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Program Assessment Report Statement of Findings

Satellite Power Systems
Concept Development and
Evaluation Program

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DOE/NASA

SATELLITE POWER SYSTEM
Concept Development
and
Evaluation Program

CONTENTS

FIGURES

TABLES

TABLES (Cont'd)

PREFACE

This report states what is known, uncertain, and unknown about the Solar Power Satellite (SPS) concept--collecting solar energy in space and delivering the energy to Earth for the production of baseload electricity.

This report fulfills the objective of the Satellite Power System Concept Development and Evaluation Program (CDEP) "to develop, by the end of 1980, an initial understanding of the technical feasibility, the economic practicality, and the social and environmental acceptability of the SPS concept."

This report discusses the important technical, environmental, and cost goal questions that must be answered prior to making a commitment to the SPS concept. Although significant technological, environmental and economic questions remain to be answered, the preliminary investigations undertaken in the CDEP do provide a basis for a policy decision on further commitment.

This report also suggests areas of research and experimentation required to acquire the knowledge by which a series of informed, time-phased decisions may be made concerning the possibility of the SPS concept playing a major role in the United States' energy future.

DISCUSSION

Systems Definition

For the past 20 years, photovoltaic energy conversion systems in space have powered communication, earth resource, and meteorological satellites, planetary probes and manned spacecraft. During this period, the remote transmission of power by means of microwaves was demonstrated. In 1968, the two ideas were brought together in the SPS concept. Since then, the SPS concept has been examined more thoroughly by the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE), academia, and industry. In 1976, on the basis that the SPS is an energy option, the Office of Management and Budget (OMB) assigned the responsibility for the evaluation of the SPS to the Energy Research and Development Administration (ERDA), the predecessor of DOE. In 1977, DOE and NASA started a three-year Concept Development and Evaluation Program.

The CDEP was implemented because the SPS concept appeared to have the following attributes that would be desirable in any future energy option:

- The SPS could provide continuous baseload electricity.
- The SPS would use an inexhaustible energy source--the Sun.
- The SPS is international in scope, capable of providing energy for domestic and world markets.

The SPS Reference System was designed to serve as a mechanism to assess the environmental and social aspects of the concept and to provide a basis for comparison with alternative concepts. Technologically, it does not represent an optimal or preferred system. System definition studies of plausible alternatives to the SPS Reference System would be required to arrive at a preferred system. Such activity could, if pursued, be linked to current DOE and NASA generic research in fields of energy conversion, space transportation, structures and materials, and space construction. Areas of research specific to an SPS preferred system would include microwave power generation, transmission, control and reception; space-to-earth laser power transmission and reception; and research associated with large-size and long-life components and subsystems.

Environmental and Social Acceptability

There are important questions about the environmental and social implications of the SPS energy concept that must be answered more definitively than is now possible if SPS is to be perceived as an acceptable energy option for the future:

- What is the quantitative risk and associated confidence that long-term exposure to low-level microwave energy (nonionizing radiation) will produce neither immediate nor lasting undesirable public health or ecological effects if a preferred SPS design is based on microwave power transmission from space to Earth?

- How much protection is needed from ionizing radiation and other hostile characteristics of space, and what is the best way to provide it? Are safe travel, adequate productivity, worker efficiency, health and safety, and amenities possible in human-occupied transportation and working and living environments in space? If not, are robotics a practical alternative in space?

- Is it possible to attain acceptable limits on contiguous land needs for microwave-based SPS ground receiving stations, consistent with desired electric power delivery levels?

- What limits must be placed on mass and energy inputs by the effluents of the space transportation systems and on electromagnetic emissions in the atmosphere to ensure that (1) telecommunications systems using this medium would not be adversely affected, and (2) the medium itself would not be altered to the extent that global weather and climate and the use of space would be adversely affected?

- What is the quantitative range of incompatibility between the SPS and scientific interest in space, such as astronomy, and what is the best combination of available ameliorative measures for achieving compatibility?

- Regardless of whether the SPS would be a solely domestic energy venture or international in scope, what is the best approach and timing for establishing necessary institutional arrangements (e.g., frequency assignment and geostationary orbit allocation, ground receiving station siting approvals, electric power and electric rate regulation, etc.)?

Although the scope of CDEP fell short of producing answers to these questions, efforts were made to develop research approaches with the objective of providing responsible answers if a further commitment were made for this purpose.

Economic Practicality

Because of the conceptual status of the SPS technology, there is uncertainty with respect to both costs of research and development and costs of commercial deployment. Nevertheless, these costs have been estimated. Estimates of R&D and industrial infrastructure costs are as much as $100 billion. Although it can be argued that costs of developing other technologies have run on the order of tens of billions of dollars and that some of the cost for the SPS might be shared or attributed to other national objectives, a decision on further commitment to the SPS concept must deal with the magnitude of this front-end expenditure for an alternative electric power producer. The capital costs of a commercial SPS system would be higher and more uncertain than those of conventional electrical power systems (including the liquid metal fast breeder reactor). However, the range of SPS generating costs are similar to those of the other renewable technologies vying for commercialization in the post-2000 period (controlled fusion, photovoltaics).

SCOPE

The U.S. Department of Energy and the National Aeronautics and Space Administration conducted a broad assessment of the Solar Power Satellite.[1] A Reference System was defined,[2] and an assessment of the key environmental, societal, and comparative issues was conducted. This report provides a statement of findings emphasizing what is known and what is still uncertain about the SPS concept and associated issues. Only key issues are discussed in detail. For detailed discussions of the findings, the reader is referred to summary assessment reports in the following areas:

- Environmental Assessment[3]
- Societal Assessment[4]
- Comparative Assessment[5]
- Systems Definition Assessment[6]

In the areas of uncertainty, means for resolution are suggested. A history of the Satellite Power System Program is outlined in Appendix A, a description of the Concept Development and Evaluation Program process is given in Appendix B, the Reference System is described in Appendix C, and the references are listed in Appendix D.

1 INTRODUCTION

1.1 POTENTIAL OF SOLAR ENERGY IN SPACE

Solar energy in space is continuous but diffuse and, accordingly, is of low power density; i.e., the amount of energy falling on a unit area is relatively low. The challenge in using solar energy from space lies in collecting this diffuse energy, transporting it to Earth, and delivering it to the user. The Solar Power Satellite (SPS) is one concept that provides a means for doing this.

1.2 GENERAL SPS CONCEPT

The SPS concept utilizes a system of satellites in Earth orbits in nearly continuous sunlight. The satellites collect solar energy and convert it to a form that can be transmitted to Earth. Earth receiving systems collect the transmitted energy and convert it to electricity for distribution in utility networks. Within the concept, a range of technological alternatives is available to achieve this objective. The CDEP Satellite Power System Reference System is only one of several possible conceptual designs of an SPS.

1.3 CONCEPT POTENTIAL

Inherent in the SPS concept are the following benefits:

- The source of energy is inexhaustible.
- The SPS could provide baseload power.
- Because the SPS is based on principles substantially different from those of other post-2000 energy technologies, it could provide a new energy option in the portfolio of electric energy.
- Energy could be available to international markets.
- Space technologies and capabilities could be applied to a national need.

1.4 CDEP OBJECTIVES AND QUESTIONS

As stated by DOE in the policy statement of October, 1977, the objectives and likely outcome of the CDEP are:

"To develop, by the end of 1980, an initial understanding of the technical feasibility, economic practicality, and the social and environmental acceptability of the SPS concept...It must be realized that this effort is unlikely to achieve a firm recommendation to implement the SPS concept. Rather, if no insurmountable barriers are found, one would expect recommendations concerning the direction of the SPS program after fiscal year 1980 toward further laboratory experimentation and field testing. It is conceivable that some space testing recommendations as a companion to the [space] shuttle program might result. On the other hand, a recommendation based on identification of a major barrier might be to discontinue further research and development."

The questions associated with the SPS that have been addressed in the CDEP assessment include:

- Technical possibility--Is the research and development base sufficiently solid to define the level of risk involved in proceeding with additional effort?
- Economic viability--What are the estimated costs of providing the R&D and infrastructure necessary for commercial deployment? What are the ranges of uncertainty in ultimate capital and power generating costs of the system, and how do these compare with other systems that might be

deployed in the same time frame as the SPS?

• Environmental acceptability--What are the risks associated with the use of microwave radiation in power transmission to both man and his environment and of ionizing radiations and other characteristics of space to which systems and maintenance personnel will be exposed? What limits must be placed on system emissions in the atmosphere to ensure that there are no effects on telecommunications, weather and climate? How compatible will the system be with the interests of astronomers?

• Social acceptability--How will society perceive the risks and benefits of the system? Will the possible availability of an additional electric power option in the next century be sufficient incentive to bear the front-end and deployment costs of the system, as well as potential environmental risks? What are the contiguous land needs of the system?

2 SPS SYSTEM CONCEPTS

The SPS concept was proposed by Dr. Peter Glaser in 1968.[7] The concept is illustrated in Figure 2.1. Because each satellite would be in geostationary orbit, it would remain stationary relative to its receiving antenna on the ground. In this orbit, each satellite would be illuminated by sunlight over 99% of the time.

Combinations of SPS energy conversion and power transmission systems were studied (Refs. 6 and 8-17) to evaluate technologies and approaches that would have significant effects on satellite size and weight, the environment, land use, and system costs. The technologies considered include photovoltaic and thermal energy conversion systems, tube-type and solid state microwave power transmission systems, and laser power transmission systems. In addition, options for the space transportation systems were studied.

2.1 SPS REFERENCE SYSTEM

An SPS Reference System was defined for the purpose of conducting environmental and societal assessments, comparing the SPS with other energy technologies, evaluating alternative SPS concepts, and identifying technology needs.[2]

In the Reference System configuration, a solar-cell array is used to convert sunlight to electricity, klystron tube-type amplifiers generate microwave energy, and a microwave beam transmits the power to Earth. With

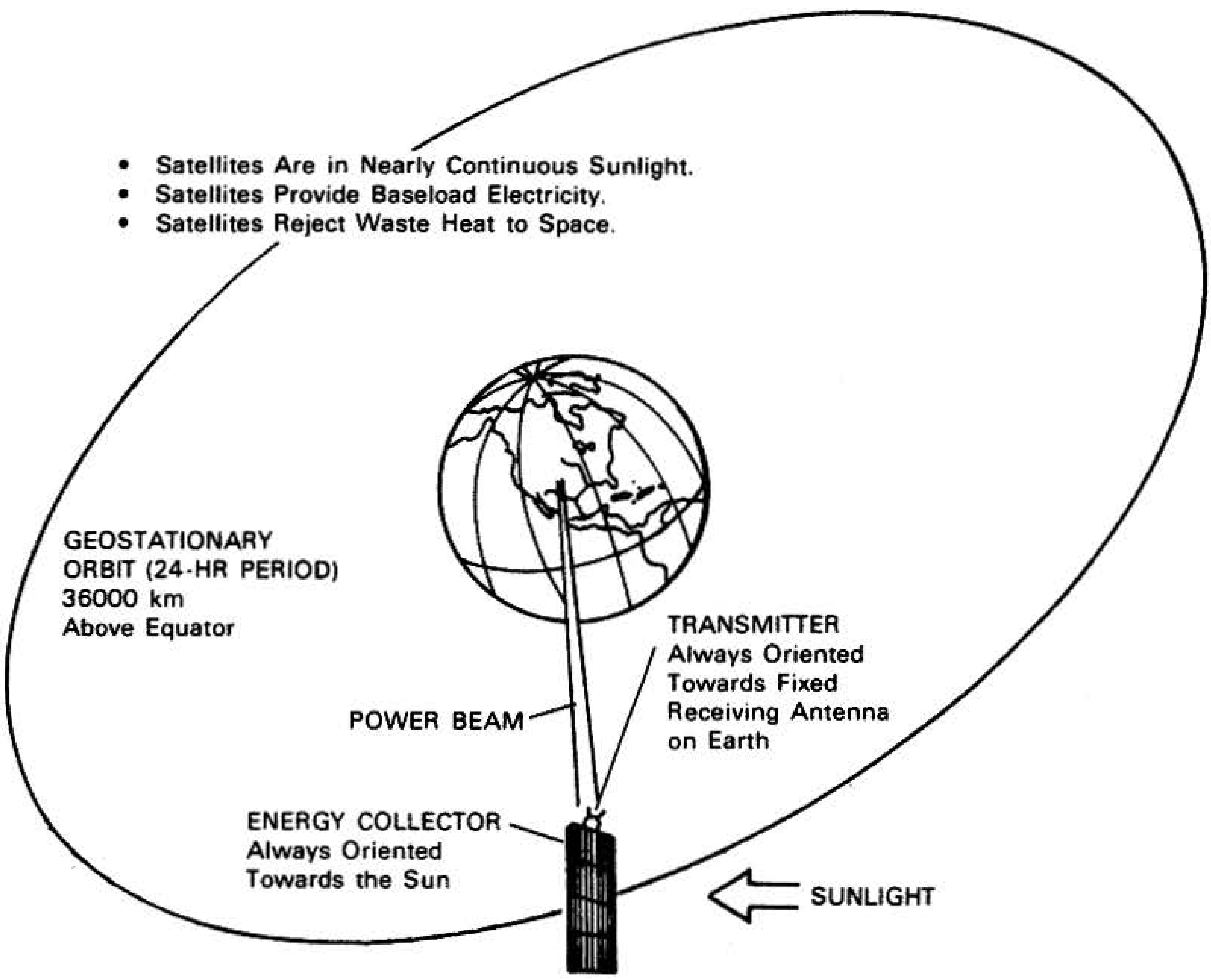

Figure 2.1 Satellite Power System Concept

solar-cell array dimensions of 5 x 10 x 0.5 km, the system delivers 5 GW of power to the utility grid. The receiving antenna (rectenna) on the ground is elliptical in planform, with typical dimensions of approximately 10 x 13 km at 35° latitude and with an additional exclusion zone of about 1 km around the periphery. At Earth, the power density of the beam is 23 mW/cm^2 on the beam center line and decreases to 0.1 mW/cm^2 at the fence line of the exclusion zone. The microwave frequency is 2.45 GHz. The rectenna design permits passage of about 80% of this sunlight, which may allow multiple use (e.g., agricultural) of the rectenna site.

The satellite is constructed in geostationary Earth orbit (GEO). The materials and personnel required for construction are transported to orbit by electrical or chemical propulsion vehicles, respectively. Largely automated operations are envisioned for satellite construction.

The SPS Reference System characteristics are summarized in Appendix C. A summary of the alternative approaches and their contribution to the SPS concept is presented in the following section.

2.2 SPS ALTERNATIVE SYSTEM CONCEPTS

A number of SPS system alternatives have emerged that could significantly affect the SPS concept in terms of:

- Technical approach and viability,
- Flexibility in selecting the level of power delivered to Earth,
- Land requirements,
- Environmental effects, and
- Cost.

These are discussed in the following paragraphs.

Because a number of options for practicable systems exist, the SPS is not dependent on the successful development of any one technology. For example, as indicated in Figure 2.2a, the Reference System photovoltaic energy conversion may employ silicon or gallium arsenide solar cells. Silicon has the advantage of operational experience, while gallium arsenide has the potential for providing a significantly lighter system. In addition, there are a number of promising solar-cell concepts (e.g., multiband gap and amorphous silicon cells) that have the potential for higher efficiency and/or lower cost than the Reference System solar cells.

As an alternative to photovoltaics, solar thermal energy conversion systems (Figure 2.2b) such as Brayton and Rankine cycles appear competitive in terms of system mass and cost. Unlike photovoltaic systems, this type of system is relatively insensitive to radiation effects during long-term exposure in space. In addition, the number of turbine-generator units required for each SPS is relatively small (40-200). However, this provides less redundancy than exists with photovoltaic conversion. Also, construction and maintenance operations in space appear to be more complex for these systems than for photovoltaic systems.

For conversion of direct current power to microwaves, klystron tubes have been assumed for the SPS Reference System. Alternatives to this type of tube are another tube-type converter (magnetron) or solid state microwave amplifiers. Magnetrons may have advantages in cost and industrial experience, while solid state microwave amplifiers are attractive because of their inherent reliability. As shown in Figure 2.2, the solid state devices were studied in two configurations. In one concept, the Reference System klystrons were replaced with solid state devices in the antenna (Figure 2.2c). In the other, solar reflectors concentrate sunlight on a solar-cell array, which is mounted back-to-back with the solid state devices (Figure 2.2d). Because solid state devices require lower operating

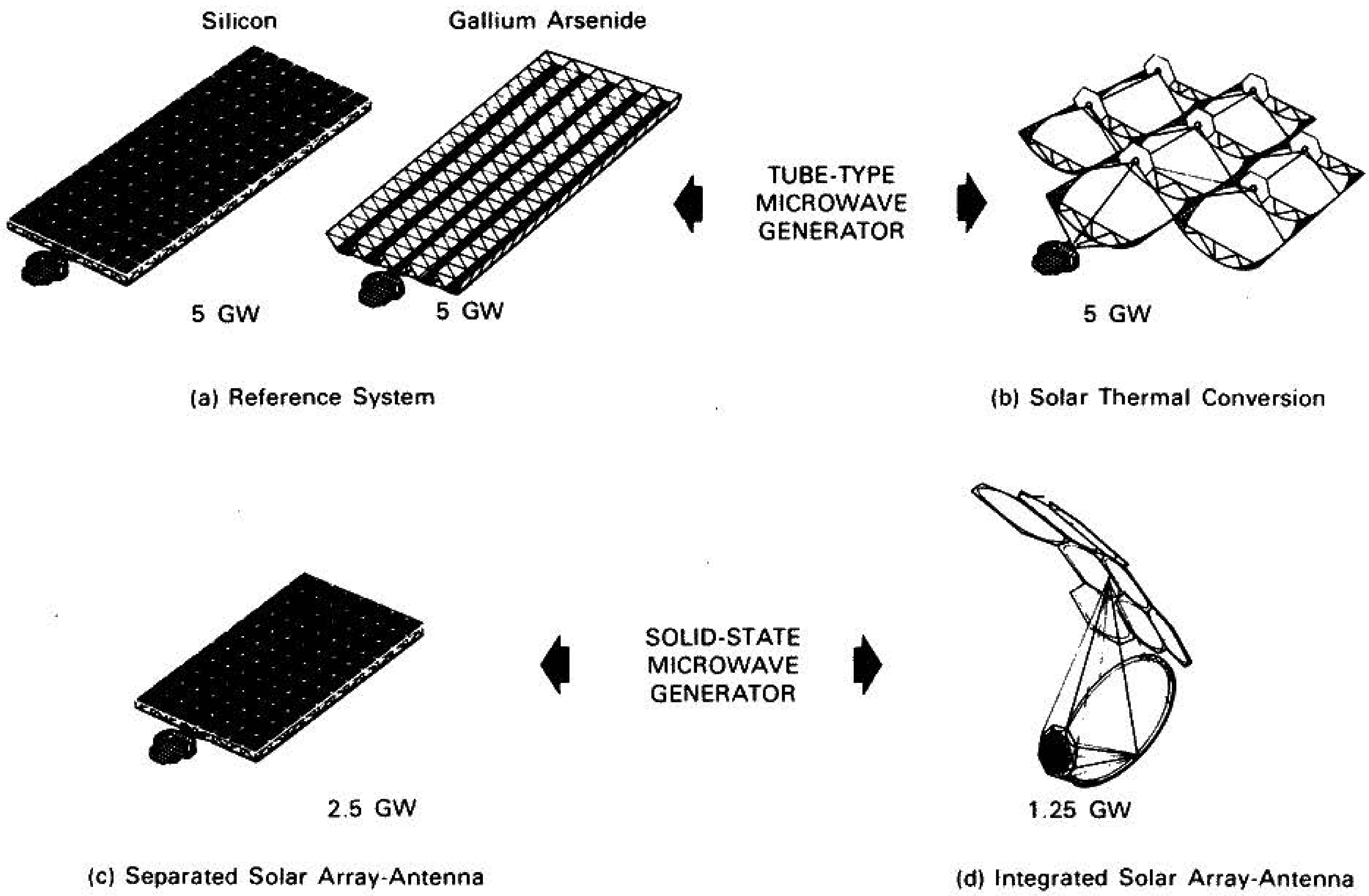

Figure 2.2 Some Alternative Systems Concepts Employing Microwave Power Transmission

temperatures, system design considerations limit the power output range over which these systems can be optimized. Tube-type systems can also be scaled down to lower power levels.

Larger satellites with multiple antenna configurations, which would permit beaming power to more than one ground receiving site from a single satellite, have also been studied. This approach would reduce the number of satellites required for a desired amount of delivered power (Figure 2.3).

For all these alternatives, operation at higher microwave beam power densities could reduce the rectenna size and total land requirements. Ionospheric heating experiments indicate so far that the 23-mW/cm^2 ionospheric power density limit arrived at by analysis for the Reference System design is probably low. If, at 2.45 GHz, the allowable power density were increased to 54 mW/cm^2, 5 GW of electrical power could be delivered to a rectenna occupying an area about one-half as large as that of the Reference System with only a small potential increase in the unit cost of electricity (Figure 2.4). Should the ionospheric heating prove to be excessive for this configuration, the frequency could be increased to, for example, 5.8 GHz. At this frequency, the ionospheric heating would be reduced by about 80%. The allowable upper limit to the power density will be established on the basis of effects on airborne biota that can enter the beam, as well as on considerations of ionospheric heating. The use of frequencies other than 2.45 GHz would be governed in part by considerations of all-weather transmission through the atmosphere.

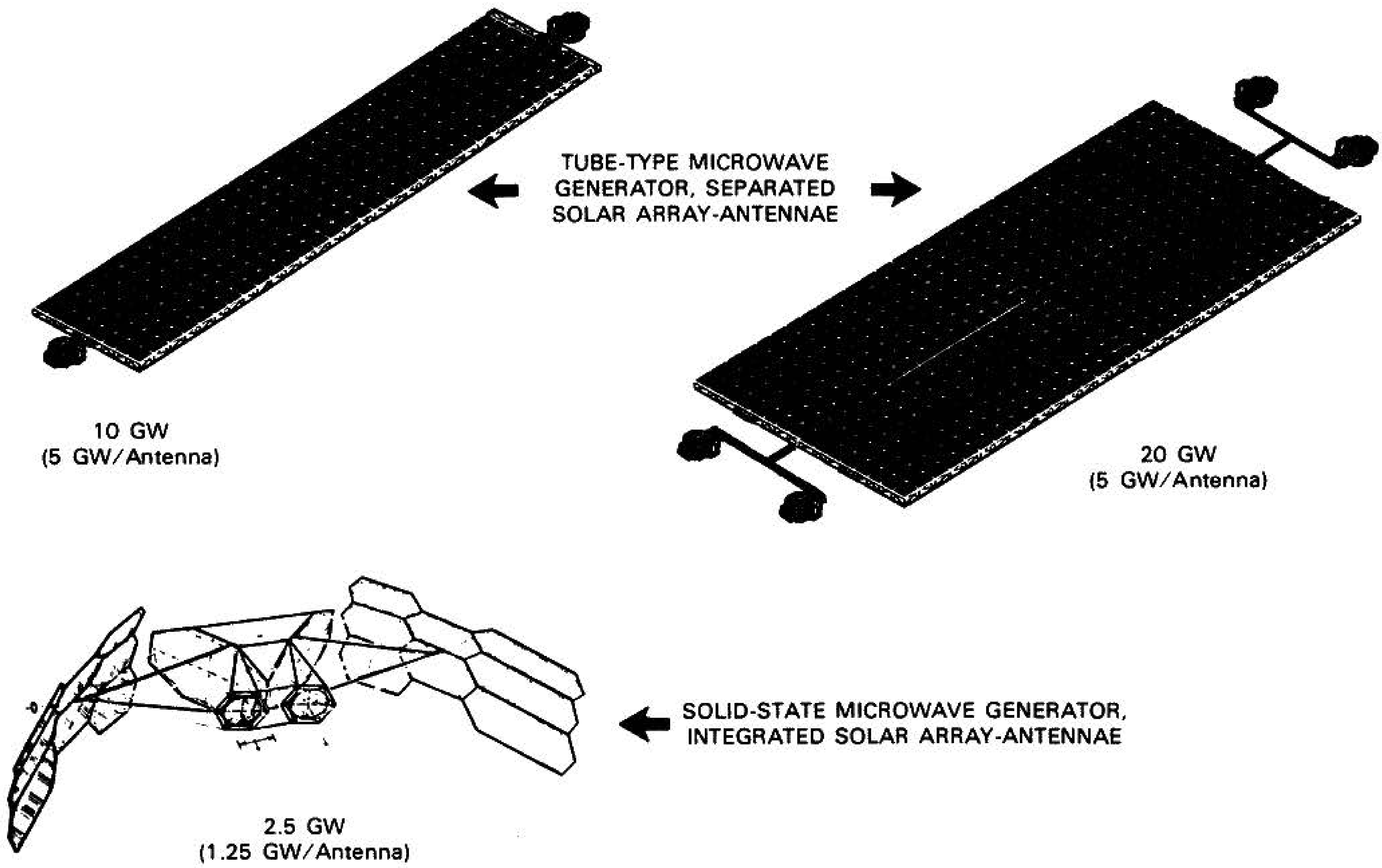

Figure 2.3 Some Alternative Systems Concepts Employing Multiple Microwave Antennae

Laser power transmission was briefly evaluated. With a laser, energy can be transmitted to comparatively small Earth receivers (tens of meters in diameter). This factor could reduce the capital costs for an SPS ground receiving system. Smaller blocks of power may be economical with a laser SPS. In addition to reducing the land requirement, laser power transmission offers several other advantages: (1) the radiation levels outside the receiving sites probably would be negligible, (2) there is no interference with conventional electromagnetic communications or other electromagnetic systems, and (3) smaller-size satellite units make small-scale demonstrations feasible. Two significant disadvantages of lasers are: (1) high-efficiency laser technology is relatively undeveloped at this time and (2) the laser beam is attenuated by clouds. However, the relatively small size of a laser receiver may make possible the use of several interconnected sites; during cloud coverage over a particular site, it may be possible to switch the beam to a site that is clear of clouds.

Options in the space transportation system also exist. For example, the large reusable heavy-lift launch vehicle used for transporting cargo from Earth to low Earth orbit (LEO) in the Reference System may be replaced by a smaller vehicle, equivalent in size to the Apollo Saturn V vehicle. This smaller vehicle would be compatible with potential future space mission needs and, therefore, would not be dependent only on the SPS for its development.

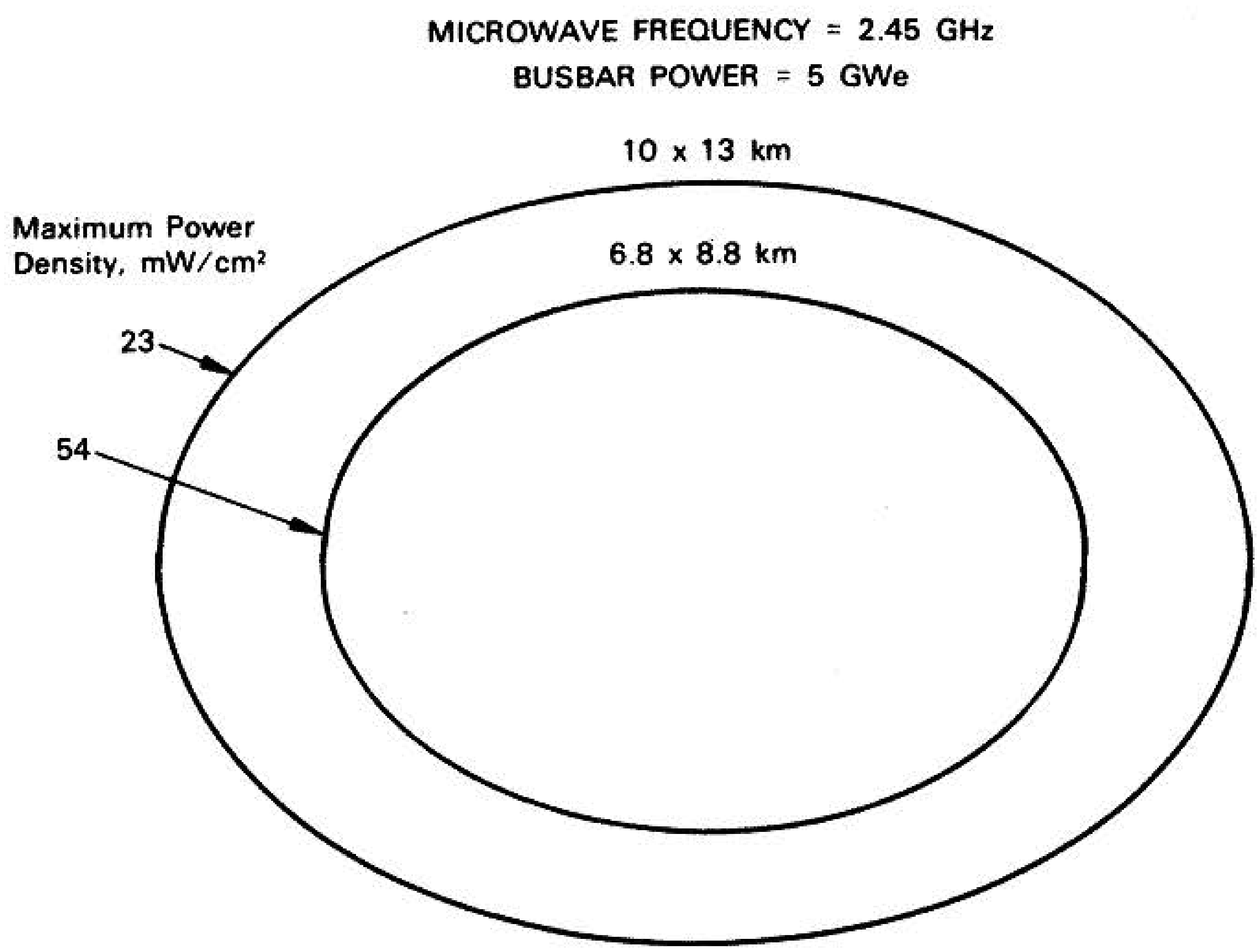

Figure 2.4 Example of Reduction in Rectenna Size with Increased Power Density

Additional options may be available for the cargo orbital transfer vehicle (COTV); these might involve: (1) construction of SPS modules in LEO that are self-propelled to GEO and assembled there or (2) use of magnetoplasmadynamic (MPD) hydrogen arc jets instead of ion engines that use argon as a propellant.

In summary, SPS alternative system concepts that utilize a variety of technologies exist. Many of these technologies are being investigated in the generic programs of DOE, NASA, and the Department of Defense. Because the SPS is not dependent on any single technology, its technical feasibility is enhanced.

3 STATEMENT OF FINDINGS

3.1 INTRODUCTION

The Satellite Power System Concept Development and Evaluation Program concentrated principally on the Reference System as a common basis for systems definition, environmental assessment, societal assessment, and comparative evaluation. While by no means representing a preferred engineering approach or design, the Reference System was characterized in sufficient detail to investigate whether any likely feature or potential side effect of the concept might imply that the SPS is not a promising future option for providing baseload electric power.

In investigating whether any potential "program stopper" is inherent in the SPS energy concept, it was important to determine whether mitigating strategies could be applied to the concept or ameliorative measures adopted to overcome key technological, environmental, or societal issues. Alternative technologies for developing power satellites and alternative delivered electric power capacities (e.g., 1, 2, etc. GW rather than the 5 GW suggested in the Reference System) and distribution were therefore studied. In the case of environmental effects, candidate engineering solutions were identified for some potential effects, but limited knowledge about others led to determining what more should be done to describe the effect adequately. Possible measures could be suggested to reduce some likely societal concerns; for example, technology alternatives that might reduce Reference System rectenna land requirements. In general, the statement of findings identifies the key findings, states what is known, identifies the current uncertainties, and suggests what could be done to increase the knowledge and thereby reduce the uncertainties about key findings.

Section 3.2 concentrates on five key environmental concerns, identified in CDEP, that are associated with basic SPS technology. Other environmental effects of the SPS that do not depend on the basic SPS technology, but would be associated with any large-scale energy project, are discussed in detail in a series of environmental assessment reports and supporting documents. The absence of detailed discussion here by no means implies that these environmental effects are unimportant, and they would not be ignored in further development of the SPS.

Section 3.3 presents the key findings of the CDEP societal assessment. They are inherent in the SPS concept or in the technology represented by the Reference System. The public participation process and its objectives also are discussed, because they are important to the findings.

Section 3.4 presents the results of comparative studies of the SPS (as represented by the Reference System) and several other energy technologies. The other energy technologies include some technologies now in use, taking into account expected near-term improvements, and several technologies now under development.

Section 3.5 presents the key findings of CDEP system definition. They are presented in generic categories of technology (energy conversion and power distribution on the satellite, for example). The findings describe what is known and what is uncertain about the technologies represented in the Reference System, and where appropriate, about alternative technologies as well. Methods for reducing uncertainties are identified for both cases.

3.2 ENVIRONMENTAL ASSESSMENT

3.2.1 Background

Two principal findings have emerged from the CDEP environmental studies:

- Many of the possible environmental effects of the SPS are not uniquely associated with SPS technology but would occur in implementing any large terrestrial energy project. Such projects require human and natural resources, manufacturing, transportation, and construction on a large scale over a long period of time. These effects were not quantified for the SPS during CDEP. However, they are important, and can be quantified and their locales and ameliorative measures identified if SPS development continues.

- Some potential environmental effects of the SPS are closely associated with SPS technology. The magnitudes of the effects and the measures that may be useful in limiting the effects would be influenced by the choice of SPS system characteristics. They are: (a) microwave exposure effects; (b) space worker health and safety; (c) rocket exhaust effluents, reentry products, and microwave energy effects on the atmosphere; (d) electromagnetic compatibility considerations that influence the use of geostationary orbit resources; and (e) effects on astronomy.

It is believed that the effects closely associated with SPS technology are the key environmental considerations of the SPS. Their potential consequences have been assessed but not quantified. It is possible that further investigation could show that one or more may be insurmountable. At the present stage of investigation, no such finding could be made.

These two principal findings emerged from five specific tasks in the CDEP environmental assessment to identify, describe, and evaluate the kinds of environmental effects that would be expected on Earth, in the Earth's near atmosphere, and in space. The tasks were:

- Microwave exposure effects on health and ecosystems,
- Nonmicrowave effects on health and ecosystems,
- Atmospheric effects,
- Ionospheric heating effects, and
- Electromagnetic compatibility.

The results obtained from these tasks have been documented in an integrated environmental assessment.[3] Moreover, the detailed findings of each task have been documented in five separate assessments.[18-22] This present statement of findings concentrates on the five key environmental considerations listed above as effects closely linked to SPS technology.

3.2.2 Microwave Effects on Health and Ecosystems

Microwave radiation, unlike ionizing radiation such as X-rays and radioactive emissions, does not have sufficient energy to ionize biological molecules but, instead, agitates them. If the radiation intensity is relatively high (on the order of milliwatts per square centimeter [mW/cm^2]), this agitation can produce internal body heating. Most of the reported adverse effects from microwave exposures of laboratory animals have been attributed to increased internal body temperatures due to intensities in the range of 4-30 mW/cm^2.

The relative immaturity of scientific study, the complexity of experimental conditions, and the complexity of biological systems contribute greatly to the difficulty in quantifying microwave biological risk. Microwave exposure conditions must be understood precisely in terms of operating frequency, polarization and modulation (if any), and laboratory chamber characteristics. Only recently has it been recognized that experimental protocol may be critical, and an understanding of nonuniform power deposition and dosimetry is just beginning to emerge. Animal-to-human extrapolation methods remain rudimentary.

Microwave power densities within and near a Reference System rectenna are illustrated in Figure 3.1. The illustration is based on continuous-wave transmission of 2.45 GHz from a single satellite. The power density well beyond a rectenna boundary would be a minimum of 10^{-4} mW/cm^2, with the 60 rectennas spaced about 300 km apart, on the average, across the continental United States.

It is currently not possible to quantify whether microwave exposure levels associated with the SPS Reference System in particular or the SPS concept in general would be acceptably safe. The scientific literature is not adequate for this determination, and research supported specifically for the SPS has not yet yielded results that would permit such determinations.[3] A qualitative assessment based principally on the available literature, however, has been made and indicates that immune, reproductive, central nervous, and thermoregulatory systems can be affected by microwaves.[23-26] For the SPS Reference System, the results of this qualitative assessment are summarized in the following paragraphs.

3.2.2.1 Public Exposure. About one-half of the U.S. population is now exposed to power densities greater than 5×10^{-6} mW/cm^2 from contemporary broadcast equipment and other electromagnetic radiators (principally near 0.1 GHz). Based on Reference System criteria, the public would be exposed to microwave power densities ranging from about 10^{-4} mW/cm^2 to 10^{-1} mW/cm^2 (rectenna site exclusion boundary) at 2.45 GHz. No thermal body heating would be expected from such low levels; nevertheless, the median U.S. population exposure to microwave energy would be

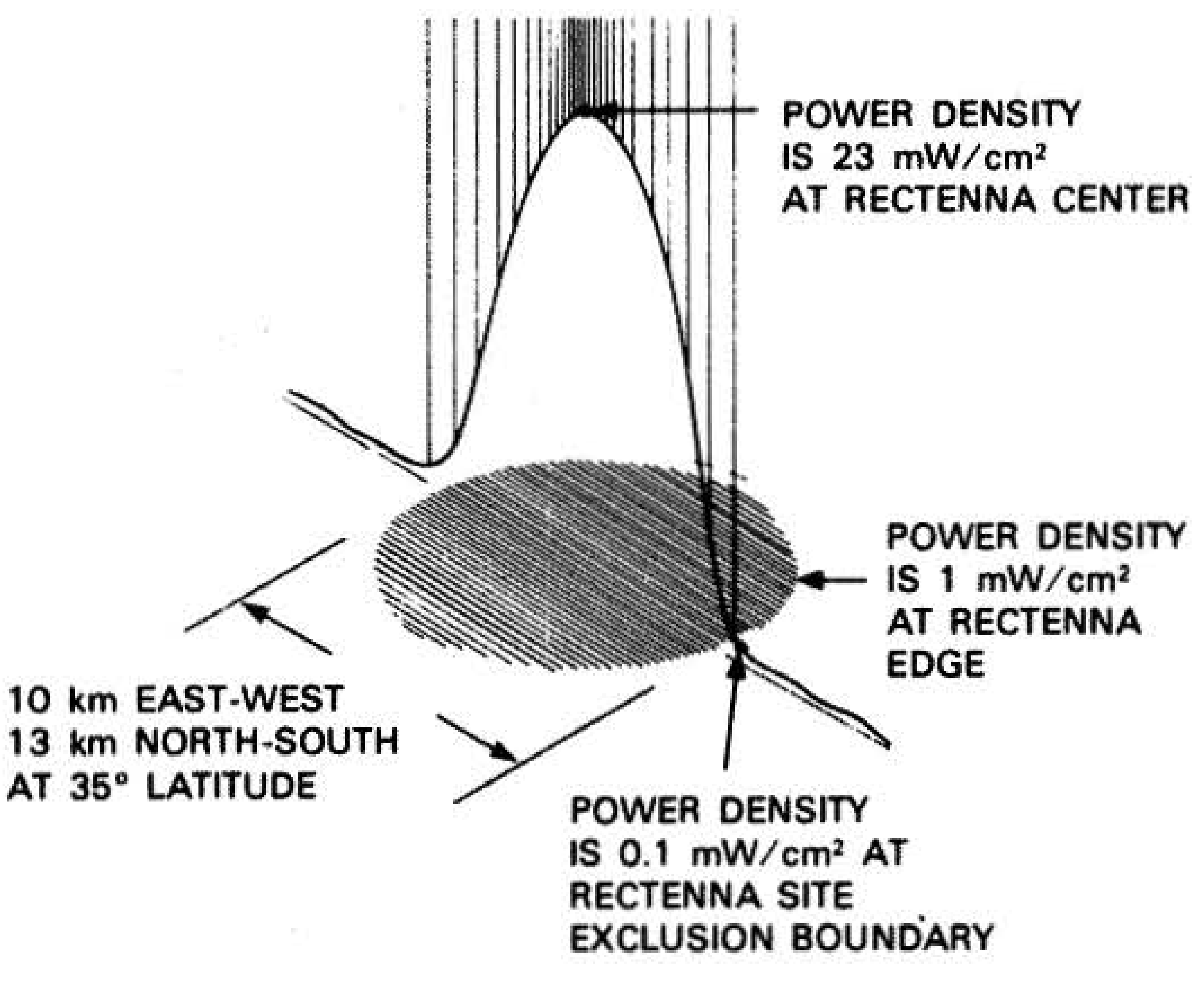

Figure 3.1 SPS Microwave Power Density Characteristics at a Reference System Rectenna Site

increased by more than an order of magnitude, and a quantitative assessment of this exposure is mandatory. Such an assessment would require a theoretical understanding of possible nonthermal mechanisms.

3.2.2.2 Occupational Exposure. The power density near the center of the transmitting antenna in geostationary Earth orbit (GEO) would be about 2,200 mW/cm^2. Occupational exposure to SPS microwave power density must be controlled in space and at rectenna sites. Maintenance to transmitting antennas in space represents the most potentially adverse exposure condition (up to 2,200 mW/cm^2). It is not known at this time whether it would be necessary to turn transmitting equipment off during maintenance, or whether protection provided against the natural space environment would suffice also as microwave exposure protection (see Section 3.2.3). Some combination of protection might be possible. Space worker microwave protection would be needed for maintenance work performed during transmissions, but criteria cannot be established until system design and operational strategies evolve. The limit of protection that can be achieved could affect the choice of system parameters.

Microwave intensities under rectenna panels would be a small fraction of the power density immediately above the panels. Nevertheless, protection would be required for workers whose duties might require their presence there. Either individual or group protection schemes could be developed. In the most severe case (that of working on the upper surface of a rectenna panel), system shutdown or beam defocusing would be necessary if no other protection scheme were found practical for rectenna workers. Employees in supporting facilities onsite could be protected by architectural shielding, which undoubtedly would be needed to prevent self-interference to control and monitoring equipment. A quantitative risk assessment is necessary to establish protection criteria for workers and guidelines for preferred system development.

Current occupational standards and guidelines for limiting exposure to potential microwave hazards vary between nations, as do the basic philosophies on which regulation should be based. There is substantial interest in the U.S. and several other nations in revising current standards and guidelines, and standards internationally agreed upon might eventually be developed. A preferred SPS design could be influenced by future events in microwave standards setting.

3.2.2.3 Ecosystems. There are virtually no definitive data available for assessing whether microwave radiation on an area-wide scale like that associated with the SPS might be harmful to ecosystems. Most of the information that is available is related to specific animal or plant species in controlled laboratory environments. The latter type of data is useful to some extent but is clearly insufficient for developing an informed judgment on ecosystems in general.

Studies were initiated on honey bees and birds during the CDEP to increase current knowledge about potential microwave exposure effects on ecosystems. Experiments on honey bees and birds were given priority. Bees are important to natural processes and, fortunately, have been studied thoroughly. Birds represent a free-ranging species that could be exposed to maximum SPS power densities near the Earth (23 mW/cm^2 for the Reference System). They also are an especially important component of the natural environment. Moreover, they are sometimes at or near their thermal limit in flight, a factor to consider in determining whether microwave stress could be adverse.

Preliminary data have been collected on honey bees, and no effects have been observed to date on behavior characteristics and survival at Reference-System-level microwave exposures. Experiments with birds were only recently initiated.

As Figure 3.1 illustrates, microwave power densities beyond rectenna exclusion boundaries would be very low. Levels within the site would be somewhat higher under rectenna panels and higher still above the panels. It is not known whether species could successfully reestablish onsite following construction. Considering the implications of adverse effects on the environment, substantially more work needs to be done to obtain a definitive assessment of microwave exposure effects on the environment.

3.2.2.4 Summary. Table 3.1 presents information about potentially undesirable effects on health and ecosystems, the uncertainties, and the actions required not only to reduce these uncertainties but also to develop requirements for a preferred SPS design.

The highest SPS-produced microwave power densities would be in space near the satellite transmitting antennas (2,200 mW/cm^2 at the selected operating frequency). Space maintenance workers must be protected from high-level exposures by operating practices or worker enclosures, or a combination of the two. The necessary degree of protection cannot be estimated at this time. More information is needed on other potential hazards that might be encountered from space radiation,

Table 3.1 Effects of Microwave Exposure on Health and Ecosystems

Known	Uncertainty	Resolution
Most scientifically credible reported effects are produced by induced body heating.	The possibility of nonthermal mechanisms and effects.	Theoretical study and experiments of acute and chronic exposure to detect and describe nonthermal mechanisms (if they exist).
Animal immune systems, reproductive processes, physiology, and behavior can be affected by microwave-induced body heating.	Extrapolation from animal species to humans, and from one set of microwave parameters to another.	Establish dose-response relationships and develop extrapolation techniques through acute and chronic exposure experiments on animals.
The general public, animals or plants will be exposed to widespread microwave power density conditions.	The possibility of making quantitative risk assessments.	Develop assessment methodology and derive quantitative risks from experimental and theoretical data noted above.
SPS space and terrestrial workers will require protection from higher-intensity microwave exposure.	The degree of protection needed to ensure health maintenance and occupational safety.	Identify requirements and select methods by comparing preferred system characteristics with assessment of risks (see resolutions above).
Free-flying species could be exposed to maximum power density.	Power density limits for preventing adverse effects on species near natural thermoregulatory limits.	Continue and expand current bird and insect experiments.

attendant required protection, and microwave safety thresholds. The degree of protection could affect microwave transmitting design criteria or the selection of alternative transmission methods for the SPS.

Maintenance workers at SPS ground receiving stations could be exposed to microwave power densities produced on Earth by the SPS (1 to 23 mW/cm^2 for the Reference System). Operating practices, protective enclosures, and protective clothing for personnel are possible short-term safety measures, but long-term effects must be determined. Safety thresholds can only be established from additional experiments, data, and analysis. As in the case of microwave exposure in space, protection criteria could influence the preferred SPS design or selection of alternatives for transmitting energy from space to Earth.

The levels of microwave power density produced by the SPS beyond rectenna sites would be low (on the order of 10^{-4} to 10^{-1} mW/cm^2) but, nevertheless, considerabley more than is experienced by most people today. The current data base is insufficient to permit quantification of the long-term effects, if any, on the population and ecosystems. Quantitative descriptions of acceptably safe thresholds of exposure to microwave radiation depend on establishing dose-response relationships for humans, animals, and plants. Both intensity level and duration of exposure could be important. Substantially more data than are available are required in order to derive those relationships. Additionally, information is needed concerning the basic mechanisms involved in microwave interactions with biologic materials and systems. Dose-response data represent the means by which public health effects can be determined, worker protection criteria and methods can be developed, and the natural environment can be protected. In utilizing the data, maximum permissible microwave power densities can be established for microwave power transmission for the SPS may be selected. A considerable amount of the scientific information that is required may be obtained from others interested in the microwave effects question, including the U.S. Environmental Protection Agency, the Department of Defense (DOD), other national and state agencies concerned with public and occupational health, and investigators in other nations.

3.2.3 Space Worker Health and Safety

Current experience with human performance in space is mostly with individuals operating in low Earth orbit (LEO); the SPS will require operations in both LEO and GEO. The maximum continuous time spent in space by humans is 175 days, and those who have experienced space travel are a small number of uniquely trained and highly motivated individuals.

Medical and occupational experiments performed in space and operational life support and monitoring systems used in space have been analyzed in great detail, and this analysis is augmented by data obtained from experiments performed under simulated space conditions on Earth. The available scientific and engineering data base, although limited mainly to low Earth orbits, suggests that with suitable protection, man can live and work in space safely and enjoy good health after returning to Earth. Data from the 84-day U.S. Skylab-4 mission are especially pertinent to the question of the ability of relatively large numbers of people to live and work in space for periods on the order of 90 days, the plan established for SPS Reference System assessment.[2]

Based on the Reference System, about 18,000 man-years of effort would be required to construct 60 power satellites in GEO at a rate of 2 per year for 30 years. Additional space activity would be needed for maintenance as satellites are completed and become operational. Construction and maintenance crews would be supported by management, logistic, and base support personnel. Health and safety issues for such an unprecedented venture have been assessed.[19] The principal cause-effect factors related to space worker health and safety are illustrated in Figure 3.2. The use of robotics and ground control could be expanded to reduce space worker population and exposure.

Many of the factors shown in Figure 3.2 require "scaling up" of current medical, safety, and occupational analyses to achieve adequate space engineering and technology methods and practices to accommodate group space travel and habitation. Examples are: (1) preventing space flight and space construction accidents, (2) preventing failures in life-support systems in LEO and GEO, (3) protecting space vehicles and habitats from collisions with space debris and meteoroids, and (4) providing habitats and a quality of living conditions that minimize psychological stress. Several NASA and DOD operational and generic research programs for improving and expanding the state-of-space technology and engineering will contribute to achieving conditions needed for building, operating, and maintaining the SPS. Specific SPS requirements have been identified and could be coordinated with these other activities.[19]

The biomedical effects of substantial acceleration and deceleration forces when leaving and returning to Earth, living and working in a weightless environment, and the potential hazards of space radiation are the three principal factors that must be dealt with if man is to achieve the capability of collecting energy in space and

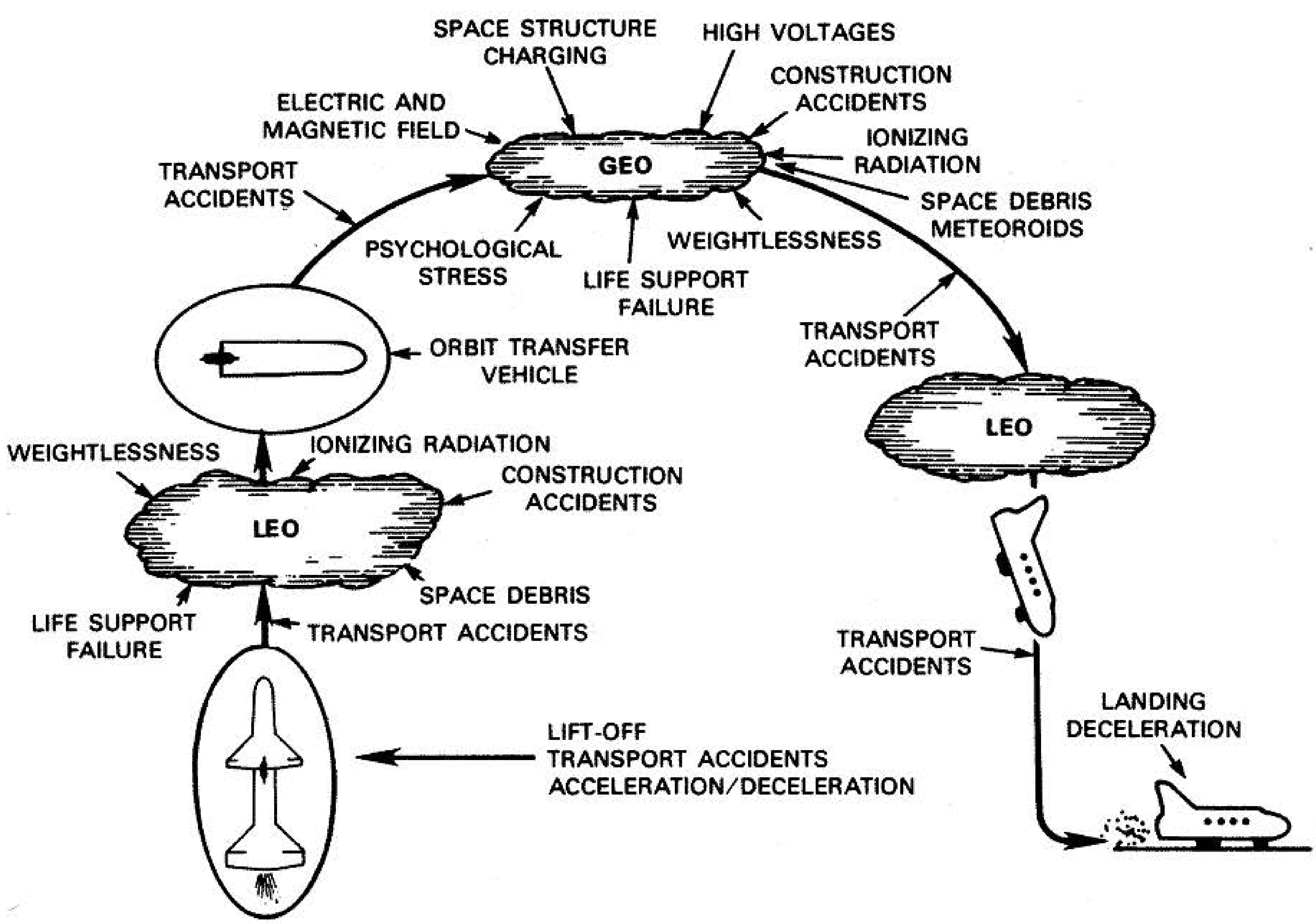

Figure 3.2 Factors Pertinent to Space Worker Health and Safety

transmitting it in a useful form to Earth. These three factors are discussed in the following paragraphs.

3.2.3.1 Acceleration and Deceleration Forces. Astronauts have adapted to weightlessness for extended periods of time in space and have experienced maximum forces equivalent to 6g during Apollo reentry. No acute operational problems, significant physiological deficits, or adverse health effects on the cardiovascular or musculo-skeletal systems have been observed from these experiences.

The space shuttle can be regarded as the forerunner of an SPS personnel launch vehicle. It has been designed to limit deceleration forces to 3g on occupants, but the forces would be imposed for somewhat longer periods of time than have been experienced in previous reentries from space. No adverse effects are anticipated, and space shuttle experience over the next several years will provide a pertinent data base for planning SPS construction scenarios.

Screening procedures and tests should be devised, and experiments should be designed and conducted to account for the fact that the SPS would require personnel possessing a broad range of specialized manual, clerical, and staff skills and a minimum background in professional engineering and scientific skills and knowledge. Thus, SPS space crews should be expected to represent a fairly broad age group and a range of physiological characteristics. The current data base and near-term space shuttle experience is unlikely to be adequate in this regard.

3.2.3.2 The Weightless Environment. A number of relatively small deviations from normal physiological ranges have been observed in U.S. astronauts during and following space missions and have been reported for Soviet cosmonauts. Most of the detected effects appear to be adaptations to zero gravity conditions, the affected parameters returning to normal ranges either during missions or shortly thereafter. No apparent persistent adverse consequences have been observed or reported to date. Nevertheless, some of these deviations could be chronic and have important health consequences if they were experienced during long durations in space or in repeated space missions--two possibilities associated with the SPS.

The particulars of unusual physiological aspects resulting from space missions are provided in Ref. 19. Generally, they can be characterized as a shifting of body fluids from the lower body and legs to the upper torso and head until a new equilibrium is reached, a feeling of motion sickness, some loss of muscle mass and strength, and a progressive loss of bone calcium at a rate of about 0.5% per month. Some minor loss in red blood cell mass, small alterations in the immune and endocrine systems, and other biochemical alterations also have been observed.

The deviations due to zero gravity described above usually have returned to normal within a few days or weeks after return to Earth. Only bone calcium loss appears to require a protracted period of recovery after returning from space (90 days were required following the 84-day Skylab-4 mission).

Strategies have been developed to ameliorate the physiological effects of weightlessness described above. An exercise regimen has been devised, and body fluid shifts can be limited by applying lower body negative pressure. Antimotion medication is useful for preventing temporary motion sickness. Mineral nutrition and exercise limit other observed effects.

Crew complements for the SPS could be large and would be comprised of people having a broad range of physiological characteristics. It is important to learn whether measures that have been found effective for highly trained and motivated astronauts in exceptionally good health would be successful for large numbers of people. It is also important to determine whether multiple space missions would be possible without exacerbating the physiological changes that seem to occur during single missions in space. It would be necessary to develop alternative ameliorative measures (possibly including substantial dependence on robotics for construction and maintenance) if current mitigating strategies were subsequently found to be ineffective for large numbers of people in space.

3.2.3.3 Ionizing Radiation. The ionizing radiation environment in which the satellite power system would be built and operated is characterized by fluxes of electrons, protons, neutrons, and atomic nuclei.[3] In LEO, electrons and protons are trapped by the Earth's magnetic fields in the Van Allen belt. The flux of radiation in LEO varies with solar activity. Trapped protons from solar activity are also of concern in the transfer from LEO to GEO. In GEO, trapped electrons, trapped protons, galactic cosmic rays and solar particle events contribute to the radiation environment. Galactic cosmic rays originate outside our solar system and are made up of protons, helium nuclei, electrons, and heavy nuclei with a charge greater than 2 (HZE). The biological effects of HZE are not well understood and could produce effects of an entirely different character for other types of ionizing radiation. Solar particle events are not predictable and can temporarily increase radiation in GEO greatly.

The imprecise knowledge of the fluence and of the time variations of ionizing radiation in space and the generally recognized limitations of present methods for estimating radiation exposure in space prohibit a confident assessment of radiation dose and effects. The present best estimate is that a person might receive a radiation dose of 40 rem during the 90-day tour in GEO proposed in the Reference System. (The present terrestrial occupational exposure limit for 90 days is less than 10 rem). If space workers were irradiated to this extent, there would probably be an appreciable increase in latent cancer and a possibility of other detrimental effects. This dose estimate is based on several important uncertainties.

There is no universal agreement at the present time on whether estimates should be based upon shielding effectiveness from flat slabs or spherical models. There also are questions on whether the human body should be represented by an aluminum equivalent or a water equivalent for purposes of radiation dose calculations. Finally, while it is recognized that thicker shielding can reduce radiation, secondary radiation can occur as thickness is increased and offset the expected shielding improvement to some degree.

The present 40-rem radiation dose presumed that a nominal amount of shielding would be provided by the Reference System (3 gm/cm^2 aluminum equivalent), and the water equivalent was used for the human body. This estimate could be in error by a factor of 5 or 10, most probably overestimating the dose. On the other hand, there could be increased exposure for persons whose tours might coincide with solar particle events. The increase could be on the order of an additional 25 rem for a 90-day tour for a total of 65 rem, based on the largest solar event yet observed.

Uncertainties notwithstanding, it is believed that the Reference System scenario for satellite construction in space would lead to ionizing radiation exposure greatly exceeding the limits recommended for radiation workers by the National Council on Radiation Protection and the International Commission on Radiological Protection. Moreover, the career limits established for small numbers of astronauts by the

National Academy of Sciences (NAS) might not be appropriate for the larger number of workers in space associated with SPS at this time.

Radiation exposure could be limited in a number of ways, each requiring considerable research. The effectiveness of laminated shielding requires investigation, with appropriate emphasis on materials and secondary radiation effects. The results of this research are critical in determining cost and weight penalties that might accrue in order to provide adequate shielding. Shielding requirements must be based upon combined exposure for the entire mission (stays in LEO, transfer between LEO and GEO, tours in GEO), with the additional possibility of solar particle events considered.

Research on the potential biologic effects of HZE particles must be continued. The energy deposition of HZE particles is different from that of other types of radiation, and precise biological effects are not yet known. Laminated shielding might not be useful against HZE, and other protective schemes require investigation.

Dosimeters are needed for monitoring radiation exposure levels. Dosimeters for individuals must be rugged, reliable and simple. Real-time monitoring is needed to account for unpredictable radiation sources, solar events and short-term fluctuations of trapped electron fluxes in GEO. A monitoring system is needed for HZE exposure, and a warning and protection system must be devised to alert persons to imminent radiation hazards.

More work is needed to improve current methods for estimating radiation fluence in space and the resulting dose levels to humans. This work would include knowledge about the spatial distribution and time duration of radiation components as well as their intensities.

Finally, a new satellite construction and maintenance scenario is needed for SPS. Consideration should be given to greater construction activity in LEO, where radiation is less severe and more predictable, with activity limited to assembly in GEO. A substantial reliance on automation and ground control should also be considered to reduce the number of people required to build SPS in space and to limit ionizing radiation exposure for those people essential to the mission of construction and maintenance.

3.2.3.4 Summary. There is limited experience and information about protecting health and promoting safety for humans in geostationary space, and there are questions not yet resolved concerning the best means to construct and maintain SPSs in space. The scenario established for building and maintaining a Reference System appears inappropriate in several respects. Areas that require further investigation to develop a realistic, low-risk space operation were identified in the CDEP process. These areas are concerned principally with the effects of ionizing radiation in space.

Research, engineering, and technology advancements by NASA and DOD and their counterparts in other nations will provide insight and direction for the additional work necessary to develop an SPS. Conversely, the remaining requirements for developing an acceptable space construction and operations program for the SPS provide an additional focus for generic space ventures.

The findings, uncertainties, and resolutions regarding space worker health and safety are summarized in Table 3.2. They require substantial lead time for resolution and suggest coordination with other ventures. Moreover, they are the issues that would most directly influence or be influenced by specific SPS design features.

Table 3.2 Effects on Space Workers

Known	Uncertainty	Resolution
Space travelers will be exposed to acceleration and deceleration forces.	Extent and duration of changes for groups of persons encompassing a broad range of age and physiological conditions.	Obtain experimental data to augment operational data (e.g., space shuttle) and develop screening and selection criteria for a range of physiological and health conditions and ages, using experimental surrogates where necessary. Coordinate research with generic programs at NASA and elsewhere.
Living and working in a weightless environment can produce temporary physiological aspects which affect performance, but ameliorative measures are known.	Same as above. In addition, the practicality and effectiveness of ameliorative measures for group applications.	Same as above. In addition, investigate the need for and efficiency of using robotics in place of some human activities as operational alternatives.
The space radiation environment is hazardous, incompletely understood, and not entirely predictable. Radiation protection and exposure monitoring and warning systems are essential.	Biologic implications of exposure to ionizing radiation in GEO and the levels of required protection for both normal exposure and during solar events.	Coordinate SPS needs with ongoing comprehensive generic research at NASA and elsewhere, augment where necessary to satisfy specific requirements; identify protection and monitoring criteria from research results and assess the alternative use of robotics.

3.2.4 Atmospheric Effects

Every level of the Earth's atmosphere from the ground surface to GEO would be affected to some extent by the construction and operation of a satellite power system.[20]

In the lowest portion of the atmosphere, the most important effects that have been identified are associated with the ground clouds formed during heavy-lift launch vehicle (HLLV) launches. The major atmospheric effects caused by these ground clouds are inadvertent weather modification and air quality degradation. Calculations supported by a limited amount of field data suggest that there is a potential for inadvertent local weather modification on a short-term basis. This potential arises both from the large thermal energy injected into the atmosphere during a launch and from the cloud condensation and ice nuclei present in the ground cloud. The degree of weather modification depends strongly on meteorological conditions and the size of the launch vehicle, and to some extent on the launch site location. Under selected meteorological conditions occurring at Cape Canaveral, for example, HLLV launches can affect convective patterns, alter cloud populations, and induce detectable precipitation. None of these effects is judged to be serious from a meteorological viewpoint for Cape Canaveral. The possibility does exist for long-term cumulative effects arising from launches once or twice per day, but this possibility has not been investigated in detail.

Air quality impacts of HLLV launches are predicted to be very small except possibly with respect to nitrogen dioxide (NO_2). If a short-term air quality standard is set by the Federal EPA as anticipated, ground-level NO_2 concentrations due to ground clouds could exacerbate existing problems. However, the ground clouds by themselves are not expected to be cause for exceeding the anticipated standard. The production of NO_2 can also lead to slight increases in acidity of precipitation on a local, intermittent basis. A preliminary analysis of this latter problem indicates that it is unlikely that the increase in acidity would be great enough to cause notable environmental effects.

The rarified nature of the upper atmosphere makes it susceptible to disturbances by external (i.e., unnatural) sources of mass and energy. Postulated SPS construction and operations would introduce both mass and energy in magnitudes and repetitive cycles never before attempted. The potential effects identified during CDEP are believed to be:

- Ionospheric modifications caused by space vehicle exhaust effluents and reentry products,
- Ionospheric heating produced by microwave power transmissions through the medium,
- Increasing the water content and altering the natural hydrogen cycle above 80-km altitude,
- Formation of clouds at mid-latitudes near 85-km altitude, and
- Effects in the magnetosphere caused principally by space vehicle exhaust effluents discharged between LEO and GEO.

3.2.4.1 Exhaust Effluent and Reentry Product Effects in the Ionosphere. The ionosphere, depicted in Figure 3.3, consists of electrically charged particles (electrons and ions). It is divided into three regions of differing chemical and electrical characteristics.

The ionosphere is important to communications, because some systems depend upon its ability to reflect radio waves, thereby providing long-range capabilities. Examples are amateur and standard broadcast radio (commercial clear-channel stations) and aircraft and ship navigation systems like LORAN and OMEGA. Systems requiring ionospheric reflection operate at frequencies between about 3 kHz and 20 MHz.

It has been hypothesized from both theoretical studies and observations that exhaust effluents from space vehicles and nitrogen oxides produced during space vehicle reentry could disrupt radio wave propagation by altering ionospheric characteristics. The hypothesis for the SPS remains uncertain for several reasons. Theoretical models of effluent-ionosphere interactions are limited by the complexity of the medium and the fact that the physical-chemical processes are not completely understood. The uncertainties are greatest for the lower ionospheric regions, one reason being the lack of supporting experimental data for corroborating theoretical predictions. There have been opportunities to compare F-Region predictions with observations, thereby reducing uncertainties about effects in the highest ionospheric region. However, effects that might be produced by recurring, frequent launches of HLLVs contemplated for SPS construction (possibly as often as twice daily for a period of 30 years) were not studied in detail during CDEP.

Although CDEP results were generally inconclusive for D- and E-Region effects, they suggest that partial ionospheric depletion could occur at F-Region altitudes for the Reference System types of space vehicles and their frequency of operation. Heavy-lift launch vehicles would produce partial depletions over regions about one-third as large as the United States for periods of 4-12 hours. These will occur each time an HLLV is launched (possibly twice daily). The personnel orbital

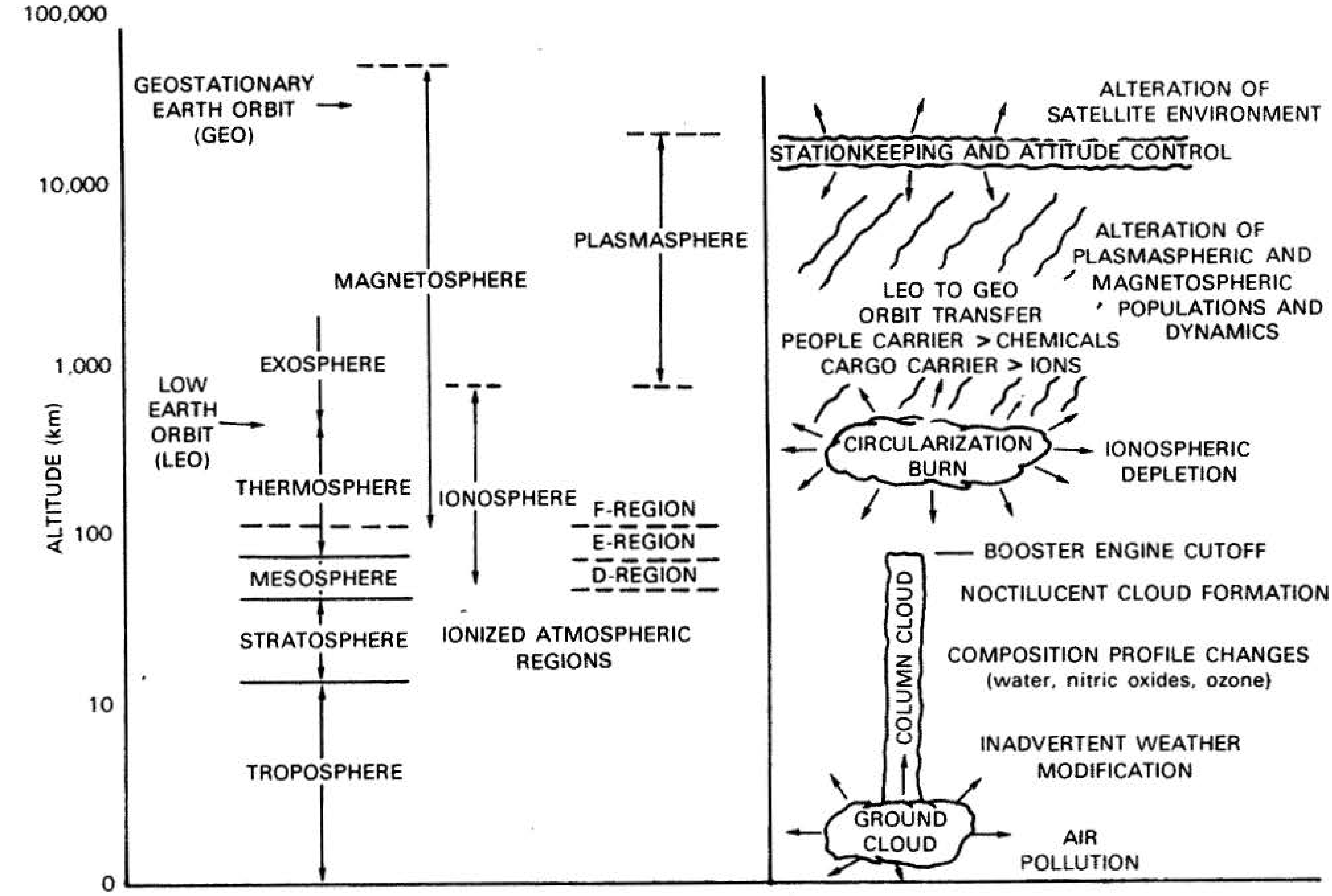

Figure 3.3 Regions of the Atmosphere and Potential SPS Effects

transfer vehicle (POTV) will produce partial depletions over areas as large or larger than the United States for 4-16 hours when used between low Earth Orbit (LEO) and geostationary Earth orbit (GEO), which will occur about once a month.

The launch of the HEAO-C satellite in September 1969 provided the first and only opportunity to date to observe effects on telecommunications of F-Region depletions caused by a launch vehicle engine burn. Reflection of radio waves from the ionosphere (frequencies less than 21 MHz) were detected, but they were not disruptive. Systems utilizing higher frequencies that normally pass through the ionosphere also were used to investigate possible radio wave propagation effects, but these observations were inconclusive. The formation of plasma striations in the F-Region was not expected because the HEAO-C launch was a mid-latitude launch. However, equatorial launches have been theoretically hypothesized to cause such striations. More experiments of this nature are required to more fully characterize and understand telecommunication effects of propulsion system injections in the ionosphere. Consequently, it cannot be predicted with confidence at this time whether the circularization burn of an HLLV or the injection burn of the POTV would so deplete ionospheric regions that telecommunications would be disrupted.

Current uncertainties not withstanding, possible mitigating strategies for preventing effects on ionospheric-dependent telecommunications have been considered. Foremost, of course, is the selection of propulsion techniques and fuels that are least likely to interact with ionospheric particles and have minimum persistence. Another strategy is to devise vehicle trajectories and burn periods in combinations that minimize possible effects in critical ionospheric regions.

3.2.4.2 Microwave Heating of the Ionosphere. Microwave power transmission through the ionosphere conceivably could increase the ambient energy levels and temperatures of the electrons comprising the D- and E-Regions. The reaction is much like the ohmic heating in a current-carrying wire. Ohmic heating that might be produced in the F-Region could cause the ionosphere to act like a lens, because the electron density is much higher in the F-Region than in the two lower regions. This lens-like reaction could concentrate the microwave energy (self-focusing) and thereby produce electron density irregularities aligned with the Earth's magnetic lines of force. Any of these effects could result in telecommunications performance degradation. Examples are illustrated in Figure 3.4.

Much is known about the relationship between ionospheric conditions and telecommunications performance, and that knowledge formed the initial basis for the SPS assessment of microwave heating phenomena and subsequent telecommunications effects. That basis and the resulting assessment were extended substantially by SPS-specific theoretical studies and ground-based experiments. The physics involved in the former and details regarding the latter are included in Ref. 21.

Based on CDEP findings, a single power satellite like the Reference

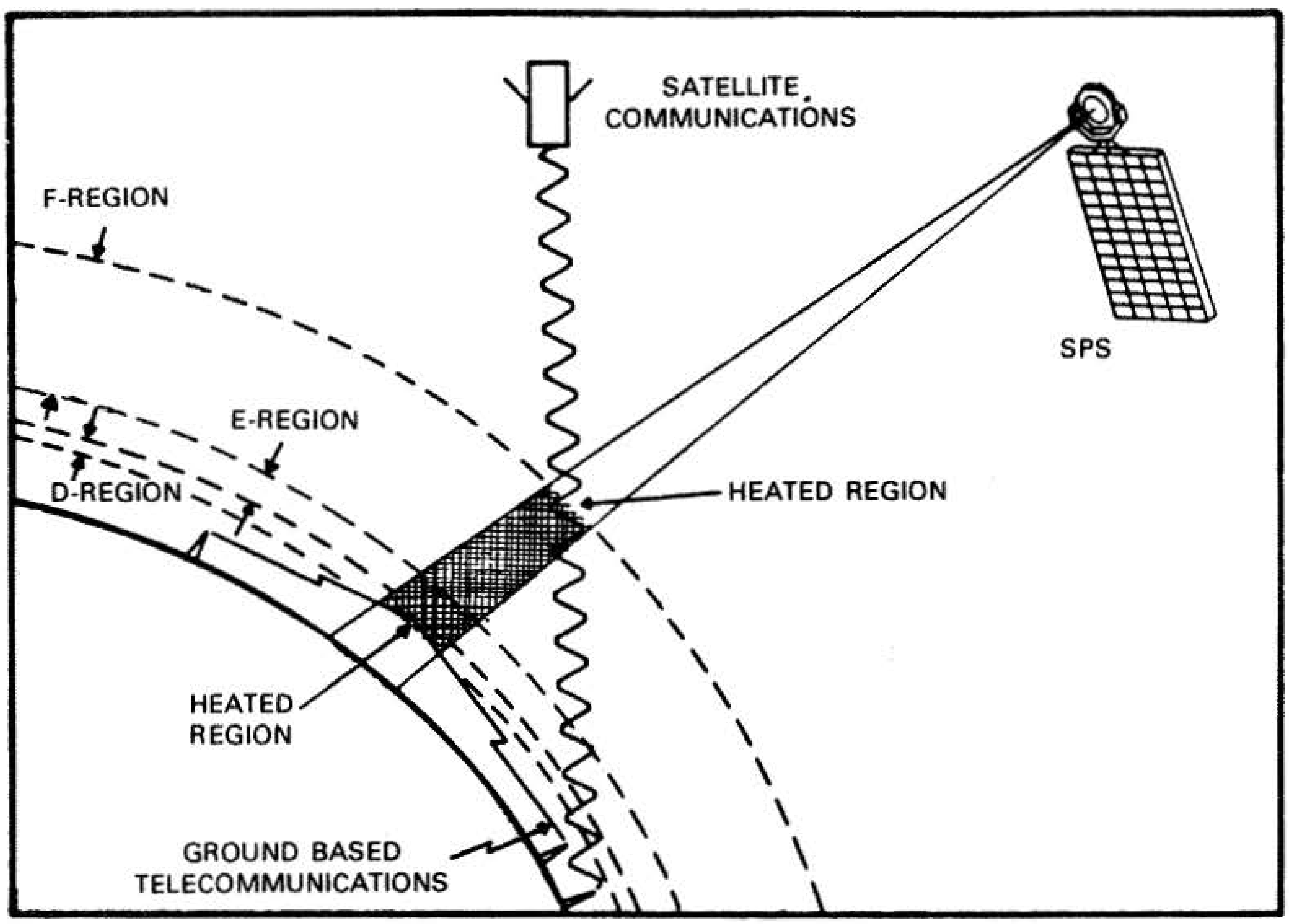

Figure 3.4 Examples of SPS Microwave Transmission Effects on the Ionosphere and Telecommunication Systems

System (23-mW/cm^2 power density at 2.45 GHz) would produce no discernible performance degradation on telecommunications systems operating at frequencies between 3 kHz and 3 MHz and dependent upon the ambient D- and E-Regions of the ionosphere. Multiple satellite situations have not been analyzed.

Theories applicable to ionospheric heating in the F-Region are less certain, because extensive experimental data are not available for corroboration of predictions of heating phenomena or related telecommunications effects. Moreover, experimental scaling laws have not yet been validated.

Based on the theoretical considerations discussed above, microwave heating of the ionosphere conceivably could affect telecommunications systems operating at frequencies higher than 30 MHz that require radio wave propagation through the ionospheric regions. Experimental data are needed to improve prediction capabilities.

3.2.4.3 Increased Ambient Water Content and Alteration of the Natural Hydrogen Cycle above 80 km. The percent change in globally averaged water content due to SPS propellant exhaust increases rapidly with altitude above 80 km. This is due in part to the decrease in the natural water content with rise in altitude as well as to the shape of the HLLV trajectory. At 80 km, the globally averaged steady-state water concentration is theoretically increased by about 8% due to the HLLV flights. Similar calculations also indicate that in a latitude band centered around the launch latitude, the steady-state buildup of water is as much as 15% above ambient at 80 km. The consequences of this increased water content are uncertain at the present time and require further investigation. One potentially important consequence is the net increase in hydrogen atoms following eventual breakdown of both molecular water vapor and molecular hydrogen (the major exhaust effluents from HLLVs, PLVs, and POTVs above 56 km). It has been estimated that the resulting hydrogen will double the natural upward flux of hydrogen through the thermosphere (see Figure 3.3). This could increase the natural rate of escape of hydrogen into outer space and increase the density of the neutral atmosphere above 800 km. Such a density increase could have potentially significant effects on natural dynamic processes in the thermosphere and exosphere and possibly enhance satellite drag above 800 km. These effects are very uncertain at this time and require more thorough investigation. It does appear relatively certain, however, that the upward flux of hydrogen will be increased.

Other potential consequences of the increased water content (and of the anticipated increase in molecular hydrogen) include a chronic, partial depletion of the ionosphere on the global scale, which is expected to be quite small compared to the local ionospheric depletions associated with the individual space vehicle engine burns mentioned above and the potential alteration of the high-altitude temperature profile, which may influence the formation of clouds (see following discussion).

3.2.4.4 Formation of Clouds (Noctilucent) at Mid-Latitudes near 80- to 90-km Altitude. Noctilucent clouds are optically thin clouds of ice crystals, naturally formed at high latitudes near 80-90 km, that are visible in the summer twilight. Theoretical calculations and some not fully understood observations of actual rocket contrails indicate that such clouds could be formed at mid-latitudes by HLLV exhaust. The passage of an HLLV through this altitude range is expected to produce an optically thick cloud having an initial cross-sectional area of about 1 km^2, expanding rapidly to about 1,000 km^2 in about 24 hours. During that expansion, the optical depth diminishes, and the cloud would probably not be visible after about 12 hours. It seems unlikely that these clouds would persist long enough to accumulate and cover a significant fraction of the globe. Hence, these clouds are not expected to have a significant effect on the global climate. A major uncertainty related to the persistence of these high-altitude clouds is the net effect of the accumulated excess water content mentioned in the preceding subsection. Although uncertain, the temperature in the vicinity of the altitude range near 80-90 km may be lowered, promoting cloud formation and persistence. It appears unlikely that such temperature effects could increase cloud persistence to the point where they would be significant from a climatic viewpoint.

3.2.4.5 Exhaust Effluent Effects on the Magnetosphere. The magnetosphere is the outermost region of the atmosphere (see Figure 3.3). The ion density is very low, and the motion of ions is dominated by the Earth's magnetic field. The composition and dynamics of the magnetosphere are complex and not completely understood.

Potential effects of personnel and cargo orbital transfer vehicles (POTV and COTV, respectively) in the magnetosphere are not based on observed phenomena and are, therefore, largely speculative. The masses and energies of effluents that would be produced from propulsion systems identified with the SPS Reference System are large, relative to naturally occurring values. Possible effects include:

- Van Allen belt radiation enhancement;
- Generation of artificial ionospheric electric currents like those produced by natural magnetic storms that are evident on the Earth's surface as interference with public utilities;
- Modified auroral response to solar activity;
- Satellite communications interference;
- Enhanced airglow, a possible source of interference to remote sensing systems on satellites in GEO; and
- Potential changes in weather and climate.

The probability of the SPS producing effects like these is largely unknown. Alternative space transportation strategies may be available if ameliorative measures are found to be necessary.

3.2.4.6 Summary. Ground clouds from launch vehicles could conceivably lead to the exacerbation of potential problems related to compliance with an anticipated Federal EPA air quality standard for nitrogen dioxide. Such clouds could also lead to potential inadvertent weather modification under selected meteorological conditions. At higher altitudes, exhaust effluents and reentry products from space transportation vehicles are likely to affect the ionosphere and, consequently, may degrade telecommunications systems that depend upon either the reflection or transmission properties of the natural ionosphere to achieve desired performance. A microwave power transmission system, if it were to be used for the SPS, could also induce atmospheric changes by virtue of ionospheric heating and thereby affect telecommunications performance.

The injection of large amounts of exhaust effluent is likely to lead to a substantial increase in the ambient water content above 80 km. The consequences of this buildup of water are not quantitatively predictable at this time. However, it is likely that, in combination with injections of molecular hydrogen, these molecules may double the natural upward flux of hydrogen into the thermosphere and mesosphere. The ultimate effects of this phenomena have yet to be quantified.

Injection of water near the altitude range of 80-90 km has been predicted to cause the formation of small-scale and short-lived noctilucent clouds. The scale and duration of such artificially produced clouds is uncertain, but it is unlikely that they would be large enough to cause significant climatic effects.

Injections of large mass and energy from the POTV and COTV flights have the potential for impacts on the plasmasphere and magnetosphere. However, in the absence of data, and in view of the inconclusive nature of theoretical studies, reliable predictions of effects cannot be made at this time.

These findings from the CDEP assessment process are based upon transportation and power transmission characteristics identified with the SPS Reference System. Since those characteristics were not defined precisely, and the nature of the upper atmosphere is incompletely understood, uncertainties remain. Approaches for resolving the remaining uncertainties are listed in Table 3.3.

3.2.5 Geostationary Orbit Allocation

The SPS, along with other satellites, would occupy positions in GEO. It is reasonable to assume that use of GEO by satellites will continue to increase. An acceptable spacing between satellites in GEO must be determined. (The Reference System presumes 1° spacing between adjacent SPSs.) Satellite stationkeeping requirements and capabilities and electromagnetic compatibility are important factors in this determination. Consideration of the international agreements covering the use of GEO is discussed in Sec. 3.3.

Precise quantitative determination of acceptable satellite spacing in GEO has not been made. This requires a knowledge of SPS radio frequency power at the fundamental frequency and its harmonics, as well as in the noise side bands, SPS off-axis antenna gain, off-axis antenna gain for the adjacent satellite, adjacent satellite filtering and shielding, and adjacent satellite system noise and interference susceptibility. As the SPS technology develops and as the characteristics of future satellites are determined, an accurate assessment of the required GEO spacings will be possible.

Rendering the use of GEO of maximal benefit will rquire cooperation among the users with regard to assignment of positions and radio frequencies and consideration of multi-use space platforms. Application of established procedures for reducing the amount of electromagnetic radiation from a given satellite in the direction of an adjacent satellite and increasing the ability of satellites to reject unwanted electromagnetic radiation will permit closer spacing between satellites. The effects associated with geostationary orbit allocation are summarized in Table 3.4.

3.2.6 Effects on Astronomy

Certain parts of a power satellite assembly would always be oriented toward the Sun and would have surface features intended to absorb solar energy. Other parts would have surface finishes that would be relatively smooth and reflective. Thus, it should be expected that power satellites would reflect considerable sunlight and contribute to night sky brightness. Since the satellites would occupy the medium of interest to astronomers, effects on the science of optical astronomy are possible.

An SPS microwave transmission system would beam substantial power from space to Earth at its intended operating frequency and within the

Table 3.3 Atmospheric Effects

Known	Uncertainty	Resolution
Launch vehicles will inject large amounts of water vapor and thermal energy into localized regions of the planetary boundary layer. The potential for inadvertent weather modification under suitable meteorological conditions exists.	The frequency of occurrence of suitable meteorological conditions. The extent of injection of cloud condensation and ice-forming nuclei. The duration and scale of the effects of the nuclei and the thermal energy inputs. The importance of anticipated small increases in cloud population, precipitation, haze, and other meteorological effects to the environs of the launch site.	Design and implement appropriate observational programs associated with rocket launches and conduct laboratory experiments to better characterize nuclei formed in the combustion of rocket propellant. Refine, test, and validate theoretical models suitable for simulating the effects of rocket launches. Examine the meteorological conditions appropriate to potential launch sites. Evaluate the importance of changes in those conditions to the environs of those sites.
Exhaust emissions and reentry products from Reference System heavy-lift launch vehicles and personnel orbit transfer vehicles will modify ion densities at high altitudes. In particular, injection of H_2O and H_2 in the F-Region will cause partial depletion of the F-Region.	Chemical-electrical interactions in the ionosphere, the effectiveness of mitigating strategies, and effects on telecommunications.	Design and implement experiments aimed at critical problems. Measure and analyze interactions through rocket experiments combined with telecommunications tests. Apply results to improve theoretical prediction capabilities. Provide guidance for system operational mitigating strategies and alternatives.
Ground clouds formed by HLLV launches will contain relatively high concentrations of nitrogen oxides that, in combination with effluents from sources in the launch site environs, will exacerbate existing air quality problems under certain conditions.	Exact value of NO_2 air quality standard to be set. Actual ground-level concentrations of NO_2 associated with vehicle launches under various ambient meteorological and air quality conditions typical of anticipated launch sites.	Utilize a range of anticipated probable "standard values" for NO_2 including the existing standard for California. Refine, test, and validate existing modeling techniques for simulating formation and dispersion of NO_2 in ground clouds. Utilize existing and acquire new data related to rocket launches for this purpose. Prepare a climatology of expected NO_2 ground-level concentrations under a range of meteorological and ambient air quality conditions typical of anticipated launch sites.
The Reference System microwave beam can produce heating effects in the lower regions of the ionosphere, but not to the extent of causing discernible degradation to telecommunications dependent upon lower ionosphere radio reflection.	The power density at which ionospheric heating would affect telecommunications, multisatellite effects.	Conduct additional experiments under simulated SPS conditions to test F-Region frequency scaling laws, perform telecommunications degradation tests for representative equipment, and apply results to improve theoretical prediction models.

Table 3.3 (cont'd)

Known	Uncertainty	Resolution
HLLV flights will deposit a large amount of water and hydrogen above 80 km. The globally averaged water content is likely to be increased by amounts ranging from 8% at 80 km to factors of up to 100 or more above 120 km. The injected water and hydrogen will increase the natural upward flux of hydrogen by as much as a factor of 2.	The quantitative increases. Whether the globally averaged increase in water content will be sufficient to alter thermospheric composition or dynamics in a significant way. Whether the increase will result in a chronic, global-scale partial depletion of the ionosphere of sufficient magnitude to degrade telecommunications. Whether the increased hydrogen flux will significantly increase exospheric density and/or modify thermospheric properties.	Obtain a better understanding of the natural hydrogen cycle and develop and implement models to simulate the effects of rocket propellant exhaust on a global scale.
Injection of water vapor from HLLV launches in the altitude range of about 80-90 km is likely to result in the formation of noctilucent clouds.	The scale and persistence of the clouds, especially in view of poorly understood competing cooling and heating mechanisms. Whether cumulative effects could arise and lead to globally significant effects such as changes in climate.	Design and implement observational programs to obtain data on the occurrence and characteristics of high-altitude clouds formed during rocket launches. Improve knowledge of the natural atmosphere near the mesopause and develop and implement models to better simulate the effects of water and hydrogen injection on cloud formation.
Reference System personnel and cargo orbit transfer vehicles would inject substantial amounts of mass and energy into the magnetosphere and plasmasphere.	Ultimate fate of effluents. Potential impacts such as increased radiation hazards to space travelers, auroral modifications, telecommunications and terrestrial utility interference, enhanced airglow emissions, and changes in weather and climate.	Design and implement experiments in the magnetosphere to obtain data for improving understanding of magnetospheric phenomena of interest, and provide system design guidance where appropriate.

Table 3.4 Geostationary Orbit Allocation

Known	Uncertainty	Resolution
Electromagnetic compatibility with other GEO satellites and satellite stationkeeping requirements are important factors in determining acceptable spacing between solar satellites and other satellites in GEO.	Precise estimates of the SPS parameters and the characteristics of other GEO satellites which would allow an accurate quantitative assessment of acceptable GEO spacings.	Research addressing the critical parameters associated with coexistence in GEO, so that quantitative tradeoff analyses can be performed.

design limits of its beam width. As with any other electromagnetic radiating system, there also would be unavoidable radiation in unintended directions from the transmitting antenna and unintentional emissions at frequencies other than the assigned operating frequency. Out-of-beam radiation at any frequency is only a small fraction of within-beam radiation, and emissions in any direction at nondesign frequencies are very much lower in amplitude than the fundamental signal. Nevertheless, unintentional radiation, if not controlled, is a principal contributor to radio frequency interference. A power satellite's location in space suggests it would be a primary concern to radio astronomers and others who are involved in deep space research and who attempt to detect and study the faintest electromagnetic signals reaching Earth from space. Rectenna reradiation also could affect radio astronomy studies.

Representatives of the astronomy community collaborated with the SPS environmental assessment team in identifying potential astronomy effects and listing possible mitigating strategies. Since that time, additional work has been performed to describe the interference effects more fully and to further develop ameliorative measures.[3,22,27,28]

3.2.6.1 Optical Astronomy. An increase in night sky brightness results in a proportional reduction in the effective aperture of an optical telescope used to study faint light sources. Estimates of scattered light based on the Reference System suggest that a power satellite would be as bright as the planet Venus at its brightest. Increased sky brightness from 60 satellites of the Reference System type would prevent optical observatories from effectively observing faint light sources in a 10° by 70° band centered on the line of satellites. There would be a lesser, but noticeable, effect on observations over a region of more than 10° by 90°, or approximately one-half of the night sky.

Aeronomers study the physics and chemistry of the upper atmosphere by observing naturally occurring optical emissions such as airglow. These emissions are difficult to distinguish from other increases in night sky brightness. Sky brightness produced by Reference System satellites would interfere with a substantial fraction of faint airglow studies.

Techniques are available for estimating the amount of light reflected from satellite surfaces of many types (finishes) and orientations. Those estimates can be compared with the sensitivity (resolution) needed or desired to study natural sources of light in the night sky. Differences in these values define the mitigation necessary to prevent adverse effects on astronomical or aeronomical observations. The required mitigation could be achieved by changing satellite features or orientations, or by technical or functional changes in astronomy instruments, or a combination of these possibilities. The principal uncertainties are whether satellite performance could be maintained at acceptable levels as structural or orientation changes were made and the resolution levels that might be needed by astronomers in the future. Last, it might be possible to provide opportunities for astronomical observations from space platforms.

3.2.6.2 Radio Astronomy. While one can easily postulate possible effects of the SPS on radio astronomy from seemingly diametrically opposed characteristics of the two endeavors, it is not yet possible to quantify either interference effects or mitigation specifications that might be necessary to prevent problems. Engineering details of a preferred microwave transmission system (both electrical and mechanical) must be developed. The radio frequency emissions from space associated with radio astronomy make it clear that the SPS presents a potential problem of interference with radio astronomy.

Undesirable microwave radiation from a single power satellite could temporarily overload or permanently damage radio astronomy receivers. Reradiation (reflected energy) from SPS rectennas could have the same effect and could hinder the operation of centimeter wave-length radio telescopes. Radiation from space could affect telescopes pointed toward the line of satellites, while reradiation could affect those located near SPS ground receiving stations.

Unintentional microwave emissions could result in power satellites seeming like individual stationary radio sources, unlike natural radio phenomena. The satellite radiation could, therefore, block out opportunities to study natural resources.

Emissions from manmade sources in allocated radio astronomy bands of the frequency spectrum are constrained by international treaty. Power satellite transmission systems would have to be designed to comply with these regulations, and that is the principal mitigating strategy for avoiding radio astronomy interference. Emissions at other frequencies also could hinder radio telescope capabilities, however, by preventing astronomers from observing spectral lines and frequencies outside protected bands. Avoidance distance criteria would be essential for SPS rectenna siting decisions in order to avoid radio telescope interference from rectenna reradiation.

Potential interference problems that could not be resolved fully by design features of the microwave transmission system or rectenna siting criteria may be amenable to technical and functional solutions applied to radio telescopes. Conventional equipment retrofit could be useful in this regard, as well as functional changes like the use of long baseline interferometry and signal cancellation techniques. Space-based radio telescopes also are a possibility.

3.2.6.3 Summary. Characteristics of power satellite structures and surfaces and the microwave power transmission system can be defined as an SPS-preferred design evolves. These characteristics would provide the basis for predicting reflected light intensities and electromagnetic spectrum signatures. Rectenna reradiation could be included in the latter. The resulting characterizations could then be compared with optical and radio sensitivities required by astronomers to identify mitigation needs and select appropriate ameliorative measures. The latter include system design changes ranging from minor refinements to the use of alternative electrical and mechanical engineering practices, tradeoffs between satellite orientation and satellite performance, conventional interference avoidance retrofits to radio astronomy instruments, functional changes in basic radio astronomy practices, and the possibility of providing astronomy capabilities on space platforms. The knowledge about potential effects between the SPS and astronomy, the related uncertainty in that knowledge, and suggested steps for overcoming uncertainty are listed in Table 3.5.

3.3 SOCIETAL ASSESSMENT

The societal assessment dealt with issues created by the interplay between the SPS and its socioeconomic environment. Primary consideration was given to the elements of this environment that were perceived as influencing the SPS design or the factors that would be most directly affected by the SPS. The primary objective of the societal assessment was to determine whether any issues related to resources, institutions, international relations, or

Table 3.5 Effects on Astronomy

Known	Uncertainty	Resolution
Light reflected from power satellites would produce night sky brightness and possibly hinder optical astronomy and aeronomy. Reflected light can be characterized, and candidate ameliorative measures have been determined.	Quantitative descriptions of degradation effects for optical observations and optimal ameliorative measures.	Identify preferred satellite materials and surface finishes to minimize light reflections, continue dialogue with astronomy community to define desired sensitivity levels for scientific observations.
SPS microwave radiation at the authorized and unintentional frequencies and directions and rectenna reradiation would affect radio astronomy observations and deep space research. Candidate mitigating strategies have been identified.	The SPS spectrum signature (microwave intensity as a function of frequency and direction) and mitigation requirements.	Develop spectrum signature data as SPS design evolves, continue dialogue with astronomy community to identify desired sensitivity levels for scientific observations, and thereby specify mitigation criteria. Analytically evaluate the effectiveness of preferred strategies through laboratory or field tests where practical.

public concerns might significantly impede SPS development. A secondary objective was to establish an information base regarding those issues.

3.3.1 Background

The societal assessment consisted of four task areas. In each, an attempt was made to identify, describe, and evaluate the kinds of societal effects to be expected if the SPS were deployed. These task areas are:

- Resources (materials, energy, and land);
- Institutional issues;
- International implications; and
- Public concerns.

Findings are briefly surveyed below. The results from all tasks are given in more detail in an integrated societal assessment.[4] What is known, what is uncertain, and the suggested resolution for several of the most important issues are highlighted.

3.3.2 Resources

3.3.2.1 General Requirements. An initial understanding of the SPS system characteristics indicates that the physical resources most likely to require early assessment are materials, energy, and land.

The assessment of materials required for SPS deployment compared the requirements for specific raw and bulk materials against domestic and world production rates, domestic and world reserves, manufacturing capacity, and required imports. More than half of the elements or compounds required for either photovoltaic design option (silicon or gallium arsenide) present no problems. The demand for solar-cell materials in both options, as well as for the graphite fiber required for the satellite structure, exceed current processing capabilities. Manufacturing capacity problems are judged to be more severe for the gallium arsenide option.[29] Materials definition for the SPS concept in terms of quantities and specific kinds is in a fairly primitive state. Improved analyses will be required as the materials requirements are defined.

Net energy analysis is used to compare alternative energy generating systems in terms of energy produced per unit of nonrenewable energy required. There have been several analyses of the SPS using many of the widely varying techniques and several variations of the SPS Reference System. Using the 1900-2000 technology estimates of the Reference System and various analytic techniques, the energy payback periods for the SPS ranged from one to six years.[30]

3.3.2.2 Rectenna Siting. The contiguous land area required for rectenna sites is the predominant SPS Reference System physical resource requirement. Each rectenna would require about 150 km^2 of land to accommodate the array of microwave receiving panels and the exclusion zone. The objectives of the siting assessment were to determine if suitable sites exist within the contiguous 48 states to accommodate 60 SPS rectennas; to determine if a sufficient number of these areas were located near major electrical load centers, and if they represent a reasonable solution to utility integration problems, and to assess the societal factors that influence specific site selection.

Assessment results indicated that there are a sufficient number of suitable areas for rectenna sites located throughout the U.S.[31] This conclusion is based on a national-level mapping exercise using USGS 7.5-minute quad maps, wherein each grid cell was approximately equal in size to an SPS Reference System rectenna. The presence of one of 15 absolute exclusion variables that would preclude rectenna siting in a particular grid cell (e.g., densely populated areas, interstate highways, inland waterways, major mountain ranges, dedicated land use) was plotted on the map to eliminate that area from further consideration. Areas not excluded were considered nominally eligible areas. Although nominally eligible areas comprise 40% of the land area of the U.S., the term "nominally eligible" is used advisedly, since there are numerous other potential exclusion variables which, upon further investigation, could preclude the siting of a rectenna. "Eligible" means only that the site is not excluded a priori by those constraints defined as absolute exclusion variables. Even when potential exclusion variables are mapped, however, 19% of the U.S. land area remains nominally eligible.

Subsequent analysis of the 9 electric power planning regions that make up the contiguous 48 states indicated an apparently adequate number of nominally eligible sites in all regions, based on projected electrical generation beyond the year 2000. A study of the placement of 60 nominal sites in relation to projected load centers revealed that, even with transmission distances limited to less than 500 km, the supply of eligible areas generally is not a key constraint.

Additional research is necessary to resolve some of the uncertainties surrounding rectenna siting. For example, the designation "eligible areas" means only that those areas were not excluded in this national-level analysis; more detailed investigations may reveal local constraints that could affect site availability. Also, excluding sites within the flyways of migratory birds (if current research determines that microwaves have a deleterious effect on birds) could significantly reduce site availability. Although site availability was assessed, the range and degree of problems associated with land acquisition were not. Specific site selection criteria inevitably will conflict with other societal needs and values. The size of the contiguous land required by the Reference System rectenna would alter both the social and natural environments.

The estimated two-year rectenna construction period would affect the environment and society. Air quality and water resources would be adversely affected by construction activities. It will be difficult for communities, especially rural ones, to provide the housing and social services for construction workers and their families and the infrastructure to support the scale of construction activities required. These effects could be mitigated by planning that anticipates community impacts and by extending the Reference System construction schedule.

The selection of a number of candidate sites could facilitate definitive research to determine the immediate and long-term consequences of siting on the ecological and human environments, as well as the possibilities for multiple use. Offshore siting is an alternative where land resources would preclude rectenna siting. Thorough assessment of the offshore rectenna option should proceed as soon as an acceptable marine design is available.

3.3.3 Institutional Issues

The SPS issues in the areas of finance and management, regulations, and utility integration will require the modification of existing institutions or the establishment of new ones. The Federal Government or a consortium of governments could be the only source of the large amount of capital required during RD&D. Once the SPS is demonstrated, single unit capital costs could require a different approach to normal utility financing. Consequently, the nature of the Federal Government-private sector relationship with regard to power plant financing will require clarification.

Power plant regulation falls primarily under the jurisdiction of state and local authorities. The regulatory framework of these entities is in a state of flux and varies widely by jurisdiction. The role of state public utility commissions (PUCs) in financing and rate regulation is changing, and PUCs' approval of utilities precommitment to the SPS might depend on Federal guarantees regarding electric power pricing.

States want and are exerting increasing control over power plant planning. This could require a regulatory framework at interstate levels to coordinate power plant regulation and the transmission interties inherent in the SPS concept. The large, contiguous land areas needed for rectennas may require federally mandated and state coordinated land use and energy planning. Not unique to the SPS are regulatory approvals for power plant siting and other regulatory actions that currently require up to 10 years to resolve.

Federal institutional mechanisms will be required to coordinate SPS deployment. Over 40 Federal entities could ultimately be involved with some phase of the SPS. Rectenna siting, as an example, will involve Federal agencies concerned with land use, human health and safety, environmental protection, and power plant planning.

Utility integration will require both technical and nontechnical institutional arrangements. It seems certain that the physical introduction of SPS electrical energy into utility grids will present no major difficulty. The resolution of nontechnical integration issues, e.g., ownership, rate setting, and bulk power sale and purchase, requires detailed study.

3.3.4 International Issues

Three international issues that were treated were: (1) international organizational structures to manage the research, development, and operations of the SPS; (2) the controls to be exercised by international organizations through enforcement of treaties governing operations in space (e.g., on microwave radiation, geostationary orbit, and radio frequency assignment) that may be required because of the SPS; and (3) real or perceived military implications of the SPS.

The effects of SPS deployment are international in scope. An SPS would use outer space and radio frequency spectrum resources that are within the international domain. At the same time, energy delivered by the SPS could be shared globally by developed and developing nations alike. International participation in the deployment of the SPS could contribute to the improvement of international relations.

The basic requirements of an organizational structure created to promote international participation and cooperation are that it must be responsive to U.S. energy needs and the energy requirements of other nations, be politically feasible, and be cost-effective. Four prospective international organizational structure models for the SPS are: (1) a public/private corporation akin to COMSAT, which would evolve into an international corporation akin to INTELSAT; (2) an international organization in which the U.S. would retain substantial influence; (3) a quasi-governmental agency like the TVA; and (4) a multinational private consortium.

3.3.4.1 International Agreements. The SPS, along with other satellites, would occupy positions in GEO. It is reasonable to assume that use of GEO by satellites will continue to increase. In the longer term, maximizing the beneficial use of GEO will require agreement among the users with regard to assignment of positions and radio frequencies and consideration of multi-use space platforms.

Under the 1967 U.N. Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, the space environment is considered to be open to all who are able to use it. The geostationary orbit, radio frequency spectrum, and high-altitude solar energy are considered natural resources of the space environment. As such, they fall within the "province of all mankind" pursuant to the 1967 Principles Treaty. In the case of the SPS, the consideration of space and its environs as the "province of all mankind" raises the question as to who should benefit from the space resource.

Some nations argue that long-term occupancy of a geostationary orbital slot is the same as appropriating it and, therefore, violates existing treaties. Other states with space capabilities have clearly established a customary rule of law whereby outer space exists beyond the sovereignty of any nation-state. This rule has been established in the absence of a formal declaration of outer space and has already encountered opposition from a number of nations without space capabilities.

The finite geostationary orbit space and increasing competition for its use will influence slot availability for the SPS. Allocation will hinge on some consensus on the first-come, first-served principle and some demonstration that the SPS would constitute efficient and economic use of space resources and be a benefit to all nations.

There could be sufficient space in geostationary orbit above the United States to accommodate an array of 60 SPSs and other projected satellites, provided GEO is developed with adequate consideration of position and radio frequency assignments and for the consolidation of services on space platforms. The number of satellites that could occupy GEO is mainly a function of the electromagnetic interference (EMI) among them, as discussed in Sec. 3.2.5.

There are technical and institutional uncertainties regarding geostationary orbit allocation. No general policy by international organizations for the orderly development of GEO has been developed, but international meetings could be organized to address this issue.

The U.N. Committee on the Peaceful Uses of Outer Space, the International Telecommunications Union (ITU), and the Committee on Space Research of the International Council of Scientific Unions are existing organizations that may provide the basis for international cooperation.[32]

3.3.4.2 Military Implications and Vulnerability. The location of the SPS Reference System in geostationary orbit and its power output give rise to two questions: (1) what are the real and perceived military applications of the SPS and their potential effect on international stability, and (2) are there unique system vulnerabilities that could inhibit SPS development?

Most perceived SPS military capabilities contradict the international framework that has been suggested for the SPS. The exchange of technical data and assistance, or the free offer of assistance among nations (including superpowers) so that satellites can be constructed, operated, and effectively monitored by several nations, is desirable from most points of view. Shared control of the SPS and shared energy output, combined with mutual monitoring, offers a deterrent against overt attack.[33]

In the absence of an effective international framework for SPS deployment, or by the contravention of international agreements, certain SPS military applications are possible. Some elements of the SPS Reference System, without modification, have modest military support capabilities. These include the space transportation of personnel and equipment or repair facilities for military satellites and vehicles. However, the use of SPS elements in these support roles would not be as effective as dedicated military systems designed specifically for these missions. Major modifications to the Reference System would be required before the SPS could exercise any strategic capabilities as a weapons platform against Earth or space targets. These modifications could not be accomplished in secret.

As for vunerability, analysis indicates that the SPS Reference System would be no more vulnerable to conventional or proposed weapons than other baseload energy systems. Similarly, the SPS Reference System presents no unique vulnerability problems to paramilitary or terrorist actions.

3.3.5 Public Concerns

The objectives of this task area were to determine public concerns and to provide a mechanism for public involvement in the SPS CDEP. The acceptance of new technologies is doubtful unless the public is involved in the decisionmaking process. The importance of the consideration of public concern has been heightened in recent years by a number of factors: national awareness of the possible environmental effects of large-scale projects, various laws and regulations for the purpose of controlling environmental degradation, direct public involvement in project review and approval, and the prominence and influence of public interest organizations.

The first step in encouraging public participation in the SPS program was communication with various segments of the public. The goal was to create a flexible structure for direct involvement of the public in SPS program development and decisionmaking. The following criteria guided the selection of appropriate participation techniques:

placement of the SPS within a broader energy perspective, making the process multidisciplinary and informational; and providing feedback to DOE.

The participatory mechanism that evolved is the SPS Participatory Technology Process (PTP) (see Appendix B). The PTP was integral to the CDEP and encouraged public participation on two levels. Individuals participated in identifying and defining issues for study, and they peer-reviewed reports of research results. In a broader area, review meetings with the public, extensive dissemination of research results to individuals and organizations, and an active feedback program with three public interest organizations have encouraged the public to participate in the CDEP.

An integral part of the PTP was the SPS public outreach experiment. This experiment involved three special interest groups: (1) the L-5 Society, (2) the Citizen's Energy Project (CEP), and (3) the Forum for the Advancement of Students in Science and Technology (FASST). It measured the response of the organizations' memberships to the dissemination of condensed CDEP research results. The experiment afforded the SPS Project Office, CDEP task managers, and contracted field researchers the opportunity to learn of the concerns and questions of the respondents and to provide specific answers to these questions.[34]

Soundings of public attitudes about the SPS have been mixed. Positive responses identified the SPS as a possible solution to the energy crisis, an application of solar energy to meet baseload electricity needs, and a general economic restorative. There is also a perception that the SPS will be cleaner than most other energy systems. Negative responses included environmental concerns (particularly the effects of microwave radiation on health and safety), the effects of launch vehicle emissions, and land-use/rectenna-siting. Social concerns included the cost, international implications, and institutional centralization due to SPS deployment.

The CDEP public involvement assessment involved three groups of the general public. Limited time and resources prohibited the participation of more "publics" in CDEP. If a decision were made to proceed with the development of the SPS, a strategy emphasizing the involvement of a number of relevant publics in each stage of that development would be necessary.

3.3.6 Summary

The societal assessment found no issue that would preclude the continuation of research and development of the SPS concept.[4] Although SPS land requirements are large and the acquisition of the 60 rectenna sites needed will be difficult, both problems appear to be manageable. Institutions seem equal to the task of accommodating the SPS, even though some of them will require modification. International implications are extensive and will require complex negotiations; assurance of geostationary orbit availability will require early consideration. The public is concerned about the biological effects of microwave radiation from the SPS, the tendency it may have to further centralize our energy resources and society in general, the economics of the system, and its international (particularly military) implications. Table 3.6 summarizes key societal assessment issues.

3.4 COMPARATIVE ASSESSMENT

3.4.1 Background

The merits of the SPS relative to six circa-2000 energy technologies were assessed, considering cost and performance, environmental effects,

Table 3.6 Societal Assessment

Known	Uncertainty	Resolution
Approximately 40% of the U.S. is nominally eligible for rectenna siting. Suitable areas to support Reference System rectenna sites exist. However, migratory bird flyways exist over most of the nominally eligible rectenna siting areas.	The extent of the problem of acquiring 150 km^2 of contiguous land for each site. The extent of potential land use conflicts at specific sites. The impact of migratory bird flyways on the availability of nominally eligible areas; the dependence on the (currently unknown) effect of SPS radiation on birds.	Determine the applicability of rectenna sites for multiple uses. Assess the potential complexity of the land acquisition problem. Conduct studies to determine if microwave radiation has adverse effects on birds.
The construction of SPS rectennas will generate significant social and economic impacts in the vicinity of the rectenna site.	The extent to which advanced planning or modifications in the Reference System construction schedule could mitigate socioeconomic impacts.	Additional studies of the impacts of SPS rectenna construction at specific sites and further studies of rectenna construction scenarios.
The allocation of SPS geostationary slots is a major international problem and will require extensive negotiations.	International long-term approach to space development in general and to GEO slot allocations specifically.	Cooperatively develop a strategy to secure international agreement on GEO allocations.
Military applications of the SPS are possible.	The nature and extent of international control and cooperation necessary to satisfy concerns about the military applications of the SPS.	Evolve an international framework that could include shared control and operation of SPS units, shared energy output, and mutual monitoring of SPS operations.
The SPS will require modifications to existing private and public institutions.	The ability and willingness of these institutions to accommodate the SPS requirements.	Continue and expand liaison with utilities, the insurance industry, the financial community, and government agencies to inform them regarding SPS and to incorporate their needs into the SPS development process.
Public concerns about SPS have been identified and ranked.	The stability, longevity, extent, and potential influence of these concerns with respect to SPS.	Continue and expand the public involvement process.

resource requirements, institutional aspects, and health and safety. The six baseload technologies were: conventional coal-fired steam plants with advanced stack emission controls (CC), light water reactors (LWR), coal gasification/combined cycle (CG/CC), liquid metal fast breeder reactors (LMFBR), central station terrestrial photovoltaic systems (CTPV), and magnetically confined fusion (MCF).

The assessment comprised the development of a traceable data base for the SPS and the alternatives, a methodology,[35] a series of studies comparing the SPS and the alternatives on the basis of the considerations noted above,[30,36-39] and a preliminary and final comparative assessment.[5,40] Two methods of comparison were used: the SPS was compared with each of the alternatives, and the SPS was allowed to interact with the various alternatives for several projections of energy supply and demand.

3.4.2 Cost and Performance

The cost estimates are based on a methodology for calculating a constant-dollar (1978) levelized revenue requirement for the production of a kilowatt hour (kWh) of electrical energy from each system; i.e., how much income exclusive of inflation must a utility take in to pay costs and make a profit averaged over the economic life of the facility. The levelized revenue requirement (expressed in mills/kWh) is the weighted average unit cost of energy production, including capital investment recovery, fuel, and nonfuel operating costs projected over the facility's economic lifetime. A typical utility's weighted average cost of capital funds, exclusive of the general inflation, was selected as the appropriate discount rate.[5]

Table 3.7 displays the low, nominal, and high capital costs projected for each technology for the year 2000. These costs are derived from the direct and indirect capital costs for contingencies (bounded, but unknown expenses during design and construction), owner's expenses, and interest during construction. Projection of these costs to the year 2000 considers ranges of uncertainty in future environmental regulations, safety requirements, and technological advances. Low year-2000 costs for coal and nuclear systems assume optimistic projections of environmental and safety requirements. As a surrogate for possible SPS cost reductions, solar-cell costs were lowered by 43% from present costs to define a lower cost bound. The upper bound on the cost range for all technologies is influenced by technical and regulatory uncertainties. Lengthened construction schedules for the SPS are included within the ranges displayed.

Figure 3.5 displays the electricity generation costs in mills/kWh derived from capital cost data and the fuel price from the three technology market scenarios defined, using the Resources for the Future (RFF) energy supply and demand projections.[41] Figure 3.5 also shows that the total costs of power production for the more highly developed technologies (CC, LWR, CG/CC, and LMFBR) overlap considerably, while those for the the less developed inexhaustible

Table 3.7 Capital Cost Ranges[a]

	CC	LWR	CG/CC	LMFBR	MCF	CTPV	SPS(Si)	SPS(GaAlAs)
Unit capacity (MWe)	1,750	1,250	2 @ 625	1,250	2 @ 660	200	5,000	5,000
Nominal 1978 costs ($/kWe)[b]	549	712	690	1,037	2,378	844	3,340	3,079
2000 costs ($/kWe)[b]								
Low	647	886	813	1,291	2,378	731	3,139	2,874
Nominal	762	1,100	957	1,603	3,677	1,057	3,646	3,362
High	1,605	2,566	2,623	5,048	?	4,229	16,698	15,398

[a]Definitions:

CC	conventional coal
LWR	light water reactor
CG/CC	coal gasification/combined cycle
LMFBR	liquid metal fast breeder reactor
MCF	magnetically confined fusion
CTPV	central station terrestrial photovoltaic
SPS	satellite power system
Si	silicon solar-cell options
GaAlAs	gallium aluminum arsenide solar-cell option

[b]Low, nominal, and high are calculated indicators of uncertainties as described in Refs. 5 and 40.

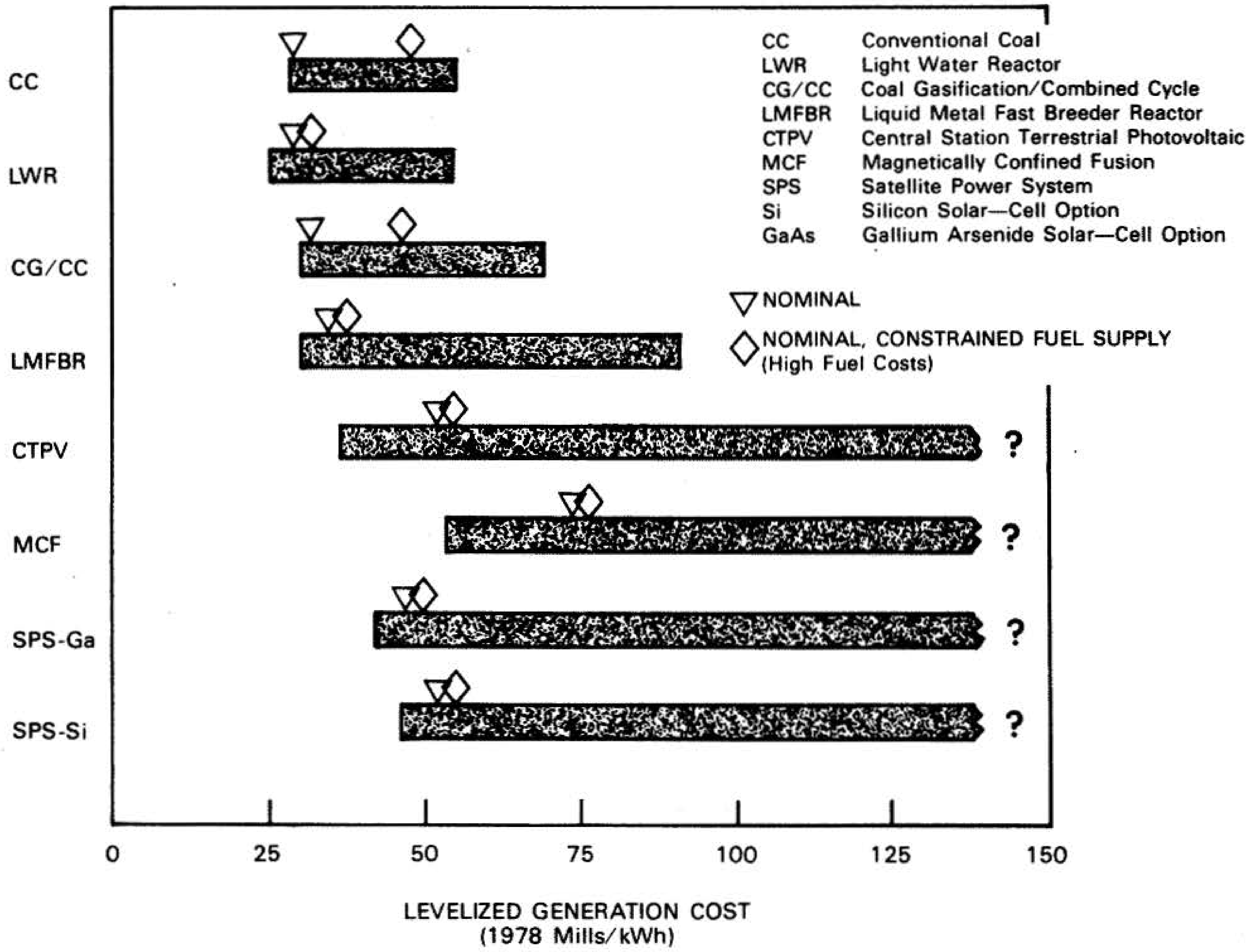

Figure 3.5 Levelized Life-Cycle Cost of Electricity

technologies (CTPV, MCF, and SPS), while overlapping, are higher and in a wider range due to inherent capital cost uncertainties. Depending on the magnitude of capital and fuel costs, the costs of power from the inexhaustible technologies could ultimately be either within range of, or a multiple of, the more highly developed technologies.

Based on the Reference System plan, which predicates a 20-year research and development schedule to the first SPS deployment and a 30-year schedule to 60 satellites at 5 GW each (two systems on line each year), front-end costs have been estimated by a NASA contractor.[42] These costs cover the following:

- Research costs--mainly ground-based research to address environmental and social issues and alternative systems. The product would be a preferred system.

- Engineering--development and testing of prototype subsystems. The product would be specifications for demonstration units and production facilities.

- Demonstration--flight tests of a 100-200 MW unit integrated with a commercial network.

- Investment--creates industrial infrastructure supporting, for example, transportation, photovoltaic, and klystron manufacturing facilities.

- First 5-GW SPS unit.

The front-end costs amount to \$100-\$110 billion. Distribution of these costs is shown in Figure 3.6.[43] It is important to note that these cost estimates assume that all effort is specific to the SPS. The benefits from generic research or from cost sharing (e.g., industry or other Federal program support for photovoltaics manufacturing facilities) have not been considered. One estimate on the magnitude of the "sharability" is 50% to 70% of the \$102.5 billion.[44]

The front-end costs were not included in the per-kWh cost shown in Figure 3.6 because comparable front-end costs (similar definitions and breakouts) were not available for the other technologies considered. Since comparable front-end cost data for the other six technologies were not available, side-by-side comparisons of costs, or of the benefits or disadvantages of public expenditures, were not attempted.

A limited macroeconomic analysis was included in the assessment of the SPS as compared to conventional coal systems. The calculation of changes in GNP for the year 2000 and the qualitative effect on inflation (i.e., increase or decrease in rate of inflation) were attempted against a target GNP of \$3.7 trillion (1978 dollars). The principal result is that, although capital-intensive, the SPS reduces total energy dollar expenditures in a high cost-of-fuel scenario (coal scenario was used) by 2030. The renewable nature of the SPS offsets the inflationary tendencies of increasing coal prices.

3.4.3 Environmental Welfare

Environmental effects not related to health and safety are classified as environmental welfare effects, e.g., weather modification by carbon dioxide, materials degradation, electromagnetic interference with communications, aesthetics, and noise. Welfare effects were identified at each part of the fuel cycle and were categorized by the environmental impact (e.g., air pollution) that produced the welfare effect (e.g., crop damage). In summary, each technology produces environmental effects that have impact on society in different ways. With the exception of possible CO_2 climatic effects and acid rain from coal combustion, all the technologies appear to be roughly equivalent with regard to environmental welfare problems.

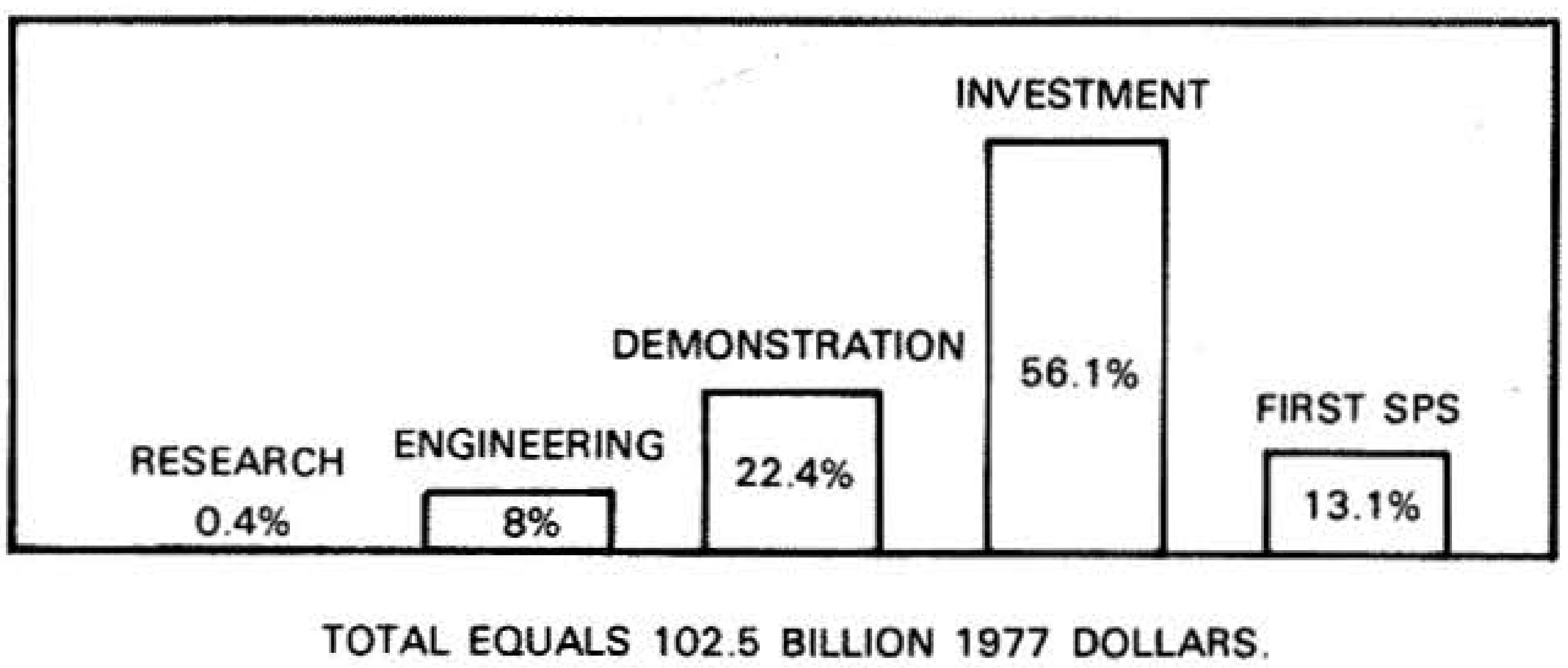

Figure 3.6 Distribution of Front-End Costs

3.4.4 Resources

Side-by-side and alternative futures comparisons were conducted for the resource requirements of the SPS and the six alternative energy technologies. Land, water, materials, and net energy were considered.

Land and water requirements were derived on a normalized basis for each of the energy technologies. The land analysis included, where appropriate, land requirements for resource and fuel extraction and processing, the power plant site, and waste disposal. Land requirements for transmission were not included because they have been shown to be about the same for all technologies. The land requirements for the SPS or CTPV are approximately equal and somewhat larger than those for CC. The SPS and CTPV require large, contiguous sites, while CC requires large mining sites. The SPS technology options available to reduce land requirements are discussed in other sections of this report. Nuclear technologies have the lowest total land requirements.

The several technologies will require water (in operation and during fuel cycle) as noted in Table 3.8. Water requirements for the SPS and CTPV are negligible relative to those of other technologies. Although the SPS and the other technologies assessed face potential materials and material processing constraints, none appears insurmountable.

Table 3.8 Water Requirements for Alternative Energy Technologies

Technology	Cubic Meters per Gigawatt Year
Conventional coal	77×10^6
Light water reactor	37×10^6
Liquid metal fast breeder reactor	32×10^6
Coal gasification/ combined cycle	14×10^6
Magnetically confined fusion	39×10^6
Satellite power system	$\approx 1 \times 10^3$
Central station terrestrial photovoltaics	$\approx 1 \times 10^4$

The net energy analysis calculated net energy balance and compared the results with those in recent publications.[30] Net energy was calculated in two ways: (1) using total input energy required to build and operate the system compared to the energy output, and (2) using total input energy required to build and operate the plant, but excluding the "fuel burned," compared to energy output.

When operating fuel consumption is excluded, all technologies are net energy producers. However, when operating fuel consumption is included, only inexhaustible technologies are net energy producers.

3.4.5 Institutional Considerations

The institutional analysis focused on regulatory issues. Using a data base for the coal and nuclear technologies, governmental regulations and responsibilities and the associated costs were considered. Recent regulatory actions have added to the cost of coal and nuclear energy production. Although similar costs cannot now be estimated for the SPS, it can be stated that the SPS will incur regulatory costs of State and Federal origin. Further, the SPS will incur costs of international origin related to resolution of issues associated with microwave power transmission, orbital positions, and microwave exposure standards. The significance of these costs cannot be determined now.

3.4.6 Health and Safety

A health and safety analysis was prepared for six of the technologies (see Figure 3.7). The estimates of public and occupational risks were

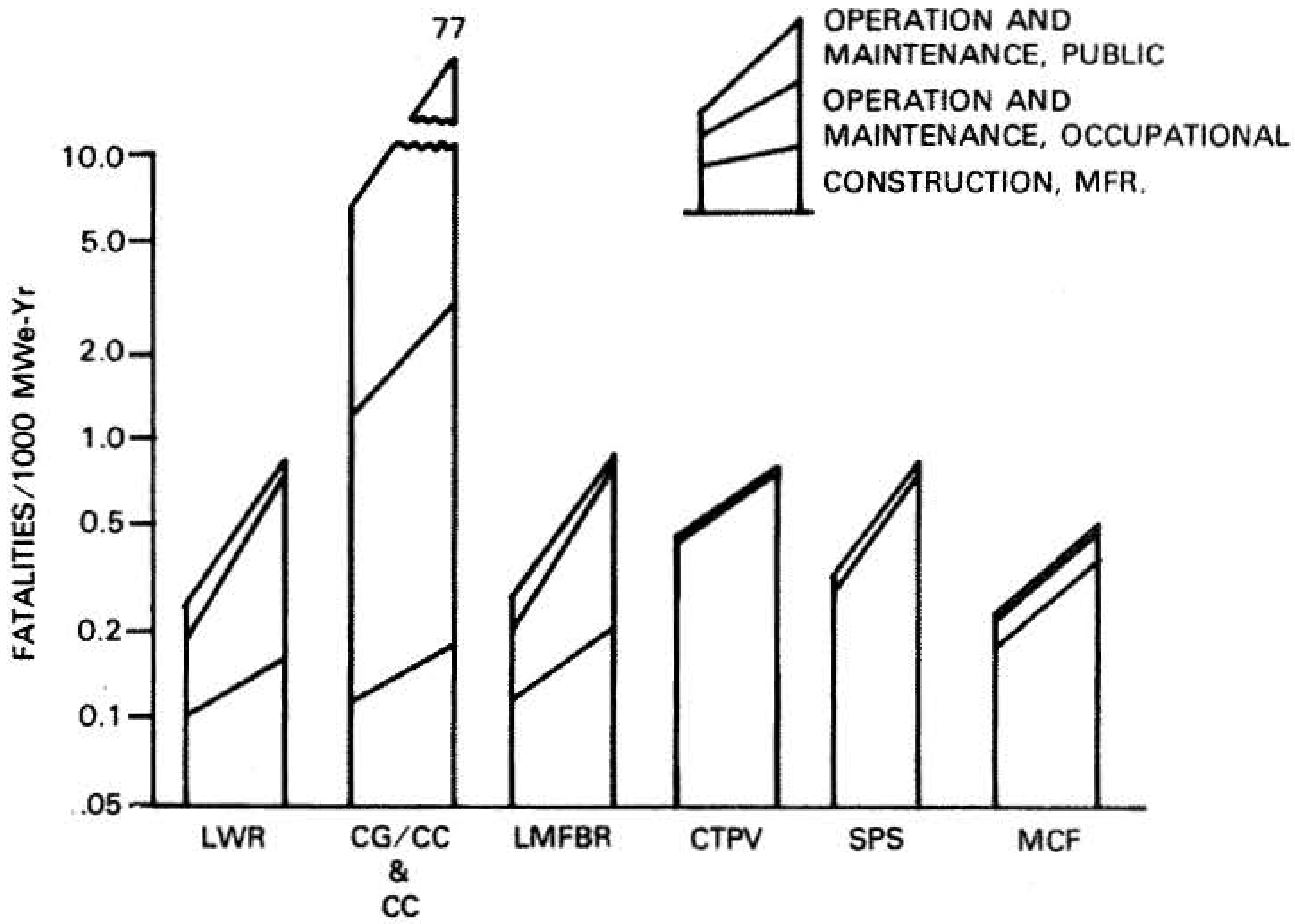

Figure 3.7 Quantified Health Effects

developed on the basis of an average system output of 1,000 MWe. Back-up or energy storage systems were not included.

For a comparative assessment that includes the more capital-intensive, advanced technologies, it is essential that onsite construction risks and direct and indirect facility component manufacturing risks be evaluated. For the solar technologies and fusion, the indirect manufacturing risks comprised a significant fraction of the relatively large construction phase impact. Except for coal, total quantified health effects were found to be similar, although causal factors are, of course, different. Coal is an order of magnitude higher.

Table 3.9 displays the unquantified health effect issues. No unquantified risks were identified for the coal system considered. No analysis of severity or probability of occurrence (i.e., no ranking) was attempted.

3.4.7 Summary Findings

The comparative assessment indicated no insurmountable barriers that would preclude the SPS from being part of a future energy alternatives plan. The life-cycle and capital costs for the SPS, CTPV, and MCF are in the same range and are dominated by uncertainties stemming from the early state of technology and the sensitivity to capacity factor.

The SPS avoids the usual environmental effects associated with present technologies but, as noted elsewhere, presents some unique issues requiring further study: (1) the potential effects of exhaust products of the space transportation system and the microwave power beam on the atmosphere, (2) the potential effects on astronomy and telecommunications, and (3) the potential effects on health of low-dose, long-term microwave exposure. All the technologies considered are net energy producers; all have materials and

Table 3.9 Unquantified Health Effects[a]

Solar Technologies (CTPV, SPS)	Nuclear Technologies (LWR, LMFBR, MCF)
Exposure to cell production emissions and hazardous materials	System failure with public radiation exposure (including waste disposal)
Chronic low-level microwave exposure to the general and worker populations (SPS)	Fuel cycle occupational exposure to chemically toxic materials
Exposure to HLLV emissions and possible space vehicle accidents (SPS)	Diversion of fuel or byproduct for military or subversive uses
Worker exposure to space radiation (SPS)	Liquid metal fire (LMFBR, MCF only)

[a]No unquantified health effects were identified for the coal system used.

material processing constraints that are tractable through early planning and implementation efforts. The SPS requires large, contiguous land areas for the microwave rectenna site. The total land requirement is about equal to that of coal. The allocation of radio frequency and orbital positions and the establishment of international microwave health standards are international regulatory issues that, although manageable, require advanced planning efforts.

For all technologies, the future regulatory environment can play a key cost role. The quantified risks to health and safety are approximately the same for all the technologies considered, with the exception of coal, which is about an order of magnitude higher.

Uncertainties in the findings result from the various states of technical definition of the alternative advanced energy systems considered and from uncertainties in economic and energy supply/demand projections for the next 20-50 years. Such projections are required, but only as tools to assess the future economic and energy climate. Such projections are plausible statements on the future and are not forecasts.

3.5 SYSTEMS DEFINITION

3.5.1 Background

As discussed under SPS System Concepts (Sec. 2), a photovoltaic-microwave system was defined as the Reference System for use in CDEP. Its function was to serve as a basis for conducting the environmental, societal, and comparative assessments and for evaluating alternative SPS concepts and technical approaches at the system and subsystem levels.

In arriving at the Reference System and in evaluating the alternative concepts studied during CDEP, a number of factors were considered, including system weight and cost, constructability, complexity of operation and maintenance, reliability, technical needs, and identification of any insurmountable obstacles. As part of this evaluation process, critical experimental and analytical investigations were conducted in the areas of microwave power transmission, structures, controls, and materials in order to assess key assumptions underlying the system studies.

The Reference System was not optimized and is not considered a preferred system. To arrive at a preferred system that is capable of achieving the projected SPS technical performance, environmental acceptability, and system cost, additional system studies and key technology advancements are required.

In identifying technology needs, it was recognized that national technology programs exist in many of the SPS technical areas that could contribute to meeting SPS needs without the initiation of SPS-unique programs. However, the scale of the SPS, its operating conditions, and, in some cases, the needed technical performance levels require SPS-specific activities that would not necessarily be addressed in national generic programs or at a pace that may be desired.

The SPS knowns, uncertainties, and technology needs are discussed in the following technical categories:

- Energy conversion and on-board power distribution
- Power transmission and reception
- Space structures, controls, and materials
- Space transportation

The following sections are based on Refs. 2, 6, and 45-50.

3.5.2 Solar Energy Conversion and On-Board Power Distribution

The function of the solar energy conversion and satellite power distribution system is to collect and convert solar energy to electrical energy and distribute the power in a controlled manner to the power transmitting antenna and to other load centers within the satellite.

The key needs in this area are: (1) a low-cost energy conversion subsystem having high performance, light weight, and long-term stability; (2) lightweight, high-voltage/high-current power control equipment (e.g., power switches and transformers); and (3) protection from high-voltage surface/space-plasma interaction.

As indicated in Sec. 2.2, both photovoltaic and solar thermal energy conversion concepts are considered workable options for the SPS. Single crystal silicon and gallium aluminum arsenide solar cells (Reference System) appear promising for photovoltaic conversion, while Brayton and Rankine thermodynamic conversion cycles employing rotating machinery are candidates for solar thermal concepts. Ease of construction, redundancy, and maintenance in space appear to favor the photovoltaic concepts at this time.

The current DOE, NASA, and DOD research programs in energy conversion continue to contribute to the technology base needed for the SPS. For example, the DOE terrestrial Low-Cost Solar Array Project will provide manufacturing techniques that could be adapted for low-cost SPS cell production;* the DOE research effort in amorphous silicon and advanced solar-cell concepts could also lead to reduced costs. The ongoing NASA and DOD research programs are concentrating on achieving the technology for thin, high-efficiency, radiation resistant, space qualified solar cells, which are a critical need for the SPS. Thin (2 mil) single crystal silicon cells at about 13% efficiency (Solarex Corporation, NASA Contract NAS 3-21250) and thick (12 mil) gallium aluminum arsenide cells at about 18% efficiency (Hughes Aircraft Company, AF Contract F33615-77-C-3150) have been demonstrated in the laboratory. Work is in progress to increase silicon efficiency to 17-18%

*The cost goals for the DOE terrestrial Low-Cost Solar Array Project for the years 1986 and 2000 are about $0.70 and $0.20 per peak watt (1980 dollars), respectively, for silicon modules.

and to produce very thin gallium aluminum arsenide cells while maintaining high efficiency. Similarly, research and technology programs addressing many aspects of Brayton and Rankine space power systems were conducted by NASA, AEC, and DOD during the 1960s and early 1970s. Current DOE programs are continuing to address these thermal systems for terrestrial application.

There are, however, key technical needs that are specific to the SPS that require research. One key need for SPS energy conversion is stability of performance over many years of operation; the Reference System calls for 30 years. Solar-cell performance is generally degraded by exposure to space radiation; for silicon, the observed degradation in geosynchronous orbit is about 3% per year in the absence of annealing. Recovery of this performance loss by annealing at about 500°C appears possible for bare silicon solar cells. It is not certain that annealing at this temperature is feasible when the cells are integrated into a solar array blanket (assembly of solar cells, cover glass, substrate, adhesives, and solar-cell interconnects) that meets the required SPS performance levels. An approach for reducing the silicon annealing temperature to about 300°C or lower by reducing carbon and oxygen impurities in the material is yet to be proven practical for the SPS application. For gallium aluminum arsenide solar cells, it is estimated that self-annealing will occur at temperatures of about 125°C; this temperature is obtained by use of concentrators that produce a concentration ratio of 2:1. However, at this time, the high-efficiency, thin-film gallium aluminum arsenide solar-cell blanket technology remains to be developed.

Another key need is low cost. Projections of cost for SPS solar cells and blanket fabrication are based on the achievement of a large-scale automated manufacturing, testing, and inspection capability where many of the results of the cost reduction effort in the terrestrial program can be utilized.

Major SPS-specific areas of research in thermal conversion include lightweight solar collectors with concentration ratios of up to 2,000, high-temperature materials needed for achieving high thermodynamic efficiency, and lightweight radiators with protection against meteoroid impacts in designs that provide redundancy (e.g., heat pipes).

In the area of power processing, distribution, and management, the Reference System klystron microwave generating tubes operate at voltage levels of 40-45 kV. Substituting magnetron tubes for klystrons reduces the voltage levels to about 20 kV, and the use of solid state devices would further lower the voltage requirements to 25-200 V. The power distribution technology for the low-voltage, solid state devices exists within the aerospace industry. In addition, the NASA research programs in power processing components and circuits are contributing technology at the low-kilovolt level that is applicable to electric propulsion and space power systems in the multihundred kilovolt size. However, operation at the higher voltage levels requires research that is specific to SPS; eg., low-weight high-voltage/high-current/high-speed, long-life switchgear that is needed to protect the system against possible equipment overloads. The interaction of the space plasma with high-voltage surfaces is also under study by NASA and DOD. These studies would need to be expanded to take into account the specific SPS operating conditions and sized in order to properly assess the possible interactions and their effect on the system.

Table 3.10 summarizes the major knowns, uncertainties, and approaches for their resolution.

Table 3.10 Solar Energy Conversion and On-Board Power Distribution

Known	Uncertainty	Resolution
Single crystal silicon and gallium aluminium arsenide solar cells are candidates for photovoltaic conversion systems.	Compatibility of lightweight solar-cell blanket with annealing temperatures, long life, and cost.	Analysis and tests to better define degradation mechanisms and recovery techniques. Ground tests of candidate blankets (e.g., proton electron irradiation).
Thermal energy conversion systems are competitive in mass and cost with photovoltaic systems.	Relative ease of construction and maintenance of thermal systems in space.	Studies of alternative thermal subsystem concepts (e.g., advanced radiator concepts and high concentration ratio solar collectors).
Solar Brayton and solar Rankine cycles are candidates for thermal conversion systems.	Feasibility of high concentration ratio (2000), lightweight solar collectors; lightweight radiators; and high-temperature materials for high-efficiency and lightweight systems.	Research on thin-film materials for collectors; high-temperature material (ceramics) research for turbines; radiator designs and small-scale tests on leak-tight joint concepts; research on advanced radiator concepts (e.g., dust particle and liquid drop radiators).
SPS Reference System requires high-voltage operation.	Feasibility of high-voltage/high-current/high-speed switchgear.	Study, analysis, and testing at subscale component levels.
Interactions between the space plasma and high-voltage surfaces are possible.	Effects of the space plasma on high-voltage operation.	Expand current analytical models to include SPS operating conditions (e.g., voltage levels and distribution over the satellite) and size. Conduct subscale tests of representative solar array sections in ground vacuum facilities with plasma source to verify analytical model. Verify in space with shuttle flight experiment.

3.5.3 Power Transmission and Reception

The function of the power transmission subsystem is to deliver electricity from the SPS to the utility on the ground. Power transmission is accomplished by beaming the energy from the satellite to a ground receiving station, where the beamed energy is converted to electricty.

Microwaves and lasers are two energy forms potentially suitable for beamed power transmission. In the CDEP, the principal assessment was performed for microwaves. The laser system concept was briefly evaluated as indicated in Sec. 2.2 (SPS Alternative System Concepts).

The key technical needs in this area are precise beam forming and pointing, secure beam control, optimum frequency, conformance to International Telecommunications Union and radio astronomy limits on radio frequency interference, and suitable subsystem efficiency and life.

As a first step, a microwave subsystem was designed for the SPS Reference System. The design provided for klystrons as microwave generators; phase control electronics to form and point the beam, with the feature that the beam must travel along a pilot signal emanating from the receiving antenna (rectenna) or otherwise be automatically defocused (for security the pilot signal was multitoned); slotted waveguides to radiate the beam earthward; and a dipole-diode type of rectenna element that had been demonstrated in field tests during 1975 to receive the beam and convert it to electricity. To assure good all-weather transmission through the atmosphere and to be within an industrial band, a frequency of 2.45 GHz was specified.

System studies were conducted with the klystron as the microwave generator. Subsequently, solid state devices and magnetrons were considered as alternatives to the klystron, and system studies were performed with these devices as the microwave generators. Also, ground-commanded beam focusing and pointing was considered as an alternative to the pilot signal approach, which requires on-board adaptive control; radiators other than the slotted waveguide were evaluated; and alternative candidate rectenna elements were identified.

Critical supporting experiments were performed on the phase distribution electronics, on magnetron and solid state microwave generators, on the slotted waveguide, and on the beam-reflecting and harmonics-generating characteristics of a model rectenna in an anechoic chamber. On the basis of analyses and experiments, the following findings related to the key needs were obtained:

- Transmission of baseload power from the SPS to Earth by means of microwave beams appears technically possible. The effects of power density, microwave frequency, and microwave generator type are discussed in Sec. 2.2.

- In the area of beam forming and pointing, wire and fiber optics options for distributing the reference phase were demonstrated in the laboratory. An on-board reference phase broadcasting procedure that would be of special utility in solid state systems, as well as in tube systems, was defined. Additionally, the studies indicated that both pilot-signal-controlled and ground-commanded approaches to phase control appear technically possible. The preferred procedures for forming and pointing the microwave beam and the accuracies obtainable for the beam shape and pointing direction remain to be determined.

- Magnetrons and solid state devices are candidate alternatives to the klystron. In laboratory tests, the magnetron operated with a signal-to-noise ratio of at least 138 dB/kHz at 1 kW output, with the cathode heater turned off after initial startup; magnetron performance at 5-10 kW output per tube, which would be used in the SPS application, would have to be investigated. In tests, a solid state device delivered 1.2 W at 72% efficiency and 5.6 W at 63% efficiency; the 80% efficiency projected for the SPS application remains to be demonstrated. The preferred choice of microwave generator and its efficiency, stability, noise, and harmonics at SPS operating conditions need to be determined.

- The slotted waveguide appears to be the most suitable antenna radiator option. In an experiment on dissipative losses, the measured efficiency of an experimental waveguide section was 99% at a 480-W power level. Performance at SPS conditions and waveguide dimensional stability remain to be investigated.

- In tests of beam scattering and harmonics generation by a small rectenna in an anechoic chamber, the reflected portion of an incident beam was scattered over a broad range of angles, and harmonics were generated. The degree of control of beam scattering and harmonic generation by the rectenna is to be determined.

As previously indicated, the use of lasers was briefly studied. However, high-efficiency laser technology is relatively undeveloped at this time. In addition, the fact that laser beams are attenuated by clouds needs to be addressed.

These knowns, uncertainties, and approaches to resolution are listed in Table 3.11.

3.5.4 Space Structures, Controls and Materials

The functions of the SPS structure are: (1) to provide structural support to the power system and (2) to provide mounting and application points for the control system. Controls to regulate the satellite attitude, its orbital station, and, possibly, the deflections and shape of the structure are needed because a number of disturbances act on an SPS in orbit.

Examples of such disturbances are: (1) gravity gradient torque, solar radiation pressure, and solar heating; (2) nonuniform structure temperatures with associated thermal stress, deformation, and cycling; (3) structures interactions as between the slowly rotating microwave antenna and the solar array in the Reference System; (4) operational loads associated with construction, maintenance, transportation, and handling; and (5) forces and moments exerted by the controls.

The key need in this technical area is to achieve the required properties of SPS materials, structures, and controls to assure long-term stability as well as accurate pointing and stationkeeping of the SPS. Studies directed at meeting this need were conducted in the CDEP. Graphite composite materials that have very low coefficients of thermal expansion (CTEs) and aluminum were evaluated for use in the structure. Truss structures were assumed. Candidate approaches for attitude control and stationkeeping were identified for the satellite, with cognizance taken of the differing requirements of the antenna and the solar array. In order to obtain insight into the fundamental aspects of SPS structure/disturbance/control interactions and structural stability, a program of analytical studies was initiated. Mathematical models were formulated for three idealized satellite configurations patterned after the photovoltaic Reference System. For each idealized configuration, the equations of motion were written, and parametric calculations were performed to obtain insight into potential vibrations of the solar array and microwave antenna, the effects of various types of applied forces, and the influence of damping. The parametric results provided preliminary information potentially useful for design of SPS structures and controls.

In the Reference System, the structural material is a graphite composite having a low CTE. The structures of both the solar array and the antenna are trusses, with beams of thin-gauge material, but designed to be stiff and to be built in space by an automated beam builder.

Analytical findings applicable to SPS design and dynamic stability are:

- For a planar SPS in geosynchronous orbit, the largest environmental source of structural loads and attitude perturbations is the gravity gradient. The prime disturbance to east-west stationkeeping is the solar pressure. The calculations indicate that these environmental loads are benign and that the forces

Table 3.11 Power Transmission and Reception

Known	Uncertainty	Resolution
Distribution of the reference signal needed for phase adjustment has been demonstrated and options for phase control have been identified.	The most suitable approach to forming and pointing the microwave beam. Beaming accuracy.	Investigations and comparative evaluations are required in the following areas. - Phase distribution concepts: hard wire, fiber optics, broadcast; - Phase control: retrodirective vs. ground commanded vs. hybrid; and - Security provisions: antijamming, antispoofing.
Principles of high-performance klystron design have been defined; low-noise, stable operation of the magnetron has been demonstrated at low power; and advancement in performance of solid state devices has been demonstrated.	The best choice of microwave generator (D.C.-RF converter). Generator efficiency, stability, noise, and harmonics at SPS operating conditions.	Performance evaluation of: klystron, magnetron, solid state and gyrocon, with respect to thermal control, efficiency, noise harmonics, and phase stability.
The slotted waveguide radiator was found to be the most suitable among the antenna element options studied.	Optimum material of construction; harmonics generation and/or suppression characteristics; efficiency and response to thermal cycling.	Material fabricability, stability, and weight of: - Low CTE (nonmetallic) composites - Metal matrix composites, and - Aluminum. Design for harmonics suppression. Efficiency, gain experiments. Dimensional and performance stability under thermal cycling.
Microwave scattering at the fundamental frequency and its harmonics will occur from the rectenna.	The microwave scattering and harmonic generation characteristics of an SPS rectenna. The amount that is tolerable.	Conception and experimental verification of the following. - Concepts for minimizing reflection and scattering of incident fundamental frequency energy, and - Improved filters to minimize radiation and reflection of harmonics.

required to counteract them are not large.

• The transient thermal environment is a major factor in terms of potential thermal distortion, thermal stresses, and thermally induced oscillations. The use of a low-CTE graphite composite material for the SPS structure reduces these effects and enables the structure to meet dimensional control requirements in both the antenna and the solar array during the eclipses that occur during the spring and fall equinoxes, as well as during the less-stringent daily cycles. On the other hand, use of aluminum as an SPS structural material involves larger deflections, higher stresses, a weight penalty, and increased complexity of design verification. However, the raw materials cost of graphite composites is high compared to the cost of aluminum ingot, and automated fabrication of graphite composites in space may be difficult.

o Structural stiffness is a major factor in achieving dynamic stability and control. The classical approach of making the structure frequency higher than the control frequency and the control frequency higher than the disturbance frequency appears to be suitable for the SPS application. The number of structural modes arising from the large scale and structural flexibility of the SPS is uncertain. In achieving dynamic stability, damping is also an important factor. Graphite composites have desirably high damping properties.

o The construction phase will be a leading factor in determining the design of the structure control system. The structure/thermal/control interaction and the required distribution of controls are uncertain.

o The SPS structure is designed to operate in zero-gravity and cannot be tested at large scale on the ground. Only component and subcomponent structural development ground testing will be feasible. Thus, design, development, and construction of the SPS will rely to a high degree on modeling and dynamic analysis.

o Assessment of structural and coating materials for the SPS will require data on basic materials properties, overall characteristics, and performance as a function of operating time in the SPS. The stability, outgassing characteristics, and fatigue resistance of composite materials are to be determined.

Analytical and experimental tasks for resolving these uncertainties are indicated in Table 3.12. Substantial aid in these areas is available from the ongoing NASA technology programs on large space structures and materials, but SPS-unique technology will also be required because of SPS scale, detailed design, and operating conditions.

As the uncertainties are resolved, the models and materials data will permit analytical SPS design. However, verification of preferred SPS structure concepts will require tests in space.

3.5.5 Construction, Operation, and Maintenance

The function of the construction, operation, and maintenance assessment area was to develop an understanding of the requirements for building, operating, and maintaining the SPS and the ground-based rectenna. The key need in this area is to achieve suitable rates, costs, and safety in the performance of these operational functions. Choice of structures that are relatively easy to build and that permit a high degree of automation will facilitate meeting these needs for both the satellite and the rectenna.

At present, detailed construction techniques for large space structures are not available. Assembly procedures, required equipment, structural loads, structural response, and control requirements are only partially understood. Both generic and SPS-specific efforts will be required to meet SPS construction needs.

Structures and operations technology activities aimed at obtaining increased understanding in these areas are in progress at NASA as part of the generic space program. These activities include analytical formulation of structural response to applied loads, automated fabrication, and remotely controlled and manned operations in space. The results of these activities will be available to support SPS needs.

In addition to the generic technology, SPS-specific efforts will be

Table 3.12 Space Structures, Controls, and Materials

Known	Uncertainty	Resolution
Environmental loads on the SPS structure in the geostationary orbit are mild. However, the final structure design is governed by internal mechanical and thermally induced loads as well. At present, no suitable analytical models exist.	The number of significant structural modes arising from the large scale and flexibility of SPS. The required distribution of mechanical controls. The interaction among the structural, thermal, and mechanical disturbances, and the forces and torques produced by the controls.	Analytical models are needed of: - Environment, - Controls concepts, and - Structure/control/thermal disturbance interactions. Experiments are needed on structural components and scaled models.
The use of low-CTE graphite composite materials for SPS structure minimizes thermal deflection and stress and enables the structure to meet dimensional control requirements during the most stringent (equinox) operating conditions.	Stability in the SPS environment, and fatigue resistance under thermal stress cycling, cost reducibility, and ease of automated fabrication.	Ground based materials technology is required. Areas of research needed are: - Candidate materials identification, - Degradation modeling, - Accelerated life testing under simulated SPS conditions with particular interest in thermal stress fatigue tests, and - Cost reduction and automated fabrication investigations.

required because of SPS scale. Current plans in the generic space program provide for maximal structure dimensions of about 300 m. The SPS scale is on the order of 2-10 km. Supplementary SPS-specific analytical models and ground simulation will be needed to define the loads, control laws, equipment, and the optimal mix of manned and automated processes required for SPS construction and operation at GEO. In studying the SPS-specific areas, a scale-related factor that will be important is the variation in size and mass of the structure as construction proceeds.

The CDEP studies indicated that both LEO and GEO construction orbits appear feasible. In the Reference System, GEO was selected as the construction location, but LEO is still viewed as an option. For the Reference System, specific facilities, material masses, manpower requirements, vehicle types and fleet sizes, payloads, and construction timelines were computed as detailed in Ref. 2. These results require verification.

Regardless of the construction location selected for the Satellite Power System, one or more elements of the total system will be located in GEO and LEO. Avoidance of unplanned reentry of these elements will be mandatory. For elements in GEO (e.g., satellite), the atmospheric density at that altitude is low, and orbital decay over the 30-year life of the satellite would not exceed 2.5 km, even in the absence of controls. Thus, reentry from GEO is not a concern. On the other hand, at LEO, active control provisions are required. An initial study indicated that under nominal conditions, hundreds to thousands of days would be required for reentry from LEO.[50] However, under the worst-case LEO conditions (tumbling combined with high-atmospheric density encountered during sunspot maximal condition), reentry could occur in as few as five days if no active controls are applied. In the Reference System design, on-board propulsion systems are provided for attitude control and orbitkeeping. The study indicated that the addition of 100% on-board propulsion-system redundancy would contribute less than 1% to the total mass of the SPS element being controlled. In addition to provisions for attitude control and stationkeeping, operational procedures are required (e.g., orbital debris removal and stationkeeping of system elements at adequate separation distances) to prevent collisions. With regard to safety during launch to LEO, shuttle operations will provide initial experience in defining rules applicable for SPS vehicles.

The rectenna is a significant factor affecting system cost. For the structure, the initial guideline was that standard construction methods and equipment would be adequate. However, in view of the projected labor intensiveness of the construction phase, the potential of automated construction to reduce rectenna cost requires additional investigation.

Rectenna site characteristics, environment, materials availability, and location can also influence schedule and cost significantly. Land siting of the rectenna has received primary consideration. Study results indicate that the rectenna could also be built offshore, but further investigations are required to determine the practicality of this approach.

Specific tasks required to reduce uncertainties of the satellite and rectenna construction phases are indicated in Table 3.13.

3.5.6 Space Transportation

The mission of the transportation system is to carry material and personnel between Earth and SPS stations in LEO and GEO. The key need in meeting the SPS projections of low payload cost (about \$30/kg or less to LEO) and high launch rate is an airline-type operation having high reliability, long time between failures, and little or no maintenance between flights (maintenance relegated to scheduled periods) to provide turnaround time of four to five days.

To meet this need, a number of vehicle concepts were analyzed for the Reference System. Four basic vehicle types were defined: the heavy-lift launch vehicle (HLLV) and personnel launch vehicle (PLV), which handle material and personnel traffic between Earth and LEO, and the cargo orbit transfer vehicle (COTV) and personnel orbit transfer vehicle (POTV), which transport cargo and crew between LEO and GEO. For each of these vehicle types, evaluations were made on the basis of their operational complexity, cost, interfaces, and technology advancement needs.

Based on these studies, a two-stage reusable chemical propulsion vehicle was selected as the HLLV for the Reference System. For the COTV application, electric propulsion was selected. Electric propulsion is characterized by low thrust and high specific impulse; the low thrust leads to long trip times, but the high specific impulse results in low propellant requirements and a capability to deliver large payloads from LEO to GEO. For the POTV, chemical propulsion was selected to provide fast delivery of personnel and priority cargo to GEO.

The major cost element in the space transportation system is the HLLV. As discussed in Sec. 2.2, an HLLV sized to meet other potential future space mission needs also appears capable of supporting the SPS launch traffic.

For the above vehicle types, a technology base is continuing to develop as a part of the ongoing NASA generic programs. For example, the current

Table 3.13 Construction, Operation, and Maintenance

Known	Uncertainty	Resolution
Detailed construction and operational techniques are not available for large space structures.	Rates, costs, and safety of SPS construction and operations.	Analysis, modeling and ground simulation are needed to define the loads, control laws, equipment, and optimum mix of manned and automated processes required for SPS construction and in operations at GEO. Results developed in ongoing space structures and operations technology programs would be available to support these needs. SPS-specific technology advancement would be required for SPS-unique areas, such as those possibly arising from SPS scale.
Active attitude and orbit maintenance controls are required.	Degree of redundancy required.	
The rectenna now accounts for about 20% of the system cost. At present, standard construction methods are considered adequate. Rectenna construction is envisioned as very labor intensive.	The potential of automated construction to significantly reduce rectenna costs.	Experiments are needed to provide information on feasibility, rates, and costs of automated construction.
Study shows that a rectenna could be built offshore.	The practicality of offshore rectenna siting.	Study and experiments are needed on the feasibility and practicality of the offshore rectenna concept.

level of technology for chemical propulsion engine systems is derived from the Apollo Saturn V (hydrocarbon-oxygen engine) and the space shuttle (high-pressure, hydrogen-oxygen engine) programs. As the shuttle program moves into an operational phase, the major needs of the SPS, such as long life, high reliability, and reusability (300 reuses for the HLLV, for example) will be continually addressed. In addition, the current NASA generic program is aimed at advancing the technology of hydrocarbon-oxygen engines. This effort involves research on high-pressure pumps, turbines, bearings, seals, nozzles, thrust chambers, and diagnostic instrumentation. Also, research on advanced reusable thermal protection systems is underway.

Similarly, past NASA programs have developed the ion engine technology for a size range of 5-30 cm in diameter, with mercury as the propellant. Current efforts are concentrating on the use of inert gases, such as argon and xenon, as propellants and on scalability of the technology to larger sizes. For the SPS Reference System, the ion engine, in the 75-100 cm diameter size and with argon as the propellant, was selected for the COTV application. An alternative to this engine type is the magnetoplasmadynamic (MPD) thruster, which can use hydrogen as a propellant and produce higher thrust per unit area. Research in this area is also underway at NASA.

In summary, the major areas of uncertainty in the SPS space transportation system arise from the need for increased reusability, reliability, long life, and maintainability. To a degree, these uncertainties are being addressed in the shuttle program and in NASA research programs. However, advancements in the various technology areas are required if the projected SPS needs are to be met.

The knowns, uncertainties, and approaches for their possible resolution are summarized in Table 3.14.

Table 3.14 Space Transportation

Known	Uncertainty	Resolution
Airline type of operation, (e.g., vehicle reusability, maintenance, and short turnaround time) required to meet SPS cost projections.	Achievement of SPS projected costs.	Shuttle operations will form a basis for projected major scale-up of flights at reduced operating costs. Continued studies and research are needed on vehicle subsystems, fault detection instrumentation, and software to minimize turnaround time and operation costs.
Vehicles must be reusable and capable of withstanding high temperatures and repeated thermal cycles.	Performance of metallic or ceramic materials for application in reusable thermal protection systems.	Evaluation of metallic thermal protection systems with or without nonmetallic insulation material.
	Availability of reusable cryogenic insulation systems that are easily inspected and require normal maintenance.	Test of reusable insulation systems concepts including foam types and metallic honeycomb types.
The Saturn V hydrocarbon-oxygen engine and the shuttle hydrogen-oxygen engine provide the technology base for future advancement.	Achievement of increased engine life, reusability and maintainability.	Breadboard component tests at subscale level for hydrocarbon-oxygen and hydrogen-oxygen engines (pumps, turbines, bearings, seals, nozzles, thrust chambers)
Electric propulsion (ion engines), using argon propellant, was selected for COTV application.	Scalability of ion engine technology. Performance capability of magnetoplasmadynamic (MPD) engines (alternative to ion engines).	Continued analysis and tests to investigate critical scaling parameters. Research and tests on MPD thrusters using hydrogen as the propellant.

APPENDIX A: HISTORICAL BACKGROUND

The Solar Power Satellite (SPS) concept of using a system of satellites in high Earth orbit to collect solar energy in space for the generation of electrical power to be used on Earth was first suggested in 1968 by Dr. Peter Glaser.[1] This concept was further developed and refined in a series of studies by NASA and by the industrial team of A.D. Little, Raytheon, and Grumman.[2]

Several variations of the concept have been proposed and studied, including solar thermal conversion systems, nuclear power satellites, power relay satellites, and the use of large, orbiting mirrors to reflect sunlight onto the night side of the Earth at selected locations. In 1976, engineering, environmental, and economic analyses of several SPS concepts were performed by NASA.[3,4]

In addressing the FY 1977 budget, the Office of Management and Budget decided that the responsibility for assessing the SPS should be transferred to ERDA (now DOE) and that ERDA should determine the appropriate support level in the context of its national responsibility for energy research, development, and demonstration. To meet this responsibility, ERDA assembled a task group on satellite power stations.[5,6] This group recommended that studies of the SPS concept and its potential should be pursued for the following purposes: (1) to assess the SPS as a promising energy technology, or (2) to identify barriers to the SPS that might suggest that significant research and development should not be conducted.

The Satellite Power System Concept Development and Evaluation Program was published in 1978 to implement a major part of the task group's recommendations.[7] It incorporated NASA's plan for an SPS program definition, which was later modified by a DOE/NASA joint agreement.[8] Basically, a period of intensive study was planned to synthesize and extend previous work, to address key issues previously identified, to identify and define new issues, and to provide an adequate information base from which recommendations for subsequent SPS efforts could be made. The overall CDEP objective was to develop an initial understanding of the technical feasibility, economic viability, and social and environmental acceptability of the SPS concept by the end of FY 1980.

Study efforts by NASA resulted in a Reference System configuration, which was used during CDEP as a basis for the environmental, societal, and comparative assessments.[9] This system configuration is by no means optimal, but it represents a credible approach. During CDEP, the SPS reference design was iterated to take advantage of technological advancements and the findings of the SPS environmental and societal assessment efforts. In addition, NASA considered candidate alternatives and emerging technologies that might increase the viability of the SPS. In 1975, NASA demonstrated the feasibility of power transmission by microwaves.[10]

In 1978, preliminary environmental and societal assessments of the SPS Reference System were completed, and laboratory and field experiments were started. The preliminary environmental assessment of the SPS Reference System was based primarily on information available in the literature along with a limited amount of experimental data.[11] In the societal area, critical SPS societal issues were identified and defined.[12] In the comparative assessment area, a methodology to compare the SPS with other energy sources, particularly sources that would generate baseload electricity during the same period as the SPS, was developed.[13] The results of the systems studies and of the environmental and societal assessments supported the data base for the comparative assessment.

In 1979, a revision of the preliminary environmental assessment and a preliminary comparative assessment were completed.[14,15] A second program review was held in June 1979. A preliminary program assessment report was published.

In 1980, an SPS symposium and program review was held. Systems definition, environmental, societal, comparative, and program assessment reports were published.

Milestones in the history of the SPS concept are as follows:

1968 -- Dr. Peter Glaser proposed the concept.

1972 -- NASA/Lewis evaluated the concept.

1973 -- Dr. Glaser patented the concept.

1975 -- NASA Office of Energy Programs evaluated the concept.

1976 -- NASA initiated intensive systems definition activities.

-- Program responsibility was assigned to the Energy Research and Development Administration.

-- ERDA task group recommended an evaluation study.

1977 -- DOE/NASA approved the plan for and initiated the Concept Development and Evaluation Program.

1978 -- DOE/NASA held the first program review.

-- DOE/NASA published the reference system description and the preliminary environmental and societal assessments.

1979 -- DOE/NASA held the second program review.

-- DOE/NASA completed the preliminary comparative assessment and updated the environmental and societal assessments.

1980 -- DOE/NASA held an SPS symposium and the third program review.

-- DOE/NASA conducted peer reviews of technology status.

-- DOE/NASA published the CDEP system definition report and the environmental, societal, and comparative assessments.

-- DOE/NASA published the program assessment report.

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APPENDIX B: CDEP ASSESSMENT PROCESS

CDEP was an integrated process for developing information on what is known and what is uncertain regarding Solar Power Satellite (SPS) issues. The results are intended to provide the Congress, the Executive Branch, and the general public with a basis for decisions regarding the SPS.

FUNCTIONAL ORGANIZATION

The functional organization to achieve the CDEP objective is shown in Figure B.1. The Solar Power Satellite Project Division, which managed CDEP, is part of DOE's Office of Energy Research, Basic Energy Sciences.

Systems Definition involved the definition, analysis, design, and description of the SPS that was assessed. In addition, the impact of emerging technologies on the SPS concept was assessed, and the required critical supporting experimental investigations were conducted.

Environmental Assessment included the assessment of: (1) the effect of microwave beams on human health and ecosystems; (2) nonmicrowave effects (e.g., due to conventional terrestrial mining, manufacturing, and transportation and space operations) on human health and ecosystems; (3) the effects of launch, orbit transfer, and reentry operations on the Earth's atmosphere; (4) effects of SPS microwave beams on the ionosphere and on telecommunications; and (5) electromagnetic compatibility.

Societal Assessment dealt with: (1) the land, energy, and material resources required to build and operate the SPS; (2) the institutional aspects (governmental, financial, and utility) to manage the development, construction, and operation of the SPS; (3) the international considerations, including the military implications of the SPS; and (4) public concerns with the SPS.

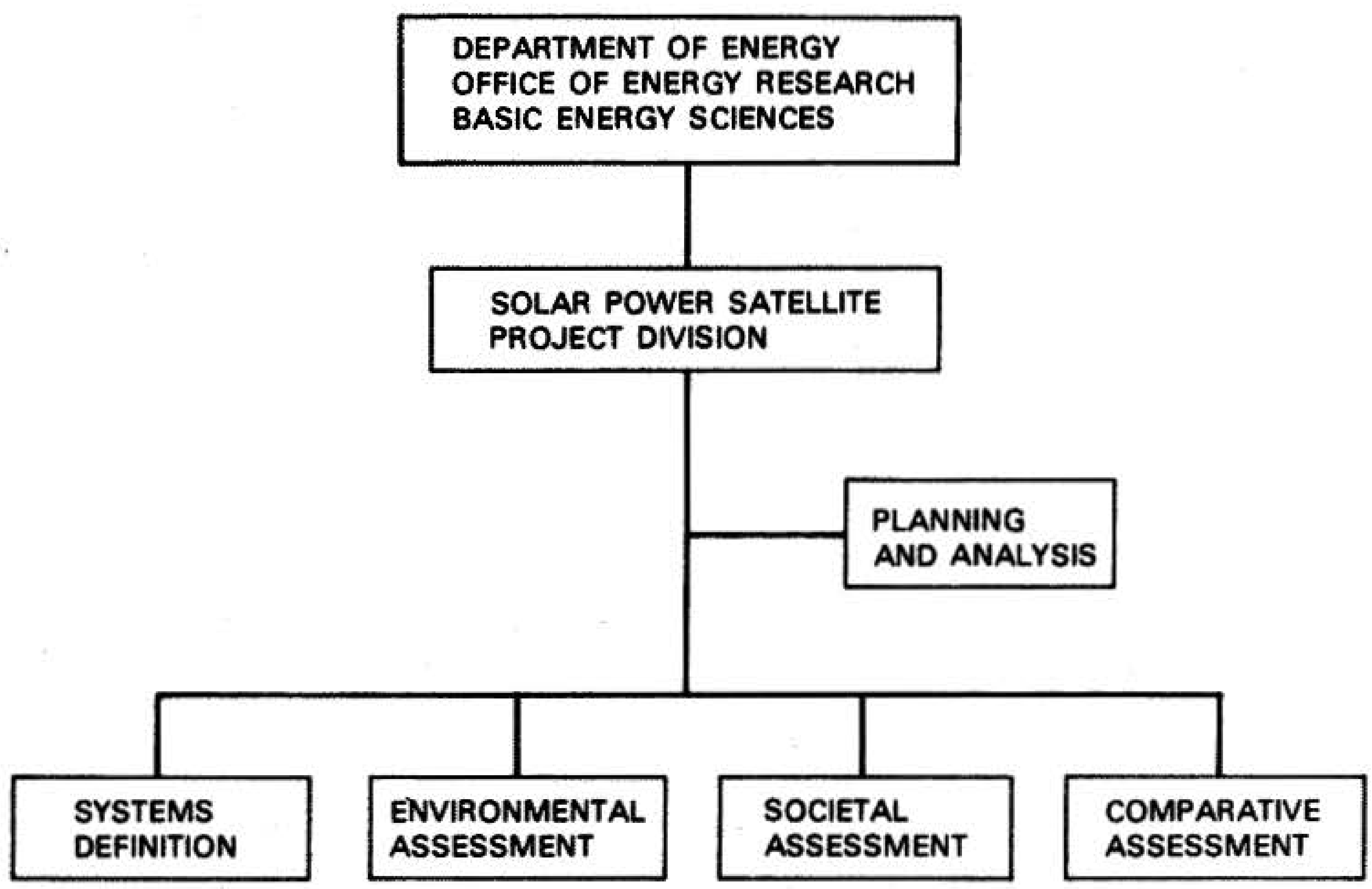

Figure B.1 SPS Functional Organization

Comparative Assessment compared the SPS with six alternative energy technologies. These included: improved conventional technologies (coal-fired steam plant, light water reactor); near-term technologies (coal-gasification/combined cycle, liquid metal fast breeder reactor), and advanced technologies (central-station terrestrial photovoltaics, magnetically confined fusion). The comparisons were based on considerations of cost and performance; environmental, climatic, and health and safety impacts; and land and energy requirements. The key organizations that supported the CDEP and their roles are shown in Table B.1.

THE PROCESS

CDEP was an evolutionary process, drawing on past studies and experiments and developing new knowledge within an expanding framework of issues.[1] The assessment process was designed to facilitate a continuing, face-to-face exchange between individuals involved in systems definition and design investigations and the environmental, societal, and comparative assessment efforts.[2-4] This process was iterative, recognizing that different groups sometimes have contradictory goals and objectives. It attempted to manage these potential conflicts by determining the areas of disagreement and by insuring that new information was immediately supplied to all as part of the overall strategy. Thus, if an environmental concern was defined, this concern was then discussed in detail with the systems designers and technologists to see if a change in the design or in the technology could eliminate or mitigate the concern. This resulted in an effective working relationship among the individuals involved in the assessment.

Table B.1 Key Organizations

Program Responsibility
Department of Energy
Project Management
Department of Energy
National Aeronautics and Space Administration
Systems Definition
National Aeronautics and Space Administration
Johnson Space Center
Boeing Aerospace Company
Marshall Space Flight Center
Rockwell International
Environmental Assessment
Department of Commerce (Institute for Telecommunication Sciences)
Environmental Protection Agency
NASA (Ames Research Center)
Argonne National Laboratory
Lawrence Berkeley Laboratory
Los Alamos Scientific Laboratory
Pacific Northwest Laboratories
Societal Assessment
Planning Research Corporation
Comparative Assessment
Argonne National Laboratory

As illustrated in Figure B.2, the systems definition process produced a Reference System from which technical issues were defined and critical supporting investigations were conducted. The results were fed back into the systems definition activities. As new concepts and emerging technologies were identified, alternative systems were configured and sent through the cycle of defining technical issues and conducting research. This process was aimed at developing a technically preferable system. As Figure B.2 shows, the information developed in the systems definition work entered the overall participatory technology process, which was designed to unify the assessment and systems definition efforts.

As shown in Figure B.2, the Reference System design and the findings from critical supporting investigations were submitted to workshop and expert peer groups that studied and defined the key issues and concerns. Of particular value were a series of in-depth peer review workshops covering the major SPS

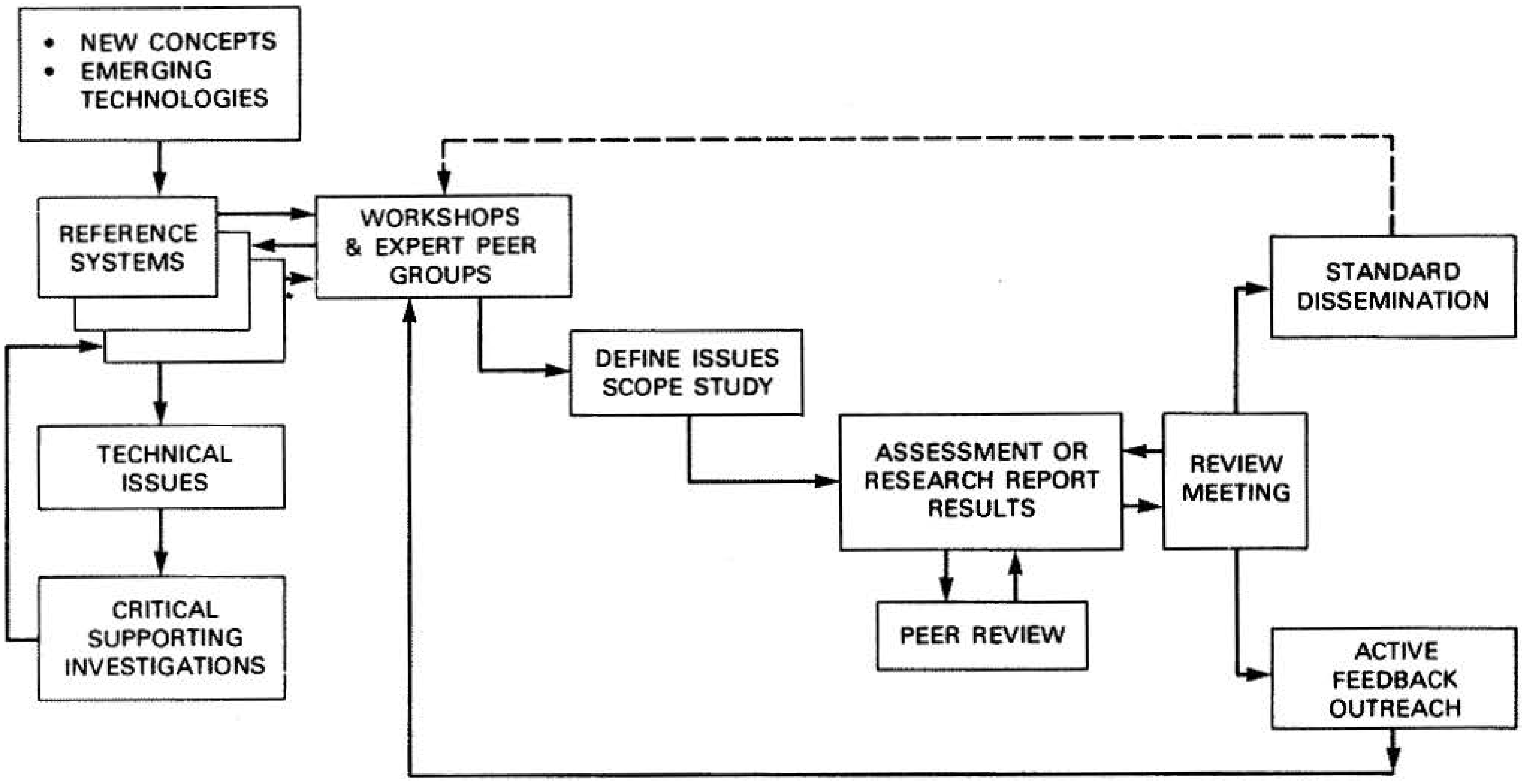

Figure B.2 SPS Participatory Technology Process

technologies. Assessments and experiments relating to key issues and concerns were conducted.

Reports were prepared and reviewed by peers. Findings were presented at periodic program reviews. Through these mechanisms, all major interest groups participated in monitoring the progress of SPS research activities. As many as 3,000 copies of each report were distributed routinely, both here and abroad, to universities; to industrial, governmental, and environmental organizations; and to individuals.

To increase public participation in the SPS assessment and to identify and respond to public concerns, a public outreach experiment was conducted. This experiment solicited comments from 9,000 individuals--3,000 from each of three diverse public groups. Each of the three groups (The Forum for the Advancement of Students in Science and Technology (FASST), the Citizen's Energy Project, and the L-5 Society) independently summarized 20 SPS reports and distributed them to their constituents with a request for feedback. Ensuing concerns and questions were answered by the principal investigators responsible for specific areas of assessment and research. Thus, both the interested individuals and the investigators learned of each other's ideas and concerns.

To obtain a completely independent overview of CDEP and as an aid in insuring that the key areas were being assessed, the National Academy of Sciences was requested to conduct a review of the work and results of CDEP. This is being accomplished through the auspices of the National Science Foundation.

The information developed in the CDEP assessment was organized as shown in Figure B.3. As indicated in the upper tier, the basic assessment information that was developed in analyses, workshops, and experiments was documented.

This information was summarized in four assessment reports dealing with systems definition, environment, society, and comparative merits. These four reports provided the basis for this program assessment report. This organization of assessment information provides traceability at any level of detail for all findings.

CDEP Budget

Table B.2 presents the CDEP budget by functional area.

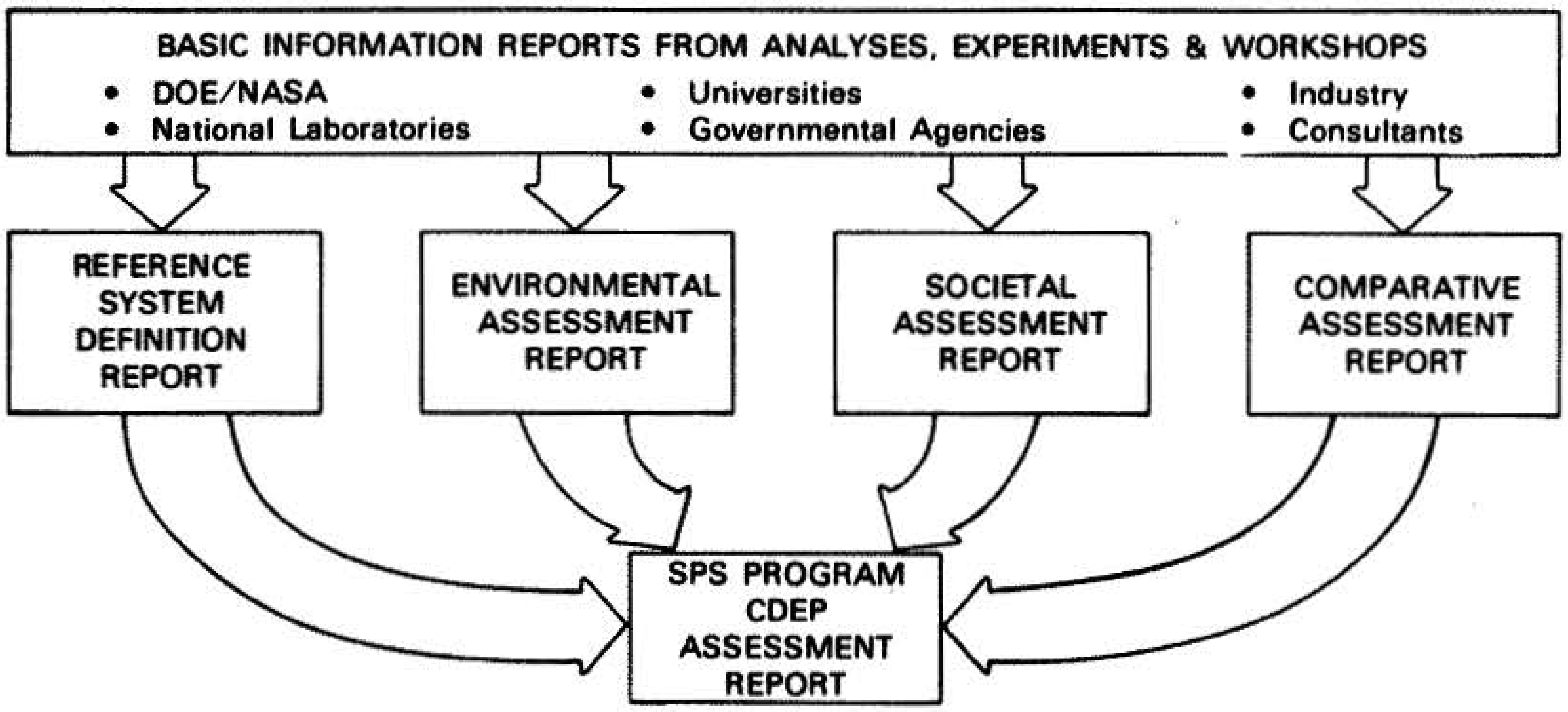

Figure B.3 CDEP Assessment Information Organization

Table B.2 CDEP Budget ($\$10^6$)

Program Element	FY77	FY78	FY79	FY80	Total
Systems Definition	2.5	1.7	2.6	1.2	8.0
Environmental Assessment	0.2	1.9	2.3	1.8	6.2
Societal Assessment	0.2	0.5	0.5	0.5	1.7
Comparative Assessment	0.1	0.4	0.6	0.6	1.7
Planning and Analysis[a]	—	—	0.6	0.6	1.2
NSF/NAS	—	—	—	0.3	0.3
Total	3.0	4.5	6.6	5.0	19.1

[a]Funding included in other program elements in FY77 and FY78.

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APPENDIX C: CHARACTERISTICS OF THE SPS REFERENCE SYSTEM

Based on previous and ongoing Solar Power Satellite (SPS) studies, an SPS Reference System was defined to serve as the basis for conducting CDEP environmental, societal, and comparative assessments; alternative concept tradeoff studies; and supporting critical investigations. This Reference System is not an optimum or even the preferred system. It does represent one plausible approach for achieving SPS goals.

The Reference System configuration is illustrated in Figure C.1, and the main characteristics are summarized in Table C.1. This configuration would provide 5 GW of electric power at the commercial grid interface. In the reference scenario, 60 units would be placed in geostationary orbit and provide 300 GW of power. Approximately six months would be required to construct each satellite.

The power satellite would have a solar array with dimensions of 10 km by 5 km by 0.5 km, or a rectangular surface area of 50 km^2. The mass would be 35-50 x 10^6 kg, depending on the materials used for photovoltaics and structures.

Of the energy conversion approaches studied, two photovoltaic options were considered for the reference design. In one option, silicon (Si) cells were used, having a basic cell efficiency of 17.3%. In another option, gallium aluminum arsenide (GaAlAs) cells with a basic cell efficiency of 20% and concentrators for focusing the solar energy on the cells were used. Although Si technology is more advanced than GaAlAs technology, the GaAlAs option

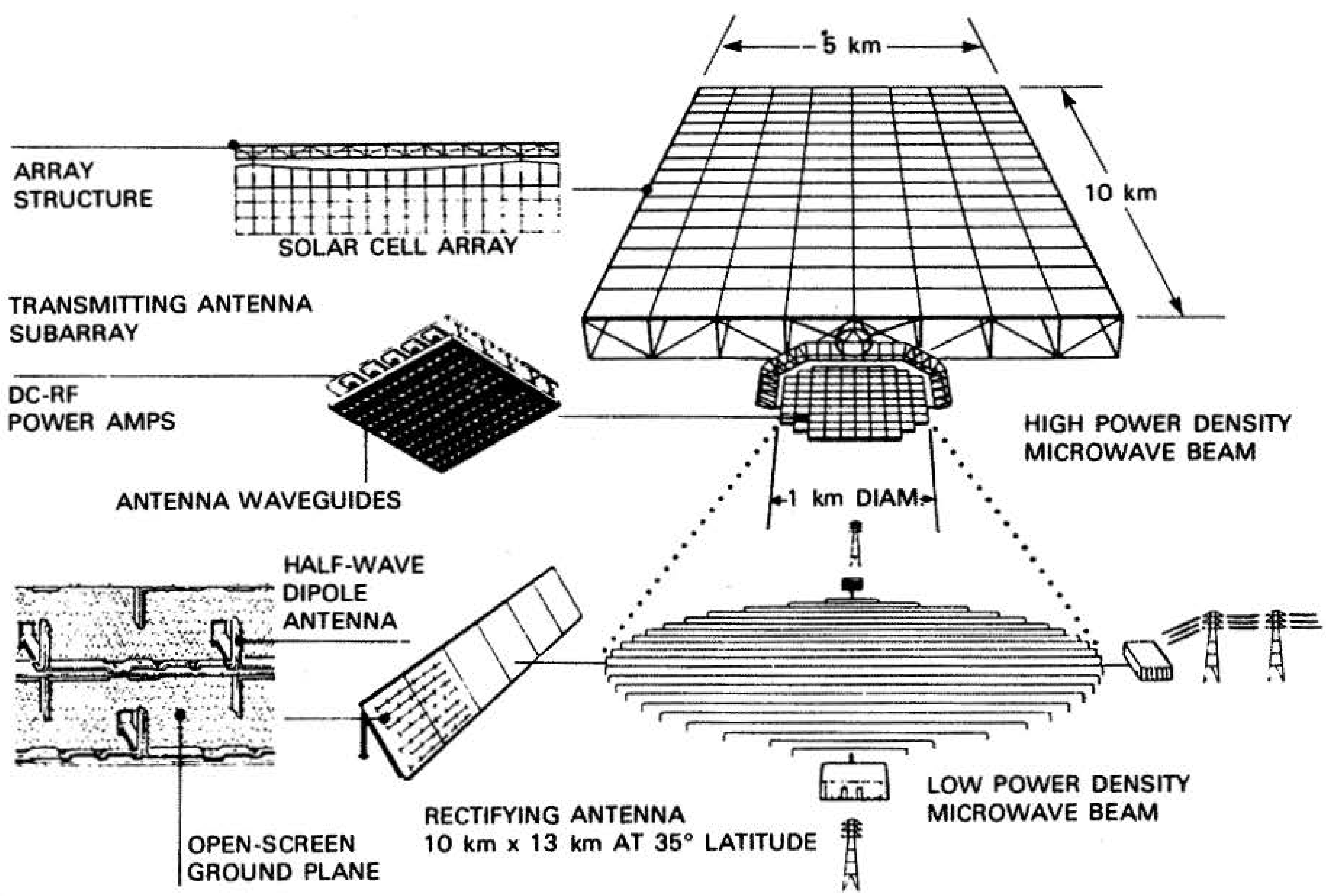

Figure C.1 SPS Reference System

Table C.1 Reference System Characteristics

<u>System Characteristics</u>	
General capability (utility interface) 300 GW - total 5 GW - single unit	Number of units: 60 Design life: 30 years Deployment rate: 2 units/year
<u>Satellite</u>	
Overall dimensions: 10 × 5 × 0.5 km Structural material: graphite composite	Satellite mass: 35-50 × 10^6 kg Geostationary orbit: 35,800 km
<u>Energy Conversion System</u>	
Photovoltaic solar cells: silicon or gallium aluminum arsenide	
<u>Power Transmission and Reception</u>	
D.C.-R.F. conversion: klystron Transmission antenna diameter: 1 km Frequency: 2.45 GHz Rectenna dimensions (at 35° latitude) Active area: 10 × 13 km Including exclusion area: 12 × 15.8 km	Rectenna construction time: ≈2 years Rectenna peak power density: 23 mW/cm^2 Power density at rectenna edge: 1 mW/cm^2 Power density at exclusion edge: 0.1 mW/cm^2 Active, retrodirective array control system with pilot beam reference
<u>Space Transportation System</u>	
Earth-to-LEO - Cargo: vertical takeoff, winged two-stage (425 metric ton payload) Personnel: modified shuttle LEO-to-GEO - Cargo: electric orbital transfer vehicle Personnel: two-stage liquid oxygen/liquid hydrogen	
<u>Space Construction</u>	
Construction staging base - LEO: 480 km Final construction - GEO: 35,800 km Satellite construction time: 6 months	Construction crew: 600 System maintenance crew: 240

has the potential for providing a lighter weight system, and by the use of concentrators, it offers the promise of self-annealing of radiation damage occurring in the cells.

A space construction crew of about 600 persons would be needed to assemble the satellite at geostationary Earth orbit (GEO) at an altitude of about 35,800 km. Heavy-lift launch vehicles (HLLVs) would be required to transport materials from Earth to low Earth orbit (LEO). Each would have a payload of about 425 metric tons. About 225-375 HLLV flights per year between Earth and LEO would be required to assemble two satellites in space per year.

A modified space shuttle would be required to transport workers between Earth and LEO. The personnel launch vehicle (PLV) would accommodate 75 persons per trip, and 30-40 trips per year between Earth and LEO would be necessary to construct two satellites.

Cargo orbit transfer vehicles (COTVs) and personnel orbit transfer vehicles (POTVs) would be used to transport materials and workers between LEO and GEO. The payloads would be 4,000 metric tons for COTVs and 400 metric tons for POTVs. About 22-30 COTV flights would be required between LEO and GEO each year, and 12-17 flights would be needed to assemble two satellites in space per year.

The energy collected and converted to electricity aboard the satellite would be transmitted to the microwave power transmission system at high voltages (≈40 kV). The transmission system would provide for the conversion of D.C. power to microwave power and for its transfer to Earth at a frequency of 2.45 GHz. Maximum power density at the center of the beam at the rectenna would be 23 mW/cm^2, while at the edge of the ground receiving antenna (rectenna) and at the outer edge of the exclusion area, the power density would be 1 mW/cm^2 and 0.1 mW/cm^2, respectively.

Each SPS rectenna would include an array of microwave receiving antennas, conversion and switchyard electrical equipment, a control center, and ancillary buildings. The receiving antenna would be shaped like an ellipse with a major axis of approximately 13 km and a minor axis of 10 km. An additional distance of 0.7 km beyond the antenna edge in each direction would be sufficient to accommodate buildings and electrical conversion equipment. Thus, the total rectenna dimensions of 12.0 km by 15.8 km translate into a total area requirement of about 150 km^2. The rectenna design is a series of panels perpendicular to the incident beam. Each panel has a steel mesh ground plane with 75-80% optical transparency.

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APPENDIX E: ACRONYMS AND DEFINITIONS

AEC	Atomic Energy Commission
CC	conventional coal systems with emissions controls
CDEP	Concept Development and Evaluation Program
CEP	Citizens' Energy Project
CG/CC	coal-gasification/combined cycle
cm	centimeter
COMSAT	communications satellite
COTV	cargo orbital transfer vehicle
CTE	coefficient of thermal expansion
CTPV	central station terrestrial photovoltaic system
dB/kHz	decibels per kilohertz
D.C.	direct current
DOD	Department of Defense
DOE	Department of Energy
EMI	electromagnetic interference
EPA	Environmental Protection Agency
ERDA	Energy Research and Development Administration
FASST	Forum for the Advancement of Students in Science and Technology
g	acceleration of gravity
GEO	geostationary Earth orbit
GHz	gigahertz (10^9 cycles per second)
GNP	gross national product
GW	gigawatt (10^9 watts)
GWe	gigawatt electric
HEAO-C	high energy astronomical observatory-C
HLLV	heavy-lift launch vehicle
HZE	high-atomic-number, high-energy particles
INTELSAT	international telecommunications satellite
ITU	International Telecommunications Union
JSC	Johnson Space Center
kg	kilogram
kHz	kilohertz
km	kilometer
kV	kilovolt
kW	kilowatt
kWe	kilowatt electric
kWh	kilowatt hour
LEO	low Earth orbit
LMFBR	liquid metal fast breeder reactor
LORAN	long-range navigation
LWR	light water reactor
MCF	magnetically confined fusion
MHz	megahertz
MPD	magnetoplasmadynamics

MW	megawatt
MWe	megawatt electric
mW/cm^2	milliwatts per square centimeter
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NSF	National Science Foundation
OMB	Office of Management and Budget
OMEGA	generic name for long-range navigation
PLV	personnel launch vehicle
POTV	personnel orbital transfer vehicle
PTP	participatory technology process
PUC	public utility commission
R&D	research and development
RD&D	research, development, and demonstration
rem	roentgen equivalent man
RF	radio frequency
RFF	Resources for the Future
SPS	solar power satellite
TVA	Tennessee Valley Authority
USGS	United States Geological Survey