SPACE-BASED SOLAR POWER CONVERSION AND DELIVERY SYSTEMS STUDY

VOLUME I

EXECUTIVE SUMMARY

(NASA-CR-150294) SPACE-BASED SOLAR POWER CONVERSION AND DELIVERY SYSTEMS STUDY. VOLUME 1: EXECUTIVE SUMMARY Final Report, 30 Sep. 1976 - 31 Mar. 1977 (ECON, Inc., Princeton, N. J.) 49 p HC A03/MF A01

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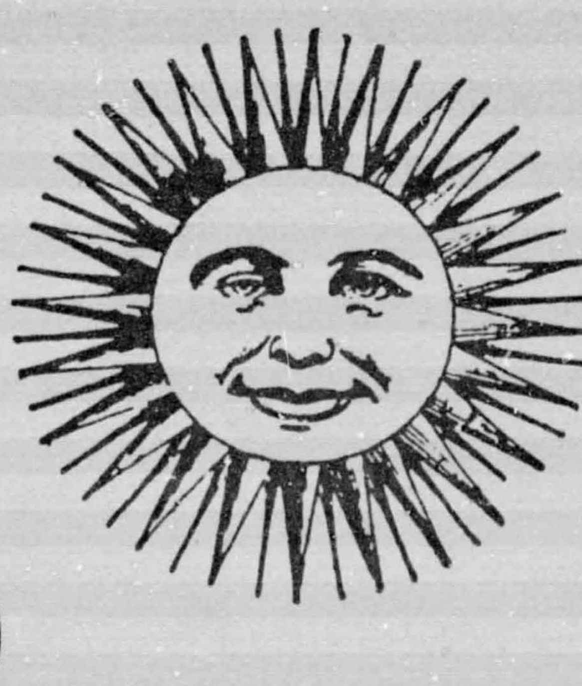

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SPACE-BASED SOLAR POWER CONVERSION AND DELIVERY SYSTEMS STUDY

FINAL REPORT
VOLUME I

EXECUTIVE SUMMARY

Prepared for the

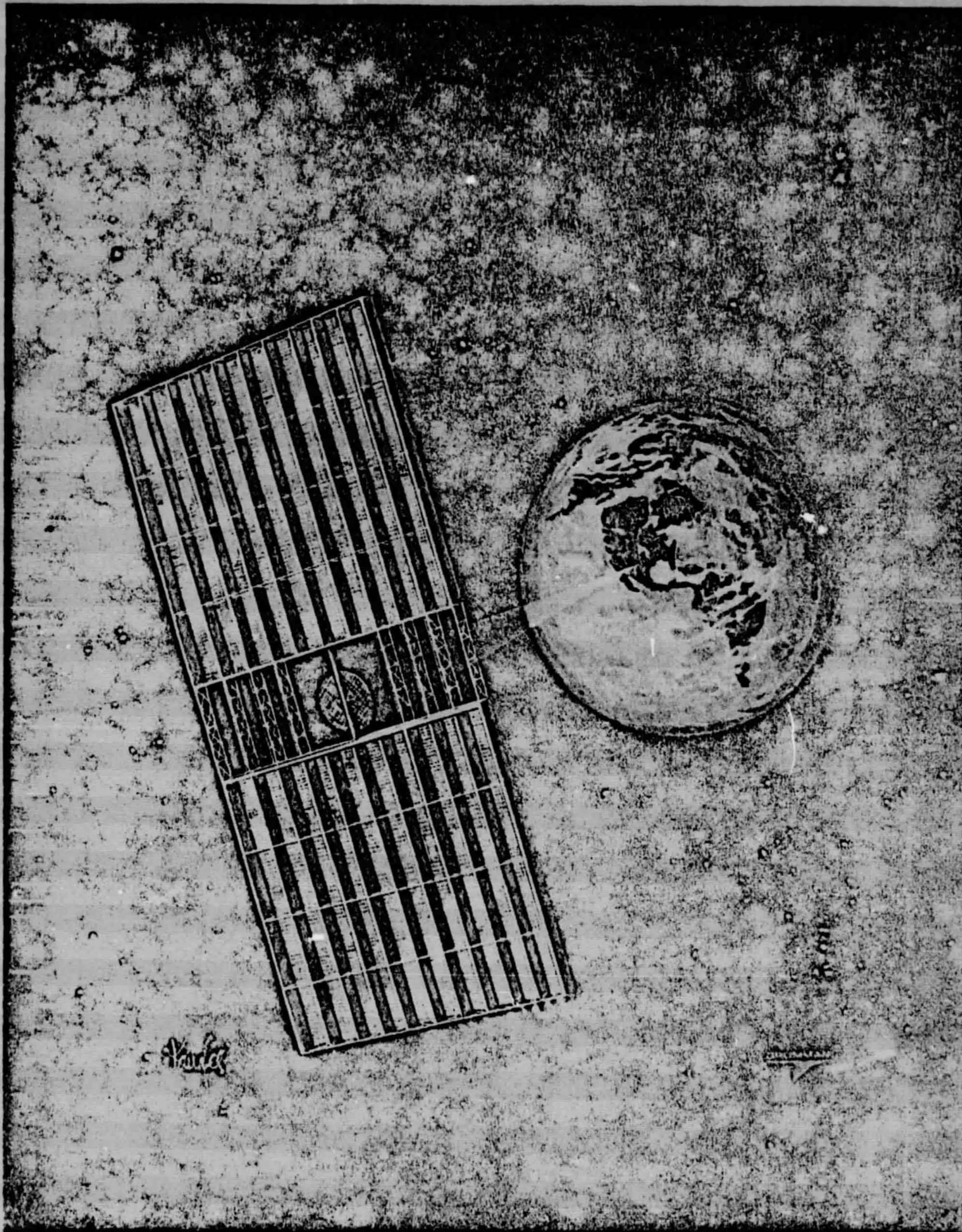
National Aeronautics and Space Administration
George C. Marshall Space Flight Center

Under

Contract No. NAS8-31308

March 31, 1977

ARTISTS CONCEPT OF A 5000 MW SOLAR POWER SATELLITE



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 ground output power levels of 5,000 MW and 10,000 MW, and a power relay satellite, and studied certain aspects of the economics of these systems. A 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. This study phase resulted in a second interim report dated June 30, 1976.

A third study phase was conducted over the period September 30, 1976 to March 31, 1977. This effort investigated in further depth technical and economic issues that appeared to be significant as a result of the previous study phases. Throughout this study, the focus has been on the economics of satellite solar power. Is satellite solar power technically feasible? Is a development program economically justified and at what level of effort? The results of this study indicate technical feasibility of the concept, and provide a preliminary economic justification for the first phase of a substantial development program. A development program containing test satellites is recommended. Also, development of alternative solar cell materials (other than silicon) is recommended.

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 1976 to 31 March 1977 has been Dr. George A. Hazelrigg, Jr. Also during this period, the Grumman Aerospace Corporation, Raytheon Company and Arthur D. Little, Inc. have been under subcontract to ECON to provide the engineering and technical analyses. 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. The Raytheon study manager has been Mr. Chester A. Wendell. The Raytheon contributions are documented in Section 4 of this volume and in Volume III of this report. The Arthur D. Little study manager has been Dr. Peter E. Glaser. The Arthur D. Little contributions are documented in Section 5 of this volume and in Volume IV of this report. These sections are included verbatim as received from the study subcontractors.

The materials included in this report comprise five volumes: Volume I, Executive Summary; Volume II, Engineering Analysis of Orbital Systems; Volume III, Analysis of the Microwave Power Transmission System Interfaces and Power Beam Ionospheric Effects; Volume IV, Analysis of Photovoltaic Energy Conversion Systems and Volume V, Economic Analysis. 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, and Second Interim Report, June 30, 1976.

ECON recognizes the assistance of Mr. Gregg R. Fawkes of ECON in the preparation of this report, and the contributions of Mr. Rudolph Adornato of Grumman, Dr. Peter E. Glaser, Dr. David Almgren and Dr. Bette M. Winer of Arthur D. Little, Inc., and Mr. Chester A. Wendell, Mr. Alan Katz, Mr. Joseph Rossi and Mr. Owen E. Maynard of Raytheon. The MSFC COR has been Mr. Walter E. Whitacre of the Payload Studies Offices.

Submitted by: George A. Hazelrigg, Jr.
Director, Systems Engineering

Approved by: Klaus P. Heiss
President

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1. INTRODUCTION

An increasing demand for energy concurrent with diminishing, proven, easily accessible reserves of hydrocarbon fuels is likely to result in an increasing real cost* for electric power throughout the remainder of this century and possibly beyond. The realization of this expectation is prompting several organizations to seek alternative energy sources. At the moment, the only significant alternative to hydrocarbon fuels is nuclear fission. Nuclear fission, however, has a number of disadvantages, chief among which are the potential for accidents and the production of weapons-grade materials. In the long term, nuclear fusion offers a potential "once-and-for-all" solution. But as yet, after some 25 years of research, it is not clear that fusion can be made to work or, if it will work, that it can be used as an energy source to provide cost-competitive electric power. And even assuming that fusion research will result in a successful outcome, commercial fusion plants may still be as much as 40 to 50 years into the future.

In recognition of the need to develop alternative energy sources, a substantial effort is currently being given to the nearer term development of various solar energy sources. But the use of solar energy on the surface of the earth is plagued by the fact that the sun shines somewhat less than half of the time, that sunshine is unpredictable (due to the weather), and that the daily motion of the sun through the sky renders earthbound, solar energy collectors inefficient. Thus, about ten years ago, Dr. Peter Glaser suggested that the problems inherent in terrestrial solar power stations might be solved by placing the power station in earth orbit, above the atmosphere, and beaming electric power to the surface of the earth in the form of microwave energy. Over the past several years, this concept has been developed and studied by a variety of NASA centers, academicians and industrial organizations, and a number of system concepts have emerged. Continuing studies are likely to refine and improve upon these concepts.

A major difference between satellite solar power and other long-range energy alternatives is that the basic physics of satellite solar power is largely understood, whereas it is not in many of the other alternatives, especially fusion. This is not to imply that the technology is ready to build a satellite solar power station today--certainly advances are necessary in many technology areas; rather the implication is that a development program can be formulated now for pursuing the satellite solar power concept. Such a development program would include schedules, milestones, major decision dates, technology and cost goals and, importantly,

*Real cost refers to the value of a commodity relative to other commodities. Obviously, uniform inflation does not affect real cost.

a measure of performance to determine the success of the development program.

With the above understanding in mind, the objectives of this study are to answer, sequentially, three questions:

1. Can it be done?

2. Should it be done?

3. How should it be done?

The first question addresses the basic technical and economic feasibility of the satellite solar power concept. Its purpose is to verify that the technology is at a point from which a development program may commence. The second question addresses the larger economic issue of whether a justification exists for undertaking the first phase of a satellite solar power development program. The last question addresses the level of effort and focus that results in an effective development program.

The approach taken in this study is one that enables an analysis of a number of economic factors. Thus, rather than considering a number of alternative system configurations, it is necessary to develop one configuration in sufficient depth to obtain the necessary data for an economic analysis. Consequently, this study has focused on the satellite configuration shown in Figure 1.1. This configuration had been analyzed to a significant degree prior to this study and, thus, had a substantial, existing data base to draw upon. Furthermore, it is believed that this configuration embodies key technical and economic issues common to most satellite solar power system configurations. It is assumed that the ultimate objective of a satellite solar power development program is to provide a capability for implementing a fleet of satellite solar power systems that would supply cost-competitive electric power for terrestrial use. It is recognized that neither the satellite system cost nor the cost of the competing alternative sources of electric power in the 1990s and beyond can be known precisely today. Thus, the purpose of the development program, from the economic point of view, is to provide information for future decisions. The value of alternative development programs is evaluated and reported in this context.

The major conclusions of this study are:

1. Satellite solar power is technically feasible and has economic potential.

2. A significant technology advancement and verification program appears economically justified.

3. The major areas of technological and economic uncertainty relating to decision making in a satellite solar power system development program are:

a. The fabrication and assembly of large structures in space

b. Solar energy conversion technology

c. The cost of electric power supplied by alternative energy sources

d. Constraints imposed by ionospheric and biological effects.

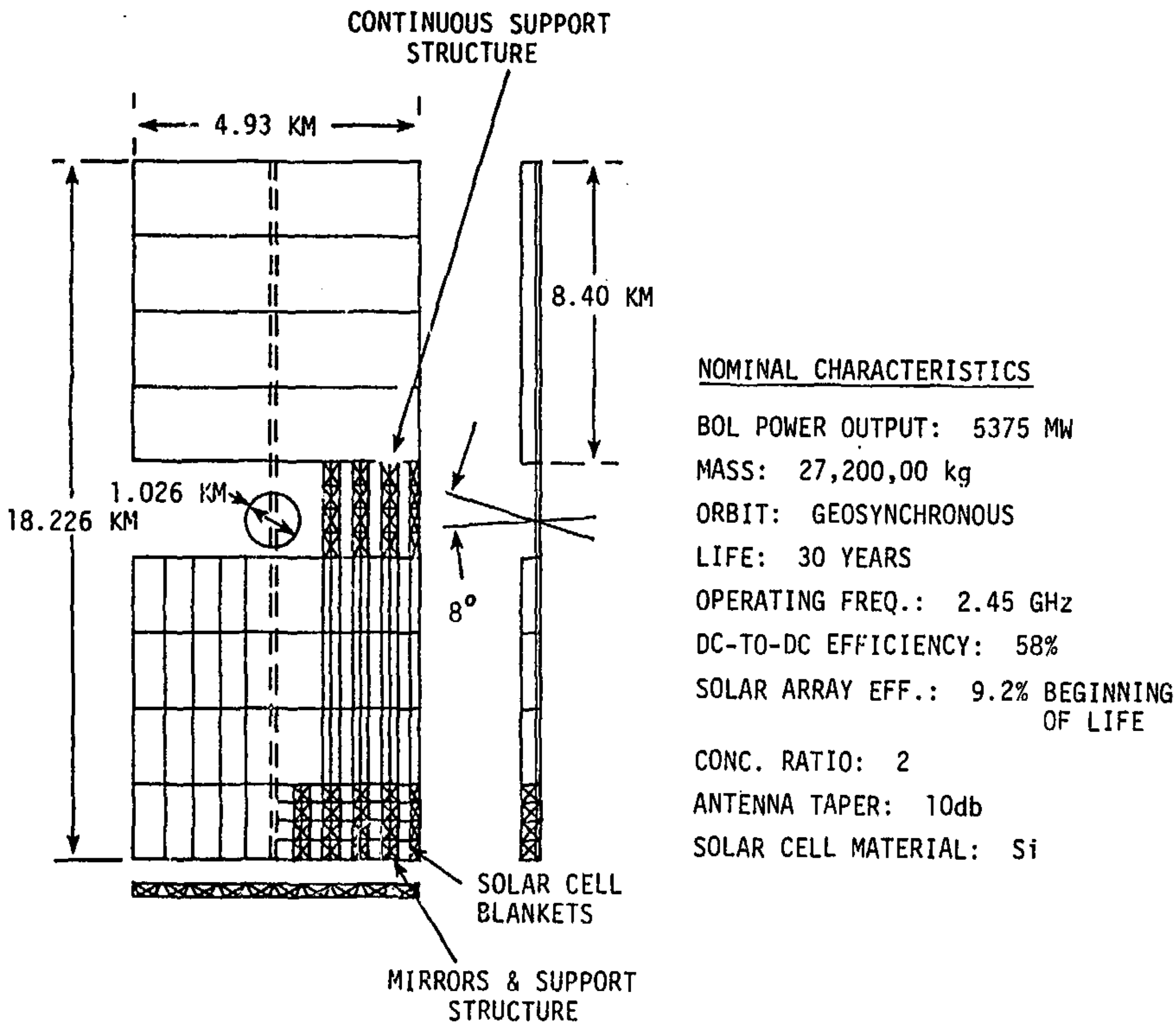

Figure 1.1 The Satellite Solar Power System Configuration Used in this Study

2. SUMMARY OF ECONOMIC ANALYSES

This section summarizes the major results of the economic analyses conducted during the course of this study, with emphasis on the results obtained in Phase III, from September 30, 1976 to March 31, 1977. Study efforts during Phase III focused on a reevaluation of cost-risk, the formulation and evaluation of effective satellite solar power system (SSPS) development program plans, a comparison of low earth orbit (LEO) versus geosynchronous orbit (GEO) satellite assembly, and an assessment of alternative solar cell materials including silicon, gallium-arsenide and cadmium-sulfide. The reader is urged to consult Volume V, Economic Analysis, of this report for a detailed explanation of the methodologies used to derive the results presented in this section.

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. Combined at a discount rate of 7.5 percent, these costs comprise the total life cycle cost of an SSPS unit as defined herein. The analysis focuses on the second unit as the first "production" unit. Unit production costs of the first unit are treated and costed as a part of the development program insofar as the first unit may be a prototype or may be constructed using techniques 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 presented as probability distributions of costs as shown in Figure 2.1 for a silicon solar cell SSPS. This distribution is a reflection of the present state-of-knowledge of the technologies required for an SSPS upon the configuration shown in Figure 1.1. That is, it is the result of projections of the state-of-the-art of the technologies needed to produce the second unit, in the configuration shown, and the uncertainties associated with these state-of-the-art projections. Thus, for the silicon solar cell configuration shown, the best cost estimate obtainable today can only place the cost of the second unit, if it were to be built in the configuration shown, between the rough limits of $7 billion to $55 billion (1974). A number of parameters can be selected to characterize this distribution, such as those shown. There is a 90 percent chance that the cost will <u>exceed</u> the 10 percent confidence cost estimate, and an equal chance that it will be <u>less</u> than the 90 percent confidence cost estimate. The expected value is equivalent to the mean of the distribution and the most likely cost corresponds to the cost at which the cost distribution curve has the steepest slope (the mode of the probability density function).

A number of different SSPS options were examined. These include configurations similar to that shown in Figure 1.1 using silicon (Si), gallium-arsenide (GaAs) and cadmium-sulfide (CdS) solar cell materials, each subject to assembly at LEO or GEO by means of a "small" factory-in-space, capable of producing nominally 4 SSPS satellites per year, or a "large" factory-in-space, capable of producing nominally 6 SSPS satellites per year. The result of these twelve solar cell material/assembly alternatives is shown in Figure 2.2. It is important to note that the SSPS configuration, designed for Si solar cells, was not re-optimized for the GaAs and CdS solar cell configurations (for example, all used a concentration ratio of 2). Thus, the fact that the GaAs and CdS configurations appear as attractive as they do is strengthened by the recognition that they could probably be improved relative to the Si configuration.

The one result that is quite clear from Figure 2.2 is that GEO assembly of this configuration SSPS is very likely to be substantially more costly than LEO assembly. Differences in costs due to assembly by a small versus a large construction base are much less significant, as are cost differences due to selection of solar cell material.

SSPS costs are only one side of the picture, however. The other side is the revenue generated by each unit. Figure 2.3 gives the revenues as a function of the price of power at the rectenna busbar on the initial operation date. The key result evidenced in this figure is that, because of the much reduced solar cell degradation rates for GaAs and CdS solar cell materials, these configurations produce substantially higher revenues over a nominal 30-year satellite lifetime. The major impact of this result is summarized in Figure 2.4 which shows the probability that the second unit will pay off (that is, that the present value of revenues will exceed the present value

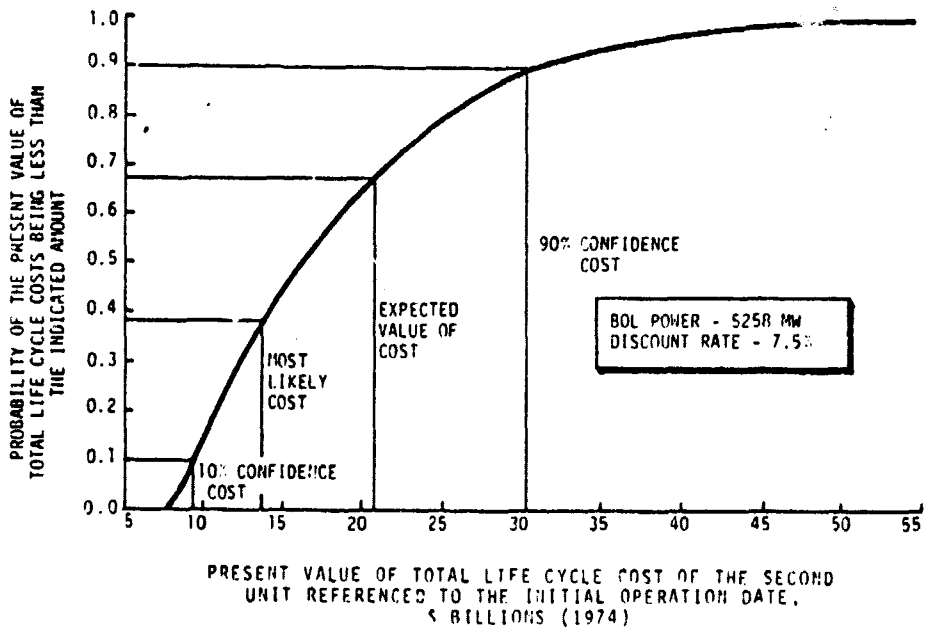

Figure 2.1 SSPS Second Unit Total Life Cycle Cost for a Si Solar Cell Configuration Assembled in LEO

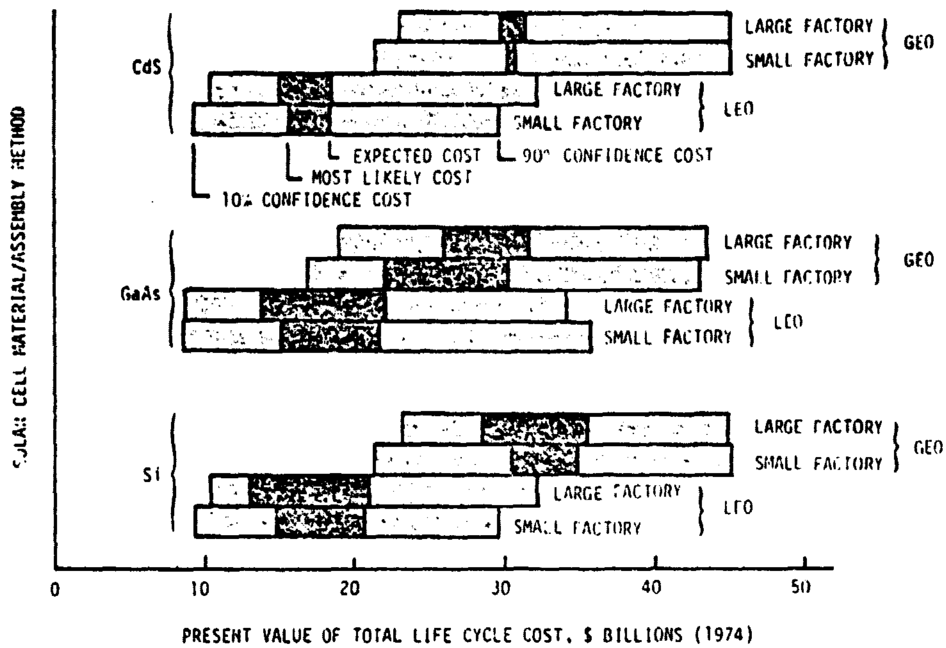

Figure 2.2 SSPS Total Life Cycle Costs for Various Solar Cell Material/Assembly Method Options

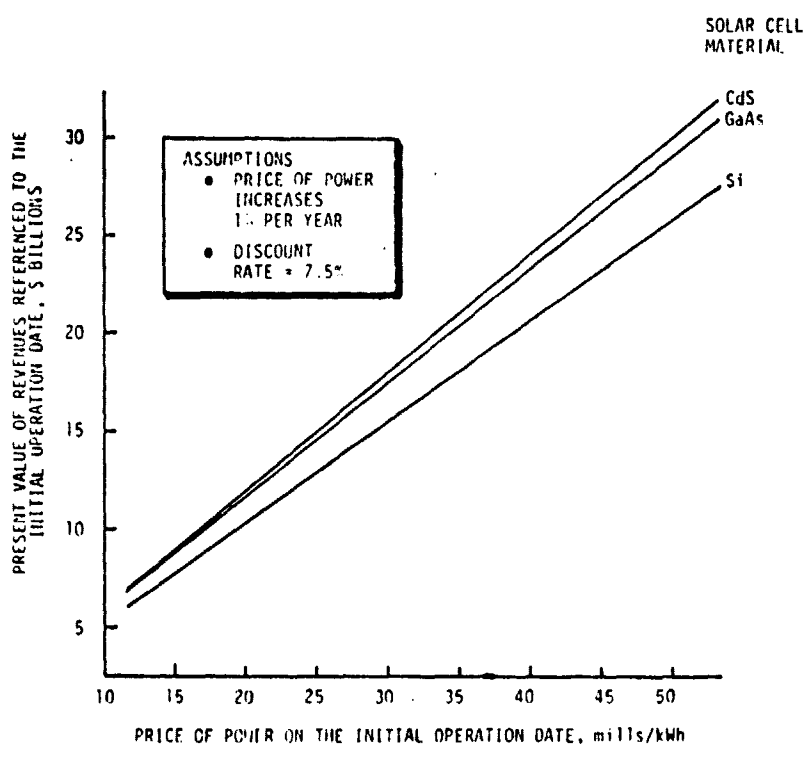

Figure 2.3 SSPS Revenues

of costs) as a function of the price of power on the initial operation date. In this figure, it is clear that over different ranges of price of power both GaAs and CdS solar cell materials offer a higher probability of achieving an economic system.

Finally, it is possible to identify the impact on cost and cost-risk that present uncertainties in the cost and physical properties of the various solar cell materials have. This is accomplished by assuming that a perfect state-of-knowledge is achieved about one parameter at a time and examining the effect of this modified state-of-knowledge on the expected cost and cost-risk with all other parameters held as they exist today. Since the final outcome of any parameter cannot be known today, three results are shown for each parameter, corresponding to the expected cost and cost-risk, given that the parameter in question achieves its best or most optimistic value, its most likely value and its worst or most pessimistic value, as shown in Figure 2.5. Thus, for example, learning precisely the efficiency of the Si solar cells that would be used in the second SSPS would move the current evaluation of the expected cost and cost-risk of that configuration from Point 1 to a point somewhere on Line 7.

The results of the cost and risk analysis can be summarized as follows:

1. For the satellite configuration and construction/transportation methods examined, LEO assembly is very likely to be substantially less costly than GEO assembly.

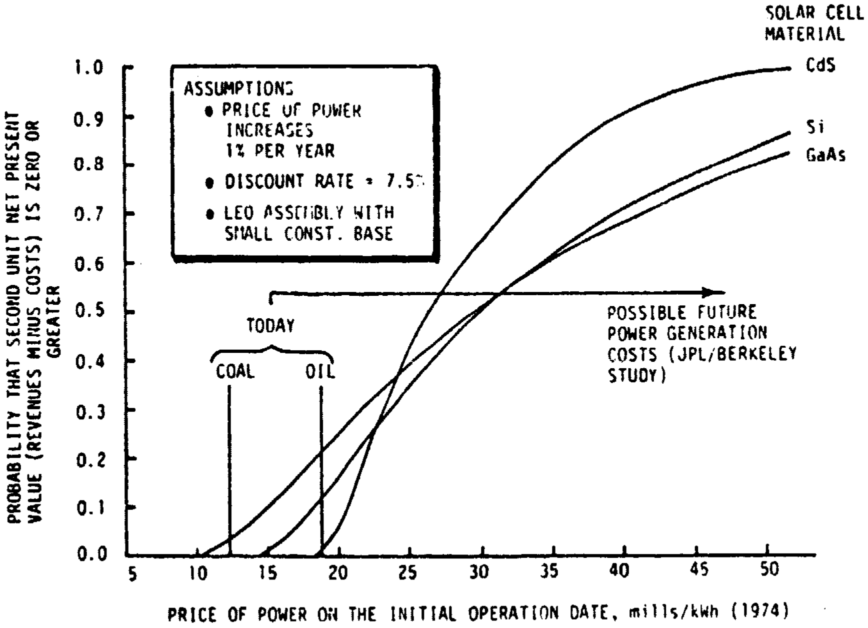

Figure 2.4 Probability that the Second SSPS Will Be Economic

2. GaAs and CdS solar cell materials SSPS configurations produce significantly more revenues than Si configurations because they do not degrade nearly as much with time.

3. GaAs and CdS solar cell materials offer potential economic advantages over Si.

2.2 Programmatic Analysis

In Phase II of this study, three SSPS development programs were analyzed. These are summarized in Table 2.1. As shown in this table, the decision date is the date on which a commitment is made to pursue each program phase. The present value (P.V.) of cost is the cost for each program phase referenced to January 1, 1977. The probability of success is the prior probability that each phase will result in a decision to continue the program and the expected value is the expected present value of each development program. A positive expected value provides an economic justification to proceed with the first phase of the development program. The preferred development program is the one with the highest positive expected value. Of the three development programs shown in Table 2.1, only Program 1 is economically sound.

As a result of the insights gained in the Phase II effort, two new program plans were formulated and analyzed. These are shown in Table 2.2

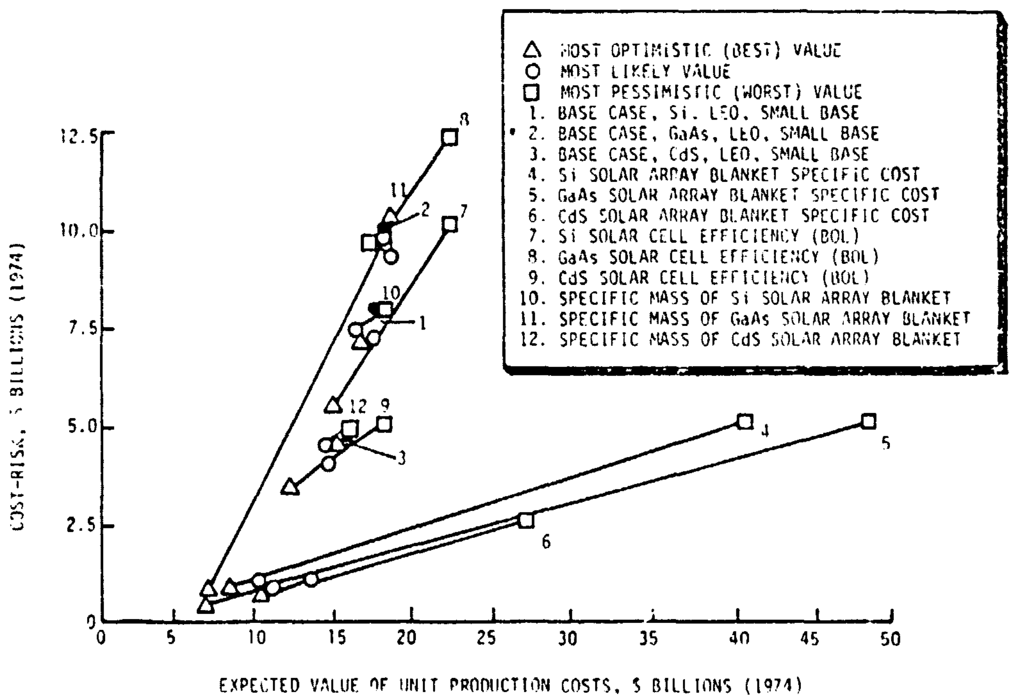

Figure 2.5 The Effect of Learning About Solar Cell Materials

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Table 2.1 Development Programs Analyzed in Study Phase II

	Decision Date	P.V. of Cost, $B	Prob. of Success	Expected Value, $B
Program 1				
Technology Advancement and Verification	1977	0.373	.376	
DDT&E	1984	7.058	.692	
Production of Prototype (1st Unit)	1987	5.374	.905	
Implementation (Total 109 Satellites)	1992			
			.236	+1.51
Program 2				
Technology Advancement and Verification	1977	0.179	.438	
GEO Test Satellite (500 MW)	1980	11.707	.628	
DDT&E	1985	1.671	.829	
Production of Prototype (1st Unit)	1987	4.960	.895	
Implementation (Total 109 Satellites)	1992			
			.204	-1.10
Program 3				
Technology Advancement and Verification	1977	0.179	.461	
LEO Test Satellite (15 MW)	1980	2.907	.687	
GEO Test Satellite (1000 MW)	1985	10.991	.699	
DDT&E	1990	1.107	.825	
Production of Prototype (1st Unit)	1992	3.227	.993	
Implementation (Total 109 Satellites)	1996			
			.181	-0.92

Table 2.2 Development Programs Analyzed in Study Phase III

	Decision Date	P.V. of Cost, $B
Program 4		
Research and Studies	1977	0.070
Tech. Dev. & 150 kW Test Satellite	1980	0.578
Tech. Dev. & 2 MW Test Satellite	1983	1.216
DDT&E	1987	3.257
Production of Prototype (1st Unit)	1992	5.513
Implementation (Total 120 Satellites)	1996	
Program 5		
Research and Studies	1977	0.070
Tech. Dev. & 150 kW Test Satellite	1980	0.679
Tech. Dev. & 2 MW Test Satellite	1983	1.413
DDT&E	1987	3.247
Production of Prototype (1st Unit)	1992	5.521
Implementation (Total 120 Satellites)	1996	

and the corresponding decision tree is shown in Figure 2.6. The differences between Programs 4 and 5 lie in the LEO and GEO test satellite subprograms as shown in Table 2.3, with Program 5 being somewhat more responsive to engineering needs for test information but at a slightly higher cost. The assumptions pertaining to the implementation phase are as follows:

1. The beginning-of-life power output (at the rectenna) of each unit is 5258 MW.

2. Power output decreases with age depending upon solar cell material.

3. Satellite lifetime is 30 years.

4. Each unit is producing power 95 percent of the time.

5. Implementation of the second and subsequent satellites begins with the initial operation date of the second unit on January 1, 1998. Thereafter, units come on line at the rate of four per year until 120 units (including the prototype) 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

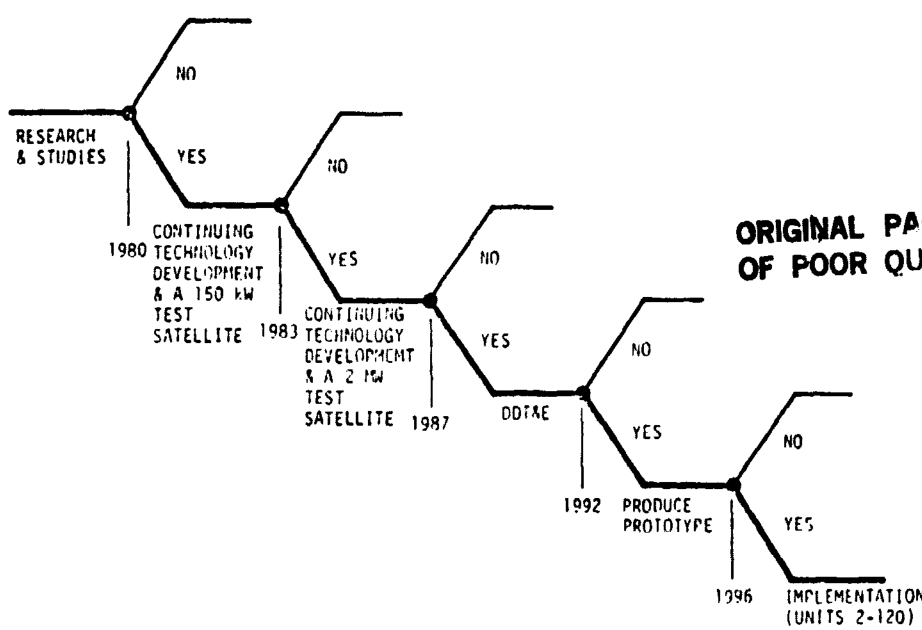

Figure 2.6 Decision Tree for Programs 4 and 5

Table 2.3 Test Satellite Subprograms

	Program 4	Program 5
LEO Test Satellite		
Power Level	150kW Cont. (330kW Peak)	150kW
Mass	13,000-21,000 kg	8,000-10,000 kg
Antenna	None	105 m Linear Array
Conc. Ratio	1	1.7 Design/1.5 Effective
Use	Power Space Station	Conduct Tests--Solar Conc., Plasma Effects, Microwave Transmission, Ground Heat Ionosphere
Remarks	Stays in LEO	Built in LEO, Transport to GEO
GEO Test Satellite		
Power Level	2 MW	2 MW
Mass	20,000 kg	35,000-45,000 kg
Antenna	20m X 20m Subarray	20m X 20m Subarray and 1000m Linear Array
Remarks		Conduct Ionospheric and Phase Control Tests

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.)

Subject to the above assumptions, the results of the programmatic analysis are summarized in Table 2.4. These results show a reasonable (preliminary) economic justification for proceeding with a significant technology advancement and verification program. They also indicate significant potential economic advantages for CdS and GaAs solar cell materials. It is thus recommended that:

1. Future studies further examine solar cell material alternatives.

2. Future studies devote a continuing effort to refine and improve upon the program plans presented here.

Table 2.4 Development Program Analysis Results*

	Solar Cell Material	Probability of Success	Expected Value, $B
Program 4	Si	.380	12.286
	CdS	.560	25.603
	GaAs	.371	18.781
Program 5	Si	.389	12.433
	CdS	.570	25.865
	GaAs	.379	18.998

*Above data are for LEO assembly using a small construction base.

2.3 Power Beam Ionospheric and Biological Effects

A major area of technical uncertainty impacting SSPS design is the effect of the microwave power beam on the ionosphere and on biological materials. These effects are likely to result in a constraint on the maximum power density somewhere in the range of 10 mW/cm^2 to 100 mW/cm^2. As a part of this study the economic impact of this constraint on the second and subsequent units was investigated. The results are summarized in Figure 2.7 for a CdS solar cell configuration SSPS. The conclusions of this study can be summarized as follows:

1. The SSPS is likely to be constrained to operate at a maximum microwave power density below 100 mW/cm^2.

2. The magnitude of the maximum microwave power density constraint will impose a design condition on the satellite, either determining power level as shown in Figure 2.7 or forcing other methods of limiting the power beam power density, for example, defocussing the beam or employing multiple beams.

3. The economics of the second and subsequent units is not strongly affected by the magnitude of the constraint. Over the full range upon which the constraint is likely to be imposed, the break-even price of power varies only about 4 mills/kWh.

Although the magnitude of the constraint is not an important economic parameter, it is nonetheless necessary to determine its value relatively early in the program to allow for the systems impacts and provide for the necessary program planning.

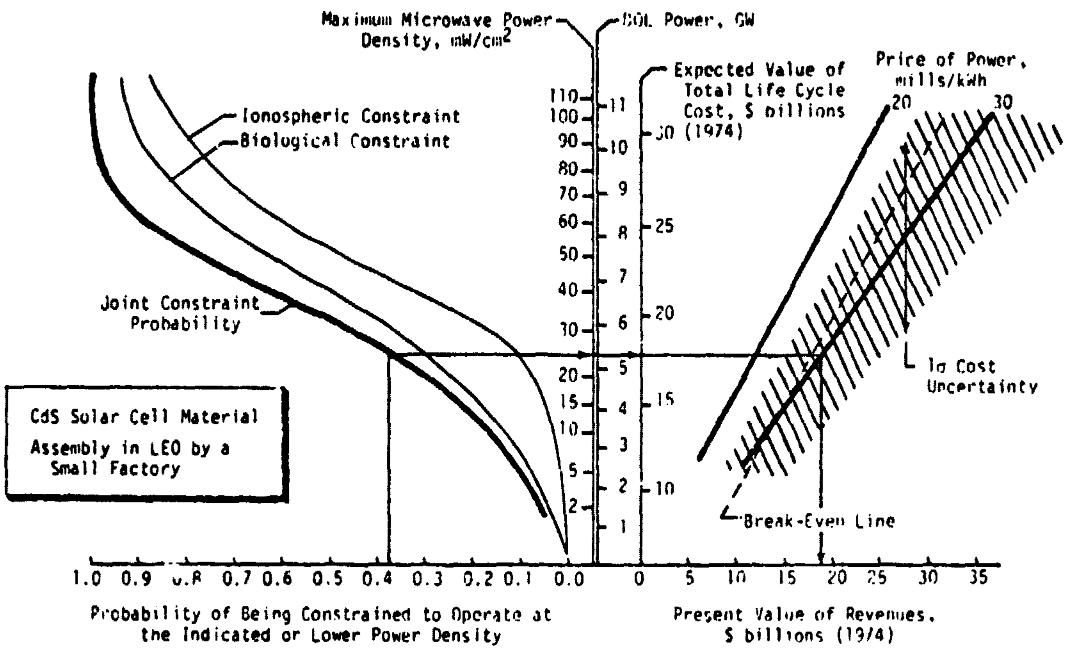

Figure 2.7 The Effect of Constraints on Microwave Power Density

3. SUMMARY OF ENGINEERING ANALYSES

This section summarizes the overall results of engineering analyses conducted during the initial and extension phases of this study. As shown in Fig. 3.1, Grumman's participation in this study was directed towards two major objectives, namely:

- The support of Satellite Power Systems (SPS) economic analyses by providing related programmatic and system cost information for the orbital system elements.
- The conduct of selected system analyses of the baseline 5 GW crystal silicon configuration to establish technical feasibility and provide substantive engineering information for use in the economic studies.

The major technical findings and conclusions, as established through these studies, are expressed herein within the framework of Subprogram Areas established by the Satellite Power Team and are subsequently followed by Grumman's study recommendations.

The scope of this study, although addressing a specific baseline configuration, has also provided results which are applicable to Satellite Power Systems in general. These results are highlighted herein with the following notation (✓).

3.1 Major Findings and Conclusions

Systems Definition

- ✓ The complete assembly of an operational SPS in low-earth-orbit (LEO) followed by transport to geosynchronous earth orbit (GEO) does not appear technically desirable, but the mix of GEO versus LEO construction activity remains to be resolved. An important issue, therein, is the influence of high productivity factory-type construction operations on the SPS configuration concept, since compatible requirements must be imposed on an SPS and its Factory (ies)-in-Space.
- The 5 GW crystal-silicon photovoltaic SPS configuration baselined for this study and having a concentration ratio of two (2) is a "workable system" .... as no unsolvable engineering problems have been uncovered, to date.
- Applying most likely values of technology projections for the 1995 time frame, system efficiency (exclusive of solar conversion) is 58.3%, and thus requires a solar array output of 8.57 GW to achieve 5 GW at the ground output.

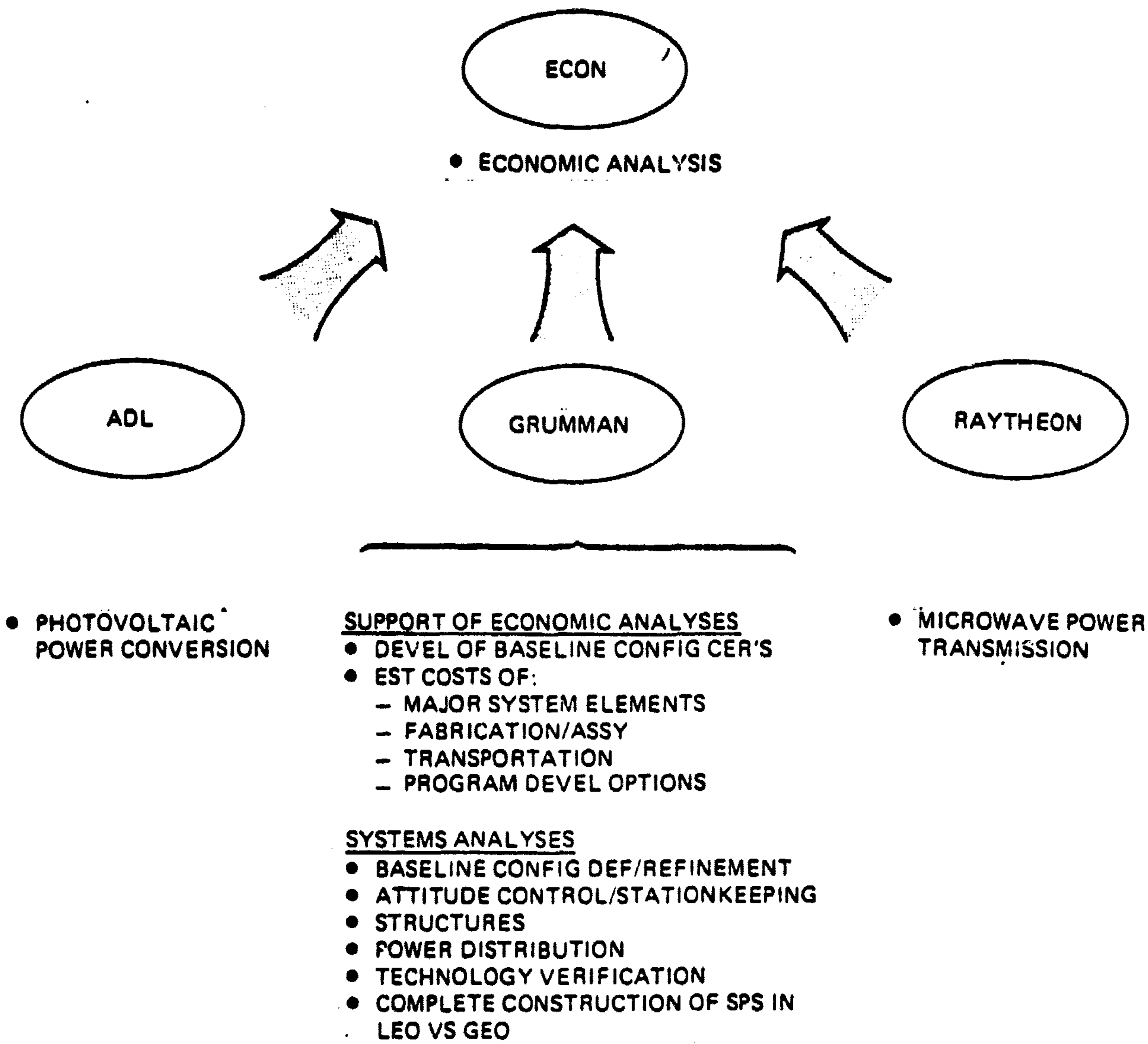

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Fig. 3.1 Grumman's Role

- A deterministic estimate of the mass-on-orbit of the 5 GW crystal-silicon photovoltaic SPS baseline configuration is 27 X 10^6 Kg.

Microwave Energy Technology

✓ • Maintenance of surface flatness tolerances of a microwave (MW) antenna favors the use of composites as basic antenna structures.

✓ • Pointing control requirements of 1 arc-min can be accommodated for the MW antenna.

Space Structures

✓ • Truss-type structural configurations are feasible, can satisy SPS needs for low mass and structural stiffness, and represent about 20% of total system mass.

✓ • Truss-type structures, characteristic of the photovoltaic SPS configurations examined, are conducive to employing automated structural fabrication/assembly techniques in orbit to improve productivity of construction processes in space (Figure 3.2).

✓ • Very large area, low mass structures configured for operation in space:

  - are controllable during operational on-orbit conditions at LEO or GEO, and during construction in GEO while joined to a construction facility.
  - could encounter higher-than-operational structural loading during construction in LEO depending on the in-orbit construction concept.
  - should be transported from LEO to GEO by electric (low acceleration) propulsion systems.
  - will face size limitations in LEO due to space debris collision considerations

- Aluminum structural materials appear to be viable candidates for solar array primary structure and current-carrying functions.

- During occultation or eclipse periods, thermally-induced deflections in a solar array configuration having a central mast (backbone) are tolerable both structurally and deflection-wise.

Power Distribution

✓ • A rotary joint comprised of slip rings and brushes is a feasible concept for transmitting electric power across the power system/antenna interface.

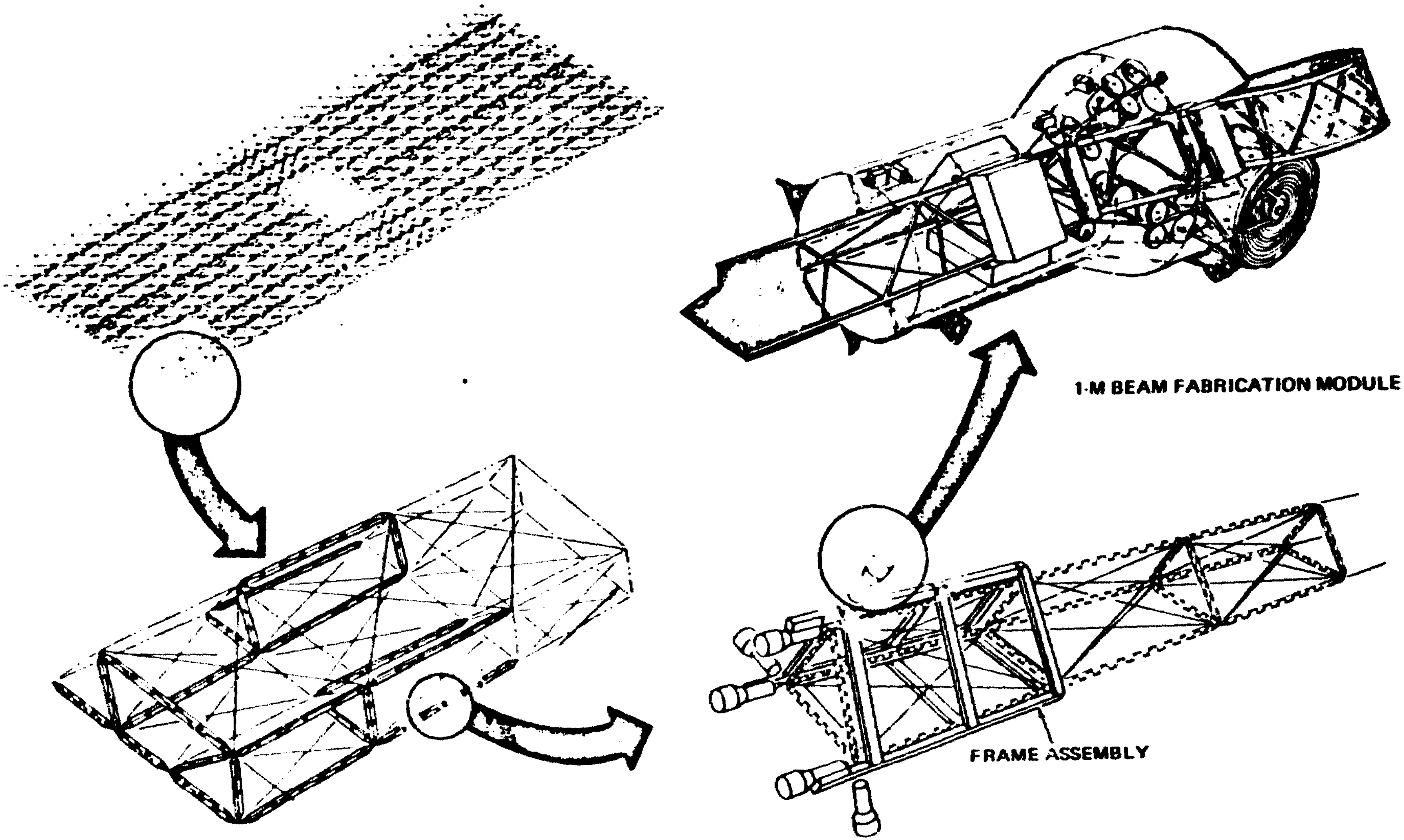

Fig. 3.2 Truss-Type Structure Fabrication/Assembly

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✓ • Both distributed or central mast power distribution approaches are acceptable, but the distributed approach offers simplifications in construction/assembly.

• Minimum overall system mass is achieved with a power distribution efficiency of 94% for a 5 GW crystal-silicon photovoltaic system operating at 40 KV.

Attitude Control and Stationkeeping

✓ • Solar array pointing control of ±1° concurrent with microwave antenna pointing control of ±1 arc-min is achievable at GEO operational conditions.

✓ • A truss-type structural configuration with a 10:1 structural-to-control frequency relationship provides acceptable structure/control system stability.

✓ • High performance, low thrust electric propulsion is necessary for attitude control and stationkeeping.

✓ • Attitude control propellant needs for:

- construction/assembly of a complete SPS in LEO represent about 10% of total SPS mass, as compared to less than 0.1% at GEO.
- fabrication of subassemblies of an SPS in LEO would appear reasonable, but maximum practical sizes/masses need to be determined.
- negating air drag effects in LEO are insignificant.

✓ • Control/structural dynamic interactions occur in LEO between very large minimum weight structures and their construction facility which could lead to SPS mass penalties.

• Annual propellant quantities of about 93,000 kg are needed for each 5 GW crystal-silicon photovoltaic SPS to satisfy attitude control/stationkeeping requirements while operating within a 120 satellite constellation system serving the US. This propellant quantity, over a thirty year period, represents about 10% of the total mass of a single SPS satellite.

Transportation

✓ • To minimize transportation costs, large-volume/low-density structures associated with photovoltaic SPS concepts require automated on-orbit construction.

✓ • Transportation of large solar array subassemblies or a complete SPS satellite from LEO to GEO:

- via chemical propulsion, would impose structural mass penalties of 100 to 400% on large-area, low-mass structures and, thus,
- requires low thrust electric propulsion.

Operations

✓ • Construction/assembly in orbit of truss-type photovoltaic SPS concepts are technically feasible. Acceptable approaches are:

  - construction of major subassembly modules in LEO, with transport to GEO by low acceleration Orbit Transfer Vehicles (OTV), and
  - construction/assembly of the complete SPS in GEO.

✓ • Factory-in-Space concepts (Figure 3.3) for fabrication and assembly of SPS-type systems will involve:

  - factory type assembly line operations in the space environment, optimized for high productivity
  - crew work stations and mobility aids located at key spacial intervals, with astro-workers accommodated in a shirt-sleeve environment
  - internal transportation systems for moving people and equipment
  - a base management organization and heirachy, and
  - supporting facilities including warehousing, cafeteria, recreational, medical, living, etc.

• Representative staffing of a Factory-in-Space, at peak activity levels, for producing a complete 5 GW crystal-silicon, photovoltaic SPS in LEO or GEO at a construction rate of 4/year are estimated at:

Base Management	45
Factory Workers	430*
Supporting Personnel (medics, warehousing, cafeteria, etc.)	225
Total	700

*Approximately 100-person-years of direct labor are required to construct one 5 GW SPS

✓ • SPS components and subassemblies apparently suited to on-orbit and/or earth fabrication and their potential for automated construction and assembly are:

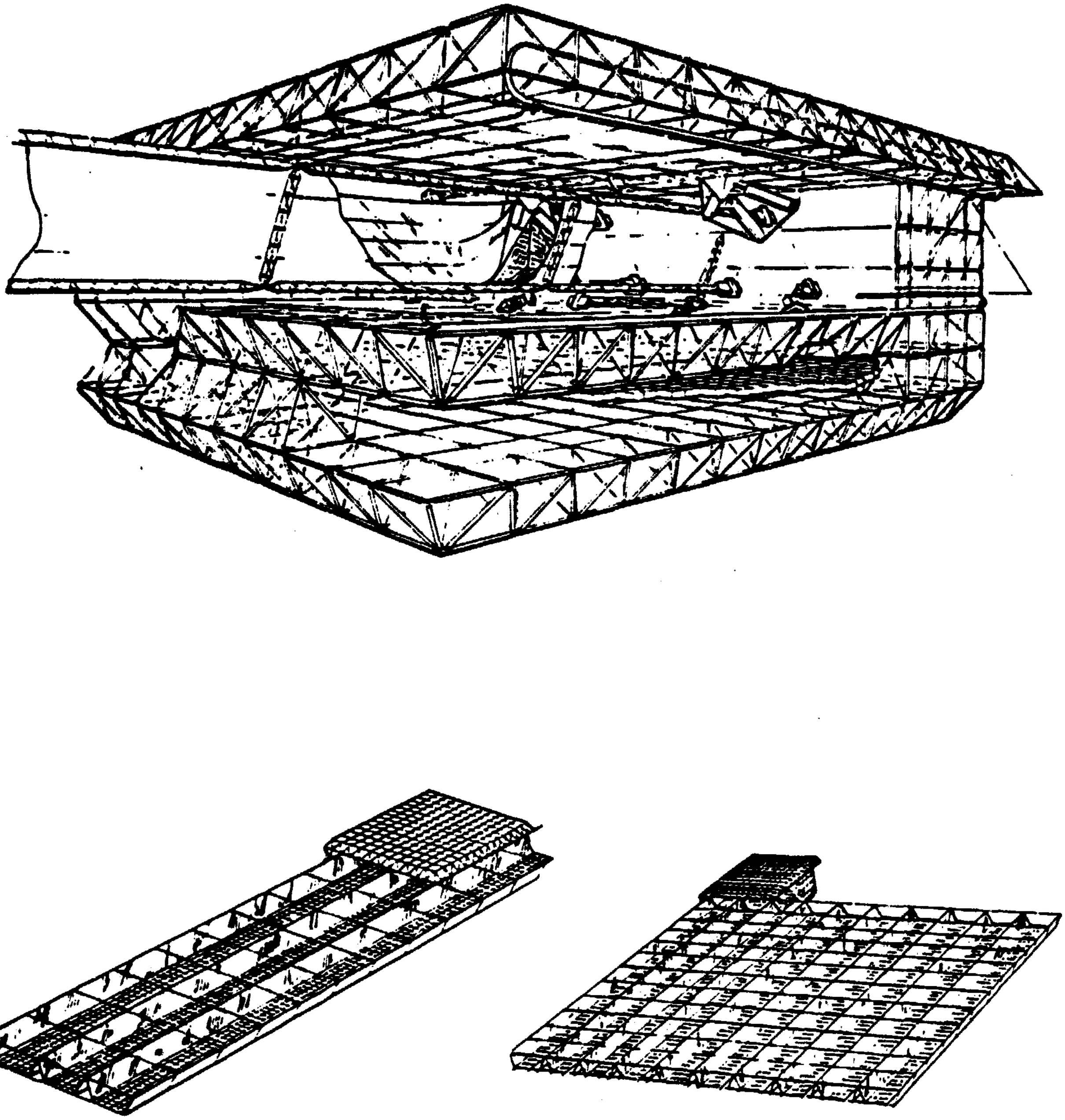

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Fig. 3.3 Factory-in-Space Concepts

ELEMENT	EARTH FABRICATION	ON-ORBIT FAB	ON-ORBIT ASSY	ON ORBIT AUTOMATION POTENTIAL
SOLAR ARRAY				
• STRUCTURE		X	X	HIGH
• BLANKETS & REFLECTORS	X		X	HIGH
MICROWAVE ANTENNA				
• STRUCTURE		X	X	HIGH
• COMPONENTS	X		X	LOW
PWR DISTRIB SYS				
• STRUCTURE		X	X	MODERATE/HIGH
• COMPONENTS	X		X	MODERATE
CONTROL SYS				
• COMPONENTS	X		X	LOW
ROTARY JOINT				
• STRUCTURE		X	X	HIGH
• COMPONENTS	X		X	LOW

✓ • A high degree of automation is envisioned for solar array construction/assembly but comparable automation of the complete microwave antenna system appears uncertain.

✓ • The microwave antenna system, rotary joint, and close-proximity portions of the power distribution system:

  - involve complex factory operations with large personnel complements and
  - because of their "denser" mass characteristics and smaller projected areas, are less susceptible to space debris collision problems.

This suggests that construction of these elements be confined to LEO .... and that construction of solar array subassemblies be also considered for LEO in preference to the complete construction of an array at GEO.

Technology Verification

✓ • Ground and space-based development/demonstration activities are necessary to provide sufficient technical confidence to commit to development of an operational 5 GW SPS. Program development options can be formulated which: (1) utilize existing or planned transportation elements, and (2) provide necessary decision-making information at key programmatic decision points.

3.2 Recommendations

Dynamic interactions occur between major SPS program elements which will have a significant influence upon system-level decisions. As illustrated in Figure 3.4 triads of interactions exist for major phases of an SPS program: Commercial Operations, Manufacturing and Construction, and Precursor Activities. The triads are interactive amongst themselves and also provide inputs to the other program phases. The SPS Manufacturing and Construction phase, for example, is the basis for establishing SPS-related requirements for a precursor Construction Base, while both Commercial Operations and Manufacturing/Construction Phases provide requirements for SPS Technology Verification.

The attainment of an economical programmatic approach, therefore, must consider the interactive nature of the major program elements, and trade-off analyses amongst the elements is necessary. Within this framework of the interactive nature of the SPS program, further studies are recommended to resolve major system issues and to provide a better understanding of major SPS options. The following areas are recommended:

Configuration Development

- Identify/define generic thin-film photovoltaic SPS configurations capable of accepting future potential improvements/advances in thin-film technology (e.g., efficiency, no-concentration, high radiation resistance).

Manufacturing and Construction

- Continue investigations and development of automatic equipments for fabricating aluminum and composite truss-type structures in space.
- Define and assess approaches for automating construction/assembly of the Microwave Antenna System (a common SPS element).
- Evaluate alternate rotary joint approaches and their in-orbit producibility potentials, followed by defining approaches for automating construction/assembly in orbit.
- Perform parametric analyses of SPS manufacturing and construction options to identify approaches optimizing productivity in-orbit and minimizing overall construction costs. These analyses would serve as the basis for establishing manufacturing and productivity verification requirements for precursor Construction Base operations and advanced propulsion systems development.

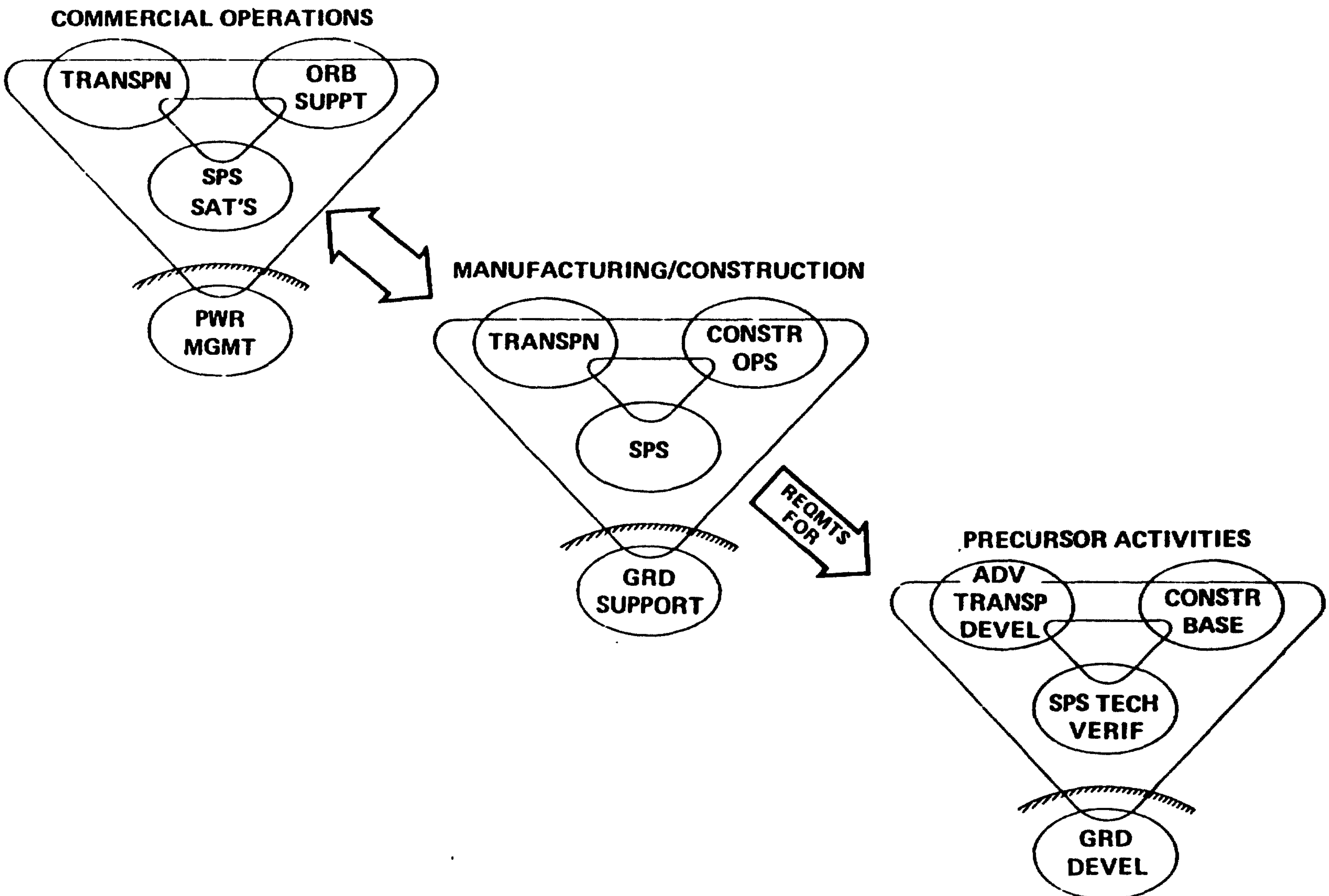

Figure 3.4 Triads of SPS Program Interactions

SPS Technology Verification

- Develop and evaluate Technology Verification Program options within the funding ranges that indicate positive program "expected net present values" as suggested by the "decision-tree analyses" conducted during this study.

Technology Development

- Provide more in-depth understanding of the probable ranges of performance requirements and technical issues associated with low thrust electric propulsion systems, to focus and accelerate supportive ground-based research and development efforts. Considerations should include:

  - attitude control/stationkeeping at GEO operational conditions for a minimal 30 year SPS lifetime, and
  - LEO-to-GEO orbit transfer of large subassemblies (e.g., microwave antenna and rotary joint) and masses that could range from 6-7 million kg to the complete mass of an SPS.

4. SUMMARY OF MICROWAVE POWER TRANSMISSION STUDIES

At the completion of the earlier phases of this study, Raytheon identified critical areas which were recommended for further study. Further definition of these areas would reduce risk by improving the data base which is available for economic and programmatic decision making. Of these, certain more critical items were selected for further study. These were: 1) power beam ionospheric effects; and, 2) analysis of critical interfaces between the satellite and the Microwave Power Transmission System (MPTS).

4.1 Power Beam Ionospheric Effects

The specific objectives of this task are to: 1) Assess the MPTS-induced ionospheric modifications and resultant effects on other users as well as on the microwave power beam and its phase control system; 2) Outline a technology advancement and verification program designed to establish quantitative information on these effects to guide the selection of limiting values for power density and thus take maximum advantage of the orbital space with controlled impact on the ionosphere and its other users.

4.1.1 Modification of the Ionosphere by the Power Beam

Based on theoretical models of Ohmic heating, the magnitude of the ionospheric effects in both the F-layer and D-layer have been calculated at 20, 80 and 320 mW/cm^2 power densities at 2.45 GHz for both a southwest and northeast U. S. site. These are representative of the densities to be associated with 5, 10 and 20 GW output baseline SSPS configurations respectively. Two sites were evaluated because the orientation of the earth's magnetic field and elevation angle from the ground station to the array in space depends on site location (Figure 4.1) and it was found that F-layer effects will vary with site location.

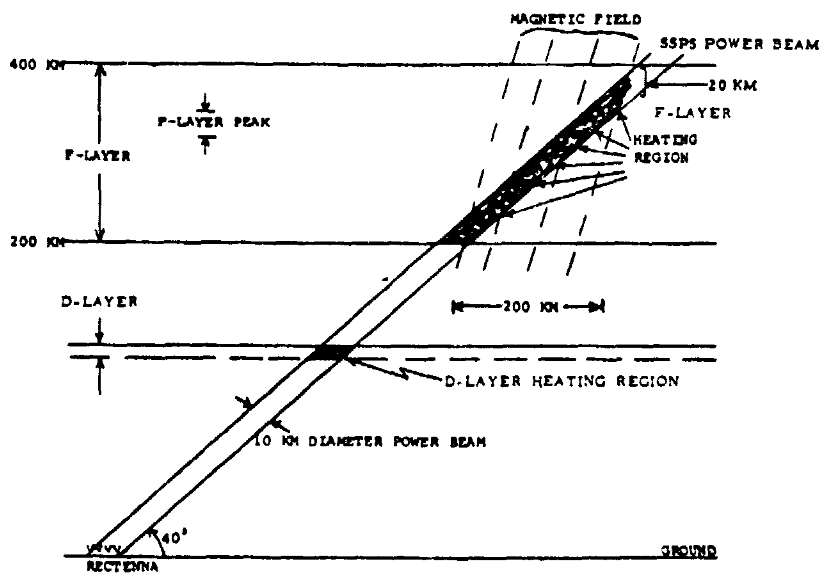

Figure 4.1 Power Beam and its Interaction with the Ionosphere at a NE Site

The D-region effects are not site dependent because the motion of the electrons is not restricted to magnetic field lines, as is the case in the F-region. Results of this analysis indicate the occurrence of large electron temperature increases (several thousands of degrees) and electron density decreases (10 to 40%) in the F-layer (the F-layer is the height range where the peak ionospheric electron densities are observed). D-layer effects (where the maximum absorption of radio waves occurs) also showed large temperature increases accompanied by increases in the electron density.

The relative impact of these changes was assessed by comparing the predicted effects such as ionization depletion in the F-layer with disturbances caused by naturally occurring phenomena. The magnitude of the power beam disturbances compares in magnitude with the natural phenomena. It is not yet known how the geometric distribution of the MPTS disturbance compares with the naturally occurring disturbance (which is one of the objectives of the experimental verification program). However, the comparison does show that the effects of the MPTS are not insignificant when compared to naturally occurring phenomena and that these natural phenomena are known to cause serious disturbances to users which interact with the ionosphere.

The study also indicates that the power density threshold where ionospheric modifications become significant is as low as 15 mW/cm^2, which corresponds to a 4 GW SSPS output. Current theoretical studies indicate increased program risk at power densities above approximately 50 mW/cm^2 (depends on site location), which corresponds to a 7 GW SSPS output, and therefore, the likelihood of each SSPS output being above 7 GW is small (see Figure 2.7). This is also supported by increased biological risk because sidelobe power densities for a 7 GW system having a 10 dB power distribution weighting (taper) at the transmitter are 0.17 mW/cm^2, a level which might mitigate operation of the SSPS due to international restrictions. Economic studies indicate that there is some economy of scale with a desire for larger systems. Thus, the likely range of operation is from 4 to 7 GW and a technology program has been developed which will quantitatively assess the ionospheric impact of a 4 to 7 GW SSPS.

4.1.2 Effects of Ionospheric Modification

4.1.2.1 Effect on Other Users

The number of individual systems which potentially are affected by the ionosphere is too large to be fully explored in this study. The approach taken was to select specific examples which span the RF domain from 10 kHz to 6 GHz in generic systems such as navigation, communication and Department of Defense radars. For example, Table 4.1 lists three of the systems studied and shows the potential power beam ionospheric effects. It is clear that, if an experimental program for evaluating ionospheric effects is undertaken (and the large number of of users which are likely to be affected by the ionospheric modification seem to indicate the advisability of an experimental verification program), a critical element will be the design and implementation of experiments which will quantitatively determine the risk that the MPTS ionospheric effects pose to other users.

Table 4.1 Example of Effects of Ionosphere Modification on Other Users	
System	Power Beam Effects
Omega Navigation System (10.2 kHz)	Ionospheric changes produce sudden phase anomaly which decreases range accuracy of Omega
HF Communications (3 to 30 MHz)	Disruption of HF communication likely which affects many users
AF SATCOM; VHF Satellite-to-Aircraft Communication System	Generation of ionospheric irregularities could produce scintillations and/or multi-path conditions

One further point is that the effects described in Table 4.1, even if they occur in a region localized with respect to the power beam, can potentially effect users at ranges upward of 2000 km from the interaction region. Another way of viewing this is that a user is potentially affected by the power beam in a region defined by the intersection of his local horizon and the ionosphere (Figure 4.2). For one power beam, the probability of interaction might be small; however, for over 100 power beams, all located within the area of interaction, the potential for user interference will increase significantly.

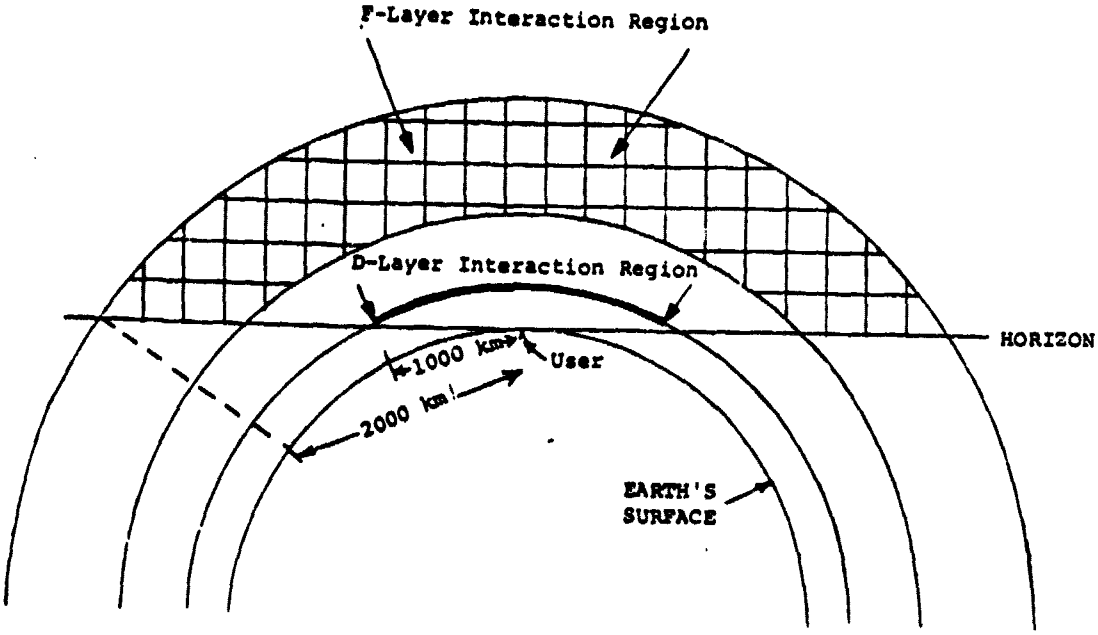

Figure 4.2 Area Where Power Beam Induced Ionospheric Modification Could Affect Other Users

4.1.2.2 Effect on the Power Beam and Phase Control Systems

A phase control system is required to keep the power beam focused on the ground rectenna. Investigation under this effort tends to confirm the conclusions of previous MPTS studies (for power densities below 100 mW/cm^2) that: 1) Negligible displacement or dispersion of the high power beam by ionospheric effects will occur; and, 2) The ground-based pilot phase front at the transmitting antenna will not be significantly affected by ionospheric perturbations. However, as the pilot beam of the phase control system is a critical element of the MPTS system, significant risk could be incurred if the above conclusions were not experimentally verified.

4.1.3 Technology and Demonstration Program

Based on the results of this study, a three-pronged technology and demonstration program is recommended:

A. Theoretical Studies: Establish a two-dimensional steady-state theoretical model of the ionosphere under the influence of microwave power transmissions. Include in the model the effects of horizontal motions and the effects of plasma instabilities caused by power beam ionospheric modifications.

B. Experimental Program - Ground Based Heater: 1) Establish a ground-based heating facility which simulates the MPTS heating due to power densities over a geographical region similar to that of an operational MPTS. A ground-based heater at a frequency of 20 MHz is recommended. 2) Establish diagnostics to evaluate effects of heating on other users and include operation of other user systems where appropriate.

C. Orbital Experimental Program for MPTS Phase Control: 1) Establish a small-scale system at GEO (geosynchronous earth orbit). For the early 1980's a linear array approximately 100 meters in length is recommended for the microwave transmission subsystem (Figure 4.3). During the mid-1980's, a 1 km linear array test at GEO is recommended before commitment to deployment of the full scale prototype. 2) Establish a ground-based pilot beam whose transmission path traverses the ionosphere region being modified by the ground-based heater. 3) Establish a ground-based monitoring system which measures the received power density distribution of the power beam from the linear array at GEO.

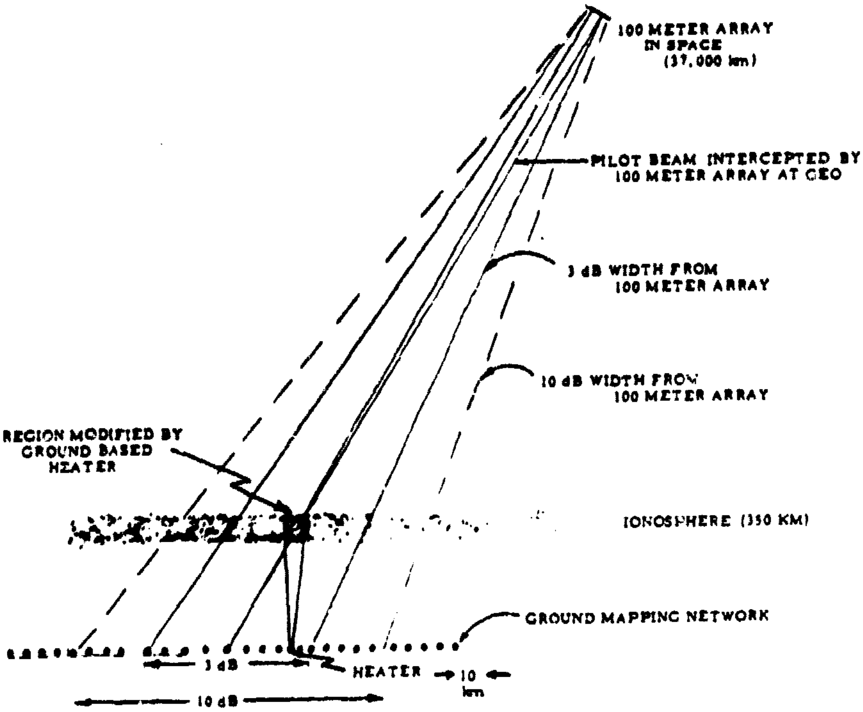

Figure 4.3 Experimental Configuration for the 100 Meter Array in Space and the Ground-Based Heater

The orbital experiments will determine the feasibility of retrodirective phase control of a phased array in space using a ground-based pilot beam as the primary means of keeping the power beam focused and pointed on target. The experiments will establish the effects of the ambient ionosphere on the pilot beam systems and power beam. Requirements for ground-based command and control systems may thereby be defined. A program schedule for the proposed MPTS Ionospheric Effects Program is shown in Figure 4.4.

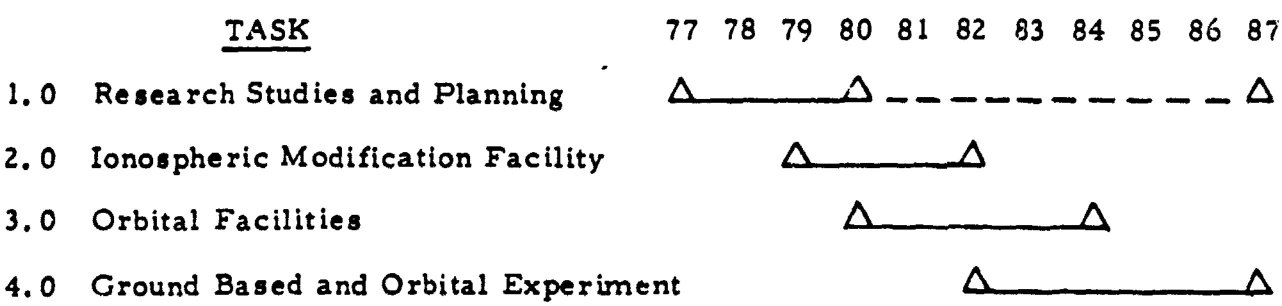

FIGURE 4.4 MPTS Ionospheric Effects Program

4.2 Analysis of Critical Interfaces Between Satellite & MPTS

4.2.1 High/Low Voltage Power Distribution

From a system point of view, the transmission of power from the solar power panels to the MPTS antenna would be more efficient in terms of the cabling mass, size and costs if the Amplitrons were to operate at a high voltage level. Cable sizes are based on the required current to be carried, and for a constant-power system this varies inversely with the operating voltage. Further savings with a high voltage system may be achieved due to the reduction in the number of crowbar units required to protect against arcing, and the reduced number of switch gear units to distribute a lower required total current flow inherent in a high voltage system. From this study, it is concluded that 40 kV Amplitrons at a 5 kW/tube output power represents a cost and mass penalty over the 20 kV, 5 kW/tube; and, a 40 kV microwave power distribution system consisting of two 20 kV, 5 kW Amplitrons in series represents a mass and cost savings. However, there is a subarray isolation problem which must be analyzed further.

4.2.2 Thermal Blockage Effect

Previous studies assumed that there was a 5% uniform solid angle structural blockage of the waste heat radiation to space from the Amplitrons, with the blockage structures at a temperature of 120° C instead of the deep-space temperature of -269° C. This study, considering the specific effects of the satellite mast, flex joint and antenna subarray structure, demonstrated that thermal blockage exceeds the 5% figure previously assumed in the central region of the antenna. Thus, the system requires further design effort to either reduce the blockage, possibly use of active cooling for some Amplitrons, or to enlarge the antenna and operate at lower power densities on orbit which will result in higher power densities at the ground.

4.2.3 Dielectric Carry-Through Structure

In the current SSPS configuration, there is a structure on either side of the MPTS antenna which is made of a dielectric material connecting the two solar panels (Figure 4.5). The MPTS antenna beam propagates through this structure twice every 24 hours. The carry-through structure does not appear, from preliminary calculations, to be a problem in terms of either RF transmission losses or structural heating from the RF power beam. Heating from the waste heat radiators could be a problem requiring further investigation. Because of the complex nature of the system, further experimental efforts are recommended, particularly with respect to the phase control system. This recommendation, of course, depends on the configuration and it is recognized that configurations could be conceived which do not include structures which interfere significantly with the MPTS RF and which are not unduly affected by either RF or thermal radiation from the MPTS antenna.

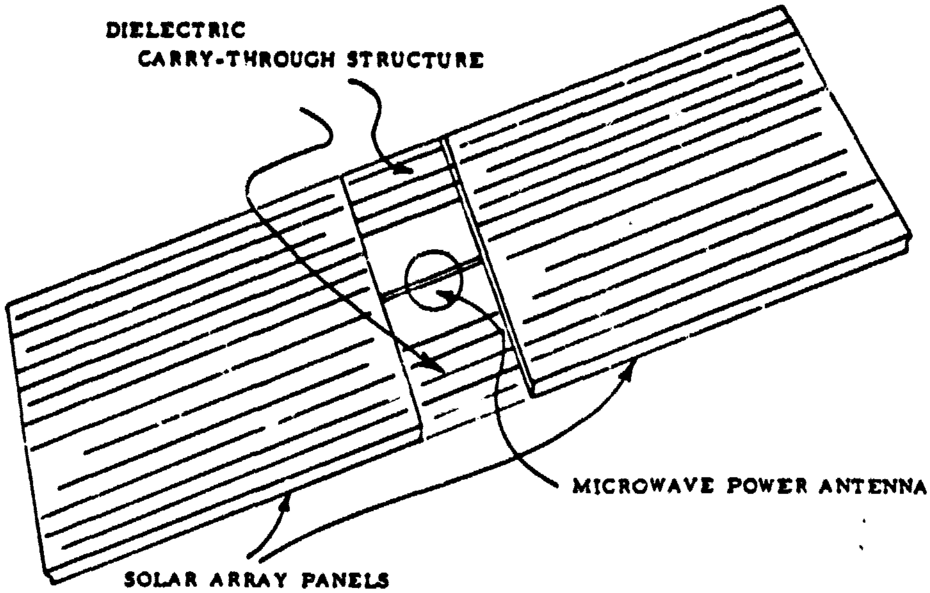

Figure 4.5 Satellite Configuration

4.2.4 Material Sublimation Effect

Analysis of the sublimation products of the various materials which comprise the microwave power transmission system was performed to determine if the resultant increased pressure immediately surrounding the Amplitron will cause the device to malfunction. The study demonstrated that the sublimation of materials adjacent to the Amplitron will probably not have a significant adverse effect on the successful operation of the Amplitron.

5. SUMMARY OF PHOTOVOLTAIC ENERGY CONVERSION SYSTEM ANALYSES

5.1 Purpose and Scope of Analyses

The purposes of these analyses were to examine alternative photovoltaic energy conversion subsystems for the SSPS based upon three specific solar cell materials: silicon, gallium arsenide and cadmium sulfide and to develop inputs for the baseline cost/risk model which represented these materials.

5.2 Results of Analyses

The results of the analyses of alternative photovoltaic energy conversion subsystems are summarized in Figure 5.1, showing the computed variation in parametric cost of generated power (\$/kw) as a function of concentration ratio for the three solar cell materials. Figure 5.2 shows the corresponding variation in total projected area (km^2) of SSPS as a function of concentration ratio for three photovoltaic materials with no augmented cooling.[1] Based upon the assumptions inherent in this subsystem study, cadmium sulfide and gallium arsenide have more promise than silicon as a photovoltaic material for the SSPS. Cadmium sulfide is a more promising material with no concentration and gallium arsenide is more promising with concentration. The optimum concentration ratio for silicon and cadmium sulfide was computed to be near 2.4 and, for gallium arsenide, greater than 7.0. Volume IV of the final report contains the details of the analysis that yielded these results and the next sections of the Executive Summary briefly discuss the methodology and assumptions inherent in the analysis. Of particular significance is that any increase in the total size of the SSPS results in additional fabrication and assembly costs, while the incorporation of optical reflectors for concentrating the sunlight increases the complexity of the construction task. These factors have not been included in this subsystem analysis but they would tend to favor a system with no reflectors or augmented cooling.

5.3 Methodology of Analyses

The examination of alternative photovoltaic materials required the development of a computerized analytical procedure to model the engineering aspects of the photovoltaic subsystem of the SSPS. This model was used to compute the reflectivity of the optical system (if present) and the operating efficiency of the three different solar cell materials over a range of concentration of sunlight. From the operating cell efficiency, a subsystem "parametric" dollar cost per kilowatt for the 5 GW of electrical energy delivered to the utility interface was

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[1] As used herein "augmented cooling" refers to a thermal design that uses radiating areas in addition to the front and back surfaces of the solar cell array.

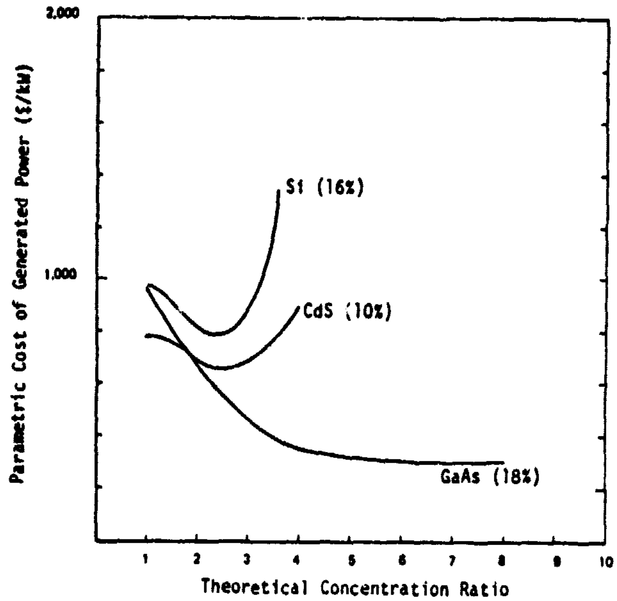

Figure 5.1 Variation in Parametric Cost of Generated Power ($/kW) As a Function of Concentration Ratio for Three Solar Cell Materials

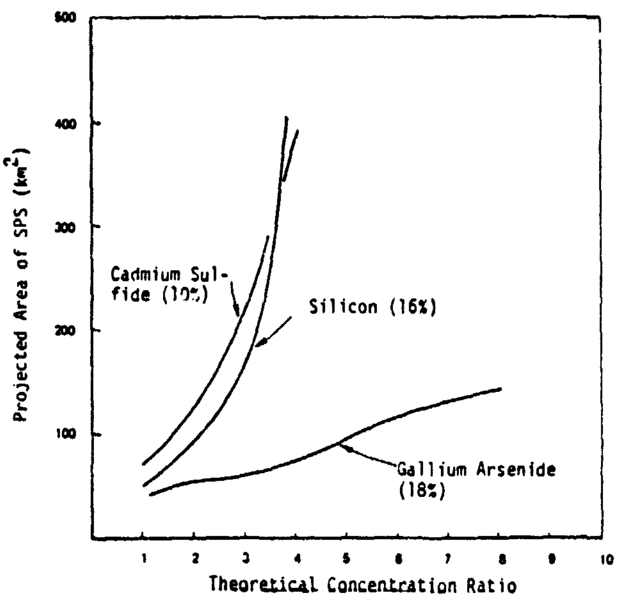

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Figure 5.2 Variation in Total Projected Area (km^2) of SSPS as a Function of Concentration Ratio for Three Solar Cell Materials - No Augmented Cooling established after five years on-orbit. As used here, the "parametric" cost of a photovoltaic subsystem includes the capital cost of the solar cell arrays, the optical reflectors and the basic support structure as well as the transportation costs to deliver these materials to geosynchronous orbit. We recognize that the minimum "parametric" cost for a photovoltaic subsystem, as generated in this task, represents only one aspect of an optimized design for the SSPS. The cost/risk model of the full SSPS was used to examine the feasibility of the SSPS and to indicate which photovoltaic materials merit further development.

The computer model requires, as inputs, values which represent basic solar cell array cost, mass and efficiency, the variation in array efficiency as a function of temperature, illumination intensity, radiation damage and angle of incident illumination, as well as the mass and cost per unit area for the basic support structure and any concentrating optics. The solar cell data were compiled from the literature and from private communications with photovoltaic specialists. The data which represents the support structure and concentrating optics was taken from the original baseline model developed in an earlier part of this program. This catalog of data is stored internal to the computer program.

5.4 Assumptions of Analyses

The assumptions inherent in the analytical model of the photovoltaic energy conversion subsystem relate to the modelling of the solar cell array, the basic support structure and the optical system.

Table 5.1 defines the range of basic solar cell efficiencies, Table 5.2 defines the range of solar cell array mass/unit area and Table 5.3 defines the range of basic solar array costs used in the analyses. The "minimum cost" number (Table 5.3) reflects an array technology that is dominated by the costs of fabrication of the array on a reliable, mass production basis and is, therefore, independent of the particular photovoltaic material being utilized for the solar cell. The "maximum cost" numbers consider significant variations in the cost of the different photovoltaic materials with gallium arsenide having the highest potential procurement cost per unit area of array. This high cost assumes that the cost per unit mass of gallium would not decrease and might escalate as the quantity being purchased reduced available gallium supplies.

Table 5.4 defines the fixed parameters that were taken from the baseline model. Of particular significance here is the assumption that the mass and cost per unit area for the basic support structure and the optical reflectors are a constant multipler and do not change with concentration ratio or size of the full SSPS.

In order to examine the photovoltaic subsystem over a range of solar concentration ratios, an optical reflector system configuration was chosen that would smoothly grow in size as the concentration ratio

Table 5.1 Assumed Solar Cell Efficiencies*				
Solar Cell Material	Pessimistic (Today's Values)	Most Likely (Emerging)	Optimistic	Theoretical Limit
Silicon	12%	16%	19%	22%
Gallium Arsenide	14	18	22	27
Cadmium Sulfide	8	10	12	18

*Air Mass Zero at 20°C

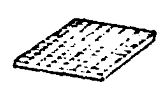
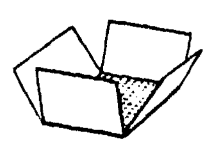
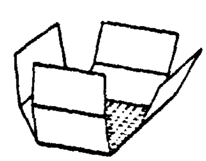
Table 5.2 Assumed Mass/Unit Area of Solar Array (mg/cm^2)			
Solar Cell Material	Minimum	Most Likely	Maximum
Silicon	28.2	40.0	115.0
Gallium Arsenide	33.2	43.2	52.6
Cadmium Sulfide	11.5	14.9	19.4

Table 5.3 Assumed Solar Array Costs ($\$10^6/km^2$)			
Solar Cell Material	Minimum	Most Likely	Maximum
Silicon	48.7	86.6	730.6
Gallium Arsenide	48.7	203.0	1488.3
Cadmium Sulfide	48.7	86.6	270.6

Table 5.4 Assumed Fixed Parameters From Baseline Model

Parameter	Fixed Value
Solar Constant	1353 W/m^2
Power Developed by Photovoltaics	9.612×10^6 kW
Mass/Unit Area Support Structure	21,300 kg/km^2
$/Unit Mass Support Structure	81 $/kg
Mass/Unit Area Reflectors	29,670 kg/km^2
$/Unit Area Reflectors	1.035×10^6 $/km
Transportation Costs to GEO	80 $/kg

Table 5.5 Optical Configurations Used in Analyses

C.R. = 1.0	
1.0 < C.R. ≤ 3.8	
3.8 < C.R.	

increased. Table 5.5 shows the three optical configurations that were utilized over the concentration ratio of 1.0 to 8.0. These optical systems minimize the area of optical reflector surfaces needed at each concentration ratio among the candidate two-, three-, and four-mirror front lit optical systems.

Because of the shallow angle of incidence onto the solar cell by the energy reflected off the mirrors at the lower concentration ratios, there is a resulting decrease in the effective absorptance of the cell and its cover glass. Fewer but larger mirror surfaces, producing a more normal incident angle onto the solar cells, with a front lit configuration, would result in an increase in cell efficiency due to the higher effective solar absorptance. This increase in conversion efficiency for a more normal angle of incidence onto the cell is partially offset by a decrease in cell efficiency caused by its higher temperature. For each theoretical concentration ratio[2], there is a corresponding effective concentration which can be defined as the ratio of the solar flux intensity absorbed by the cell with normal illumination at one sun to the flux intensity absorbed by the same cell from both the direct and reflected components with a concentrating system illuminated by one normal sun.

5.5 Conclusions

As a result of the work carried out on alternative photovoltaic conversion systems for satellite power systems, the following conclusions can be drawn.

1. Among the three photovoltaic materials which were examined at the subsystem levels, cadmium sulfide and gallium arsenide have more promise than silicon on the basis of parameters which included performance, mass, cost, and system design considerations. Cadmium sulfide is a more promising photovoltaic material with no concentration and gallium arsenide would be preferred with concentration. The subsystem analyses show an optimum solar concentration ratio near 2.4 for silicon and cadmium sulfide and greater than 7.0 for gallium arsenide.

2. Optical concentrators and augmented cooling result in increasing complexity of the solar energy conversion system, tighter pointing requirements and an increased difficulty of fabrication and assembly in orbit. A reduced operational life due to degradation of reflecting surfaces may also result. These effects were not quantified in this study.

3. Increased concentration ratios will result in a reduction of the required total area of solar cell arrays but will reduce solar cell efficiency, without augmented cooling, because of higher cell equilibrium temperatures. This

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[2] The theoretical concentration ratio as defined for the SSPS is the total area of intercepted sunlight to the solar cell array area.

results in an increase in the total solar energy conversion system area. The increased costs of fabrication and assembly of the larger solar energy conversion system with optical concentration drives the "optimum" concentration ratio for the system towards 1.0.

4. Solar energy conversion system designs, which utilize thin film solar cells without concentration and without augmented cooling can result in a simpler structural design, thereby reducing complexities of orbital fabrication and assembly at an acceptable performance, lower mass system design, and a more competitive SSPS compared to alternative energy production methods.

5. The SSPS baseline design utilizing single crystal silicon solar cells with optical concentrators, which has performed a very useful function for technical and economic feasibility and system studies, does not represent an optimum design approach. Future designs should utilize evolving thin film solar cell technology and alternative structural approaches, which are more consistent with the projected lightweight solar cell arrays of the future and which lend themselves to less complex fabrication and assembly procedures in orbit.

5.6 Recommendations

1. SSPS designs based on thin film solar cells without concentration and utilizing new structural approaches should be developed and associated fabrication and assembly costs established for inclusion in system trade-off studies. The effects of reduced pointing requirements and station keeping on the attitude control system and its propellant consumption should be established.

2. A power distribution system which can operate effectively with new structural designs and thin film solar cell arrays should be investigated. The benefits which may be gained from passive cooling or active cryogenic cooling of main power distribution lines should be examined.

3. The design and selection of solar cell array and structural materials should include considerations of the space-charging phenomena. The effects on assembly procedures and potential degradation of SSPS system performance caused by space-charging should be established.

4. Uncertainties and inconsistencies in the properties and performance of photovoltaic materials and solar cells should be reduced through a standardization of test methods, so that photovoltaic materials properties of different cells can be documented on a consistent basis.

5. The current data base on photovoltaic materials should be expanded to include other candidate solar cells, particularly those applicable to the SSPS solar energy conversion system.

6. The solar cell materials whose performance, production processes and costs show the most promise for applications to the SSPS solar energy conversion system should be investigated in greater detail to reduce the uncertainties in the projected cell parameters.

7. The activities directed towards the development of photovoltaic materials for the SSPS should be coordinated with the development activities pertaining to terrestrial photovoltaic conversion applications.

8. Orbital experimental tests should be conducted to verify on-orbit performance of promising photovoltaic materials to provide design data required for the solar energy conversion system.

9. Figure 5.3 shows a recommended decision tree for the choice and development of the photovoltaic materials and solar array blankets for the SSPS over the time period from today to 1996.

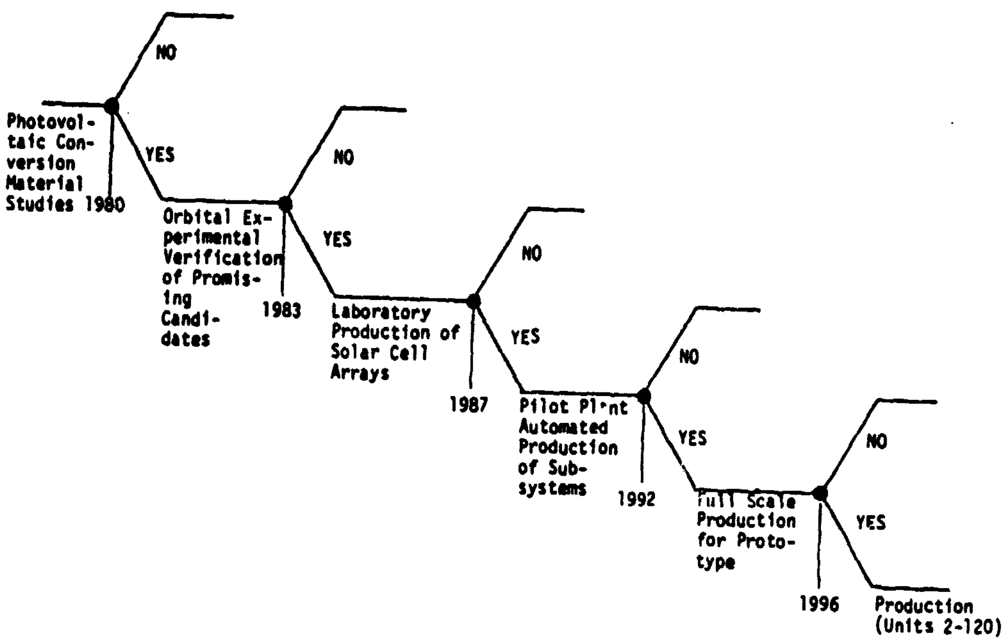

Figure 5.3 Recommended Decision Tree for the Choice and Development of Photovoltaic Materials for the SSPS

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