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Satellite Power Systems (SPS)

Concept Development and Evaluation Program

Preliminary Assessment

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DOE/NASA

SATELLITE POWER SYSTEM
Concept Development
and
Evaluation Program

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PREFACE

The Satellite Power System (SPS) is an emerging concept for capturing solar energy in space for use in producing electrical energy on earth. To develop an understanding of the technical and economic feasibility and of the environmental and societal acceptability of the SPS is an enormous challenge. The Department of Energy and the National Aeronautics and Space Administration are engaged in a three-year assessment of the SPS that began in the fall of 1977 and will be completed in the summer of 1980.

The DOE/NASA assessment is engaging the efforts of many organizations in the United States and is developing a large body of information. At approximately the mid-point of the assessment, this preliminary project assessment report describes what has been done and what has been learned with an emphasis on the overriding issues. The document is a preliminary report.

INTRODUCTION

The Satellite Power System (SPS) is a concept that transforms solar energy intercepted in space into electrical energy useable on earth. The current SPS concept includes a number of large satellites in geostationary orbit. Each satellite would be equipped with a solar cell subsystem to convert solar energy to electrical energy, a subsystem for generating microwave frequency energy, and an antenna to beam microwave energy to earth. A subsystem on earth would receive and process the microwave energy for insertion into electrical utility systems. The SPS will require a new space transportation system as well as facilities for space construction.

The SPS concept provides baseload electrical energy. It would appear to have the potential for low thermal and chemical pollution and could be "turned off" cleanly. There should be minimal residual environmental impacts. However, the magnitude of the environmental impacts of the microwave beam and launch vehicle effluents are not fully known.

The Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA) are conducting a broad assessment of SPS under the Concept Development and Evaluation Program (CDEP) which started in 1977 and will be completed in 1980. The assessment includes technical and economic feasibility; the effects of the microwave power transmission beam on biological, ecological, and electromagnetic systems; the impact of SPS construction, deployment and operations on the biosphere and on society; and the merits of SPS compared to other future energy alternatives.

SPS could be deployed over the years 2000-2030, a time when the world will need to rely increasingly on renewable and/or inexhaustible energy sources.

The purpose of this report is to provide a preliminary assessment of the SPS on the basis of what has been learned at the midpoint of the CDEP.

BACKGROUND

The following dates mark major milestones in the evolution of the SPS concept:

- 1968 Dr. Peter Glaser proposed concept.
- 1972 NASA evaluated concept.
- 1975 NASA/Office of Energy Programs evaluated concept.
- 1976 NASA started intensive systems definition.
- 1976 Office of Management and Budget (OMB) assigned responsibility to Energy Research and Development Administration (ERDA), a predecessor to DOE.
- 1976 ERDA task group recommended evaluation study.
- 1977 DOE/NASA approved Concept Development and Evaluation Program Plan.
- 1978 DOE/NASA published reference system and preliminary environmental and societal documents.
- 1978 DOE/NASA held first program review.
- 1979 DOE/NASA held second program review.

The evolution of the current SPS assessment is illustrated in figure 1. The period from late 1977 to 1980 embraces the DOE/NASA Concept Development and Evaluation Program in which the systems definition is developed further, key issues are explored, critical assessments are completed, and planning for possible future activities is conducted. The CDEP will culminate in 1980 with statements of what is known and not known with respect to the SPS concept and with recommendations based on the existing state of knowledge.

The period beyond 1980 is being planned in the event that CDEP leads to a decision to proceed. The next phase, called Ground Based Exploratory Development (GBED), would include experiments, analyses, and technological activities that would support a soundly based decision on whether or not to proceed with a series of projects for verification of the concept.

OBJECTIVES

The objectives and likely outcome of the SPS CDEP, as stated by the Secretary of Energy in the policy statement of October 1977, 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 should expect recommendations as to 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 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."

At midpoint in the current evaluation, the objective remains the same and the observations on outcome are still valid.

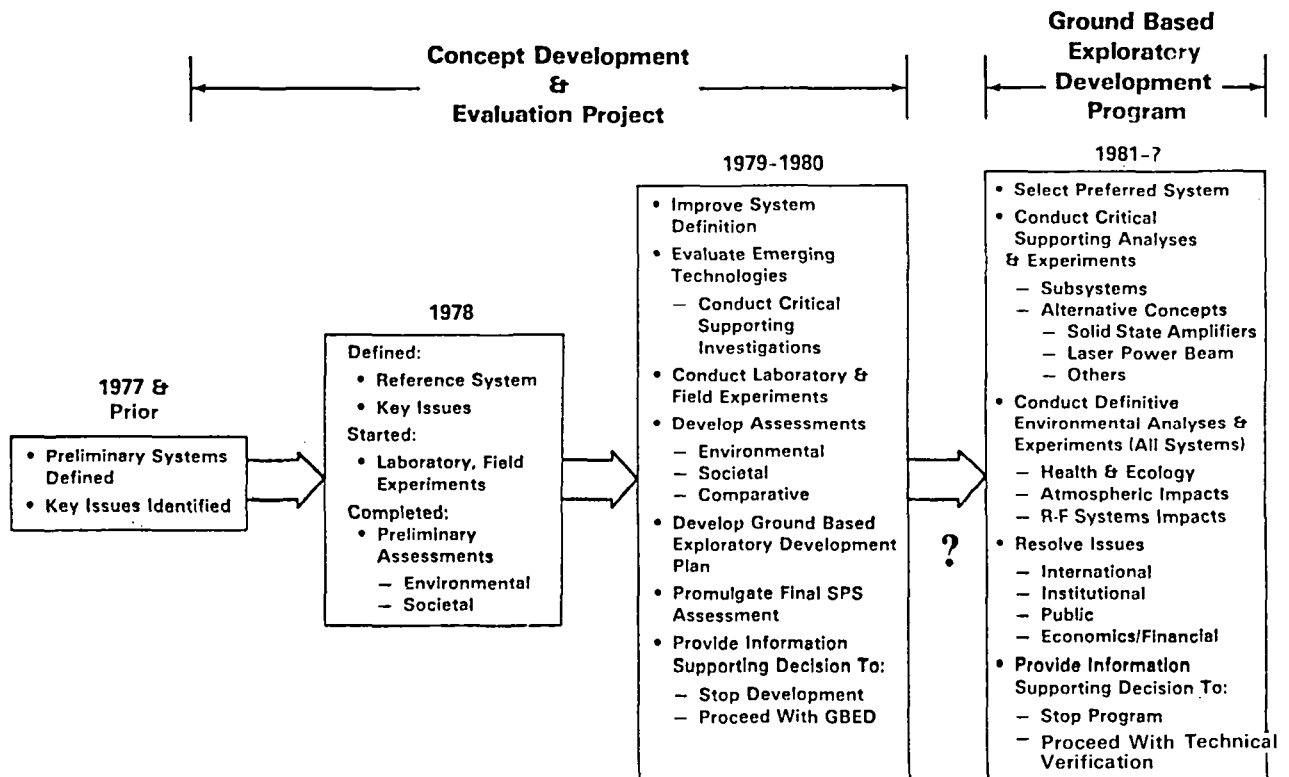


Figure 1. SPS Assessment Evolution

FUNCTIONAL ORGANIZATION

The functional organization to achieve CDEP objectives is shown in figure 2. The Satellite Power Systems Project Office (SPSPO) is part of the Department of Energy's Office of Energy Research.

Systems Definition is aimed at defining the Reference System for which the assessment is being made. In addition, the impact of emerging technologies on the SPS concept is assessed, and the required critical experimental supporting investigations are conducted.

Environmental Assessment includes effects of (1) microwaves on health and ecology, (2) other (nonmicrowave) impacts on health and ecology, (3) launch vehicle effluents on the atmosphere, (4) ionospheric disruptions on telecommunications, and (5) direct coupling of SPS microwave energy on electromagnetic systems.

Societal Assessment deals with resources (land, material, and energy), institutions (governmental, utilities, and financial), international aspects (agreements, organizations, and military implications), and society (public acceptance and centralization issues).

Comparative Assessment compares SPS with future energy alternatives--including coal, nuclear, and terrestrial solar energy systems--on the basis of cost, performance, and environmental and societal impacts.

Planning and Analysis provides for programming, monitoring, and evaluating the CDEP activity.

Key government agencies, universities and industries supporting the CDEP include:

Program Responsibility
Department of Energy

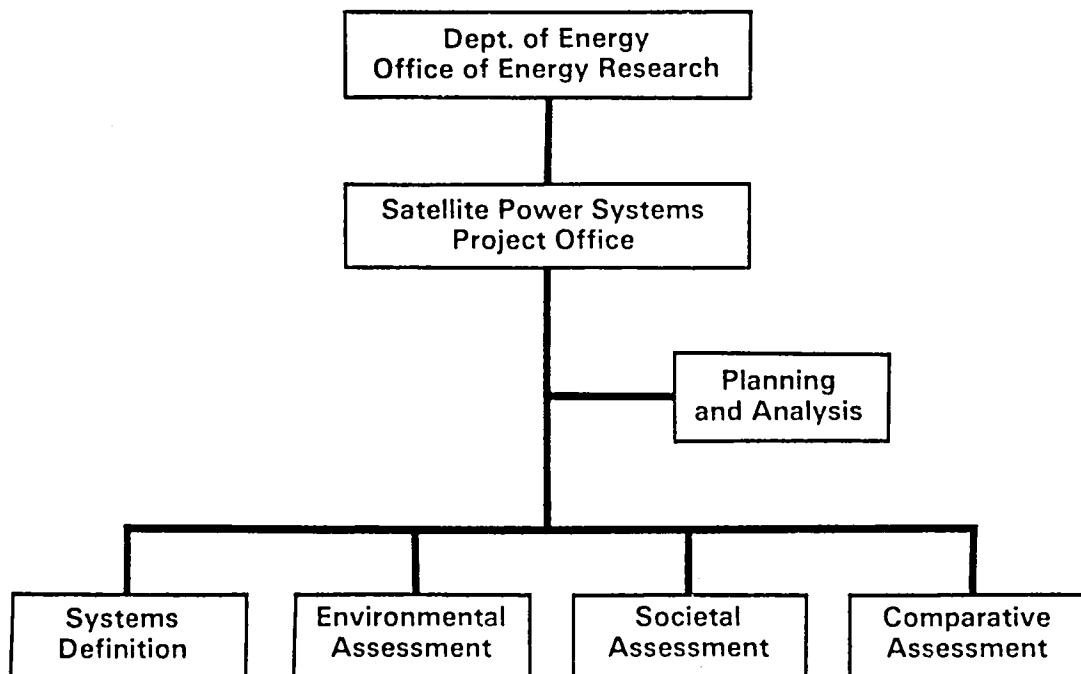


Figure 2. SPS Organization

Table 1 . CDEP Budget

	<u>FY 77</u>	<u>FY 78</u>	<u>FY 79</u>	<u>FY 80</u>	<u>TOTAL</u>
SYSTEMS DEFINITION	2.5	1.7	2.6	1.2	8.0
ENVIRONMENTAL ASSESSMENT	0.2	1.9	2.3	2.1	6.5
COMPARATIVE ASSESSMENT	0.1	0.4	0.6	0.6	1.7
SOCIETAL ASSESSMENT	0.2	0.5	0.5	0.5	1.7
PLANNING AND ANALYSIS*	—	—	0.6	0.8	1.4
NSF/NAS	—	—	—	0.3	0.3
	<u>3.0</u>	<u>4.5</u>	<u>6.6</u>	<u>5.5</u>	<u>19.6</u>

*FUNDING INCLUDED IN OTHER PROGRAM ELEMENTS IN FY 77 AND FY 78.

Project Management
 Department of Energy
 National Aeronautics and Space Administration

Systems Definition
 National Aeronautics and Space Administration
 Johnson Space Center
 Marshall Space Flight Center

Environmental Assessment
 Ames Research Center - NASA
 Argonne National Laboratory
 Environmental Protection Agency
 Institute for Telecommunication Sciences (Department of Commerce)
 Lawrence Berkeley Laboratory
 Los Alamos Scientific Laboratory
 Pacific Northwest Laboratories

Societal Assessment
 Planning Research Corporation

Comparative Assessment
 Argonne National Laboratory

An additional 39 contractors are supporting the effort.

BUDGET

The budget for the CDEP is shown in table I by functional areas.

ASSESSMENT APPROACH

The CDEP facilitates a continuing exchange of information between systems definition activities and environmental, societal, and comparative assessment activities. It also provides for an interaction between those activities and the interested public. In this interplay, potential problems should quickly become evident.

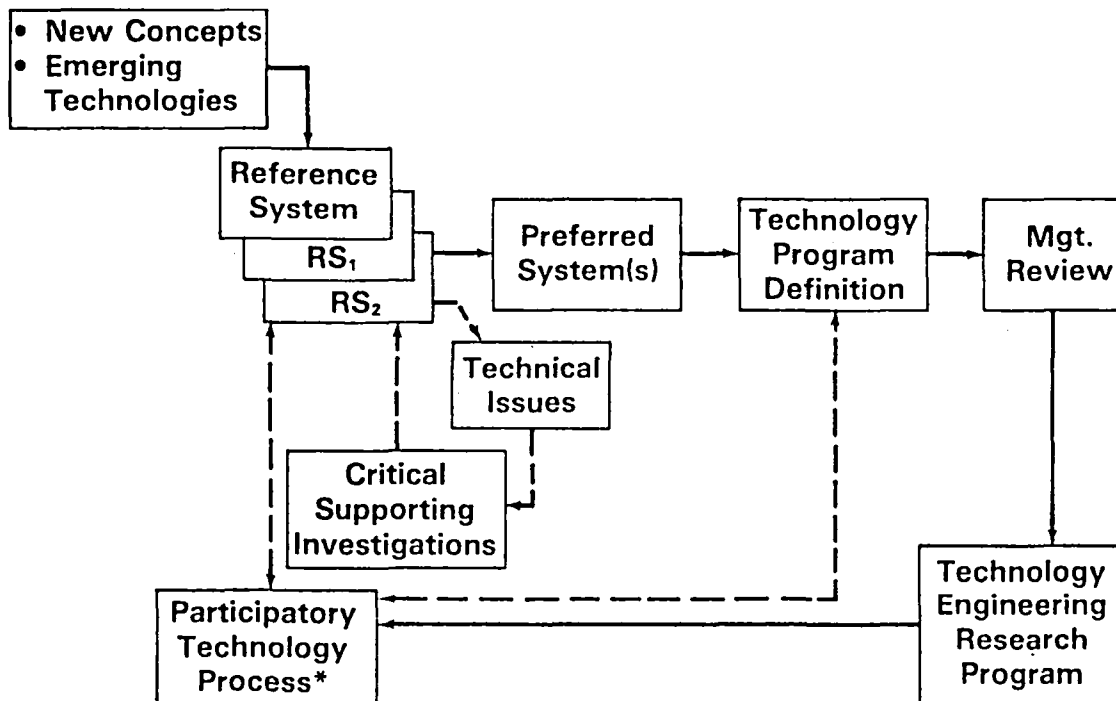
The systems definition process (figure 3) refines the reference system in the context of new concepts and technologies. The process provides for examination of technical issues, implementation of critical supporting investigations, and definition of required technology development. The research programs for the environmental, societal, and comparative assessment elements are refined through the Participatory Technology Process shown in figure 4. The results of experiments and analyses are drafted, reviewed by peers, reported, and disseminated through normal channels and channels created especially for active feedback. Judgments are made in national workshops, and issues and studies are reviewed by peer groups. The results are also fed back into the design effort so that mitigating design changes can be explored. This iterative process is intended to lead to a preferred system(s) that may be economically viable and environmentally and socially acceptable.

PRELIMINARY ASSESSMENT Systems Definition

Concept Status

The SPS requires no scientific breakthroughs; it is recognized as a difficult engineering development project requiring substantial advancements in technology in many areas. Success depends on projected reductions in the cost of space transportation; improvements in energy conversion technology (including reductions in unit weight and cost and increases in efficiency); advances in space structures, construction, and operations technology; and achievement of desired characteristics in transmission of energy from satellite to earth.

Should all environmental, technical, economic, and societal issues be resolved, the SPS development could move through technology verification, engineering development, demonstration, and commer-



*Interaction with Environmental, Societal and Comparative Assessments

Figure 3. SPS Systems Definition Process

cialization with an initial operating capability forecast for the years from 2000 to 2030.

Reference System

The SPS concept has evolved since its inception in 1968. Numerous configurations involving various thermodynamic and photovoltaic techniques for converting solar energy to electrical energy have been studied. Other investigations have considered structures and materials, transportation systems, microwave energy transmission, assembly techniques, and other aspects of a complete SPS system. On the basis of these studies, an SPS reference system was defined for the purpose of concept evaluation. The reference system represents one plausible approach to achieving the goals of SPS, the delivery of energy to earth from space. The main features of the reference system are given in table 2.

Emerging Technologies

As the SPS concept evolves, modifications can be expected depending on the products of technology programs. Several emerging technologies are being evaluated for SPS, and it is worthwhile to note their potential impact.

Several concepts for solid-state microwave SPS systems have emerged. In one version, solid-state amplifiers replace the klystrons assumed for the reference concept. A second version arranges solar cells, solid-state amplifiers, and microwave antennae in a sandwich configuration. A thorough investigation is warranted since a solid state system has the potential for high reliability.

Some potential problems associated with microwave energy transmission might be obviated by using lasers to transmit power to earth. Potential benefits of the laser

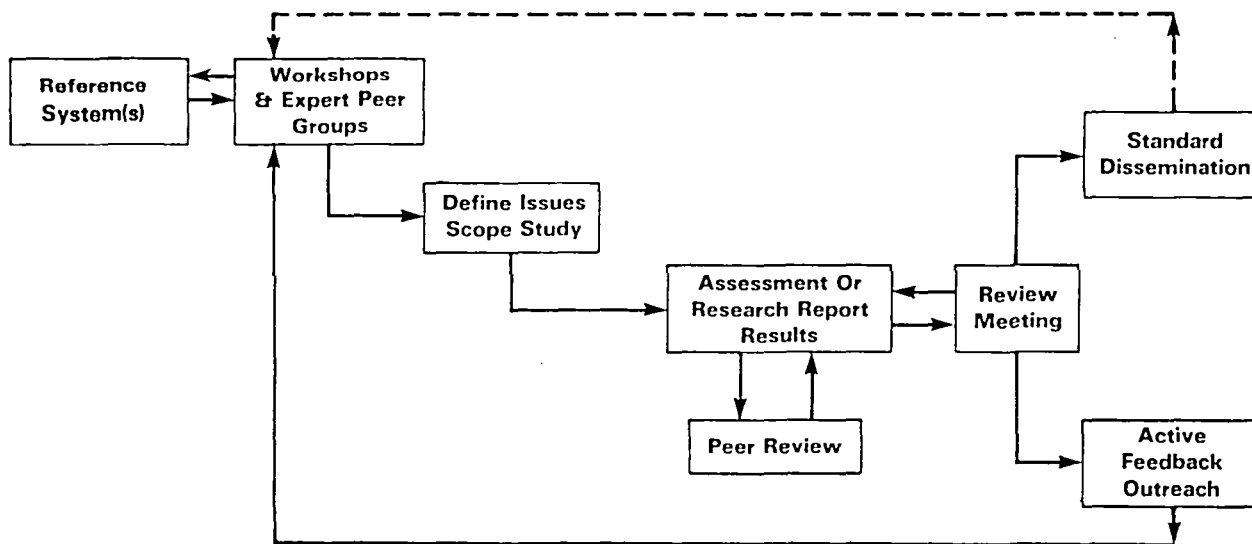


Figure 4. SPS Participatory Technology Process (Environmental, Societal, and Comparative Assessments)

Table 2. Reference System

SATELLITE

Overall Dimensions (Km)	10 x 5 x 0.5
Satellite Mass (Kg)	35 x 10 ⁶ (Gallium Aluminum Arsenide) 50 x 10 ⁶ (Silicon)
Structure Material	Graphite Composite
Construction Location	Geostationary Orbit (GEO)
Delivered Power	5 GW*
Power Conversion	
- Solar to Electrical	Photovoltaic (Gallium Aluminum Arsenide; Silicon)
- Electrical to Radio Frequency	Klystrons
Microwave Frequency (Gigahertz)	2.45
Antenna Diameter (Km)	1.0

RECTENNA (35° latitude)

Dimensions (Km)	13 x 10** (elliptical)
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TRANSPORTATION

Earth to Low Earth Orbit (LEO)

- Cargo	Heavy Lift Launch Vehicle
- Personnel	Shuttle Derivative

LEO to GEO

- Cargo	Electric Propulsion Transfer Vehicles
- Personnel	Two-Stage Liquid Oxygen/Liquid Hydrogen

* Maximum power permitted by microwave transmission system having characteristics of Reference System. (Lower powers are technically feasible.)

** The rectenna is surrounded by a 0.7-km wide exclusion area to provide power densities levels less than 0.1 mw/cm² (milliwatt per square centimeter). The overall dimensions of a rectenna site are 14.4 km x 11.4 km.

system include (1) smaller land area requirements for the receiver (the diameter of the laser beam is measured in tens of meters, while that of the microwave main beam is about 10 kilometers), (2) elimination of radio frequency interference, and (3) reduction of biological and ecological impacts. The laser option is being studied.

Feasibility Aspects

The feasibility of the SPS concept is enhanced because of two or more options for each of the critical subsystems including:

- Conversion of solar energy to electrical energy (photovoltaic and thermodynamic cycles),
- Conversion of electrical energy to radio frequency energy (klystrons, magnetrons, and solid-state),
- Power transmission to earth (microwaves and lasers),
- Transportation (shuttle derivatives, heavy lift launch vehicles, chemical and electrical orbit transfer vehicles), and
- Space construction and manufacturing (earth-based, non-earth-based, or combinations thereof).

ENVIRONMENTAL ASSESSMENT

Effects of Microwaves on Human Health and Ecology

Exposure of humans to SPS microwaves at higher power densities approaching existing and projected standards, should they occur, will be infrequent and will involve small numbers of individuals.

The major uncertainty regarding human health involves the potential long-term or late effects of continuous exposure of

large general populations to very low-power densities. Relevant experimental data are scant. Definitive experiments to reduce the uncertainty are being designed.

Other Effects on Human Health/Ecology

The main impacts of SPS construction and operation are likely to arise from the required large-scale extraction, transportation, manufacturing, and construction activities. The greatest uncertainty regarding potential human health impacts is in the area of space operations. Data supporting assessments, now in progress, appear to be adequate to both define the potential hazards of ionizing radiation in space and zero gravity as well as to provide the bases for developing the requisite space construction strategies.

Effects on the Atmosphere

Existing information appears to exclude the possibility that effluents from the SPS space transportation systems will cause significant modifications of local or regional climate. The data indicate that compliance with existing laws and regulations regarding air and noise pollution is possible. One of the major uncertainties is the magnitude of ionospheric disturbances produced by effluents from the SPS transportation systems and the magnitude and nature of potential telecommunications and climatic impacts associated with such disturbances. Additional data to support an adequate assessment of the impact of ionospheric disturbances will be obtained prior to June 1980.

Effects on Other Radio Frequency Systems

Because of the power density of the SPS microwave power beam and the non-negligible power in the side lobes, the potential exists for impacting other users of the radio frequency spectrum, either through ionospheric disruptions caused by

microwave heating or by direct coupling with SPS microwave energy in the main beam and in the side lobes.

With regard to ionospheric heating, experiments using the Arecibo, Puerto Rico, and the Platteville, Colorado, facilities concern only the D- and E-layers. Both facilities require upgrading to conduct the necessary F-layer experiments.

The Arecibo facility is instrumented to study the basic physics of ionospheric heating. The facility is being modified to provide the required heat pulses, and experiments using this new capability are being conducted.

Direct testing of the impacts of ionospheric heating on telecommunication systems is underway at the Platteville facility. Preliminary experiments, that heat the D- and E-layers for long periods to ensure steady state ionospheric temperatures, show that telecommunication impacts are minimal for power densities of $23\text{mW}/\text{cm}^2$, the presently prescribed upper limit for the SPS power beam. The economics of the SPS are enhanced by increasing the beam power density. Unfortunately, the Platteville facility cannot operate at higher power to establish an allowable upper limit for the SPS beam power.

With regard to the direct coupling of SPS microwave energy with other electromagnetic systems, models have been developed to predict the spatial and frequency distribution patterns of candidate antenna-rectenna concepts. An assessment has been made of the effects of atmospheric propagation on these patterns. Potential degradation of the performance of other satellites has been analyzed and appears to be no problem for adjacent satellites in geostationary orbit. Problems with the operation of sensors on satellites in lower orbits have been identified along with mitigation techniques that appear acceptable. Some effects on ground-based computers and communication systems have been identified that appear to be amenable to mitigation procedures, in-

volving redesign of antennae and circuits, and the use of shielding. The greatest uncertainty appears to be in the area of radio-frequency emissions from the rectenna and associated structures. Experimental study of these questions is required.

The potential impact of SPS on other users of the radio frequency spectrum will be discussed this fall at a meeting of the international body that governs worldwide use of the radio frequency spectrum. The fall meeting of the International Telecommunications Union is designated as the General World Administrative Radio Conference.

Potential impacts on radio and optical astronomy have been identified. It will be necessary to design SPS to operate within radio-frequency regulations designed to protect the radioastronomy service and to reduce the reflectance of the satellite structure to levels that will minimize the impact on optical astronomy.

Integration

A preliminary environmental assessment was published in October 1978. An updated assessment is now in review.

SOCIETAL ASSESSMENT

Resources

The materials requirements have been assessed considering availability (differentiating between foreign and domestic sources), cost, energy requirements for production, and manufacturing capacity. The following materials will require special efforts to insure supply: gallium, gallium arsenide, sapphire, and graphite (for graphite fiber composites).

Regardless of how the system is defined, the net energy ratio is positive.

Potentially eligible land areas for rectenna placement have been found, but they are not congruent with the present

geographical distribution of energy demand. Water sites are also being studied.

Institutional Issues

Current state and local regulations that could affect SPS are probably inadequate to deal with SPS.

Public sector financing would be required for the research and development phase. Cooperative U.S.-international management, possibly modeled after INTELSAT, would ease those SPS impacts that have international implications. Private sector participation would hinge on profitability during the operational phase.

International Issues

There are no obvious impediments to SPS in space law or custom. However, the claims of some equatorial nations to space over their boundaries will require attention.

The SPS has military implications, both real and perceived. Its potential as a nonmilitary, nonthreatening system must be fully realized to win international acceptance.

Social Impacts

Trends in our society toward decentralized institutions (including power stations) and towards regionalization must be and are being included in the assessment of the SPS.

The general public, particularly younger people, must be and are being involved in the SPS assessment.

COMPARATIVE ASSESSMENT

General Status

To date, the comparative assessment efforts have concentrated on developing a methodology, on collecting traceable data for selected alternative technologies, and on auditing SPS cost information.

Peer review of the methodology report has been completed and the report will be published shortly. A data base has been developed for alternative technologies that include (1) advanced clean coal systems, (2) combined coal, (3) nuclear breeders, (4) nuclear fusion, (5) nuclear light water reactors, and (6) central station photovoltaics. A preliminary report comparing SPS with these technologies will be published soon. Comparisons will be based on cost and performance, health and safety, resource requirements, and environmental issues.

Results

The costs of the SPS and the alternative technologies estimated for the years 2000-2030 are subject to serious uncertainties. Within these uncertainties, the lowest cost alternatives and the SPS costs overlap slightly. In the light of previous experience with cost estimates of new technologies, the costs should be regarded as goals rather than forecasts.

Each energy alternative has distinct health and safety impacts. The probability of serious impacts from each is low. Each alternative has a high probability of causing small impacts which may be difficult to quantify, and therefore it is difficult to compare effects between alternatives.

The total land use requirements for each of the technologies are difficult to assess. Comparisons will include land required for mining, transportation, transmission corridors, and waste disposal. Supporting documentation is scant.

The construction of the rectenna is similar to other large earth-based construction efforts.

PROGRAM STATUS

The program is on schedule according to the March 1977 plan. Major accomplishments include:

- Publication of documents
 - Reference System
 - Preliminary Environmental Assessment
 - Preliminary Societal Assessment
- Reviews (October 1978 and June 1979)
 - Systems Definition
 - Environmental Assessment
 - Societal Assessment
 - Comparative Assessment
- Establishment of peer groups
- Starting laboratory and field research
 - Biological effects of microwaves
 - Effects on the eye caused by high energy particles in geostationary space
 - Telecommunication impacts caused by microwave heating of the ionosphere
 - Physics of ionospheric heating
 - Electromagnetic compatibility
 - Launch effluent monitoring
- Starting formulation of Ground Based Exploratory Development Plan.

The program will remain on schedule with delivery of draft final assessment in July 1980. Steps to be taken to keep this target date include:

- Analysis of key subsystems
- Preliminary study of solid-state microwave system
- Preliminary assessment of laser option
- Experiments on the biological effects of higher-level microwave ex-

posure on rodents, birds, and insects

- Design of experiments to determine biological effects of low-level, chronic exposure to microwaves
- Experiments to simulate SPS heating of the F-layer of the ionosphere
- Cost estimates of implementing RFI-EMI mitigating strategies
- Analyses of atmospheric impacts of effluents from heavy lift launch vehicles and orbital transfer vehicles
- Completion of systems definition and environmental, societal, and comparative assessments

INFORMATION ORGANIZATION

The information developed in the assessment is organized as shown in figure 5. The SPS assessment information is developed in analyses, workshops, and experiments, and is documented following peer review. This information will be summarized in four assessment reports dealing with: (1) the Reference System, (2) the environment, (3) society, and (4) comparative merits. These four reports will provide the bases for the final assessment report that will include statements of what is known, and equally important, what is not known about the SPS concept. The final report will provide the basis for future program recommendations. Should the government decide to proceed, a plan for a Ground Based Exploratory Development (GBED) program will be forthcoming.

This organization of assessment information will provide traceability at any level of detail for all findings.

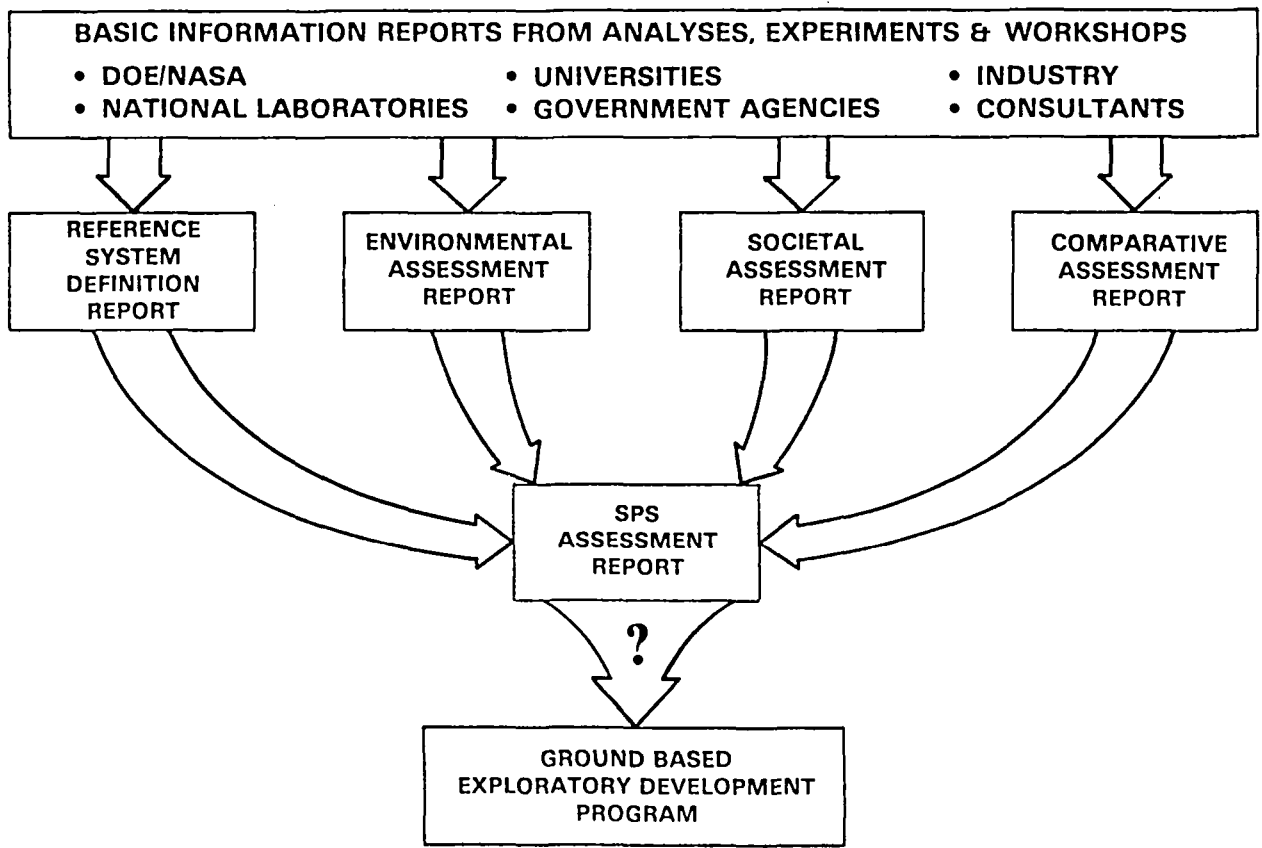


Figure 5. SPS Assessment Information Organization

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All of the reports, except No. 21, are available from National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.