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Part 1 Volume I

Executive Summary

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Solar Power Satellite

SYSTEM DEFINITION STUDY

D180-20689-1

Contract NAS9-15196
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SYSTEM DEFINITION STUDY

Part 1 Volume I

Executive Summary

June 28, 1977

Submitted to
The National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
In Partial Fulfillment of the Requirements
of Contract NAS 9-15196

Approved By: G.R. Woodcock

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FOREWORD

The SPS systems definition study was initiated in December 1976. Part I was completed on May 1, 1977. Part I included a principal analysis effort to evaluate SPS energy conversion options and space construction locations. A transportation add-on task provided for further analysis of transportation options, operations, and costs.

The study was managed by the Lyndon B. Johnson Space Center (JSC) of the National Aeronautics and Space Administration (NASA). The Contracting Officer's Representative (COR) was Clarke Covington of JSC. JSC study management team members included:

Lou Livingston	System Engineering and Analysis	Dick Kennedy	Power Distribution
Lyle Jenkins	Space Construction	Bob Ried	Structure and Thermal Analysis
Jim Jones	Design	Fred Stebbins	Structural Analysis
Sam Nassiff	Construction Base	Bob Bond	Man-Machine Interface
Buddy Heineman	Mass Properties	Bob Gundersen	Man-Machine Interface
Dickey Arndt	Microwave System Analysis	Hu Davis	Transportation Systems
R. H. Dietz	Microwave Transmitter and Rectenna	Harold Benson	Cost Analysis
		Stu Nachtwey	Microwave Biological Effects
Lou Leopold	Microwave Generators		
Jack Seyl	Phase Control	Andrei Konradi	Space Radiation Environment
Bill Dusenbury	Energy Conversion		
Jim Cioni	Photovoltaic Systems	Alva Hardy	Radiation Shielding
Bill Simon	Thermal Cycle Systems	Don Kessler	Collision Probability

The Boeing study manager was Gordon Woodcock. Boeing technical leaders were:

Vince Caluori	Photovoltaic SPS's	Jack Gewin	Power Distribution
Dan Gregory	Thermal Engine SPS's	Don Grim	Electric Propulsion
Eldon Davis	Construction and Orbit-to-Orbit Transportation	Henry Hillbrath	Propulsion
		Dr. Ted Kramer	Thermal Analysis and Optics
Hal DiRamio	Earth-to-Orbit Transportation	Keith Miller	Human Factors and Construction Operations
Dr. Joe Gauger	Cost		
Bob Conrad	Mass Properties	Jack Olson	Configuration Design
Rod Darrow	Operations	Dr. Henry Oman	Photovoltaics
Bill Emsley	Flight Control	John Perry	Structures

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The Part I Report includes a total of five volumes:

Vol. I	D180-20689-1	Executive Summary
Vol. II	D180-20689-2	System Requirements and Energy Conversion Options
Vol. III	D180-20689-3	Construction, Transportation, and Cost Analyses
Vol. IV	D180-20689-4	SPS Transportation System Requirements
Vol. V	D180-20689-5	SPS Transportation: Representative System Descriptions

Requests for information should be directed to Gordon R. Woodcock of the Boeing Aerospace Company in Seattle or Clarke Covington of the Future Programs Division of the Johnson Space Center in Houston.

D180-20689-1

SOLAR POWER SATELLITE SYSTEM DEFINITION STUDY
PART I TECHNICAL REPORT

1.0 EXECUTIVE SUMMARY

1.1 THE SPS CONCEPT

Solar power satellites represent a proposed means of tapping baseload electric utility power from the sun on a large scale. The advantages of the space environment for generation of electric power can thereby be "brought down to Earth." These advantages include essentially continuous sunlight. the ability to construct very large solar collectors with minimum resource investment, and the ability to always aim the collectors at the sun. Studies presently in progress sponsored by ERDA and NASA, of which this SPS Systems Definition Study is one element, are defining the systems, development approaches, and risks and costs for this venture and evaluating the probable benefits of the system against these risks and costs.

SYSTEM CONCEPT

An SPS system for utility electric power would include a number of satellites in geosynchronous orbit, each with one or two associated power receiving stations on the ground. Receiving stations can be located near load centers (weather is not a significant factor); each will provide 1000 megawatts or more of baseload electrical output. A satellite system is pictorialized in Figure 1-1. Power is transferred from the satellites to the ground stations by high-precision electromagnetic beams. The transmissions would presumably use the industrial microwave band at 2.45 GHz; an alternative industrial allocation available at 5.8 GHz could be used but has received comparatively little attention.

A complete SPS system is depicted in Figure 1-2. In addition to the satellites and their ground systems it will include:

- A space transportation system capable of delivery of the SPS's to geosynchronous orbit and capable of supporting all required space operations needed to establish and maintain the SPS system.

- One or more construction bases, located either in geosynchronous orbit or low Earth orbit, capable of constructing the satellites. Satellite hardware delivered to the construction bases will be prefabricated to the extent practicable.

- Maintenance and service bases capable of supporting the maintenance operations required to keep the SPS's operating.

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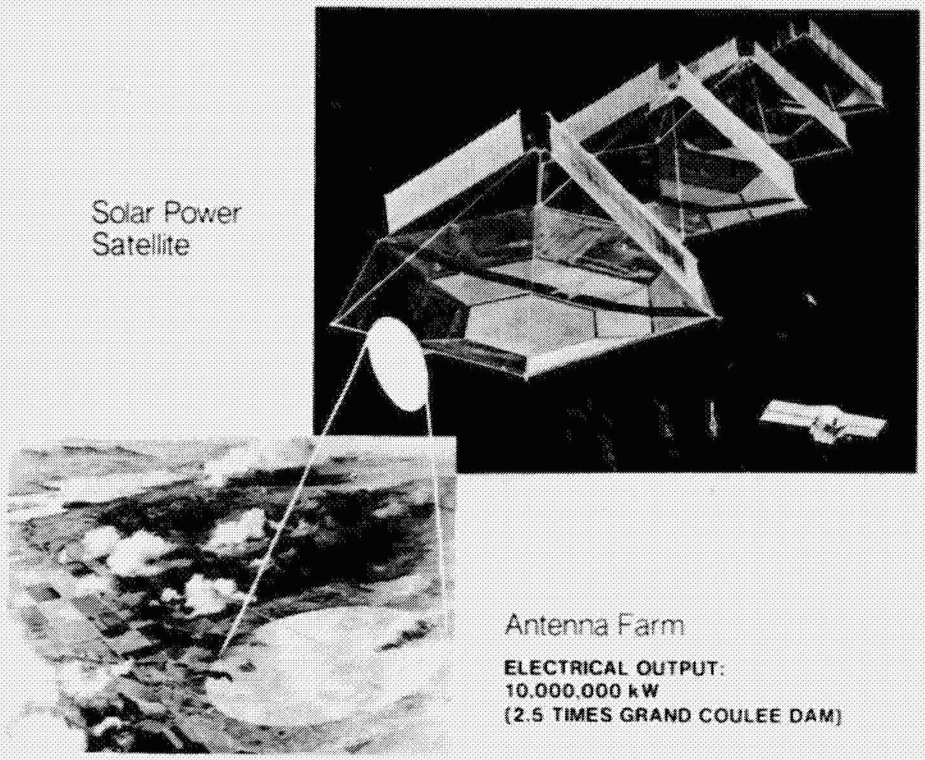

Figure 1-1. The SPS Concept

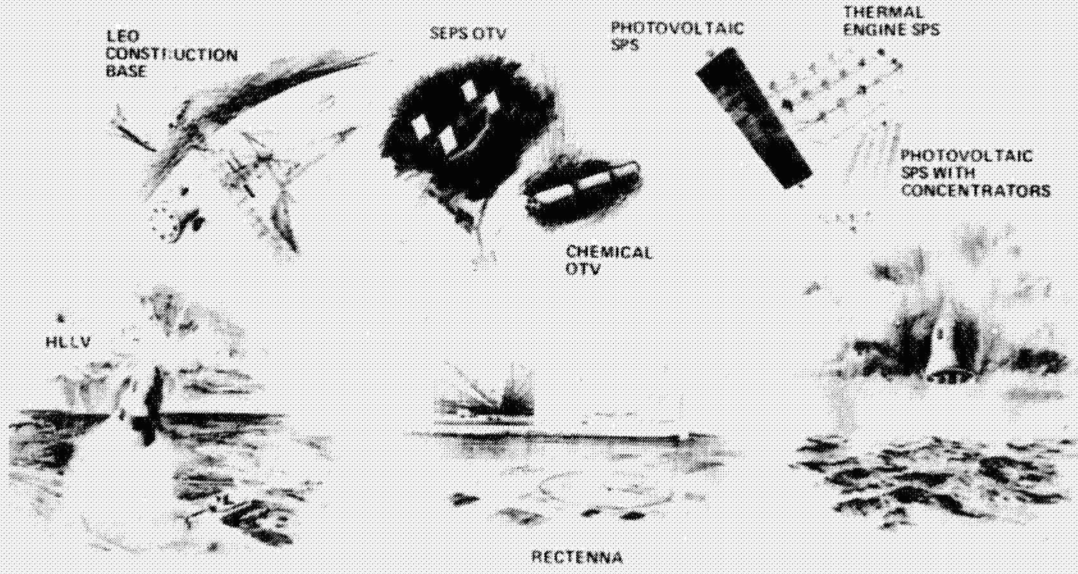

Figure 1-2. Major Program Elements

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- One or more Earth-based space transportation ports (launch sites) capable of supporting space transportation operations.

- One or more space-based transportation operations support bases, capable of supporting space transportation operations. This function could conceivably be combined with that of either a construction base or a maintenance base.

- Earth-based manufacturing facilities capable of producing the hardware and consumables necessary to transport, construct and maintain the SPS system.

- An Earth-based logistics system capable of delivering the hardware and consumables to the space transportation parts.

1.2 STUDY OBJECTIVES

The objectives of Part I of the study, as specified by the NASA statement of work, were as follows:

(1) **Issues**—To derive specific, comprehensive supporting data necessary for NASA evaluation of the following two major SPS system issues:

a. What is the overall most effective means of accomplishing solar energy-to-electrical energy conversion on an SPS in geosynchronous orbit?

b. At what location (or locations) in space could the various phases of SPS construction and assembly be done?

(2) **Transportation**—To increase the scope and depth of understanding of the space transportation systems necessary to support an SPS program.

a. Provide a set of transportation system requirements and reference transportation system elements descriptions appropriate to the conduct of an SPS program as represented by JSC Scenario "B".

b. Identify and define analyses and tests necessary to advance the confidence level in projected SPS transportation systems performance and cost sufficient to recommend initiation of an SPS technology advancement program.

1.3 STUDY APPROACH AND PLAN

The SPS System Definitions study is being conducted in two parts as indicated in Figure 1-3. It began with two reference systems: the photovoltaic system from what is popularly known as the JSC green book (JSC 11568); and the Brayton thermal system from prior study work by Boeing. We have also in this phase considered the other options shown: high technology gallium arsenide, thin films, and Rankine and thermionic thermal options. Part I provided evaluation data that would allow selection of one or two energy conversion options and evaluate LEO and GEO space construction locations. In Part II we will analyze the microwave power transmission system and develop an integrated system definition. The objective of Part II is to reduce the system mass and cost uncertainties as much as possible.

The program under study is basically an operational or commercial SPS program. Ground rules are summarized in Table 1-1. It starts with the first full capability 10,000 megawatt satellite and goes through a program of many satellites. In a few instances where the cost of money was important we have used a 7½% discount rate as recommended by Econ in earlier studies. We are assuming a 30 year system life for purposes of financial horizon analysis, even though there is no particular life limit on the SPS's. There are a few cases where creep rupture analysis was required. A safety factor of 1½ on 30 year creep-rupture-life material thickness was used. The reference data for transportation came from the Heavy-Lift Launch Vehicle study and Future Space Transportation Systems Analysis study data base (contracts NAS 8-32169 and NAS 9-14323, respectively). That data base was updated as part of this study.

Table 1-1. SPS Program Ground Rules

- IOC date: end of 1995
- 112 SPS program
- 10-gigawatt SPS size
- 7.5% discount rate (1977 constant dollars)
- 30-year satellite life
- Transportation system reference data to be taken from HLLV and FSTSA data base and JSC-11568
- Operational system design and performance projections based on 1987 technology baseline

The program scenario used for SPS installation rate was JSC scenario B, shown in Figure 1-4. The first satellite was completed in 1995 and production rate increases gradually to 7 per year at the end of the program. For purposes of predicting transportation cost, we have taken a snapshot of the mid-point of the program at the rate of four SPS's per year.

Point of Departure

Reference Systems:

Silicon photovoltaic from JSC study

Brayton thermal from Boeing study

Options

Gallium arsenide and thin-film photovoltaics

Rankine and thermionic thermal engines

Part I
December 1976 to May 1977

Design:
Carry reference designs to next level of detail.

Analyze:
Construction and transportation systems and operations.

Characterize:
Options and delta off reference designs

Compare:
Performance, practicality, operations, environmental factors, cost, and technical risk.

Select:
One or two energy conversion options and low versus geosynchronous orbit construction.

Part II
May 1977 to December 1977

Analyze:
Microwave power transmission system.

Design:
Integrated SPS systems—energy conversion, power transmission, construction, transportation, and overall operations.

Develop:
- Integrated system conceptual definition.
- System mass estimates
- System cost estimates
- System development plans
- Technology advancement requirements

Figure 1-3. Solar Power Satellite Systems Study Overview

	1995					2000					2005				2010
NUMBER OF SYSTEMS COMPLETED	1	0	1	1	1	1	1	2	2	2	2	3	3	3	3
CUMULATIVE TOTAL	1	0	2	3	4	5	6	8	10	12	14	17	20	23	26

	2010					2015					2020				2025
NUMBER OF SYSTEMS COMPLETED	4	4	5	5	5	6	6	6	6	6	6	6	7	7	7
CUMULATIVE TOTAL	30	34	39	44	49	55	61	67	73	79	85	91	98	105	112

- Corresponds to JSC scenario B

Figure 1-4. Baseline Operational Program Scenario

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During Part I no power transmission system analysis was done. The data shown in Table 1-2 came from the JSC "green book." This information was used for purposes of sizing satellites to delivery 10,000 megawatts of ground output to the receiver antenna system.

Table 1-2. Reference MPTS/MCRS Nominal Efficiencies*

Antenna power distribution	.98
DC-RF conversion	.87
Phase control	**
Waveguides (I^2R)	.98
Mechanical alignment	.98
Atmosphere	.98
Energy collection	.88
RF-DC conversion	.90
Power interface	.99
Overall	.629

* From JSC 11568, fig. IV-A-1-1, "SPS Efficiencies"
** Included in energy collection

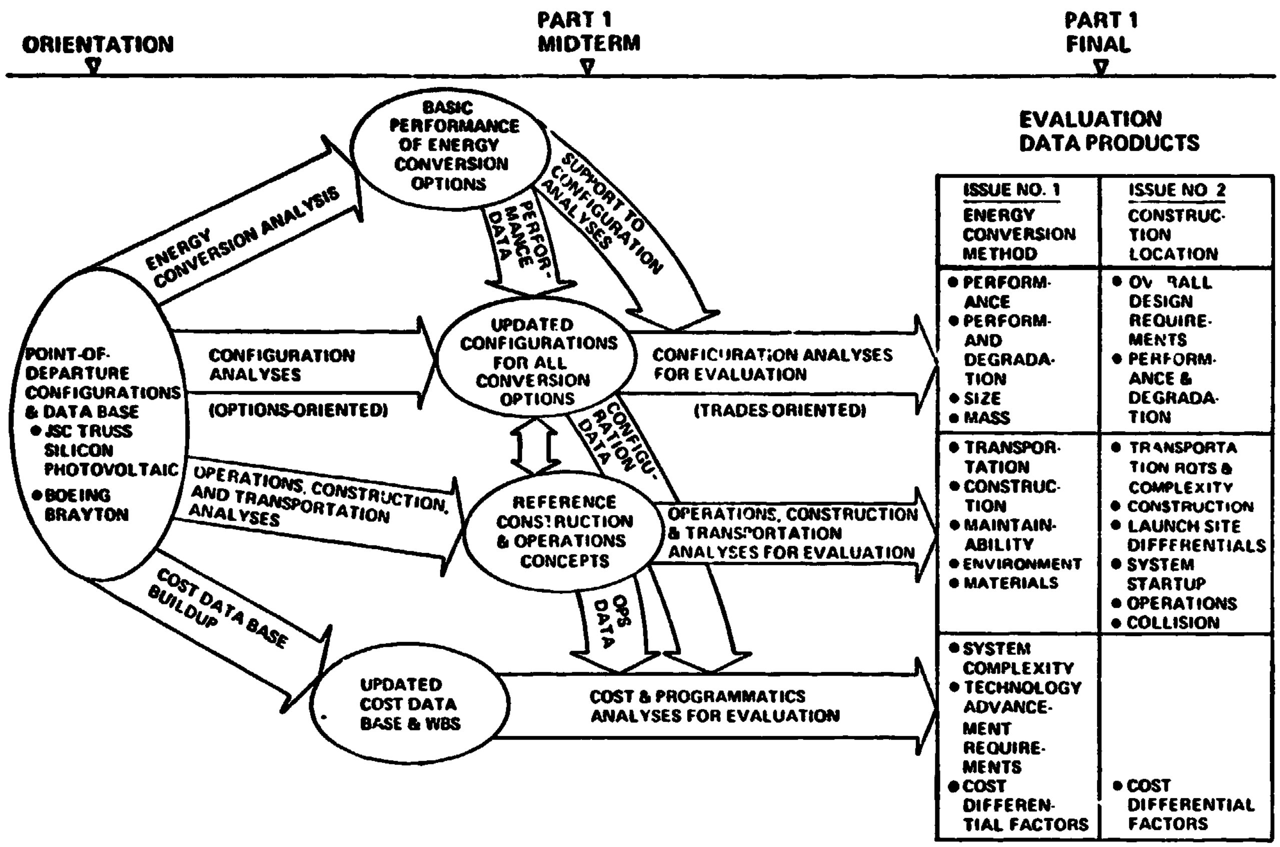
The Part I analysis effort was grouped into four higher-level task types as shown in Figure 1-5. These analyses were based on the point-of-departure configurations. Results of the analyses were integrated as indicated in the figure. Additional tradeoffs and analyses effort after the midterm led to the evaluation data summarized in the summary section of this report.

The silicon single crystal photovoltaic SPS system and the Brayton thermal engine system reference designs were used to carry out analyses such as performance, structures, and power distribution. The construction and transportation analyses considered both geosynchronous orbit and low earth orbit as construction locations. The analyses resulted in the configuration evolutions shown in Figure 1-6. These analyses led to concepts for facilitization of construction, influencing the satellite design, especially in the thermal engines where a configuration change from compound curvature concentrators occurred. In both cases modular SPS designs at approximately 1,000 megawatts of onboard busbar power per module were developed.

The thermionic system was recommended for discontinuance about halfway through the Part I effort.

1.4 DOCUMENT STRUCTURE

This executive summary describes the results of the Part I evaluations of energy conversion and construction location options. Volumes II through V provide detailed reporting of the Part I effort.



ISSUE NO. 1 ENERGY CONVERSION METHOD	ISSUE NO 2 CONSTRUCTION LOCATION
• PERFORMANCE • PERFORMANCE AND DEGRADATION • SIZE • MASS	• OVERALL DESIGN REQUIREMENTS • PERFORMANCE & DEGRADATION
• TRANSPORTATION • CONSTRUCTION • MAINTAINABILITY • ENVIRONMENT • MATERIALS	• TRANSPORTATION RQTS & COMPLEXITY • CONSTRUCTION • LAUNCH SITE DIFFERENTIALS • SYSTEM STARTUP • OPERATIONS • COLLISION
• SYSTEM COMPLEXITY • TECHNOLOGY ADVANCEMENT REQUIREMENTS • COST DIFFERENTIAL FACTORS	• COST DIFFERENTIAL FACTORS

Figure 1-5. Synopsis of Part 1 Study Logic

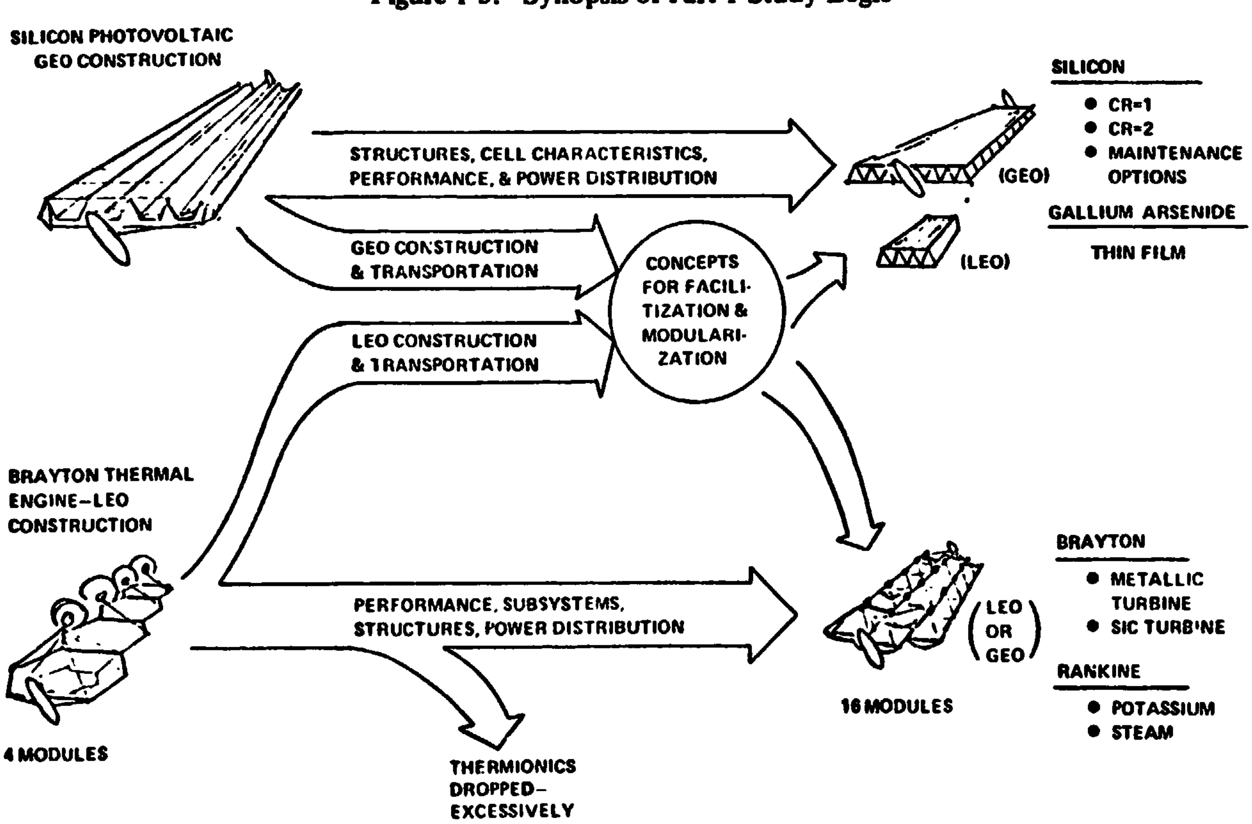


Figure 1-6. Part 1 Analyses and Configuration Evolution

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1.5 ENERGY CONVERSION EVALUATION

The statement of work specified the evaluation factors listed in Table 1-3 for energy conversion. The cost differential factors are presented at the end of this summary because they combine results of both evaluation efforts.

Table 1-3. Energy Conversion Evaluation Factors

	Evaluation Factor
a)	SPS Performance
b)	Performance Degradation
c)	SPS Size
d)	SPS Mass
e)	System Complexity
f)	Maintainability
g)	Construction Requirements
h)	Transportation Requirements
i)	Technology Advancement Requirements
j)	System Cost Differential Factors
k)	Environmental Effects Differential Factors
l)	Materials Differential Factors

SPS Performance—The first factor is performance (efficiency). When this study began it was believed that there was quite a difference between thermal engine and photovoltaic performance. There is much less than we had thought. Efficiency generally follows the technology advances and advanced systems tend to be more efficient, except for the thermionics option. Efficiency is not an important discriminator unless very low. Efficiency results are summarized in Figure 1-7.

Performance Degradation—Degradation effects were found in all of the systems. The silicon photovoltaic degrades more than thermal engine systems, with gallium arsenide in between.

On the left hand side of Figure 1-8 is the magnitude of the degradation effect and on the right hand it is normalized to indicate what percentage of SPS mass is affected. For example, thin film reflectors are the degradation mode for thermal engines but represent only a small fraction of satellite mass. In all cases maintaining the satellite output seems to be promising. We compensated for degradation in our recommended SPS's. Performance degradation is reflected in size, mass, and cost and therefore carries little weight as an independent evaluation factor.

SPS Size—Figure 1-9 is a size comparison of the principal systems. The smallest system is the gallium arsenide annealable followed by the Brayton. The silicon systems show that concentration

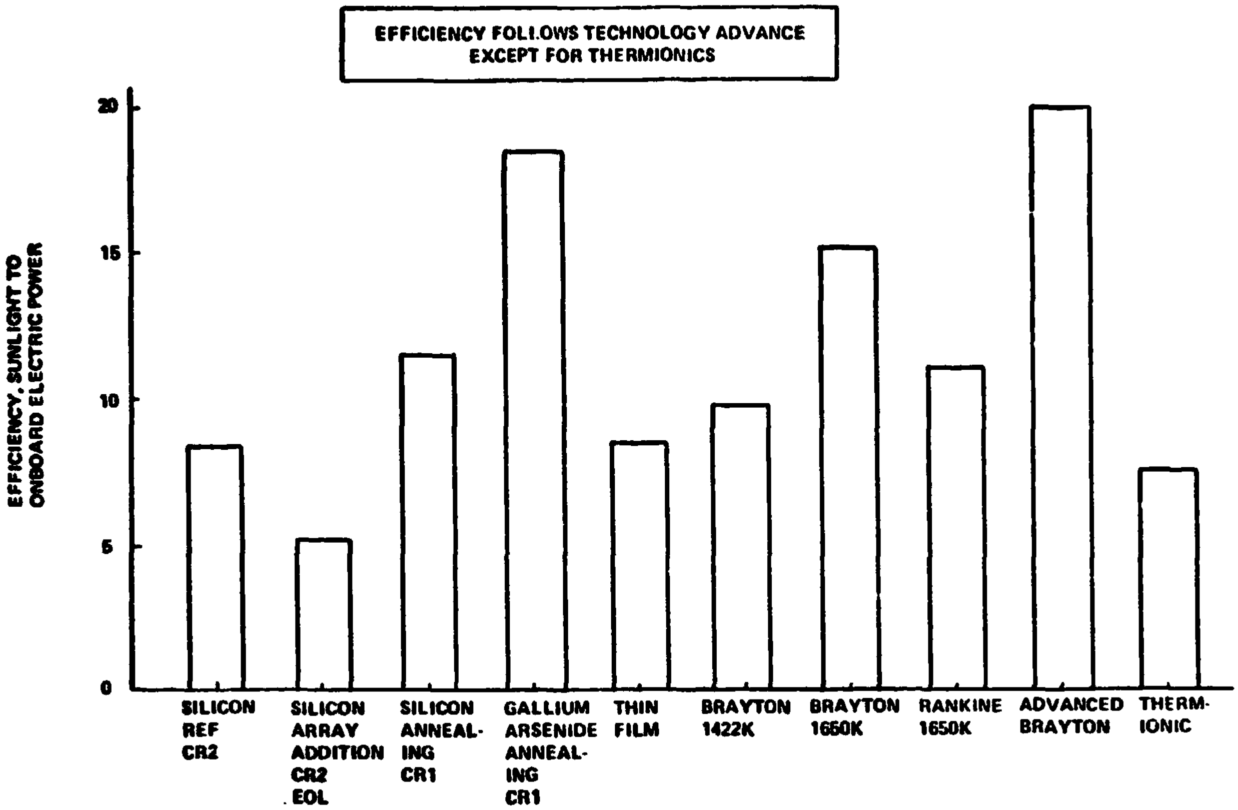

Figure 1-7. Energy Conversion Comparison SPS Performance

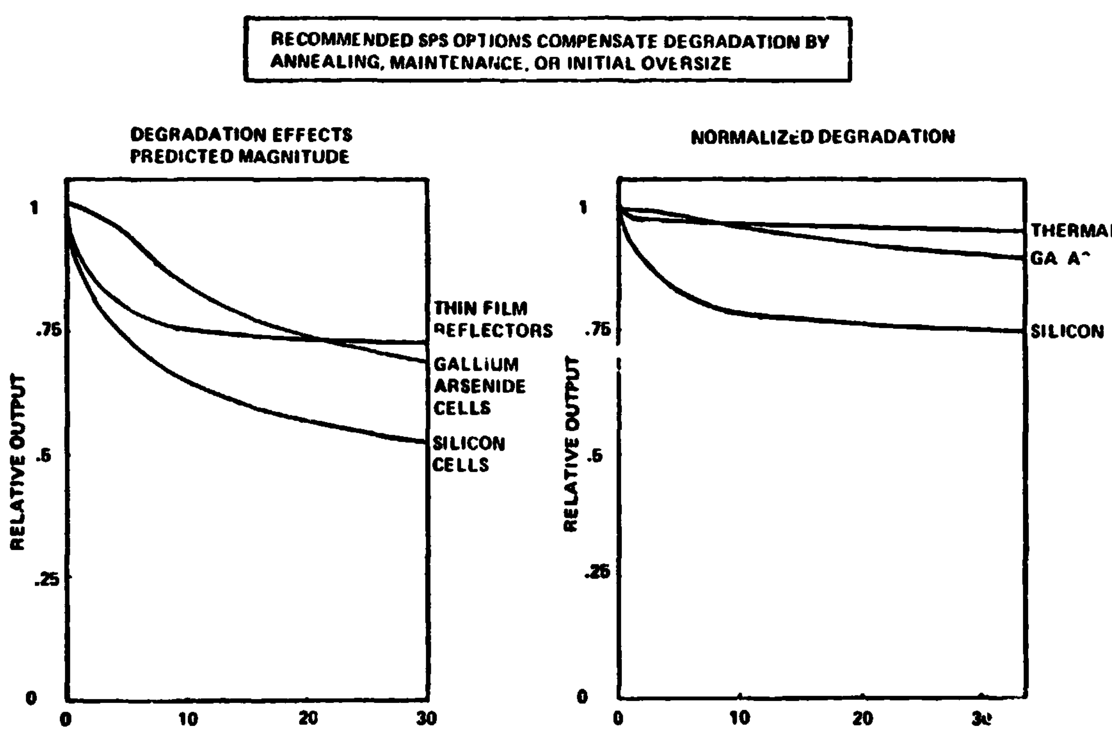

Figure 1-8. Energy Conversion Comparison Performance Degradation

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ratio 1 leads to a significant reduction in size. The thin film size estimate is a guess because of the uncertainty in the data base. Size does not seem to be a strong discriminator: much more important is mass.

SPS Mass–Mass comparison for the systems is shown in Figure 1-10. Note that annealing is a much better system from the mass standpoint than array addition. The annealing method employs electron-beam or laser heating. A thermal pulse directly into the solar cell raises the temperature momentarily and anneals out the degradation. Heat generated in the cell diffuses only slightly into the substrate. Rough estimates indicate that we need about a half dozen annealing machines, two meters square by three meters long. This number of machines operating continually during satellite operation will keep the performance up. These machines could be operated remotely by operators via RF links. Annealing is like painting the Golden Gate Bridge: as soon as it is finished, it must start again.

The lightest system of all is gallium arsenide. We have found that there is a considerable variation in Brayton system mass as a function of technology. The steam Rankine system was excessively massive and could not be plotted on the chart. Thermionics conversion was also quite massive.

System Complexity–There are two ways to measure complexity: one way is to estimate the number of unique parts or subassemblies. The thermal engine system has about five times as many unique parts as the photovoltaic. Total parts is the other measure. If one counts individual solar cells, photovoltaics have about 1,000 times as many total parts. Integration complexity of the system is determined primarily by the number of unique parts. System complexitites are compared in Figure 1-11.

Maintainability Factors–For both types of energy conversion we found maintenance problems, and in both bases we found solutions. The results after applying the solutions are summarized in Table 1-4. Roughly 5 to 10 manhours per hour for annealing are needed with the photovoltaic system and slightly more than 10 mh/h with the thermal system for mechanical repair and replace. It is conceivable that those manhours might be spent on the ground if we can develop suitable automated systems that can be man-directed from a remote distance. It does not necessarily mean that the SPS's have to be manned. It is likely that these maintenance requirements will be overshadowed by that for the microwave transmitter.

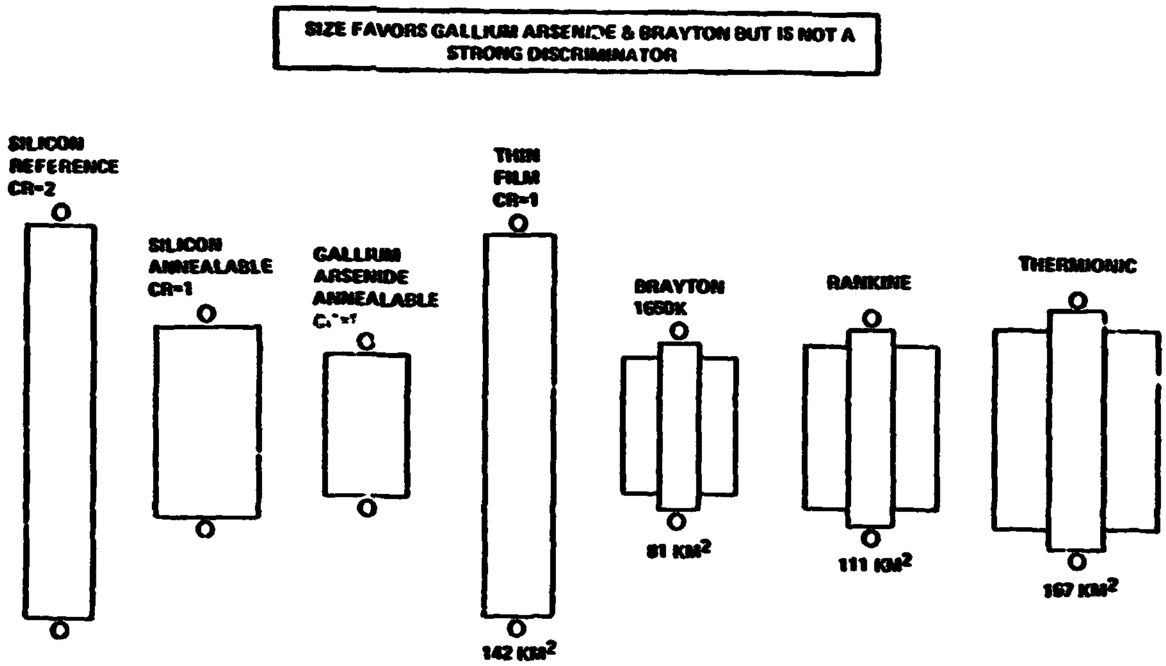

Figure 1-9. Energy Conversion Comparison SPS Size

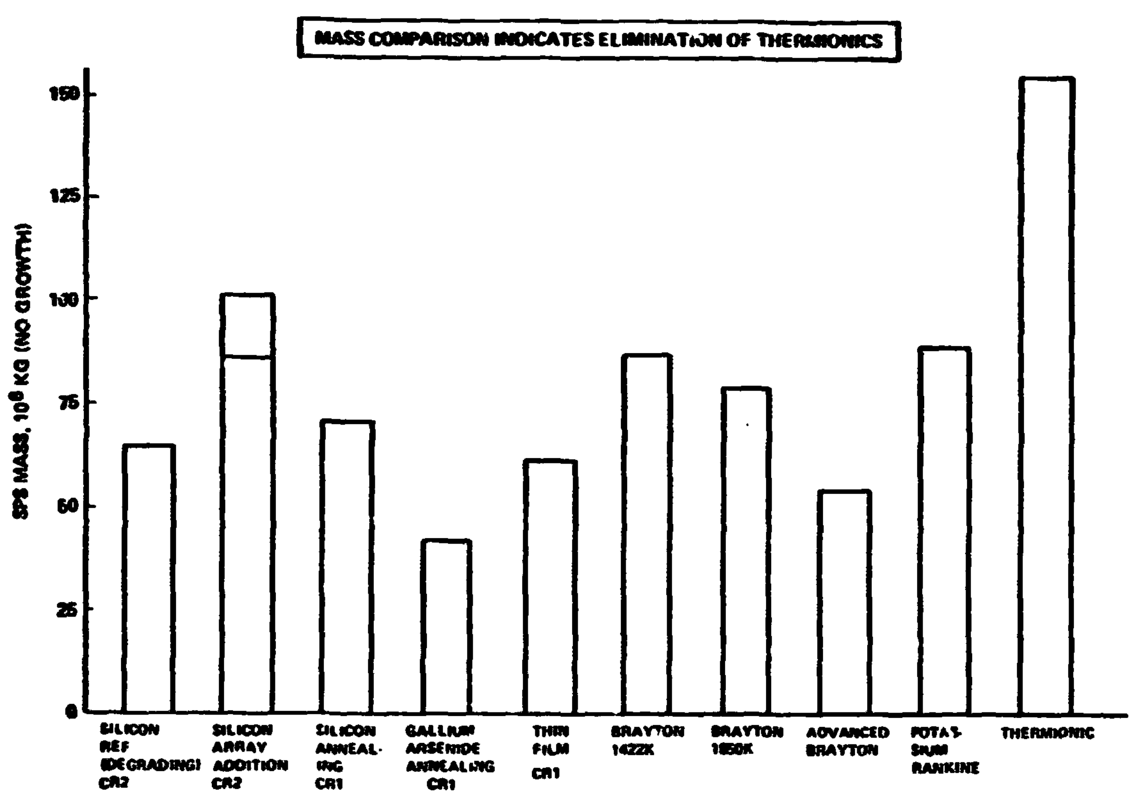

Figure 1-10. Energy Conversion Comparison SPS Mass

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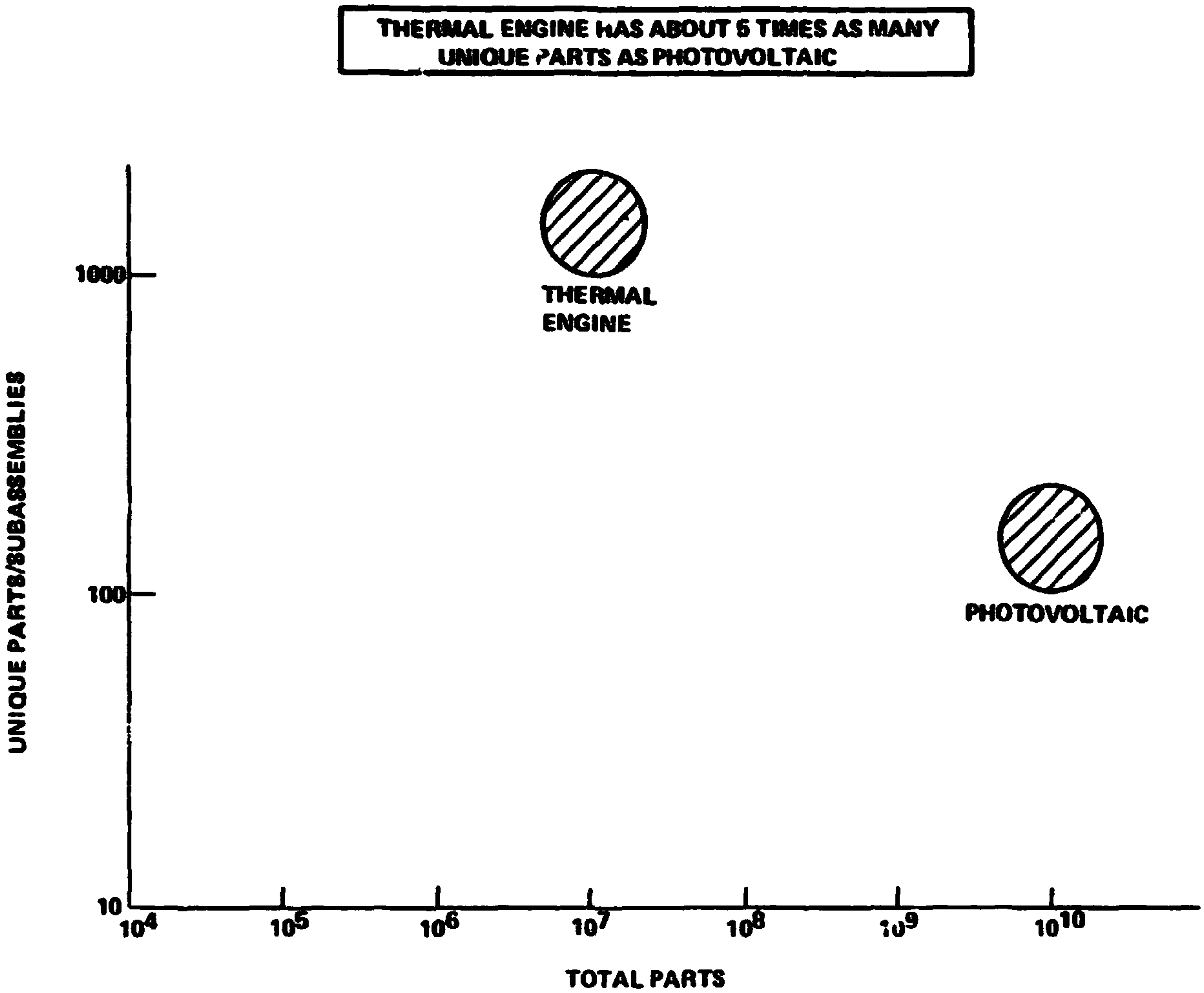


Figure 1-11. Energy Conversion Comparison System Complexity

Table 1-4. Energy Conversion Comparison Maintainability Factors

Photovoltaic	Thermal Engine
<u>Problem</u> Sensitivity of Solar Cell Strings to Cell Failures	<u>Problem</u> Reliability of NaK System
<u>Solution</u> Paralleling and Diode Shunting	<u>Solution</u> Technology Advancement Program or redesign to eliminate NaK
<u>Result</u> Equivalent maintenance load roughly 5 to 10 MH/H for annealing or array addition	<u>Result</u> Equivalent maintenance load roughly 10 MH/H for mechanical repair and replace

Construction Requirements—A constructability rating is shown in Figure 1-12 that involves a number of factors as developed by the construction analysis task. The LEO/GEO comparison is shown as well as the thermal engine and photovoltaic comparison. This is a weighted score comparison. The numbers in parenthesis are weighting factors; a long bar is good. A long bar means a smaller facility, less complexity, and a smaller crew size. It is a "goodness" rating and not a measure of the physical size or numbers of people. There is not a dramatic difference between the systems but some preference for the simpler photovoltaic, as expected because the system is less mechanically complex.

One of the reasons that the concentration ratio = 1 photovoltaic satellite is preferred is that it is simpler to construct. It avoids having to install the large flat V-ridge reflectors; that is a significant advantage.

Transportation Requirements—In transportation requirements, there was not a great deal of difference in the mass between the systems but the photovoltaic systems packaged to roughly 20 times the density of the thermal engine systems. Some difficulty was experienced in packaging the latter. We finally got down to a density compatible with the launch vehicle capability; further improvements appear possible. Most of the elements of the photovoltaic system can fold into a dense package. For the thermal system unless plumbing is produced in space or prefilled, there are limits on attainable packaging density.

Values shown in Figure 1-13 are an average but we achieved that average in actual packaging for each type. The size shown in the figure represents a volume large enough to contain the entire SPS as packaged for launch.

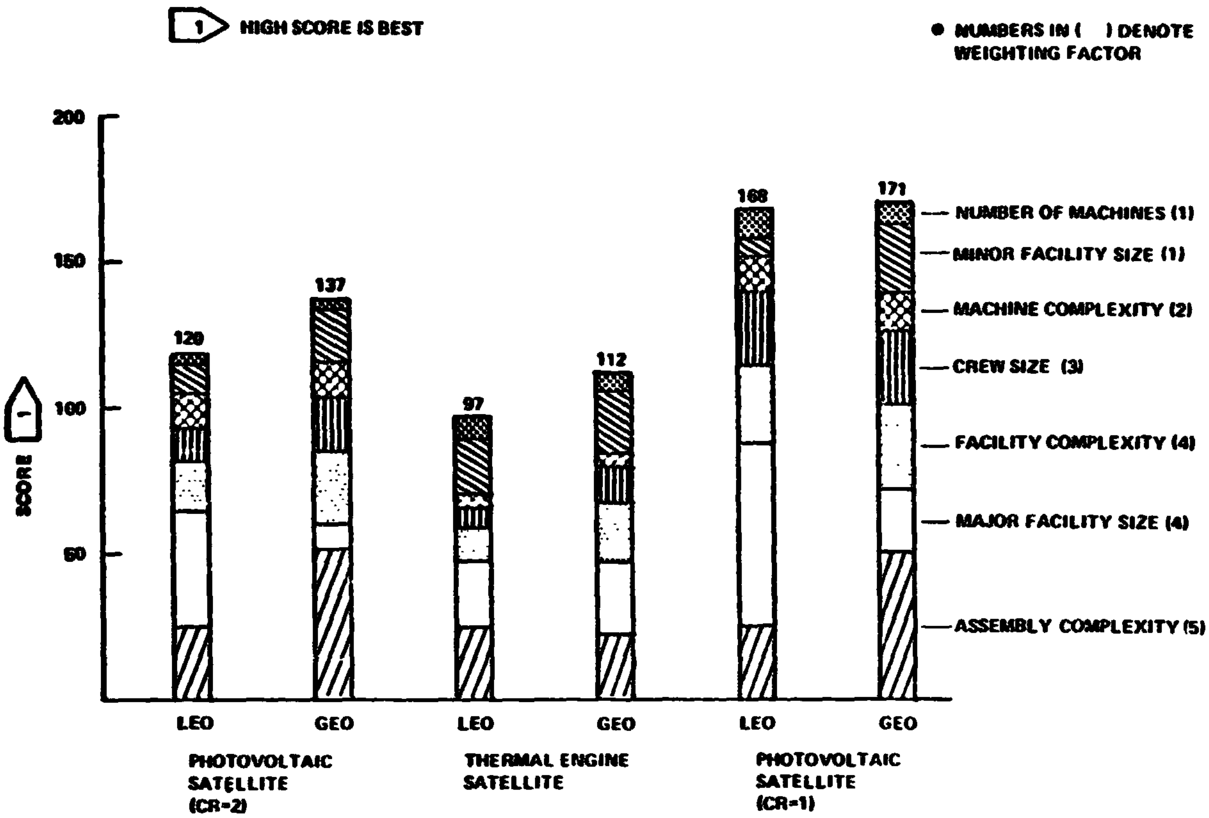


Figure 1-12. Preliminary Relative Constructability Rating

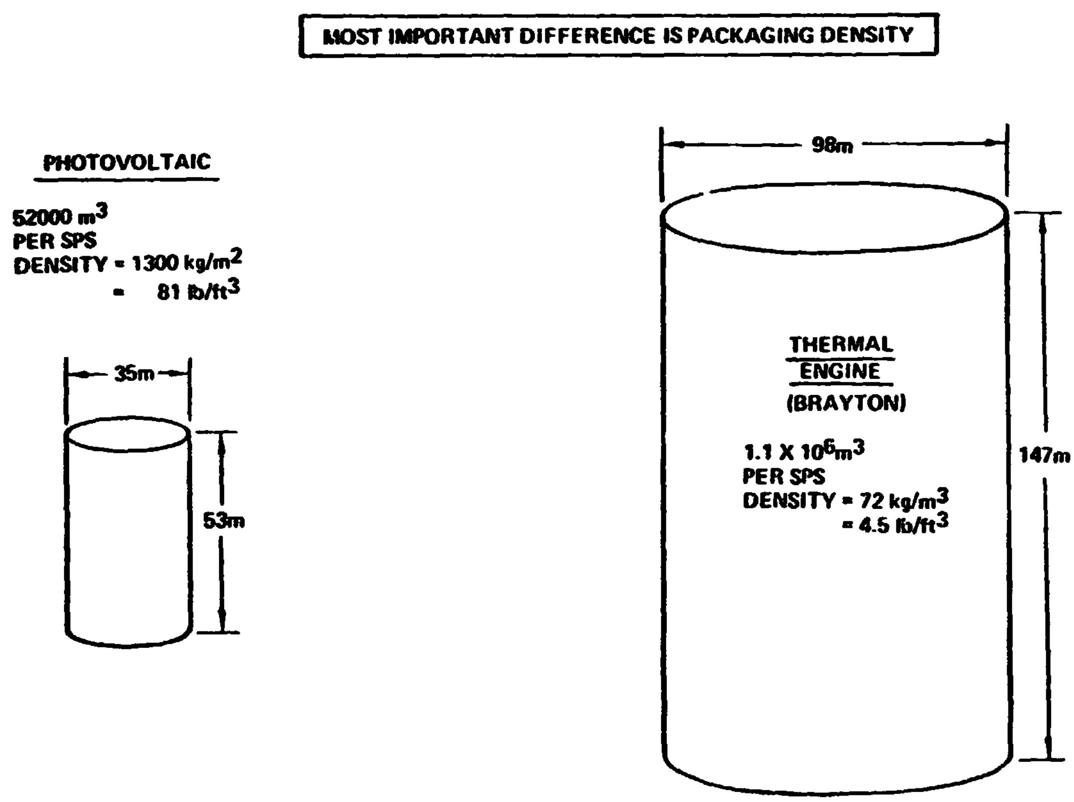


Figure 1-13. Energy Conversion Comparison Transportation Requirements

Technology Advancement Requirements—Technology advancement requirements listed in Table 1-5 are the most important ones. The Brayton thermal cycle requires the least technology advance. The silicon photovoltaic system is the next least. Continuous photovoltaic cell and blanket production is much more important than obtaining maximum possible efficiency. 14% solar cells made by continuous production processes would make the silicon system attractive. 18% cells made by today's processes would not yield an economically attractive system.

The other systems require more technology advance: Brayton and silicon are the least risky.

Environmental Effects Differential Factors—Environmental effects differences are summarized as follows:

- No significant environmental effects associated with energy conversion were found.
- The principal factor is launch vehicle emissions, which are proportional to SPS mass.
- A launch pad fire with gallium arsenide (arsenic) appears less of a toxicity problem than the hydrochloric acid effluent from shuttle SRB's.

Arsenic was specifically investigated. Launch accident cloud analyses indicate that concentrations get below allowable levels quickly. Further, this is not a routine condition, but an exceptional condition.

Materials Differential Factors—Materials factors are displayed on a very compressed logarithmic scale in Figure 1-14. We have picked five materials that are used in sufficient quantity in SPS systems to present potential concerns. The figure shows how many SPS's can be built per year with today's production rates and finally, how many SPS's total could be built with the total known reserves. Reserves are quantities available by today's recovery process at today's costs. Silicon is produced in large quantities for metallurgical reasons. The reserves are on the order of half the crust of the earth, so there is no supply problem.

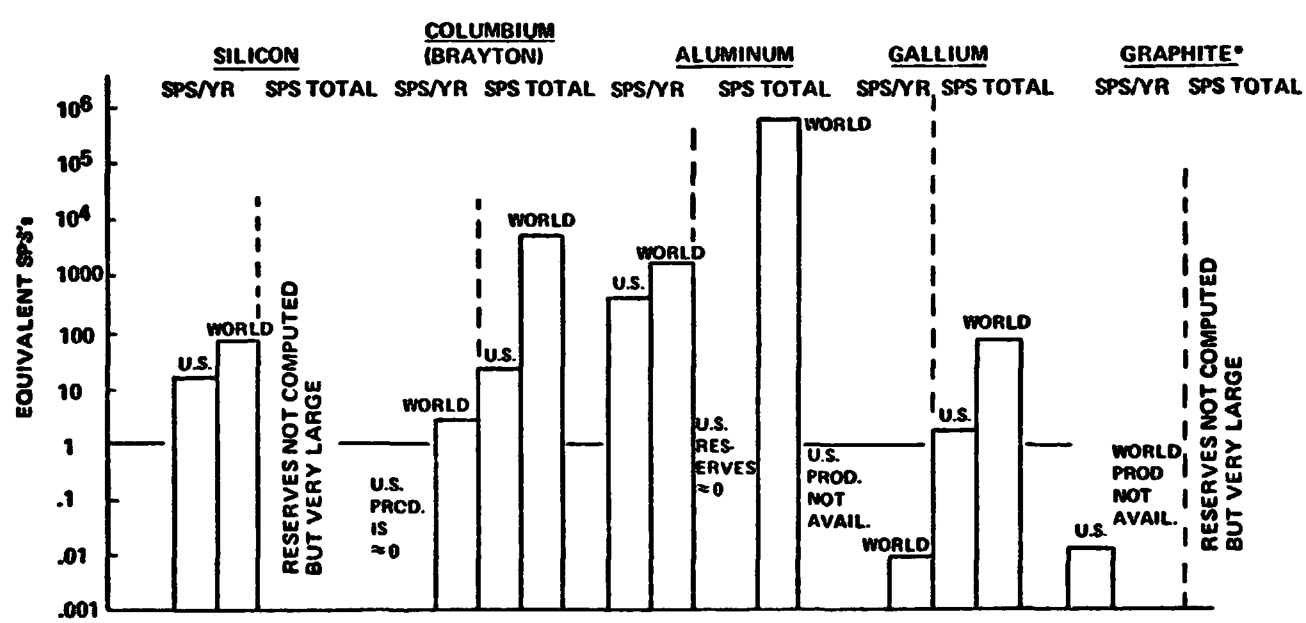
Presently the U.S. production of columbium is essentially zero. But the world production is sufficient to build several SPS's per year. The reserves in the United States are not large, but world reserves are adequate. Aluminum is no problem. Gallium was the only material indicating a potential problem. The assumptions are very important for gallium. We show 2,000 tons of gallium per SPS and no process improvement. There are known potentials for process improvements up to about a factor of 4. Gallium today is produced as a byproduct of aluminum production. The yield is about one-fourth of what it could be. Alcoa, for example, has stated that if more gallium is needed from aluminum, it could be obtained with more investment in recovery equipment. Gallium production rate may be more of a problem than total reserves.

Table 1-5. Energy Conversion: Technology Advancement Requirements

PHOTOVOLTAIC			THERMAL CYCLE		
SILICON	GALLIUM ARSENIDE	THIN-FILM	BRAYTON	RANKINE	THERMIONICS
CONTINUOUS CELL/BLANKET PRODUCTION PROCESS – ANNEALING	THIN-FILM GALLIUM ARSENIDE APPLICATION PROCESS – CONTINUOUS CELL/BLANKET PRODUCTION PROCESS – ANNEALING	THIN-FILM TECHNOLOGY – PRODUCTION PROCESSES	RELIABLE FLUID CONTAINMENT	HIGH TEMPERATURE METAL VAPOR TECHNOLOGY – RELIABLE FLUID CONTAINMENT	THERMIONIC DIODE TECHNOLOGY

CONCLUSION BRAYTON AND SILICON LEAST RISK

GALLIUM WAS ONLY IDENTIFIED MATERIALS AVAILABILITY PROBLEM. VALUES SHOWN ASSUME 2000 TONS GALLIUM PER SPS AND NO PRODUCTION PROCESS IMPROVEMENT



*GRAPHITE FIBER PRODUCERS ARE TOOLING UP FOR THOUSANDS OF TONS PER YEAR

Figure 1-14. Energy Conversion Comparison Materials Differential Factors

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Graphite today (graphite fibers of an Aerospace quality, not total graphite), is a small production item. But the producers are presently tooling up for very high production rates; graphite fiber is becoming a commercial product.

Energy Conversion Evaluation Summary—Four energy conversion options were found that make SPS look promising. Any one of them would work; they are not remarkably different in overall potential. Thermal engines are more complicated but require less technology advance. The photovoltaics require continuous production cell process development more than they need anything else. As will be shown in the cost summary, there is not much difference in production cost projections for the Silicon and Brayton systems Gallium arsenide looks slightly cheaper, but there is a huge uncertainty in the data.

We propose to concentrate on the silicon concentration ratio = 1 with annealing capability and Brayton systems. We propose gallium-arsenide as an advanced technology option, showing one way that the SPS system could grow to achieve potentially lower costs with technology improvement. There are certain things in the potassium Rankine system that need further evaluation, especially machinery mass properties.

A problem was experienced with thin films in that the data base was just not sufficient to draw definitive conclusions. Finally, we recommend rejecting two systems, specifically thermionics and steam Rankine. The recommendations stated apply to the Part II study and not necessarily to an SPS program. They relate to the fact that the study objectives are, in part, to minimize uncertainties in mass and cost.

Construction Location Evaluation—The statement of work specified the evaluation factors listed in Table 1-6 for construction location. The construction locations to be evaluated are low Earth orbit (LEO) and geosynchronous orbit (GEO). A significant proportion of the evaluation relates to selection of orbit-to-orbit transportation, because with LEO construction the satellite (or satellite modules) must be moved with low thrust to prevent structural failure. The power output from the modules can be used to operate an electric propulsion system for the transfer. With GEO construction the satellite hardware is not capable of self-powered transfer; conventional means must be used. For the purposes of this study reusable LO_2/LH_2 orbit transfer vehicles were baselined. In summary, LEO construction implies self-powered electric rocket transfer; GEO construction implies chemical vehicle transfer of HLLV-sized payloads to the GEO construction base.

Table 1-6. Construction Location Evaluation Factors

Evaluation Factor
a) Transportation Requirements
b) Construction Requirements
c) SPS Overall Design Requirements
d) SPS Performance and Degradation Potential
e) Launch Site Differential Effects
f) System Startup Requirements
g) Operations Considerations
h) Collision Considerations
i) System Cost Differential Factors
j) Orbital Transfer Complexity Factors

Transportation Requirements—The principal difference in transportation requirements between LEO and GEO construction location is the difference in total delivery to low Earth orbit, shown in Figure 1-15 in terms of numbers of HLLV launches. The difference results primarily from the differences in propellant required for the transfer due to the great difference in propulsion specific impulse, typically 5000 sec for electric rockets versus 470 seconds for LO_2/LH_2 chemical rockets.

Construction Requirements—Construction requirements in low Earth orbit involve several nuisance factors. As noted in Figure 1-16 atmosphere drag results in an average propellant consumption (to keep the construction facility orbit trimmed) of about 800 kilograms per day. The construction approaches that we have developed do not appear sensitive to light/dark cycling on crew productivity. For gravity gradient effects, the only practical thing to do is to select a stable attitude and construct in that attitude. One simply cannot afford to expend enough propellant to hold a non-stable attitude.

Thermal effects may have some influence on construction, but with low-coefficient-of-expansion graphite epoxy, (the baseline structure) that does not appear to be a strong consideration. There are similar thermal effects in geosynchronous orbit, although less frequent.

In geosynchronous orbit, radiation environment may be an issue if massive shielding is required. With the Apollo/Skylab crew radiation exposure standards, construction bases can provide most of the shielding required without mass penalties. The solar flare contribution can be avoided with a "storm cellar." If it is necessary to go to a lower level radiation standard, and add shielding, there is not much difference in the amount of shielding required, but there is quite a difference in the transportation cost (a one-time cost for each facility).

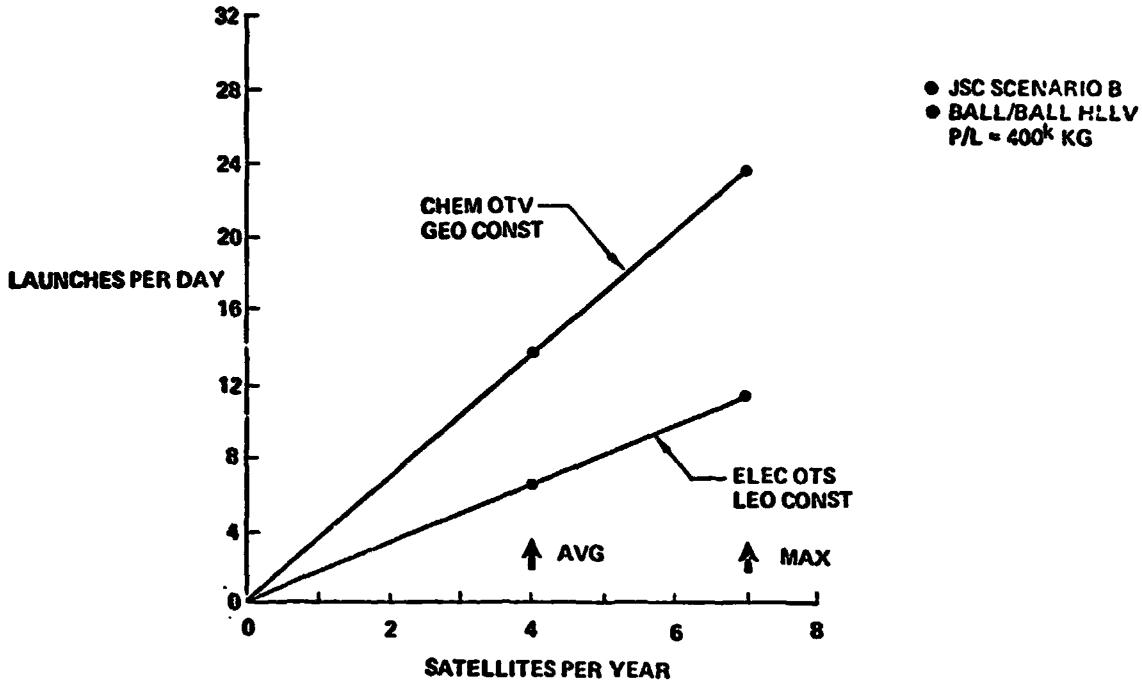

Figure 1-15. Construction Location Evaluation

SPS 810

LEO

- DRAG–AVERAGE PROPELLANT CONSUMPTION (O_2 - H_2) 700 TO 800 Kg /DAY TO KEEP ORBIT TRIMMED
- LIGHT/DARK – NOT A MAJOR PROBLEM WITH MECHANIZED CONSTRUCTION
- GRAVITY GRADIENT–CONSTRUCT IN STABLE ATTITUDE

GEO

- RADIATION ENVIRONMENT IS ISSUE IF MASSIVE SHIELDING REQUIRED
- CONSTRUCTION BASE LIKELY TO PROVIDE 5 TO 15 g/cm^2

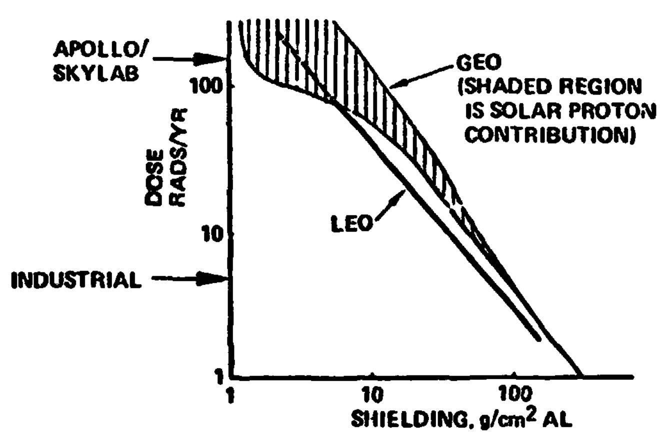

Figure 1-16. Construction Location Evaluation Construction Requirements

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SPS Design Requirements—A number of design requirements on the satellite were found for LEO construction. First is modularization, (which may be a blessing in disguise). The satellite must be modular, because otherwise it is not controllable during the orbit transfer. The photovoltaic system must have the capability to operate the proportion of the array used for electric propulsion at reduced voltage; and must incorporate additional power distribution provisions. Further required is the capability to accept propulsion installations and then provide for their removal at GEO. All of these were reflected as satellite impact costs as part of the LEO/GEO construction cost differential factors. In most cases, the costs were trivial, but these additional design requirements represent additional design complexities.

SPS Performance and Degradation Potential—An SPS module being transported from LEO to GEO must pass through the Van Allen trapped radiation belts. If the transfer is accomplished by a high-thrust system in a total time of roughly six hours the radiation dose received is minimal, even with the scantiest of shielding. Electric propelled transfers (low thrust), however, are likely to require 2 months to a year, and substantial doses will be received. (The electric-powered trip time can be varied over a wide range by selection of power level and specific impulse. Radiation degradation is a significant factor in trip time selection.)

Significant radiation degradation phenomena were identified for solar cells and for plastic film reflectors. Representative solar cell degradation data are shown in Figure 1-17 and plastic film reflector estimates are shown in Figure 1-18. Additional potential degradation concerns include plastic matrix composite structural materials; no data were found on radiation degradation of these materials.

As a design practice, the identified modes of degradation were compensated by oversizing or, in the case of solar cells, in certain cases by annealing. Consequently, radiation degradation effects were reflected in cost trades for LEO versus GEO construction.

Launch Site Differential Effects—The principal effect on launch site operations was due to the aforementioned difference in launch rates. This difference was also reflected in costs of providing facilities capable of supporting the requisite launch rates, with estimated values of 10.6 billion for LEO construction and 15.8 billion for GEO construction. These facilities would be incrementally procured over a period of years as the launch rate increased along with the rate of SPS capacity addition.

System Startup Requirements—Certain startup factors were identified that are unique to the LEO construction option:

SPS 762

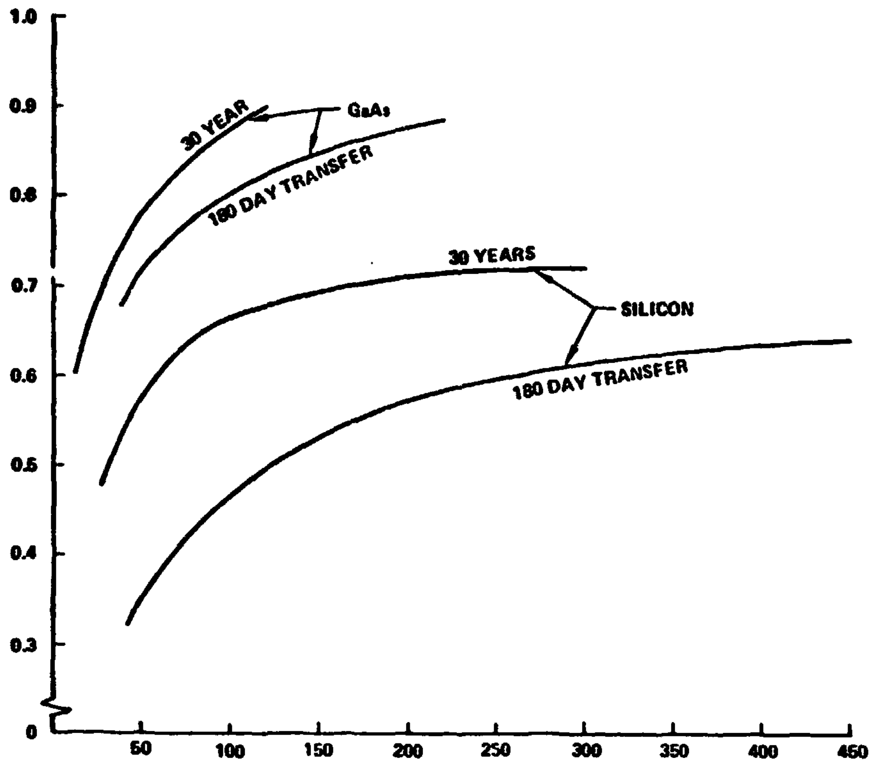

Figure 1-17. Photovoltaic Array Radiation Degradation Characteristics

SPS-627

- THUS ALL FACETS WILL BE INSTALLED AT LEO
- GEO-ASSEMBLED SPS IS LESS THAN 1% LIGHTER

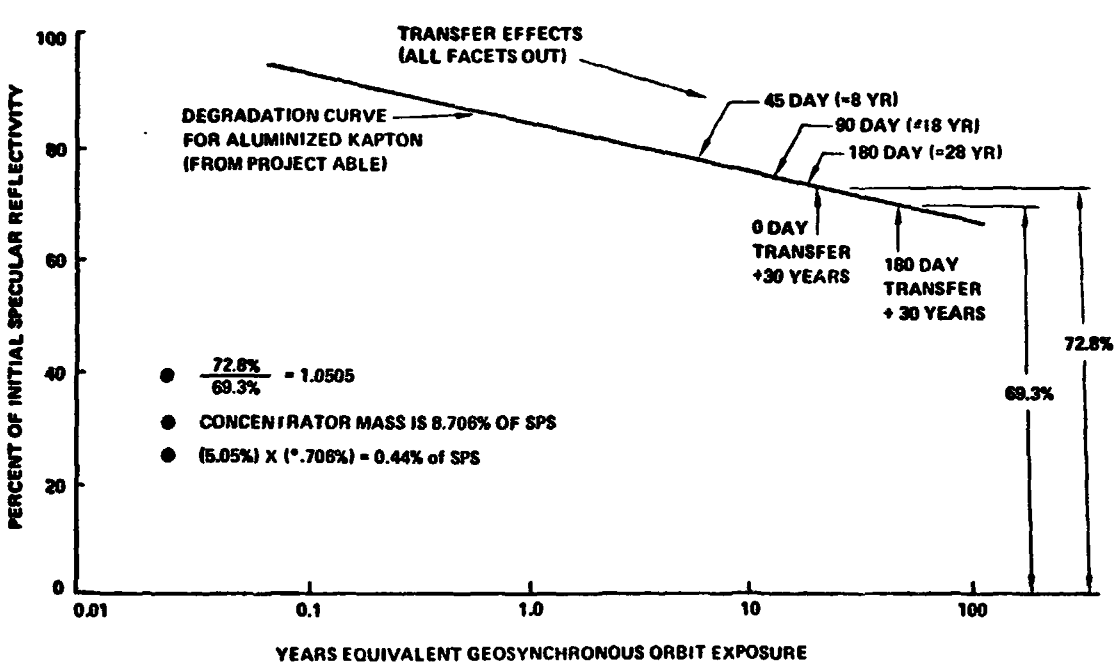

Figure 1-18. Self Power Transfer Has Little Oversizing Impact

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(1) The SPS modules must have chemical propulsion attitude control capability with sufficient control authority to establish a sun-pointing orientation to activate the power generation system. This capability is also required to successfully execute the orbit transfer, in view of frequent passage through the Earth's shadow.

(2) Orbit transfer simulations by the FSTSA study indicated that a typical 180-day transfer would experience 800 to 1000 occultations by the Earth's shadow. In GEO service the satellite will experience about 80 occultations per year.

(3) Satellite modules arriving at GEO must be joined together, whereas if constructed at GEO the satellite may be of a monolithic design, or if modular can be constructed with modules joined. One concept for module joining is illustrated in Figure 1-19. This concept is discussed in more detail in the body of the report.

Operations Considerations—No strong discriminators in operations were found. LEO construction has more distinct kinds of operations, notably chemical and electric orbit transfer operations (chemical for crew rotation and resupply at GEO) and SPS module assembly operations at GEO. The number of orbit transfer vehicles in flight at one time all requring control is about double for LEO construction, (32 vs 16 at an SPS addition rate of 4 per year) but the number of HLLV operations is less, as discussed above.

Collision Considerations—LEO construction operations result in an increased risk of collisions. The situation for the photovoltaic SPS is summarized in Figure 1-20. The collision analysis is described in the body of the report.

System Cost Differential Factors—These are discussed in conjunction with energy conversion cost differentials. LEO construction consistently shows lower overall cost as a result of reduced cost for Earth-to-orbit transportation.

Orbit Transfer Complexity—The self-powered operations associated with LEO construction are more complex as regards propulsion systems, flight control, guidance and navigation, and software. Orbit transfer systems are discussed in some depth in the body of the report.

Figure 1-21 summarizes the construction location evaluation. A bullet shows the preferred option for each evaluation factor. There are 6 bullets for GEO and 3 for LEO which indicates GEO construction. However, the cost of LEO construction has consistently been found to be cheaper than GEO. Either option is workable. LEO is cheaper, but more complex. In a commercial environment costs will eventually drive the decision. Much more interesting is the question, not where satellite number 10 or 50 will be built but where will the first one be built. The conclusions of our analysis may not apply to this question. The recommendations in the Figure are aimed at reducing sensitivity of the continuing analysis to the LEO vs GEO issue.

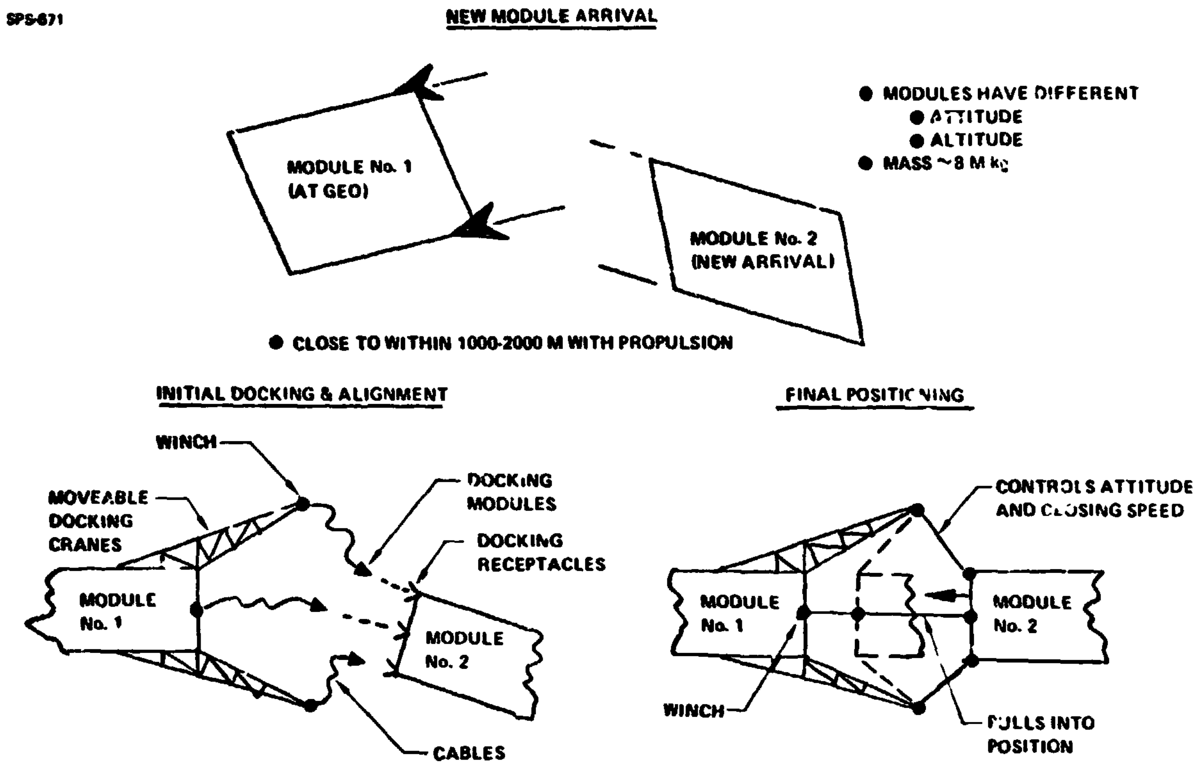
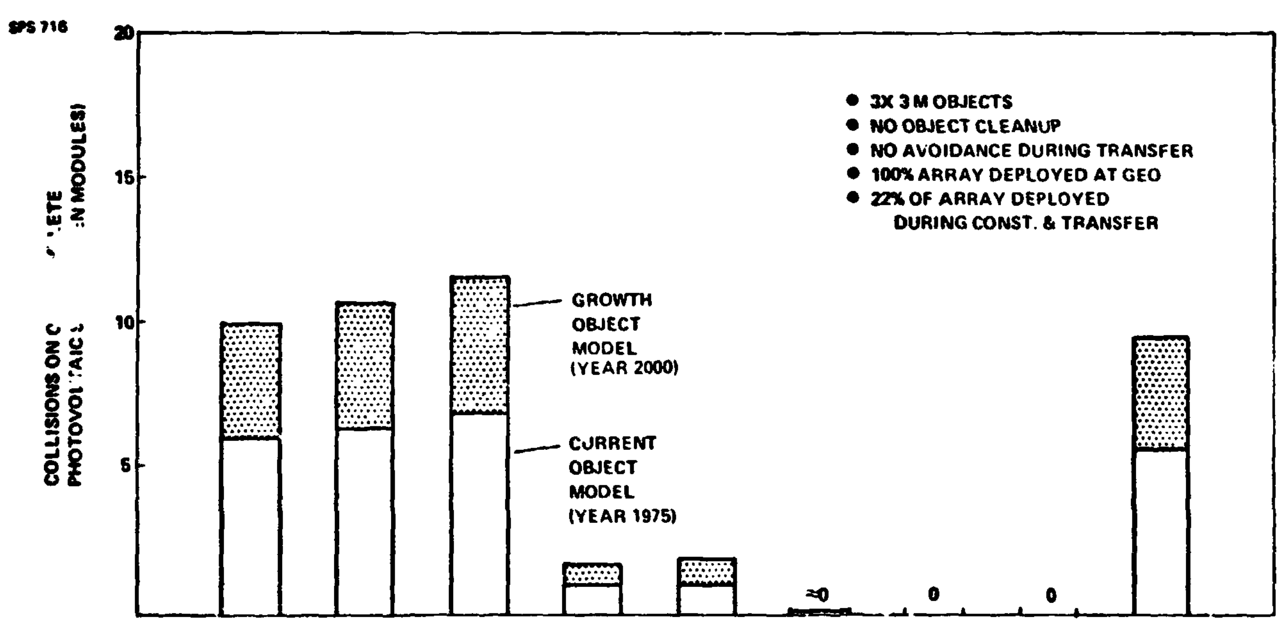


Figure 1-19. Satellite Module Docking at GEO



REGION (KM)	CONSTRUCTION 500	500 TO 1000	1000 TO 2000	2000 TO 3000	3000 TO 5000	5000 TO 10 000	10 000 TO 20 000	20 000 TO 35 786	GEO OPS
TIME IN REGION (DAYS)	22.5	14.8	22.2	17.0	22.3	29.9	34.2	39.6	10,950

Figure 1-20. Number of Collisions

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For a development program, these kinds of questions are important:

- When must manned GEO operations begin?
- What are relative transportation costs with developmental Earth launch system (e.g., shuttle-derived HLLV)?
- Can the developmental SPS configuration (such as 1-GW module) be transferred to GEO with transmitter installed or stowed?
- Can the developmental SPS configuration survive the transfer radiation environment?
- What is the program funding vs time comparison?

Program funding versus time is always an important factor in development decisions. For LEO construction, electric propulsion must be developed, while for GEO, more investment may be needed in space stations and in earlier manned GEO operations.

Cost Differential Factors—This discussion begins with energy payback considerations. Solar cells are very energy intensive. Presented in Figure 1-22 are energy costs in kilowatt hours per kilogram of cells. The energy payback for solar cells as a function of this energy cost is also shown on two scales. These scales show SPS and ground applications. Pricing the energy at 40 mills per kilowatt hour, the actual cost of the energy is shown on the outside scale.

The main reason today's cells are so intensive is that yields are very poor. Most of the silicon, in which a great deal of energy is invested, ends up as waste (saw filings and grindings). Continuous processes can probably reach a yield range of 60% to 80% making the payback very attractive. Energy cost is a basic factor in the cost of solar cells, like materials cost in building hardware. If the energy cost is below 10¢/watt one might be reasonably confident that cells in the 20¢/watt range, made by a continuous production process, would be possible.

Why is energy cost important? The reason is that energy payback time is economically significant. Typical economics equations used, for example, by Caputo and Truscello in the JPL report, predict the cost of energy from an energy system. One can close the loop in these equations by setting the capital cost of the energy invested in the system equal to the capital cost of energy that the system produces. In other words one does not borrow from a cheap energy system to create an expensive energy system. With typical economic factors, energy payback less than about 8 years is essential. Otherwise, energy cost will spiral upward ever more rapidly, as indicated in Figure 1-23. With continuous production processes for solar cells (or with thermal engines), SPS payback (for the total system) is 1½ to 3 years where this curve is not very steep. With its short payback, SPS should have economic advantages when the system technology is mature.

EVALUATION FACTOR	PREFERRED CONSTRUCTION LOCATION: LEO	GEO	DECISION DRIVER
a) TRANSPORTATION REQUIREMENTS	●		LEO REQUIRES LESS FLIGHTS AND LESS ON-ORBIT PROPELLANT TRANSFER
b) CONSTRUCTION REQUIREMENTS	NO SELECTION		*LEO DRAG & DARK PERIODS VS. GEO RADIATION & DISTANCE
c) SPS OVERALL DESIGN REQUIREMENTS		●	LEO REQUIRES MODULARIZATION & OTHER SPECIALIZATION
d) SPS PERFORMANCE AND DEGRADATION POTENTIAL		●	DEGRADATION DUE TO VAN ALLEN RADIATION CAN BE COMPENSATED
e) LAUNCH SITE DIFFERENTIAL EFFECTS	●		FEWER LAUNCHES FOR LEO
f) SYSTEM STARTUP REQUIREMENTS		●	LEO STARTUP MORE COMPLEX
g) OPERATIONS CONSIDERATIONS		●	LEO HAS MORE DISTINCT KINDS OF OPERATIONS
h) COLLISION CONSIDERATIONS		●	ABOUT 15 COLLISIONS/SPS FOR LEO VS 2 FOR GEO
i) SYSTEM COST DIFFERENTIAL FACTORS	●		LEO ABOUT 25% CHEAPER OVERALL TRANSPORTATION
j) ORBITAL TRANSFER COMPLEXITY FACTORS		●	ELECTRIC PROPULSION (LEO) MORE COMPLEX

HIGHLIGHTS

- EITHER LEO OR GEO CONSTRUCTION IS A VIABLE OPTION
- LEO IS LOWER COST BUT MORE COMPLEX FLIGHT CONTROL; PROPULSION
- IN A COMMERCIAL ENVIRONMENT COST WILL DRIVE THE DECISION
- INITIAL DECISIONS DEPENDENT ON DEVELOPMENT PROGRAM

RECOMMENDATIONS

- NO CLEAR ANSWER—BOTH MODES PROBABLY HAVE THEIR PLACE
- DEFER DECISION UNTIL PROGRAM EVOLUTION MORE CLEAR
- SELECT MODULAR SPS FOR CONSTRUCTION BASE ANALYSIS

Figure 1-21. Construction Location Evaluation Summary

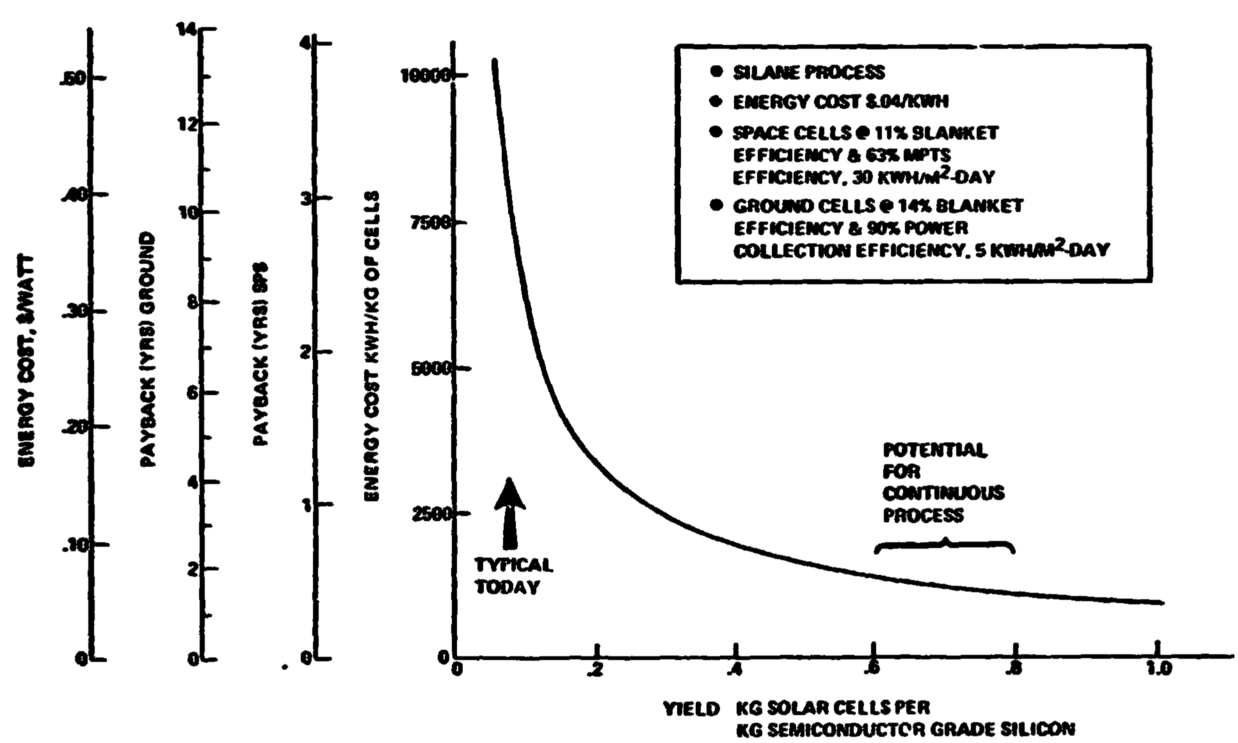

Figure 1-22. Energy Costs and Payback for Silicon Solar Cells

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Cost differential factors reflect cost impacts of all the evaluation factors. The data shown in Figure 1-24 are for a 112-SPS program, for our preferred SPS designs. The number 1 unit SPS will be a significantly higher cost than the program average. Also, note that there are some things that were not costed in Part I. Our ROM estimate of the range for the uncosted items is shown.

We did the costing in two ways. First was in a mature industry fashion, a projection of things in a commercial environment with high quantities of mass production. The second method was aerospace cost prediction techniques, using our parametric cost model. For satellite production, the mature industry projection and the higher aerospace prediction are shown. Transportation costs used only the aerospace methods. The results were mature industry system costs trending to less than $2,000 a kilowatt for the 112-SPS. No significant differences were seen between the silicon photovoltaic and Brayton thermal engine. Typical LEO versus GEO differences are also shown.

Shown in Figure 1-25 are two alternate systems costs to provide an idea of cost ranges. The silicon array addition system is more massive than the annealable system and suffers a significant satellite impact if constructed in LEO. The gallium arsenide system costs are a rough-order-of-magnitude projection because of the relatively great technology extrapolation. Because it is low in mass, very low potential costs are projected for the future. We did not know how to estimate an uncertainty. Also in the gallium arsenide case, the LEO-GEO difference is less, because the satellite is low in mass and the transportation cost contribution is less significant.

Transportation Evaluation Summary--The results of the transportation add-on task are summarized in Figure 1-26.

Two Earth launch options were analyzed: (2) A ballistic, two-stage sea recovery vehicle with a retractable payload shroud that was 100% recoverable. (2) A two-stage wing-wing vehicle that was also 100% recoverable. No significant differences were found in cost per flight or performance. For the ballistic system the main technical concern is sea recovery. It appears feasible, but there is not much data base. For the winged system, the lowest achievable payload density is considerably higher. There are concerns about launch and recovery siting because the booster is a down range lander and a suitable place to launch must have a down range recovery site. The wing-wing vehicle also has a somewhat higher DDT&E cost.

Orbit transfer options included a space-based and a ground-based OTV, and self-power. Self-power lessens transportation costs about 25%. The space based OTV showed 15% better performance than the ground based OTV. The space-based orbit transfer vehicle requires on-orbit propellant transfer but based on work done by General Dynamics, it appears possible to transfer the propellant without rotating the staging base. It may be sufficient merely to rotate the propellant by using electric pumps to withdraw the propellant and inject it into the OTV tanks in such a way that a rotation is set up within the tanks.

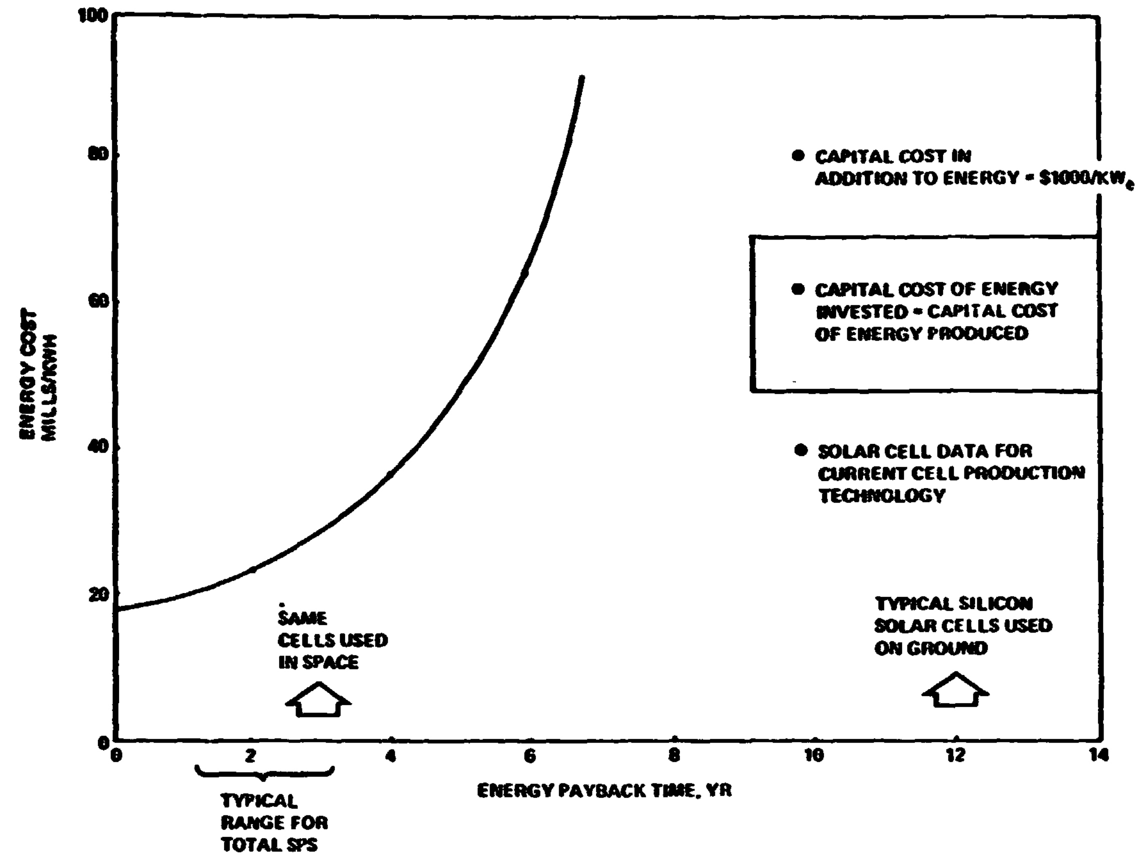

Figure 1-23. Energy Payback Time Is Significant!

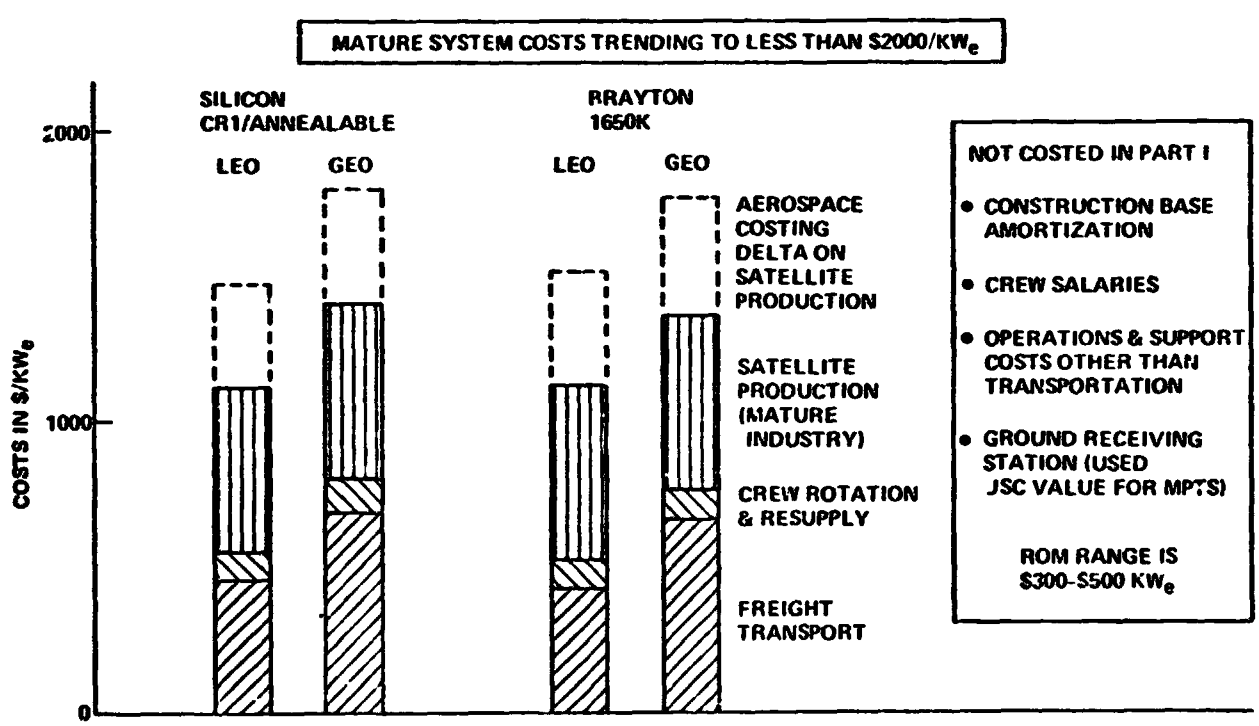

Figure 1-24. Cost Differential Factors Recommended Reference Systems (112 SPS Program)

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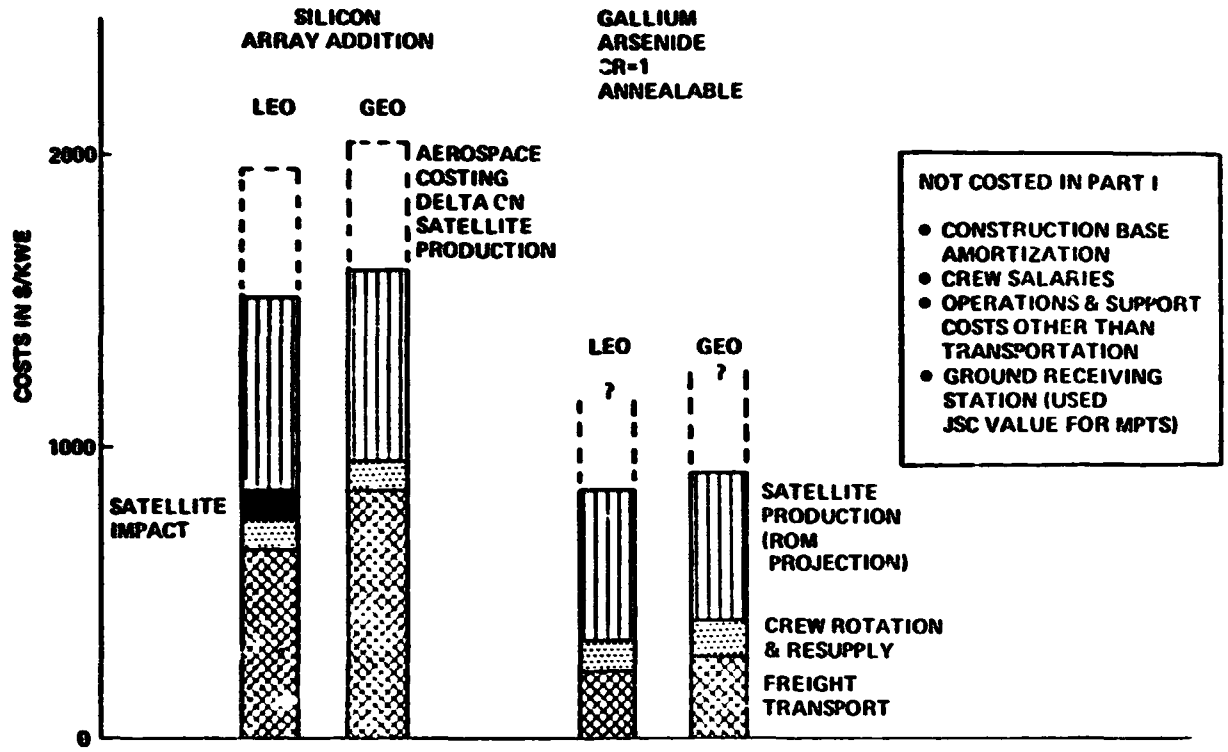

Figure 1-25. Cost Differential Factors (112 SPS Program)

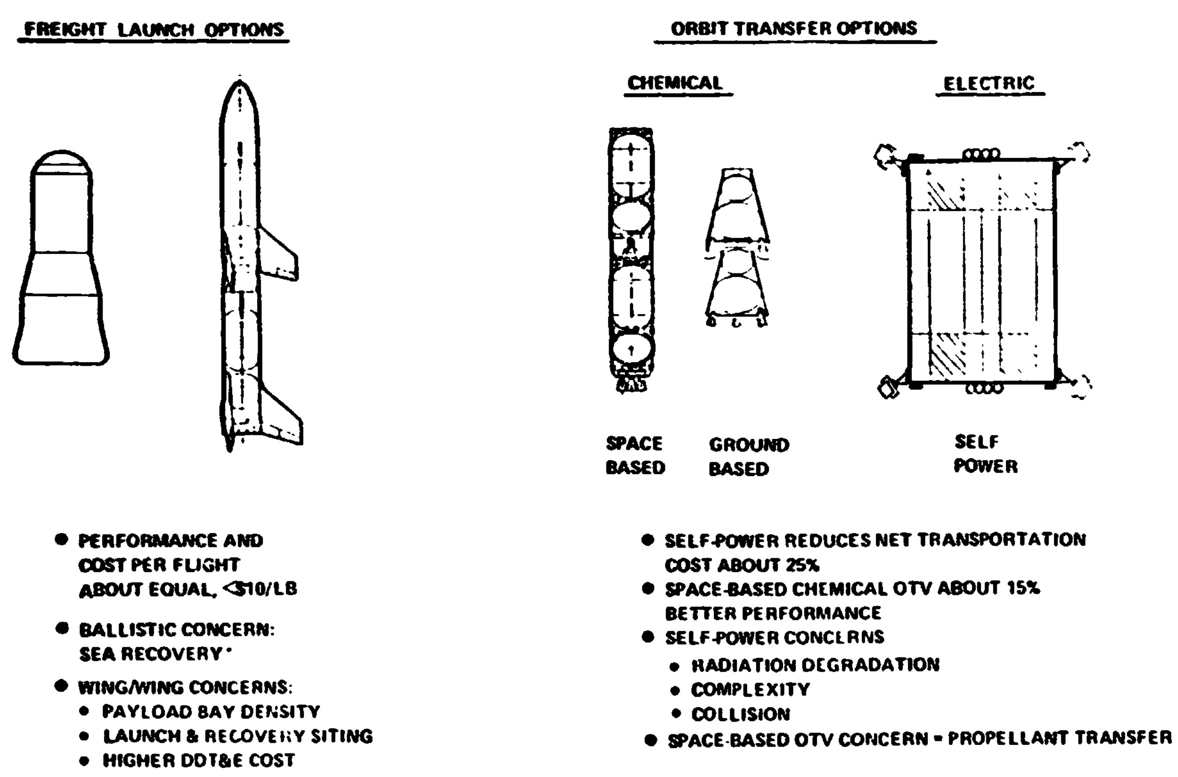

Figure 1-26. Transportation Evaluation Summary