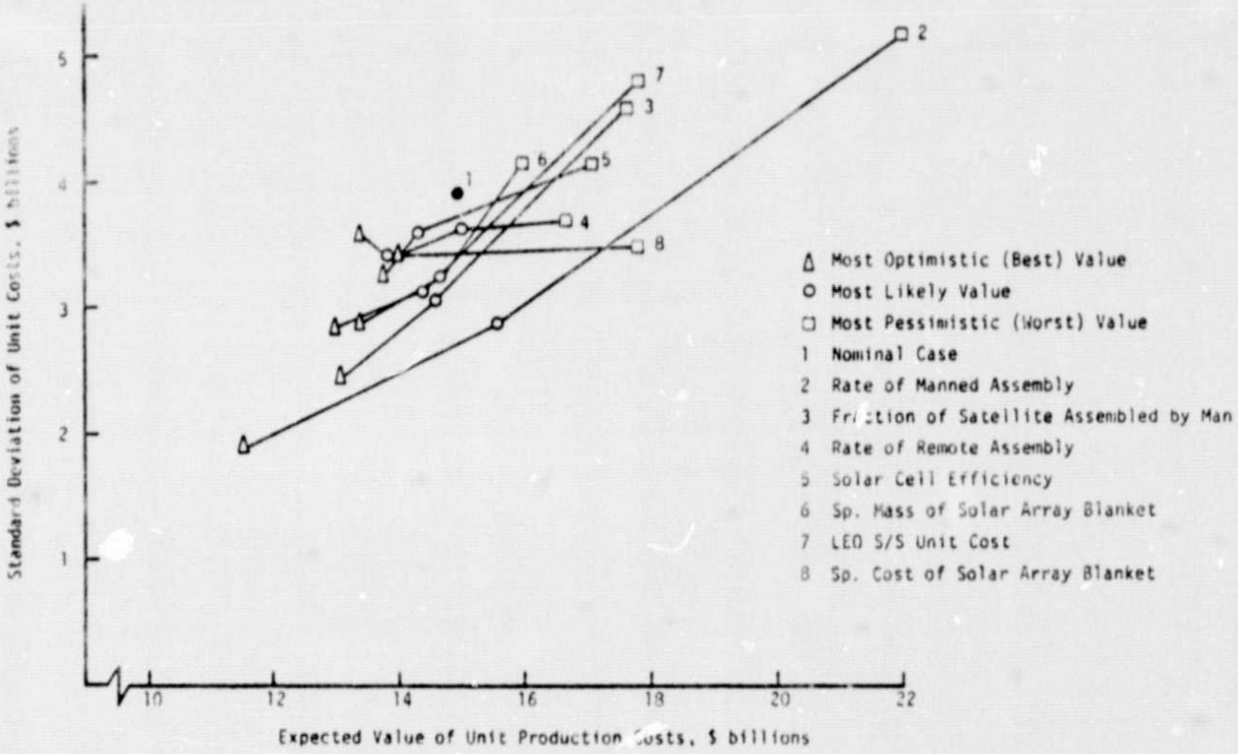


Figure 2.4 Effect of Removing Uncertainty on Cost Components--Major Cost- and Risk-Driving Factors

2.3 Analysis of Alternative Program Plans

Three alternative program plans were analyzed to test the economics of low earth orbit (LEO) and geosynchronous orbit (GEO) test satellites. The three program plans analyzed are as follows:

Program I: This program provides for the direct development of a full-scale SSPS. DDT&E begins January 1, 1984, and initial operation date (IOD) of the first unit is December 31, 1991.

Program II: This program makes use of a 500 MW GEO test satellite to provide data for the development of the full-scale SSPS. The GEO test satellite DDT&E begins January 1, 1980, and the IOD is December 31, 1985. DDT&E of the full-scale SSPS begins January 1, 1985, and the IOD of the full-scale SSPS is December 31, 1991.

Program III: This program makes use of a 15 MW LEO test satellite and a 1,000 MW GEO test satellite to provide data for the development of the full-scale SSPS. The DDT&E for the LEO test satellite begins January 1, 1980, and the IOD of this satellite is December 31, 1985. The DDT&E for the GEO test satellite begins January 1, 1985, and the IOD of the GEO test satellite is December 31, 1990. The DDT&E of the full-scale SSPS begins January 1, 1990, and the IOD of the full-scale SSPS is December 31, 1995.

Figure 2.5 shows the Program I schedule. The program is supported by a supporting research and technology program that runs from January 1, 1977, to December 31, 1988. The final social and environmental (FS&E) statement for SSPS is required at the end of 1983, the technology is frozen at the end of 1986 and the heavy lift launch vehicle (HLLV) is required at the end of 1988.

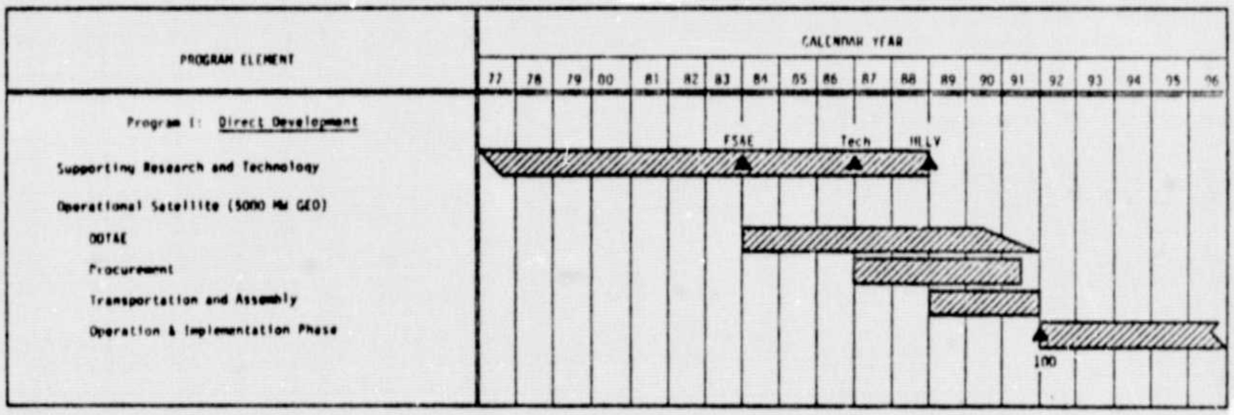


Figure 2.5 Program I Schedule

The program plan shown in Figure 2.5 can also be illustrated in the decision tree form shown in Figure 2.6. This figure indicates that decision points are assumed to exist at points which correspond to major milestones in the program schedule. The analysis proceeds subject to the following assumptions:

1. The beginning-of-life power of each unit is 5,258 MW (5,000 MW nominal at the beginning of the sixth year).
2. The SSPS power output decreases at 1 percent per year from the beginning of life throughout the unit lifetime.
3. Each SSPS unit has a lifetime of 30 years.
4. Each SSPS unit is producing power 95 percent of the time.
5. Implementation of second and subsequent satellites begins with the initial operation date of the second unit as follows:

   Program I - January 1, 1996
   Program II - January 1, 1994
   Program III - January 1, 1997

   Thereafter, units come on line at the rate of two per year through 1999, then at the rate of four per year until 109 units have been produced.
6. The cost of the third and subsequent satellites is related to the cost of the second satellite according to a 90 percent learning relationship. That is, the cost of the nth unit, C_n, is given as a function of the cost of the second unit by the relation

   $$C_n = C_2\, 0.859^{\ln (n-1)}$$
7. The price of power at the rectenna busbar is assumed given on January 1, 1992, to be 20 mills/kWh (1974). After that date, the real price increases at the rate of 1 percent per year. (No taxes or insurance are included.)

Given the above assumptions, a decision logic for each program plan was developed. The decision logic for Program I is shown in Figure 2.7. In order for the SSPS program (109 satellites and ground stations) to be economically viable, the present value of total (life cycle) SSPS costs referenced to the IOD must be less than $18.9 billion (1974). This, then, is the technology target. Decision making is performed at the 80 percent confidence level. Based upon

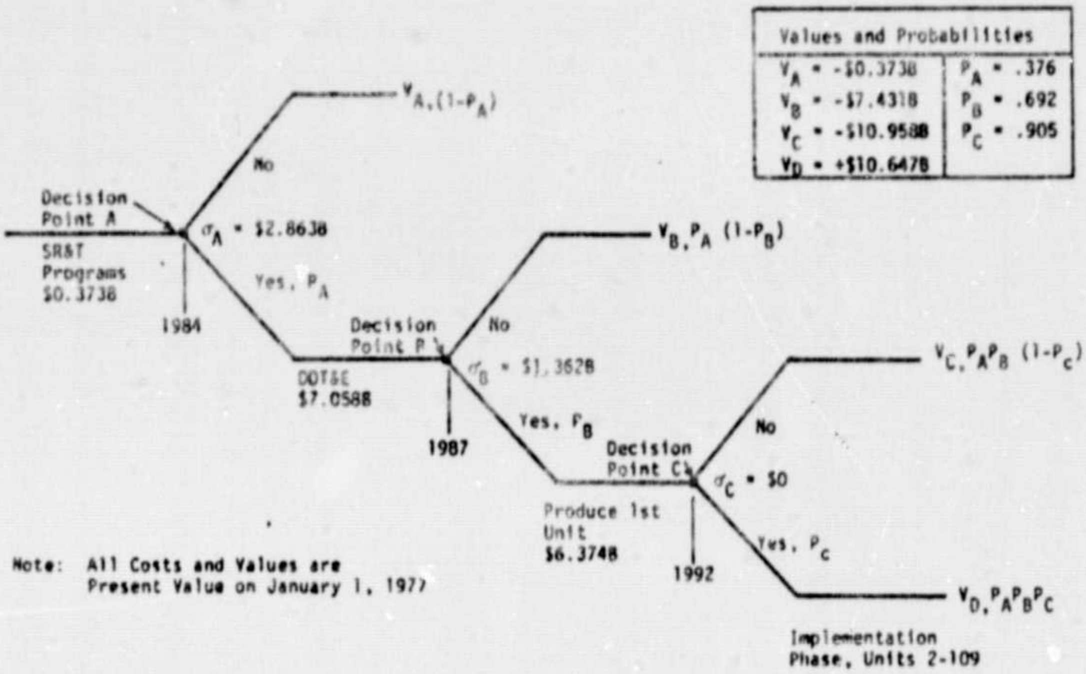


Figure 2.6 Decision Tree Representation of Program I

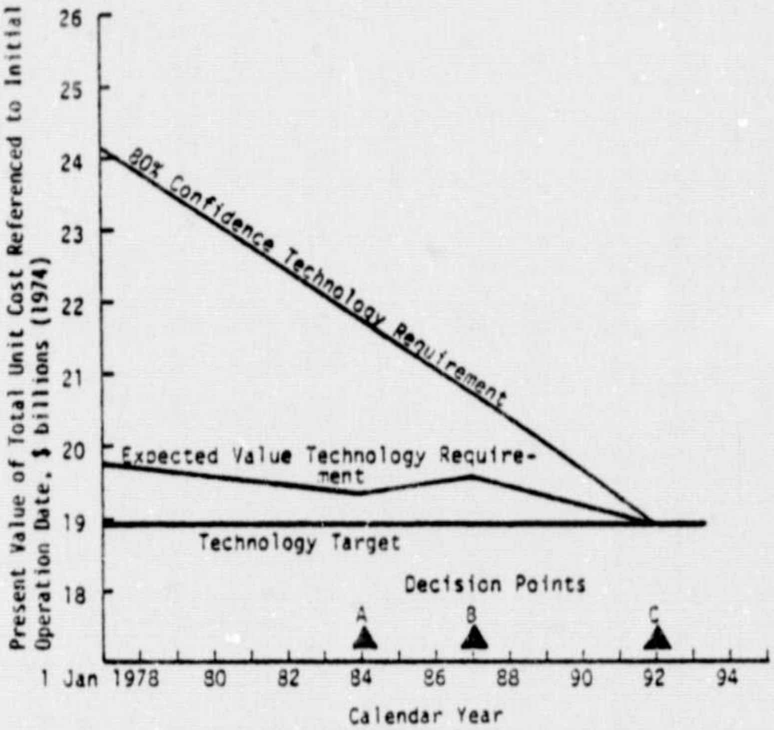


Figure 2.7 Decision Rule for Program I

today's state-of-knowledge, the 80 percent confidence level cost is \$24.1 billion. The decision rule chosen requires a linear improvement of the 80 percent confidence technology bound with time up to Decision Point C at which time the decision to proceed with implementation of the second and subsequent units is made. With this decision rule, the probabilities and net present values associated with each possible outcome of the program decision tree are as shown in Figure 2.6. The expected net present value of Program I is \$1.15 billion (1974), and the probability of success of this program is 0.235.

The expected net present values of Programs II and III are -\$1.10 billion (1974) and -\$0.92 billion (1974) respectively. Thus, not only are these program alternatives less desirable than Program I but, since their values are negative, a decision to undertake them is not justified, even independent of the alternative Program I.

The results of the above analysis depend upon the assumptions made. Changes in the assumptions may charge the conclusions. Thus, while the insights gained may be valuable, decisions should be based on this analysis only after a thorough review of the cost model, the cost model (state-of-knowledge) data and the assumptions made for the analysis. If the results of this analysis stand up under thorough review, then one is justified in recommending a go-ahead decision on Program I since the expected value of this program is positive. However, it should be observed that the expected value of Program I is only a small fraction of the total monies to be expended on the program. Thus, before one makes a recommendation to proceed with this program, it is probably wise to try to refine the program plan so as to increase its expected value.

2.4 Utility Interface Issues

An effort was made in this study phase to identify issues which might be important concerning the interface between an SSPS and terrestrial utility systems as they are forecast to exist in the 1990 and beyond time period. Three issues were addressed in this study: the effects of SSPS reliability/availability versus that for conventional powerplants, the effect of power outages due to solar eclipses, and the effect of power fluctuations at the rectenna busbar.

Utility systems are designed to meet prescribed levels of reliability in providing power. Currently, this reliability requirement is that the cumulative probability that the demand exceeds the available generating capacity not be greater than one day in ten years. This reliability is achieved by installing greater generating capacity than will be needed to meet the projected peak demand. How large this reserve margin must be to assure the required level of reliability is affected by both the forced outage rates of the units in the system and the sizes of the units. The trend presently in utility systems is toward systems that are larger (many will have doubled or tripled in capacity by 1990), composed of larger individual generating units with greater interconnections and pooling among systems.

The experience of utilities has been that the larger the size of conventional power plants the higher the forced outage rate. The projected reliability level for SSPS is fairly high compared with the conventional power plants expected for the 1990 and beyond time period. This higher reliability for SSPS allows it to produce power at the same busbar cost as conventional plants while having a somewhat higher installed cost. Also, the effect on various power pools (with sizes that might be typical in 1990 and beyond) of the introduction of an SSPS was analyzed with respect to reserve capacity requirements. Under some circumstances, the SSPS was found to be advantageous (that is, its presence reduced the reserve requirement for the system), and in others it was found to be disadvantageous. Whereas more detailed study than was possible here is necessary, it is not thought at this time that the reserve requirements (and accompanying costs) posed by SSPS will prove to be a critical economic issue.

The SSPS satellite is eclipsed for periods up to 72 minutes around midnight for three weeks before and after the two equinoxes. These eclipses occur at "valley" periods in demand, and therefore, if sufficient alternate capacity exists, these eclipses may be treated as planned outages (such as those for maintenance), not incurring the cost of additional installed reserve. Under the worst case examined--that of needing dedicated peaking plants to cover the eclipse period--the effect on the cost of SSPS-generated power was not critical, raising the average annual generating cost by 0.5 mills/kWh. Further study is needed, particularly including the effects of system interconnections, multiple occultations of SSPS satellites, and occultations of one satellite by another.

Finally, the effect of fluctuations in transmitted power was examined. If the fluctuations are sufficiently rapid and unpredictable, the daily operating reserve of the utilities cannot compensate for the difference in power level. If it is not possible to put such fluctuating power to economic use, then the effect would be a derating of the capacity of an SSPS. With the currently projected maximum rate of fluctuation, the effect of such a derating would not be critical, raising the generation cost of SSPS by about 0.3 mills/kWh.

3. SUMMARY OF ENGINEERING ANALYSES

This section summarizes the major results of the engineering analyses conducted during both initial and extension phases of the contract performance periods. In the initial contract phase emphasis was placed on identifying system requirements for the orbiting systems, providing cost data for the orbiting systems and associated fabrication, assembly and transportation systems, and defining near-term research activities to assure development and operational feasibility in the 1990 time frame. In so doing, a baseline configuration was evolved representing the orbiting systems technology and performance requirements projected to that time frame.

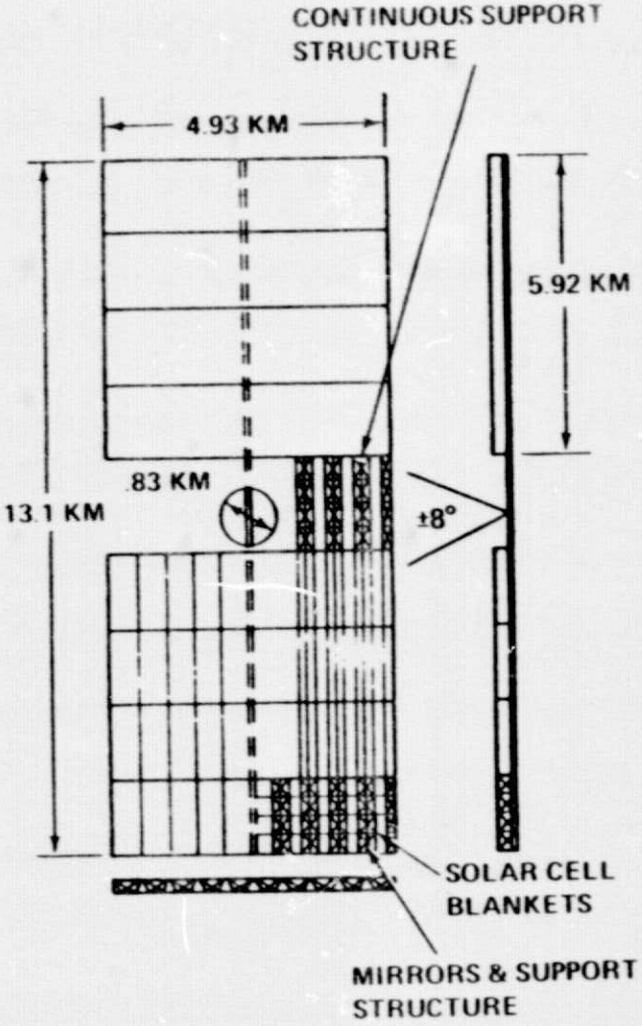
In the contract extension phase the studies were directed to providing technical support on engineering issues considered critical to a viable initial economic assessment. These included the analysis of structures during low earth orbit operations, during transport to geosynchronous orbit and during geosynchronous orbit operations, station keeping analysis, and control analysis of solar array and microwave antenna pointing. In addition, three program development plans were formulated and cost estimated for use by ECON in developing the methodology for analyzing the economics of low earth orbit and geosynchronous orbit test satellites.

3.1 Baseline Satellite Solar Power Station

A series of system trade studies were conducted to evolve a baseline SSPS configuration to serve as a starting point from which further studies could be directed to define overall system design requirements. Figure 3.1 depicts an overview of the baseline established. This SSPS configuration generates 5000 MW of power, measured at the end of 5 years into life, at the output of the receiving antenna. It has two large photovoltaic solar cell arrays, each approximately 6 by 5 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 is attached to the mast by a rotary joint system with unlimited freedom of rotation in azimuth (East-West) and ± 8 degrees in elevation (North-South).

The solar cell blankets, which are positioned between channel concentrators, operate at an overall efficiency of 11.3% at the end of 5 years into life. The microwave subsystem operates at a frequency of 2.45 GHz and has a dc-to-dc efficiency of 58%.

Development cost for the satellite itself has been estimated at \$20.4B (1974). Supporting programs that could be developed independently of SSPS (for example, transportation vehicles, space stations, etc.) have been estimated to cost \$23.5 B (1974). The unit cost for SSPS has been estimated at \$7.6 B (1520 \$/kW)(1974). Included in unit costs are the costs of the satellite subsystems, the cost of transportation, and the cost of assembly. Operating costs for the satellite and ground receiving antenna have been estimated at below \$218 M/yr (at 50% confidence). In arriving at this maintenance cost, it was assumed that a space station is fully manned at all times.



- CONCEPT DESCRIPTION

  COLLECTS SOLAR ENERGY USING PHOTOVOLTAIC CONVERTERS & TRANSMITS POWER TO EARTH AS MICROWAVE ENERGY. THE MICROWAVE ENERGY IS RECTIFIED TO DC POWER AT THE GROUND RECEIVING STATION

- CHARACTERISTICS

– POWER	5000 MW
– WEIGHT	18.1 X 10^6 KG
– SIZE	13.1 X 4.9 KM
– ORBIT	GEOSYNCHRONOUS
– LIFE	30 YR
– OPERATING FREQ	2.45 GHZ
– DC-TO-DC EFFIC	58%
– SOLAR ARRAY EFFIC	11.3%

- COSTS (1974 DOLLARS)

– IOC	1990-1995
– DDT&E	
· DIRECTLY RELATED	\$20.4B
· SUPPORT PROGRAMS	\$23.5B
UNIT COSTS	\$ 7.6B
- OPERATING COSTS	\$218M/YR

Figure 3.1 Satellite Solar Power Station

Figure 3.2 summarizes the SSPS mass properties at the start and conclusion of the initial study phase. The increase in mass from 11.5 x 10^6 kg to 18.1 x 10^6 kg is due to refined estimates of the microwave subsystem resulting from Raytheon's MPTS studies (NAS3-17835, see CR-134886). The largest increases are in the microwave tubes and waveguides. Refined estimates of the microwave efficiency chain are the dominant forces in the increase of the solar array mass from 9.6 x 10^6 kg to 12.3 x 10^6 kg. The array structure increased due to analysis that indicated that lateral support structure was needed to improve column stability of the main longitudinal beams.

For purposes of comparison, a 5000 MW and 10,000 MW system are presented. The power-to-mass ratios of the major subsystems are:

- Solar Array = 0.7 KW/kg (power measured at output of array)
- Transmitting Antenna = 0.9 KW/kg (power measured at output of ground rectenna)

The major element efficiencies used in sizing the baseline SSPS are summarized in Figure 3.3.

The total solar array efficiency is projected at 11.3%. The system is sized to generate 5000 MW of ground output power during the summer and winter months, accounting for the cosine losses that result from fixing the array normal to the equatorial plane. The nominal solar cell efficiency is 13.7% (5 years into life) at a concentration ratio of 2. The total degradation due to radiation damage over 30 years is 20 percent. The power distribution efficiency was selected through a mass tradeoff, which considered power bus system material, cross-section, and operating temperature.

The total microwave system efficiency, measured from the input bus to the transmitting antenna to the output bus of the ground rectenna, is 58%. An amplitron efficiency of 85% has been reached experimentally, adding confidence to our projection of achieving 87% over the next ten years. Beam collection efficiency was selected to minimize cost based on the product of the areas of the transmitting and receiving antennas.

Figure 3.4 shows the key inputs to this study from the Raytheon MPTS studies. Specific mass, specific cost, and efficiency trends with frequency are shown for the amplitron. These favor a selection near 2.45 GHz, which is in the center of the industrial microwave band. An output power level selection at 2.45 GHz should be near 5 KW for the individual tubes.

A critical factor in the selection of operating frequency and system power level is the ground power density. Also shown are peak ground power density as a function of frequency and power level. Reference values of power density are shown for sunlight (100 mW/cm^2), the USA standard for continuous exposure to microwave (10 mW/cm^2), and an estimate for onset of ionospheric modification (20 mW/cm^2). Based on these trends, the baseline system size was limited to 5000 MW, consistent with the biological standards and the impact of ionospheric changes.

	SSPS MASS PROP. AT START OF STUDY		SSPS MASS PROPERTIES RESULTING FROM STUDY			
	5GW; 1 Km DIAM ANTENNA		5GW; 0.83 Km ANTENNA MASS		10GW; 1.18 Km 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
• BUSSES, 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	10.2[illegible]
• 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	0.28	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 WGT FROM MPTS STUDIES NAS 3-17835
  - – REFINED ESTIMATE OF MICROWAVE EFFIC CHAIN INCREASES POWER SOURCE SIZE

Figure 3.2 Mass Properties

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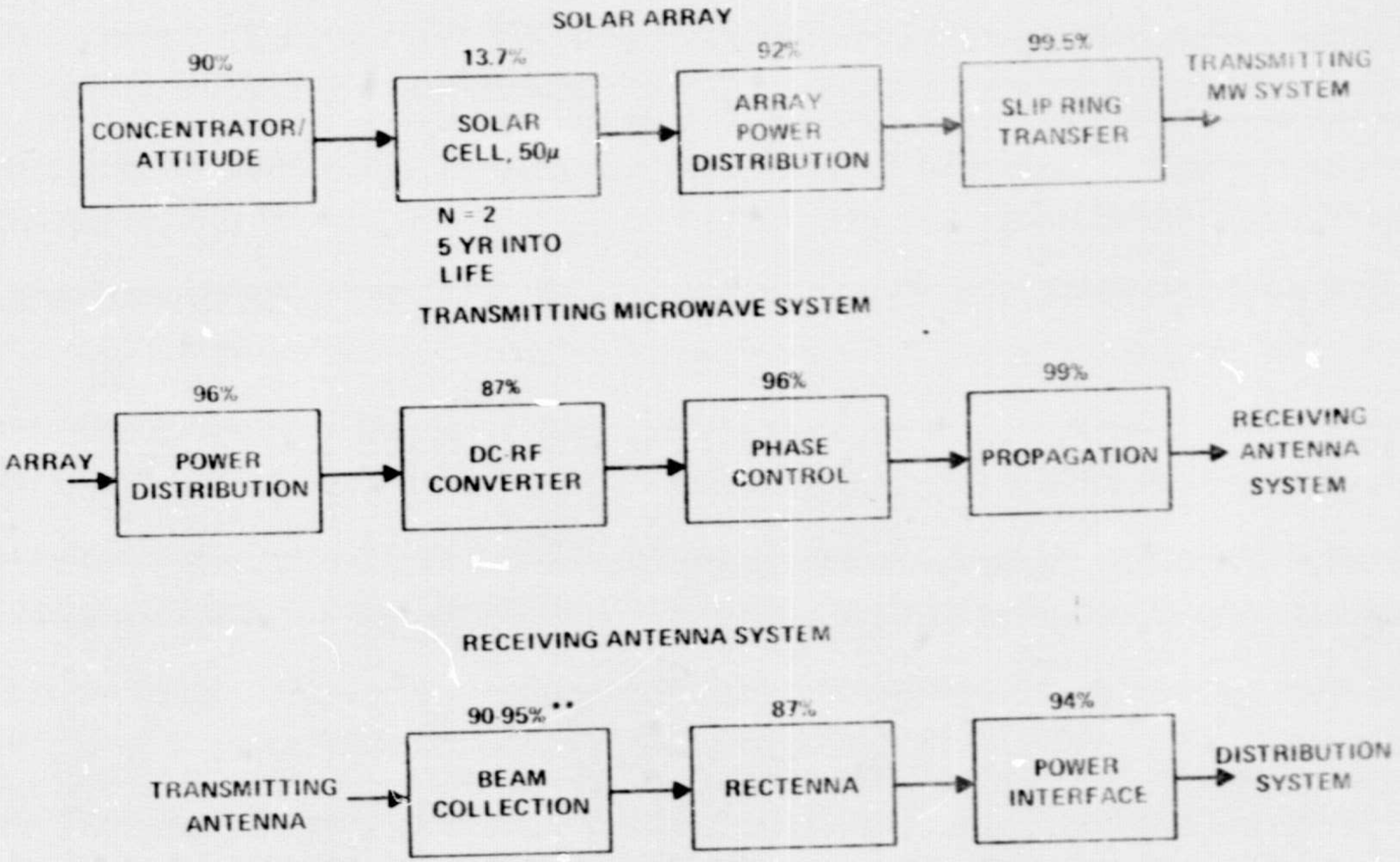
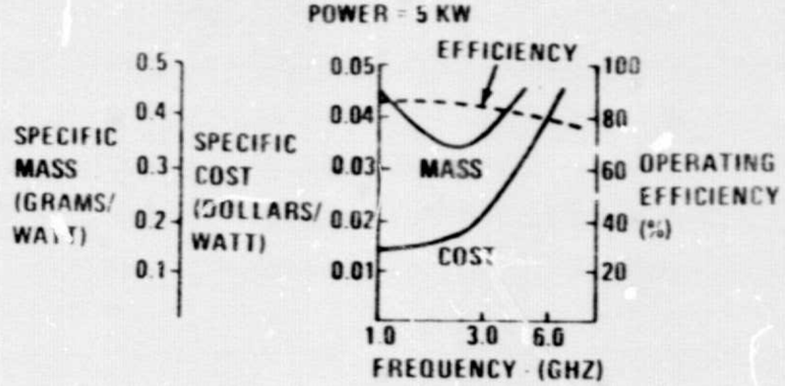
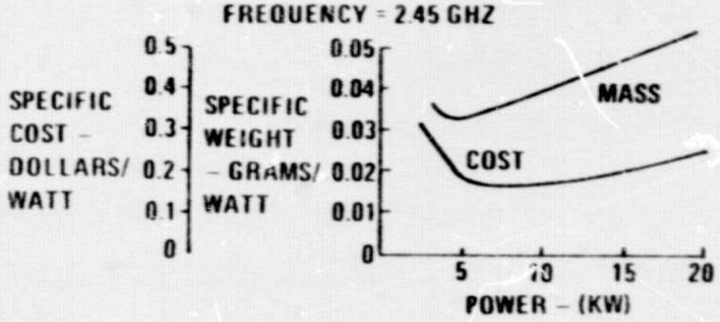


**DEPENDS ON ORBITAL ANTENNA AND GROUND RECTENNA SIZE WITH ASSOCIATED COST, LAND USE, POWER DENSITY TRADEOFFS

Figure 3.3 SSPS Nominal System Efficiency Chain



AMPLITRON WEIGHT/COST/EFFICIENCY VS FREQUENCY



AMPLITRON WEIGHT AND COST VS POWER

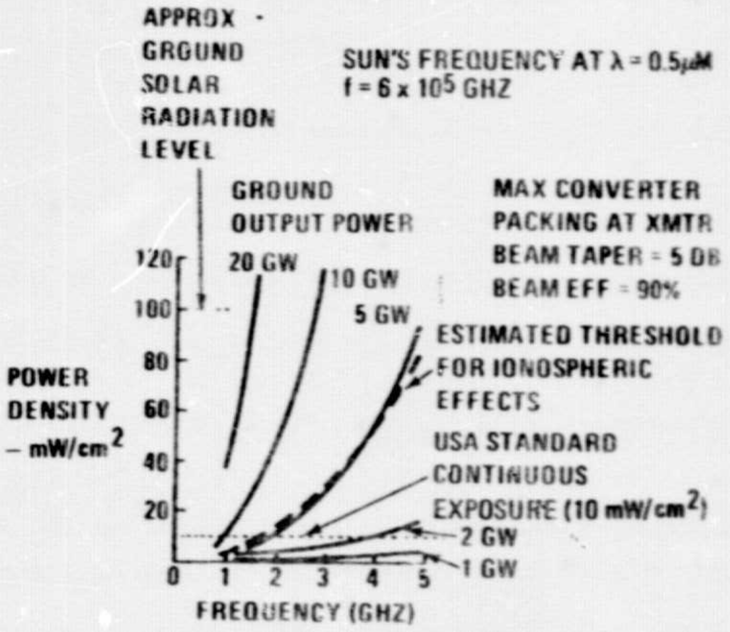
SYSTEM POWER LEVEL SELECTION

- SSPS OUTPUT POWER WAS SELECTED TO:
  - LIMIT PEAK POWER DENSITY ON GROUND TO BE NEAR USA STANDARD FOR CONTINUOUS EXPOSURE ($10MW/cm^2$) AND
  - LIMIT POWER DENSITY AT THRESHOLD FOR CHANGES IN IONOSPHERE ($20MW/cm^2$) FOR 2.45 GHZ AT 5000MW)
- 5000MW GROUND OUTPUT POWER LEVEL USED FOR INITIAL PLANNING PURPOSES BASED ON POTENTIAL TO MEET THESE CONSTRAINTS

MICROWAVE CONVERTER PARAMETER SELECTION

- SPECIFIC WEIGHT, SPECIFIC COST & EFFICIENCY TEND TO FAVOR:
  - SELECTION OF FREQ = 2.45 GHZ
  - POWER LEVEL = 5000W

  FOR MICROWAVE CONVERTER



PEAK GROUND POWER DENSITY VS FREQUENCY

Figure 3.4 Microwave Configuration Tradeoffs (Ref: NAS3-17835)

Figure 3.5 summarizes the tradeoff used to select the basic solar array configuration. A comparison of a 2-mirror corrugated design and a 4-mirror "petal" design was made for various solar cell thicknesses and concentration ratios. System mass was shown to be minimum at a concentration ratio of approximately 2 for the options considered.

In an effort to simplify the mechanical devices used in the system, solar tracking was restricted to one axis. Solar tracking in the north-south direction was not adopted. The impact of this approach on system efficiency at the summer and winter solstices shows that the 2-mirror "corrugated" design is more forgiving than the 4-mirror system. The 2-mirror approach was baselined for this study.

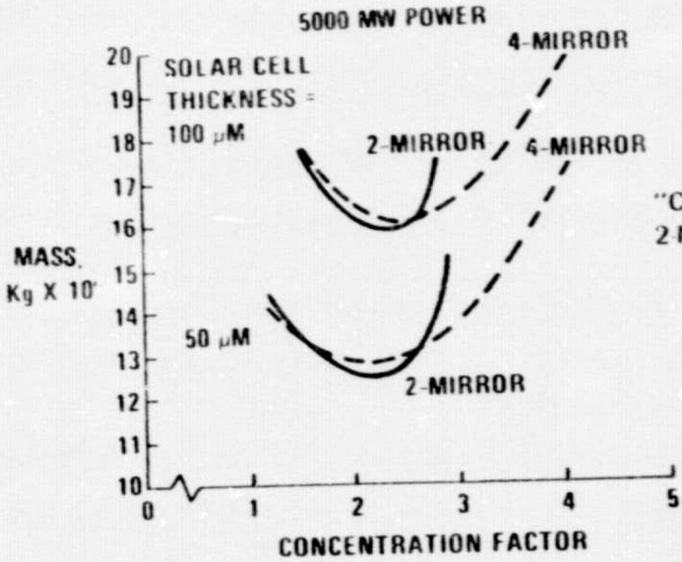
Transportation costs were determined to be a large contributor to the total cost of the system. Figure 3.6 summarizes the tradeoffs used to identify transportation system characteristics needed to provide an economically viable SSPS. A cost target of 4 mills/kWh was established for the launch system and orbit transfer vehicle based on an overall SSPS competitive cost of 25 mills/kWh. To satisfy these goals, a launch system must have a high recoverability rate or heavy lift capability. A heavy lift launch vehicle with 181,000 kg payload to low earth orbit was baselined for these initial economic studies. An orbit-transfer-vehicle with a specific impulse in excess of 1000 sec desensitizes the effects of mass fraction on overall SSPS cost for transfer to geosynchronous altitude. An ion stage was baselined for this study.

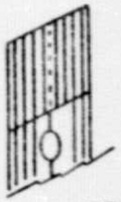
3.2 Engineering Analyses and Major Findings

Using the mission scenario wherein the SSPS is assembled in low earth orbit (LEO) and transferred in its entirety to geosynchronous orbit (GEO), structural analyses were conducted to evaluate the major load effects resulting from LEO operations, the orbit transfer maneuver and operations at GEO altitude. The major loadings considered were aerodynamic drag and gravity gradient forces acting in LEO, the forces resulting from thruster application during orbit transfer, and the thruster forces resulting from attitude control and station-keeping maneuvering at GEO.

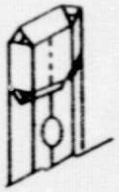
Aerodynamic and gravity gradient forces commensurate with those acting at an altitude of 370 km on the baseline SSPS with one half the solar blanket deployed, were evaluated. This configuration was representative of the condition where a sufficient amount of the solar blanket was deployed in LEO for providing power to the ion thrusters used for orbit transfer. The results of this analysis, as shown in Figure 3.7a, reveals that the bending and torsion moments resulting from these forces are significantly lower than the allowable limits. Thus, it was established that aerodynamic and gravity gradient loads acting in LEO are not major factors in defining SSPS structural design requirements.

Loads imparted to the baseline structure from forces applied during low thrust orbit transfer maneuvering were analyzed for three thrust application techniques, to determine orbit transfer trip times and their impact on structural design requirements. One technique, representative of ion thrust powered by the SSPS solar array, consisted of a concentrated thrust, located





"CORRUGATED"
2-MIRROR SYSTEM



"PETAL"
4-MIRROR SYSTEM

STUDY ASSUMED

- ARRAY FIXED NORMAL TO EQUATORIAL PLANE
- PASSIVELY COOLED ARRAY
- SOLAR CELL EFFICIENCY DROPS WITH INCREASED CONCENTRATION RATIO DUE TO INCREASED TEMPERATURE

PRELIMINARY FINDING

- BOTH 2-MIRROR "CORRUGATED" DESIGN AND 4-MIRROR "PETAL" DESIGN TEND TO HAVE MIN. WGT AT A CONCENTRATION RATIO SLIGHTLY ABOVE 2
- THE 2-MIRROR SYSTEM IS SIGNIFICANTLY LESS AFFECTED BY ATTITUDE MISALIGNMENTS RELATIVE TO SUN LINE
- 2-MIRROR SYSTEM SELECTED FOR PRELIMINARY PLANNING PURPOSES

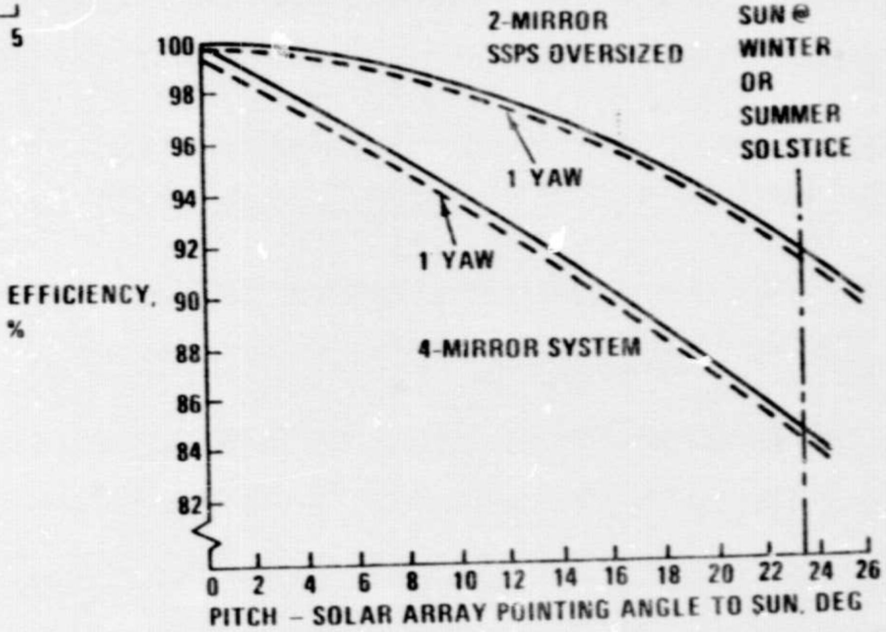
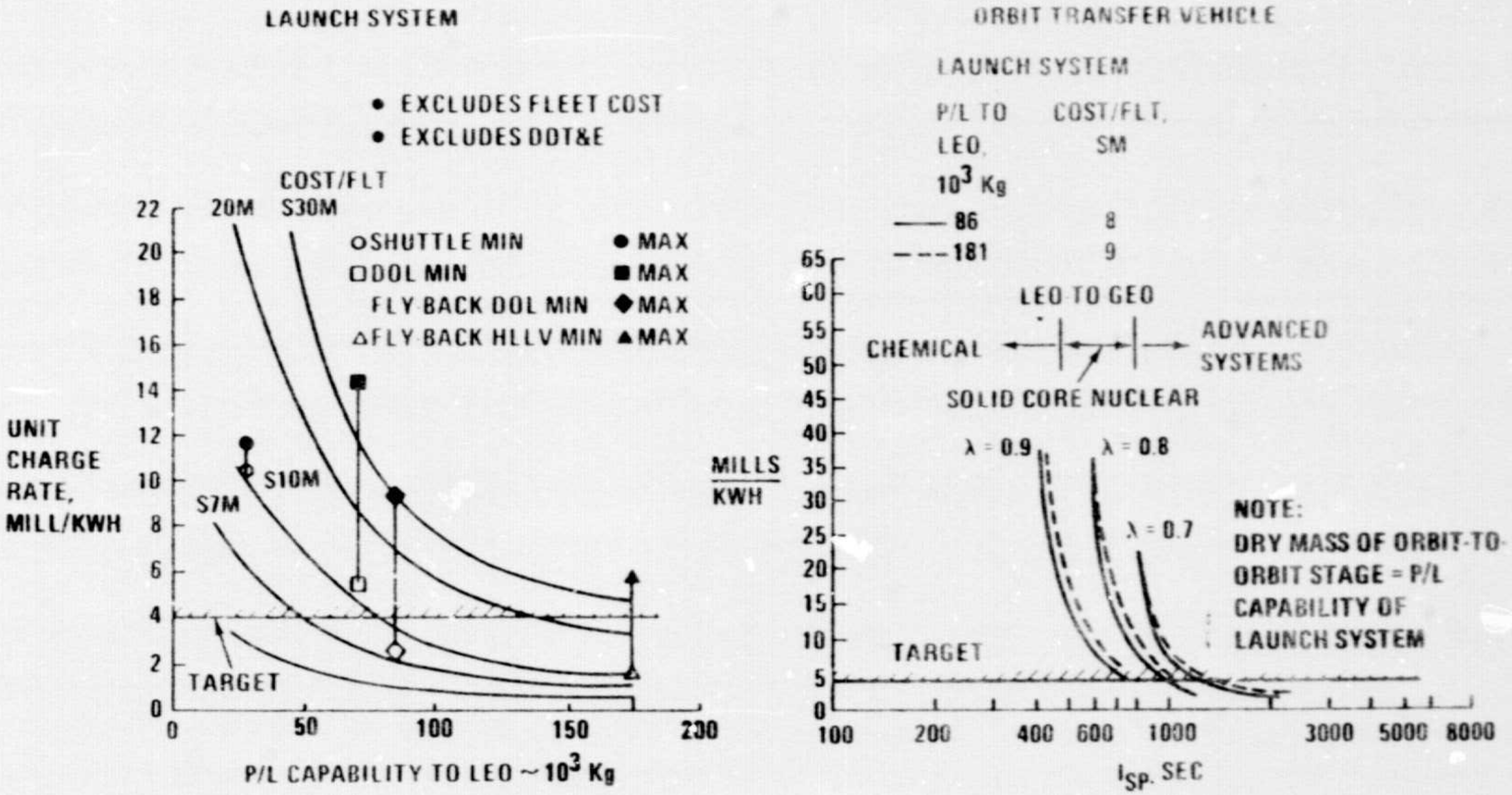
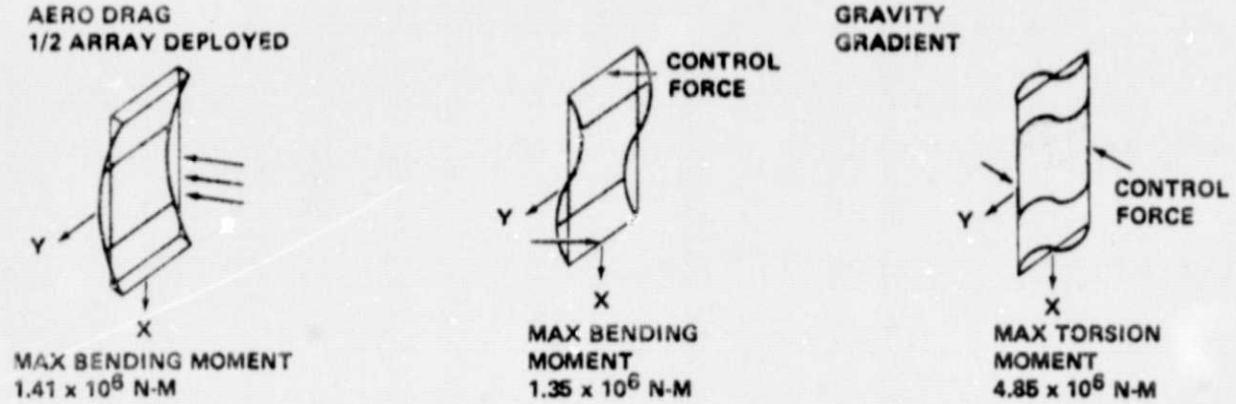


Figure 3.5 Solar Array Configuration Tradeoffs



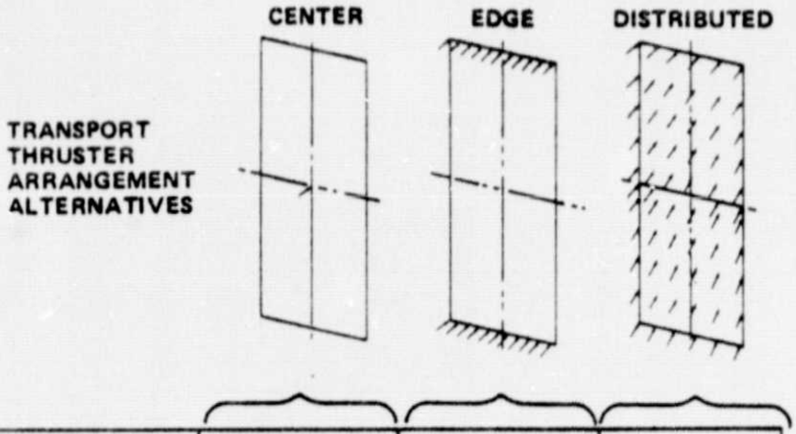
- LAUNCH SYSTEM PAYLOAD TO LEO GREATER THAN 181,000 KG OR LOW COST PER FLIGHT (FULLY RECOVERABLE SYSTEM) REQUIRED TO MEET SSPS COST TARGETS
- ADVANCED ORBIT TRANSFER VEHICLES (I_{SP} > 1000 SEC) NEEDED TO MEET COST TARGETS
- ASSUMPTIONS USED FOR COSTING & PLANNING
  - FULLY RECOVERABLE HLLV ($9M/FLT, $400M/UNIT)
  - 10N STG TRANSFERS ENTIRE SSPS TO G E O ($190M/UNIT)

Figure 3.6 Transportation Tradeoff

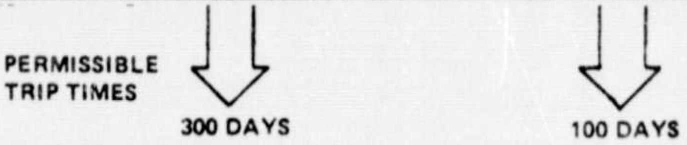


- TRIP TIMES TO 365 DAYS PERMISSIBLE
- ALLOWABLE BENDING MOMENT 12.7 x 10^6 N-M

a. LEO CONTROL EFFECTS



ALLOWABLE THRUST (N)	5793	2570	13,802
MAX AXIAL MEMB LOAD (N)	5431	5431	5431
MAX WIRE LOAD (N)	−422	−223	−651
MAST BEND MOMENT (N-M)	5,936,000	3,938,000	6,473,0
ANT. LOAD FACTOR	9.06×10^{-5}	6.18×10^{-5}	1.51×10^{-4}



b. TRANSPORT ALTERNATIVES (ENTIRE SSPS)

Figure 3.7 Structural Loads Sources

on the antenna rotary joint at the center of the satellite, gimballed to maintain the thrust force tangent to the orbit plane while the solar array is maintained inertially fixed toward the sun. Other techniques considered consisted of distributed thrust applied to the solar array, in one case applied to the upper and lower edges and in another uniformly distributed across the entire array. The results of this analysis are summarized in Figure 3.7b and show that the critical factor governing the magnitude of allowable thrust is the maximum allowable axial member load. For the baseline analyzed, the maximum allowable axial member load, 5431 N, corresponds to permissable trip times of approximately 300 days for the concentrated thrust and 100 days for the uniformly distributed thrust. The 300 day trip time may be reduced to approximately 170 days by a gradual buildup of thrust over a period of one hour. Consequently, using the solar array for powering ion thrusters to transfer from LEO to GEO, trip times between 170 to 300 days are compatible with the baseline structure. Trip times as low as 100 days could be achieved by applying thrust uniformly across the entire array.

In performing the structural analysis, a structural model was developed by representing the structure as finite element bar members and concentrating the mass into node points (462 were utilized for half the structure). Modes and frequencies for this model were computed and utilized to analyze the structural loading resulting from attitude control system thruster excitation and stationkeeping maneuvering. The results of this analysis have shown that the on-orbit loads resulting from attitude and stationkeeping maneuvering at GEO are about an order of magnitude smaller than the allowable loads and, consequently, not a factor in establishing satellite structural design requirements.

An alternate mission scenario, wherein the satellite is transported to GEO in major subassembly units, was analyzed to determine the structural loadings resulting to these units as a function of trip time. Two such cases were investigated. One assumed the satellite was transported to GEO in three segments of equal mass, and another in three segments of equal area. In both cases, the results showed that higher thrust forces could be accommodated by these subassemblies resulting in trip times to GEO of from 25 to 80 days. An additional analysis considered the use of a single stage (LOX/LH_2) chemical Orbital Transfer Vehicle (OTV) for transporting subassembly modules to GEO. The baseline OTV used delivers a payload of 72,560 kg (160,000 lbs) to geosynchronous altitude from low earth orbit. Because of this low payload capability only 8 bays of structure (each 493m X 493m) could be transported per trip. The loads resulting on these segments were approximately nine times greater than the allowable axial member loads making this scenario unfeasible for further consideration.

A thermal-structural analysis has been conducted to evaluate the structural loads imposed at GEO, both during sunlit and earth shadowing conditions. Average temperature profiles were estimated for major members of the baseline configuration during steady state sunlight conditions and during the 1.189 hours of maximum earth shadowing conditions. Uniform α/ε values were utilized. These temperature profiles were utilized with the structural model to determine the deflections and internal loads resulting during two specific conditions, in earth shadow with the mast power off, and in sunlight with the mast power on. A summary of these results are presented in Figure

3.8 showing that in both cases, the longitudinal expansion of the central mast causes perpendicular deflections of the solar array with a maximum slope of 1.1 degrees (1 degree required) over a small section. Unacceptable compressive loads, more than 13 times the design value, occur in the cables directly attached to mast. That is, the cables require pre-tension loads 13 times the baseline value to prevent them from slackening under the thermal conditions assummed. It should be noted that the results indicated are highly correlated to the temperature differentials estimated between the structure and mast and should be further substantiated before redesign is initiated. If, however, these results are corroborated, potential corrections to be considered include strengthening the structure to prevent local deflection slopes greater than 1 degree and allowing the cables to go slack, strengthening the structure to permit higher cable preloading, or isolating the electrical transmission from the mast structure. Further design requirements and definition of the central mast are planned during follow-on study activities.

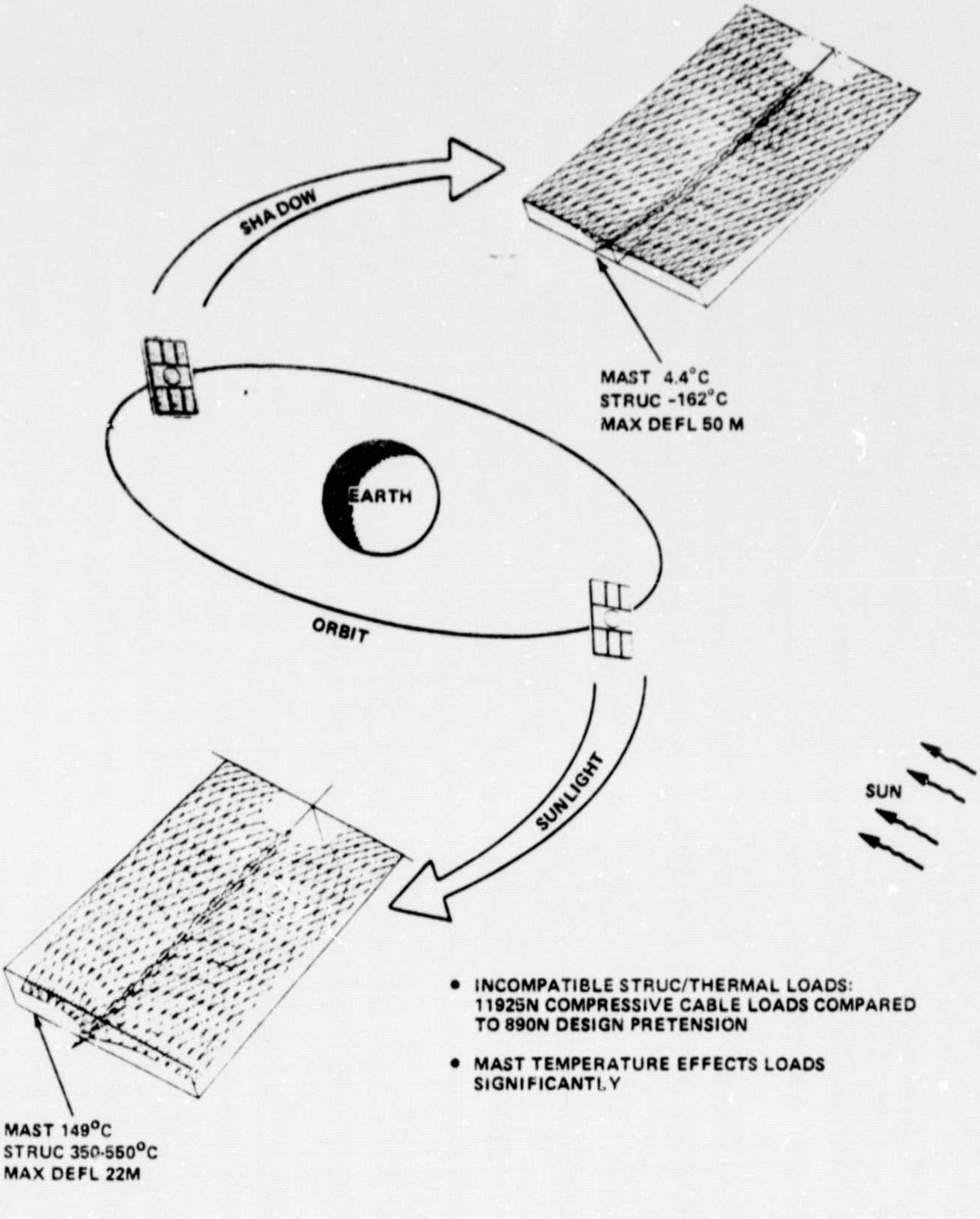
Attitude control analysis for on-orbit pointing requirements were conducted to evaluate the interaction between the roll control of the sun-oriented solar array and the earth pointed antenna. Results of a simulation, which included models for structural compliance of the central mast and significant structural modes, are summarized in Figure 3.9. These results showed that the solar array limit cycle coupling has a significant impact on antenna control. By tightening the array limit cycle to approximately ± .5 deg (± 1.0 deg is required), antenna pointing to ± 1 arc min was achieved. It was also shown that a unidirectional slip ring drag torque results during steady state operations, thereby avoiding attitude disturbances from slip ring reversals. Further study is recommended to develop candidate rotary joint designs in more detail with subsequent dynamic analysis.

The effects of orbital perturbations on ground rectenna output power have been evaluated; the results indicate a significant impact on overall system performance. Figure 3.10 summarizes the results of the stationkeeping analysis, defining the forces acting, the resulting satellite motions and the thrusting requirements needed to control satellite relative motion. Thruster maneuver corrections are identified, requiring thruster application every 57 days for solar radiation eccentricity and earth ellipticity effects. This duty cycle is based on controlling East-West satellite drift to within ±2.5°. For closer control tolerances, the duty cycle must be increased. Inclination effects (North-South drift) requires corrections on a yearly basis whereas solar radiation forces effecting orbital period are nulled continuously. For thrust levels associated with ion thrusters (4.45N), a total of approximately 14,000 thrusters are required for three-axis translation with burn durations of from 5 to 10 days.

3.3 Program Plans and Costs

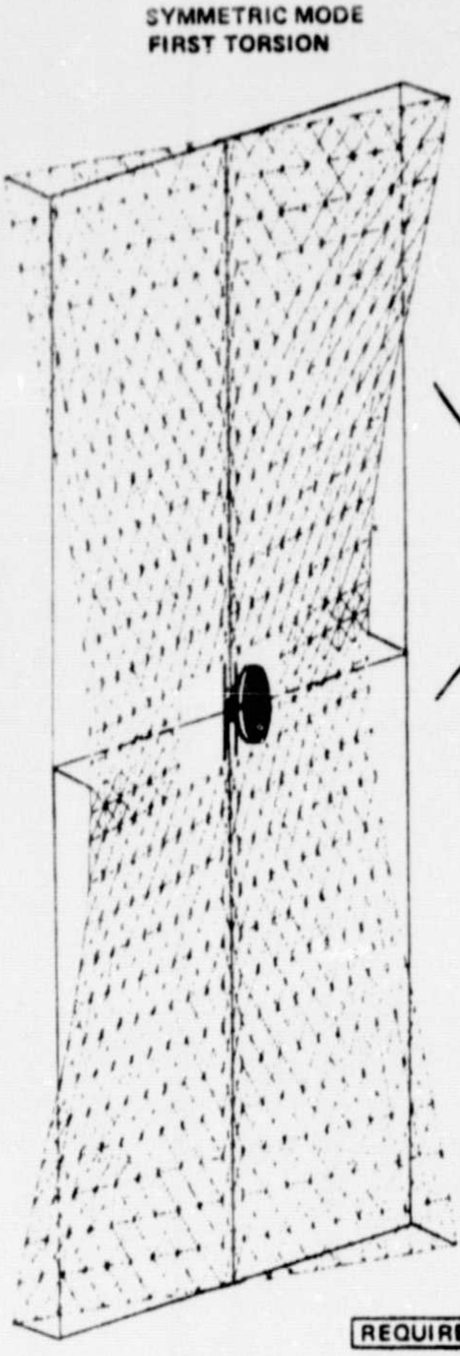
In support of the economic analysis of low earth orbit demonstration satellites and geosynchronous earth orbit pilot plants, program development options leading to the on-orbit operation of the first 5 GW satellite were formulated and ROM cost estimated. Three program options were considered:

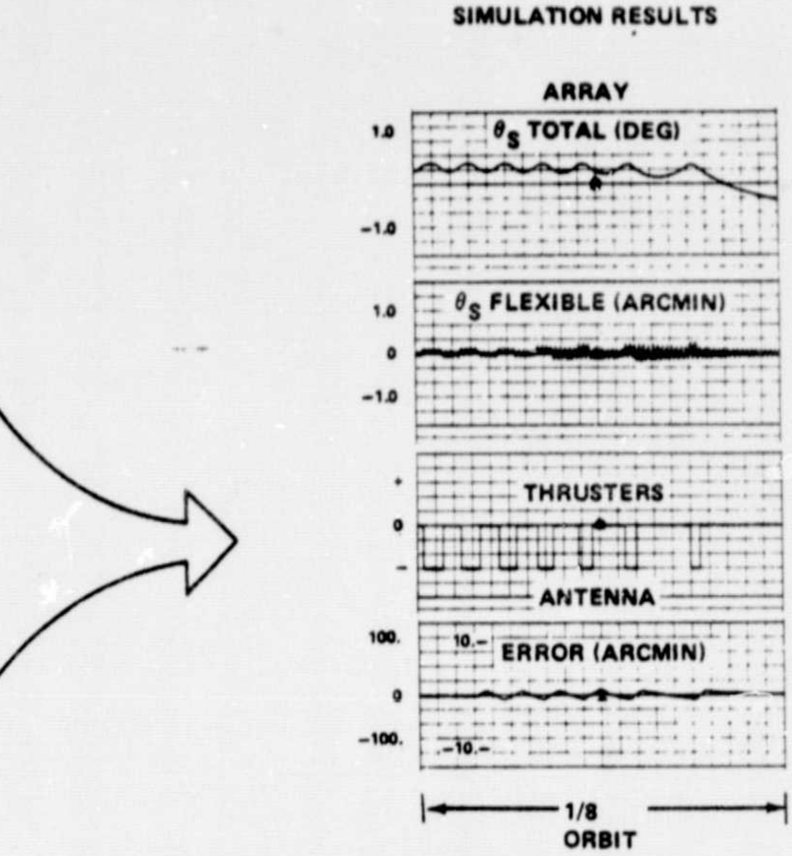
- Program I - consisting of the direct development of an operational satellite.



- INCOMPATIBLE STRUC/THERMAL LOADS: 11925N COMPRESSIVE CABLE LOADS COMPARED TO 890N DESIGN PRETENSION
- MAST TEMPERATURE EFFECTS LOADS SIGNIFICANTLY

Figure 3.8 Structural/Thermal Analysis Results





SIGNIFICANT PARAMETER		VALUE
SOLAR ARRAY INERTIA	–	2.44×10^{13} Kg-M
ANTENNA INERTIA	–	2.44×10^{11} Kg-M
MAST STRUC COMPLIANCE	–	5.02×10^{9} N-M/rad
SLIP RING DRAG TORQUE	–	1.36×10^{6} N-M
LOWEST STRUC MODE FREQ	–	14.14 C/HR

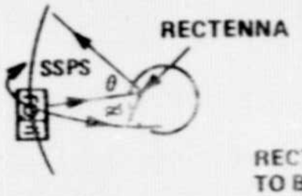
REQUIRED PERFORMANCE ACHIEVED

- LIMIT CYCLE ARRAY CONTROL – ±1 DEG
- ANTENNA POINTING – ±1 ARCMIN
- UNIDIRECTIONAL ANTENNA MOTION & SLIP RING DRAG
- 10/1 STRUC-TO-CONTROL FREQUENCY
- CONTROL THRUST NOT CRITICAL IN STRUC SIZING

Figure 3.9 Antenna/Solar Array Roll Control Interaction

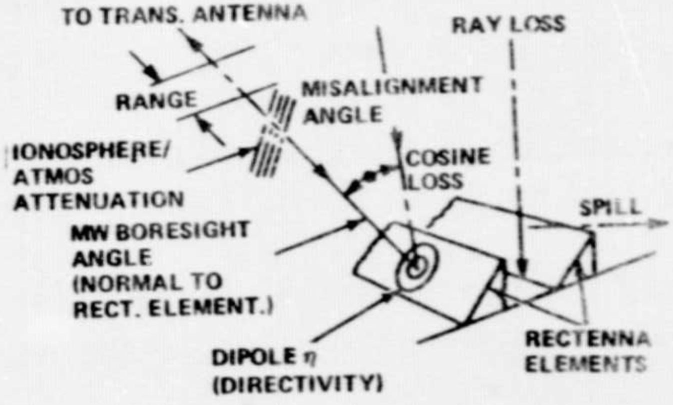
STATIONKEEPING

- ORBITAL PERTURBATIONS OF SATELLITE IF UNCHECKED CAN RESULT IN A SIGNIFICANT POWER LOSS AT THE GROUND RECTENNA

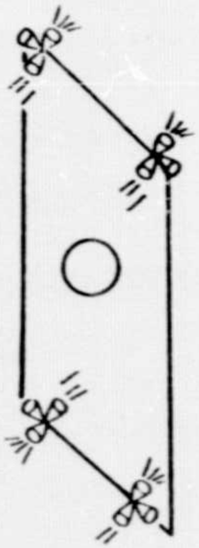


CAUSES (PERTURBATIONS)	EFFECTS	CORRECTION DUTY CYCLE (DAYS)
• GRAVITATIONAL POTENTIAL OF THE SUN & MOON	ORBITAL INCLINATION DRIFT	365
• SOLAR RADIATION PRESSURE	ORBITAL ECCENTRICITY VARIATION ALTITUDE VARIATION	57 DAYS CONTINUOUS
• MICROWAVE RADIATION PRESSURE	SATELLITE ALTITUDE VARIATION	57 DAYS
• ELLIPTICITY OF EARTH EQUATORIAL PLANE	SATELLITE LONGITUDINAL DRIFT	57 DAYS

RECTENNA POWER OUTPUT SENSITIVITY TO BEAM ANGLE DEVIATION



14,000
.445 N
THRUSTERS
REQUIRED
FOR
STATION-KEEPING



THRUSTER REQUIREMENTS
(BASED ON ± 2.5° ALLOWABLE LONGITUDINAL DRIFT)

CAUSES (PERTURBATIONS)	ANNUAL ΔV REQTS, M/SEC	TOTAL THRUST REQTS, N
GRAVITATIONAL POTENTIAL OF SUN & MOON	45.7	602
SOLAR RADIATION PRESSURE	146 (ECC) 23 (ALT)	905.8 8.5
MICROWAVE RADIATION PRESSURE	9 (ECC) .6 (ALT)	8 .5
ELLIPTICITY OF EARTH EQUATORIAL PLANE	2	8.5

Figure 3.10 Orbital Mechanics Analysis Results

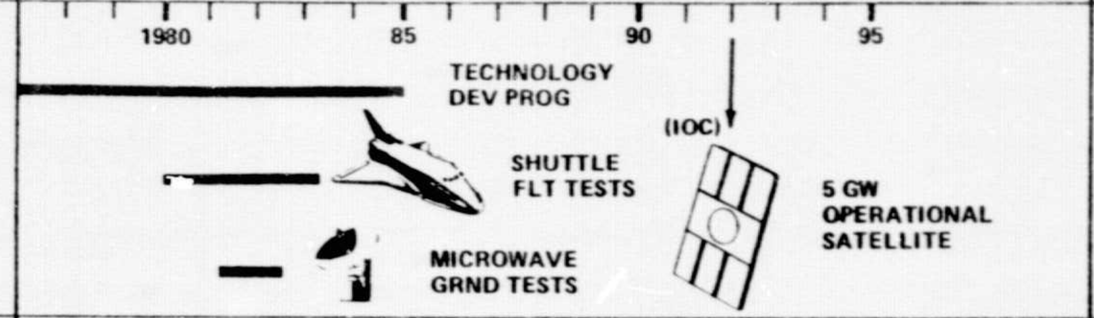
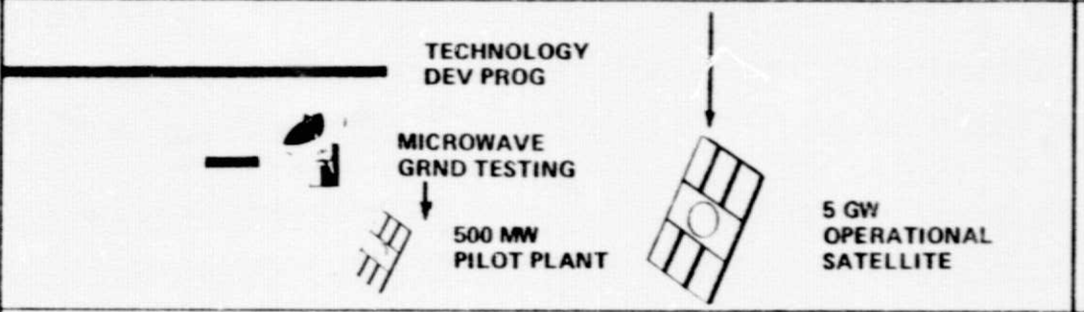
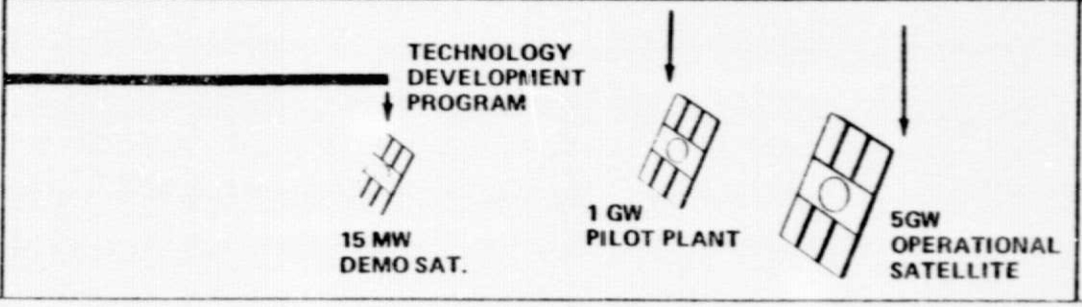
- Program II - a two-step program consisting of a 500 MW pilot plant placed at geosynchronous altitude prior to the placement of the first 5 GW operational satellite.

- Program III - a three-step program consisting of a low earth orbit 15 MW demonstration satellite, followed by a 1 GW pilot plant at geosynchronous orbit prior to the placement of the first 5 GW operational satellite.

A summary of the major activities associated with each of these programs is shown in Figure 3.11. Also shown is the total ROM undiscounted overall program costs. These data were compiled using Program III DDT&E and unit production cost data, as generated during the initial contract phase, and projected to Programs I & II using the Koelle model. This projection is based on the percentage of new technology estimated in the development of the demonstration satellite, pilot plants and operational satellites of Programs I & II as compared with Program III. Assembly and operations costs, however, were newly generated for all three programs, using a format similar to that used in the initial study. The major differences used in arriving at these cost estimates were in the types of transportation systems assumed available and the accounting policies adopted in representing assembly equipment and transportation system purchase costs. In these estimates, equipment costs were amortized over their expected lifetime rather than applied totally to the cost of demonstration and pilot plant satellite programs.

In combination with these program cost estimates, projections were made of the advances in technology resulting from the accomplishment of each of the major program milestones. These projections were expressed as the percentage by which the uncertainties in each of the risk model input parameters are reduced. The values projected for the three program options described are presented in Vol. III, Appendix E. In these data, the percentage notation refers to the percentage of certainty to which that specific input parameter is known, 100% indicating that the parameter is accurately known, the specific value being listed as "most likely". The combined sets of data, that is, program cost estimates and technology advancement projections, were used by ECON to evaluate the methodology and provide results for the economic assessment of demonstration and pilot plant satellites.

A word of caution, regarding the use of the cost estimates and technology advancement projections for each of the program options described is warranted at this point. The data derived were based on extremely preliminary estimating techniques, assumptions and individual judgement, and were not intended for use in establishing quantitative conclusions. Rather, they were provided for use in developing a methodology by which an economic assessment could be made. Thus, the results established using these data should be interpreted accordingly.

PROGRAM OPTIONS	SCHEDULE OF EVENTS	UNDISCOUNTED PROGRAM COSTS,* $M
1		28,724
2		31,806
3		31,398

*COSTS INCLUDE TECHNOLOGY DEVELOPMENT PROGRAMS, DDT&E, UNIT PRODUCTION, AND TRANSPORTATION AND ASSEMBLY COSTS.

Figure 3.11 Program Options and Costs

NASA—MSFC