Solar Power Satellites

August 1981

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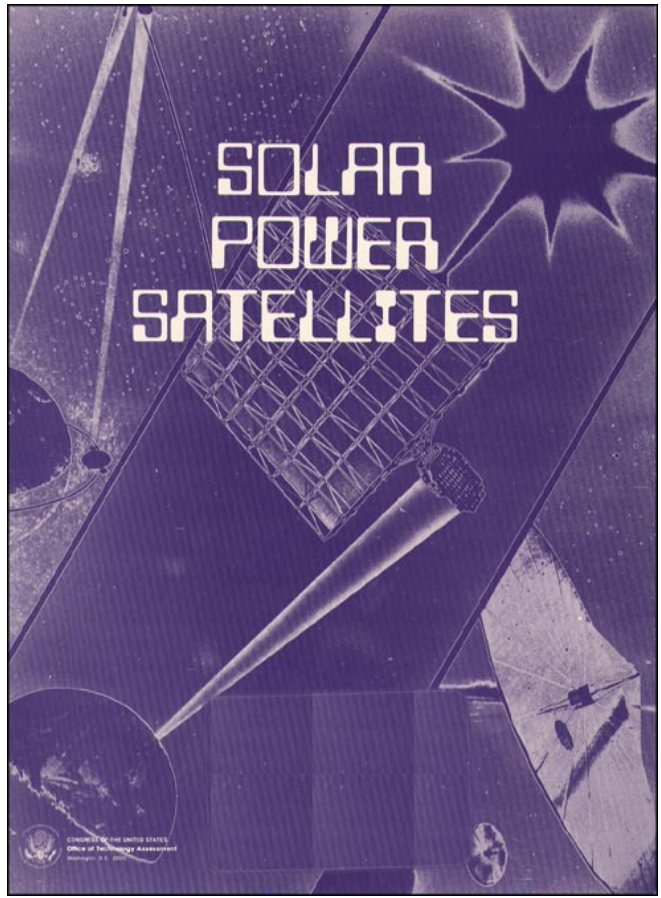

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Foreword

The energy difficulties the Nation has faced over the past decade have given rise to an increased awareness of the potential long-term, inexhaustible, or renewable energy technologies. This assessment responds to a request by the House Committee on Science and Technology for an evaluation of the energy potential of one of the most ambitious and long-term of these technologies, the solar power satellite (SPS).

In assessing SPS, OTA has taken into account the preliminary nature of SPS technology by comparing four alternative SPS systems across a broad range of issues: their technical characteristics, long-term energy supply potential, international and military implications, environmental impacts, and institutional effects. The SPS options are also compared to potentially competitive future energy technologies in order to identify how choices among them might be made. In addition, OTA developed a set of Federal research and funding options to address the central questions and uncertainties identified in the report.

We were greatly aided by the advice of the SPS advisory panel, as well as by the participants in three specialized workshops: one on alternative SPS systems, one on public opinion, and another on competing energy supply technologies. The contributions of a number of contractors, who provided important analyses, and of numerous individuals who gave generously of their time and knowledge, are gratefully appreciated.



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SUMMARY

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Chapter 1
SUMMARY

The solar power satellite (SPS) concepts envision using the constant availability of sunlight in space to generate baseload electricity on Earth. Orbiting satellites would collect solar energy and beam it to Earth where it would be converted to electricity. Three major alternative systems have been suggested.

- *Microwave transmission.* **Solar radiation would be collected in space and converted to microwaves. Microwave energy would be beamed to a receiving antenna on Earth where it would be converted to electricity.**
- *Laser transmission.* **Solar radiation would be collected in space and converted to infrared laser radiation. The lasers would beam power to an Earth receiver.**
- *Mirror transmission.* **Orbiting mirrors would reflect sunlight directly to central locations on Earth. Terrestrial solar receivers would convert the resulting 24-hour illumination to electricity.**

Since SPS would be a major future energy system with diverse potential impacts and implacations, this assessment of SPS technology is interdisciplinary. It includes the study of SPS interactions with society, the environment, the economy, and other energy systems. in addition, because space is an international realm and energy is a global need, this assessment also undertakes a broad look at the international aspects of SPS.

CURRENT STATUS

Too little is currently known about the technical, economic, and environmental aspects of SPS to make a sound decision whether to proceed with its development and deployment. I n addition, without further research an SPS demonstration or systems-engineering verification program would be a high-risk venture. An SPS research program could ultimately assure an adequate information base for these decisions. However, the urgency of any proposed research effort depends strongly on the perception of future electricity demand, the variety and cost of supply, and the estimated speed with which the major technical and environmental uncertainties associated with the SPS concept can be resolved. For instance, if future demand growth is expected to be low it may not be necessary to initiate a specific SPS research program at this time, especially if more conventional electric-generating technologies remain acceptable. If this is not the case or if demand growth is expected to be high, SPS might be needed early in the 21st century, and a timely start of a research effort would be justified.

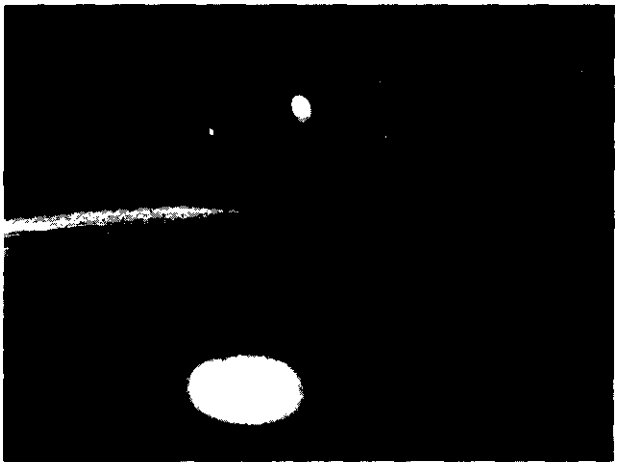
Should it be decided not to start a dedicated SPS research effort now, it may be desirable to designate an agency to track generic research which is applicable to SPS, to review trends in electricity demand, and to monitor the progress of other electric supply technologies. Such a mechanism could provide the basis for periodic assessment of whether to begin an SPS research program. Information relevant to SPS could be derived from other research programs, microwave bioeffects, space transportation, laser, and photovoltaic development appear to be the most critical technical issues. However, it is unlikely that such "generic" research programs by themselves would adequately answer all of the high-priority questions on which SPS development decisions depend

If a dedicated SPS research effort is started now, the level of effort chosen would, to a large degree, determine the time it takes to obtain the information needed for a development decision. An effort set at $5 million to $10 million per year could be sufficient to gather the minimum necessary information while minimizing the risk of insufficient or untimely information. A $20 million to $30 million per year effort could gain the maximum necessary



Photo credit: National Aeronautics and Space Administration

Microwave concept



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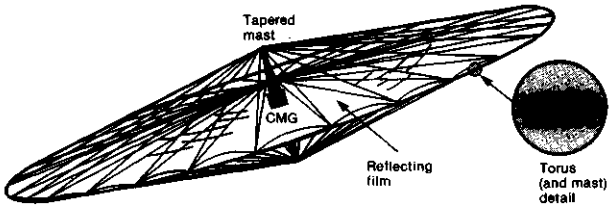


Mirrored concept

SOURCE: K. W. Billman, "Space Orbiting Light Augmentation Reflector Energy System: A Look at Alternative Systems," SPS Program Review, June 1979.

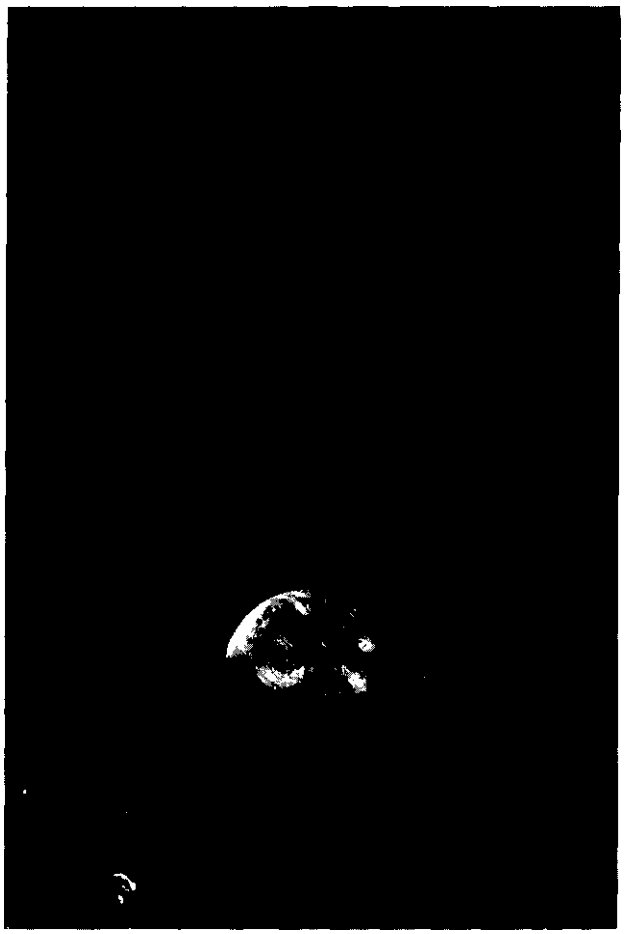


Photo credit: Painting by Frank G. Ellis, Lockheed Missiles and Space Co.

Laser concept

information at the earliest possible time. It reduces the risk of not generating enough information in time to make an adequate development decision. Whatever the level, if a research program is instituted, it should investigate those areas most critical to SPS economic, technical, and environmental feasibility **Particular attention should be given to studying and comparing the various technical alternatives; but the feasibility of SPS also ultimately depends on its social, political, and institutional viability. Thus, a research program should continue to explore these aspects of SPS development and deployment as well. The following are the major stages such a program would have to go through:**

SPS Program Steps

Concept *feasibility stages*	*Development stages*
Basic research	Systems engineering
Component testing	Demonstration satellite
Concept definition	Deployment

ENERGY CONTEXT

Even if it were needed and work began now, a commercial SPS is unlikely to be available before 2005-15 because of the many uncertainties and the long leadtime needed for testing and demonstration. Therefore, SPS could not be expected to constitute a significant part of electricity supply before 2015-25. By that time, the United States will be importing very little foreign oil. Consequently, SPS cannot reduce our dependence on imported oil in this century. However, if efficient electric vehicles or other electric end-use technologies are developed by about 2010, electricity from SPS or other sources could substitute for synthetic liquid fuels generated from coal or biomass.

Along with other electric generating technologies, SPS has the potential to supply several hundred gigawatts of baseload electrical power to the U.S. grid by the mid-21st century. However, the ultimate need for SPS and its rate of development will depend on the rate of increase in demand for electricity, and the ability of other energy supply options to meet ultimate demand more competitively. SPS would be needed most if coal and/or conventional nuclear options are constrained and if demand for electricity is high.

An aggressive terrestrial solar and conservation program that could lead to an electricity demand level of only 8 Quads electric (Qe)* in 2030 (equal to current consumption) would make the development of SPS and other large new centralized generating technologies less urgent in the United States. In any event, coal could continue to fuel the greatest share of U.S. electrical needs well into the 21st century, provided no barriers to its use become evident. Coal, conventional nuclear, terrestrial solar in its many forms, and geothermal usage could satisfy the entire domestic electricity requirement for demands totaling 20 Qe (2.5 times current level) or less in 2030. If demand is higher than 20 Qe, then presumably one or more of the following, SPS, breeders, and/or fusion will be needed. Electricity demand will be strongly affected by the degree that efficient technologies for using electricity can be developed. Such technologies can have the effect of lowering the overall cost of electricity compared to competing energy forms.

If generation from coal on a large scale proves to be unacceptable, domestic electrical consumption of 8 Qe or less could still be met by nuclear, geothermal, and terrestrial solar (central plant and onsite) technology. For demands up to about 20 Qe, SPS could compete with terrestrial solar, breeders, and/or fusion for a share of the centralized baseload market. If electricity demand exceeds 20 Qe, it will be difficult to satisfy that demand without vigorous development of al I renewable or inexhaustible forms of generating capacity. For these higher demand levels, SPS, breeders, and fusion could all share in supplying U.S. electricity needs. A 30 Qe (3.8 times current consumption) total demand would create a market potential for up to 6 Qe of SPS-delivered energy (225,000-Mw-installed generating capacity at 90-percent capacity factor). *

Upper Range of Possible SPS Use* *

Electric demand in 2030 (Qe]	*SPS capacity (CW]*	
	With coal	*Without coal*
75	***0***	**0-30**
20.0	***0-60***	***100-200***
30.0	***100-200***	***100-200***

***A Quad is equal to 1 quadrillion Btu. It is equivalent to the energy contained in 500,000 barrels of oil per day for 1 year, and is also approximately the electric energy produced by a 33,500-MW generator running without interruption for a year As used in this report, Quads electric (Qe) of demand refer to the energy equivalent of electricity at point of use Primary energy input at the generating source of electricity is somewhat more than three times these figures**

***Current U.S. generating capacity is about 600,000 MW. Current demand represents about 45 percent of this capacity operating 100 percent of the time,**

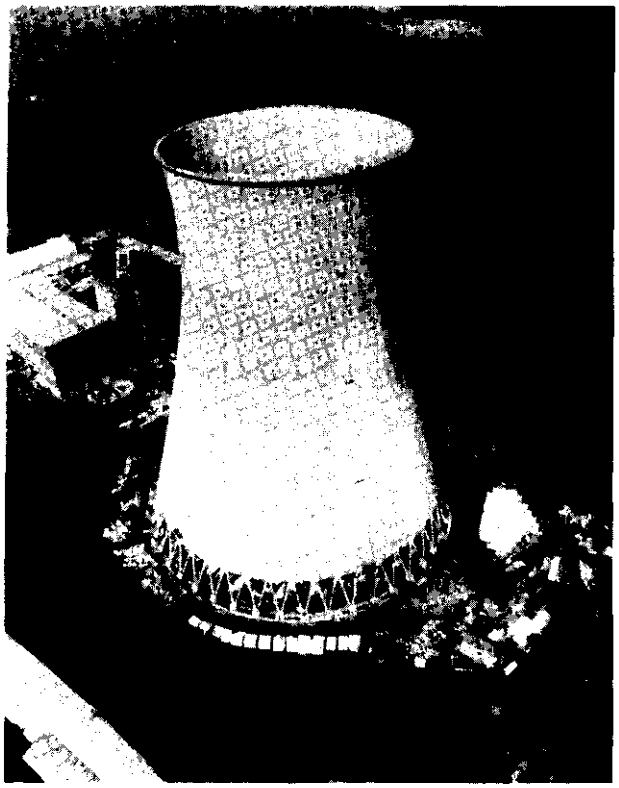
****Coal is used as the swingfuel for our analysis because it has the largest resource base of any of the current forms of centralized, electric generating technologies It is expected that conventional nuclear would be available but its smaller resource base would prevent it from having the large effect on generation-mix choices** that coal does **It is assumed that breeders, which would greatly extend the nuclear fission resource base, would be comparable to SPS and fusion in terms of its rate of market penetration (ie, 5 to 10 GW/yr)**

SPS is designed to provide baseload electricity. By contrast, except for ocean thermal energy conversion, terrestrial solar electrical generation is intermittent. Because our energy future will require a mix of baseload and intermittent generating technologies, without storage capability, terrestrial solar would not compete directly with SPS. However, the development of inexpensive storage, if achieved, could enable terrestrial solar electricity generation in all its forms-wind, solar thermal, and solar photovoltaics–to assume some share of baseload capacity.* These technologies are less complex, have fewer uncertainties, and are considerably nearer to commercial realization than SPS. Furthermore, they have the flexibility to be introduced into the electrical grid in small increments as needed to meet demand increases on a local scale.

Even if inexpensive storage is not available, onsite generating technologies could compete indirectly with SPS. Total need for baseload power will decrease if a significant portion of total electrical demand can be met by a combination of dispersed technologies such as solar photovoltaics, wind, and biomass at costs that are competitive with centrally generated electricity. Low demand for centrally generated electricity would consequently reduce the need to introduce new, large-scale electrical technologies such as SPS, except as replacement capacity.

As an energy option for the first half of the 21st century, the potential electrical output and uncertainties of SPS are comparable to fusion. These energy options will proceed along different development paths. Except for a laser system, the basic SPS technologies have been proven technically feasible. Research would be needed to develop low-noise microwave tubes; high-efficiency, low-mass photovoltaics; efficient continuous-wave lasers; low-mass mirrors; and space construction and transportation capabilities. Although the fusion community is confident that fusion is feasible, "energy breakeven, " the production of more energy than is put into the fusion process, has

*The percentage share of baseload capacity which would be feasible for these technologies to assume would depend on their geographical location and the time of year (see ch 6)



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Trojan nuclear powerplant on the Columbia River near Prescott, Wash., **1972**

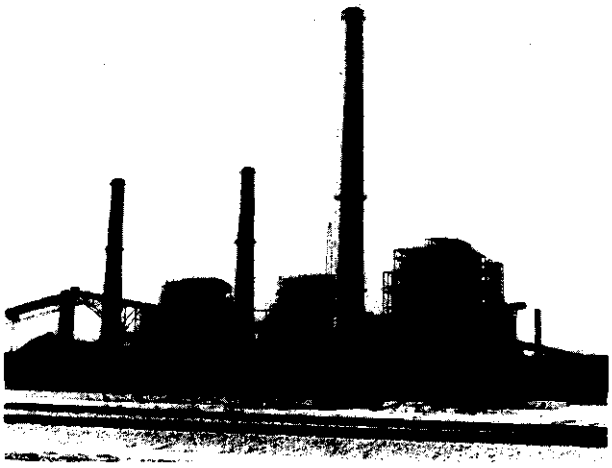


Photo credit: Texas Power & Light

Martin Lake electric generating plant in east Texas

not been achieved. For both SPS and fusion, an economic generating plant would still have to be developed and demonstrated.

Both energy options are designed to produce baseload central station power in units from 500 to 5,000 MW. For both, development cost is high. For fusion, much of the manufacturing infrastructure for the balance of plant, i.e., other than the fusion device itself, is in place. Most of the supportive infrastructure for SPS, including the industrial plants and the transportation system, would have to be developed.

INTERNATIONAL AND MILITARY IMPLICATIONS

There could be important economic and political advantages to developing SPS as a multinational rather than a unilateral system. These include cooperation in establishing legal and regulatory norms, shared risk in financing the R&D and construction costs, improved prospects for global marketing, and forestalling fears of economic domination and military use. Although a multinational effort would face inevitable organizational and political difficulties, the strong potential interest of energy-poor, non-U. S. participants in increased electrical supplies could help make a multinational venture more feasible than a unilateral one by the United States. Global electricity demand may quadruple by 2030, and will be especially strong in developing countries. Western Europe and Japan would be likely partners for a joint project. Depending on the size and expense of the system used, a number of the more rapidly developing but less developed countries might also be interested in participating at lower levels of involvement.

The Soviet Union is carrying on an aggressive space program that may give them an independent capacity to develop SPS, but little is known about their long-range space or energy plans. Real or perceived competition with the Soviet Union could spur a U.S. commitment to SPS.

The development of fleets of launch and transfer vehicles (for SPS), as well as facilities for living and working in space, would enhance this Nation's military space capabilities. Such equipment would give the possessor a large breakout potential for rapid deployment of personnel and hardware in time of crisis, though for nonemergency situations the military would prefer to use vehicles designed specifically for military purposes. SPS itself could be used for military purposes, such as electronic warfare or providing energy to military units, but is technically unsuited to constitute an efficient weapon. Weapons-use of SPS would be prohibited by current bilateral and multilateral treaties. The satellite portion of SPS is vulnerable to various methods of attack and interference but the likelihood of its being attacked is only Slightly greater than for major terrestrial energy systems. The military effects of SPS will depend largely on the institutional framework within which it is developed; international involvement would tend to reduce the potential for use of SPS by the military sector,

SYSTEMS AND COSTS

The optimum SPS system has not been identified. A National Aeronautics and Space Administration/Department of Energy (NASA/DOE) microwave reference system* was developed to provide a basis for review and analysis but was not intended to represent the best possible system. An optimum system should be able to deliver power in smaller units (about 1,000 MW or less), use smaller terrestrial receivers, and cost less to develop than the reference system. Alternative systems may use

*See chs 3 and 5 for a description of the reference system

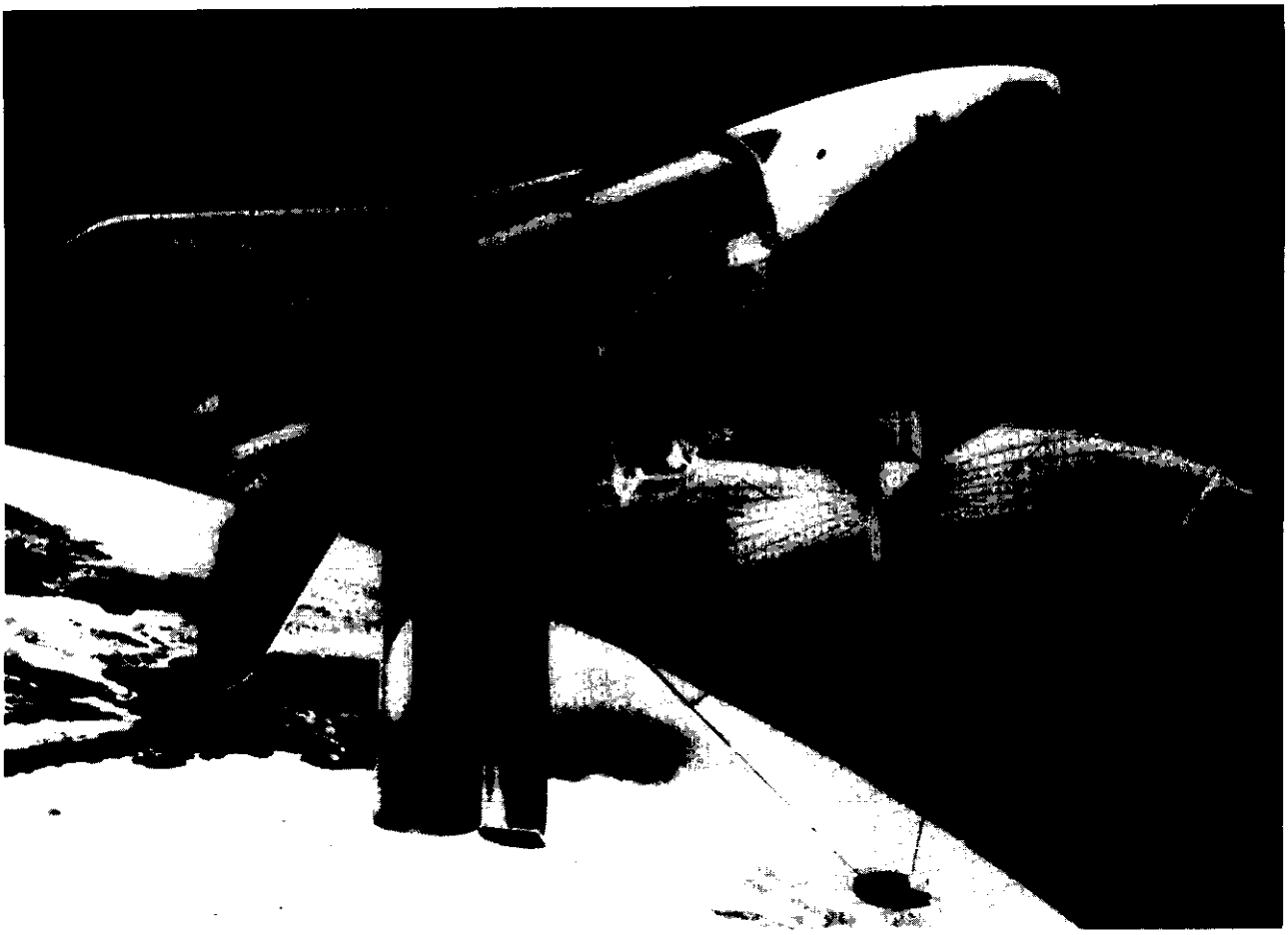


Photo credit: National Aeronautics and Space Administration

The Space Shuttle could serve as both transporter and as a test bed for orbital development work, but is too small to be used for full scale construction of an SPS

lasers or mirrors to transmit solar energy from space to Earth. Variants of the reference system or other completely different systems may offer certain improvements; each will need full study before choosing a system for development.

Current overall cost estimates for the SPS and its major components are highly uncertain. The assessments of up-front costs range from $40 billion to $100 billion. The most detailed estimates have been made by NASA for the reference design. These call for a 22-year investment of $102.4 billion (1977 dollars) (including transportation and factory investment costs) to produce the first 5-GW satellite, with each additional satellite costing $11.3 billion. The costs for most improvements to the reference design, or for alternative systems, are less certain due to the less developed state of nonreference technology. Preliminary studies indicate that the total reference system costs are likely to be significantly higher. On the other hand, alternative systems may well be cheaper than the reference system. The total costs estimated by NASA include major elements, such as space transportation and photovoltaic cells, whose development is likely to proceed regardless of SPS; these costs should not be charged solely to SPS. With the possible exception of fusion, the up-front costs for SPS would be significantly higher than competing baseload electric generating systems. Apportioning the various investment costs and management

Characterization of Four Alternative SPS Systems

Scale				
Satellite size	55 km^2	18 km^2	5 km^2	50 km^2
Number of satellites	60 (300 GW total)	Not projected	Not projected	916 (810 GW total)
Power/satellite	5,000 MW	1,500 **MW**	**500 Mw**	**135,000** MW
Mass	5 x104 tonnes/satellite; 0.1 kW/kg	Less mass than reference/O. 1 kW/kg	Less mass than reference/O.05 kW/kg	2 x 10^5 tonnes mirror system 2 kW/kg
Land use rectenna site	174 km^2 (including buffer) x **60=10,440** km^2	50 km^2	0.6 km^2	1,000 km^2
km^2/1,000 MW	35	33	1.2	7.4
Energy	Electricity Fairly centralized 23 mW/cm^2 Gaussian distribution	Electricity Less centralized Unknown	Electricity, onsite generation. Less centralized Unknown (10 mW/cm^2 at edge)	Electricity, light Highly centralized 1.15 kW/m^2 (1 Sun)
Atmosphere				
Transmission	Ionosphere heating might affect telecommunications		Tropospheric heating might modify weather over smaller area; problems with clouds?	
Effluents	Possible effects include alteration of magnetosphere (AR+), increased water content; formation of noctilucent clouds; ionosphere depletion		LEO orbit, smaller size, smaller launch vehicles	
Electromagnetic Interference	RFI from direct coupling, spurious noise, and harmonics, Impacts on communications, satellites etc from 245 GHz Problem for radio astronomers (GEO obscures portion of sky always) optical reflections from satellites and LEO stations Will change the night sky		If visible light is used there may be problems for optical astronomy if Infrared is used may Increase airglow optical reflection from LEO satellite.	Problem for optical astronomy, optical reflec-hens and Interference from beam change night sky in vicinity of sites
Bioeffects	Microwave bioeffects midbeam could cause thermal heating, unknown effects of long term exposure to low-level microwaves Ecosystem alteratlon? Birds avoid/attracted to beam?		Direct beam ocular and skin damage ocular damage from reflections? Other effects? Birds flying through will burn up? If visible Will birds avoid? Ecosystem alterations?	Psychological and physiological effects of 24-hour illumination not known. Possible ocular hazard if viewed with binoculars? Ecosystem alteration
National security weapons potential	GEO gives a good vantage point over hemisphere –Provides a lot of power m space platform for surveillance, jamming– –Requires development of large space fleet with/military potential–		Direct weapon: as ABM, antisatellite, aimed terrestrial targets Indirect: power killer satellite, planes space platform Laser defend self, best, LEO more accessible	at Indirect: night illumination psychological–possible weather modification
Vulnerability	Satellites may need self defense system to protect against attack Size and distance strong defenses–			Less ground sites; a lot of mirrors-redun-dancy; individual mirrors fragile; ground sites still produce power in absence of space system
International	Will require radio frequency allocation and orbit assignment Smaller parcels of energy make system more flexible Meet environmental and health standards?		LEO more accessible to U S S R and high-latitude countries, smaller parcels of energy make system more flexible	

[a] smaller SOLARES systems, e g , IO **GW/site would be possible and probably more desirable**
[b] **$I02 billilon–NASA estimate+ncludes Investment Costs**
[c] **Estimates byArgonneNational Laboratory, Office of Technology** Assessment, u.s. Congress

SOURCE **Office of Technology Assessment.**

responsibilities between the public and private sectors, and among potential international participants, would be an essential part of SPS development.

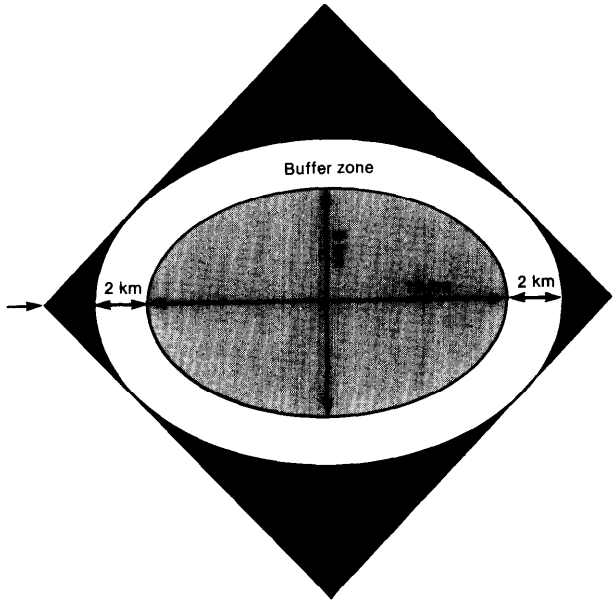
PUBLIC ISSUES

Public opinion about SPS is currently not well-formed. Discussion of SPS has been limited to a small number of public interest groups and professional societies. In general, those in favor of SPS also support a vigorous U.S. space program, whereas many of those who oppose SPS fear that it would drain resources from small-scale, terrestrial solar technologies. Assuming acceptance of a decision to deploy SPS, public discussion is likely to be most intense at the siting stage of its development. Key issues that may enter into public thinking include environment and health risks, land-use, military implications, and costs. Centralization in the decisionmaking process and in the ownership and control of SPS may also be important. From the standpoint of public perceptions, the siting of land-based receivers could be an obstacle to the deployment of SPS unless:

- the public is actively involved in the siting process;
- health and environment uncertainties are diminished; and
- local residents are justly compensated for the use of their land.

Offshore siting of receivers could minimize potential public resistance to SPS siting.

Reference System —Rectenna/
Washington, D. C., Overlay



SOURCE: Off Ice of Technology Assessment.

ENVIRONMENT AND HEALTH

Many of the environmental impacts associated with SPS are comparable in nature and magnitude to those resulting from other large-scale terrestrial energy technologies. A possible exception is coal, particularly if CO_2 concerns are proven justified. While these effects have not been quantified adequately, it is thought that conventional corrective measures could be prescribed to minimize their impacts. However, several health and environmental effects, which are unique to SPS and whose severity and likelihood are highly uncertain, have also been identified. These include effects on the upper atmosphere from launch effluents and power transmission, health hazards associated with non ionizing radiation, electromagnetic interference with other systems and astronomy, and radiation exposure for space workers. More research in these areas would be required before decisions about the deployment or development of SPS could be made. Little information is currently available on the environmental impacts of SPS designs other than the reference system. Clearly, environmental assessments of the alternative systems will be needed if choices are to be made between SPS designs.

Too little is known about the biological effects of long-term exposure to low-level microwave



Photo credit: National Aeronautics and Space Administration

An artist's concept of an offshore antenna that would receive microwave energy beamed from a large space solar power collector in geosynchronous orbit

radiation to assess the health risks associated with SPS microwave systems. The information that is available is incomplete and not directly relevant to SPS. Further research is critically needed in order to set human-health exposure limits. Currently, no microwave population exposure standard exists in the United States. The recommended limit for occupational exposure is set at 10 mW/cm^2 in the United States, 1,000 times less stringent than the present U.S.S.R. occupational standard. Public exclusion boundaries around the reference design have been established at one one-hundredth of U.S. occupational guidelines. It is anticipated that future maximum permissible U.S. occupational standards will be lower by a factor of 2-lo; population standards, if established, may well be lower than the occupational standards. Even more stringent microwave standards could increase land requirements and system cost or alter system design and feasibility. In light of the widespread proliferation of electromagnetic devices and the current controversy surrounding the use of microwave technologies, it is clear that increased understanding of the effects of microwaves on living things is vitally needed even if SPS is never deployed.

Exposure of space workers *to* ionizing radiation is a potentially serious problem for SPS systems that operate in geosynchronous orbit (CEO). Recent estimates indicate that the radiation dose of SPS reference system personnel in CEO would exceed current limits set for astronauts and could result in a measurable increase in

Summary of SPS Environmental Impacts

System component characteristics	Environmental impact	Public health and safety	Occupational health and safety
Power transmission			
Microwave	—[b]Ionospheric heating could disrupt telecommunications. Maximum tolerable power density is not known. Effects in the upper ionosphere are not known —Tropospheric heating could result in minor weather modification. —[b]Ecosystem: microwave bio-effects (on plants, animals, and airborne biota) largely unknown; reflected light effects unknown. —[b]**Potential interference** with satellite communications, terrestrial communications, radar, radio, and optical astronomy.	—[b]Effects of low-level chronic exposure to micro-waves are unknown. — Psychological effects of microwave beam as weapon. —Adverse aesthetic effects on appearance of night sky.	—Higher risk than for . public; protective clothing required for terrestrial worker. —Accidental exposure to high-intensity beam in space potentially severe but no data.
Lasers	—Tropospheric heating could modify weather and spread the beam. — Ecosystem: beam may incinerate birds and vegetation. —[b]**Potential interference** with optical astronomy, some interference with radio astronomy.	—Ocular hazard? — Psychological effects of laser as weapon are possible. —Adverse aesthetic effects on appearance of night sky are possible.	—Ocular and safety hazard?
Mirrors	—[b]Tropospheric heating could modify weather. —Ecosystem: effect of 24-hr light on growing cycles of plants and cir-cadian rhythms of animals. —[b]potential interference with optical astronomy.	—Ocular hazard? —Psychological effect of 24-hr sunlight. –[b]Adverse aesthictic effects on appearance of night sky are possible.	—Ocular hazard?
Transportation and space operation			
Launch and recovery HLLV PLV COTV POTV	—Ground cloud might pollute air and water and cause possible weather modi-fication; acid rain probably negligible. —[b]Water vapor and other launch effluents could deplete ionosphere and enhance airglow. Result-ant disruption of com-munications and satellite surveillance potentially important, but uncertain. —[b]possible formation of noctilucent clouds in stratosphere and meso-sphere; effects on climate are not known.	—Noise (sonic boom) may exceed EPA guidelines. –Ground cloud might affect air quality; acid rain probably negligible. —Accidents-catastrophic explosion near launch site, vehicle crash, toxic materials.	—b Space worker's hazards: ionizing radiation (potentially severe) weightlessness, life support failure, long stay in space, construction accidents psychological stress, acceleration. —Terrestrial worker's hazards: noise, trans-portation accidents.

Summary of SPS Environmental Impacts—Continued

System component characteristics	Environmental impact	Public health and safety	Occupational health and safety
	—[b]Emission of water vapor could alter natural hydrogen cycle; extent and implications are not well-known. —[b]Effect of COTV argon ions on magnetosphere and plasma-sphere could be great but unknown. —Depletion of ozone layer by effluents expected to be minor but uncertain. —Noise.		
Terrestrial activities			
Mining	— Land disturbance (stripmining, etc.). —Measurable increase of air and water pollution. —Solid waste generation —Strain on production capacity of gallium arsenide, sapphire, silicon, graphite fiber, tungsten, and mercury.	—Toxic material exposure. —Measurable increase of air and water pollution. — Land-use disturbance.	—Occupational air and water pollution. —Toxic materials exposure. —Noise.
Manufacturing	—Measurable increase of air and water pollution. —Solid wastes.	— Measurable increase of air and water pollution. —Solid wastes. —Exposure to toxic materials.	—Toxic materials exposure. —Noise.
Construction	—Measurable land disturbance. —Measurable local increase of air and water pollution.	— Measurable land disturbance. —Measurable local increase of air and water pollution.	—Noise. —Measurable local increase of air and water pollution. —Accidents.
Receiving antenna	—[b]Land use and siting— —Waste heat and surface roughness could modify weather.	—[b]Land use—reduced property value, aesthetics, vulnerability y (less land for solid-state, laser options; more for reference and mirrors).	— Waste heat.
High-voltage transmission lines (not unique to SPS)	—[b]Land use and siting— —[b]Ecosystem: bioeffects of powerlines uncertain.	—[b] Exposure to high intensity EM fields—effects uncertain.	—[b]Exposure to high intensity EM fields—effects uncertain.

[a] **impacts based on SPS systems as currently** defined and do not account for offshore receivers or possible mitigating system modifications.
[b]Research priority.

SOURCE: Office of Technology Assessment.

cancer incidence. However, there are a large number of uncertainties associated with quantifying the health risks of exposure to ionizing radiation. More research would be required to reduce these uncertainties and to identify and evaluate system designs and shielding techniques that would minimize risks at an acceptable cost. In addition, acceptable SPS radiation limits would have to be determined. If CEO SPS systems are to be considered, an assessment of the health risks associated with space radiation is a top priority.

The potential for interference with other users of the electromagnetic spectrum could constitute a severe drawback for the microwave option. Satellite communications and optical and radio astronomy would be seriously affected. The effects on radio and optical astronomy would be the most difficult to ameliorate. The minimum allowable spacing between geosynchronous power satellites and geosynchronous communications satellites is not well-known. The optical interference effects of either the mirror or laser transmission options would be of great concern to ground-based astronomers. Any of the SPS options would alter the appearance of the nighttime sky. Some may find this esthetially objectionable.

SPACE CONTEXT

The hardware, experienced personnel, and industrial infrastructure generated by an SPS project would significantly increase U.S. space capabilities and, in conjunction with other major space programs, could lay the groundwork for the industrialization, mining, and perhaps the settlement of space. NASA is likely to play a major role, especially in the initial stages of development. Non-SPS programs could be aided by accelerated development of transportation and other systems; on the other hand, they could be harmed by the diversion of funds and attention to SPS. An SPS research and development program would be in accord with current space policy that calls for peaceful development of commercial and scientific space capabilities

Given the current absence of long-term program goals for the U.S. civilian space program, it is difficult to predict the effects of an SPS project on NASA plans or on private-sector capabilities These effects will need to be carefully considered.

Chapter 2

INTRODUCTION

Chapter 2
INTRODUCTION

As the United States and the world have begun to face the realities of living with a limited supply of oil and gas, and the political uncertainties that accompany impending scarcity, the search for reliable, safe means of using the radiant energy of the Sun has intensified. Solar radiation is already used in many parts of the Nation for direct space heating and for heating water. It can also produce electricity by photovoltaic and thermoelectric conversion. However, nearly all terrestrial solar collectors and converters suffer from the drawbacks of the day-night cycle. On Earth, sunlight is only available during daylight hours, but energy is consumed around the clock. In the absence of inexpensive storage, nighttime and cloud cover limit the potential of terrestrial solar technologies (with the exception of ocean thermal energy conversion) to supply the amounts of energy required for use in homes, businesses, and industries. By placing the solar collectors in space where sunlight is intense and constant, and then "beaming" energy to Earth, the solar power satellite (SPS) seeks to assure a baseload supply of electricity for terrestrial consumers.

Several radically different versions of SPS have been proposed, most of which will be described and analyzed in this report. In the most extensively studied version, a large satellite would be placed in the geosynchronous orbit so that it remains directly above a fixed point on the Earth's Equator. Solar photovoltaic panels aboard the satellite would collect the Sun's radiant energy and convert it to electricity. Devices would then convert the electricity to microwave radiation and transmit it to Earth where it would be collected, reconverted to electricity, and delivered to the electric power grid. An alternative concept envisions using large orbiting reflectors to reflect solar radiation to the ground, creating immense solar farms where sunlight would be available around the clock. Laser beams have also been proposed for the energy transmission medium. These concepts may have significantly different economic prospects, as well as different degrees of technical feasibility. In addition, they would affect the environment and political and financial institutions in different ways.

The first serious discussion of the SPS concept appeared in 1968.[1,2] During the next few years several companies conducted preliminary analyses with some support from the Advanced Programs Office of the National Aeronautics and Space Administration (NASA).[3] In May 1973, the Subcommittee on Space Science and Applications of the House Science and Astronautics Committee held the first congressional hearings on the concept.[4] Following those hearings, NASA began a series of experiments in microwave transmission of power at the Jet Propulsion Laboratory. In 1975, NASA created an SPS study office at the Johnson Space Center that performed several additional systems studies. A number of papers were published,[5] culminating in an extensive report that established most of the basis for the Department of Energy's (DOE) reference system design.[6]

In the beginning it had been assumed that NASA would be the Federal agency with prime responsibility for satellite power stations. However, the Solar Energy Act of 1974 clearly placed the responsibility for all solar energy R&D aimed at terrestrial use under the jurisdic-

[1] P E Glaser, "The Future of Power From the Sun, " Intersociety Energy Conversion Engineering Conference (I ECEC), IEEE publication 68C-21 -Energy, 1968, pp. 98-103,

[2] P E Glaser, "Power From the Sun: Its Future," Science 162, Nov 22, 1968, pp. 857-886,

[3] P E Glaser, O. E. Maynard, J. Mockovciak, and E.L. Ralph, "Feasibility Study of a Satellite Solar Power Station," Arthur D. Little Inc , NASA CR-2357 (contract No. NAS 3-16804), February 1974.

[4] "Power From the Sun via Satellite, " hearings before the Subcommittee on Space Science and Applications and Subcommittee on Energy of the Committee on Science and Astronautics, U S House of Representatives, May 7, 22, 24,1973.

[5] Will Iam J. Richard, "Geosynchronous Satellite Solar Power," ch. 8 of *Solar Energy for Earth: An A /AA Assessment,* H. J. Kill ian, G L Dugger, and J. Grey (eds.), AIAA, Apr. 21, 1975, pp. 59-71. (Also see abridged version in *Astronautics and Aeronautics,* November 1975, pp. 46-52.)

[6] "Initial Technical, Environmental, and Economic Evaluation of Space Solar Power Concepts, " report No. J SC-11568, vols. I and II, NASA, Aug. 31, 1976.

tion of the Energy Research and Development Administration (ERDA). ERDA set up a Task Group on Satellite Power Stations, and in November 1976 recommended two options for conducting a joint ERDA/NASA 3-year SPS concept development and evaluation program, one costing $12 million and one $19 million. ' ERDA elected to pursue a median course, and proposed a 3-year, $15.5 million effort which began in fiscal year 1977, the SPS Concept Development and Evaluation Program.

ERDA's efforts were given impetus by two congressional hearings, one held in January 1976 by the Subcommittee on Aerospace Technology and National Needs of the Senate Aeronautical and Space Sciences Committee[8] and one held in February 1976 by two subcommittees of the House Committee on Science and Technology.[9]

When DOE was created in 1977, it established a special Satellite Power System project office in the Office of Energy Research to complete the Concept Development and Evaluation Program. Its final report was released on December 1, 1980.'0

The SPS research, development, and demonstration bill, ' which was introduced in the House of Representatives on January 30, 1978, reflected a desire by a number of Members of Congress to accelerate the evaluation of SPS and to introduce a more ambitious technology verification effort. It was reported out by the Science and Technology Committee after another round of hearings, '2 and eventually passed by the full House. No Senate bill was introduced. A similar bill,[13] reintroduced in 1979, was passed by the House on November 16, 1979, but again died in the Senate.

The DOE/NASA Concept Development and Evaluation Program[14] was established to identify and evaluate the possible technical, environmental, social, institutional, and economic aspects of the SPS concept. It has generated a broad range of reports that reflect this intent.[5] In order to have a fixed technical basis for the study, DOE and NASA developed two versions of a "reference" satellite power station system, based on extensive studies undertaken by two NASA contractors.[16,17] Although the reference system represented the best choice based on the information available at the time, it was not intended to be the last word in systems definition; the multitude of other options that have been proposed since also need to be evaluated before ultimately settling on a "baseline" system design.

OTA was requested by the House Committee on Science and Technology to pursue an independent study to "assess the potential of the SPS system as an alternative source of energy.'"[8] Hence, this study primarily addresses the benefits and drawbacks of SPS as an energy system. It also identifies the key

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[7]Robert A. Summers (chairman), "Final Report of the ERDA Task Croup on Satellite Power Station," report No. ERDA-76/l 48, November 1976.

[8]"Solar Power for Satellites, " hearings before the Subcommittee on Aerospace Technology and National Needs of the Committee on Aeronautical and Space Sciences, U S. Senate, J an, 19, 21,1976, GPO stock No, 66-608-0, 1976

[9]"Solar Satellite Power System Concepts," hearings before the Subcommittee on Space Science and Applications and the Subcommittee on Energy Research, Development, and Demonstration of the Committee on Science and Technology, U.S. House of Representatives, Feb. 20,1976 (No 67)

[10]"Satellite Power Systems Concept Development and Evaluation Program, "Program Assessment Report Statement of Findings, " DOE/E R-0085, November 1980,

[11]Ronnie Flippo, "Solar Power Satellite Research, Development, and Demonstration Program Act of 1978, " H .R 10601, J an. 30,1978.

[12]"Solar Power Satellite, " hearings before the Subcommittee on Space Science and Applications and the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development, and Demonstration of the Committee on Science and Technology, U.S. House of Representatives, Apr 12-14, 1978 (No, 68), GPO stock No. 28-155-0, 1978,

[13]Ronnie Flippo, "Solar Power Satellite Research, Development, and Evaluation Program Act of 1979, " H R. 2335, Feb. 22, 1979

[14]"Satellite Power System Concept Development and Evaluation Program Reference System Report," U S. Department of Energy report No DOE/E R-0023, October 1978.

[15]See the extensive set of references in note 10

[16]C Woodcock, "Solar Power Satellite System Definition Study, " Boeing Aerospace Co., Johnson Space Center (contract No NAS 9-151 96), pt. 1, report No. D1 80-22876, December 1977, pt III, report No D180-24071, March 1978

[17]C Hanley, "Satellite Power System (SPS) Concept Definition, " Rockwell International Corp., Marshall Space Flight Center, (contract No. NAS 8-32475), report No. SD78-AP-0023, April 1978

[18]Letter of request to OTA from the House Committee on Science and Technology, Aug 8,1978

uncertainties of the various SPS concepts and related needs for R&D.

Although SPS would be an energy system it is unique in being a major space system as well. It would therefore require a large new commitment to the development of space technology. Hence, this report also addresses the relationship of an SPS program to other space programs.

OTA has divided the assessment into four major areas: 1) SPS technical alternatives and economics, 2) issues arising in the public debate, 3) institutional and international questions, and 4) the programmatic context, i.e., the place of SPS within our national energy and space programs. A number of working papers were written to provide data for these areas. OTA also convened three workshops to refine and amplify the data presented in several of the working papers: 1) SPS Technical Options and Costs, 2) SPS Public Opinion Issues, and 3) The Energy Context of SPS.

- • *SPS technical options and costs.* The major task of the workshop was to assess the DOE/NASA reference system from a technical perspective and to study alternatives. It discussed the key uncertainties of each major system or subsystem that has been suggested in SPS literature and chose four generic systems for further evaluation in later workshops: 1) the reference system, 2) a solid-state variant of the reference system, 3) a laser system, and 4) a mirror system.
- SPS *public opinion issues.* Participants with experience in analyzing and responding to a variety of public interests and concerns met to identify the major issues that could affect the public perceptions of SPS. The workshop was not an exercise in public participation. Rather, it sought a range of viewpoints from participants who have a sense of the issues, the political players, and public attitudes involved.
- The energy context of SPS. SPS will succeed or fail in competition with other energy supply options and in the context of national and global demand for electricity. This workshop developed criteria for choosing between technologies and compared the major future alternative renewable or inexhaustible sources of baseload electrical power. Participants discussed the many factors that would affect future electricity demand and compared breeder reactors, fusion, terrestrial solar thermal, and solar photovoltaic baseload options. They also discussed the potential role of dispersed photovoltaic systems in meeting part of the Nation's electrical needs.

Because the SPS concept would use a complex future technology about which there are many uncertainties, this assessment is fundamentally different from an assessment of current technology. While it is thought to be technically feasible, many of the details are uncertain; economic projections or possible environmental effects based on them are also uncertain, sometimes by more than an order of magnitude. Hence at this point OTA must be satisfied with identifying the key uncertainties of SPS and, where applicable, suggesting alternate strategies for resolving them. The study also analyzes the major institutional and international issues that accompany decisions about SPS, i.e., how it may affect national security, the international energy market, the utilities industry, and how an SPS project might be financed and managed. Although a definitive treatment of any of these issues must wait for the future, this report attempts to lay the foundation for further consideration of SPS.

Chapter 3

ISSUES AND FINDINGS

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TECHNICAL OPTIONS

What technical options might be available for SPS?*

A number of technical options for the solar power satellite (SPS) have been proposed. Because SPS is a developing technology, the specific design parameters of each of these approaches are evolving rapidly as research continues. Hence no single option is completely defined, nor are there detailed systems studies of any designs other than the National Aeronautics and Space Administration/Department of Energy (NASA/DOE) "reference system" that uses microwaves for transmitting energy from space to Earth. The reference design is the basis for the NASA/DOE environmental, societal, and comparative assessments. The two other major SPS variants depend on laser transmission of power from space and on reflected sunlight.

Microwave Transmission

The Reference System Design

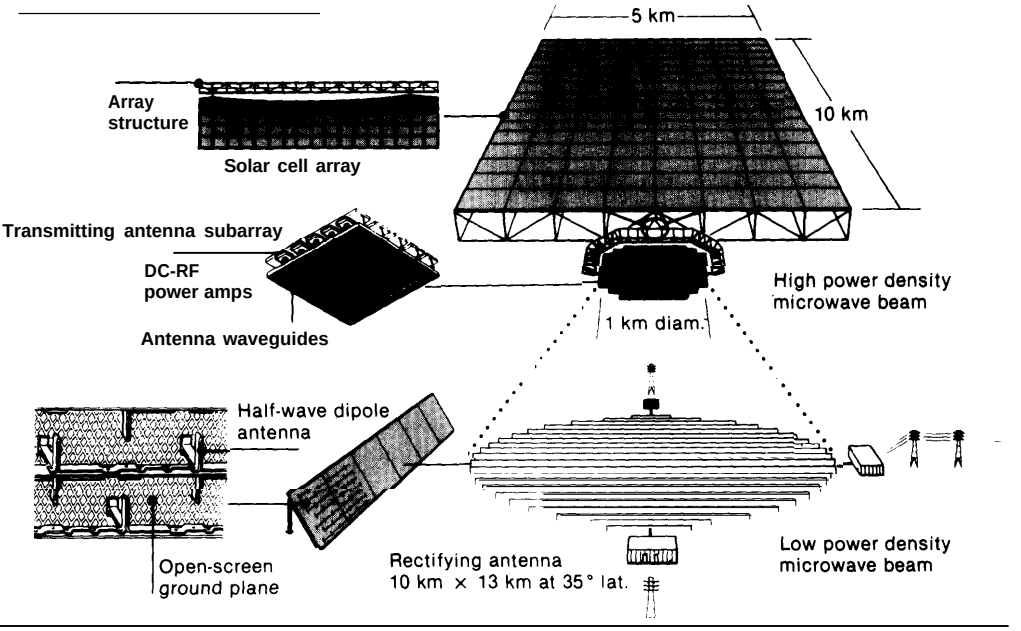
The reference system satellite conceptual design consists of a 55 square kilometer (km^2) flat array of photovoltaic solar cells located in the geostationary orbit 35,800 km above the Earth's Equator (fig. 1). The cells convert solar energy into direct-current (de) electricity that is conducted to a 1-km diameter microwave transmitting antenna mounted at one end of the photovoltaic array. Microwave transmitting tubes (klystrons) convert the electrical current to radio-frequency power at 2.45 gigaHertz (GHZ), and transmit it to Earth. A ground antenna receives the electromagnetic radiation and rectifies it back to direct current; hence its designation "rectenna." The direct-current (de) power can be inverted to alternating-current (ac) and "stepped up" to high voltage. It would then be either rectified to dc and delivered directly to a dc transmission network in the terrestrial utility grid or used as conventional ac power. The rectenna covers a ground area of 102 km^2 and would require an "exclusion area" around it of an additional 72 km^2 to protect against exposure to low-level microwaves. The beam density at the center of the rectenna is 23 milliwatts per square centimeter (mW/cm^2). The beam is shaped in such a way that at the edge of the exclusion area it reaches 0.1 mW/cm^2.**

For the given set of design assumptions for the reference system, i.e., beam density, taper, and frequency, the maximum power per transmitter-receiver combination would be 5,000 MW. Except for a small seasonal variation in output due to the variation of the Sun's distance from the Earth, and short periods of shadowing by the Earth near the time of the spring and fall equinoxes, each reference system satellite could be expected to deliver the maximum amount of power to the grid approximately 90 percent of the time. This power level was selected by NASA/DOE for the reference system in the belief that it would provide energy at the lowest cost. 1 n subsequent discussions it is used to consider the impact of the reference system design on utilities and their systems; however, the power level could be set at any value permitted by the design constraints.

The reference system, which was developed to provide a base for further studies and is now several years old, is far from an optimum microwave system and could be substantially improved. In addition, alternative concepts that depend on laser transmission or passive reflection of sunlight each offer certain specific benefits over the microwave designs. Because none of these alternatives are as well defined as the reference system, they are discussed here in more general terms.

*See ch. 5.
**Equivalent to about 13,600 acres

Figure 1 .—The Reference System



SOURCE: C. C. Kraft, "The Solar Power Satellite Concept," NASA publication No. JSCp14898, July 1979.

The Solid-State Variant

Using solid-state devices that convert electricity from the satellite's solar array directly to microwave power would be a possible alternative to the reference system's klystrons. Such devices might have a longer working lifetime and require less mass in orbit; when coupled with photovoltaic cells in a "sandwich" design, they would also allow for a much larger transmitting antenna (the entire surface area of the solar cells would, in effect, be the antenna), smaller earthside antennas, and lower power delivered to Earth per satellite (i.e., about 1,000 MW per rectenna). In combination, these effects would make it possible to position rectennas closer to the cities, which would be the major users of SPS generated power, than would the reference system design.

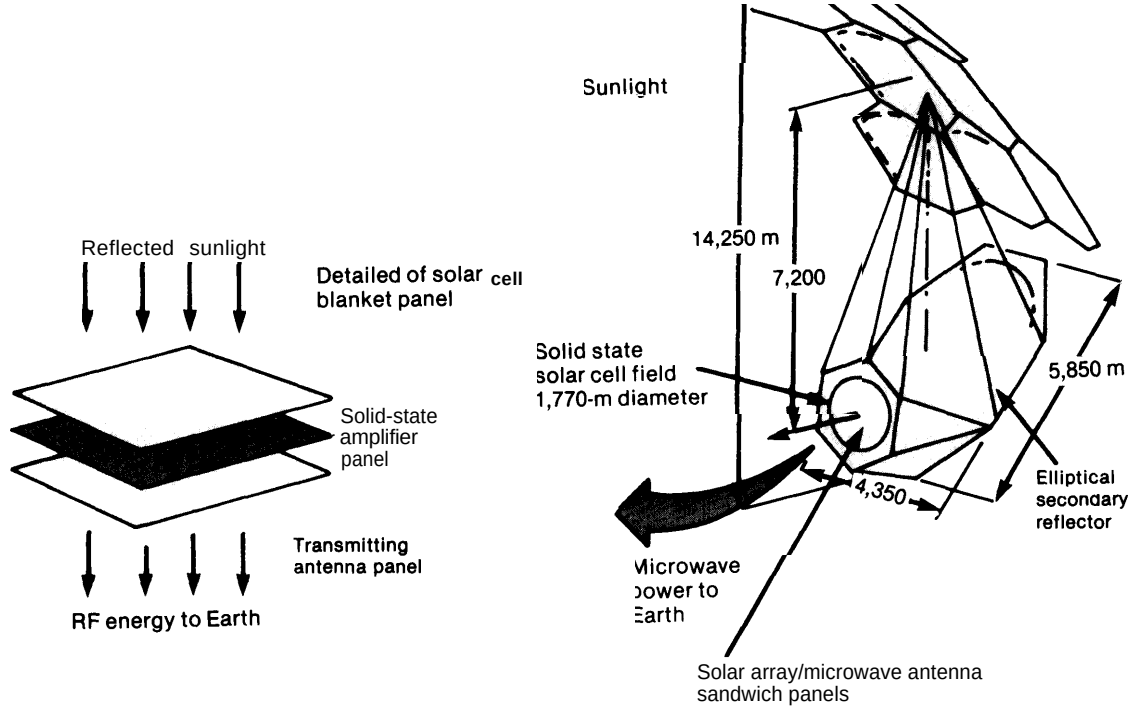
Solid-state devices are now in the very early stages of being evaluated for SPS application. It is still unclear whether they would be able to reach the efficiency and cost goals that would be necessary for SPS.

Laser Transmission

Lasers constitute an obvious alternative to microwaves for the transmission of power over long distances. Compared with microwaves, lasers have a much smaller beam diameter; since the aperture area of both transmitting and receiving antennas decreases as the square of the wavelength, light from an infrared wavelength laser can be transmitted and received by apertures over 100 times smaller in diameter than a microwave beam. This reduces the size and mass of the space segment and the area of the ground segment. Perhaps even more important, the great reduction in aperture area permits consideration of fundamentally different systems. For example:

- **It would become possible to use low Sun-synchronous rather than high geostationary orbits for the massive space power conversion subsystem (a Sun-synchronous orbit is a near-polar low Earth orbit that keeps the satellite in full sunlight all the time while the Earth rotates beneath it). The primary laser would then beam its**

Figure 2.—The Solid-State Variation of the Reference System



SOURCE: G. M. Hanley, et al., "Satellite Power Systems (SPS) Concept Definition Study First Performance report No. SS D 79-0163, NASA MSFC contract No. NAS8-32475, Oct. 10, 1979.

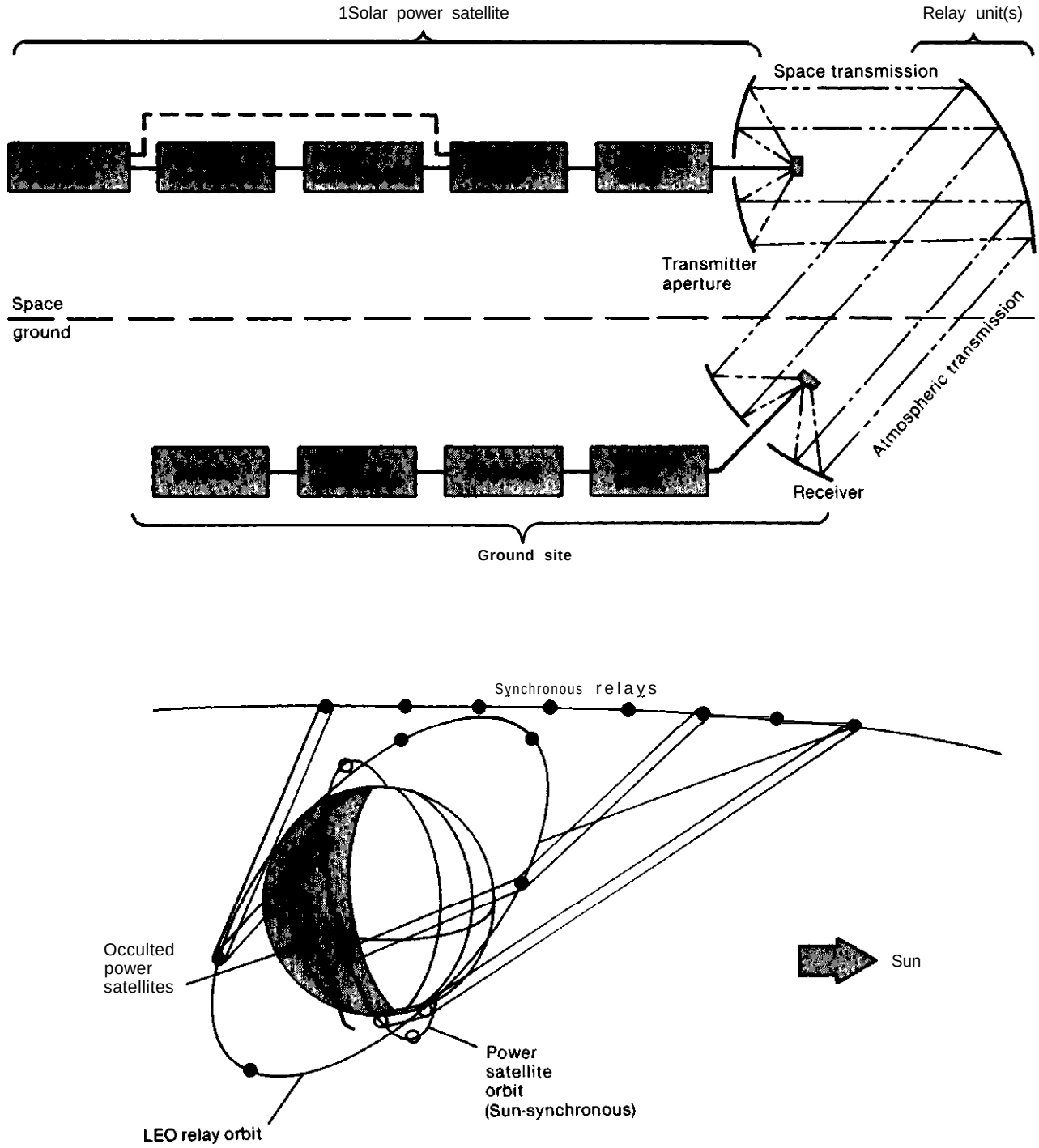
power up to low-mass laser mirror relays in geostationary orbit for reflection down to the Earth receiver. This arrangement, while complex, would considerably reduce the cost of transportation, since the bulk of the system would be in low Earth orbit rather than in geostationary orbit. It also could be built with smaller transportation vehicles than the reference system's planned heavy lift launch vehicle (HLLV).

- **A laser system might be able to operate efficiently and economically on a smaller scale (100 to 1,000 MW). Thus, it would offer the flexibility of power demand matching on the ground, making possible higher degrees of redundancy and a smaller and therefore less costly system demonstration project.**
- **The potentially small size of the receiving station would make it possible to employ multiple locations close to the points of use, thereby simplifying the entire ground distribution and transmission system.**
- **Laser power transmission would avoid the problem of microwave biological effects and would reduce overall interference with other users of the electromagnetic spectrum.**

A laser SPS would suffer from three important disadvantages:

- *Absorption of laser radiation.* **Infrared radiation is subject to severe degradation or absorption by clouds. A baseload system, unlike the microwave option, would require considerable storage capacity to make up for interruptions. Multiple re-**

Figure 3.—The Laser Concept (One Possible Version)



SOURCE: W. S. Jones, L. L. Morgan, J. B. Forsyth, and J. Skratt, "Laser Power Conversion System Analysis: Final Report, Vol. II," Lockheed Missiles and Space Co., report No. LMSC-D673466, NASA report No. CR-159523, contract No. NAS3-21137, Mar. 15, 1979.

ceivers at different locations to achieve some redundancy are also possible, but expensive (seeUtilities, ch. 9).

- *Efficiency.* Current high-power, continuous-wave lasers are only capable of very low overall power conversion efficiencies (less than 25 percent). Converting the beam back into electricity is also inefficient, though progress in this area has been rapid. The relatively undeveloped status of laser generation and conversion means that considerable basic and applied research would be needed to determine the feasibility of a laser SPS.
- *Health and safety hazard.* The beam intensity would be great enough to constitute a health and safety hazard. Preventive measures could include a tall perimeter wall, and/or a warning and defocusing system.

Several types of continuous wave lasers currently exist. Of these, the most highly developed and most appropriate laser for SPS would be the electric discharge laser (EDL). At present, EDL models have achieved only modest power levels and relatively low efficiencies when operated in a continuous mode.

Another future option that has been considered is the solar-pumped laser. In this device, concentrated sunlight is used directly as the exciting agent for the laser gases. Although a solar-pumped laser has been built and operated successfully at NASA Langley, it would require considerable basic research, development, and testing before it could be a realistic prospect for SPS.

Free electron lasers (FELs) offer another possible means of transmitting power from space. These new devices are powered by a beam of high-energy electrons which oscillate in a magnetic field in such a way that they radiate energy in a single direction. Although the FEL has been demonstrated experimentally, it is too early to predict whether it would reach the efficiencies and reliability necessary for an SPS.

Reflected Sunlight

Instead of placing the solar energy conversion system in orbit, large orbiting mirrors could be used to reflect sunlight to ground-based solar conversion systems. Thus, the system's space segment could be much simpler and therefore cheaper and more reliable.

One such system would consist of a number of roughly circular plane mirrors in various nonintersecting Earth orbits, each of which directs sunlight to the collectors of a number of ground-based solar-electric powerplants as it passes over them. Conversion from sunlight to electricity would occur on the surface of the Earth.

In one approach, (the so-called "SOLARES baseline" concept) about 916 mirrors, each 50 km^2 in area, would be required for a global power system projected to produce a total of 810 gigawatts (GW) (more than three times current U S. production) from six individual sites. This is not necessarily the optimum SOLARES system. It was selected here to demonstrate the magnitude of power that might be achieved with such a system. However, a number of different mirror sizes, orbits, and ground station sizes are possible. A more feasible option would be a lower orbit system (2,100 km) to supply 10 to 13 GW per terrestrial site. One of the principal features of the SOLARES concept is that it could be used for either solar-thermal or solar photovoltaic terrestrial plants. The fact that energy conversion would take place on the surface of the Earth keeps the mass in orbit small, thereby reducing transportation costs.

However, a major disadvantage of such a mirror system would be that the entire system would require an extremely large contiguous land area for the terrestrial segment (see table 4, p. 47). As with the laser designs, transmission through the atmosphere would be subject to

Figure 4.–The Mirror Concept (SOLARES)

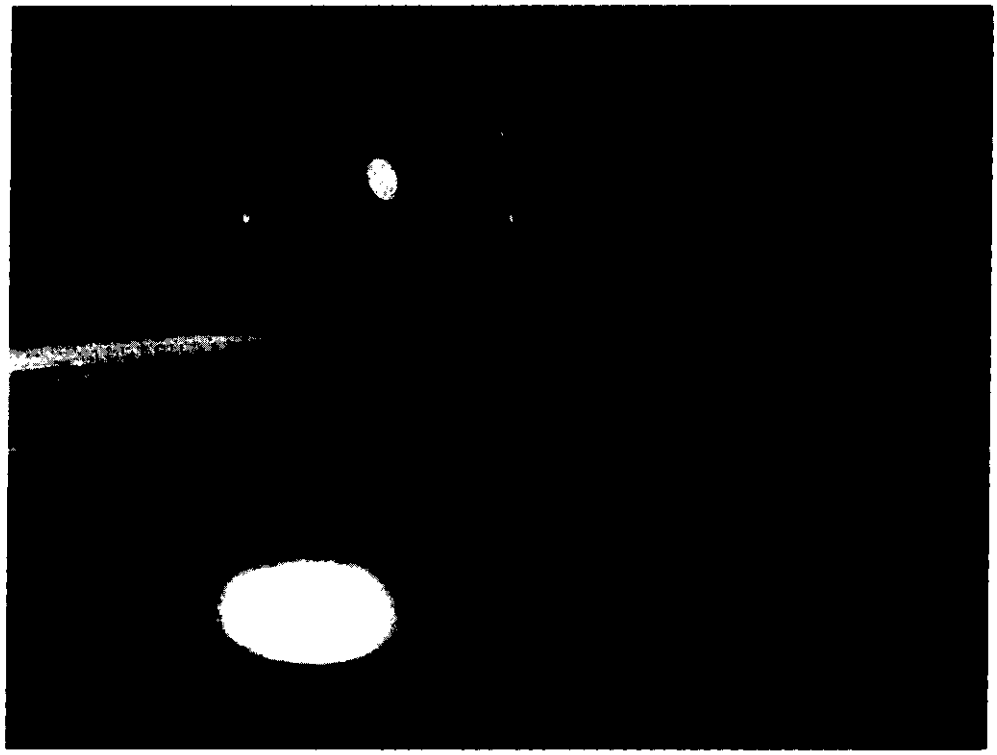
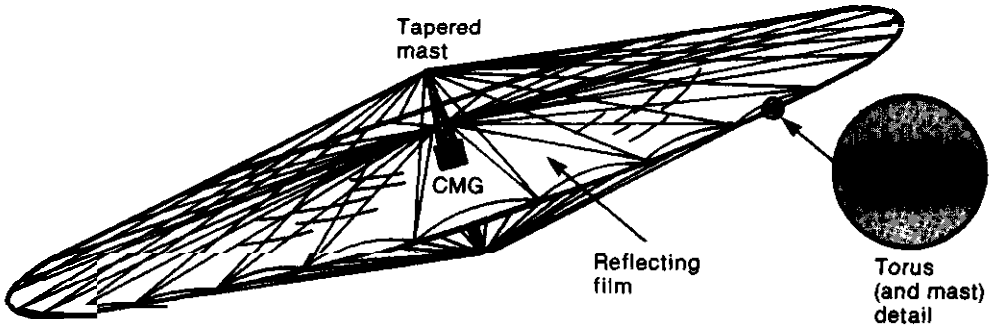


Photo credit National Aeronautics and Space Administration



SOURCE: K. W. Billman, "Space Orbiting Light Augmentation Reflector Energy System: A Look at Alternative Systems," SPS Program Review, June 1979.

reduction or elimination by cloud cover. It would also illuminate much of the night sky (see issue on electromagnetic interference) as seen by observers within a 150-km radius of the groundsite center.

SPS Scale

As presently conceived, the reference system is a large-scale project that has the potential of delivering hundreds of gigawatts of electrical power to the United States or to other countries. However, its very scale is seen by many as a serious drawback to deployment. The utilities here and abroad would find it hard to accommodate power in 5,000 MW blocks (see Utilities, ch. 9), and the space transportation system needed to build and maintain such a massive system would be very expensive. Thus, it is of considerable interest to investigate ways in which the scale of the various components, and of the system itself, could be reduced to a more manageable size.

The laser system would offer the potential for the most substantial reductions, both in overall system size and in the size of the first demonstration project. This reduction in scale might also bring with it a concomitant reduction of costs. There are also a number of possible ways in which to reduce the physical scale of portions of the microwave system. However, economies of scale tend to drive microwave systems to sizes of 1,000 MW output or more.

SPS would require a massive industrial infrastructure for space transportation and construction and for related terrestrial construction, comparable in scale to that developed for existing ground-based coal and nuclear systems.

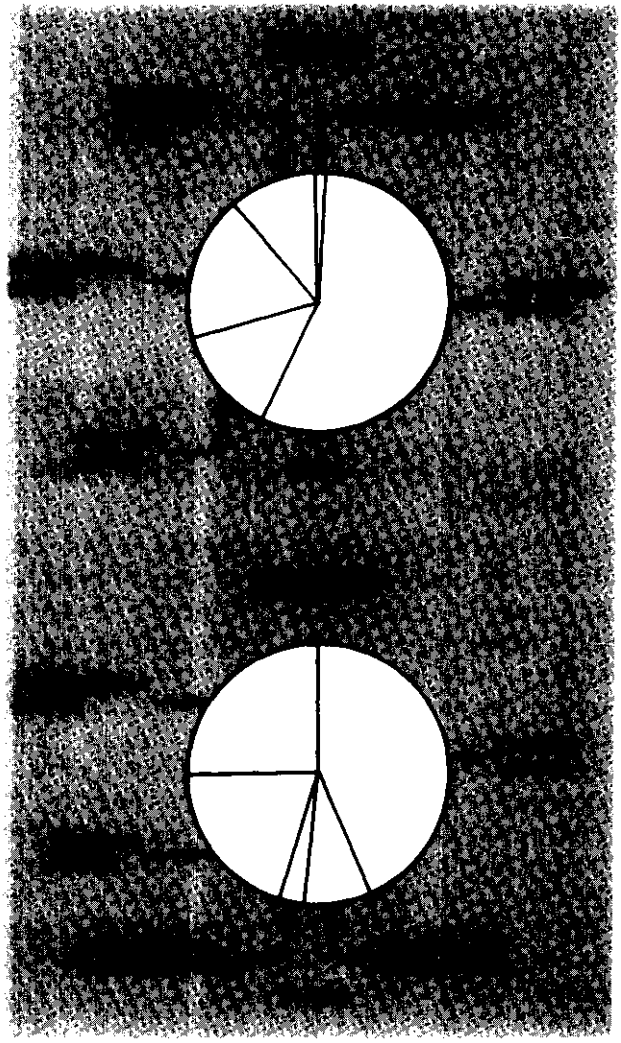
- **Space transportation. The reference system assumes the construction and use of a large third-generation, shuttle-type transportation system. Construction of a single reference system satellite (silicon photovoltaics) would require approximately 190 flights of an HLLV. However, launch vehicles somewhat larger than the current shuttle, but smaller than the HLLV, are capable of operating with less load per flight but with many more flights and might be more economical. I n addition, an intermediate size vehicle would be more appropriate for other uses in space. No other currently planned space project envisions using vehicles the size of an HLLV.**
- *Space construction.* **SPS would require construction bases in low Earth orbit and, for some designs, at geostationary orbit. It might be possible to achieve substantial cost reductions by constructing the satellites in low Earth orbit and transporting them to geostationary orbit, rather than by constructing them in geostationary orbit.**

costs

Although the costs of many SPS components have been estimated by a number of different agencies, it is not yet possible to establish them with any reasonable level of confidence. The most detailed cost estimates have been made by NASA for the reference system (fig. 5): $102.4 billion to achieve the first complete reference system satellite, and $11.3 billion to construct each satellite thereafter.

These estimates included the costs of the entire transportation system, the costs of establishing the launch sites and construction facilities in low-Earth and geosynchronous orbits, as well as all of the component development

Figure 5.—Reference System Costs[a]
(dollars in billions)



[a]NASA estimates— 1977 dollars.

SOURCE: National Aeronautics and Space Administration

costs. However, they do not include interest on the invested capital or the potential use of SPS facilities for other space or terrestrial projects. According to one possible development scenario generated by NASA (see fig. 24, p. 93), including interest of 10 percent per year more than doubles the development cost of SPS.

By using a smaller capacity transportation system (assuming more flights per satellite), and apportioning the development costs of generic space technology among all the space programs that benefit from it, it might well be possible to deploy a single reference satellite for $40 billion to $50 billion, or roughly one-half of the above estimate.

Other systems might cost more or less than the reference system, depending on the state of development of the alternative technologies (see table 1). For example, since lasers would need considerable development before they would be suitable for use in a laser-powered SPS, they would be likely to be more expensive to develop than the microwave transmitter of the reference system; however, some of the development cost could conceivably be borne by other laser applications, e.g., directed energy weapons or inertial fusion. The cost of a laser demonstration satellite might well be less than the reference system demonstrator. Because of the relatively low mass and ease of construction and operation of a SOLARES system, it may prove to be much more attractive than other alternatives. Cost estimates suggest that if the cost of terrestrial photovoltaics can reach the goals implied by reference system estimates, the costs of a total SOLARES system would be less than the reference system. More exact costs for the SPS await further information on the details of the preferred system. Whatever system might be chosen, it is clear that the startup costs would be in the tens of billions. How much of this cost would have to be borne by the U.S. taxpayer depends on the breadth and depth of industrial and international interest in the development of SPS (see ch. 7).

SPS AND THE ENERGY FUTURE

How could SPS flt into the U.S. energy future (2000-30)?*

SPS will ultimately be accepted or rejected in the full context of future electrical demand and supply technologies. It would compete with other renewable or inexhaustible energy sources such as hydro, wind, terrestrial solar, ocean thermal energy conversion, fusion, fission breeder, and geothermal. Their technologies are all quite different; some serve a demand for baseload, some for peaking or intermediate needs. Together, they would constitute a mix of technologies designed to supply the full range of electrical needs for the United States. SPS must be considered in light of its potential contribution to this mix, as well as of future electrical demand.

*See ch. 6, *Energy* section.

SPS Is Not Likely To Be Commercially Available Before 2005-15

Experience with other new electric generating technologies indicates that new technologies take from 30 to 45 years to become a significant source of electrical capacity in the utility grid. SPS is unlikely to constitute a major exception to this rule of thumb. If a decision to develop SPS were made, some 15 to 25 years of development, engineering, and demonstration would be needed to reach a commercial SPS. However, because of the many uncertainties surrounding SPS, it is not yet possible to make a development decision. If, after considerable further research a decision is made in the next decade to proceed with SPS, then it could be commercially available in the period between 2005 and 2015. Several years of operational testing beyond that would

Table 1.—Characterization of Four Alternative SPS Systems

Information matrix	Reference design	Solid state	Laser system	SOLARES ("baseline")a
costs				
R&D	$400 million	More R&D needed than reference system	More R&D needed than reference system	Relatively simple technical lower cost
Demonstration	$102 billion DDT&E (one sateilite)[b]		Smaller, demonstration with shuttle?	$44 **billion, demonstration with shuttle?**
Construction	**$11,5 billion/satellite**	**Unit cost lower, smaller rectenna**	**$3 billion satellite (0,5 GW)**	**$1,300 billion for 810 GW total system**
Operation	**$200 million/yr-5GW**	**Greater reliability, long lifetime**	**25 million/yr-satellite (0.5GW)**	**Higher ground conversion cost**
Dollars/kW	**$2,900** -19,000/kW[c]	**$1 ,800** -3,000/kW **(probably low)**	**$6,000/kW probably low)**	**$1,500/kW (probably low)**
Scale				
Satellite size	55 km^2	18 km^2	5 km^2	50 km^2
Number of satellites	60 (300 GW total)	Not projected	Not projected	916 (810 GW total)
Power/satellite	5,000 MW	1,500 MW	500 MW	135,000 MW
Mass	5 $X10^4$tonnes/satellite, O 1 kW/kg	Less mass than reference/O 1 kW/kg	Less mass than reference/O .05 kW/kg	2 x 10^5tonnes mirror system 2 kW/kg
Land use rectenna site	174 km^2 (including buffer) x 60=10,440 km^2	50 km^2	0.6 km^2	1,000 km^2
km^2 1,000 MW	35	33	1,2	7.4
Energy	Electricity Fairly centralized 23 mW/cm^2 Gaussian distribution	Electricity Less centralized Unknown	Electricity, onsite generation. Less centralized Unknown (10 mW/cm^2 at edge)	Electricity, light Highly centralized 1.15 kW/m^2 (1 Sun)
Atmosphere				
Transmission Effluents	Ionosphere heating might affect telecommunications Possible effects include alteration of magnetosphere (AR+); increased water content; formation of noctilucent clouds; ionosphere depletion		Tropospheric heating might modify weather over smaller area; problems with clouds? LEO orbit, smaller size; smaller launch vehicles	
Electromagnetic interference	RFI from direct coupling, spurious noise, and harmonics: impacts on communications, satellites etc from 245 GHz Problem for radio astronomers (GEO obscures portion of sky always) optical reflections from satellites and LEO stations Will change the night sky		If visible light is used there may be problems for optical astronomy; if Infrared is used may Increase airglow optical reflection from LEO satellite	Problem for optical astronomy, optical reflections and interference from beam; change night sky in vicin of sites
Bioeffects	Microwave bioeffects midbeam could cause thermal heating unknown effects of long-term exposure to low-level microwaves, Ecosystem alteration? Birds avoid/attracted to beam?		Direct beam ocular and skin damage ocular damage from reflections? Other effects? Birds flying through Will burn up? If visible will birds avoid? Ecosystem alterations?	Psychological and physiological effects of 24-hour illumination not known Possible ocular hazard if viewed with binoculars? Ecosystem alteration
National security weapons potential	GEO gives a good vantage point over hemisphere –Provides a lot of power in space platform for surveillance, jamming– –Requires developement of large space fleet with/militarv potential–		Direct weapon: as ABM, antisatellite, aimed terrestrial targets Indirect: power killer satellite, planes space platform Laser defend self, best, LEO more accessible	at Indirect: night illumination psychological–possible weather modification
Vulnerability	Satellites may need self defense system to protect against attack Size and distance strong defenses—			Less ground sites; a lot of mirrors-redundancy; individual mirrors fragile; ground sites still produce power in absence of space system
International	Will require radio frequency allocation and orbit assignment Smaller parcels of energy make system more flexible Meet environmental and health standards?		LEO more accessible to U.S.S.R. and high-lahtude countries, smaller parcels of energy make system more flexible	

[a]Smaller SOLARES systems, e g 10 GW/site would be possible and probably more desirable
[b]$102 billion—NASA estimate–mcludes Investment costs
[c]Estimates b, Argonne National Laboratory, Office of Technology Assessment, US Congress

SOURCE Office of Technology Assessment

be needed before utilities developed enough confidence in SPS to invest in it for their use (see ch. 9).

SPS Would Not Reduce U.S. Dependence on Imported Oil

Currently the biggest energy problem facing the Nation is dependence on unreliable sources for imported oil. This dependence will persist for the next two decades, since our domestic supplies will continue to decline. We now produce about 10 million barrels per day (bbl/d) of petroleum liquids and this will likely fall to 4 million to 7 million bbl/d by 2000. The supply of abundant domestic energy resources such as coal, solar, uranium, and natural gas can increase but not enough to offset the decline in oil. Over this period our best opportunity for reducing dependence on imports will be conservation, which has the potential of cutting current dependence by more than 50 percent. However, the real problem will be the substantial reduction in availability of world oil for export to the United States. The total amount of oil available is not likely to exceed the current level of 52 million bbl/d and may be as much as 15 percent below this level. Further, overall world demand will likely be higher because of increased needs by less developed countries (LDCS), including oil producing countries. As a result, the United States will find it necessary to reduce imported oil dependence considerably by 2000. This reduction will be even more marked past 2000, when we can expect synthetic fuels from all sources to make a substantial contribution. Since the SPS will not be able to make a significant contribution until well past 2000, it cannot be expected to substitute for foreign oil. However, the satellite could eventually begin to substitute for coal-fired powerplants since coal, too, is a finite fuel, and regardless of the outcome of the CO, controversy, use of it for electric production will eventually (though probably not for the next 100 years) be reduced and reserved for nonenergy needs, i.e., for plastics, synthetic fiber, etc.

Potential Scale of Electrical Power

The reference system is designed to deliver 5 GW (5,000 MW) of power to each rectenna. If a 60-satellite U.S. fleet were completed, the SPS could deliver a total of 300 GW, an amount nearly one-half the current total U.S. generating capacity. Converted to energy at a capacity factor of 90 percent, a 60-satellite system would produce about 8 Qe/yr, more electrical energy than we currently consume from all supply sources (7.5 Qe). An international fleet of satellites could achieve a much greater capacity than this by placing more satellites in geostationary orbit. A SOLARES-type system could achieve an even greater generating capacity on an international scale.

other proposals, such as the laser system and variants of the microwave system might be economical in somewhat smaller unit sizes (500 to 1,000 MW). Precisely how much total energy they might supply is less clear, however. For example, a laser system supplying power in 1,000 MW units would need 300 such satellites and ground receivers in order to equal the capacity of a 60-satellite reference system.

Electricity Demand Would Affect the Need for Solar Power Satellites

The level of electricity demand in the United States and the world will greatly affect the time that new centralized electric generating technologies, such as SPS, might be needed. The demand for electricity could vary considerably over the next several decades. For the United States, current forecasts show a range in possible electrical demand from less than today's level of 7.5 Qe end-use to more than 30 Qe by 2030. The demand level will be a major determinant of the rate at which new electric generating technologies need to be introduced. At the lowest levels, all of our baseload capacity could easily be supplied by hydro and coal or nuclear for well into the 21st

century provided $C0_2$ buildup does not preclude increased coal use. At high demand levels, however, it is unlikely that any one technology could provide all the needed baseload capacity and several possibilities would be needed. In this case, development of SPS may be attractive, even assuming successful development of fusion or breeder reactors.

An emerging factor that will strongly affect electricity demand is the success in developing demand technologies that use electricity very efficiently. It is likely over the next several decades that the price of electricity will come close enough to other forms of energy (synthetic fuels, direct solar, etc.) that the relative efficiencies of the end-use equipment will determine which energy form is the cheapest. Therefore, electricity demand could grow considerably if such things as very efficient space and water heat pumps, electrochemical industrial processes, and high-capacity storage batteries are developed. If these are not forthcoming and the conventional ways of using energy–direct combustion of liquid and gaseous fuels–continue to be most prevalent, then electricity demand in the United States will not increase rapidly if at al 1. Therefore, the eventual need for solar power satellites and other central electric technologies would be determined as much by the development of efficient electric demand technologies as by its economics relative to other electric energy technologies.

Comparison to Other Renewable Options

Ultimately the United States and the world will choose or reject SPS as an energy supply option on the basis of comparative costs as well as environmental and social impacts. OTA has generated a number of criteria for the choice of energy technologies and compared SPS with other renewable or inexhaustible options (fusion, nuclear breeder, terrestrial solar thermal, and solar photovoltaic) on the basis of those criteria (see table 16, p. 11 6). What emerges from such comparisons is that if the research, development, demonstration, and testing (RDD&T) costs and the estimated cost per installed kilowatt can be lowered significantly, SPS could compete with the alternatives on an economic basis. SOLARES, for instance, might already be economical compared to conventional nuclear. SPS technical uncertainties are much higher than for the breeder, but lower than for fusion. Social costs are extremely difficult to determine, but if research demonstrated the microwave and Ionizing radiation hazards to be low, SPS could substitute low-risk environmental hazards for the high risks of coal or nuclear as well as contribute to an expanded space program. It would take longer to commercialize than terrestrial solar or breeder, but less than fusion. In competition with other technologies, overall demand for electricity, and the timing of the commercial introduction of SPS vis-a-vis other options will be crucial.

UTILITIES

Would SPS be acceptable to the utilities?*

The major factors that would affect the utilities' decision about SPS technology are cost, reliability, unfamiliarity with space systems, and institutional questions. Only demonstration, and successful experience with an operational SPS over several years, would assure the utilities that it is a viable technology for their use. If the microwave systems were as reliable and available as their designers suggest they could be (90 percent or more), the utilities would welcome them for baseload generation, assuming their size and costs were also appropriate. The laser system might be of interest to the utilities if it could be used to repower existing thermal facilities. The suggested unit size of the laser system (500 to 1,000 MW) would fit well into the present size mix of terrestrial powerplants. A mirror system with its highly centralized, energy producing facility (10 to

*See ch 9, *The Implications for the Utility Industry* section

100 GW) would be too large for the present size mix, but would offer the potential for some flexibility in energy production. Direct electricity and hydrogen generation are both possible in a SOLARES-type energy park. However, because the SPS would be an integral part of the utility grid, it would impose certain constraints on grid dispatch management. The physical requirements of the rest of the utility grid would in turn impose constraints on the design of SPS. Integrating SPS into the grid involves several difficult system problems.

Microwave Transmission. —

- Stability. Because a microwave SPS is an electronic system, not a mechanical one, any power fluctuations due to beam-pointing errors or to large-scale component failure would be rapid (the order of a second or less). The rest of the grid would only be able to respond relatively slowly (minutes), creating difficulties in controlling the frequency of current and overall power levels in the grid. The importance of this difficulty is directly dependent on the size of the SPS contribution. The smaller the output from a satellite-rectenna combination, the easier it will be to control. Some, if not all of this drawback of the microwave system could be alleviated by including short-term battery storage to act as a buffer between the SPS rectenna output and the grid. The stability of the grid would not then depend on the stability of the microwave mode of transmission. However, buffer storage would increase system costs. The optimum amount of storage that might be needed has not been determined, but cost estimates range from 0.5 to 5 percent of the total system costs.
- *Load following and variations of SPS power.* The rectenna output would vary seasonally depending on the distance of the Earth from the Sun. The amount of the variation, and the rate at which SPS power changes, would in principle pose no technical problem for the grid.

  Because any satellite that lies in a geostationary orbit experiences eclipses (1 to 72 minutes) around the equinoxes (March 21 and September 21) when the Earth's shadow falls across the satellite, a reference system satellite would suffer power interruption. A number of satellites would be eclipsed at one time. The rate at which the eclipsing occurs would cause the SPS power to fall at a rate of about 20 percent per minute, much faster than the utility grids are expected to be able to respond. This could be alleviated by shutting the satellite down slowly in advance of the shadow, with a consequent extra small loss of SPS power for the period, or by including buffer storage as suggested above. If daily load curves maintain their current shape, the eclipse would occur near the daily minimum (local midnight), necessitating less backup capacity than would otherwise be the case.

  In principle, SPS could be designed to follow the daily load, but because of its high capital costs it would be uneconomical to do so. It is designed to deliver continuous, baseload power. Hence the burden of following any shifts in load would be placed on conventional terrestrial intermediate load units in the utility system.
- *Microwave beam positional errors.* The beam could be centered on the rectenna by means of a pilot beam directed towards the satellite antenna from the center of the rectenna. Because the signal would take about 0.2 seconds to sense a position error and correct the pointing of the beam, the antenna output would be subject to a potential frequency variation of about 5Hz (5 cycles/see). Power variations of tens of megawatts from this source could make utility grid management extremely difficult. Weather fronts could adversely affect the position of the beam, but the resultant power variation would be slow. Again, buffer storage could be used to alleviate these difficulties.

Because the difficulties posed by each of the above factors increase with size, the utilities might not find the single 5,000-MW unit proposed by the reference system accept-

able even in the future. Although nuclear, fusion, or coal energy parks having about 5,000 MW total capacity have been proposed, they would be composed of several smaller units, each of which are only about 1,000-MW capacity. In addition, in planning for overall system reliability, utilities generally use the criterion that no single unit in the system can account for more than 10 to 15 percent of the total system. Thus, in order to place a 5,000-MW unit in the grid, the grid should have a total system capacity of 33,000 to 50,000 MW. At current rates of electrical growth (3.2 percent per year), only the Tennessee Valley Authority (TVA), the country's largest utility, will have a grid large enough to accommodate a 5,000-MW SPS in 2000. TVA currently has a capacity of 23,000 MW, but it has stopped construction on several new powerplants because of slower demand growth. A national power grid might alleviate the problem of utility grids being too small to accommodate a 5,000-MW SPS.

Laser Transmission.— From the utilities' perspective, the most serious difficulty facing laser transmission is absorption by clouds. Although in a few locations in the country it appears to be technically possible to switch from a cloud covered area to one that is cloud-free, utilities would have little incentive to construct the extra facilities to accommodate such switching unless the economic benefits were commensurate with the expense of the extra facilities. In general, the various sites are unlikely to be all in the same service area, further complicating the ability of the utility to follow the load.

Mirror Reflection. —

- Reflection of sunlight from space suffers from the same disadvantage as that of the laser option: the reflected beam could easily be degraded or occluded by cloud cover. it has been suggested that the additional radiant energy might be enough to dissipate clouds, but this might have detrimental environmental effects and alter weather patterns over a wide region around the energy park.
- As conceived in the "baseline" case, the mirror system would require large energy parks capable of producing more than 100 GW. Smaller parks of 10 GW might also be possible. Even the relatively smaller parks would necessitate major changes in current utility operation and load management. Among other changes, such parks would necessitate building an extensive new network of major transmission lines to distribute electrical power from remote receiving areas to end-users.

In principle, all of the technical problems for the different systems are resolvable at some cost. However, they would require considerable further study and testing as well as a close look at the system economics.

Nontechnical Considerations

In addition to the technical difficulties that SPS can be expected to face, there are a number of potential institutional barriers to SPS acceptance by U.S. utilities:

- SP5 as a *space system.* The current utility management and regulatory infrastructure is much more receptive to the terrestrial renewable or inexhaustible options— breeder reactor and fusion for baseload, and solar thermal and solar photovoltaic for intermediate and peaking loads.
- *Regulatory framework.* Utilities are currently regulated on a State or local basis. SPS could be expected to hasten the move towards greater centralization of the regulatory process (i.e. Federal level). A SOLARES-type SPS, because of its large centralized energy parks, would make a high degree of centralization mandatory. However, other SPS modes may also lead to more centralized regulation, particularly if the SPS were constructed and managed by a federally chartered monopoly (see Ownership *and Finance)* or Government agency.

  Nuclear powerplants are currently regulated at the Federal and State level for health, safety, and environmental impacts. However, their effect on the rate structure is regulated at the State and

local level. An SPS corporation might lead to Federal involvement in setting rates for power as well as regulating SPS technology. The utilities and local regulatory agencies could be expected to resist any pressures toward greater Federal involvement in what has traditionally been their province.

Ownership and Finance

Electric utilities currently face a serious problem raising the capital necessary to install new generating capacity. Because of this, and because they lack launch and space construction capability, they are unlikely to own or operate the space segment of an SPS system directly; they could more easily be responsible for the ground receivers. This raises the question of how domestic SPSs would be financed and managed.

The central issues are: 1) the degree and kind of government involvement; and 2) how to differentiate between the R&D and construction/ operation phases.

- Government involvement. The arguments for Government financing and ownership would be that the high fronnt-end costs and high-risk long pay-back times inhibit private sector investment, and that lack of competition would necessitate Government ownership. Certain aspects of TVA or NASA could provide possible guidance for SPS ownership and operation.

  On the other hand, it can be argued that direct Government involvement is contrary to American preference for private enterprise, that centralized control would lead to inefficiencies, and that U.S. Government ownership would make military participation far more likely. Furthermore, it is feared that Government investment in SPS would drain resources from other energy technologies that need Federal support. A Government-chartered but privately owned and operated company similar to Comsat, or a regulated private monopoly such as AT&T, might be preferred. Since the United States is party to international law that requires national governments to bear the responsibility for space activities, even when carried out by nongovernmental entities, some degree of Federal supervision and involvement will be required in any case.
- R&D and operating phases. Raising private capital would be especially difficult during the research, development, and demonstration phase. A successful prototype demonstration would probably be necessary to attract private investment. If SPS is judged to be a feasible energy option, prototype development is likely to require Federal funding, perhaps via taxes, similar to the Interstate Highway System trust fund, or through "Space Bonds." After that, it is likely that Government loans or guarantees would be required, at a minimum. At some stage the technology could be turned over to the private sector. Instances of such practices have included nuclear reactors, first developed for military use in submarines; and telecommunications technology, funded by NASA and then turned over to Comsat and commercial carriers. Clarification of current patent provisions for NASA and other Government research contracts would facilitate such transfers. Upcoming examples that should be examined for their applicability to SPS are the Space Shuttle, which has been developed by NASA but may eventually be turned over to private enterprise, due to restrictions on NASA operation of commercial ventures; the newly established U.S. Synfuels Corp., which is intended to provide money for a variety of private synthetic fuels ventures; and the European Space Agency's (ESA) Ariane launcher, which will be operated by a private consortium called Arianespace. Private joint ventures, such as Satellite Business Systems or the Alaska pipeline consortium, are another possible way to establish a "Solarsat" Corp. for the construction and operating phases.

  A combination of the suggested models, involving different degrees of Government and private financing, may be more

feasible than any of the specific models mentioned. Providing for a smooth transition between public and private investment phases would be an important concern. A critical consideration should be the ability of an SPS organization to attract foreign capital and to involve foreign participants at early stages of development. (See International Implications.)

INTERNATIONAL IMPLICATIONS

What are the international implications of solar power satellites?*

Development and construction of an SPS system would necessarily involve a number of international dimensions. At a minimum, current and future international treaties and agreements, especially those dealing with the allocation of the electromagnetic spectrum, would require consultation with foreign states and multinational organizations. Beyond this, there may be good reasons to consider an active multilateral regime to regulate, build, and/or operate the SPS.

International organizations, multinational corporations, and domestic interest groups will all be involved in SPS decisions. However, due to the SPS's cost, benefits, and military/foreign policy impacts, which would directly affect the vital national interests of other nations involved, such decisions will ultimately be made at the national level by political leaders.

Economic Impact.– If successful, the SPS promises to deliver significant amounts of electricity y. Estimates of future global electricity demand by the International Institute for Applied Systems Analysis (IIASA) indicate that, even with low rates of economic growth, electricity usage will increase by a factor of 4 over the next 50 years. Regional variations in growth rates will be considerable, with developed countries increasing at a much slower rate than developing ones. Recent studies for the United States that take into account marked reductions in usage rates, such as the National Academy of Sciences' Energy in Transition 1985-2010 indicate that demand in the developed countries may remain constant or rise only Slightly over the next 30 years. On a global scale, this might indicate a rise less than that predicted by IIASA. Meeting this demand will be particularly difficult in energy-scarce areas such as Western Europe, Japan, and much of Latin America, Africa, and South Asia. Countries in these regions will be especially interested in SPS development.

Noneconomic Impact. -The noneconomic effects of SPS would influence the decisions of the major space powers, the United States and the U.S.S.R. The prestige of such a major space and energy accomplishment would be considerable. The military advantages of high-capacity launch vehicles and a large energy-producing platform in high orbit would be significant, even if SPS were not used for direct military purposes.

The United States and the U.S.S.R. both have extensive conventional energy sources– oil, coal, oil shale, and uranium. Thus, neither country can be expected to develop an SPS unilaterally unless unpredictable obstacles to the use of coal and/or nuclear power develop. SPS is therefore likely to be pursued in conjunction with foreign partners who contribute capital and expertise and buy completed satellites. Both Western Europe and Japan, who have extensive space programs and a history of cooperation with the United States, would be probable partners. Soviet secrecy and military domination of their space program makes international cooperation on their part unlikely.

International Cooperation.– Experience with multilateral organizations suggests that estab-

*See ch. 7.

1 The global estimates cited in *Energy in Transition,* however, are similar to IIASA's; a rise of three to five times in electricity consumption by *2010. See Energy in Transition,* National Academy of Sciences, 1979, p. 626.

lishing and running a successful international venture would be difficult. Reconciling the different interests of the participants regarding overall system design, decision making, and allocation of contracts and financial returns would be time-consuming and might compromise timely and efficient results. The example of Intelsat suggests the importance of strong national support by interested parties, of independent corporate management, and a profit-incentive. However, it is unlikely that an agency modeled on Intel sat could be duplicated today for SPS. In particular, the role of LDCs would be greater and could be disruptive unless North-South conflicts can be kept from dominating day-to-day decisions. Strong leadership by the United States and the Organization of Economic Cooperative Development partners would be required to maintain an effective program.

International Law.– International law currently requires allocation of satellite frequencies and geostationary positions by the international Telecommunication Union (ITU). If SPS were to interfere with global communications, this could be a major obstacle to gaining ITU approval. ownership and control of the geostationary orbit has not been completely resolved, and attempts by equatorial states to claim sovereignty over it could hamper development of any geostationary SPS. The proposed Moon Treaty, which calls for an international regime based on the principle of the Common Heritage of Mankind, provides a precedent for international control over space resources, and may affect plans to construct SPS from lunar materials. In each of these cases it can be expected that future LDCs will seek to gain leverage over any SPS regime by controlling access to space. Accommodating LDC interests in a manner compatible with SPS development may be difficult or politically impossible; the precedent set by the uncompleted Law of the Sea negotiations should be carefully considered.

Military Impact. – The military uses of an SPS, especially for directed-energy weaponry, would be restricted by the 1972 Anti-Ballistic Missile (ABM) Treaty and by provisions in the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space banning weapons of "mass destruction" in orbit. Although SPS would not lend itself to efficient use as a weapons-system,* objections to the SPS on military grounds, and demands for inspection and/or redesign to preclude military uses, can be expected. Multilateral development would alleviate many such problems.

Foreign Interests.—To date, space agencies and private firms in foreign countries such as England, France, West Germany, and Japan, along with ESA, have expressed interest in SPS. Most foreign studies have focused on regional applications; technical and operational studies have been done almost exclusively in the United States. Soviet interest has been expressed for several years, with several technical papers published, but no details are known. Third World interest has been informal and cautiously favorable. Future discussion at the United Nation's Committee on the Peaceful Uses of Outer Space and other international bodies will be forthcoming. Any further U.S.-sponsored study of SPSs must take into account international participation in SPS development, and demand for SPS power, in order to evaluate properly the feasibility of SPS programs.

*See ch 7, *Military Uses of SPS* section

NATIONAL SECURITY IMPLICATIONS

What are the national security implications of SPS?*

The military importance of SPS would derive from its very large size, its geostationary orbital position (for certain designs), and its ability to provide tremendous amounts of power. Aside from the important result of reducing

*For extended discussion see ch, 7

the user state's dependence on imported energy, SPS would be strategically significant as a target, as the catalyst for new space transportation and construction capabilities, and as a possible weapons-system.

Vulnerability. –A full-scale SPS system would constitute a high-value target for enemy action. Whether an SPS would in fact be targeted in the event of hostilities will depend above all on how crucial it is to a country's electrical supply. Can SPS power be made up from other sources? Is the attacker vulnerable to a counter-attack in kind? Best estimates are that an SPS system would be unlikely to constitute more than 10 to 20 percent of total generating capacity, in the countries that use SPS, over the next 50 years. Holding SPS to this percent would make it possible to replace SPS power from conventional reserve capacity. However, usage could be much higher in specific regions or industries. A widespread national grid could alleviate the threat of SPS outages. In general, SPS would be no more Vulnerable than other major energy systems.

SPSs could be attacked in a number of ways: 1) by ground-launched missiles carrying nuclear or conventional warheads, 2) by orbiting antisatellite platforms, 3) by ground- or space-based directed-energy weapons, 4) by strewing debris in the satellite's path, and 5) by interfering with or redirecting the SPS's energy transmission beam.

The large size of most SPS options would make it difficult for conventional explosives to do serious damage. Lasers would likely be more effective. Strewing debris in geosynchronous orbit would destroy a reference system SPS, but also affect many other targets, including friendly and neutral spacecraft. Beam interference would be less damaging and would require special preparation to protect against. Nuclear weapons could damage SPSs by direct blast, and also by the electromagnetic pulse (EMP) effect, which might overload the satellite's electrical systems — a large (1 megaton or more) nuclear explosion could damage a photovoltaic SPS at ranges up to hundreds of kilometers.

The use of nuclear weapons outside of a major nuclear exchange would carry great dangers of escalation. Any attack, nuclear or conventional, would depend on perceptions of whether SPS is considered part of national territory and how leaders would react to such a provocation. The analogy to ships on the high sea suggests that an SPS in orbit might be considered fair game even short of full-scale war. Attacks on SPS would also be affected by whether the SPS was manned; destroying an unmanned craft might be undertaken as a relatively unprovocative demonstration of will. At present, neither the United States nor the U.S.S.R. has the ability to attack objects in geosynchronous orbit, but both are working on various antisatellite devices and there appear to be no insurmountable obstacles to their development.

Defense of space craft is possible through: 1) maneuverability, 2) hardening, and 3) antimissile defenses.

The SPS would be too large and fragile to evade attack. Hardening against explosives or EMP bursts would add significantly to weight and costs, and could not be effective against a determined attack. Stationing missile or satellite defenses on a geostationary SPS, whether directed-energy weapons or antimissile missiles, would be feasible due to the power generated by the SPS and its position at the top of a 35,800-km "gravity well". However, such weapons would have unavoidable offensive capabilities and would therefore invite attack. Defense of civilian SPSs could probably be best done by independent military forces, on the ground or in space, rather than by turning the SPS itself into a space-fortress.

Receiving antennas or (for the mirror-system) PV 'parks' would make unattractive targets due to their large size and redundancy; they would certainly be no more vulnerable than other generating facilities. It should be noted that the SOLARES system could continue to produce power, albeit at approximately one-fifth rated capacity, by operating on ambient sunlight even if the space mirror system were destroyed.

Military Uses. –The military usefulness of an SPS stems from: 1) the launchers and other facilities used to construct the satellite portion; 2) the energy beams used by the SPS to transmit power; and 3) its strategic orbital location.

HLLVS or other transportation and construction systems would be perhaps the most direct military benefit of SPS. These could be used by the military to build large space platforms for communications, surveillance, or weaponry. Such activities might be disguised by being carried out during SPS construction, but it is unlikely that they could escape detection by interested parties. Development of such systems would be most important, and destabilizing, in providing a "break-out" capacity for rapid emergency deployment of military satellites by fleets of SPS construction vehicles.

Laser beams built as part of SPS, or more militarily efficient weapons placed on the SPS but not used in transmitting electricity, could be used as strategic weapons. In recent years both the United States and the U.S.S.R. have undertaken large programs to develop directed-energy weapons for use against satellites and/or international ballistic missiles (ICBMs). However, a geostationary SPS is 35,800 kilometers distant from low-flying ICBMs. This distance complicates tracking and requires very high beam intensities. Much greater effectiveness can be achieved by weapons placed in lower orbits. However, a geostationary SPS could play a role in supplying power to remotely located directed-energy platforms. A laser SPS in low Sun-synchronous orbit, of course, would represent a much greater military potential than one in geosynchronous orbit.

Use of SPS, even indirectly, for ABM purposes is currently prohibited by the 1972 ABM Treaty. A militarily effective SPS would be a major factor in strategic planning and would likely be a subject of arms-control negotiations between interested states. Provisions for direct inspection, or design specifications to reduce an SPS's military usefulness, could be negotiated to reduce the various threats it poses. Such provisions might be needed even if SPS would not be militarily useful, but was nevertheless perceived to be a military or political threat.

Using an SPS directly against targets on the ground would ease tracking requirements. High-energy lasers (H EL) or particle-beams could conceivably be used to destroy quickly tactical targets such as ships, planes, or oil refineries without jeopardizing one's own personnel or risking the use of nuclear weapons. However, SPS lasers used for energy transmission would probably not make effective weapons without considerable modification. SPS could also be used to supply electrical power to military units in remote areas, and perhaps even directly to ships or planes.

SPS could serve as a platform for certain surveillance and communications needs. Because of its power, it might be especially suited for conducting jamming and electronic warfare operations.

SPS platforms, because of their size and facilities, would be likely to serve as multipurpose space bases similar to major seaports. If military units used SPS for resupply or rest and recreation, it might be difficult to separate military from civilian uses, or to convince outside observers that SPS was not a military threat.

Any such direct uses of SPS would be determined by the way in which future SPSs are built and managed. Construction by an independent multinational enterprise would reduce any state's ability to use an SPS for military purposes; conversely, unilateral development would enhance it. Use of SPSs as weapons platforms by future superpowers would invite considerable foreign criticism, especially if such attempts interfered with their electricity-generation function. A sudden diversion of SPS power to the military in time of crisis could lead to domestic and/or foreign electricity shortages, resulting in legal or diplomatic protests.

PUBLIC ISSUES

The SPS debate: what are the issues arising in the public arena?*

While public awareness of SPS is growing, most discussion has been confined to a small number of public interest groups and professional societies. In general, many of the individuals and groups who support the development of SPS also advocate a vigorous space program. The L-5 Society has been a particularly vocal SPS supporter and views the satellite system as an important stepping-stone in the colonization of space, a goal to which the society is dedicated. The SUNSAT Energy Council, a group formed to promote interest in SPS, believes that it is one of the most promising options available for meeting future global energy and resource needs. Professional associations such as the American Institute of Aeronautics and Astronautics (AIAA) and the Institute of Electrical and Electronics Engineers (1 E E E), have supported continued research and evaluation of the concept.

Many opponents of SPS are concerned that it would drain resources from the development of terrestrial solar technologies. The Solar Lobby and other public interest groups argue that compared to these ground-based solar options, SPS is inordinately large, expensive, and complex, and that it poses greater environmental and military risks while precluding local decisionmaking. Many opponents also maintain that all future energy demand can be easily met with existing and future terrestrial energy technologies; there is little need to develop SPS, especially in view of the formidable costs to initiate the technology and the highly uncertain cost of the product. The Citizen's Energy Project (CEP) has been an active lobbyist against Government funding of SPS and has coordinated the Coalition Against Satellite Power Systems, a network of solar and environmental organizations. Objections to SPS have also been raised by individuals in the professional astronomy and space science communities who see SPS as a threat to the funding and practice of their respective sciences. In the future, it is conceivable that antinuclear, antimilitary and tax groups could also join the opposition.

Public opinion about SPS can be influenced by a multitude of factors; concerns articulated today may not be as important in the future. In addition, in much of the current public discussion, SPS is treated as a U.S. system alone. If SPS were to be developed on an international basis, the flavor of present opinion could change. Currently, debate about SPS focuses on the question of R&D funding. This and other issues are highlighted in table 2.

*See ch 9, Issues Arising in the Public Arena section

ENVIRONMENT AND HEALTH

How would SPS affect human health and the environment?*

As an energy system operating both in space and on Earth, SPS involves some rather diverse and unique environmental issues (see table 3). While one advantage of SPS is that it would avoid many of the environmental risks typically related to conventional energy options such as nuclear and coal, it would also generate some unconventional environmental effects which are poorly understood at present. The resolution of the uncertainties associated with these effects is critical to the assessment of the environmental acceptability of SPS. More research is needed to understand and quantify these impacts and to investigate modified system designs that would minimize environmental risks. At present, there are three major areas of concern.

1. Bioeffects of Electromagnetic Radiation.—The effects of exposure to SPS power transmission and high-voltage transmission lines

*See ch. 8.

Table 2.—Major Issues Arising in SPS Debate[a]

Pro	Con
R&D funding	
. SPS is a promising energy option	• SPS is a very high-risk, unattractive technology
. The Nation should keep as many energy options open as possible	• Other more viable and preferable energy options exist to meet our future energy demand
• An SPS R&D program is the only means of evaluating the merit of SPS relative to other energy technologies	• SPS would drain resources from other programs, especially terrestrial solar technologies and the space sciences
• SPS R&D will yield spinoffs to other programs	• No matter what the result of R&D, bureaucratic inertia will carry a Government program too far
cost	
• SPS is likely to be cost competitive in the energy market	• SPS is unlikely to be cost competitive without Government subsidy
. Cost to taxpayer is for R&D only and accounts for small portion of total cost; private sector and/or other nations will invest in production and maintenance	• Like the nuclear industry, SPS would probably require ongoing Government commitment
. SPS will produce economic spinoffs	• Projected costs are probably underestimated considerably
	• The amount of energy supplied by SPS does not justify the cost
Environment, health and **safety**	
• SPS is potentially less harsh on the environment than other energy technologies, especially coal	• SPS risks to humans and the environment are potentially greater than those associated with terrestrial solar technologies
	• Major concerns include: health hazards of power transmission and high-voltage transmission lines, land use, electromagnetic interference, upper atmosphere effects, and "skylab syndrome"
Space	
• Space is the optimum place to harvest sunlight and other resources	• SPS is an aerospace boondoggle; there are better routes to space industrialization and exploration than SPS
• SPS could be an important component or focus for a space program	• SPS is an energy system and should not be justified on the basis of its applicability to space projects
. SPS could lay the groundwork for space industrialization and/or colonization	
. SPS would produce spinoffs from R&D and hardware to other space and terrestrial programs	
International ***considerations***	
• One of the most attractive characteristics of SPS is its potential for international cooperation and ownership	• SPS could represent a form of U.S. of industrial nations' "energy imperialism"; it is not suitable for LDCs
. SPS can contribute significantly to the global energy supply	• Ownership of SPS by multinational corporations would centralize power
. SPS is one of the few options for Europe and Japan and is well-suited to meet the energy and resource needs of developing nations	
• An international SPS would reduce concerns about adverse military implications	
Military implications	
• The vulnerability of SPS is comparable to other energy systems	• Spinoffs to the military from R&D and hardware would be significant and undesirable
• SPS has poor weapons potential	• Vulnerability and weapons potential are of concern
• As a civilian program, SPS would create little military spinoffs	
Centralization and scale	
• Future energy needs include large as well as small-scale supply technologies; urban centers and industry especially cannot be powered by small-scale systems alone	• SPS would augment and necessitate a centralized infrastructure and reduce local control, ownership, and participation in decision-making
. SPS would fit easily into an already centralized grid	• The incremental risk of investing in SPS development is unacceptably high
Future energy demand	
• Future electricity demand will be much higher than today	• Future electricity demand could be comparable to or only slightly higher than today's with conservation
• High energy consumption is required for economic growth	• The standard of living can be maintained with a lower rate of energy consumption
• SPS as one of a number of future electricity sources can contribute significantly to energy needs	• There is little need for SPS; demand can be met easily by existing technologies and conservation
. Even if domestic demand for SPS is low, there is a global need for SPS	• By investing in SPS development, we are guaranteeing high energy consumption, because the costs of development would be so great

[a] arguments mainly focus on the SPS reference system

SOURCE: Office of Technology Assessment.

Table 3.—Summary of SPS Environmental Impacts

System component characteristics	Environmental impact	Public health and safety	Occupational health and safety
Power transmission			
Microwave	—[b]Ionospheric heating could disrupt telecommunications. Maximum tolerable power density is not known. Effects in the upper ionosphere are not known. —Tropospheric heating could result in minor weather modification. —[b]Ecosystem: microwave bioeffects (on plants, animals, and airborne biota) largely unknown; reflected light effects unknown. —[b]potential interference with satellite communications, terrestrial communications, radar, radio, and optical astronomy.	—[b]Effects of low-level chronic exposure to microwaves are unknown. — Psychological effects of microwave beam as weapon. —Adverse aesthetic effects on appearance of night sky.	—Higher risk than for public; protective clothing required for terrestrial worker. —Accidental exposure to high-intensity beam in space potentially severe but no data.
Lasers	—Tropospheric heating could modify weather and spread the beam. —Ecosystem: beam may incinerate birds and vegetation. —[b]potential interference with optical astronomy, some interference with radio astronomy.	—Ocular hazard? —Psychological effects of laser as weapon are possible. —Adverse aesthetic effects on appearance of night sky are possible.	—Ocular and safety hazard?
Mirrors	—[b]Tropospheric heating could modify weather. —Ecosystem: effect of 24-hr light on growing. cycles of plants and circadian rhythms of animals. —[b]potential interference wit h optical astronomy.	—Ocular hazard? —Psychological effect of 24-hr sunlight. —[b]Adverse [a]esthetic effects on appearance of night sky are possible.	—Ocular hazard?
Transportation and space operation			
Launch and recovery HLLV PLV COTV POTV	—Ground cloud might pollute air and water and cause possible weather modification; acid rain probably negligible. —[b]Water vapor and other launch effluents could deplete ionosphere and enhance airglow. Resultant disruption of communications and satellite surveillance potentialy important, but uncertain. —[b]possible formation of noctilucent clouds in stratosphere and mesosphere; effects on climate are not known.	—Noise (sonic boom) may exceed EPA guidelines. —Ground cloud might affect air quality; acid rain probably negligible. —Accidents-catastrophic explosion near launch site, vehicle crash, toxic materials.	—[b]Space worker's hazards: ionizing radiation (potentially severe) weightlessness, life support failure, long stay in space, construction accidents psychological stress, acceleration. —Terrestrial worker's hazards: noise, transportation accidents.

Table 3.—Summary of SPS Environmental Impacts—Continued

System component characteristics	Environmental impact	Public health and safety	Occupational health and safety
	—[b]Emission of water vapor could alter natural hydrogen cycle; extent and implications are not well-known. —[b]Effect of COTV argon ions on magnetosphere and plasma-sphere could be great but unknown. —Depletion of ozone layer by effluents expected to be minor but uncertain. —Noise.		
Terrestrial activities			
Mining	—Land disturbance (stripmining, etc.). —Measurable increase of air and water pollution. —Solid waste generation. —Strain on production capacity of gallium arsenide, sapphire, silicon, graphite fiber, tungsten, and mercury.	—Toxic material exposure. — Measurable increase of air and water pollution. — Land-use disturbance.	—Occupational air and water pollution. —Toxic materials exposure. —Noise.
Manufacturing	—Measurable increase of air and water pollution. —Solid wastes.	—Measurable increase of air and water pollution. —Solid wastes. —Exposure to toxic materials.	—Toxic materials exposure. —Noise.
Construction	—Measurable land disturbance. —Measurable local increase of air and water pollution.	—Measurable land disturbance. —Measurable local increase of air and water pollution.	—Noise. —Measurable local increase of air and water pollution. —Accidents.
Receiving antenna	—[b]Land use and siting. —Waste heat and surface roughness could modify weather.	—[b]Land use—reduced property value, aesthetics, vulnerability (less land for solid-state, laser opt ions; more for reference and mirrors).	—Waste heat.
High-voltage transmission lines (not unique to SPS)	—[b]Land use and siting. —[b]Ecosystem: bioeffects Of powerlines uncertain.	—[b]Exposure to high intensity EM fields—effects uncertain.	—[b]Exposure to high intensity EM fields—effects uncertain.

[a]Impacts based on SPS systems as currently defined and do not account for offshore receivers or possible mitigating sYstem modifications.
[b]Research priority.
SOURCE: Office of Technology Assessment.

(HVTL) on humans, animals, and plants are highly uncertain. The existing data base is incomplete, often contradictory and not directly applicable to SPS. While the thermal effects of microwave radiation (i. e., heating) are well-understood, research is critically needed to study the consequences of chronic exposure to low-level microwaves such as might be experienced by workers or the public outside of the receiver site. The biological systems that may be most susceptible to microwaves include the immunological, hematological (blood), reproductive, and central nervous systems. The DOE SPS assessment has sponsored three studies of the effects of low-level microwaves on bees, birds, and small mammals. No significant effects have been observed, but the experiments are far from complete. More research is vitally needed to expand the experimental and clinical data base, and to improve theories which may facilitate the extrapolation from animal studies to assessments of human health hazards.

It appears that the United States will establish a microwave standard in the near future that is more stringent than the present occupational 10.0 mW/cm^2 voluntary guideline (the new occupational standard at 2.45 GHz will probably be 5.0 mW/cm^2), thereby approaching the standards in other countries (e. g., Canada: population —1.0 mW/cm^2, occupational —5.0 mW/cm^2; U. S. S. R.: population—0.001 mW/cm^2, occupational —0.01 mW/cm^2). This does not have an immediate impact on SPS land use for the reference system, since it is designed to produce less than 1.0 mW/cm^2 at the rectenna boundary and less than 0.1 mW/cm^2 outside the rectenna boundary. Nevertheless, establishing population standards that are more stringent could mean more land for each buffer zone and could affect system design (power density and beam taper) as well as public opinion.

With respect to spaceworkers, exposure to ionizing radiation (including that from the radiation belts, galactic cosmic rays, and solar flares) would be a health hazard unless steps are taken in future planning to minimize dose. Studies are needed to determine acceptable exposure limits. Research is needed to determine more precisely the expected dose rates, the types and energies of ionizing particles, and the effectiveness rate of various types and thicknesses of shielding. The results will determine the number of spaceworkers, the duration of the stay, the mass needed in orbit (for shielding), and space suit and system designs. All of these impacts may strongly affect SPS costs and feasibility.

For SPS systems other than the microwave designs, very little assessment of the health and safety effects has been conducted. The power density of a focused laser system beam could be sufficiently great to incinerate some biological matter. Outside the beam, scattered laser light could constitute an ocular and skin hazard. More study would be needed to quantify risks, define possible safety measures and explore the effects of long-term exposure to low-level laser light.

The light delivered to Earth by the mirror system, even in combination with the ambient daylight, would never exceed that in the desert at high noon. The health impacts that might be adverse include psychological and physiological effects of 24 hour per day sunlight and possible ocular damage from viewing the mirrors, expecially through binoculars.

2. Effects on the Upper Atmosphere.– Atmospheric effects result from two sources: heating by the power transmission beam and the emission of launch vehicle effluents. While the most significant effect of the laser and mirror systems is probably weather modification due to tropospheric heating, ionospheric heating is most important for the microwave systems operating at 2.45 GHz. Of most concern is disruption of telecommunications and surveillance systems from perturbations of the ionosphere. Experiments indicate that the effects on telecommunications of heating the lower ionosphere are negligible for the systems tested. As a result, a few researchers have suggested that microwave power densities of up to 40 to 50 mW/cm^2, or two times the level assumed for the reference design, could be used before significant heating would occur.

The largest uncertainty is related to heating and nonlinear interactions in the upper ionosphere. To investigate the heating effects in this region, more powerful heating facilities would be required.

The atmospheric effects resulting from the emission of rocket effluents from SPS space vehicles are of concern because of the unprecedented magnitude and frequency of the projected SPS launches. In the magnetosphere, construction of the SPS reference system as presently designed would lead to a dramatic increase in the naturally occurring abundance of argon ions (from the electric propulsion system proposed for orbital transfer) and hydrogen atoms. While several possible effects have been identified, including enhanced airglow and Van Allen belt radiation, and altered atmospheric electricity and weather, the likelihood and severity of these effects are highly uncertain.

The injection of water vapor at lower altitudes would significantly increase the water content relative to natural levels. One possible consequence is an increase in the upward flux of hydrogen atoms through the thermosphere. Another consequence of increasing the concentration of water in the upper atmosphere might be the formation of noctilucent clouds in the mesosphere. While global climatic effects of these clouds appear unlikely, uncertainties remain.

The injection of rocket exhaust, particularly water vapor, into the ionosphere could lead to the depletion of large areas of the ionosphere. These "ionospheric holes" could degrade telecommunication systems that rely on the ionosphere. While the uncertainties are greatest for the lower ionosphere, experiments are needed to test more adequately telecommunications impacts and to improve our theoretical understanding of chemical-electrical interactions throughout the ionosphere.

In the troposphere, ground clouds generated during liftoff could modify local weather and air quality on a short-term basis.

Additional experiments and improved atmospheric theory are needed to understand and quantify the above impacts under SPS conditions. In addition mitigating steps such as trajectory control, alternate space vehicle design, and the mining of lunar materials need to be assessed. Atmospheric studies would play a major role in the choice of frequency for power transmission.

3. Land Use and Receiver Siting.– Receiver siting could be a major issue for each of the land-based SPS systems. Offshore siting and multiple use siting might each alleviate some of the difficulties associated with dedicated land-based receivers, but require further study. There are two components to the siting issue: technical and political. Tradeoffs must be made between a number of technical criteria: 1) finding geographically and meteorologically suitable areas; 2) finding sparsely populated areas; 3) keeping down the cost of power transmission lines and transportation to the construction site; 4) siting as close to the Equator as possible (for GEO systems) so as to keep the north-south dimension of the receiver reasonably small; 5) coordinating receiver sites with utility grids and the regional need for electricity; 6) the cost of land; and 7) ensuring that the receivers are sited away from critical and sensitive facilities that might suffer from electromagnetic interference from SPS, e.g., military, communications, and nuclear power installations. In addition, for the reference and SOLARES systems, as presently designed, large contiguous plots of land would have to be located and totally dedicated to one use (table 4). The laser options might require less land area per site, but a greater number of sites to deliver the comparable amount of power.

It is clear that the choice of frequency, ionospheric heating limits, and radiation standards could have an impact on the land requirements. Further study is needed to understand fully the environmental and economic impacts of a receiver system on candidate sites and to determine if enough sites can be located to satisfy the technical requirements. In addition the plausibility of multiple uses (e.g., agriculture or aquiculture), offshore siting (especially for land-scarce areas such as

Table 4.—SPS Systems Land Use

SPS system	km²/site	km²/1,OOOMW	Number of sites for 300,000 MW	Total land area(km²) for 300,000 MW	m²/MW-yr
Reference	174	35.0	60	10,400	1,233[b]
Solid state[c]	50	33.0	180	9,000	1,163[b]
Laser I[d]	0	1.2	600	360	42-51[e]
Laser II[d]	40	80.0	600	24,000	2,819-3,382[e]
Mirror I	1,000		-29	***2,200***	***261-313***[e]
Mirror II[f]	100	9.6	30	2,880	338-406[e]
For comparison					
Washington	174.0				
New York City	950.0				
Chicago	518.0				

[a]Rectenna at 34. latitude covers a 117 km² ellipitical area. Microwave power density at edge of rectenna is 1.0 mw/cm². If an exclusion boundary is set at 0.1 mW/Cm², then the total land per site is approximately 174 km². J. B. Blackburn, *Sate//ire Power System (SPS) Mapping of Exclusion Areas for Rectenna Sites,* DOE/NASA Report HCP/R-4024-10, October 1978 does not include land for mining or fuel transport.
bThe values for the reference and solid-state designs assume a 30-year lifetime and a capacity factor of 0.9
cThe solid-state sandwich design is described in G. M. Hanley et al., "Satellite Power Systems (SPS) Concept Definition Study, " First Performance Review, Rockwell International Report No. SSD79-0163, NASA MSFC Contract NAS8-32475, October 10, 1979.
dLaser I and Laser II are two laser systems considered b DOE. Both deliver the same amount of power but the beam of Laser I is more narrow (and hence more intenSe) than that of Laser II. See C. Bain, *Potential of Laser for SPS Power Transmission,* October 1978, Department of Energy, HCP/R-4024-07.
eThe values for the laser and mirror systems assume a 30-year lifetime and capacity factors of 0.75-0.9.
fMirror I system parameters are defined by SOLARES "baseline system" and Mirror II system for low (1,100 km) orbit.
gThe SOLARES baseline system is designed to deliver 81O GW to 6 sites; 2 SOLARES baseline sites actually provide 270 GW.

the Northeast United States, Europe, and Japan) and possible receiver siting in other nations, with their particular environmental constraints, need to be explored.

The regional political problems may be more severe than the technical ones, especially in light of past controversies over the siting of powerplants, powerlines, and military radar and other facilities. While the construction and operation of receivers might be welcomed by some communities on the basis of economic benefit, others might oppose nearby receiver siting for a number of reasons, including: environmental, health and safety risks; fear that the receiver would be a target for nuclear attack; fear of decreased land values; preference for an alternate use of the land; objection to the receiver's visibility; and for rural Americans, resistance to the intrusion of urban life.

It is essential that many of the environmental uncertainties be diminished and that the effects are shown to be, at worst, comparable to those of alternate inexhaustible energy sources, before commitment to the development of SPS because:

1. **environmental effects may be identified for which there are no acceptable mitigation strategies or for which mitigation is too costly to make SPS competitive; and**
2. **they have a great bearing on the system design, e.g., choice of frequency, power level and distribution may be determined by the results of bioeffect and atmospheric studies and these may in turn control hardware design, cost, and land use.**

If an SPS program is pursued, the assessment of environmental risks should receive the highest research priority. Some studies such as bioeffects research may require substantial time to complete; the resolution of environmental uncertainties could affect the development schedule of SPS. Much of the environmental research needed in the assessment of SPS is applicable to other studies and would be valuable whether or not an SPS program is undertaken. Conversely, many of the environmental questions associated with SPS are also being addressed in other "generic" research programs such as those investigating microwave bioeffects and upper atmosphere physics. The delineation of which environmental risks are most important would, to a large extent, depend on the specific design concepts that showed the greatest promise.

ELECTROMAGNETIC COMPATIBILITY

How would SPS affect other users of the electromagnetic spectrum?*

Whether SPS were to be eventually deployed as a microwave, laser, or mirror system, it would affect some portion of the electromagnetic spectrum. Other users of the spectrum would be concerned about the nature of potential detrimental effects, whether they are amenable to amelioration and, if so, what the costs would be. A microwave system would be the most problematic because communications of all sorts share this general portion of the spectrum. In addition, a wide range of other electronic devices (e. g., sensors, computers) are susceptible to microwave interference.

The Public

Deploying SPS would markedly change the visual appearance of the night sky. A set of reference system satellites equally spaced along the Equator would appear as a set of bright stationary "stars" whose total effect for observers on longitudes near the middle of the set and for all latitudes along these longitude lines would equal the Moon at about quarter phase. Nonstationary satellites such as an LEO deployed laser or mirror system would create the effect of bright moving "stars." The effect of such satellites on the night sky has not been calculated. However, it could be expected to equal the overall effect of the 60-satellite set of reference satellites.

Some observers might well enjoy the sight of manmade "stars" added to the night sky. Many, especially those in countries who failed to benefit from the generated power, might strongly resent the intrusion on the celestial landscape.

Space Communications

All artificial Earth satellites use some portion of the electromagnetic spectrum for communication. Some also use the spectrum for remote sensing. All would be affected in some way by SPS.

Geosynchronous Satellites.– These would be most strongly affected by the microwave systems. They could be expected to experience microwave interference from noise at the fundamental SPS frequency (e.g., 2.45 Ghz for the reference design), spurious emission in nearby bands, harmonics of the fundamental SPS frequency, and from so-called intermodulation products. All radio frequency transmitters generate such noise and receivers are designed to filter out unwanted effects. However, the magnitude of the power level at the central frequency and in harmonic frequencies for a microwave SPS is so great that the possibility of degrading the performance of satellite receivers and transmitters from these spurious effects is high.

In addition to the direct effects from microwave power transmissions, geosynchronous satellites could also experience "multipath interference" from geostationary power satellites due to their sheer size. In this effect, microwave signals traveling in a straight line between CEO communications satellites would experience interference from the same signal reflected from the surface of the power satellite.

The sum of all these effects would result in a limit on the distance that a geosynchronous satellite must have from the SPS in order to operate effectively. The minimum necessary spacing would depend directly on the physical design of the satellite, the wave length at which it operated, and the type of transmission device used (i.e., klystron, magnetron, solid-state device).

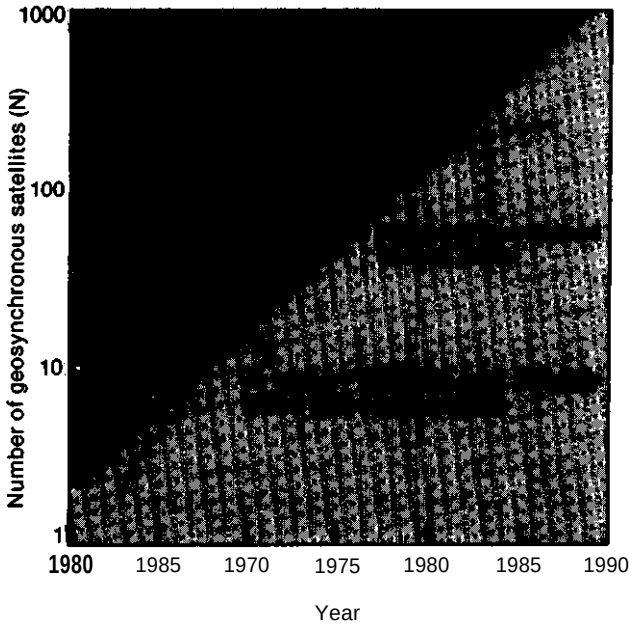
Since a microwave SPS would have to share the limited resource of the geostationary orbit with other satellites, the value of the minimum spacing has emerged as one of the most critical issues facing a geostationary SPS. However, in the absence of a specific design, it is impossible to characterize the exact form and

*See ch. 8

nature of the interference. Additional information is essential to calculate the minimum required spacing. In addition, even if the design parameters were known accurately, the theory of phased arrays is insufficiently developed today to predict the minimum distance. Estimates of the minimum necessary spacing range from 1/2 to 10. The lower limit would probably be acceptable. However, a minimum spacing much greater than 10 would result in too few available geostationary slots to allow both types of users to share the orbit unless many communications functions could be accommodated on a few large space platforms.

At present, some 80 satellites share the geostationary orbit worldwide, and by 1990 that number is expected to increase significantly (fig. 6). Even though improvements in technology will lead to a reduction in the total number of satellites necessary to carry the same volume of communications services, total service is expected to rise dramatically.

Figure 6.—The Number of Geosynchronous Satellites as a Function of Time



SOURCE: W. L. Morgan, *Comsat Technical Review,* 10 vol. 1,1980.

At present the minimum spacing for domestic geostationary satellites is 40 in the 4/6 GHz band and 30 in the 12/14 HGz band. At these spacings, a maximum of 90 4/6 GHz band satellites and 120 12/14 GHz band satellites could theoretically coexist at geostationary altitudes, in the absence of SPS. Current research activity in the 20/30 GHz band is likely to lead to much greater capacity and smaller spacings for that band by the time an SPS might be deployed. But even with these and other unpredictable advances in communications technology in space and on the ground, competition for geostationary orbit slots is likely to be high.

The laser and mirror systems in low-Earth orbit are unlikely to interfere with geosynchronous satellites except in the relatively improbable event that one of the mirrors passes precisely between the geosynchronous satellite and its ground station, and even that interruption would be for so short a time as to pose no serious problem.

Other Satellites. – In addition to geosynchronous satellites operating at the same altitude as the CEO SPS, there are numerous military and civilian satellites in various low-Earth orbits that might pass through an SPS microwave beam. Such satellites could in principle protect themselves from adverse interference from the SPS beam by shutting down uplink communications for that period, and improving shielding for data and attitude sensors, computer modules, and control functions. Whether this action would be feasible depends on the particular mission the satellite is to perform. For some remote sensing satellites, a shutdown could mean loss of significant data. It would not be feasible for the SPS to shut down for the few seconds of satellite passage. It might also be possible for many satellites to fly orbits that will not intersect the SPS beam.

The laser and mirror systems might interfere with nongeosynchronous satellites by causing reflected sunlight to blind their optical sensors or by passing through communications beams. Of the two systems, the mirror system would

cause the most problems because of the size of the mirrors and their orbital speed. To date, no one has calculated the possible adverse effects due to this cause.

Deep Space Communications. – Because deep space probes generally travel in the plane of the solar system (known as the ecliptic), they would be especially affected by a geostationary microwave SPS. A microwave SPS would effectively prevent ground communication with the probe when the latter happens to lie near the part of the ecliptic that crosses the Equator. This interference is especially serious for deep space vehicles because it is essential to be able to communicate with them at any time for the purposes of orbit control and for timely retrieval of stored data.

It would be possible to avoid such interference by establishing a communications base for deep space probes in orbit. As we penetrate deeper into space, this may be advisable for other reasons. If not, such a communications station would effectively add to the cost of the SPS.

Terrestrial Communications and Electronic Systems

Both civilian and military terrestrial communications, radar, sensors, and computer components would suffer from a number of possible effects of a microwave beam. Direct interference can occur from the central frequency or the harmonics. In addition, scattered and reflected radiation at these frequencies from the rectenna, and rectenna emissions could cause additional interference problems for terrestrial receivers. At the very least, rectennas would have to be located far enough from critical sites such as airports, nuclear powerplants, and military bases to render potential interference as small as possible. In addition, equipment would have to be redesigned to permit far better rejection of unwanted signals than is now necessary. This appears to be feasible given enough time and funds for the electronics industry to respond.

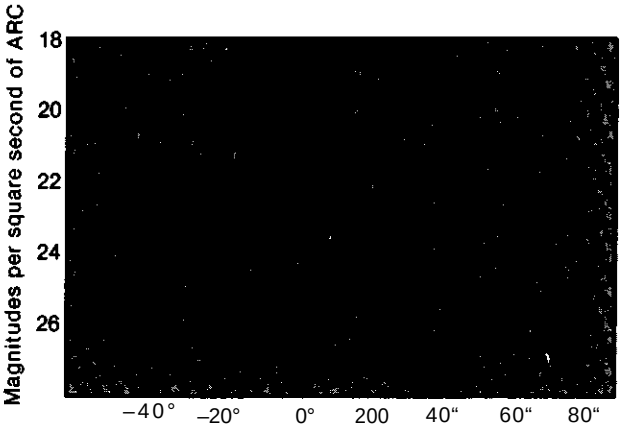
Effect on Terrestrial Astronomy and Aeronomy

None of the proposed SPS systems benefit astronomical research except insofar as they would indirectly provide a transportation system and construction capabilities for placing large astronomical facilities in space. The detrimental effects would vary depending on the system chosen. The impacts of a microwave system are likely to be severe for both optical and radio astronomy. An infrared laser system is likely to have fewer detrimental effects on both forms of astronomy, and the mirror system would have its most serious effect on optical astronomy.

Optical Astronomy.– Diffuse reflections from the reference system satellites would cause each to be as bright as the brightest phase of the planet Venus, and produce a diffuse halo of light around it. Because the satellites appear to remain stationary along the celestial Equator, a system of 15 to 60 satellites would meld together to block observation of very faint objects along and near the Equator for telescopes located on Earth between the longitude limits of the satellites (fig. 7). Some major non-U. S. telescopes would be affected as well. Telescopes in orbit, such as the U.S. Space Telescope scheduled to be launched in 1984, will travel in nonequatorial orbits and therefore would not be affected significantly by a reference SPS except to require increased pointing and control complexity on the Space Telescope.

The effect of diffuse reflections from an LEO-based laser SPS could be expected to be much less of a problem for observations of objects near the Equator because the laser portion of the satellite system would be constantly in motion. Thus, no part of the sky would be permanently blocked from view. The relay satellites located in geostationary orbit would subtend a very small angle as seen from the surface of the Earth. Though they would be visible as small points of light, they would be considerably fainter than the geostationary

Figure 7.—The SPS Brightness Profile



Note: This figure shows the predicted brightness of the sky as a result of a 60-satellite SPS system along the meridian at local midnight for Kitt Peak National Observatory at the vernal equinox. The calculation of this profile is based on an assumed 4 percent diffuse albedo

SOURCE: Workshop on SPS Effects on Optical and Radio Astronomy, DOE/Conf 7905143, P. A. Ekstron and G M Stokes (eds.).

satellites of the reference system and would not interfere with optical observations. However, large moving satellites would present optical astronomy with another observational obstacle. Scattered light from them would vary in intensity as the satellite passes near a celestial object of interest, making calibration of the nearby background light very difficult. The laser satellite would interfere with infrared astronomy studies involving wavelengths near the transmission wavelength of the beam. Photometry and spectrometry experiments would be severely compromised during any brief orbital period when the relay satellite passed within a few degrees of an observing telescope.

The mirror system, which would involve a number of large, highly reflective moving mirrors in low Earth orbit, would have very serious effects on optical astronomy. While the precise effect has not been calculated, it would render a large area (a circle of radius 150 km) around the ground stations unacceptable for telescopic viewing. Because of diffuse reflections from the atmospheric dust and aerosols that are up to 3 km above the ground station, the individual mirrors would create moving patches of diffuse light that would completely disrupt the observation of faint objects that lie in the direction of the satellite paths. Thus, astronomers would need to remain outside a 30()-km diameter circle surrounding the site in order to avoid this problem.

Radio Astronomy. – Radio astronomy would suffer two major adverse affects from microwave systems: 1) electromagnetic interference from the main SPS beam, from harmonics, from scattered or reflected SPS signals, and from reradiated energy from rectennas; and 2) additional sources of thermal noise radiation in the sky that have the effect of lowering the signal-to-noise ratio of the radio receivers. Studies by terrestrial radiotelescopes of faint radio objects near the Equator would be impossible. Neither the laser nor the mirror systems would contribute to the first effect; however, they would raise the effective temperature of the sky background. Low-level measurements such as scientists now routinely conduct to measure the amount of background radiation from the primordial explosion of the universe would thus be impossible from terrestrial bases. Thermal microwave radiation from the satellites would exceed present standards for radio interference at nearly all wavelengths.

Space basing of radio telescopes, especially on the far side of the Moon, would eliminate the impact of SPS and other terrestrial sources of electromagnetic interference. However, such proposals, though attractive from the standpoint of potential interference, are unlikely to be attractive to astronomers for many decades because of their high cost and the relative inaccessibility of the equipment.

Optical Aeronomy. –Much of our knowledge of the upper atmosphere is gained by nighttime observations of faint, diffuse light. Some of the observations that are made today must be carried out in the dark of the Moon. The presence of satellites equal in brightness to a quarter Moon would effectively end some studies of the faint airglow and aurora. Other observations would be severely limited in scope.

SPACE PROGRAM

How would development of the SPS affect our civilian space program?*

If pursued, an SPS program would be the largest and most ambitious space program ever undertaken. SPS development could provide: 1) new capabilities for future space ventures; 2) spinoffs for civilian and military use, in space as well as other areas; 3) a political and programmatic focus for the civilian space program; and 4) potential furtherance of U.S. domestic and foreign policy goals.

An SPS program would require the development of a high-capacity space transportation system, the construction of large space structures, and perhaps the deployment of manned space bases. I n addition, an extensive industrial infrastructure would be needed to support these activities. The hardware, knowledge, and facilities generated by such a program would significantly increase our overall space capabilities and lay the groundwork for future industrialization, mining and, perhaps, the colonization of space.

Direct technological spinoffs can be expected in the development of improved large space platforms, energy transmission devices, ground illuminating systems, high-efficiency solar cells, and life-support systems.

Conversely, SPS development will benefit from prior developments in space technology, most notably in space transportation and systems for automated construction of space structures.

An important consideration is the extent to which an SPS program would serve as the focus and driving-force for the space program as a whole. In the 1960's, the U.S. civilian effort was centered on Apollo; in the 1970's on the Space Shuttle. However, in 1978, the Carter administration stated that: "it is neither feasible nor necessary at this time to commit the United States to a high-challenge space engineering initiative comparable to Apollo. " In the absence of a long-term goal such as SPS, some have predicted that future space efforts would lag, or become overwhelmingly military in nature. On the other hand, there is concern that an SPS commitment would draw resources from or otherwise interfere with other space activities, leading to an unbalanced effort. In addition, for SPS as well as other less expensive programs, the annual appropriations procedure for NASA often results in budgetary and programmatic uncertainty; development of SPS would require long-term financial planning and long-term commitment to the project.

In addition to its use as a source of electrical power, the SPS should be judged by whether it is in accord with national interests as reflected in national space policy. The NASA Act of 1958 (as amended), states that space activities should be for peaceful purposes, and can be undertaken in cooperation with other countries, to further the "general welfare and security" of the United States. In 1978 the Carter administration, in its October "Fact Sheet on U.S. Civil Space Policy," reaffirmed these goals while emphasizing the practical and commercial benefits of the civil space program. A civilian-run SPS program open to international participation would further current space policy goals.

Involvement by NASA in SPS operation might require a change of NASA's current charter, which restricts the direct operation of commercial ventures. Currently, DOE has prime responsibility for solar energy research, while NASA is responsible for the U.S. civilian space program. An SPS program would require extensive cooperation between the two agencies; if this caused difficulties, a separate agency or some other organizational alternative might prove preferable.

*For extended discussion see ch. 6

Chapter 4

POLICY OPTIONS

Chapter 4

POLICY OPTIONS

Because the solar power satellite (SPS) is a new energy concept, much of this assessment has led across previously uncharted territory. SPS has potential for supplying a portion of U.S. electrical needs, but current knowledge about SPS, whether technical, environmental, or sociopolitical is still too tentative or uncertain to decide whether SPS would be a wise investment of the Nation's resources. Further research and study, based on the findings of this and other assessments, [2] would be needed in order to formulate such a decision properly. The kind and pace of a research program, if one is to be conducted, will be determined by perceptions of when development decisions need to be made.

Decisions about SPS development involve an important tradeoff. In time, more can be learned about the context within which SPS would operate. Furthermore, in view of this study's analysis of future U.S. electricity demand and the availability of alternate energy sources (see ch. 6), domestic need is not likely to be high enough for SPS before 2015-25. Therefore, development and deployment decisions do not have to be made before the 1990's. However, action should be taken in a timely manner. Since the development of a major energy and space system may take more than 20 years, a decision about whether to develop SPS will probably need to be made before the end of the century. The development of SPS may need to be started as early as 1990, if high-growth projections for electricity seem plausible at the time. If an SPS development program is eventually initiated, the Nation must also decide whether it wishes to pursue SPS as a unilateral or as an international venture. The tasks before the United States in this decade are to determine how much and what kinds of information are needed in order to make a sound decision sometime in the next decade. The Nation must also decide when to proceed with a research program and at what pace.

Figure 8 represents a series of possible decision points for SPS. If research on SPS finds no impediments to continued pursuit of SPS, the first in the series of development decisions could occur sometime between 1990 and 2000. By that time, the factors that relate to energy demand and supply and space transportation will be much clearer than they are today. The United States will have had about 10 years of experience with the space shuttle and with initial testing of space platform components. Planning and perhaps testing will have begun for a second-generation space transportation system. The results of the Nation's long-term energy conservation efforts will be felt and assessed, and electricity demand projections for 2000 and afterwards will be better defined than currently possible. Further, a decision about the breeder may have been made and the potential of the fusion, energy storage, and terrestrial solar technologies may be more certain.

The results of continued tracking of the international, institutional, and public opinion factors relevant to SPS will also contribute to the decision. In particular, the international community's future energy needs and supply potential will be better known, as well as its willingness to cooperate in a multinational development program.

Finally, the results of research related to SPS will be available and can be used to support or reject a decision whether to proceed with SPS development. Some of the needed research is generic in nature, and will be done in other programs whether or not SPS is developed. Among others, these include most of the National Aeronautics and Space Administration's (NASA) activities in space transportation, space structures, photovoltaics, materials and humans in space, as well as the Department of Defense's (DOD) and the Department of Energy's (DOE) laser programs. To some extent

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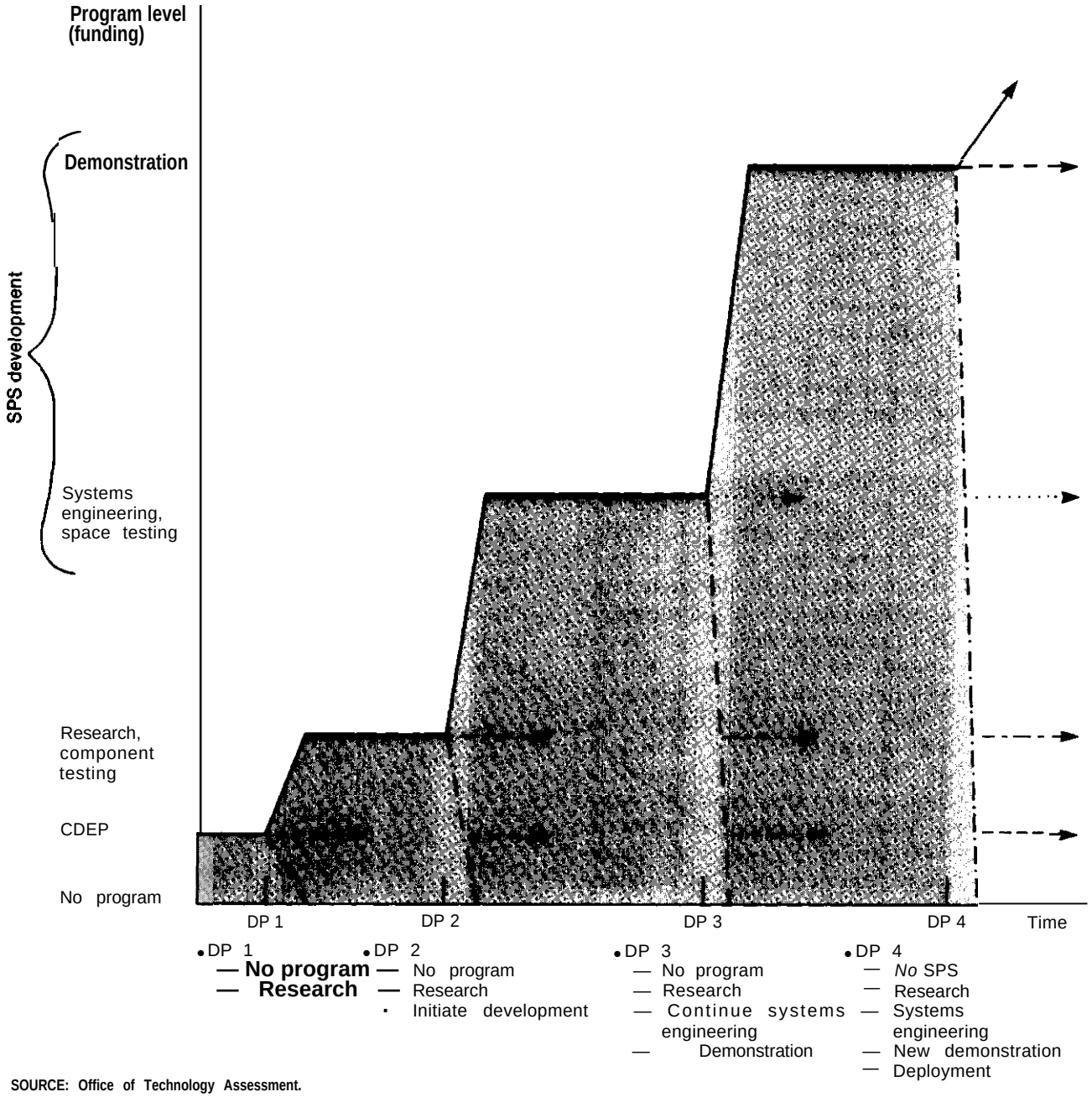
[2] *Program Assessment Report Statement of Findings, SPS* Concept Development and Evaluation Program, DO E/E R-0085, November 1980.

[3] National Research Council Report of the Committee on Satellite Power Systems, June 1981

Figure 8.—SPS Program Phases and Decision Points



SOURCE: Office of Technology Assessment.

they also include work done in the terrestrial photovoltaics (DOE) and microwave bioeffects (the Food and Drug Administration, the Environmental Protection Agency, etc.) programs. However, many needs are directly related to SPS technology and therefore will eventually require a research program specifically funded for SPS.

In order to make an informed decision about the SPS, information about three different types of factors will be needed:

1. **Contextual, independent factors. These are factors that are independent of SPS but which will markedly affect the need for SPS or the ability to conduct the project:**
   - *Future U.S. and global electricity demand.* **If demand is relatively low, the need for a new, capital-intensive energy system will be low as well. If future demand is very high, there could be a commensurate need for SPS. Conservation, increased end-use efficiencies, and the expansion of dispersed electrical generation could all affect overall demand for centralized electricity.**
   - *Cost, kind, and availability of alternative electricity sources.* **If other potential future electric energy sources turn out to be more expensive than a projected SPS, then SPS may be desirable even if electricity demand is relatively low. On the other hand, the development of other technologies might preclude the need for SPS. The status of breeder and fusion technologies, the cost of terrestrial solar and the advisability of expanding the use of coal will all affect the need for SPS.**
   - *U.S. and global space capabilities.* **A rapidly expanding space program with extensive experience and capabilities would make an SPS program much more feasible than would a low-level program. The experience with the shuttle and other space vehicles will shed light on space transportation capabilities and costs.**

Although an SPS research program is not likely to be affected by these factors, they will have a great effect on an SPS development decision. Each of the factors needs to be tracked, studied, and continually reevaluated for its impact on an SPS decision. Projections of these factors 10 to 20 years in the future will have to be made as well, and amended as more information becomes available. Because these factors are of universal interest, such studies need not be funded by a specific SPS program; they will be investigated by other energy and space programs.

Sometime in the next decade, the contextual framework for the future of SPS may be known well enough to make an informed decision about the need for SPS. As time goes on, a narrowing of future projections will occur and knowledge of these factors will be integrated into the overall decision about SPS.

2. *Contextual, semi-independent factors.* **These are the factors that arise largely from the public perceptions and international and institutional framework of SPS. Though they are markedly diverse in content, they have the unifying feature that they will each affect an SPS research program only slightly but an SPS development program rather strongly. They will need to be tracked, studied, and evaluated as any SPS research program progresses. They also possess the characteristic that there is no point at which one can say that enough is known about them. Rather, a development decision must take them into account as factors that must be considered in light of what is known about them at the time.**
   - *International interest and involvement in SPS.* **The worldwide community will be interested in SPS for its potential to provide energy. They will also be concerned about the effects it may have on the use of the geostationary orbit, military and national prestige implications, how it may affect communications, and how it may affect the appearance and use of the night sky. They may also be interested in joining with the United States in multinational development of SPS. Hence, it will also be important to explore possible modes and means of international cooperation.**
   - **Institutional framework. A main concern of any SPS program would be to continue to study the institutional structures that now exist in the utilities industry, the financial community, and Government, and to identify the major factors that could influence the course of SPS development and affect its feasibility.**

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- **Public opinion issues Public perceptions and public involvement are important components of any publicly funded program. Dissemination of information and sharing of research results would be essential to the SPS program, even in the research phase. It would also be important to continue to solicit responses from segments of the public that would be especially affected, either positively or negatively, by SPS development.**

3. Technical factors specific to SPS. Knowledge about these factors can be gathered or generated by deliberate effort. Answers to specific questions in this group will have an immediate effect on SPS development decisions. The kind, quantity, and quality of the information as well as the time at which it can be available are partly dependent on the level of funding. Four general categories of this sort of information are evident:

- *Environment and human health:*
  - **— microwave and laser bioeffects,**
  - **–high energy particle and ionizing radiation effects on humans in space,**
  - **— ionospheric effects due to microwave transmission,**
  - **– land-use impacts,**
  - **—offshore rectenna environmental effects,**
  - **– launch vehicle exhaust effects on atmosphere, and**
  - **—weather modification from mirror systems.**
- *General system studies:*
  - **—alternate systems (identify which areas need further research, and possible testing of components),**
  - **— component and system costs, and**
  - **—comparison of alternate systems.**
- *Component testing and evacuation:*
  - **–Klystrons/magnetrons/solid-state devices,**
  - **– high-powered, continuous-wave lasers (EDL, solar pumped, FE L),**
  - **— Slip ring designs,**
  - **–deployable, large-area, lightweight space structures,**
  - **— space charge effects, and**
  - **– photovoltaic design and testing.**
- *Space construction and space transportation:*
  - **— evaluate best transportation scheme for demonstration and**
  - **— evaluate best construction scheme.**

information from all three sorts of factors will set the framework and determine the appropriate time for development decisions. It is important to emphasize that a decision not to develop SPS depends on the same information as a decision to proceed with SPS. If further research finds no major technological impediment to proceeding with SPS and the combination of supply alternatives and demand needs indicate that it would be prudent to proceed with the next stage, the program could enter the engineering verification phase where various systems are tested and a demonstration system chosen. This would set the stage for the next decision point.

[f it were possible to make a decision to proceed with the project early in the process (i. e., during the research phase) the various phases could overlap considerably. For instance, the early stages of demonstration could begin before the engineering verification phase is entirely complete. Some economic benefits might accrue from such a procedure. However, because of the very high front-end costs for SPS, any proposal to proceed with development will need to be scrutinized very carefully to be sure it is cost effective. That will necessitate more time and study in the verification stage than might be true for a less costly technology, making it less likely that the various phases will overlap.

SPS research could proceed at different rates and along different lines, depending on the level of funding that is made available. The following presents two different policy options. One is characterized by zero funding for specific SPS research; the other by a sliding scale of funding. They do not exclude one another, i.e., pursuing one option today would not necessarily exclude changing to a different option as time proceeds and information

grows. For example, it could be considered prudent to begin with no specific funding for SPS and proceed to allocate a few million dollars per year after a few years. Conversely, a vigorous funding pace may produce results quickly enough so that from the standpoint of those factors that are amenable to research, a development decision could be made before 1990. But because the independent factors are unlikely to be known well enough before 199o, research funding might then be reduced to a lower level to keep the program going pending a decision based on the independent factors.

Option A:
No specific funding for an SPS program.

Although it would be nearly impossible to pursue an SPS program without specifically allocating funding for it, this option would not necessarily mean terminating all interest in SPS. A zero level option could be followed by designating an agency (e.g., NASA or DOE) to track generic research that is applicable to SPS, as well as monitoring and coordinating international interest in SPS. One possibility is to set up a high-level advisory committee to serve this latter function. As in the other option, periodic reevaluation of the potential of SPS would also be needed, in this case to decide whether specific funding should be instituted or the program terminated altogether.

The rationale behind option A is to keep SPS alive as part of our arsenal of possible energy supply options without making a serious commitment at this time. It has the advantages that the risk of premature funding is greatly reduced, as well as the upfront costs. The longer the country can wait before funding a program directed towards SPS research, the more likely it is that other programs will have generated helpful data for SPS.

On the other hand, there is little margin for error in such an approach. If, under option A, inadequate information is generated, the SPS option might be neglected or foreclosed at a time of future decision; or, if the independent factors indicate a strong need for SPS, then an expensive crash program of research to resolve the questions specific to SPS may be necessary. in addition, appropriating no specific funding for SPS carries with it the risk of discouraging future international cooperation, or of allowing other countries to take the lead in SPS development. A final problem with option A is that the agency designated to track SPS may find it very difficult to allocate its financial resources for SPS without some specific allocation in its budget (even though small).

What could be learned from such an option? Other Federal and non-Federal programs are currently exploring issues that are related to SPS development. By tracking this generic research, information of great value to the development decision could be gathered and analyzed.

- Microwave bioeffects.The proliferation of microwave devices at various frequencies makes research into this important area mandatory whether there is an SPS program or not. FDA, EPA, and DOD are studying microwave bioeffects.
- Photovoltaics DOE maintains a strong terrestrial photovoltaics program. Together with private industry and university projects, this program is studying some aspects of photovoltaics that are of great interest to SPS. However, because terrestrial photovoltaic systems have vastly different needs and constraints than space photovoltaic systems, additional research would probably be needed for SPS.
- Space-related activities. NASA, DOD, and the European Space Agency (ESA) are pursuing programs in space transportation, space structures, humans in space, and space photovoltaics by designing and building the shuttle, advanced expendable launch vehicles, space lab, a 25 kW space power supply, etc.
- Laser programs. High-powered, continuous-wave lasers are currently in an early stage of development. Some of the research on high energy pulsed lasers being pursued by the DOD for weapons applications and by DOE for fusion studies will be relevant to the SPS laser concept. Universities and other research labs are studying high-powered, con-

tinuous-wave lasers. This research would be directly applicable to a laser SPS.

- Alternateve energy sources. The results of R&D, prototype construction, and operation of other electricity sources, including solar thermal, breeders, ocean thermal energy conversion, and fusion, will be of great importance in determining future need for SPS.

However, many issues directly pertinent to SPS cannot be answered by generic research programs. For instance, while microwave bioeffects experiments are being performed in generic research programs, the number of studies on low-level, long-term exposure to SPS frequency microwaves is small. To gain information directly relevant to SPS, some specific SPS funding will be needed.

Option B:
Funding of $5 million to $30 million per year.

This option is designed to gather the necessary information before a development decision is needed. It minimizes the risks of not gaining the sufficient and timely information necessary for a rational decision.

This program would, like option A, make as much use as possible of generic research. It would extend the generic research into areas specific to SPS by making small amounts of funding available for expanding generic programs essential to the SPS development decision. It would also initiate research that is not being done in generic programs and explore ways in which to pursue some of this research jointly with other nations. In addition, it would track and study the various semi-independent factors (international, institutional, and public opinion) which would also have a profound effect on SPS decisions. It would actively seek and encourage international cooperation in SPS research.

Table 5 summarizes the most important research and study needs and gives a very rough estimate of what it would cost to do each item. The starred items are ones that could be pursued in the context of a few million dollars of funding per year. The most critical issues relate to the environmental and health area, since they are the most important in determining the feasibility of SPS. However, they could also take the longest to resolve. Some component testing and studies of alternative systems could receive high priority. The amount of funding which would be made available would depend on an evaluation of previous research findings and the state of projected supply and demand for electricity in the 21st century.

It may be prudent to start at a low level of funding and later accelerate research that is specific to SPS as well as make greater funding available for SPS related generic studies. Another possibility is to actively solicit funding for projects of joint international-U. S. interest, perhaps by offering to match foreign funding for research projects undertaken outside the United States, but which are of interest to U.S. planners. An accelerated research program ($30 million per year) could include some component testing in space as well as at the Earth's surface. It could also include at least one shuttle mission (post 1985) and some space-related experiments on other shuttle flights. It would seek to answer the major environmental and health and safety questions before 1990 and also conduct extensive systems studies. If these concerns are seen to pose no impediments, accelerated funding would provide the quickest way of entering a development phase.

Making funds available for SPS-specific research should ensure that enough information is eventually available in order to make a rational development decision. This approach also has the advantage that it could provide for extensive international cooperation early in the research phase before seeking more extensive financial and managerial cooperation in any subsequent development or construction phase. This would spread the decision to proceed or drop SPS development to other countries as well.

However, a higher level of spending ($30 million or so per year), here and abroad, would make it more likely that an entrenched SPS constituency would form, giving the program momentum and making it harder to stop; more information may not make a program easier to

terminate. Under such conditions, our understanding of SPS technology may outstrip our knowledge of future electricity demand. It is also possible that support for a given mode of transmitting power will develop too early and close out SPS options which are uncertain in the near term but which may have more long-run potential.

Table 5.—Summary of Research and Study Needs

Research/study area	Expansion of generic research to SPS-specific needs	Estimated cost	SPS-dedicated projects	Estimated costs
Environmental and human health				
• Microwave bioeffects		$5 million to **$10 million**	Quantify SPS risks. **Epidemiological** microwave **studies.**	$2 million
	● **Laboratory studies of long-term exposure to low-level microwaves at 2.45 GHz. Determine possible nonthermal effects, and dose-response relationships, establish extrapolation laws.**			
• Ionospheric studies	● Study of ionospheric scaling laws.	—	'Ionospheric equivalent heating. Upgrade Arecibo facility. Study SPS equivalent heating in upper atmosphere. Test scaling laws and effects on representative telecommunication systems.	$10 million
• Atmospheric studies	● Track and augment observations of the atmospheric effects of launch effluents from the shuttle, other expendable launch vehicles and high altitude rockets.	*$2* **million**	● Experiments to test effects of SPS effluents on magnetosphere and to increase understanding of that region. Quantify and study SPS effects on the hydrogen cycle, and formation of noctilucent clouds.	$1 million
	Refine and test ground cloud models. Study meteorological and air quality impacts.	*$0.3* million to $5 million	● Study effect on local climate of SOLARES-type system using an array of ground heaters or a solar pond.	
	Determine the nature and effect of ionospheric depletion, especially in **lower ionosphere. Utilize other rocket launches and observe the effects on representative telecommunication systems.**	$0.5 million	*Studies of possible weather modification, beam scattering and spreading. Identify transportation scenarios that minimize impacts.	
• **Ionizing radiation**	● **Track and augment existing studies of effects of ionizing radiation on humans. Study shielding methods.**	$2 million to $3 million		
• Space	● Track and augment existing programs examining the risks and protection measures for humans in space.	$0.2 million		
• Electromagnetic interference	● Study potential electromagnetic interference and design mitigating techniques. Improve theory of phased array.	$2 million	• Investigate antenna patterns of klystron, magnetron, solid-state devices (see below), their noise levels, and out-of-band harmonics.	$1 million

Table 5.—Summary of Research and Study Needs—Continued

Research/study area	Expansion of generic research to SPS-specific needs	Estimated cost	SPS-dedicated projects	Estimated costs
• Environmental impacts of receiver siting			Offshore receiver studies Land use studies	$0.5 million $2 million
General system studies				
• Laser system			● Develop a "reference" laser system	$0.5 million to $1 million
• Mirror system			*Develop a "reference" mirror system	$0.5 million to $1 million
• Alternative microwave			*Develop alternative microwave systems	
			*Perform a true comparative study between SPS alternatives using common technology and cost basis.	$1 million
Component testing and evaluation				
• Microwave transmission	● Continue solid-state device improvement, study noise, interference problems	$3 million to $6 million	Develop solid-state **phased array**	*$2* **million to $10 million**
	● Test intermediate power magnetron, high-power klystron	$2 million	**Study alternative microwave devices, such as photoklystron**	**$.3 million to $1 million**
• Solar thermal conversion		$1 million		
. Photovoltaics	• Extend research to low mass, thin film cells for space	$2 million	● Adapt optimum photovoltaics for SPS, i.e., low mass, high efficiency, radiation resistant	$2 million
• Lasers	● Improve efficiency of EDL lasers, develop cooling mechanisms for space lasers	$3million to **$10 million**	● Build solar pumped lasers	$1 million to $3 million
			● Laser optics (feasibility studies)	*$0.1* million to $0.3 million
. Mechanical components			● Study means of constructing slip ring and rotating joint	*$0.3* million
			*SOLARES mirror materials structures	
• Mirror			Develop prototype mirror design for shuttle launch of a single SOLARES mirror	$0.5 million

'Research priority.

SOURCE: Office of Technology Assessment.

Chapter 5

ALTERNATIVE SYSTEMS FOR SPS

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Chapter 5

ALTERNATIVE SYSTEMS FOR SPS

A variety of systems have been proposed for collecting, transmitting, and converting solar power from space. Each system has its advantages and disadvantages, its benefits and drawbacks. Each alternative system would use one of three transmission modes — microwave, laser, or optical reflector–to transmit power to Earth where it is collected and converted to electricity or some other highly useful form of energy. Each system would use numerous subsystems to collect and convert energy in space or on the ground. This chapter will characterize the alternative systems and subsystems and discuss their potential for generating power from space. It will also describe four representative systems that serve as the technical basis for discussion of the environmental, institutional, and public acceptance issues in the chapters that follow.

In order to estimate reliably and fully the range of costs and potential technical uncertainties for a given solar power satellite (SPS) option, it would be necessary to subject it to the same detailed analysis that the reference system has undergone during the last 5 years. Unfortunately, this analysis has not been accomplished for the alternative systems. Hence, detailed comparisons between systems will not be possible. At this stage it is possible only to compare the major features of each technology and note the uncertainties that should be addressed as conceptual development of the various alternatives continues.

MICROWAVE TRANSMISSION

Because the atmosphere is highly transparent to microwaves, they constitute an obvious candidate for the SPS transmission mode. In addition, microwave technology also is well-known and is used today in a number of space and terrestrial communications and radar applications. Microwave power transmission was first demonstrated experimentally in 1964, [1] and tested in 1974.[2] [3]

The Reference System[4] [5] [6]

The reference system was selected by the Department of Energy/National Aeronautics and Space Administration (DOE/NASA) as a basis for study. It consists of a large planar array of photovoltaic cells located in the geosynchronous orbit 35,800 km above the Earth's Equator (fig. 9). The cells convert solar energy into direct-current (de) electricity that is conducted at high voltage to a phased-array microwave transmitting antenna mounted at one end of the photovoltaic array. Klystron amplifiers convert the dc electricity to high-voltage radio-frequency power that is then radiated to Earth by slotted waveguides. A receiving antenna (rectenna) on the ground reconverts the electromagnetic radiation into electric current and rectifies it into dc. After being converted to high-voltage, low alternating current (ac), the power can then be either delivered directly to the conventional ac grid or converted back to dc at high voltage and delivered to a dc transmission network.

The amount of power delivered to the grid by each reference system rectenna has been

[1] J. F Degenford, M D. Sirkis, and W H Steir, "The Reflecting Beam Waveguide, " I E EE *Transactions 01 Microwave Theory Technology MIT-72,* July 1964, pp 445-453

[2] Richard M Dickinson, "Evaluation of a Microwave High-Power Reception-Conversion Array for Wireless Power Transmission, " Jet Propulsion Laboratory Technical Memorandum No 33-741, Sept 1, 1975

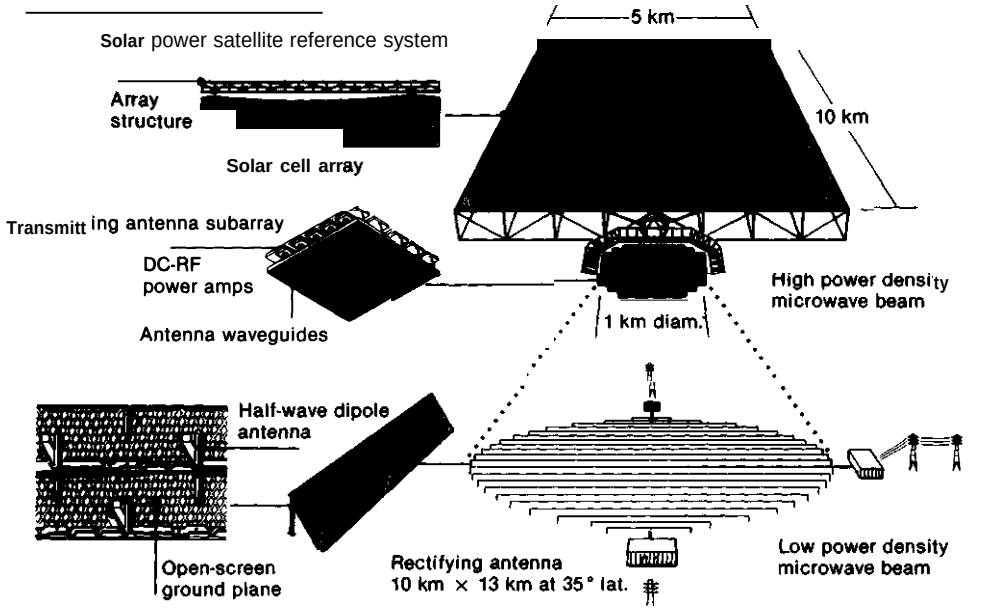
[3] R i chard M Dick inson, "Microwave Power Transmitting Phased Array Antenna Research Project Summary Report, " Jet Propulsion Laboratory publication No 78-28, Dec 15, 1978

[4] Department of Energy, "Satellite Power System Concept Development and Evaluation Program Reference System Report, " report No. DOE/E R-0023, October 1978

[5] C. C. Kraft, "The Solar Power Satellite Concept, " NASA publication No JSC-14898, July 1979

[6] R O Piland, "SPS Cost Methodology and Sensitivities, " *The Final Proceedings of the* Solar *Power Satellite Program Review,* DOE/NASA Conf-800491, July 1980.

Figure 9.—Solar Power Satellite Reference System



SOURCE: C. C. Kraft, "The Solar Power Satellite Concept," NASA publication No. JSC-14898, July 1979

set at 5 gigawatts (GW)—or 5,000 megawatts (MW). The microwave transmission frequency was chosen to be 2.45 gigahertz (GHz). Maximum microwave power density at the center of the rectenna (on Earth) was set at 23 milliwatts per square centimeter (mW/cm^2), and the maximum power density at the edge of the rectenna was set at 1 mW/cm^2 (one-tenth the current U.S. recommended occupational limit). The reference design assumes that all materials would be obtained from Earth, and that the system lifetime would be 30 years with no residual salvage value.

The area of the satellite's photovoltaic array would be approximately 55 square kilometers (km^2); the diameter of the transmitting antenna 1 km. The total in-orbit mass of the complete system, including a 25-percent contingency factor, would be either 51,000 or 34,000 metric tons (tonnes), depending on whether silicon or gallium arsenide photovoltaic cells would be used.

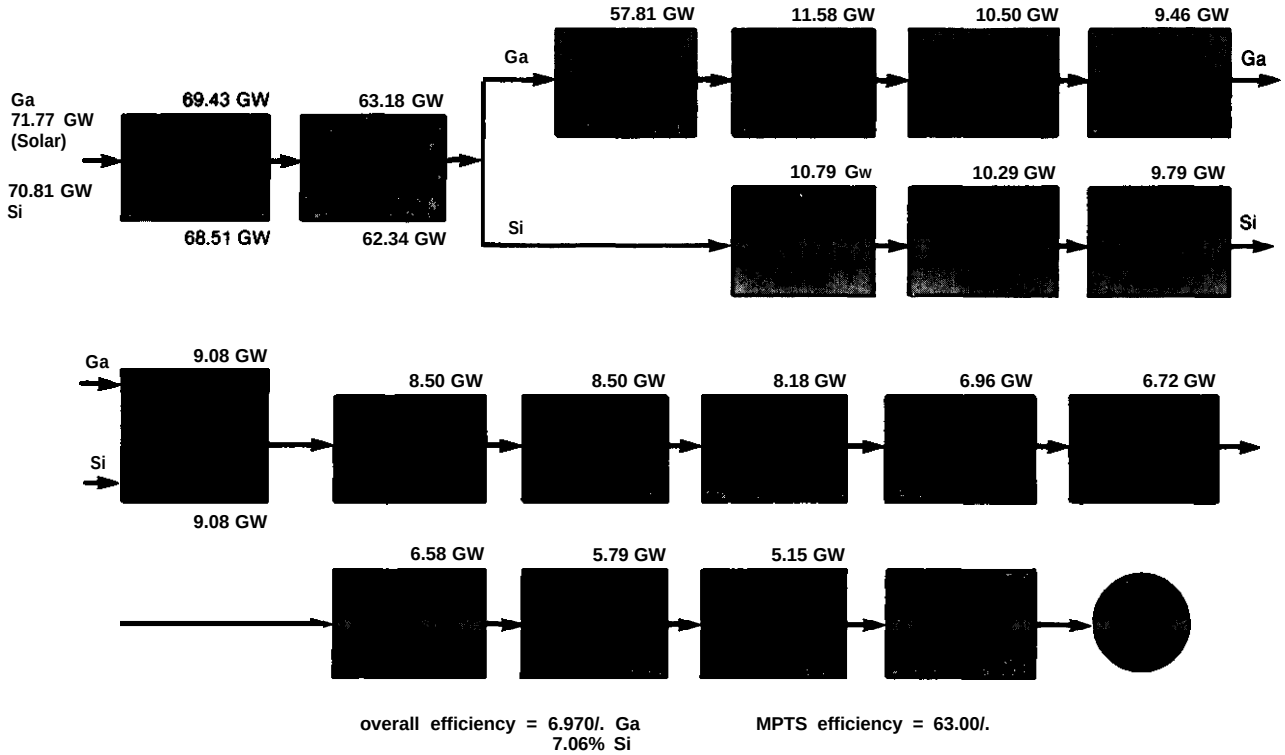
The system is designed to deliver baseload, i.e., continuous 24-hour power to the electric grid. However, some variations in delivered power would occur. A seasonal fluctuation in output due to the variation of the Sun's distance from Earth would cause variations in both incident insolation and photovoltaic cell temperature, the latter producing a consequent change in efficiency. In addition, around the spring and fall equinoxes the Earth's shadow would occult the SPS, resulting in a short period each night for about 6 weeks at local midnight (about 75 minutes maximum, at the equinoxes) where no solar radiation impinges on the satellite and therefore no power could be delivered to the grid (see ch. 9 for a discussion of this effect).

Subsystem Description

ENERGY COLLECTION AND CONVERSION

Two photovoltaic concepts were considered for the DOE/NASA reference system. One uses

Figure 10.-Satellite Power System Efficiency Chain



Abbreviation: "Ga" indicates the gallium-alum aluminum-arsenide option, "Si" the silicon option.

SOURCE: Department of Energy, "Satellite Power System Concept Development and Evaluation Program: Reference System Report," DOE report No. DOE/ER-0023, October 1978.

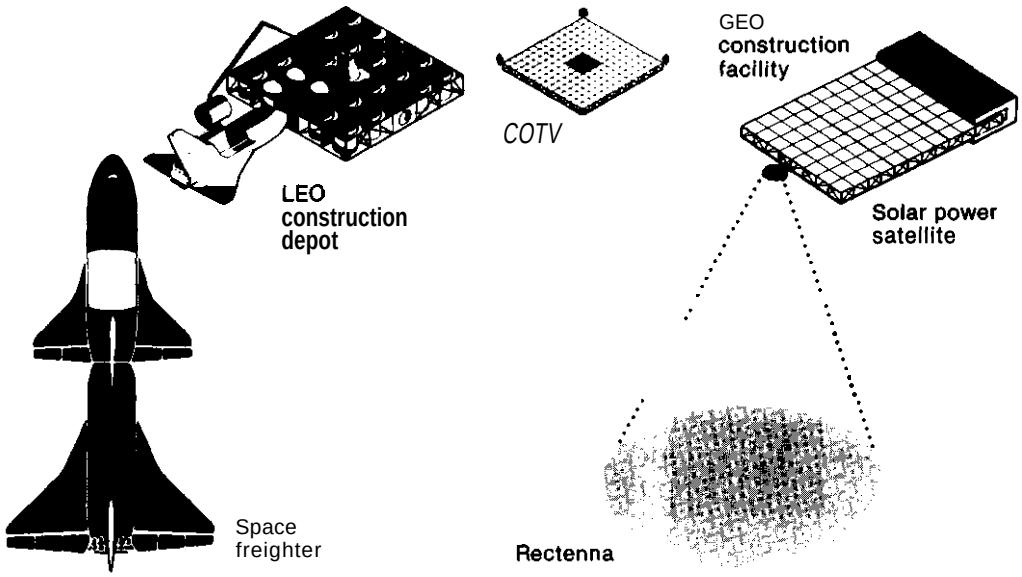
single crystal silicon converters that would receive sunlight directly; the other uses gallium-arsenide (GaAs) photovoltaic cells illuminated directly and by mirrors in a 2:1 concentration ratio.

Silicon cells, currently used in all solar powered spacecraft, have the advantages of an extensive manufacturing base, abundant resource materials, and lower cost per cell, as well as an R&D program in DOE aimed at major cost reduction for terrestrial cells. However, silicon cells in space suffer degradation from radiation effects and from high-operating temperatures, and hence would probably require periodic annealing of the array surface (possibly by laser or electron beam techniques) or the development of silicon cells less affected by ionizing radiation.

Gallium-aluminum arsenide photovoltaic cells have several advantages over silicon cells: low mass per unit area, resistance to thermal and radiation degradation, and higher efficiency. They have the disadvantages of relatively high cost, the limited production availability of gallium, and a smaller technology base than for silicon cells. Because of these latter characteristics, these cells would be used in a 2:1 concentration ratio in the reference system, trading the relatively expensive cells for less expensive lightweight reflectors to concentrate sunlight on the cells.

The structure that supports the solar cells would be an open-truss framework made of graphite-fiber reinforced thermoplastic composite (fig. 9). Because the solar array must be oriented toward the Sun and the transmitting antenna toward the Earth, a massive rotary joint is essential in order to provide the necessary mechanical coupling. Sliprings about 400 m in diameter would be used in conjunc-

Figure 11 .—Major Reference System Program Elements



SOURCE: R. O. Piland, "SPS Cost Methodology and Sensitivities," *The Final Proceedings of the Solar Power Satellite Program* Review, DOE/NASA Conf-800491, July 1980.

tion with the rotary joint in order to transfer electric power from the array to the antenna.

POWER TRANSMISSION AND DELIVERY

The power transmission and delivery system for the reference system design is common to both photovoltaic options. It is composed of three major elements: the transmitting antenna, the rectenna, and the substation.

The selection of the microwave transmission frequency was based on tradeoffs between atmospheric attenuation and interactions with the ionosphere as well as the sizes of the antenna and rectenna. The optimal frequencies were found to be between 1.5 and 4 GHz. The reference frequency was selected to be 2.45 GHz, which lies in the center of the international Industrial, Scientific, and Medical (ISM) band of 2.4 to 2.5 GHz.

The size of the antenna is determined by the transmission frequency, the amount of heat it is feasible to dissipate at the antenna, the theoretical limits of ionospheric heating, and the maximum power densities chosen at ground level, i.e., at the rectenna.[7] For the reference system, these design considerations resulted in a l-km diameter antenna. It would be constructed of 7,220 subarrays each containing from four to thirty-six 70-kW klystron power amplifiers connected to slotted waveguides for transmitting power to Earth. Klystrons were chosen because their technology and operating characteristics at low power levels are well-known. However, they require a cooling system (probably heat pipes). Klystrons of 70-kW continuous power rating have not been built and tested at this frequency, so their characteristics are not known in detail.

Each of the more than 100,000 klystrons in the antenna must be properly adjusted or "phased" to provide a uniform power beam and to point it. This adjustment is especially critical at the very high, gross power level of the SPS beam. Were the antenna a totally rigid array of amplifiers precisely fixed in space, the adjustment could be accomplished once and for all just after the antenna is fabricated in space. However, because it would be desirable for the antenna to be relatively flexible it would be necessary to use an active system of phase control, a so-called "adaptive electronic control" in which a pilot beam, installed in the center of the rectenna and pointed toward the

[7] Raytheon Corp., "Microwave Power Transmission System Studies," report No, ER75-4368, contract No NAS3-I 7835, December 1975.

satellite, establishes a phase reference or standard clock against which the individual klystrons compare and adjust their phases (fig. 12).[8]

An important safety feature inherent in this system is that loss of the pilot beam from the rectenna would eliminate all pointing and phase control. Without the pilot beam, the klystron subarrays would immediately lose synchronization with one another and al l focus would be lost, resulting in the spreading of the beam to very low power (0.003 mW/cm^2). The transmission system would therefore require continual ground-based guidance to keep it operating as a coherent beam. By incorporating relatively well-known anti jamming techniques in the pilot-beam generator, deliberate or accidental diversion or misuse of the SPS beam could be prevented.

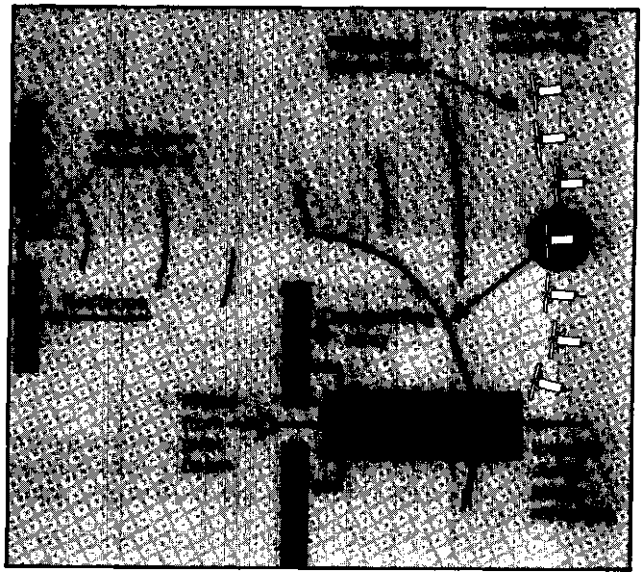
The parameters of the microwave beam are of critical importance in assessing the environmental impacts of the SPS. The peak power density at the transmitting antenna is calculated to be 21 kW/m2. By the time the beam reached the upper atmosphere it would have spread considerably and the intensity reduced to 23 mW/cm^2, a power limit that was set because theoretical studies suggested that at higher power densities, nonlinear instabilities could appear in the F layer of the ionosphere (200 to 300 km) as a result of the interactions between the beam and the electrically charged particles in this region. Recent experimental studies indicate that the limit in the lower ionosphere might be able to be set much higher, ' thereby making it possible to decrease the size of the antenna and/or rectenna significantly.

With these design constraints, a theoretical beam power distribution was conceived resulting in the radiation pattern at the rectenna shown in figure 13, on which are noted the present U.S. recommendations for public exposure (10 mW/cm^2) and the current U.S.S.R. occupational guideline (0.01 mW/cm^2).

The off-center peaks in figure 13 are called "sidelobes;" the level of intensity shown is a consequence of the 1-km antenna aperture (which is optimized to minimize orbital mass) and the projected cumulative antenna errors. The first sidelobe would have a peak intensity of 0.08 mW/cm^2, less than one-hundredth the current U.S. occupational exposure recommendation, about 8 km from the beam centerline; the intensity at the edge of the reference system rectenna (5 km from the beam centerline) would be 1 mW/cm^2–one-tenth the U.S. occupational exposure guideline.

[8] William C Brown, "Solar Power Satellites Microwaves Deliver the Power, " *Spectrum,* June 1979, pp 36-42.

Figure 12.—The Retrodirective Concept

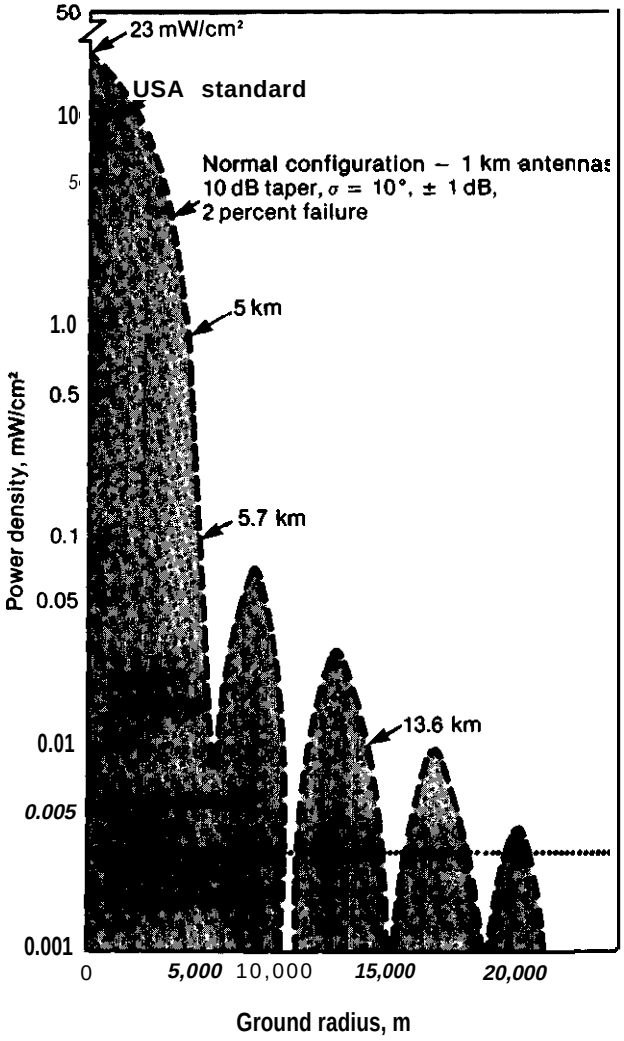


In the retrodirective-array concept, a pilot beam from the center of the rectenna establishes a phase front at the transmitting antenna. Central logic elements in each of the antenna's 7,220 subarrays compare the pilot beam's phase front with an internal reference, or clock phase. The phase difference is conjugated and used as a reference to control the phase of the outgoing signal. This concept enables the transmitted beam to be centered precisely on the rectenna and to have a high degree of phase uniformity. If this phase-control system fails, the beam would automatically be defocused, dropping the power density to 0.003 mW/cm^2, an intensity acceptable by current standards. This feature has been referred to as the "fail-safe" aspect of the microwave transmission system.

SOURCE: William C. Brown, "Solar Power Satellites: Microwaves Deliver the Power," *Spectrum,* June 1979, pp. 36-42.

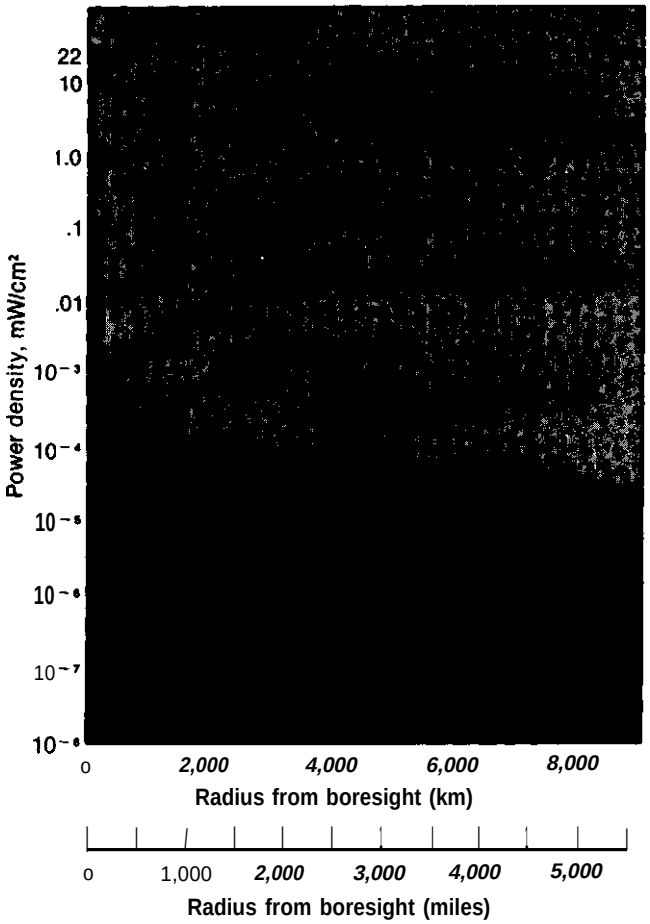
[9] W E Cordon, and L M Duncan, "SPS Impacts on the Upper Atmosphere," *Astronautics and Aeronautics, July/August* 1980

Figure 13.—Power Density at Rectenna as a Function of Distance From the Beam Centerline



SOURCE: Department of Energy, "Satellite Power System Concept Development and Evaluation Program: Reference System Report," DOE report No. DOE/ER-0023, October 1978.

Figure 14.—Peak Power Density Levels as a Function of Range From Rectenna



Grating lobe spikes occur every 245 km for the 18-m subarrays used on simulations although only two grating lobes are shown. The SPS 10-m subarrays have grating lobes every 440 km.

SOURCE: Department of Energy, "Satellite Power System Concept Development and Evaluation Program: Reference System Report," DOE report No. DOE/ER-0023, October 1978.

In addition to the relatively strong sidelobes, the finite size of the antenna subarrays and their projected misalinements would produce much weaker "grating lobes, " which for the reference system would occur at 440-km intervals from the rectenna. The integrated intensity of these grating lobes, even for hundreds of operational SPSs, would be well below even the U.S.S.R. public-exposure guideline, as shown in figure 14.

The rectenna design is quite insensitive both to the angular incidence of the microwave beam (within 100, and to variations in phase or amplitude caused by the atmosphere. Hence, rectennas would be interchangeable; the same satellite could power different rectennas, as long as they were equipped with the appropriate pilot beam needed for phase control of the transmitting antenna. The reference rectenna would be composed of billions of dipole an-

tennas placed above a transparent wire grid. The microwave energy received by each dipole would pass through a rectifier circuit that would convert it to dc power at high current and low voltage. Several more conversions would be necessary to condition the power for the grid. The received power would first be converted to ac and then transformed to high-voltage low-current 60-cycle ac power and then either fed into ac transmission lines for delivery to the users or reconverted to high-voltage dc for transmission, a relatively new transmission technology.

Estimates of overall rectenna conversion efficiency run from about 80 to 92 percent, and the extreme simplicity and repetitive-element construction of the electrical components would facilitate mass production at extremely low unit cost. Reliability of the rectenna should be extremely high, because each component would be ultrareliable and could operate redundantly. Hence replacement would be necessary only after a large number of individual failures.

None of the substation equipment involves technological advances beyond those that are projected through normal development by the electric utility industry. The major concern that has been expressed is the large scale of the minimum individual power unit. Current grid control systems are quite adequate to handle near-instantaneous switching of single power units as high as 1,300 MW. Single unit variations of 5,000 MW could present major control difficulties to the utilities as they currently operate[10 11] (see ch. 9 for a detailed description of utilities interface problems).

SPACE CONSTRUCTION

The mass and physical size of the space segment needed for an operational 5-GW satellite power station are larger by several orders of magnitude than any space system heretofore launched and therefore require careful consideration of the transportation options. The basis for all projected Earth-to-low-orbit transportation concepts is the current U.S. space shuttle, scheduled to become the operational mainstay of the U.S. (and much of the world's) space program.

Of the many possible shuttle derivatives and other new transportation prospects, 12 NASA selected four different types of vehicles to supply the four basic transportation functions:

- carrying cargo between Earth and low-Earth orbit (LEO),
- carrying personnel between Earth and LEO,
- transferring cargo between LEO and the geosynchronous orbit (CEO), and
- transferring personnel between LEO and CEO.

The designs of these four vehicles, called respectively, the heavy-lift launch vehicle (HLLV), the personnel launch vehicle (PLV), the cargo orbital transfer vehicle (COTV), and the personnel orbital transfer vehicle (POTV), are based on existing technology, although all would require considerable development before reaching operational status.[13 14 15 16]

Both the HLLV and the PLV would utilize fully reusable flyback boosters similar to those originally considered by NASA in early shuttle designs in the late 1960's. Both boosters would employ methane-oxygen rocket engines for (vertical) takeoff and airbreathing (turbofan) engines for flyback to base for horizontal landings. The HLLV orbiter would use oxygen-

[10] J. G. Bohn, J. W. Patmore, and H W Faininger, "Satellite Power Systems: Utility Impact Study," EPRI AP-1 548 TPS 79-752, September 1980.

[11] P J. Donalek, and J. L. Whysong, "Utility Interface Requirements for a Solar Power System, " Harza Engineering Co , DO E/E R-0032, September 1978

[12] Robert Salkeld, Donald W Patterson, and Jerry Grey (eds), 'Space Transportation Systems, 1980-2000, " VOI 2, AIAA Aerospace Assessment Series, A IAA, New York, 1978

[13] G Woodcock, "Solar Power Satellite System Definition Study, " Boeing Aerospace Co., Johnson Space Center contract No NAS9-1 5196, pt 1, report No D180-20689, June 1977; pt II, report No D180-22876, December 1977, pt I I 1, report No D180-24071, March 1978

[14] C Hanley, "Satellite Power System (SPS) Concept Definition," Rockwell International Corp., Marshall Space Flight Center, contract No NAS8-32475, report No SD78-AP-0023, April 1 '378

[15] Gordon R Woodcock, "Future Space Transportation Systems Analysis Study, " Johnson Space Center contract No. NAS9-1 4323, Boeing Aerospace Co. report No D1 80-20242-1 (three volumes), Dec. 31,1976

[16] Donald P. Hearth (Study Director), "A Forecast of Space Technology 1980-2000," NASA SP-387, January 1976.

hydrogen rockets essentially identical to those of the current space shuttle, and then glide back to base much like the shuttle does. Unlike the shuttle, it would be fully reusable; it would have no disposable external propellant tank.

The PLV orbiter would be very much like the current space shuttle, but would employ a passenger-carrying module in the payload bay. Like the shuttle, it would also use a disposable external propellant tank, but a somewhat smaller one. It could carry 75 passengers, plus the normal shuttle crew.

A fleet of COTV, all reusable, would make the round trip from LEO to CEO, carrying the cargo payloads up to CEO and returning empty to LEO for reuse. They would be propelled by efficient but slow electrostatic engines. Using low-thrust electric propulsion would require very long trip times, of the order of 4 to 6 months. The bases for selecting this propulsion option were essentially minimum cost and ready availability of the argon propellant and other materials. Such long trip times, although suitable for cargo, are clearly not acceptable for personnel, so a high-thrust propulsion approach was chosen for the POTV. The design utilizes a basic oxygen-hydrogen propulsion stage now undergoing research evaluation at NASA as part of its Advanced Space Engine program. It employs essentially the same level of "technology as that used in the current space shuttle main engine. It could carry up to 160 people from LEO to CEO and back, or 98 tonnes (480 man-months) of consumables from LEO to CEO.

Because it would be impractical to launch a full-sized power satellite by single launch vehicle, a strategy for constructing the satellite in Earth orbit would be necessary. The basic space construction strategy selected for the reference system is to launch all materials, components, and people to staging areas in LEO (fig. 15). The COTVs, because of their large solar arrays, would be assembled in LEO as well. The main construction base would be located in CEO, although not necessarily at the eventual geostationary-orbit location of the operational SPS. Hence the LEO staging area would serve as the transfer point for all materials and personnel both up to CEO and back down to Earth. Alternative strategies have been considered, some of which will be discussed later.

The principal factor that governs the cost and effectiveness of in-space construction is generally accepted to be the productivity of the construction crew and cost, and requirements for shielding. The replacement of some crew by automated equipment is therefore a major consideration in all construction strategies or scenarios, e.g., effort has already been devoted to automatic beam-building systems. [17] The use of teleoperators and robot manipulators for assembly of large structures has also been considered. The current growth of technology in these areas is extremely rapid, [18] and incorporation of such techniques would almost certainly benefit all aspects of SPS construction. Despite the wide range of construction options, estimated personnel requirements for them are approximately the same: 750 ± 200. [19]

GROUND-BASED CONSTRUCTION

Building the rectenna, although a very large and relatively unique structure, nevertheless would involve far fewer uncertainties than constructing the space segment. A detailed analysis [20] of both the basic structure and construction aspects concluded that the primary structural material should be galvanized or weathering steel rather than aluminum (which is more scarce and requires a higher energy cost to produce).

SYSTEM OPERATION

An active control system would be needed both to keep the satellite in the proper orbit

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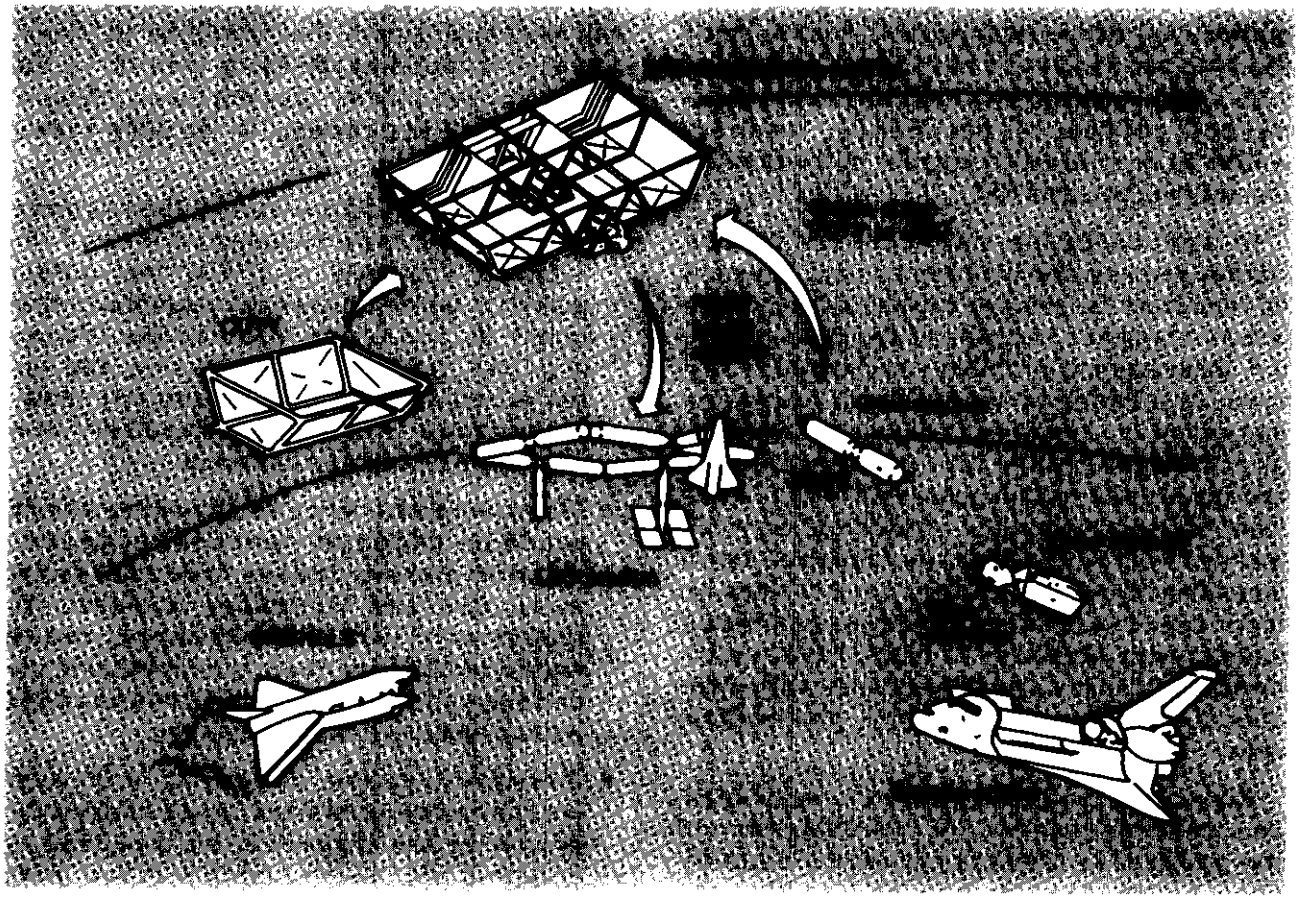
[17] Denis J Powell and Lee Brewing, "Automated Fabrication of Large Space Structures," *Astronautics* and *Aeronautics*, October 1978, pp 24-29

[18] Antal K Bejczy, "Advanced Teleoperators," *Astronautics* and *Aeronautics*, May 1979, pp. 20-31

[19] W H Wales, "SPS Program Review Transportation Perspective," In *The* Final *Proceedings of the Solar Power Satellite* Program *Review*, DOE/NASA Conf-800491, July 1980

[20] "Feasibility Study for Various Approaches to the Structural Design and Arrangement of the Ground Rectenna for the Proposed Satellite," NASA contract No.NAS-1 5280, Bovay Engineers, Inc, May 1977

Figure 15.—SPS Space Transportation Scenario



SOURCE: W. H. Wales, "SPS Program Review Transportation Perspective," in *The Final Proceedings of the Solar Power* Satellite *Program Review,* DOE/NASA Conf-800491, July 1980.

(stationed above the rectenna) and to maintain the solar array's orientation to the Sun. The mass of the necessary control system is estimated at 200 tonnes; its average electric power consumption would be 34 MW.

Because of its low coefficient of thermal expansion and relative stiffness, a graphite composite structural material was selected for the reference system in preference to the aluminum alloys so widely used in aerospace structures. Although a complex engineering problem and, furthermore, one not readily subject to testing at an adequate scale prior to deployment in space, it does not appear likely that dynamic stability would cause any major unexpected problems in either performance or costs, partly because of the predictability of the space environment as compared, for example, with the uncertain environment in which aircraft structures must be designed to operate, and partly because of the extensive body of applicable design, testing, and operational experience with high-performance aerospace structures. However, questions of dynamic instability resulting from low-probability occurrences such as major meteor strikes or aggressive military action would have to be evaluated.

Orientation of the transmitting antenna relative to that of the solar array would be maintained via the large rotary joint. Physical aiming of the antenna itself would be accom-

plished by gyroscopes, which would feed control signals to the mechanical-joint turntable so that it could follow the antenna pointing requirements. However, mechanical pointing of the antenna would not have to be performed with high accuracy, since the electronic phasing and pointing of the antenna subarrays would be insensitive to angular deflections of the antenna of upto100.

In addition to the equipment for satellite station keeping and attitude control, it would be necessary to provide routine maintenance of both the space and ground segments. Potential maintenance problems in the space segment, in addition to the expected routine replacement of components, include the effects of solar wind, cosmic rays, micrometeoroids, and impacts by station-generated debris. Aside from the solar wind and cosmic radiation effects on solar cells, which would require active annealing of the silicon cells, none of these effects would appear to introduce significant maintenance problems or costs, based on extensive past and current experience with operational satellites powered by photovoltaic cells.

Repair and replacement of the solar blankets and more than 100,000 70-kW klystrons in the transmitting antenna are estimated to require a crew of from 5 to 20 people at the geostationary orbit construction base,[21] along with the necessary transportation, support, and resupply (e. g., station-keeping propellant) services.

Maintenance requirements of the rectenna and substation are also primarily associated with repair and replacement of their billions of components. Although a certain degree of redundancy is built into the system, a maintenance crew would still be required to replace storm-damaged rectenna sections and routine failures of both rectenna and substation equipment.

Technical Uncertainties of the Reference System

Although most observers accept the basic scientific feasibility of the SPS system concept, there are many technical uncertainties associated with the reference system. This section identifies specific issues or problems in the reference system that would be of importance in formulating decisions concerning the research, evaluation, development, demonstration, and deployment of satellite power stat ions.

- Performance. A major issue in the reference system design is the tremendous scale of the satellite. The level of 5 GW (net output power) is based on scaling assumptions that could be subject to considerable change (e.g., the transmission frequency, the antenna and rectenna power densities); multiple rectennas served by a single satellite also constitute a potential variation.
- The overall efficiency of the entire system would be subject to considerable variation either up or down, and would be a key factor in all cost and technology tradeoffs. Although all system elements would involve known technology, there is considerable uncertainty about how their efficiencies might add up when assembled together.
- Powerplant lifetime, assumed to be 30 years for the reference system, could actually be greater or less depending on a number of economically interrelated factors (e. g., ease of replacement of damaged components, sudden technological advances in component efficiencies, etc.) This would affect all economic projections, even allowing for high-discount rates.
- The total mass in orbit, one of the critical parameters in assessing costs and launch-related environmental impacts, depends on a number of factors still subject to considerable variation. The power Collection/conversion system is an obvious factor; the reference system's two photovoltaic options are indicative of the significance of that tradeoff. The antenna mass is also important. Prospects for revising the reference-system's 100:1 ratio of rectenna-to-antenna area could have major impact on the overall system cost and performance. The 25-percent contingency factor is another major factor subject to revision if R&D mature.

[21] DOE, op cit

SPS would require an extensive program of research and testing of the numerous satellite and terrestrial components of the system before planning for a demonstration satellite could be completed. In addition, substantial improvements in components and overall technology would have to occur before the SPS could meet the performance specifications of the reference system. However, the current reference system does not constitute a preferred system. It is, perhaps, technically feasible but certainly not an optimum design. It was chosen by NASA/DOE as a model and a reference to be used in the assessment process. As such it has the inherent I imitation that as new information becomes available the design becomes progressively obsolete.

The following items summarize the major technical uncertainties for the reference system and suggest possible ways to alleviate them.

. Photovoltaic cells. The reference system specifies a silicon solar cell efficiency of 17-percent and a mass of 2 grams per peak watt (g/Wp). Current space-rated single crystal silicon cells operate at 12- to 16-percent efficiency. However, they are about nine times as massive (18 g/Wp) as called for in the reference system and they cost about $70/Wp (1980). The reference system assumes a cell cost of about $0.17/Wp. Although the issue of costs will be addressed in more detail in a separate section, it is clear that meeting all three goals for the silicon cell blanket would present manufacturers of current cell technology with an extremely difficult task. Normal advances in cell production techniques would readily result in the necessary efficiency increase. However, the burden of achieving a nine times reduction in weight along with a reduction in costs of a factor of 400 makes it highly unlikely that an SPS could be built using single crystal silicon cells.

  If efficiency-mass-cost goals were met, there would still be the problem of cell lifetime in space and the related problem of the feasibility of annealing the surface. Silicon cells are subject to serious degradation by high energy electrons and protons in the solar wind released by solar flares. One study" estimates that the accumulated particle damage would degrade the output from the cells by 30-percent during the 30-year nominal life of the satellite. The resulting damage could be repaired periodically by annealing the cells by either a laser or an electron beam. The beam would sweep across the surface of the cells and heat them briefly to several hundred degrees centigrade. Very little is known about either process in the laboratory and nothing at ail about how they would work in space or how much energy they would use to anneal the surface of the photovoltaic cells. However, experiments have shown that annealing by electron beam is much more efficient than laser annealing.[23] Because no long-term studies have been done, the suitability of silicon cells for extended duration space applications is in question; however, they have demonstrated excellent performance over a period of about 10 years in operating spacecraft.

  GaAs cells appear to be a more realistic candidate for a reference-type satellite, though they have received much less attention than the silicon cells. GaAs cells reach higher efficiencies and can operate at higher ambient temperatures than silicon cells. Laboratory models of GaAs cells have reached efficiencies as high as 18 percent.[24] Because of their currently higher unit cost, the GaAs array would probably require reflectors to concentrate the Sun's rays on the cells and thereby reduce the required cell area. Aluminized Kapton has been suggested as a reflective material because of its low thermal coefficient of expansion and low mass density.

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[23] C R Woodcock, "SPS Silicon Reference System," *The Final Proceedings of the Solar Power Satellite Program Review*, DOE/NASA Conf-800491, July 1980,

"B E. Anspaugh, J. A Scott-Monck, R. G. Downing, D W. Moffett, and T. F Miyahira, "Effects of Electrons & Protons on Ultra Thin Silicon Solar Cells, " J PL contract No, NAS7-1OO.

[24] Ibid

Here, again, whether Kapton and GaAs cells can maintain their integrity over the 30-year design lifetime of the satellite is unknown. Considerably more study would be needed to determine the feasibility of this option.

- Space charge and plasma effects. Because of the high voltages associated with operation of the klystrons, electrical charge buildup in the satellite components could cause arcing and subsequent failure of certain components.
- *Rotary joint/slip rings.* Although the basic technology of building a rotary joint and an associated slip ring (for electrical continuity) is well-known, considerable uncertainty surrounds their construction and operation on the scale of the reference satellite in a space environment. Because it would operate in a gravity-free environment, the design demands would be different than they are for terrestrial designs.
- Klystrons. Current klystrons last about 10 years, but these are tubes especially selected for their long life characteristics and they operate at much lower power levels than the 70 kW required of reference system klystrons. High-power klystrons do exist, but they operate in a pulsed mode, not continuously as the reference system klystrons would have to. The antenna's phased array control system would need considerable development and testing. Although pilot beams have been used in other applications, and the technology is therefore known, it is unclear whether the power beam would leave the ionosphere sufficiently unaffected to allow for undisturbed passage of the pilot control beam.

Although harmonics and other noise produced by the klystron or alternative transmitting device would seem unlikely to affect the natural environment adversely, they could cause radio frequency interference for communications systems (see the discussion of ch. 8). This problem might be severe and would need extensive study, but most experiments could be carried out in ground-based testing. Alternatives to the klystron may provide better noise and harmonic control (see section on alternatives below).

- *Space transportation.* The problems inherent in developing the capability to transport SPS components to LEO and CEO are those of extending a mature technology, i.e., there is sufficient understanding of the problems to be faced that there is little doubt that the appropriate vehicle could be developed. The most important question is whether the necessary massive loads could be transported for sufficiently low costs, i.e., would reusable vehicles prove economic? In this area, much can be learned from experience with the shuttle

In addition to economic concerns, there are additional technical questions relating to environmental effects that would require study. For instance, can the launch vehicles fly trajectories that would keep the effects of ionospheric contamination to a minimum? Would it be possible to substitute other technologies for the argon ion engine proposed for the reference system (see ch. 8).

- *Construction, operations, and maintenance.* There are unresolved questions about the productivity of humans and machines in the space environment. Some automated equipment has been built and tested on Earth, but considerable development would be needed to choose the best ratio between automated and human tasks.

Alternatives to the Reference System Subsystems

One of OTA's goals is to explore the possible alternatives to the reference system. Some options improve specific components of the reference system. Others would require significant redesign of the overall system. This is because the reference system is composed of a number of interlocking components, some of which depend heavily on the other elements of the system. Thus, a radical change in one component might require numerous other system

changes in order to create the most efficient overall design.

A number of alternative subsystems and systems were considered in the process of electing the reference system design. Advances have been made in some components that were previously rejected. In addition, consideration of some of the above-mentioned technical uncertainties has engendered new designs that could alleviate these uncertainties or resolve some of the technical problems encountered in the reference system.

The following summary lists a number of subsystem options that could be considered as alternatives to the reference system. A more detailed discussion of each can be found in appendix A.

- *Solar thermal power conversion.* Either a Brayton- or Rankine-cycle engine offers higher efficiency energy conversion than photovoltaics. However, they currently suffer from limitations on the means for heat rejection.

  Thermionic, magnetohydrodynamic or wave energy exchanger technologies might eventually find use in combination with the Rankine or Brayton cycle.
- *Photovoltaic alternatives.* Materials other than silicon or gallium arsenide may eventually prove more viable for use in the SPS. Currently none of the other obvious options meet the projected standards for efficiency, low mass, materials availability, etc., that would be needed for satellite use. Different sorts of concentrator systems are also of interest, as is the possibility of using single cells or a combination of cells that respond to a wide portion of the solar spectrum. A possible approach would be to use a combination of al I these variations.
- *Alternative microwave power converters.* Several devices other than the klystron have been considered for converting electricity to microwaves and transmitting them to Earth including the magnetron, which offers the principal potential advantage of cost and low noise, and the solid-state amplifier whose reliability could be very high and mass low.
- Photoklystron. This device, which is still in the very early stages of study, both converts the sunlight directly to microwave power, and transmits it. If successful, it could replace both photovoltaic cell and amplifier.
- Offshore rectennas. For highly populated European and U.S. coastal areas, rectennas mounted in the shallow offshore seabeds offer some advantages over long transmission lines from suitable land-based rectennas.

THE SOLID-STATE SYSTEM

Two system approaches using solid-state devices have been considered for the SPS. The most direct of these simply replaces the kylstrons and slotted waveguides in the reference system by solid-state amplifiers and dipole antennas maintaining essentially the same basic configuration as that of the reference system (fig. 9); the second approach completely revises the satellite configuration by integrating the antenna and solar array in the Earth-facing "sandwich" configuration, using a movable Sun-facing mirror to illuminate the solar array (fig. 16). A number of alternative sandwich configurations have been explored but at the moment the configuration of figure 16 seems to be the best.[25]

Another related subsystem option uses the multibandgap photovoltaic cells discussed earlier, possibly in conjunction with selective filtering to reduce solar-cell temperatures. When such cells are utilized in the sandwich configuration of figure 16, they offer considerable potential mass reduction. A recent preliminary case study[26] compared sandwich-type systems such as that of figure 16 employing single-bandgap GaAs photocells similar to those of the reference system but having higher concentration ratios (CR) with optimized multibandgap photovoitaics. Such a configuration would result in an approximate W-percent increase in power delivered per kilogram.

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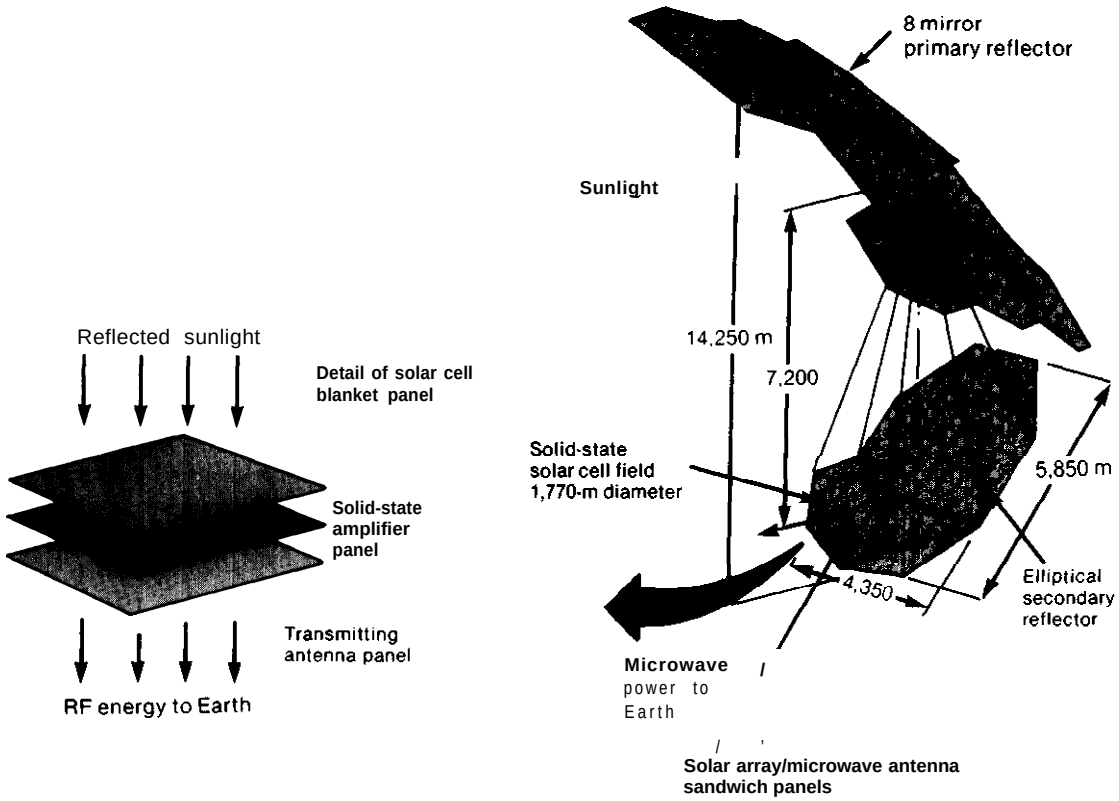
[25] G M Hanley, et al , "Satellite Power Systems (SPS) Concept Definition Study, " First performance Review, Rockwell International report No SSD79-01 63, NASA MSFC contract No NAS8-)2475, Oct 10, 1979

[26] Ibid

Figure 16.—The Solid-State Variant of the Reference System



SOURCE: G. M. Hanley, et al., *"Satellite Power Systems (SPS) Concept Definition Study,* "First Performance Review, Rockwell International report No. SSD-79-0163, NASA MSFC contract No. NAS-8-32475, Oct. 10, 1979.

LASER TRANSMISSION

Lasers constitute an alternative to microwave transmitters for the transmission of power over long distance.[27] They offer the fundamental advantage that at infrared wavelengths, energy can be transmitted and received by apertures over a hundred times smaller in diameter than the microwave beam. This obviously would reduce the size and mass of the space transmitter and the land-area requirement of the ground receiver. But perhaps even more important, the great reduction in aperture area would permit consideration of fundamentally different systems. For example:

- **The use of low Sun-synchronous rather than high geostationary orbits for the massive space power conversion subsystem might be possible. (A Sun-synchronous orbit is a near-polar low orbit around the Earth that keeps the satellite in full sunlight all the time while the Earth rotates beneath it.) In this suggested system, the laser would beam its power up to low-mass laser mirror relays in geostationary orbit for reflection down to the Earth receiver, an arrangement that might considerably reduce the cost of transportation, since the bulk of the system mass is in LEO rather than in GEO. However, system complexity would be increased due to the need for relay satellites.**

[27] Wayne S. Jones, and Maxwell W Hunter, II, "Solar power Satellites: The Laser Option," *Astronautics and Aeronautics,* March 1979, pp. 59,67,

- Because the mass of the laser transmitters would not dominate the satellite, as does the reference-system microwave transmitter, laser satellites would not benefit nearly so much by large scale as the reference system satellites. The resulting smaller systems would improve the flexibility of terrestrial power demand matching, provide high degrees of redundancy, permit a smaller and therefore less costly system demonstration project, and might even preclude the need for ultimate development of an HLLV.
- The small size of the receiving station would make it possible to employ multiple locations close to the points of use, thereby simplifying the entire ground distribution and transmission system. It would also open up the possibility of repowering existing powerplants, regardless of their size, simply by replacing their steam generating units with laser-heated boilers and/or superheaters.

The most important technical disadvantages of laser-power transmission are the very low efficiencies of present laser-generation and power-conversion methods, low efficiency of laser transmission through clouds and moisture, and the relatively undeveloped status of laser power-system technology in general.

The laser system would consist of three distinct elements: the laser-generation subsystem, the laser-to-electric power-conversion subsystem, and the laser beam itself.

Laser Generators

Although the laser has become a well-known and widely utilized device in industry, the high-power continuous-wave (CW) laser generators needed for SPS are still in the advanced-technology or, in many cases, the early research phase.[28] However, the technology is improving dramatically as exemplified by the growth of laboratory-demonstrated conversion efficiencies (input power to laser beam) from about 1 to nearly 50 percent during the past decade.

Of all the currently operating CW lasers, only the electric discharge laser (EDL)[29] seems a feasible alternative for the SPS. The gas dynamic laser (CDL) suffers from very low efficiency if used in the closed cycles necessary for space (i.e., the gas supply must be circulated, cooled, and reused). Chemical lasers require a continuous propellant supply that makes them also unsuitable for long-term use in space.

High-power density at 50-percent conversion efficiency levels has been achieved for EDLs, but only in the open-cycle mode for short time periods. The closed-cycle systems needed for SPS have yet to be tested, even in the laboratory. In theory, they should achieve high efficiencies in that mode as well, but considerable improvement in the available technology would be required to reach the necessary goals.

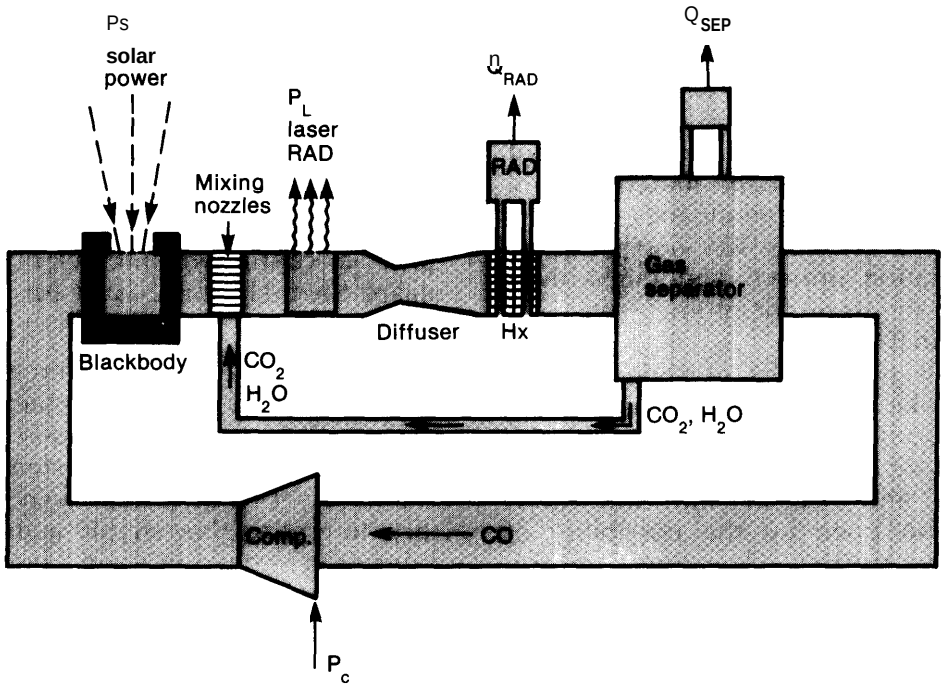
In addition to using improved designs of currently operating lasers, several advanced concepts have been suggested. Of these, the solar-pumped laser and the free electron laser (FEL) seem most promising for the long term.

- Solar-pumped lasers. Figure 17 illustrates the concept of a solar-pumped laser. The energy contained in sunlight directly excites a combination of gases confined between two mirrors, which subsequently "lase" and transmit the captured energy. It suffers the drawback that because only a part of the solar spectrum is useful in exciting any given lasant gas, its conversion efficiency is likely to be fairly low. However, elimination of the need for a separate electric power-generating system, and the consequent reduction in mass and complexity, could more than compensate for this drawback. Further, in comparison with other laser systems, the solar-pumped laser's efficiency need be only as good as the combined power-generating

[28] J Frank Coney bear, "The Use of Lasers for the Transmission of Power," in *Progress in Astronautics, vol. 61,* AIAA, N Y, July 1978, pp. 279-310

[29] G W Kelch and W. E. Young, "Closed-Cycle Gasdynamic Laser Design Investigation," Pratt & Whitney Aircraft, NASA Lewis Research Center report No CR-135530, Jan 1,1970.

Figure 17.—Indirect Optically Pumped CO/CO_2 Mixing Laser



SOURCE: R. Taussig, P. Cassady, and R. Klosterman, "Solar Driven Lasers for Power Satellite Applications," in *Final Proceedings of SPS Program Review,* Department of Energy, p. 267

system and laser generator of other laser systems (about 7.5-percent for a photovoltaic-powered carbon monoxide (CO) EDL[30]).

Although the information exists to determine the applicability of solar-pumped lasers to SPS, adequate studies have not been done. There is as yet little or no realistic basis for the mass, efficiency, and cost projections proposed by several authors.[31 32 33 34]

[30]R.E. Beverly, "Satellite Power Systems (SPS) Laser Studies Technical Report, Vol. 1, Laser Environmental Impact Study," Rockwell International SSD-80-0119-1, August 1980

"W. S. Jones, L. L. Morgan, J. B. Forsyth, and J Skratt, "Laser Power Conversion System Analysis: Final Report, Vol. I I," Lockheed Missiles and Space Co., report No LMSC-D673466, NASA report No. CR-1 59523, contract No NAS3-21 137, Mar 15, 1979

[32]Claud N Bain, "Potential of Laser for SPS Power Transmission, " report No R-1 861, PRC Energy Analysis Co , DOE contract No. EG-77-C-01-4024, September 1978

[33]John D. G. Rather, "New Candidate Lasers for Power Beaming and Discussion of Their Appl ications," I bid., pp. 313-332.

[34]Daryl J. Monson, "Systems Efficiency and Specific Mass Estimates for Direct and Indirect Solar-Pumped Closed-Cycle High-Energy Lasers in Space," ref 105, pp 333-345

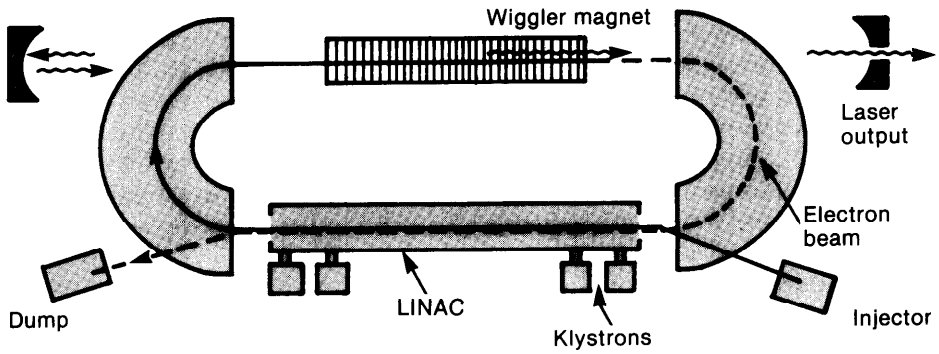
Free-Electron Lasers (FEL)

An FEL is powered by a beam of high-energy electrons oscillating in a magnetic field in such a way that they radiate in the forward direction (fig. 18). A number of pulses reinforce the stored light between the mirrors, generating a coherent laser beam. The high-energy density of the relativistic electron beam is theoretically capable of producing very high-power density lasers, and the emitted frequency is tunable simply by changing the electron energy.

Although efficiencies are theoretically projected to be quite high (around 50 percent for the combined FEL and storage ring[35]), it is not known whether such efficiencies could be reached in practice. In addition, the system mass per unit power output and the ability to

[15]John W Freeman, William B. Colson, and Sedgwick Simons, "New Methods for the Conversion of Solar Energy to R. F. and Laser Power, " in *Space Manufacturing ///,* Jerry Grey and Christine Krop (eds) (New York AIAA, November 1979).

Figure 18.—The CATALAC Free Electron Laser Concepts



SOURCE: R. Taussig, P. Cassady, and R. Klosterman, "Solar Driven Lasers for Power Satellite Applications," in *Final Proceedings of SPS Program Review,* Department of Energy. p. 267

scale to the size and power levels of a laser SPS are impossible to predict reliably at this time. [36]

Laser Transmission

As in the case of microwave transmission, the fundamental parameter that governs much of laser transmission performance is the frequency (or wavelength). At ultraviolet or visible wavelengths, absorption losses in the atmosphere are higher than for infrared wavelengths. The wavelength also affects the efficiency of the laser power absorption and conversion equipment.

At the wavelengths of CO or CO, EDLs, (5 to 10 microns), the primary mechanism of beam attenuation is molecular absorption. Scattering by molecules or by aerosols in clear air is relatively unimportant. Attenuation of the beam by aerosols under hazy or cloudy conditions is quite significant and can completely block the beam if the clouds are thick enough. Although it is apparently possible to burn a hole through thin clouds,[37] the attenuation of energy is appreciable, and because clouds are seldom stationary, the laser would continually encounter new water droplets to vaporize.

Transmission of the laser beam through the atmosphere is also affected by a phenomenon called "thermal blooming;" i.e., heating of the atmosphere that causes it to act like a lens and distort the laser beam. Scientists are currently divided on the significance of this issue and opinions range from assertions that it is a major factor[38] to suggestions that it could be avoided altogether by selecting the transmitting wavelengths carefully.[39] Considerable classified research is now being carried out on this effect in connection with laser-weapons research. Some of this work might be applicable to SPS use, though in general the military lasers are pulsed, not CW systems. The difference could be critical and should be studied carefully.

With regard to laser optics, it is important to develop components capable of low-loss, high-power-density transmission and reflection of laser light.[40] It appears that adequate technology for SPS systems has a high probability of being available within the next 20 to 30 years, due primarily to advances being made in current military laser research and technology programs.

[36] Beverly, op. cit.
[37] E. W. Walbridge, "Laser Satellite Power Systems, " Argonne National Laboratory report No AN L/ES-92
[38] Jones, et al , op cit
[39] Beverly, op. cit
[40] Bain, op cit

Transmission options for SPS lasers are essentially of two types: a narrow, highly concentrated beam or a wide, dispersed beam (fig. 19). Advantages of the narrow beam are the reduced land area needed and the small size of the ground power-conversion system; problems include potential environmental and safety impacts of the high-intensity beam, concerns over military uses, and the need for sophisticated high-temperature receivers and power-conversion equipment. Advantages of the dispersed beam are its less severe environmental impact, the possible use of low-performance optics, and simplicity of low-power-density receiving systems. Disadvantages include relatively high atmospheric dissipation, larger land area required and the large mass of Earth receptors. It is probably too early to make an informed selection between the two options, but the narrow-beam approach appears to offer the principal benefit compared to reference-system microwave transmission.

A final concern is the ability to point and control the beam to make sure it would always remain within the designated receiver area and to shut it off instantly should it stray. The adaptive-optics approach to beam control (e.g., phased-array) such as would be used for the microwave beam, appears adequate to provide the necessary pointing accuracy and to ensure safety, since any loss of phasing control would cause loss in coherence of the several lasers making up the beam, and each beam by itself would transmit far too little power to cause any problems. Adaptive optics systems are being studied for use in military directed energy weapons and look promising." It should be emphasized that the overall system constraints might be quite different for the large CW lasers needed for SPS than for pulsed military examples.

Laser-Power Conversion at Earth

Several approaches are possible for converting high-energy-density laser radiation to useful electric power. The technology of laser energy converters is relatively new, but progress has been rapid. Laboratory models have achieved conversion efficiencies of 30 to- 40 percent and designers project eventual efficiencies of 75 percent for some versions. Table 6 summarizes the available technology and projects future potential efficiencies. [42]

The Laser-Based System

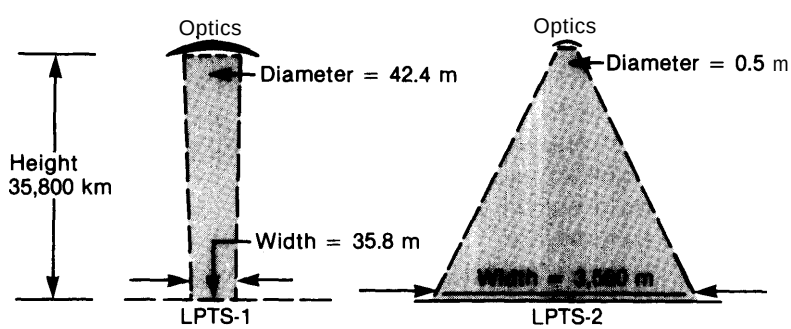
Lockheed [43] has generated one possible laser system (fig. 20) that utilizes power satellites in

[41] Claud N Bain, "Power From Space by Laser," in "High-Powered Lasers in Space, " *Astronautics* and *Aeronautics,* vol. 17, March 1979, pp 28-40

[42] George Lee, "Status and Summary of Laser Energy Conversion, ' in *Progress in Astronautics,* vol *61* Al AA, N Y , July 1978 pp 549-565

[43] Jones, et al , op cit

Figure 19.—Optics and Beam Characteristics of Two Types of Laser Power Transmission System (LPTS) Concepts



SOURCE: Claud N. Bain, "Potential of Laser for SPS Power Transmission," report No. R-I WI, PRC Energy Analysis Co., DOE contract No. EG-77-C-01-4042, September 1978.

Table 6.—Projections for Laser Energy Converters in 1981-90

	Current	1981-90
Photovoltaics.	—30% efficiency —megawatt power levels —wavelengths below 1 micron	—45% efficiency —megawatt power levels —wavelengths below 1 micron
Heat engines	—Piston engine: Otto or diesel cycles —50% efficiency —1-10 k W —wavelengths near 10.6 microns	—Turbine —75% efficiency —megawatt power levels —wavelengths near 5 microns
Thermionics	—40% efficiency —1-10 kW —wavelengths near 10.6 microns	—50% efficiency —megawatt power levels —wavelengths near 5 or 10 microns
Photochemical cells	—Photoassisted dissociation of water —15Y0 efficiency —wavelengths near 0.4 microns	—Photoassisted dissociation of water —30% efficiency —wavelengths near 0.6 microns
Optical diodes	—Evaporated junction arrays —not ready to convert power	— Evaporated junction arrays —50% efficiency —megawatt power levels —respond to wavelengths from UV to over 10 microns

SOURCE: George Lee, "Status and Summary of Laser Energy Conversion," in *Progress in Astronautics, vol. 61,* AIAA, N. Y., July 1978, pp. 549-565.

low Sun-synchronous orbit and relay satellites (laser mirrors) both in LEO and CEO. One geostationary relay serves each power satellite. Based on an analysis of five candidate systems in three power ranges, Lockheed selected a CO, EDL powered by a wave energy exchanger (EE) binary cycle and a similar binary cycle for ground power conversion.

The specific 500 MW system selected is diagramed in figure 21; hardware details of the power satellite appear in table 7, and the Overall system characteristics are summarized in table 8.

A major potential advantage of the laser system is that it could be demonstrated via a subscale 500-kW pilot program using the space shuttle to deliver the power and relay satellites into LEO orbits.

Other laser systems are possible. For example, Rockwell[44] has investigated a geosynchronous laser SPS powered by photovoltaic ceils and using 20 to 24 100-MW CO EDL lasers. The CO laser was chosen because it has greater overall efficiency and is lighter than a $C0_2$ laser.

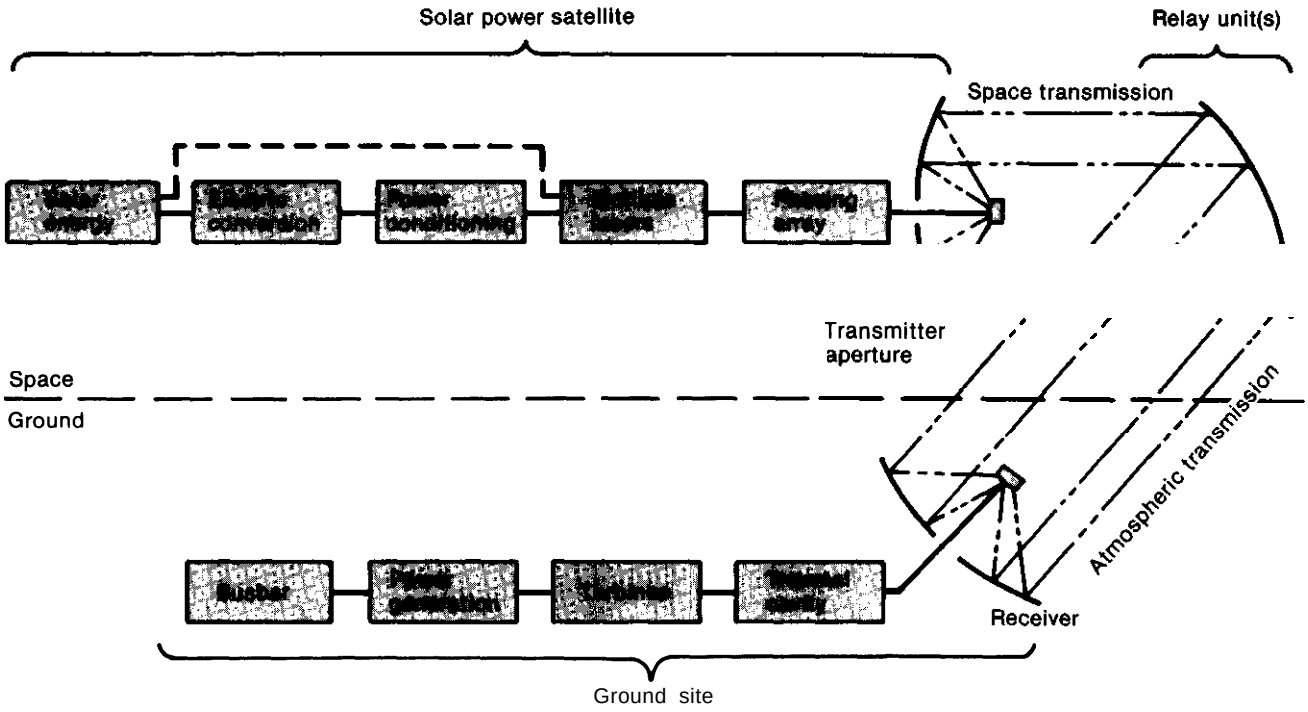
This study will use the LEO-based $C0_2$ laser system in its subsequent analysis because of the significant difference in space basing (i. e., LEO rather than CEO) which it presents compared to the reference system. Because of the significant uncertainties present in the laser systems concepts and the relative lack of technology base for laser devices, the optimum laser system would undoubtedly look rather different from any system so far devised.

A laser system that used photovoltaic arrays to collect and convert the Sun's energy would suffer from the fundamental difficulty that the overall efficiency of the system would be quite low compared to projected reference system efficiency .45 The major limiting factors are the projected efficiencies of the laser itself (50 percent for an EDL), the atmospheric transmission (84 to 97 percent), and the conversion efficiency of the terrestrial receptor (40 to 75 percent). When multiplied together with the higher efficiency of other system components, they result in an overall efficiency of 17 to 36 percent after photovoltaic conversion of sunlight to electricity to power the laser. When the efficiency of the solar cells (17 percent) is taken into account, the overall system efficiency falls to only 2.8 to 6 percent compared to the projected reference system efficiency of 7 percent. Although this decrease would con-

[44]Beverly, op. cit.

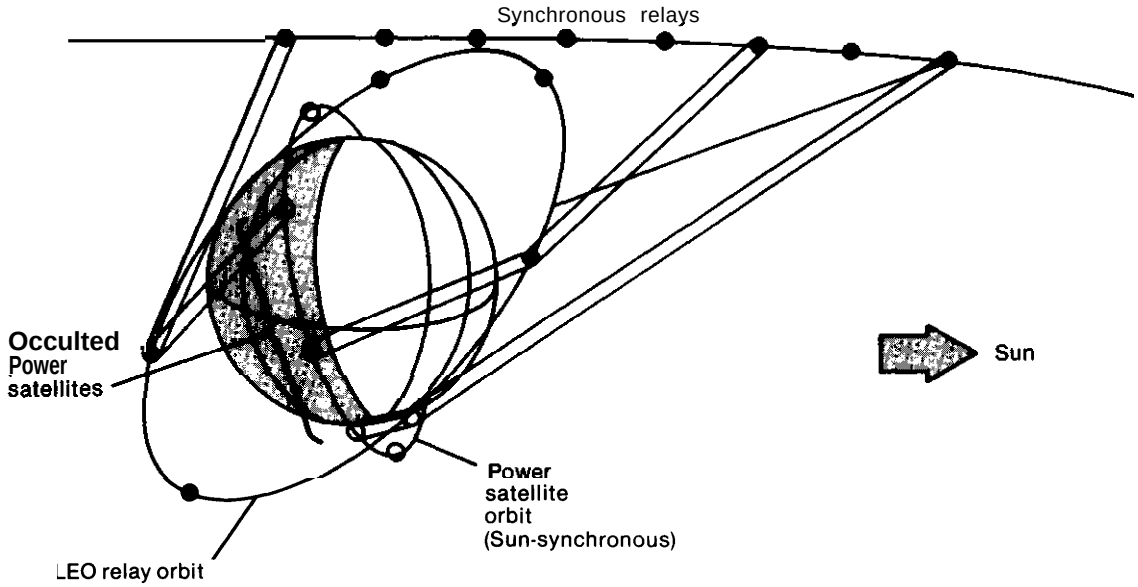
[45]DOE, op. cit.

Figure 20.—The Laser Concept (one possible version)



SOURCE: W. S. Jones, L. L. Morgan, J. B. Forsyth, and J. Skratt, "Laser Power Conversion System Analysis: Final Report, Vol. II," Lockheed Missiles and Space Co., report No. LMSC-D673466, NASA report No. CR-159523, contract No. NAS3-21137, Mar. 15, 1979.

Figure 21 .—Components of the Laser Concept



SOURCE: W. S. Jones, L. L. Morgan, J. B. Forsyth, and J. Skratt, "Laser Power Conversion System Analysis: Final Report, Vol. 11," Lockheed Missiles and Space Co., report No. LMSC-D673466, NASA report No. CR-159523, contract No. NAS3-21137, Mar. 15, 1979

Table 7.—500 MWe Space Laser Power System

	Collector	Solar cavity	EE/binary cycle	Power generation and conditioning	Laser	Spacecraft, structure, radiators, etc.	Transmitter aperture and optical train
Unit efficiency (%)	**85**	**86**	**73.5**	**93.1**	**23**	—	**98.7**
System efficiency (%)	**85**	**73.1**	**53.7**	***50.0***	***11.5***	**—**	11.4
Power in (MW)	7,913	6,726	5,784	4,251	3,958	—	910
Power out (MW)	6,726	5,784	4,251	3,958	910	—	899
Orbital weight (kg)	242,850	517,750	1,326,330	717,660	1,809,000	128,653	97,811
						Spacecraft 4,108	Telescope (2) 89,812
						Structure 94,433	Beam reduction 5,379
						Radiators 6,032	Phasing array 1,539
						Stabilization 24,080	Optical train 1,181

	Space transmission	Space relay	Atmospheric transmission	Ground receiver	Thermal cavity	Binary cycle	Electrical generation
Unit efficiency (%)	95	99	85	96	98	75.5	98
System efficiency (%)	10.8	10.7	9.1	8.7	8.5	6.5	6.3
Power in (MW)	899	854	845	718	690	676	510
Power out (MW)	854	845	718	690	676	510	500
Orbital weight (kg)	–	105,438	—	—	—	—	—
		Transmitter 44,703					
		Receiver 46,729					
		Optical train 945					
		Spacecraft 5,900					
		Radiators 5,762					
		Structure 1,023					
		Miscellaneous 376					

SOURCE: W. S. Jones, L. L., Morgan, J.B. Forsyth, and J. Skratt, "Laser Power Conversion System Analysis: Final Report, Vol. 11," Lockheed Missiles and Space Co., report No. LMSC-D673466, NASA report No CR-159523, contract No. NAS3-21 137, Mar 15, 1979.

Table 8.—Laser Power Station Specification

Solar power collected (MW)	7,913.0
Collector diameter(m)	2,710.0
Electrical power to laser(MW)	3,958.0
Laser power output (MW) (20 lasers at 45.5 MW each)	910.0
Transmitter, aperture diameter (m)	31.5
Secondary mirror diameter (o)	3.0
Transfer mirror size (m)	3.0 x 4.2
Mirror reflectivity (%)	99.85
Optics heat rejection (MW)	11.8
Radiator area (m^2)	2,656.7
Mirror operating temperature (“C)	200.0

SOURCE: W. S. Jones, L. L., Morgan, J. B. Forsyth, and J. Skratt, "Laser Power Conversion System Analysis: Final Report, Vol. 11," Lockheed **Missiles and Space Co., report No.** LMSC-D673466, **NASA report No. CR-159523, contract No.** NAS3-21137, **Mar 15, 1979.**

stitute a potential problem for the laser system, it must be emphasized that many other complex factors (e. g., the smaller terrestrial receivers, or lower mass in GEO), might compensate in complex ways for lower efficiency. When added up, the combination might make the laser system more acceptable overall than the microwave systems. ’b

“Abraham Hertzberg and Chan-Veng Lau, "A High-Temperature Rankine **Binary Cycle for Ground and Space Solar** Applications, **" m "Radiation Energy Conversion in Space, " K W,** Billman **(cd,),** *Progress in Astronautics and Aeronautics,* **vol. 61 (New York, AIAA, July 1978), pp 172-185.**

MIRROR REFLECTION

Instead of placing the solar energy conversion system in orbit as in the reference SPS, several authors have suggested using large orbiting mirrors to reflect sunlight on a 24-hour basis to ground-based solar-conversion systems.[47] [48] [49] [50]

Typically, this option would use plane mirrors (fig. 22) in various nonintersecting low-altitude Earth orbits, each of which directs sunlight to the collectors of several ground-based solar-electric powerplants as it passes over them (the so-called "SOL ARE S" concept).

Each mirror would be composed of a thin film reflecting material stretched across a supporting structure made up of graphite-reinforced thermoplastic. As they pass within range of the terrestrial receiving station, the mirrors would acquire the Sun and the ground station nearly simultaneously. They would maintain pointing accuracy by means of built-in reaction wheels.

Two typical "limiting cases" have been identified from among several alternatives.[51] one would use a 1,196-km circular equatorial orbit (O ° latitude) serving 16 equatorial ground stations each generating about 13 CW (baseload, with minimum storage) and another 6,384-km 40 '-inclination circular orbit serving four 375 GW ground stations at 300 latitude. Additional ground stations in each case (to accommodate demand growth) could be achieved simply by increasing the orbit altitude and mirror size, which increases the size of the illuminated ground circle and thereby permits the use of larger ground stations.[52] The orbiting mirrors themselves could probably be quite large (up to 50 km' each) with very low mass density[53] and still maintain their required optical surface flatness in the presence of disturbing forces.

A mirror system would offer the following potential advantages:

- The space segment would be simple and of low mass. It would consist only of planar reflective thin-film mirrors.
- It would minimize the need for large-scale space operations, since recent designs allow terrestrial fabrication and packaging with automatic deployment i n space.
- The system would be modular and highly redundant, i.e., there would be many identical mirrors capable of mass production.
- The mirrors would operate at low-orbit altitudes, thus not requiring the CEO transportation system of some other alternatives.
- It would eliminate the need for developing microwave- or laser-transmitting technology.
- The mirrors would reflect ordinary sunlight, thus eliminating many of the potential damaging environmental effects due to laser or microwave transmission.
- It could be used for a variety of terrestrial uses where enhanced 24-hour sunlight would be useful. SOLARES could increase the solar product fivefold over the same system operating on ambient sunlight.
- Demonstration would be very inexpensive compared to laser or microwave options.

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[47] Hermann Oberth, "Wege zur Raumschiffahrt," Oldenburg-Verlag, Berlin, 1929; also see "Ways to Spaceflight," NASA technical translation TT F-662

[48] Krafft A Ehricke (for example), "Cost Reductions in Energy Supply Through Space Operations," paper IAF-A76-24, 27th *International Astronautical Congress*, Anaheim, Calif , Oct. 10-16, 1976.

[49] K. W. Billman, W. P Gilbreath, and S W Bowen, "Introductory Assessment of Orbiting Reflectors for Terrestrial Power Generation," NASA TMX-73,230, April 1977

[50] K. W. Billman, W. P. Gilbreath, and S W Bowen, "Orbiting Mirrors for Terrestrial Energy Supply," in "Radiation Energy Conversion in Space," K.W. Billman (ed), *Progress in Astronautics* and Aeronautics Series, VOI 61 (New York Al AA, July 1978), pp 61-80

[51] K. W. Billman, W. P. Gil breath, and S W. Bowen, "Solar Energy Economics Revisited: The Promise and Challenge of Orbiting Reflector for World Energy Supply," DOE SPS Program Review, June 8,1979.

[52] K W Billman, "Space Orbiting Light Augmentation Reflector Energy System: A Look at Alternative Systems," SPS Program Review, June 1979.

[53] John M Hedgepeth, "Ulti ghtweight Structures for Space Power," in "Radiation Energy Conversion in SpaceJ" K W, Billman (ed), *Progress in Astronautics* and *Aeronautics, vol. 61 (New* York Al AA, July 1978), pp. 126-135.

Figure 22.–The Mirror Concept (SOLARES)

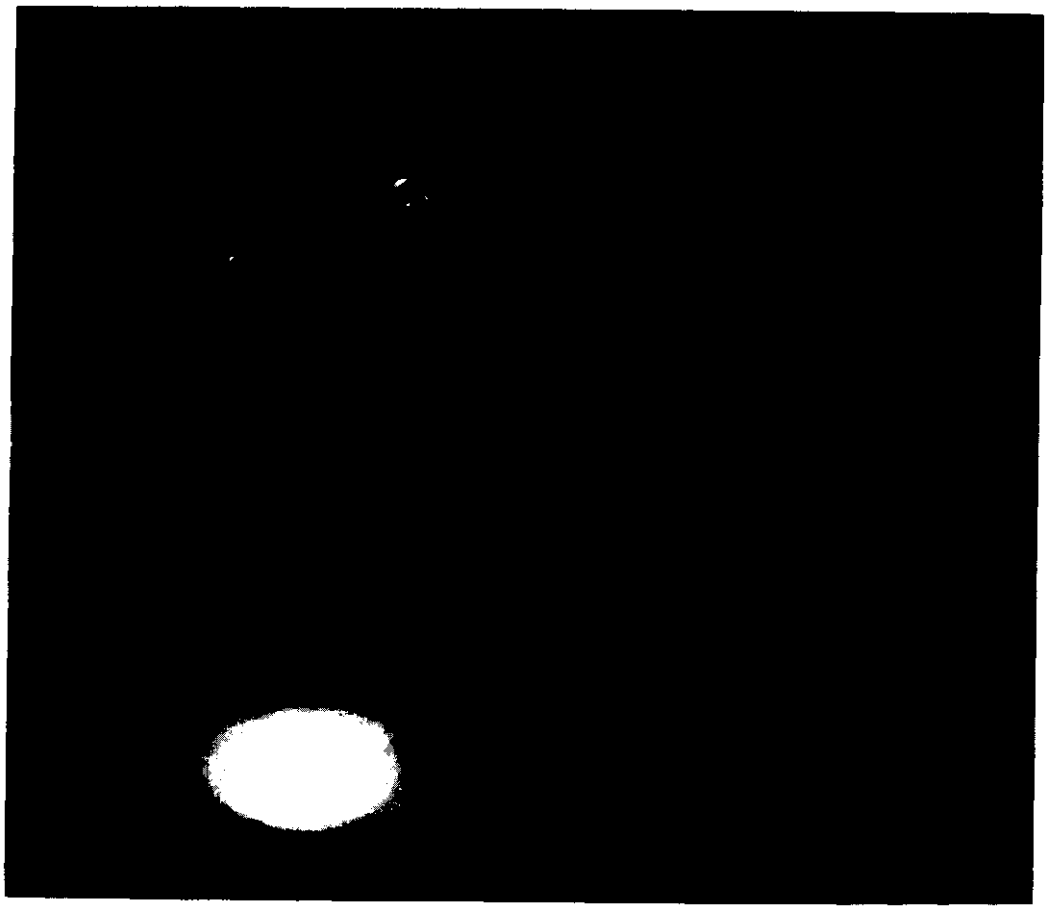
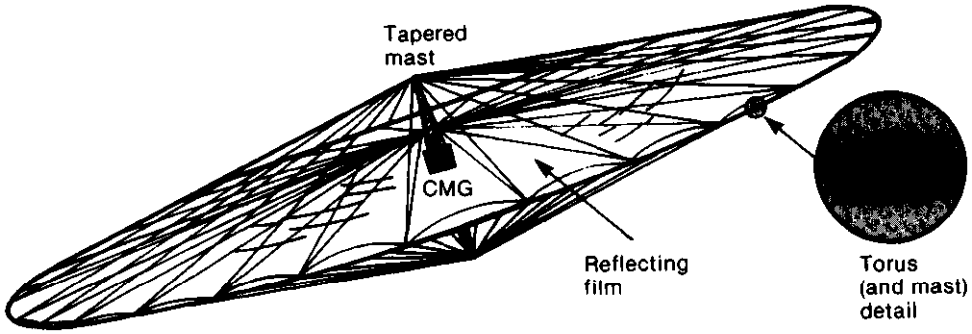


Photo credit: National Aeronautics and Space Administration



SOURCE: K. W. Bill man, "Space Orbiting Light Augmentation Reflector Energy System: A Look at Alternative Systems," SPS Program Review, June 1979.

On the other hand, mirror systems would possess the following potential disadvantages:

- **They would require a large number of satellites each with individual attitude control. Maintenance might be expensive and difficult to accomplish.**
- **The mechanisms needed to keep the mirrors pointed accurately might be complicated.**
- **The mirrors might cause unwanted weather modifications around the ground stations (see below and ch. 8).**

- **Scattered light from the mirrors and the light beams in the atmosphere would interfere with astronomical research (see ch. 8).**
- **The large power production per site (10 to 135 GW) and necessary centralization of the electrical supply from them would not be attractive to the utilities (see ch. 9).**
- **The large area of the receiving sites (100 to 1,000 km^2) would be likely to make land-based siting extremely difficult if not impossible from a sociopolitical standpoint (see ch. 9).**

The Mirror System

The "baseline" Mark 1 SOLARES[54] design (table 9) would require a total mirror area of nearly 46,000 km^2. If each mirror were 50 km^2, about 916 of them would be necessary for a global power system that would produce a total of 810 GW from six individual sites, or about twice 1980 U.S. electric generation. It was chosen for comparative purposes because it demonstrates the potential for large scale energy output that might be achieved with mirrors. It is by no means the optimum SOLARES system. A low-orbit version (altitude 2,000 km) with 15 smaller ground stations (10,000 to 13,000 MW output) might be more feasible or desirable. One of the principal features of the SOLARES concept is that it could be used for any energy use where enhanced sunlight would be used to advantage. By using many more smaller mirrors, the mass per unit area could be minimized, and the total mass in orbit for the entire baseline system then becomes about 4X105 tonnes. Thus, the entire SOLARES baseline system would require only the same mass in space as eight 5,000 MW reference system satellites.

Several Earth-based energy production methods currently under development might be used in conjunction with orbital reflector systems: 1) photovoltaic arrays of varying sizes are projected for commercial deployment in the late 1980's, and 2) solar-thermal electric plants should become commercially feasible in selected locations about the same time, possibly also for "repowering" of existing coal- or oil-fired fossil-fuel plants with solar boilers. Much of the economic disadvantage of both types of solar-electric powerplants is associ-

Table 9.—SOLARES Baseline System

configuration:	
Space system	
4,146km inclined orbit, 45,800km^2 total mirror area	
Ground system	
6 sites with DOE 1986 goal solar cells @ 15% efficiency	
11 % overall system conversion efficiency, $\eta\alpha$-circle area = 1.168km2 each, 135 GWe each	
Impact:	
Total system would produce 3.24 times current U.S. consumption, total area = 84 x 84km^2 (52 x 52 mi^2)	
Baselined costs (in 1977 dollars)	
Implementation schedule	
5-year development, design, test, and evaluation (DDTE)	
2-year manufacturing and transport fleet facilities preparation	
6-year space and ground hardware construction	
System complete about 1995	
Direct costs estimate (billions of dollars)	
Facilities	$ 47.30
Hardware	885.65
Total direct	$932.95
Indirect costs estimate (billions of dollars)	
15% contingency on direct costs	$139.94
Design, development, test, and evaluation	43.80
Interest[a]:	
Facilities	23.58
Hardware	101.26
DDTE	41.01
Total indirect	$349.59
Total cost	$1,282.54
Indirect cost factor	1.38
Installed cost per rated output ($/kWe)[b]	1,508
Capacity factor(%)	95
1995 O&M costs:	
Fixed ($/kW-y)	3
Variable (mills/kWh)	2
Levelized capital cost (mills/kWh)[c]	27.2
Levelized O&M cost (mills/kWh)[d]	4.5
Levelized busbar energy cost (mills/kWh)[e]	31.6
Comparison baseload power systems (CIRCA 1995):	
Conventional coal/nuclear mix[f]	
Levelized busbar energy cost (mills/kWh)[e]	45
Ambient sunlight photovoltaic[f,g]	
Levelized busbar energy cost (mills/kWh)	115

[a] 4% first year, 8% per annum until positive cash flow after Year 11.
[b] Includes all direct costs, 15% contingency, interest during implementation at 8% per annum.
[c] 15% fixed charge rate 30 years at 60/0 annual inflation.
[d] 30 years at 6% annual' inflation,
[e] 15% fixed charge rate.
[f] See text; these d. not include their historically extensive R&D costs that are Included, in SOLARES costing.
[g] Uses same terrestrial costing algorithm as SOLARES that results in indirect cost factor of 1.37.

SOURCE: K. W. Billman, W. P. Gilbreath, and S. W. Bowen, "Solar Energy Economics Revisited: The Promise and Challenge of Orbiting Reflector for World Energy Supply," DOE SPS Program Review, June 8, 1979.

[54] Billman, et al., "Solar Energy Economics Revisited. The Promise and Challenge of Orbiting Reflector for World Energy Supply, " op. cit

ated with the energy storage needed to allow them to serve as intermediate or baseload plants. Should these plants prove to be even marginally successful, relieving their storage needs by keeping them I it for 24 hours a day by sunlight from orbiting reflectors would enhance the attractiveness of these terrestrial options.

The various benefits of a mirror system must be weighed against the percentage of time the ground-based energy production facilities would be obscured by clouds, smog, fog, and other atmospheric obstruct ions. However, there is some evidence" that the concentrated sunlight provided by the orbiting mirrors would tend to disperse water-based obscurations such as clouds and fog, as a consequence of the accelerated evaporation produced by the high-intensity solar radiation.

If the orbiting mirrors can disperse clouds of moisture around the SOLARES ground station, what effects may they have on the climate nearby? Large orbiting mirrors have been suggested for use in climate modification,[56] but their possible detrimental side effects have not been studied (see ch. 8). However, even if reflected sunlight could be shown to have a salutary effect on certain regions of the Earth, there is no reason to believe, without further study, that regions whose weather patterns could benefit from enhanced sunlight would necesssarily coincide with the SOLARES ground stations.

"Ibid

[56] I Bekey and J E Nagle, "Just Over the Horizon in Space," *Astronaut/es* and *Aeronautics*, May 1980.

SPACE TRANSPORTATION AND CONSTRUCTION ALTERNATIVES

Space transportation and construction (with the possible exception of SOLARES) are common to all the options. NASA contractors who developed the transportation, construction, and assembly plan for the reference system devoted considerable effort to the process of winnowing out a host of alternative approaches. Nevertheless, several other construction/assembly schemes have been proposed for various phases of SPS program development. If feasible, they would mostly serve the purpose of reducing costs by using technology developed for other programs or by reconfiguring the reference system scenario. Because transportation costs are a significant percentage of any systems cost (see section on costs below), it would be important to explore these alternatives fully.

Transportation

Transportation strategy in the early development phase and engineering verification is to use the shuttle or an upgraded shuttle to their maximum capacities. In these, as well as later demonstration and production phases, using shuttle size vehicles at high launch rates could be cheaper than developing and using larger launch vehicles (see section on costs). Perhaps the most obvious approach is to upgrade the shuttle-based space transportation system to perhaps five times the capability (i.e., total mass to space in a given time as represented by payload size, launch rate, and turn-around) of the present shuttle.[57]

The need to conduct relatively sizable experiments, and possibly prototype or demonstration projects in geostationary orbits rather than in low-Earth orbits, would pose a serious transportation problem. Current space-shuttle upper stages, or "orbital transfer vehicles, " are not capable of carrying large payloads to geostationary orbit and are not able to support any servicing operations there, since these units are not reusable.

Several innovative approaches have been suggested that circumvent the need for developing new vehicles. One such approach employ; an in-orbit propel ant processing facility

[57] Salkeld, et al., op. cit.

built into one of the shuttle's big "throwaway" propellant tanks to convert water into hydrogen and oxygen –the best propellants for high-performance rocket engines. The water required as the feedstock for this process would be carried into LEO as an "offload" on every space shuttle flight whose payload is less than the maximum shuttle capability. The hydrogen and oxygen, after being liquefied and stored in the propellant processing facility's tank, are then used as the propellants for a reusable low-thrust "space tug" whose principal component is also a leftover shuttle propellant tank. The tug, which replaces the cargo orbital transfer vehicle of the reference system, would carry SPS prototype or demonstration hardware up to CEO. Although such a system is rather completely defined,[58] considerable technology advancement and development would be required, e.g., for the in-orbit electrolysis and liquefaction plants, the space-tug-development, and the system logistics and integration. Cost estimates have not yet been released. Nevertheless, this concept represents an interesting suggestion for eliminating the development of a major new (or upgraded) launch vehicle just for an SPS demonstration, thereby reducing the "up-front" costs of any sizable SPS prototype or demonstration project.

Another scheme would use an electromagnetic propulsion device[59] called a "mass driver" to provide orbital transfer thrust instead of the chemical-rocket-powered space tug. The mass driver is simply a solar-powered linear electric motor, which derives its thrust by accelerating chunks of waste mass (e.g., chopped-up or powdered shuttle propellant tanks) into space at high exhaust velocities. [60] [61] Since it uses electricity, its energy could come directly from the Sun via photoelectric conversion. This concept is far more ambitious than the in-space propellant processing scheme; furthermore, it depends on a device that, although tested extensively on Earth in experimental high-speed trains and in the laboratory, has yet to be demonstrated at the scale and acceleration levels required by the orbital transfer application. A modest research effort on this concept is currently being supported by NASA's Office of Aeronautics and Space Technology.

The production phase of the SPS program would present a number of opportunities for transportation alternatives that could not only reduce production costs, but could also mitigate environmental and other impacts. Because of the high proportion of total space segment construction costs (both nonrecurring and recurring) taken up by transportation, many of the proposed innovations center on alternatives to the family of four transportation vehicles selected for the reference system.

The most direct approach to transportation cost reduction would be to improve the HLLV, since it absorbs the bulk of transportation development and operations costs. The most likely technological alternative appears to be the use of fully reusable single-stage-to-orbit (SSTO) vehicles. [62] Very advanced winged SSTO vehicles that could reduce LEO payload delivery costs to the order of $1 5/km are projected as becoming practical in the last decade of this century, provided sufficient demand exists. [63]

For orbital transfer the personnel and cargo orbital transfer vehicles selected for the reference system probably represent the best available technology in the two principal options: chemical and electric propulsion.

Alternatives for routine high-mass payload hauling might include solar sails, laser propulsion, and various forms of electric propulsion other than the ion (electrostatic) rocket described for the reference system, e.g., elec-

[58] Central Dynamics Corp (Convair Division), "Utilization of Shuttle External Tank in Space, " unpublished presentation, June 1978.

[59] F. Chilton, B, H ibbs, H. Kolm, G K O'Neill, and J. Phil lips, "Electromagnetic Mass Drivers," in "Space-Based Manufacturing From Nonterrestrial Material s," G K C)'Neil I (cd.), *Progress in* Astronautics and *Aeronautics, vol. 57 (New* York AIAA, August 1977), pp. 37-61.

[60] Chilton, et al., "Mass-Driver Application s," ibid , PP. 63-94.

"Gerard K O'Neill, "The Low (Profile) Road to Space Manufacturing," *Astronautics & Aeronautics,* March 1978, pp. 24-32.

[62] Beverly Z. Henry and Charles H Eldred, "Advanced Technology and Future Earth-Orbit Transportation System s," in *Space Manufacturing* Facilities *II*, Jerry Grey (ed) (New York: Al AA, Sept 1, 1977), pp 43-51

[63] Ibid

tromagnetic (plasma) thrusters or the mass driver discussed above. None of these options has been studied in enough detail to make choices about them at the present time.

Space Construction

As currently designed, the space component of the reference system would be constructed in CEO. However, it may be more cost effective to build the necessary facilities and satellites in LEO and transport them to CEO fully constructed. Such a scenario would reduce the number of personnel needed in CEO as well as lower the total mass that must be transported there.

Introducing one of the LEO scenarios (i. e., laser or mirrors) would open up significant changes in the construction and transportation option for the SPS. Even a change in one major component of the reference system satellite could alter the ways in which the transportation and construction components are configured. For example, if the photovoltaic cells were to be replaced by solar thermal conversion systems, it would be attractive to construct satellites in LEO and transport them to CEO on their own power because they would suffer less from passage through the Van Allen radiation belts.

Of all the alternative options for SPS construction in the production phase, the prospective use of nonterrestrial materials is perhaps the most innovative and, ultimately, capable of the maximum potential return on investment.

The basic premise of the nonterrestrial materials option is that the cost, energy and materials requirements, and environmental impact of lifting the enormous cumulative masses needed to establish and operate a system of many satellite power stations off the Earth can be markedly reduced by utilizing first lunar materials, and eventually materials obtained from asteroids. The fundamental physical principle that supports this premise is that it takes over 20 times as much energy to launch an object to geostationary orbit from the Earth as it does from the Moon, and the situation for asteroidal materials could be even more favorable. The primary drawback is the high "up-front" cost of establishing the necessary mining base on the Moon and the space-based facility needed to construct and assemble the SPS. Hence, it is not likely that nonterrestrial materials would be used in the prototype, demonstration, or even the early phases of SPS production. However, if a commitment is made to produce a large-scale SPS system in CEO, the lunar materials supply option could well be less expensive than the Earth-launched option (including payback of the initial investmerit).[64] It has been argued that by "bootstrapping" the operation (i. e., using nonterrestrial material right from the beginning, not only to build the SPS but to build all the necessary facilities as well), there is no need for any new launch-vehicle development (a major element in the "up-front" investment); i.e., the present space shuttle can provide all the Earth-launch space transportation needed to implement an operational multi-SPS network.[65]

Decisions on the nonterrestrial materials option clearly hinge on the results of current and projected SPS technology studies and experiments. Sufficient research on the two technological factors unique to nonterrestrial materials development—the mass driver (both for lunar materials transfer and for in-space propulsion) and lunar materials mining and processing capability—should be done so that a decision to proceed with either the Earth or nonterrestrial materials options could be properly made. Other study and research requirements for the nonterrestrial materials option include system analyses (including design of an SPS that maximizes the use of lunar materials), more intensive searches for appropriate Earth-approaching asteroids, and establishing capabilities for the host of space operational functions needed for other space programs.

As is clear from the preceding discussion, it is difficult to establish a priori alternatives to construction, assembly, and transportation,

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[64] David L Akin, "Optimization of Space Manufacturing Systerns, " in *Space Manufacturing ///*, Jerry Grey and Christine Krop (eds) (New York. AIAA, November 1979)

[65] O'Neill, op cit

since each of the SPS alternative options would call for a different approach. General guidelines can be identified, minimizing transportation and construction costs during the evaluation, development, prototype, and demonstration phases by: 1) utilizing a phased, step-by-step approach (e. g., ground-based experiments, only then followed by dedicated space experiments); 2) maximizing use of the essentially developed space shuttle; 3) maximizing the common utilization of technology and development efforts by other programs having related requirements (e.g., large communications antennas and other large space structures, spacecraft power generation, control and transmission, etc.); and 4) developing new transportation vehicles and construction hardware only when economically necessary.

SPS COSTS

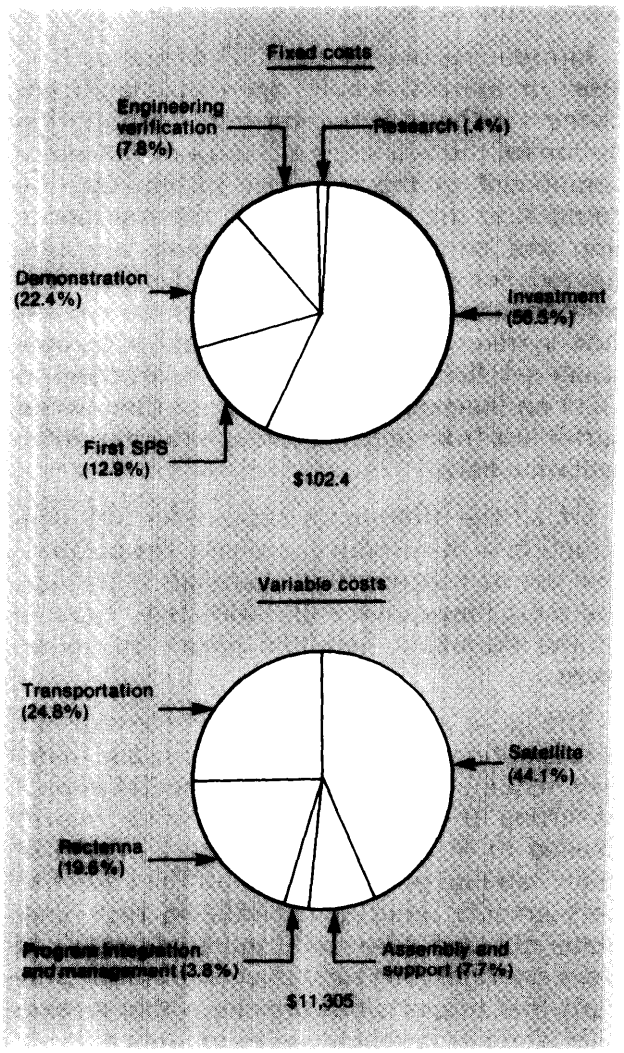
Although knowledge of the overall costs of an SPS program will be essential to making a decision about developing the SPS, current cost estimates are inadequate. Today's projections are based on extrapolations from current technology and in most cases assume major advances. Thus, the technical uncertainties of the concept are too great to provide a firm basis for economic analyses. Here, as in most other areas, it is only possible to develop the foundation for future analysis that would seek to reduce the current uncertainties.

Reference System Costs

The most detailed cost estimates have been made by NASA[66] for the reference system (fig. 23). According to these estimates, which are based on detailed hardware specifications and associated transportation and industrial infrastructure, achieving the first complete reference system satellite will require an investment of $102.4 billion over a 20-year period. Figure 24 illustrates one estimate[67] of how the costs could be allocated over time. Each additional copy of the satellite and associated terrestrial facilities would cost $11.3 billion. Expenses are divided into the following phases:

- *Research* — $370 million. This phase of SPS development (table 10) is by far the smallest, constituting less than 0.4 percent of the total SPS program. About half of these

Figure 23.—Reference System Costs (dollars in billions)[a]



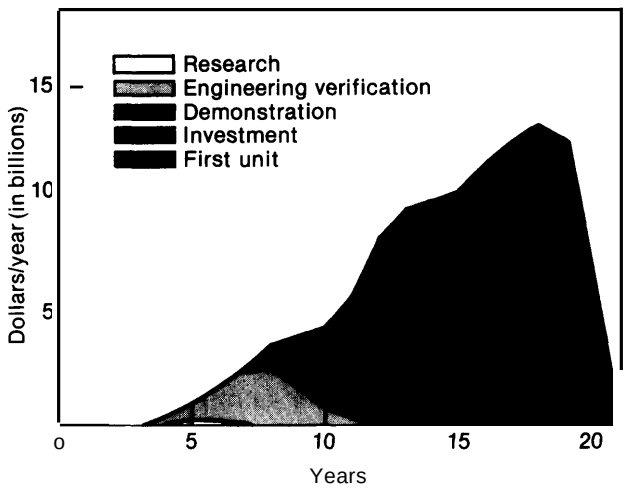
[a]NASA estimates—1977 dollars.

SOURCE: National Aeronautics and Space Administration

[66]Piland, op. cit.

[67]Woodcock, "Solar Power Satellite System Definition Study," op. cit.

Figure 24.— How Cost Could Be Allocated



SOURCE: National Aeronautics and Space Administration.

Table 10.—Research—$37O Million

	Millions of dollars	Percent of total
Power generation	$ 79	21
Power transmission	40	11
Structures and control	22	6
Space construction	25	7
Space transportation	20	5
System studies	19	5
Research flight test	165	45
	$370	

SOURCE: National Aeronautics and Space Administration.

Table 11 .—Engineering—$8 Billion

	Millions of dollars	Percent of total
SPS	$ 370	5
Test article hardware	210	3
LEO base (8 man)	2,400	30
Manned orbital transfer vehicle	1,200	15
Shuttle flights	870	11
Shuttle booster	2,900	36
Management and integration	61	1
Total	$8,000	

NOTE: Percentages do not total 100% due to rounding errors.
SOURCE: National Aeronautics and Space Administration.

Table 12.—Demonstration—$23 Billion

	Millions of dollars	Percent of total
Demonstrator:		
DDT&E	$2,700	12
Hardware	2,500	11
Pilot production facilities	400	2
Shuttle DDT&E and fleet	3,000	13
Construction:		
DDT&E	3,100	13
Hardware	3,000	13
Space operations (4 years operations, construct bases, and demonstrations)	2,800	12
Personnel orbital transfer vehicle (DDT&E and hardware)	1,700	7
Electric orbital transfer vehicle (DDT&E)	1,800	8
Demonstration rectenna	1,800	8
Management and integration	200	1
Total	$23,000	

SOURCE: National Aeronautics and Space Administration.

costs are chargeable to the development of the transportation system.

- **Engineering–$8 billion. This part of the program (table 11) contributes the complex engineering knowledge necessary for creating a useful space structure. The work includes developing an engineering test article in LEO, capable of generating 1 MW of power. It is the direct precursor to the demonstrator and provides the testing ground for constructing and using collector and transmitting subarrays, a rotary joint and satellite attitude control.**
- *Demonstration –$23 billion.* **This phase of the reference program (table 12) culminates in a 300-MW satellite and the associated rectenna and ground facilities to collect and disperse electrical power to the grid. The demonstrator requires a second generation shuttle and orbital transfer vehicle to provide the transportation capability to GEO.**
- *Investment—$57.9 billion.* **By far the largest percentage (57 percent) of the nonrecurring costs of the reference system are devoted to this phase (table 13). In addition to providing for the transportation and construction capabilities for the space component, it also includes the costs ($7.8 bill ion) for developing the terrestrial factories needed to produce satellite components.**

Table 13.—SPS Investment—$57.9 Billion

	Millions of dollars	Percent of total
Heavy lift launch vehicle	$16,600	29
Development	$10,500	18%
Fleet (6 boosters, 7 orbiters)	$ 6,100	11 %
Electric orbital transfer Vehicle (21 x 284)	6,000	
Construction bases	17,200	30
Development	$ 4,300	8 %
Hardware and launch	$12,900	22%.
SPS development	2,200	4
Ground-based factories (klystrons, solar cells, etc.)	7,800	13
Launch and recovery sites	7,300	13
Program management and integration	800	1
Total	$57,900	

SOURCE: National Aeronautics and Space Administration.

Though these are the best estimates currently available, they suffer from an unavoidable lack of specific engineering details, as well as from insufficient manufacturing experience for most of the system components. Moreover, in some areas, (e. g., klystrons, slip ring, phase control) current technology is inadequate to define solutions to engineering problems. Thus, the estimates could eventually turn out to be high or low. The DOE SPS Cost Review[68] examined five different elements of the SPS reference design and concluded that the projected costs are "based on optimistic assessments of future technological and manufacturing capabilities. "

- **Rectenna support construction. Projected costs were found to be low by a factor of 3 to 5. Automated production might reduce costs to a level more in keeping with the reference system estimates, but significant advances over today's methods would be needed.**
- **Graphite fiber-reinforced thermoplastic. Currently used for golf clubs, fishing rods, and for any other use where low weight and high stiffness are required, this is the recommended material for the satellite truss work. The proposed structures are insufficiently defined to specify the costs. Estimates of future costs for the materials alone vary by a factor of 30 ($40 to $1 ,250/kg).**
- **Photovoltaic cells. GaAs cell cost estimates are extremely optimistic given the current state of technology. Breakthroughs will be needed to reach the design goals for mass, efficiency, and costs. Silicon cell cost estimates are less optimistic but will still require significant simultaneous reductions in mass and cost and an increase in efficiency to achieve the SPS goal (2 g/W, $0.17/Wp, and 17-percent efficiency).**
- **Slip ring.** It **is not well enough defined to appraise the slip ring components or their operational capability.**
- *Satellite electrical systems.* **The degree of detail is insufficient to judge the credibility of the cost estimates of the subsystem.**

Thus, the $102.4 billion estimate of "front end" costs and the $11.3 billion estimates for each satellite may be an optimistic estimate of SPS **costs.**

On the other hand, if unexpected breakthroughs were to occur in space transportation, rectenna or satellite technology, the costs of the reference system could be lower than now estimated. Since NASA estimates already assume some technological breakthroughs (e.g., in solar cell production, space construction, rectenna construction), they are more likely to be low than high. In either case, the estimates reflect a troublesome feature of the reference system —the high costs that are necessary to demonstrate the feasibility of the SPS (about $31 billion). A further $71 billion would be needed to build and use a single reference system satellite (investment of $57.9 billion and a first satellite costing $13.1 billion). Because the initial costs have a direct bearing on financing the project, they are more fully discussed in chapter 9.

A number of opportunities exist for reducing SPS development expenses. Some involve pursuing alternative concepts; others, revising the reference system. Because the reference system is by no means an optimal design, improvements could lead to significant cost reductions. Common to all potential systems

[68] **J. H.** Crowley **and E J. Ziegler, "Satellite Power** Systems (SPS) **Cost Review," DOE/TIC-11190,** May **1980**

would be the division of SPS development into the phases outlined above: research, engineering verification, demonstration, and investment, with increasing commitment of resources in each successive phase. For microwave and laser systems, space transportation and construction would constitute a high percentage of the system costs in all phases. It is in these areas that there would be a high potential for reducing overall costs.

The precise costs of an SPS program would also depend strongly on the nature and scope of national and global interest in space. If commercial ventures in space grow at a strong enough rate (e. g., for telecommunications satellites, space manufacturing, etc.), the current shuttle and its related technology would be inadequate, and pressures would be strong for developing expanded space capabilities. The explosive growth of the domestic airline industry since the 1930's has been suggested as the appropriate model to use to investigate this eventuality. [69]

Much of the technology and experience needed for space construction (manned LEO and GEO bases, large-scale antennas, studies of space productivity, etc.) and space transportation (manned and unmanned orbital-transfer vehicles, shuttle boosters, HLLVS, etc.) of SPS would be developed for other programs as well. Of these, the SPS program should bear only its share. By charging only those costs that are unique to SPS to the SPS program, its front end costs would be reduced by a significant amount. Seen in this light, the massive space capability needed for mounting an SPS program would be less of an anomaly (given the future evolution of space technology), '" and SPS would need to shoulder fewer of the development costs for this capability.

There is also the possibility that a percentage of the investment phase could be shouldered by private investment, thereby reducing the burden to taxpayers. This would be all the more likely to happen in a milieu in which private investment in space is strong for other reasons. Under these combined circumstances, the total risk to the U.S. taxpayer would be substantially reduced.

One interesting option for reducing transportation costs of a CEO SPS would be to assemble the satellite in LEO and send it to CEO under its own power. This might be particularly applicable to the demonstration phase of the reference program, since it would avoid the need for premature investment in an expensive manned geosynchronous construction/assembly facility.

Whatever their potential savings, all of these possibilities could only be evaluated after the proper scale of a demonstration satellite had been determined. This decision, in turn, would depend on considerable terrestrial and space-based testing, some of which will take place in other space programs (see ch. 5).

Because the HLLV would be used later on in the production phase of the reference SPS absorbs the bulk of transportation costs, it is of considerable interest to find less expensive ways of transporting mass to space. Some of the alternative high-capacity transportation vehicles have been discussed earlier in this chapter. The heavy lift launch vehicles achieve their cost reductions by economies of scale. It has been suggested that smaller vehicles, perhaps only slightly larger than the current space shuttle, could be used instead of the much larger HLLV.[71] The smaller vehicles would use higher launch frequencies to achieve the same or better benefits. According to this proposal, the minimum-cost individual payload necessary to launch as many as five reference SPS satellites to orbit is about 50 tonnes (compared to the Shuttle's 30 tonnes). The prospects for employing routine airline-like launch practices opens a whole new approach to the logistics of major space manufacturing enterprises as well as providing potential cost reductions for SPS.

[69] G. R. Woodcock, "Solar Power Satellites and the Evolution of Space Technology," *AIAA Annual Meeting,* May 1980.

[70] 1 bid.

"R. H Miller and D. L. Akin, "Logistics Costs of Solar Power Satellites," *Space Solar Power Review,* VOI 1, pp. 191-208,1980.

ALTERNATIVE SYSTEMS

Systems other than the reference system might be more or less costly, depending on factors such as the achievable efficiency, the mass in orbit, and the state of development of the alternative technologies that make up these systems. At present, these alternatives are much less defined and their costs accordingly even more uncertain than the reference system costs. The following discussion summarizes available cost data and the greatest cost uncertainties of the alternative systems.

The Solid-State System

- *The unit cost of the solid-state devices is unknown.* **However, the semiconductor industry has considerable experience in producing large numbers of reliable solid-state components at low cost, and the learning curve for such production is well-known. In principle, it should be possible to make a realistic prediction of costs when the appropriate device or devices are well characterized.**
- **Solid-state efficiencies. Present efficiencies are much lower than for the klystron. Current research is aimed at increasing their operating efficiency (to reach at least 85 percent).**
- **Mass in space. Current estimates of the mass per kilowatt of delivered power[72] suggest that the mass in space would be higher than that of the reference system making the transportation costs higher as well.**

Since many components of the solid-state system are shared with the reference system (e.g., the graphite fiber reinforced thermoplastic support structures, the photovoltaic arrays, the rectenna design, etc.), it would be possible to generate realistic relative costs if the above uncertainties are reduced.

[7]*G. Hanley, "Satellite Power Systems (SPS) Concept Definition Study," vol. 1, Rockwell International SSD-8O-O1O8-I, October 1980.

The Laser System

The largest unknowns for the laser system are the efficiency, specific mass and the cost of the transmitting lasers themselves. This is because the technology of high-power CW lasers is in a relatively primitive state (current CW lasers achieve outputs of 20 kw or greater, operated in a so-called loop move, i.e., the lasant is recirculated). Space lasers for SPS would have to operate at much higher outputs (megawatts) and at higher efficiencies (i.e., 50 v. 20 percent) for current lasers. Concepts such as the solar pumped laser and the free electron laser are completely untried in a form that would be appropriate to SPS. Therefore their costs are even more difficult to ascertain. In general it can be said that the cost of the system would be tied to the overall efficiency of the system and the amount of mass in space, but considerable study and some development would be needed to make suitably reliable projections.

- *Transportation.* **The laser systems that have been explored project higher mass in orbit than for the reference system, which may drive the cost of the laser system up. However, if a substantial portion of this mass is in LEO rather than in CEO, the overall transportation costs might not exceed the transportation costs of the reference system and could turn out to be lower.**
- *Demonstration.* **Because the laser system is intrinsically smaller it should be possible to mount a demonstration project for considerably less than for the reference system.**
- *Terrestrial component.* **The ground stations would have to have a certain amount of redundancy in order to accommodate laser transmission when cloudy weather obscures one or more receivers. The precise amount of redundancy would depend on the particular location and would include extra transmission lines as well as extra ground receivers.**

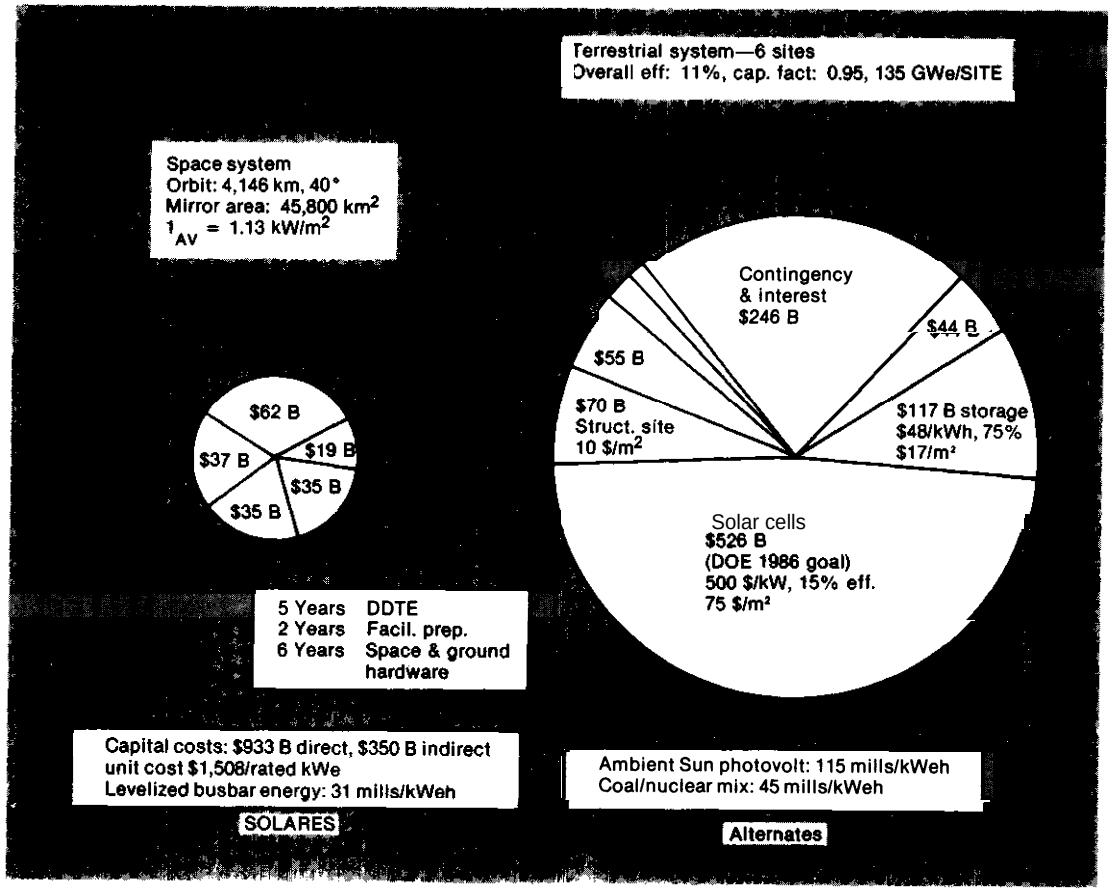
The Mirror System

Figure 25 summarizes mirror system cost estimates for the SOLARES baseline case[73] based on the DOE 1986 cost goals for photovoltaic cells. These "up front" cost estimates, which include contingency and interest on the borrowed money, lead to an estimated levelized busbar energy cost of 31 mills/kWehr compared to 1990 estimated costs of nuclear/coal mix of 45 mills/kWehr. In comparison, a strictly terrestrial system of photovoltaics producing the same overall output computed on identical assumptions would cost 115 mills/kWehr.

Since electricity production from the mirror system would depend heavily on the use of terrestrial solar photovoltaic or solar thermal systems, cost variations of either conversion system would have a strong effect on total system costs. Figure 26 summarizes the effect of varying several system parameters on the cost of electricity delivered to the busbar in the SOLARES system. The three most sensitive parameters are solar cell efficiency, solar cell cost per peak kilowatt and total space cost

[73] Billman, et al., "Solar Energy Economics Revisited: The Promise and Challenge of orbiting Reflector for World Energy Supply," op. cit.

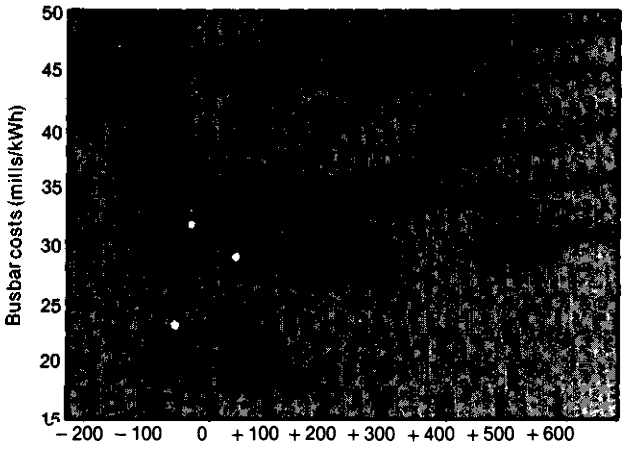
Figure 25.—Elements and Costs, in 1977 Dollars, for the Baseline (photovoltaic conversion, 4,146 km, inclined orbit) SOLARES System



NOTE: Total costs are proportional to the areas of the circles. Interest and contingency constitute 33 percent of the total SOLARES costs.

SOURCE: K. W. Billman, W. P. Gilbreath, and S. W. Bowen, "Space Reflector Technology and Its System Implications" AIAA paper 79-0545, AIAA 15th Annual Meeting and Technical Display, 1979.

Figure 26.—Sensitivity of the SOLARES Mirror System to Variations in System Parameters



SOURCE: Ken Billman, W. P. Gilbreath, and S. W. Bower, "Space Reflector Technology and Its System Implications" AIAA paper 79-0545 AIAA 15th Annual Meeting and Technical Display, 1979,

(transport, construction, mirrors in space). A cost over-run of about 2 times (to $1,000/pk kWe) could be tolerated before a busbar cost of 45 milis/kWehr would be reached. Similarly, a space system total cost over-run of a factor of 4.25 could be tolerated. Finally, because of the projected high energy production per unit of mirror mass in space, a twenty-three-fold increase in space transport cost (or $1 ,380/kg) would still result in a production cost of 45 mills/kWehr. For comparison, the charge for transporting mass to space by means of the space shuttle is estimated to be between $84 and $154 (1975 dollars). "

[74] National Aeronautics and Space Administration, "Space Transportation Reimbursement Guide," JSC-11-802, May 1980

Chapter 6

SPS IN CONTEXT

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Chapter 6

SPS IN CONTEXT

ENERGY

Introduction

Because of its long development leadtime, solar power satellites (SPS) will not be available to any extent before the early part of the next century and will therefore do very little to relieve our dependence on imported oil. SPS's primary use would be to replace old powerplants and meet any new demand for electricity. Consequently, the potential value of the SPS must be determined in competition with other future electricity sources and in the context of U.S. and global electricity demand. This chapter examines this topic in detail by looking at the future demand for energy, and electric power in particular, in the United States, and the various supply options that could compete with the SPS. Global energy demand and the SPS in a worldwide context is examined in chapter 7.

Overview

The U.S. energy future can be divided into three time periods according to the supply options that will be available. These periods are roughly the next 10 years (near term), from 1990 to approximately 2020 (the midterm or transition period), and beyond 2020 (the long term). Although these boundaries are not hard and fast, they roughly define periods in which particular energy supply forms will dominate.

Near Term

In the near term, there will be no significant change from our current reliance on oil, natural gas, and coal. Currently about 92 percent of our Nation's energy supply comes from these fuels. About one-quarter of the total is imported (almost all in the form of oil). Because of finite supplies, overall consumption of these liquid and gaseous fossil fuels must eventually be reduced. However, the most important goal over the next decade is the reduction of oil imports in order to avoid the severe economic problems that would result from potential supply interruptions and to improve the U.S. trade deficit. To do this, concentration must be placed on lowering demand growth by increasing the efficiency of energy use, and switching to the use of more abundant domestic fuels. Of the two, improving energy efficiency will be the major new source of energy because of the much longer leadtime needed to bring on new fuel supplies such as coal and nuclear. Domestic oil and natural gas can be developed more quickly, but it is not likely that they will contribute to reducing oil imports since both will probably decline in production for the decade. A recent OTA technical memorandum' estimates a 25-to 45-percent drop in U.S. oil production by 1990. Thte use of nuclear energy will increase, but at a slower rate than in the 1970's. Finally, solar and biomass energy production will grow rapidly during the 1980's but the absolute magnitude will be low compared to oil imports. Therefore, although an increase in the amount of coal, solar, biomass, and possibly nuclear energy sources is expected, they will probably not be able to contribute enough by themselves to relieve the pressures caused by U.S. dependence on imports.

Transition Period: Midterm

In the period from 1990 to 2020, substantial supply shifts will occur. Although the period will begin with heavy dependence on coal, oil, and natural gas, it will end with a much greater reliance on renewable and inexhaustible energy resources. U.S. dependence on imported oil will almost surely come to an end if for no other reason than that the availability of oil on the world market will have dropped substantially. World oil production may drop as much as 20 percent by 2000 and fall off sharply thereafter. The dominant fuels during this

'Office of Technology Assessment, U.S. Congress, "World Petroleum Availability, 1980-2000," technical memorandum, October 1980, OTA-T M-E-5

period are likely to be coal (for synthetic fuels, direct combustion, and electricity generation), natural gas, and possibly conventional nuclear. During this period, strong growth of renewable and inexhaustible sources such as solar and biomass can be expected. Uranium is a small enough resource that conventional nuclear must be considered a transition energy source. However, the supply of coal appears to be substantial enough to play a major role well into the 22d century. Whether these fuels contribute significantly beyond the midterm depends on the successful resolution of their short- and long-term environmental and safety questions.

It is also during this period that SPS and other long-term candidates such as breeder reactors and perhaps fusion may begin to reach commercial status. The transition period will be the time when a number of long-term technologies will compete with one another for a role in the future on the basis of economics and public acceptance. This competition will also depend heavily on the relative economic efficiency of different ways of using energy, as will be discussed below.

Long Term

In the long term, the United States and the world will be almost totally fueled by inexhaustible energy sources. Although rapid growth of sources such as the SPS during the first decades of the century may be seen, it will not be until the middle of the next century that they could become as commonplace as coal, electric, or even nuclear plants are today.

It is not clear which renewable and inexhaustible sources will dominate. It may be that small-scale, onsite solar systems coupled with an extremely energy-efficient economy will be the ultimate future. It may also be that a mix of technologies such as onsite solar, biomass, fusion and/or SPS will be used. However, the choice will be made in the transition period and will be based primarily on the projected costs of competing supply systems and demand technologies.

Determinants of Demand

SPS would fit most easily into a high electric growth future. Such a future is contrary to recent low growth trends. In fact, many conservation initiatives have been directed at reducing the use of electricity because of the high energy losses at powerplants. Nevertheless, changes in relative fuel prices and gains in the efficiency of electric generation and use could dramatically change the picture.

The energy technology choices the United States and the world will make in moving through the three periods described above will be primarily dictated, as always, by relative costs. Until recently the dominant factor determining the development of energy technologies has been the type of resource and its availability. The abundance of oil and natural gas, and the ease with which it could be transported and burned, dictated the development of most of the energy-using equipment currently in existence. Some of this equipment could have been powered more efficiently by electricity, but this advantage was often dwarfed by the cost advantage these fuels had over electricity. However, many applications such as electric motors can be made significantly more efficient, reducing the fixed cost penalty.

In the past few years the relative prices of these energy forms have changed because of the rapid increase in oil and natural gas prices. Current average electricity prices are about twice that of oil and four times that of natural gas. In 1960, the ratio of electricity to oil and natural gas prices was 7 to 1. Even though the costs of new powerplants are rising rapidly, those of electricity will probably rise more slowly than oil and natural gas, primarily because of the relative abundance of coal and uranium. It is even possible that synthetic fuels from coal and biomass may be more expensive than electricity from coal, particularly as newer, more efficient coal combustion technologies are introduced.

The total cost to the energy user also includes the cost of the energy consuming equip-

ment. Electric powered equipment is often cheaper than gas or oil fired counter parts. This advantage will become increasingly important as the prices of oil and gas narrow the gap with the price of electricity.

The implication of these effects is that electricity may become the cheapest energy form, when both supply and demand are considered, for many applications that could use a multiplicity of energy forms. The reason is that the price differential between electricity and the other energy forms (liquid and gaseous fuels, direct solar, etc.) will likely be small enough that it could be overcome by cheaper and more efficient electric end-use technologies. Some of these, such as heat pumps for space and water heating, are already in use, while others, such as inexpensive electrochemical processes and long-life storage batteries, require further development, [f such development is successful and electricity does become the cheapest energy form for most uses, then electric demand growth could become quite rapid even though total energy demand may grow very slowly or not at all.

If this holds, solar power satellites will have an easier market to penetrate than if the electric utilities continue their recent slow growth. Thus, the fate of SPS rests as much on the ability to create energy efficient electrical end-use technologies as it does on the relative economics of other electric generatin$_g$ technologies. One caveat must be added, however. If demand technologies for fuels keep pace with the efficiency improvements of electric demand technologies, such dramatic switchin$_g$ may not occur.

Electric Demand Technologies

To see if such a future is technically possible a closer look is taken at current and potential uses of electricity. Because of electricity's unique properties it has been used for specialized tasks such as lighting because of the high temperature needed to excite the visible spectrum. Here, electrical energy is converted to visible electromagnetic radiation as well as to heat. Nearly 60 percent of all electricity is used to perform mechanical work through the use of motors. Electricity is also used for industrial electrochemical processes such as in aluminum and steel production, for specialized induction-heating applications and for microwave and infrared furnaces. A small but crucial amount is used to power the Nation's electronic systems. Finally, electricity is used in the crudest form possible, namely for direct conversion to heat.

Although these uses are more varied than for the other major fuels, they account for less than 12 percent of the total end-use energy demand in this country. The other 88 plus percent is direct combustion to provide direct heat, steam and mechanical drive. As indicated, for electricity to penetrate this latter market it will be necessary to make technical advances to give electricity a cost advantage at the end-use that can compensate for its higher cost at the production point.

To do this requires making use of the special character of electricity as an energy form. Electricity is a high-quality fuel (thermodynamically work that is heat at infinite temperature). Therefore, it can be used for any kind of mechanical work or it can be converted to heat at any temperature. The best known example of the latter property is the heat pump for space heating. This is now being applied to water heating and certain drying applications with a substantial reduction in energy use over electric resistance heating and apparent cost advantages over solar.

In the industrial area, there is considerable potential for increased use of electricity. For instance, in steel making it can be used for the plasma-arc process and direct-electrolytic reduction of iron. Although these processes have been arourd for several years, technical development is still needed. In a nearer term application, the direct reheating of steel by high, pulsed electric currents could result in a significant reduction in fuel use compared to direct-fired processes, and also reduce material loss by eliminating oxide formation that occurs with direct firing. In other areas advances have been seen recently in the efficiency of electric motors that are now competitive with steam drives in many applications such as

mechanical presses for metal forging. A more speculative but very interesting area is the use of laser or microwave radiation to drive industrial chemical reactions, instead of heat.

In ground transportation the principal problem is the development of long-lived, lightweight, reliable storage batteries. Electric drive using motors with precise solid-state speed control can be made very efficient, as has been demonstrated on many of the world's railroads. Advances have recently been made in battery technology but the general feeling is that "ideal" batteries are at least a decade away.

The industrial sector is presently only 13-percent electrified, while the transportation sector only uses a negligible amount of electricity. Thus, these are the markets that electricity must penetrate to become the dominant energy form. However, some new technologies have the potential to reduce industrial demands without creating new markets for electricity. In the chemical industry, for instance, biogenetic methods of feedstock synthesis could replace thermochemical methods, reducing fuel usage without substituting electricity. About half the present industrial electric demand could be offset by cogeneration, a technology that is not strictly a demand technology but which could nevertheless reduce electricity needed from the grid. ın the transportation sector, battery research as a key to electric vehicles must compete with the efficiency improvements possible with high-mileage advanced vehicles using synthetic or biomass-derived liquid fuels. The buildings sector is already the most heavily electrified and some electric technologies, such as common appliances, are nearing saturation.

The achievement of highly efficient, electric demand technologies would change not only the balance of fuels now used but also the sectoral usage patterns of electricity, with dramatic growth in the industrial and transportation sectors, and less in the buildings sector which has shown the greatest postwar growth in electric demand.

Conclusion

It is likely that as technologies using electricity are improved or new efficient uses are found, improvements will be made in using other future nonelectric energy sources such as biomass and direct solar. While all of these developments are many years away, it is this environment in which the SPS will compete. The success or failure of these new electric technologies will have a great deal to do with determining whether or not a market exists for SPS as well as the other large-scale, electric-generating technologies.

Energy Supply Comparisons

Introduction

Comparisons with other energy technologies, both current and future, are a critical part of assessing a proposed new energy technology. A host of criteria, only some of which are readily quantifiable, is available for comparison purposes. Costs, environmental impacts, scale, complexity, versatility, safety, and health risks are some of the more important factors of choice that ultimately determine the relative desirability of a given energy technology. For technologies currently in place these factors are generally well known. For future technologies they are more often only poorly known. Nevertheless, choices among future energy technologies must be made, either in the R&D phase, or, later, in the marketplace.

Criteria for Choice

Whenever decisions to proceed with or halt the development of a given technology are made, it is important to lay out the framework of choice, to develop a set of criteria by which one may judge the relative benefits and drawbacks of different technologies. In addition to providing a basis for choice, such a list can also help to identify the essential distinctions between technologies and highlight areas that will need further R&D.

Table 14 lists 32 criteria developed in an OTA workshop that are often used in compar-

Table 14.—Criteria for Choice

Plant *description*
1. **Scale** of power output (range in megawatts)
2. Power output in relation to load profile (baseload, intermediate, peaking)
3. Versatility (other output besides electricity)
4. Complexity (high, medium, low) and maintenance requirements (controllability)
5. Reliability (percent of time available to the grid)
6. Nominal capacity factor (percent time operating)
7. Material requirements
8. Labor requirements
9. Land requirements
10. Construction leadtime (years)
11. Lifetime (what are key determinants)

costs
12. Opportunity costs of RD&D (dollars and people)
13. Net energy ratio
14. Operating costs (cents/kWh)
15. Capital costs ($/kW)
16. T&D costs (cents/kWh)
17. "Decommissioning" costs

Impacts
18. Institutional (organization and ownership) impacts
19. Safety and health risks (magnitude and distribution)
20. Environmental risks (magnitude and distribution)
21. National security risks of normal or unintended use
22. Military vulnerability

Deployment consideration
23. Time period to commercialization
24. Geographic location; location of plant with respect to load centers
25. Compatibility with other technologies and utility grid

Other
26. Probability for success (high, low, medium)
27. Initial demonstration requirements (large or small)
28. Resource constraints (domestic, international)
29. Risks/impacts of RD&D failure (chance it may become prematurely obsolete)
30. Relative uncertainties to be resolved by RD&D (e.g., sensitivity of efficiency to design parameters)
31. Is it a viable example for rest of world?
32. Nature of R&D process (public, private, classified)

SOURCE: Office of Technology Assessment

ing electrical generating technologies. Most fit into four broad categories: plant description, costs, impacts, and deployment considerations. These criteria establish a context for evaluating the SPS in relation to other future energy technologies.

Five Future Energy Technologies

In the timeframe that the SPS would be most likely to play a role in the U.S. energy future, the other energy sources that are likely to contribute will be predominantly the renewable and inexhaustible ones. OTA has chosen to study the SPS in comparison to terrestrial solar thermal technologies, terrestrial solar photovoltaics, advanced fission (the breeder), and fusion. If the health and safety problems of coal are satisfactorily solved, it could also be a major electric supply technology in the period that SPS could become available. In addition, there may also be a component of conventional nuclear power still operating in the second and third decades of the 21st century (the timeframe after 2010 that is most likely for SPS deployment).

The data that OTA generated for these technologies are supplemented by the electrical supply comparisons which Argonne National Laboratory made for the Department of Energy (DOE/SPS) assessment program.[3] DOE chose to study conventional and advanced coal technologies, light water reactors, liquid metal fast breeder reactor (LMFBR) breeders fusion, the reference system SPS, and terrestrial photovoltaics operating in a peaking mode. Their data will be discussed along with the results that OTA obtained. Coal and conventional nuclear power will be presented first to provide a reference for the future energy technologies in the discussions that follow.

THE COAL BENCHMARK

The coal resources of this country are almost incomprehensibly large. Even if production were to triple, in that case coal would serve about half the present U.S. energy needs, known recoverable reserves would not be exhausted until late in the next century. Estimated additional reserves could take this production well into the 22d century. Thus, for all practical purposes, the supply of coal is inexhaustible.

Unlike any other long-term energy source, coal can be exploited with known, proven technology at costs that are competitive now. Advanced coal technologies such as combined-cycle gasifiers and magnetohydrodynamics, are not vital to coal's future but could

[2] M E Samsa, "SPS and Alternative Technologies Cost and Performance Evaluations," *The Final Proceedings of the Solar Power Satellite Program Review, CON F-800491* (DOE), 1980.
[3] *Program Assessment Report* Statement of *Findings*, SPS Concept and valuation Program, DO F/E R-0085, 1980

improve the efficiency and economics of coal-fired electric power. Thus, of all the options for large-scale, long-term production of electricity, coal is the least uncertain technologically and economically and it is appropriate to view it as a benchmark for evaluating the others, including SPS.

Technological and economic criteria are not the only alternatives to consider. Any energy source must have generally acceptable health and environmental impacts. Coal evokes depressing memories of scarred landscapes, suffering miners and smokey skies. Today, this reputation is no longer deserved. Modern coal mining and combustion techniques, when properly applied, have reduced virtually all these objectionable impacts to the point where damage is clearly a small fraction of what it once was.

The actual future of coal, however, is much less certain than its potential. Issues arising when expanded mining and use are considered can be divided into three categories: interruptions, control costs, and risks. These will be discussed in some detail because if coal does not realize its potential, the reasons will probably be found here.

Interruptions are intermittent events that prevent scheduled plans from being fulfilled. Strikes by miners and transportation breakdowns are obvious examples. Opposition by intervenors that prevent facilities from being built might be included here. These factors can't be completely eliminated, but proper planning can reduce disruption. The major long-term effect is to deter potential users from turning to coal if they have other options and are concerned about the reliability of the coal supply.

The cost of controlling coal's negative impacts is high. Reclaiming surface mined lands and reducing the emissions of combustion have received the most attention. For instance, the Clean Air Act Amendments of 1977 have required the use of the "best available control technology" for limiting emissions of sulfur oxides. Utilities have been concerned not only because of the expense of the flue-gas scrubbers, but also because the equipment in use has generally shown disappointing reliability. However, current systems appear to be considerably better than early designs, so utilities can, if they are careful, be confident that their equipment will function reliably and effectively.

The regulatory approach has been to ensure that the impacts are controlled to the point where it is clear that known damages are sharply reduced. As mentioned above, it appears that this goal has been achieved. As more information is gained, it is possible that control can be loosened without increasing the risk. For instance, new data on the damage caused by sulfur oxides and sulfates, and better data on the long range transport and chemical transformation of these and other pollutants might allow more selectivity in emissions control. Thus, the costs of controlling impacts may be reduced rather than increased in the future. Such a reduction would improve coal's competitiveness with nuclear power or SPS, unless some of the unproven risks are confirmed.

There are three major *risks* to long-term coal combustion that could limit expansion or make it much more expensive: public health effects, acid rain, and carbon dioxide ($C0_2$). Coal combustion pollutants have been linked by statistical analyses to tens of thousands of deaths per year. These studies are highly controversial and have been neither proven nor disproven. If they are generally accepted, considerable reduction of sulfur and nitrogen oxides would probably be necessary. This reduction would probably call for greater use of coal cleaning before combustion, combustion modifications and higher efficiency flue-gas desulfurization systems. Such changes would be expensive but unavoidable if the public demands cleaner air because of concerns over health risks.

The documentation for damage by acid rain is better than for public health effects, but is still not conclusive. Acid rain is evidently caused by the same pollutants suspected in the public health issue, but the scientific under-

standing of pollutant transport and chemical conversion is poor. Furthermore, while acidification of certain lakes and streams is strongly suspected, extensive damage to terrestrial ecosystems is only surmised. If this damage is proved and found too costly, the remedy would be the same as for public health effects. However, it must be emphasized that proof of damage is insufficient. The pollutants must be traced back to their source in order to know where to implement controls. Otherwise ineffectual or overly expensive control strategies may be implemented.

The final risk, excessive CO_2 released to the atmosphere, is by far the most intractable. The adverse impacts that have been suggested dwarf those of any other human activities with the possible exception of nuclear war, The $C0_2$ produced by burning fossil fuels and clearing forests accumulates in the atmosphere. Some of the CO_2 that is produced is absorbed in the oceans, but the dynamics of the CO_2 balance are not well-understood. The concentration in the atmosphere is increasing by 5 percent per year since 1958. $C0_2$ is transparent to most of the incoming sunlight that warms the Earth. Normally much of this is radiated back to space in the form of infrared radiation, but CO, tends to absorb and block this longer wavelength radiation. This mechanism, the greenhouse effect, is an essential ingredient in maintaining the proper temperature balance on the Earth. However, if sufficient quantities of CO_2 are added to the atmosphere, additional heat will be trapped to warm the Earth significantly.

A number of studies of atmospheric CO_2 levels predict that concentration will rise to two to eight times today's level in the 21st and 22d centuries. While there is continuing discussion about the effects of this buildup, the majority of the scientific community agrees that the probability of global warming and other climate changes is sufficiently high to warrant exceptional attention.[4] Changing climate patterns, even if they turned out to be ultimately beneficial, would cause enormous disruption, especially with agriculture. At least 10 years will be required before enough is known to make intelligent decisions about the significance of the effects of increased CO_2 in the atmosphere. The contribution of fossil fuel combustion to the CO_2 buildup, the results of this buildup on the heat balance and climate, and the effects of climate changes must all be studied extensively. At some point, however, it may be necessary to limit coal combustion in order to limit CO_2 emissions since it is highly unlikely that any practical means of removing CO_2 from the flue gases will be devised.

In summary, as far as we can tell now, coal is capable of supplying most of the electric power this country is likely to need for many generations. The effects of the release of extra CO, to the atmosphere are sufficiently in doubt that other options must be prepared in case they are required. However, until we know that it constitutes a serious problem the development of other options must be justified on the basis that they will be cheaper or more attractive in some other way than properly control led coal.

CONVENTIONAL NUCLEAR

Conventional nuclear plants totaling 55,000 MW of power are now operational and another 106 reactors totaling 118,000 MW are either on order or under construction.[5] This is a substantial base for the nuclear technology, but it is questionable whether it will be fully realized or expanded because of public opposition, licensing problems, financial uncertainties, and eventually resource limitations.

Public opposition has been especially visible. While public opinion polls still show support for nuclear energy, this support has been weakened for several reasons. Low-level radiation release and other problems with routine operations contribute to public concern. Public support has also eroded because of continued lack of a suitable site and demonstrated means for nuclear waste disposal. Further mishaps such as the accident at Three Mile Island could condemn the technology in the eyes of many who now reluctantly accept it. Finally,

[4] Office of Technology Assessment, U S Congress, *The Direct Use of* Coal, OTA-E-86, 1979

[5] Department of Energy, "U S Central Stations Nuclear Generating Units, " September 1980

the possibility that nuclear energy could contribute to nuclear weapons proliferation disturbs many, though it is debatable whether renunciation of the nuclear option by the United States would materially reduce this risk.

Most of these problems, except proliferation, can be ameliorated by improved technology, procedures, and regulations. But if improvements are not made quickly, public opinion could swing against nuclear power in the United States as it has on occasion in other Western democracies (e.g., Sweden and Austria). Even if opponents remain in a minority, they can find many opportunities to trouble the industry through legal actions, regulatory appeals and ballot initiative. None of these may kill a particular project, but they could discourage utility executives from choosing the uncertainty and frustration associated with nuclear power as long as they have other options such as coal.

Utility decisionmakers also have to consider licensing and financial uncertainties. At present, many design criteria for nuclear plants are so poorly defined that it is virtually impossible to get a new reactor licensed. ' This problem may be resolved over the next few years, but recent trends have not been reassuring. For instance, a review now underway—to determine if fundamental changes in reactor designs are necessary to contain melted fuel cores in case of severe accidents— is expected to last several years.

Some regulatory rulemaking problems stem from a lack of conclusive data. Others appear to reflect the Nuclear Regulatory Commission's lack of a clear picture of what it wants to accomplish and how to do it. Both types of uncertainties have to be resolved before the utilities will consider ordering many more reactors.

Utility companies also face uncertainty concerning both the capital available to build plants and the risk of a long-term shutdown. The cost of a new nuclear plant is now close to $2 billion. Not many utilities can raise that much capital, even when the projected costs of power at the busbar are favorable. Even now, many plants are being built as joint ventures by several companies. A continuation of high interest rates could delay many plans for capital-intensive projects. And after an expensive reactor starts operation, the utility bears an additional economic risk due to the possibility of unplanned shutdowns. The Three Mile Island (TMI) accident and the Browns Ferry f ire led to lengthy shutdowns that forced huge expenditures by the owner utilities, which then had to generate or buy expensive replacement power. The present financial difficulties of the owner of Three Mile island, General Public Utilities, illustrate how critical this concern will be for other utilities.

Availability of fuel will eventually be a serious constraint if conventional reactors are used in the midterm to long-term future, without a shift to advanced nuclear breeders. The Committee on Nuclear and Alternative Energy Systems (CONAES) estimated that enough uranium exists in this country to fuel at least 400,000 MW for the lifetime of the reactors (40 years). ' This would allow the construction of another 227,000 MW of capacity. If ordering of new reactors resumes in 1985 and continues at the rate of 10 reactors per year, the last one would be ordered in 2008. Because of retirements, by 2050 nuclear power would be back to near its present level. Peak energy output under this scenario would be about 5.6 (end use) Quads in 2015. However, discovery rates for uranium ore and imports and exports of uranium could change the total availability in an unpredictable way.

The greatest single long-term uncertainty facing the industry is the future electricity growth rate, just as it is for the SPS. Over the next several decades, moderately high growth rates might require much more nuclear power, but as discussed in this chapter, the growth rate may be more modest. However, low growth need not preclude nuclear, and might

[6]Office of Technology Assessment, U S Congress, *Nuclear Powerplant Standardization,* OTA-E-1 34, April 1981

[7]*Energy in Transition,* Committee on Nuclear and Alternative Energy Systems (CONAES), National Academy of Sciences, Washington, D C , 1979

enhance the attractiveness of nuclear compared to other future central power options, such as SPS, that require large deployments to justify the development cost.

Nuclear energy can have a future if its problems are addressed effectively and decisively. To some extent this is happening. The accident at TM I has revealed weaknesses in reactor plant design and operator training, to which the industry and the NRC are responding with initiatives such as the Institute for Nuclear Power Operations and the Nuclear Safety Analysis Center. As a result of the events in the past 2 years, both regulators and utilities seem more conscious that extreme safety is in everyone's interest.

Whether these measures will ensure safety in the future and enhance the industry's public image without pricing the technology out of reach is still an open question.

FIVE FUTURE TECHNOLOGIES

The following discussion summarizes the salient characteristics of the four central renewable or inexhaustible energy technologies that have been chosen for comparison with the SPS. While each of these alternatives is compatible with centralized electricity production in a utility application, they are not equally applicable for baseload power production. Photovoltaics and solar thermal sources vary over the course of a day and the season in a fashion that makes them well-suited for peaking applications. Fusion, the breeder and SPS would work most efficiently producing constant power 24 hours per day, so they are naturally suited for baseload power production. The applicability of photovoltaics and solar thermal can be broadened to cover intermediate and possibly baseload applications by the addition of storage capability, but over the next 10 to 20 years there may be little cause to do so, for two reasons. The first is that the most cost-effective application of solar thermal and photovoltaic systems is likely to be as fuel savers until all the oil and gas-fired generating facilities have been retired from utility systems. Second, electric storage is far more versatile and cost effective for a utility if it is not restricted for use with a single plant. A recent study by the National Academy of Sciences' concludes that when wind, photovoltaics, or solar thermal is used in a utility system, "it is typically not desirable to have dedicated storage but wiser to provide the backup energy from the grid." Except for a small amount of storage to handle short-term variations of sunlight in solar thermal applications, the conclusion that dedicated storage is not appropriate for terrestrial renewable electric technologies is generally well-accepted.

Currently, electrical generation is fueled largely by oil, natural gas, coal, fissionable material, and stored water. For the time period when the SPS is most likely to find applicability, there may not be as great a diversity of energy supply technologies connected with the utility grid as is now enjoyed; hence terrestrial solar technologies may be used in a different mode than the one that seems most desirable now (i. e., peaking or intermediate). It is also desirable to compare all the future electric technologies on a common basis. For this reason, OTA has prepared cost estimates for solar thermal and photovoltaics operating in a baseload mode. Because photovoltaics also possess the unique property among these future energy systems of being modular on a very small scale, its use in a dispersed mode—both connected to the electric grid and independent of it– will be discussed in a separate section. In the future, it would be also worthwhile to compare SPS to an energy scenario composed of a number of dispersed solar technologies working in complementary fashion.

The following discussion will give the major characteristics, cost sensitivities and uncertainties, factors affecting deployment, and foreseeable impacts of the different renewable and inexhaustible energy sources. First, a short summary of each technology will be given, followed by comparisons. Table 15 presents the relevant characteristics of each of the 5 technologies in matrix form.

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*"Energy Storage for Solar Applications," Committee on Advanced Energy Storage Systems, National Academy of Sciences, 1981

Table 15.—Characteristics of Five Electrical Technologies

Criteria	Fusion	Breeder	SPS	Solar thermal	Photovoltaics
Plant description					
Scale of power output	500-1,500 MW	500-1,500 MW	1-100 GW (lasers smaller)	10 kW to greater than 100 MW	10 kW-100 MW
Power output in relation to load profile	Baseload	Baseload	Base load	Peaking, intermediate, baseload (with storage, but expensive at high-capacity factor)	Peaking, intermediate, baseload (with storage expensive)
Versatility	Also large-scale, high-temperature process heat; synfuels, production of fissile materials	Also large-scale, low-temperature process heat; synfuels; production of fissile materials	Centralized, limited versatility. Some military connection and relevance to space colonies and space manufacturing	Also cogeneration, high-temperature process heat	Cogeneration?
Complexity	High	Medium	High	Low	Lowest
Reliability	Between 0.6 and 0.75	Same as LWR (fuel cycle reliability?)	No good reason to think it's worse than steam technologies. Between 0.6 and 0.9 (laser-exception)	Between 0.6 and 0.9, like other steam plants	Greater than 0.9 (= 1-time for repair)
Nominal capacity factor	0.6 to 0.75	Same as LWR	Between 0.6 and 0.9	Without storage: 0.2 to 0.25. With storage: up to 0.9	Without storage: 0.2 to 0.25. With storage: up to 0.9. Also depends on region
Material requirements	Design specific, can design around; stay away from specialized alloys	None	Can design around, common material, sophisticated processing	Plentiful, domestic materials; need to build manufacturing industry	Plentiful, domestic materials, like nuclear
Labor requirements	Like LWR	Like LWR	Few and skilled for space construction, less skilled for receiver construction	Moderate to large, decentralized larger	Moderate to large, decentralized larger
Land requirements	Same as LWR. Less than 1 acre/MW (including fuel cycle)	Same as LWR	Comparable to other centralized solar systems; 6.5 acres/MW or less	5 to 10 acre/MW	10 acre/MW incremental addition could be zero
Construction leadtime	5 to 12 years?	5 to 12 years (including licensing)	Similar to other centralized technologies, 5 to 12 years	5 years for 1OO-MW plant	Short; minimum 48 hours for 7 kW
Lifetime	Greater than 30 years (first wall material)	Greater than 30 years (replace steam generator;	Greater than 30 years; design like other systems, but limited experience	Greater than 30 years	Greater than 30 years
Costs of RD&D	$20 Billion to $30	$10 billion to $15 billion (?)	$40 billion to $100 billion to achieve first operating satellite	Low $0.5 billion plus $0.5 billion to $1.0 billion	$1 billion to $2 billion
Net energy balance	Unknown	l-year payback	2- to 20-year payback	1- to 2-year payback	2- to 20-year payback
Operating costs	Almost no fuel costs. Same as LWR, but less confidence	1 to 2¢/kWh	0.3 to 1.5¢/kWh; low as percentage of delivered cost	1 to 4 percent of capital costs; $40 to $60/kW/yr	1 percent; $20/kW/yr; less for centralized
Capital costs	$2,000 to $2,500/kW; lower for a 5-GW plant	$1,500 to $2,000/kW	$1,500 to $17,000/kW	$1,500 to $3,000/kW	$2,000 to $3,000/kW (peak) ($1.60 to $2.20/PW) (without storage)
T&D costs	Same as any central system	Same as any central system	Similar or greater than other central systems (reliability). Need to consider outage problem	Centralized—same as other systems; decentralized is negligible	Centralized—same as other systems; decentralized is negligible
Decommissioning costs	Minor	Minor	Push out of orbit. Small at 4-percent discount rate over 30 years	Negligible	Negligible
Impacts					
Institutional impacts (ownership)	Similar to present institutional structure	Similar to present institutional structure	Requires new management organization; international involvement possible	Decentralized— medium to high impacts; centralized— similar to present infrastructure	Decentralized— medium to high impacts; centralized— similar to present infrastructure

Table 15.—Characteristics of Five Electrical Technologies (continued)

Criteria	Fusion	Breeder	SPS	Solar thermal	Photovoltaics
Safety and health risks	Safer than PWR	Fuel cycle? Same as PWR (higher power density, lower pressure)	Microwave bioeffects uncertain; ionizing radiation in GEO	Small	Low; possible safety hazard with decentralization in event of fire
Environmental risks	Small for routine operation	Small for routine operation	Upper atmosphere effects uncertain	Small	Low possible manufacturing risk of PV
National security implications	Designs other than hybrid less significant than breeder	Significant weapons Proliferation potential	Not efficient weapon but transportation capabilities significant	None, possible benefits of exporting benign technology are good	None, possible benefits of exporting benign technology are good
Military vulnerability	Same as any centralized powerplant	Same as LWR	Slightly greater than other central powerplants, depends on space capability of other nations	Low	Low
Deployment considerations					
Time to commercialization	30 years plus	(Developed) 15 to 20 years domestic (licensing)	Long (greater than 20 years)	Between 5 and 10 years	Decentralized—5 years; centralized— 10 years
Geographic location with respect to load centers	Low population area	Low population area	Low population, no water needed; mixed	Decentralized—very close; centralized—S. W.-less than or equal to other systems. Geographic dependence high	Decentralized—very close; centralized—S. W.-less than or equal to other systems. Geographic dependence high
Compatibility with other technologies and utility grid	Good	Good	Penetration may be limited to 20 percent. Competes with other technology. Nothing obviously unsolvable	Goes down with higher percentage penetration; negligible problems	Goes down with higher percentage penetration; negligible
Other					
Probability for commercial success	Low to medium	High	Low to medium	High	High
Demonstration requirements	Large, but not as large as SPS	Moderate cost for 500 to 1,000 MW. About $1 billion	Large cost (0.3 to 1 GW)	Small (1OO-MW aggregate of 2 to 3 demos)	Small (community systems are medium)
Resource constraints	None	None	Manageable	Small	Small
Risks of RD&D failure	High, but for next 10 years little risk, $20 billion	Technology is here, but public views regarding waste?	High—big program; depends on program size (wait until HLLV available)	Negligible	Negligible
Relative uncertainties	High, complex	Small	High	Small (O&M costs)	Cell costs
Is it a viable example for the rest of the world?	Yes	Proliferation? for developed countries only?	Yes, if t works	Easier to digest in small to moderate chunks	Easier to digest in small chunks; need manufacturer capacity, but good example
Nature of RD&D process	Magnetic—public; inertial —classified	Much public money spent, remainder might be private, but for regulatory uncertainties	Public funds for RDD&T. Then private capital	Needs to be demonstrated by Government with private participation; industry will develop	Need not be demonstrated by Government, large private contribution

SOURCE: Office of Technology Assessment.

1. Central Solar Thermal.– Solar thermal technology is the oldest of the technologies under study. It may also be the one that is nearest to commercial application, since a pilot plant is already under construction in this country. The concept involves simply collecting concentrated solar radiation to heat a working fluid in a central receiver (boiler), which in turn drives a turbine to generate electricity. It has the versatility to provide either electricity or process heat (steam) for industrial applications.

Two generic systems have been proposed for the solar thermal approach: line-focus and point-focus systems. In the line-focus scheme, the Sun's radiant heat is reflected and focused by parabolic trough mirrors onto tubes containing the working fluid. The working fluid is pumped to a central site where it may be used to drive an irrigation pump, produce hot water or steam for a factory, or produce a combination of heat and electricity for a small community. The line-focus approach is also favored for process heat applications such as enhanced oil recovery, but is not being actively considered by DOE for central electric applications.

In the point-focus or "power tower" system, a field of reflectors (called "heliostats") is focused on a central receiver atop a tower in the center of the field. Although there are several designs, a heliostat is basically a flat reflective surface mounted on a computer-monitored gimbal that allows it to automatically track the Sun's course across the sky. The heliostat/power tower approach is being pursued by DOE as a central generating system, though not exclusively so. * It can be used for electrical generation either in a stand-alone system or as a method for repowering existing fossil-fueled power stations. The place of solar thermal in a utility system —whether it serves as a peaking, intermediate, or baseload unit— depends on the storage capability of the solar thermal plant. Without any auxiliary storage, its effective capacity factor will be about 23 percent in a location such as the southwestern United States. Addition of a modest amount of storage (sufficient for 3 hours of extended operation per day) will increase the capacity factor to about 40 percent and make it possible for the plant to supply part of the late-afternoon electric consumption peak that occurs in many utilities. Because it is desirable to smooth out the effects of short periods of cloud cover, it is likely that the technology will incorporate at least a small amount of thermal storage (up to 1 hour). Solar thermal plants could be made to operate in a baseload mode with the addition of a large amount of storage, but this increases the system's conversion loses and raises the overall cost per kilowatt installed. Solar thermal will, therefore, probably be better suited for intermediate or peaking uses since its daytime availability corresponds closely with the peak of the electricity load profile in many areas.

Solar thermal plants will be intermediate in scale between today's coal or nuclear plants and small onsite generators. They can be expected to be deployed relatively quickly– perhaps within 5 years for a 100-MW plant.

The technical feasibility of solar thermal technology is established. Engineering questions remain about the materials to be used in the design of the central receiver. What is at stake in making the technology commercially viable is whether plants can be produced economically. The single most important factor is the cost of heliostats, which accounts for about one-half the cost of solar thermal designs. Present cost estimates range from $1,000 to $3,000/kW of capacity installed.

Much of this high cost reflects the cost of materials. Savings realized from future automated production techniques are built into these projections. Thus, the economic viability of solar thermal technology depends on attaining heliostat cost goals.

The research, development, and demonstration (RD&D) costs associated with the solar thermal development are expected to be in the range of $0.5 billion to $1 billion. In addition

*In 1980, DOE initiated six major studies of the applications of the power tower to a variety of industrial heat demands, ranging from low-quality steam for uranium leaching to high-temperature steam for reforming methane to ammonia,

to continuing tests and studies to reduce heliostat costs, R&D for efficient and cost effective storage methods, improved receiver designs and transport fluids are also needed.

2. Solar Photovoltaics. This technology is the newest of the terrestrial solar options under study and it is conceptually the simplest, since it converts sunlight directly to electricity without any working flu ids, boilers or generators. Because the essential element—a semiconductor wafer or "cell" — is modular at a very small size, the technology has a versatility in scale of deployment that surpasses any other option. Photovoltaic (PV) cells have already proved feasible in small-scale applications for both space and terrestrial purposes. However, central PV systems have not been tested yet, even in a pilot plant size. Because the technology is so intrinsically modular, the R&D program is not geared to the demonstration of a series of prototype plants but to the improvement of the cost and performance characteristics of the cells.

A variety of different semiconductor materials is being developed for possible use in central PV systems. When sunlight falls on wafers of these materials, it produces a direct current of electricity. The efficiency of this process depends on many semiconductor properties, and how well those properties match the wavelength spectrum of sunlight. Typically, the materials produce a direct current (DC) voltage level of about 0.5 volts. Some of the more promising PV developments include the four technologies discussed below.

- The single cell silicon technology is the most highly developed, and its introduction dates back 23 years to the beginning of the National Aeronautics and Space Administration (NASA) space program. Its properties are well understood and cells sold commercially for small-scale applications routinely achieve efficiencies of 10 to 13 percent; experimental cells have achieved 15 percent and the theoretically probable maximum is 20 to 22 percent. The single most important barrier to commercial use is the high production cost, even though costs have dropped and performance improved over the past decade in line with DOE projections. Further cost reductions to ($95/m^2) $0.70/peak watt) and performance improvement to 13.5-percent efficiency are the DOE goals for 1986.
- The cadmium sulfide/copper sulfide technology is another approach that is commercially available and holds promise for improvement. This material can be used in thin films because of its high absorbance of sunlight, with a reduction in fabrication costs and materials requirements. Experimental cells have achieved efficiencies of 9 percent, with limited lifetime. Improved cells have the potential for cost reductions to $10/m^2 at 10-percent efficiency. A number of other cadmium sulfide technologies are under study for thin film and standard cells.
- The gallium arsenide technology is another alternative that has achieved efficiencies up to 24.5 percent in experimental cells. The material can be fabricated in thin films (with experimental efficiencies to 15 percent) and can withstand concentrated sunlight at high temperatures. Its major disadvantage is that commercial production is still some time away and costs remain much higher than for single-crystal silicon.
- *The polycrstalline and amorphous silicon* technologies have the potential for orders of magnitude cost reductions compared to the single-crystal silicon technology, but the experimental cell efficiencies have so far only reached 9 to 10 percent. (The probable maximum is estimated to be at least 15 percent for the amorphous technology in thin film cells.) These technologies are not limited to silicon, but are currently being investigated along with other novel materials concepts.

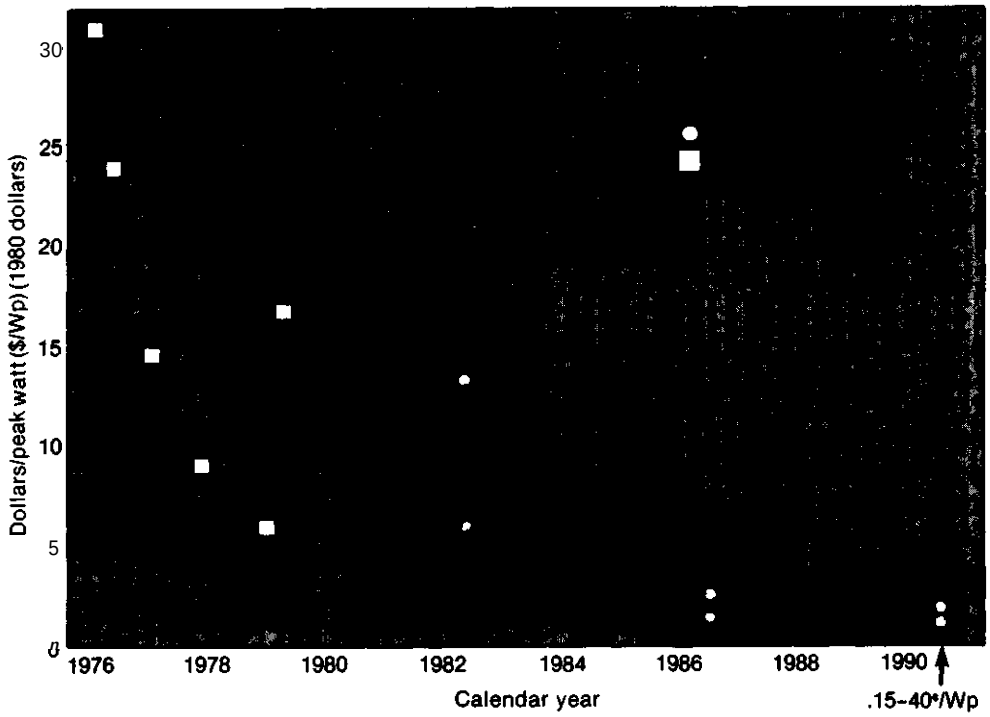
All the technologies discussed above are candidates for use in flat-plate arrays of cells that absorb unconcentrated sunlight. Gallium arsenide is also an example of a high-efficiency material that can be used with a con-

centrating system. Concentrating systems involve different tradeoffs and are further from commercial viability than flat-plate systems. Both line- and point-focus collectors are under consideration for PV concentrating systems. Costs of concentrating systems can in principle be low, since the receiving area needs only to be covered with a thin reflective sheet, but the technology is not developed enough to make project ions yet.

Up to half the cost in a flat-plate design terrestrial solar photovoltaic plant today is for the cells themselves. Other requirements for a complete plant are materials for packaging and supporting arrays of cells, support structures, cabling to connect the arrays and modules, and power conditioning equipment to convert the DC voltage to alternative current compatible with the utility grid. About 300 cells would be combined into one panel, 30 panels into one array, and 10,000 arrays into one module supplying 25 MW of peak power. A central plant might produce 200 MW from 8 modules. Storage could be added to extend the capacity factor of the plant, at additional system cost. As discussed in the introduction to this section, the economic merit of dedicated storage for utility-based PV systems has been seriously questioned.

The pace of technological breakthroughs in PV technology is impressive. Today single-crystal silicon cell arrays cost 15 percent of what they did in 1974, as can be seen in figure 27. It is on further orders-of-magnitude cost reductions that both terrestrial and SPS PV systems depend. Such price reductions are common in the semiconductor industry for products with large markets (e.g., digital watches, hand calculators, and now hand computers), but they are nearly unheard-of in the energy industry. Therefore, planners familiar with conventional thermal and nuclear energy technology sometimes find them difficult to accept. The goals for the DOE PV program are

Figure 27.—Recent and Projected Solar Photovoltaic Prices



SOURCE: Department of Energy.

for array prices of $2.80/peak watt in 1982, $0.70 in 1986, and $0.15 to $0.40 in 1990 (all in 1980 dollars). At the 1990 level, complete systems are expected to cost $1.10 to $1 .80/peak watt.

Although significant breakthroughs have occurred in the past 5 years, the principal thrust of PV research is still directed toward the identification, selection, and engineering refinement of the cheapest possible semiconductor materials. A concomitant part of this effort is the development of suitable mass-production techniques (now being most intensively pursued for single-crystal silicon and cadmium sulfide) to open the way for mass market penetration. It is upon the outcome of this two-pronged effort (development of cells and development of better manufacturing techniques) that the success of central terrestrial PV plants will depend.

The time-scale for commercial readiness of central terrestrial PV plants could be as short as 5 years or as long as 15 years. The balance of a central PV plant uses familiar building materials and readily available power-handling equipment. Once arrays are available, plant construction leadtime should be short. According to the DOE program, commercial readiness could occur in the early 1990's. If the RD&D program for PV cells is accelerated this date could be earlier; on the other hand, slippage in the schedule for cell development could delay commercial introduction.

Subsequent deployment of central PV systems would be paced by the rate of growth of national manufacturing capacity for PV cells. To achieve substantial penetration of central PV in the time period of 1990 to 2010 will require an aggressive program for PV manufacturing plants. It is possible that decentralized PV centralized terrestrial and SPS energy systems could all be competing for the output of the PV industry during this period.

3. Advanced Fission (Breeder Reactor).– Conventional reactors use uranium ore very inefficiently because only a small fraction of the uranium is tapped for energy. Natural uranium consists of two isotopes 99.3 percent U-238 and 0.7 percent U-235. Only the U-235 is usable directly in a conventional reactor. With conventional reactors, uranium resources would be exhausted relatively rapidly by an expanding nuclear energy base. Breeder reactors on the other hand, can extract 100 times as much energy from a ton of uranium ore and thus extend the nuclear energy resource by several centuries.

In a breeder, the core of the reactor is surrounded by a blanket of the type of uranium not burnable in conventional nuclear plants. This uranium captures neutrons escaping from the chain reaction in the core and is transmuted into plutonium, a premium value nuclear fuel. In this fashion, a breeder "breeds" new fuel that is extracted from the blanket, converted into fuel rods, and later burned in the same or another reactor. An advanced breeder will produce about 10 percent more fuel than it burns. A different fuel cycle could use thorium in the blanket. Thorium is an element similar to uranium, but it cannot be used directly as a fuel. In the blanket, it transmutes to U-233 which is a good fuel.

Breeders may also be distinguished by the different types of coolants used to carry heat from the core to the generating side of a nuclear plant. Because the interconnections between the core and the generators are quite complex, requiring considerable engineering refinement, the choice of coolant defines conceptually different types of breeders as much as or more than the choice of fuel. Early in its program, the United States emphasized breeders with liquid metal (usually molten sodium) coolants and the reactor concept that evolved —the liquid metal fast breeder or LMFBR– has become the reference system for breeder research in other countries, representing more than 95 percent of the dollar effort devoted worldwide to breeders. Thirteen reactors using the LMFBR concept have been built, the most successful being the French Phenix reactor, and seven countries with major breeder programs (table 16) have all emphasized the LMFBR type. Alternatives are helium gas, molten salt coolants, and water.

Table 16.—Description of Milestones of Major Breeder Programs

France	Federal Republic of Germany	Japan
Reactors		
Rapsodie (24 MWt)	KNK-I (58 MWt)	Joyo (100 MWt)
Phenix (250 MWe)	KNK-11 (58 MWt)	Monju (300 MWe)
Super Phenix (1,200 MWe)	SNR-300 (300 MWe)	
	SNR-2 (nominally 1,600 MWe)	
Milestones ►Planned		
1. 1962—Rapsodie construction starts	1. 1960—GFK, Karlsruhe project begins	1. 1967-Joyo conceptual design
2. 1967—Rapsodie goes critical	2. 1964—Design study for 1,000 MWe LMFBR	2. 1969—Joyo safety evaluation
3. 1969—Phenix construction starts	3. 1966—SNEAK startup	3. 1970—Joyo construction begins
4. 1973—Phenix goes critical	4. 1975—SNEAK experiments for SNR 300	4. 1977—Joyo goes critical
5. 1976—Super Phenix construction starts	5. 1967—INTERATOM F.R.G. and BENELUX cooperation begins	5. 1968—Monju preliminary design
►6. 1985—Super Phenix goes critical	6. 1972—KNK-I goes critical	6. 1969—Monju conceptual design
►7. 1983—1987 Early Super Phenix orders	7. 1976—KNK-11 goes critical	7. 1973—Monju safety evaluation
	8. 1969—SNR-300 safety report	8. 1978—Monju construction begins
	9. 1970—SNR-300 company established	► 9. 1984—Monju goes critical
	10. 1971—SNR-300 revised safety report	-10. 1986—Demo plant begins
	11. 1972—SNR-300 sodium fuel pumps tested	-11.1991 —Demo plant goes critical
	12. 1973—SNR-300 construction begins	-12. 1988—Commercial plant 1 construction begins
	13. 1974—SNR-300 steam generators and IHX test	►13. 1995—Commercial plant 1 goes critical
	14. 1975—SNR-300 specification of fuel and cladding	-14.1991 —Commercial plant II construction begins
	15. 1980—SNR-300 goes critical[a]	►15. 1996—Commercial plant II goes critical
	16. 1974—SNR-2 company established	
	17. 1976—SNR-2 preliminary design[a]	
	18. 1981 —SNR-2 construction begins[a]	

[a]Schedule as of 197& In 1980, the SNR program currently in flux. SNR-300 designed but not yet licensed. SNR-2 not Yet designed. Entire program will slip substantially, but the new schedule is not known at this time.

SOURCES: ***France:*** U.S. **Energy Research and Development Administration,** *The LMFBR Program in* France, ERDA 76-14, March 1976; M. D. Chauvin, "The French Breeder Reactor Program," 1976.
Federal Republic of Germany: U.S. Energy Research and Development Administration, *The /_ MFBR Program in Germany,* ERDA 76-15, June 1976.
Japan: **Report of Ad Hoc Study Committee organized by Japanese Government** Science **and Technology** Agency, October 1977.

SOURCE: International Energy Associates Limited, 1980.

United Kingdom	United States	U.S.S.R.
Reactors		
DFR (60 MWt)	Clementine (25 kWt)	BR-5 (10 MWt)
PFR (250 MWe)	EBR-1 (1.2 kWt)	BOR-60 (60 MWt)
CFR (commercial size)	Fermi (200 MWt)	BN-350 (1 ,000 MW)
	EBR-11 (16.5 MWe)	DN-600 (600 MWe)
	Clinch River (375 MWe)	
	Fast Flux Test Facility (equivalent of 160 MWe)	
	PLBR (commercial size)	
	CBR (commercial size)	
Milestones ►Planned		
1. 1953—first nuclear power program begins	1. 1946—Clementine goes critical	1. 1958—BR-5 goes critical
2. 1964—second nuclear power program begins	2. 1951—EBR-1 goes critical	2. 1965—BR-5 operates full core
3. 1963—DFR goes critical	3. 1963—Fermi goes critical	3. 1969—BOR-60 goes critical
4. 1984-PFR construction begins	4. 1966—Fermi shuts down	4. 1973—BN-350 goes critical
5. 1972—PFR goes critical	5. 1983 -EBR-II goes critical	5. 1973—BN-600 construction begins
	6. 1971–SEFOR (U.S. and F. R. G.) goes critical	6. 1979—BN-600 goes critical
		7. 1975—1,600 MWe reactor design underway

Table 16.—Description of Milestones of Major Breeder Programs (continued)

United Kingdom	United States	U.S.S.R.
Milestones ►Planned		
6. 1973—PFR shuts down for repairs	7. 1979—Fast Flux Test Facility construction complete	
7. 1974—third nuclear power program begins	8. 1975—Clinch River order components	
8. 1972—CFR design	9. 1977—Clinch River construction begins	
	►10. 1982—Clinch River construction complete[a]	
	11. 1975—PLBR start conceptual design[a]	
	►12. 1982—PLBR construction begins[a]	
	►13. 1988—PLBR construction complete[a]	
	►14. 1986—CBR-I construction begins[a]	
	►15. 1988—CBR-I goes critical[a]	
	►16. 1989—GCFR 300 MWe demonstration plant goes critical[a]	

[a]This was th, U.S. program i, 1978. Currently there is no planned pLBR schedule, penal ing final decisions on CRBR. CRBR is "in Construction, " but has been in a holding pattern for 2 years.

SOURCES: United Kingdom: **Prepared by IEAL from compilation of U.K. documents.**
United States: U.S. Energy Research and Development Administration, *Liquid Metal Fast Breeder Reactor Program,* January 1977; U.S. Energy Research and Development Administration, *The LMFBR Program in France,* ERDA 76-14, March 1976; Ford Foundation, *Nuclear Power Issues and Choices: Report of the Nuclear Energy Policy Study Group, 1977.* Note on U.S. program: Items 9-15 refer to the program as it stood in April 1977, The plan and schedule has been in revision since then, but it is not yet available.
U. S. S. R.: United States Nuclear Power Reactor Delegation, "Report of the United States Nuclear Power Reactor Delegation Visit to the U. S. S. R., June 1-13, 1975," 1975.

SOURCE: International Energy Associates Limited, 1980.

As a source of centrally generated electricity, the breeder has been proven feasible at the pilot plant scale and at an intermediate scale but awaits demonstration at commercial scale —that is the 1,000-MW size of new conventional reactors. Its operating characteristics are expected to be similar to a conventional (light water) reactor, except that it will have higher thermal efficiency and therefore less thermal pollution. Breeders may also in principle be used for industrial process heat. The Russian breeder BNR-600 produces electricity and desalinated water.

The technology was demonstrated at a pilot plant scale in the United States in 1963, when a 10-MW reactor named EBR-II started producing electricity in Idaho. Between the 1960's and 1970's, technical leadership shifted from the United States to France. The Phenix which has produced electricity for more than 5 years at Marcoule, France, demonstrated successful scaling from 10 to 250 MW, but suffered some technical problems that required the plant to shut down for more than a year. Its breeding rate is considered too slow for commercial use, and some components (especially steam generators) are not extrapolatable to commercial size. France, together with the Federal Republic of Germany and Italy, is now building a 1,250-MW reactor incorporating an improved design – Superphenix – at Creys-Malville. Due to go critical in 1985, it will be the first commercial prototype breeder.

The time until commercialization of the breeder is 5 to 20 years depending on which breeder technology (French or U. S.) is meant. On the face of it, commercial readiness will occur in 1985, assureing success of the Superphenix. After that, France plans an aggressive program of breeder deployment, starting a new plant every 2 years for the rest of the century. * The French central utility (EdF) has already ordered the first two of these "commercial" plants. Progress on the U.S. plant comparable to the Phenix (the Clinch River breeder) has stalled, and its technology is outmoded in some respects. Some argue this intermediate plant step should be skipped to go to a commercial-size or nearly commercial-size plant.

***A reevaluation of these plans is apparently underway in France following the recent election**

The leadtime for constructing a conventional nuclear plant in the United States is 12 years and design and construction of a full-scale breeder prototype under the same ground rules could take 15 years. Thus, U.S. breeder technology could be commercialized sometime in the 1990's, depending on the development sequence.

The major difference between the French and American technologies is whether the reactor vessel uses a "loop" or "pool" method of bathing the core with liquid sodium coolant. The pool method is simpler, has more thermal inertia, and is considered by the French to be an added safety factor. The loop method is more similar to conventional reactor technology and has been tested on an intermediate-scale U.S. breeder used for fuel development (the FFTF). Britain and France espouse the pool approach; the United States and Japan use the loop method; and the Soviet Union and the Federal Republic of Germany are testing both.

In principle, a U.S. utility could order a Superphenix reactor now for delivery in the early 1990's and in that sense the breeder could be said to be commercially available already. But no utility would invest in a central nuclear plant without reasonable assurance it would be reliable and could be licensed in this country. The licensability of the French technology is an open question.

The RD&D cost of commercializing the breeder is uncertain because the national policy for 1976-80 was to not deploy the breeder. It is also dependent on the demonstration strategy chosen (i. e., whether to go straight to a commercial prototype). Estimates made by the U.S. program managers in 1975 of $10 billion to $15 billion for commercial demonstration should still apply.

The obstacles that the breeder program must overcome before commercialization are not primarily technical. There is little doubt that a strong breeder RD&D effort could result in a reactor that utilities could order in a few decades. The questions are economic and institutional and generic to nuclear power. For the purposes of this discussion, the economic questions are less important. Unless the breeder costs are so high that it is uneconomic compared to other options, the major concerns are related to light-water reactors. These will not greatly affect the SPS decision.

Deployment of the breeder is predicated on the continued expansion of light-water reactors. The problems facing the industry are complex and difficult as discussed in the section on conventional nuclear reactors above. If these problems are not resolved, the fission option will be foreclosed, at least as a major energy source. Fusion may also be threatened. The breeder exacerbates some of these problems. Proliferation of nuclear weapons will be considerably harder to control if breeders are worldwide articles of commerce. While this might not have a direct bearing on a utility's decisionmaking process, the safeguards implemented to prevent diversion might be quite onerous, and public opinion could be hostile. Health and safety issues will be important because of the plutonium and the operating characteristics of the reactor. Waste disposal will not be qualitatively different, but the vastly greater potential of breeders to produce waste make the problem greater, especially if disposal sites are difficult to find. While these problems, individually or collectively, need not be overwhelming, they can all adversely affect a utility's inclination to order a nuclear plant. As long as a utility has a choice within a reasonable economic range, it is likely to select the less controversial options. Thus, while breeders could in principle supply all the electric power needed in the 21st century, they may in fact supply little or none.

4. Fusion.– Of the future energy sources considered here as competitors to the SPS, fusion is the furthest from realization. Fusion consists of nuclear reactions that are created by bringing together light nuclei at speeds great enough to exceed their mutual repulsive force. The result of this reaction is the creation of nuclear energy that is carried off by neutrons and/or charged particles, depending on the nature of the reactants. In order to create this reaction it is necessary to: 1) raise the temperature of the fusion fuel to very high

levels and, 2) confine the fuel for sufficient time. The criterion to be met by these two conditions is that more energy is released by the nuclear reactions than is used to heat and confine the fuel that is in a wispy, gaseous form (plasma).

Since the fusion reaction would be rapidly cooled by the reactor walls, containment by solid materials is not possible. Such an approach would quench the plasma. This difficulty, incidentally, would also make a fusion reactor easier to turn off, making it safer than fission. Two alternate approaches are being taken: using a magnetic field in one of many possible shapes that have been proposed, (magnetic fusion); and using a laser or ion beam to produce a miniexplosion of the fuel in solid form so that confinement occurs by the inertia of the fuel (inertially confined fusion or ICF). The second approach draws on nuclear weapons work for some of its research and is partially classified. The discussion to follow will center on the magnetic approaches.

Among different magnetic confinement concepts—or types of "magnetic bottles" —the leading contender is a toroidal shape called the tokamak, after the Russian acronym given by its inventors. As a reactor, it would be considerably more complex than a conventional powerplant. The mixture of deuterium and tritium fuel planned for use in first-generation fusion reactors burns at a very high temperature, 100 million °C. The natural current in a tokamak system is not sufficient for heating the fuel that hot, so additional and complex heating systems are required. The fusion core will be large enough that electrical losses in the magnets would be a significant drain on the output of the plant, unless superconducting magnets are developed specifically for fusion applications. Other complexities arise from the fuel requirements and operating requirements. Any fusion system must breed half its fuel (the tritium component), and tokamak systems currently under development must operate in a pulsed (few hour) mode rather than a continuous power mode.

These factors make fusion more complex than either conventional reactors or breeders. Particular difficulties in understanding the behavior of the fusion fuel in its very hot (plasma) state explain why scientists have had so much difficulty making progress in fusion research (which began in 1954).

Fusion is unique among future energy technologies because it has not yet been proven technically feasible—that is to say, no controlled fusion reaction has yet operated in a self-sustaining fashion or produced electricity even on a small scale. It has a broad range of potential applications, e.g., electricity production, high temperature process heat, synthetic fuel production, and fissile fuel production.

The fusion community can point to a recent string of successful experiments as evidence that fusion is on the verge of a scientific breakthrough. One of the goals is "breakeven," meaning the achievement of positive net energy production. DOE expects breakeven to be achieved before 1985, and a recent review by the research oversight board of DOE[9] concluded that fusion was ready to move from the research stage to the engineering development stage. Nevertheless, the weaker understanding of the principles of controlled fusion compared to other energy technologies means that more emphasis is necessarily being placed on basic research. Consequently, the engineering-related considerations that influence commercial readiness and acceptability—that is the technical, economic, and environmental factors — are more uncertain than for breeders, solar thermal, PV or SPS.

Despite the high degree of uncertainty, much more can be said about the engineering features of fusion than was possible a few years ago, based on a set of thorough and detailed engineering studies. Using the tokamak as a reference system, a powerplant is likely to be in the range of 500 to 1,500 MW, with 1,000 MW being the nominal planning size. A tokamak fusion reactor would operate as a baseload plant, with capacity factors, construction leadtimes, plant lifetimes, land, labor, and materials requirements similar to

[9] ERAB Report (DOE), 1980

conventional nuclear plants. The high-technology core would constitute a substantially larger percentage of the total plant than for conventional (or breeder) nuclear plants, and fusion would have some unusual maintenance problems that arise from the character of the fusion reaction itself. Since the nature of the fusion core must be considered hypothetical until technical feasibility is proven, the economics of fusion is perhaps the most uncertain characteristic at this time. Two different engineering studies prepared at the University of Wisconsin[10] and Argonne National Laboratory" put the busbar costs at 75 and 44 mills/kW respectively (in 1980 dollars).

Because of the special character of fusion, estimates of the timetable to commercial readiness vary widely. A recent survey of opinion found the majority of estimates to fall between 2000 and 2025, with some as early as 1990 and a few extending to the 22d century or never. [2] It appears unlikely that fusion will be commercialized before 2010— the earliest likely date for SPS – and the present DOE program is on a schedule calling for "demonstration" in 2015, with the dates 1995 or 2000 considered possible at increased cost. The DOE program calls for two steps after breakeven in 1985, the first a fusion engineering demonstration in 1990 that produces thermal power but no electricity. Pending success with this plant, a fusion demonstration plant would be started by about 2000, that could produce 500 to 1,000 MW of electricity. However, more steps are likely to be needed prior to commercialization. Fusion research is in such an early phase vis-a-vis other technologies that it is difficult to determine reliably the path to "commercial" fusion.

To be commercialized, fusion must also find public acceptability. From an environmental, health, and safety standpoint, the principle advantage of fusion over fission power is that there is no conceivable possibility of a runaway reaction. But first-generation fusion plants will use relatively large quantities of tritium, a radioactive gas harmful to humans. Advanced fusion fuel cycles would greatly reduce the quantity of tritium that must be handled. To make fusion safe, the problem of handling industrial quantities of tritium without routine small emissions will have to be solved. There will also be a substantial waste disposal problem, because the "first wall" of the containment chamber for magnetic systems will have to be replaced every few years due to radiation damage. Since the replaceable "wall" may be up to 1-m thick, the quantity of waste could be high, measured in the tens or hundreds of tons per reactor per year. This material will be highly radioactive and will present a long-term waste disposal problem, though the radioactivity will not be as long-lived as conventional fission reactor wastes. The amount and lifetime of radioactive material can possibly be reduced substantially by using other materials for the first wall without changing the nature of the fusion reaction. Analogous changes for fission reactors are not possible since the waste material generated is an inherent part of the fuel element. Finally, fusion carries some proliferation risk because the energetic neutrons of the fusion reaction comprise a high quality source for producing weapons material. It is conceivable that unless proper safeguards are developed, a world full of fusion reactors could be highly proliferation prone. However, there are many other technologies that are available or could be available for the same purposes earlier, more readily, and more cheaply than fusion.

To a degree, fusion may also inherit the public acceptance problems of nuclear fission. Fusion is a different technology, with fewer intrinsic risks but greatly increased complexity. But since it is a nuclear technology, even if it turns out to be relatively benign compared to fission, it may remain associated with conventional nuclear power in the public mind.

The greatest uncertainty in the development of fusion remains the physics associated with

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[10] NUWMAK: A Tokamak Reactor Design Study, " Fusion Engineering Program, Nuclear Engineering Department, University of Wisconsin UWFDM-330, March 1979

[11] Argonne National Laboratory, Starfire

[12] Chase Delphi Study on Fusion, First Round Results, " Chase Manhattan Bank, September 1979

breakeven. Although many of these uncertainties can be resolved by small experiments costing on the order of $1 million to $10 million, complete resolution will still require a few large sophisticated experiments, costing in excess of $1 billion. It should be noted, however, that the nature of the fusion reactioc is such that a demonstration reactor would require very little increase in scale or cost from these large experiments. The total cost to develop fusion to the stage of commercial viability depends significantly on the cost of this "hardware" and is projected by DOE to be $20 billion to $30 billion. If more than two major steps are needed before a commercial prototype can be built, the cost will be somewhat higher.

5. Comparisons of Central Electrics. -Because each of these future electric technologies is designed for use in a central plant mode, they are best compared in the context of a utility company's needs. If each of the different technologies were at the same stage of development, comparison based on projected power costs would be the most powerful and appropriate method of analysis, particularly if all were close to commercial maturity. But the five are at quite different states of technical maturity — so much so that even the definitions used for "commercial" maturity used in the different programs may be qualitatively different. Lacking information that may take 5 to 20 years to acquire, a close look was taken at other characteristics, with particular attention to properties–such as complexity, health effects, and safety — which past experience has shown to be closely related to both capital and operating costs.

After costs, the most important issue the utilities must consider in deciding to risk capital on a particular investment in a generating technology is the way in which a plant is expected to function and its associated impacts. Can the proposed technology be successfully integrated in the grid and meet the associated requirements for reliability and capacity? These issues are discussed for the SPS in chapter 9. This section will highlight the factors most important for the other central base load technologies.

Scale of Power Output. – Plants must be designed on a scale that can be readily integrated into the existing grid at the time of deployment. Using the rule of thumb that no one plant should comprise more than 10 to 12 percent of the system's capacity to guarantee integrity of the grid during a plant failure, the largest plant that could be presently accommodated by a single utility in the United States would be 2,500 MW, and that only by the Tennessee Valley Authority. (See ch. 9. for a discussion of this issue.) Cooperative agreements among utilities on the same grid can expand the maximum acceptable size. Current baseload plants generate from 500 to 1,300 MW. Both fusion and breeder plants are planned to fit closely within this range. Very large powerplants (greater than 1,500 MW) were the rule in fusion planning several years ago, but encouraging new research results coupled with new interest in smaller powerplants allowed fusion engineering designers to direct efforts toward conceptual designs in line with present powerplant scales. Larger plants would mean improved economies of scale for the breeder (as it would for fusion), but for utility compatibility reasons (as well as licensability), the projected size of the breeder has also been kept below 1,500 MW.

Solar thermal and solar PV plants achieve their economies of scale at much lower outputs–100 to 200 MW maximum. Both can function economically at still smaller scales. Photovoltaics are modular and economic at a few kilowatts or less.

Only the reference system SPS appears to have economies of scale that make it impractical at a size that can be accommodated by the present utility systems. Whether it could be accommodated in future utility systems depends on the growth of future electric demand. Smaller microwave systems or a laser system would fit the utility grid more readily.

Reliability and Capacity Factor. – Prior to the demonstration of a technology, both its

capacity factor and its projected reliability are subject to considerable uncertainty. However, it is expected that breeders will operate much as conventional light water reactors do today, with capacity factors of 60 to 75 percent and forced outage rates (that is, unplanned shutdowns) of less than 15 percent.

The steam and electric generation parts of fusion plants are expected to be similar to conventional reactors and breeders. But the fusion core will be much more complex than the nuclear parts of a conventional or breeder plant. One indication of this is that the fusion core is expected to represent a much larger fraction of the plant investment (50 v. 10 percent for nuclear). Because of the vast uncertainties surrounding the actual operating characteristics of fusion technology, it is impossible to predict what capacity factors and forced outage rates are likely to be. It is clear that to compete with breeders or light water reactors, fusion should be just as reliable and capable as they are.

Solar thermal is a steam technology, with a balance of plant that will be similar to, though smaller than, that for a conventional baseload plant. The solar-thermal part will be chiefly vulnerable to failure of the heliostats or the boiler. The heliostat fields could have tracking or maintenance problems, the boilers could have materials and integrity problems due to the high solar flux. Nevertheless, it is projected to operate with reliability similar to other steam technologies —60 to 90 percent.

Solar PV is the simplest technology, without steam systems or moving parts or (necessarily) high solar flux, if flat plate systems prove most economic. Because it is simple, the reliability of solar PV is expected to be very high (greater than 90 percent). There may be unsuspected durability problems with some solar PV cells, however. Although PV are an intrinsically simple technology, it currently has higher material and manufacturing costs than other alternatives. Both solar thermal and solar PV have an inherent limitation of plant capacity factor, due to the daily and yearly variation of ambient sunlight, which differs with latitude and climate. In the Southwestern United States, the capacity factor of a plant without storage would be 23 to 25 percent. Storage for a solar thermal or solar PV plant redistributes the collected energy to other times of day, but does not appreciably change the amount of energy Collected per year per acre of plant area.

The SPS would circumvent the 25-percent capacity factor limitation of terrestrial solar plants by being exposed in space to direct sunlight 24 hours per day all year (except for brief, predictable eclipses if located in geostationary orbit, or unpredictable cloud cover if a laser or mirror system). The question with SPS is not solar capacity but availability. As with fusion, it is impossible to predict just how reliable the SPS would be. As a system it is very complicated, involving a massive transportation system, untried satellite technology, and large ground systems. Reliability factors as high as 95 percent have been predicted for the operation of the satellite and rectenna combined, [13] but they have not taken into account the entire SPS system, including maintenance and repair. Research on transportation and space platforms will provide considerable insight into the expected reliability of the satellite.

Complexity. –Given the extreme range of physical requirements for a sustained, controlled fusion reaction, fusion is clearly the most complex technology under consideration, requiring a plasma hotter than the core of the Sun, powerful large superconducting magnets bigger than any yet built, and materials problems in a radiation environment more severe than that of the breeder. The reference system SPS is less complex than fusion, since it uses more nearly proven technologies. Nevertheless, the overall engineering and logistics problems of the SPS could make it an undertaking that approaches the complexity of fusion when all the technical hurdles are considered. It should be noted, for in-

[13] "SPS/Utility Grid Operations," sec 14 of Boeing Corp., report No. D 180-25461-3

stance, that the SPS as it is described in the reference system could only begin to be assembled as a system after major breakthroughs in two other technologies—space transportation and PV — are achieved.

The breeder is considerably less complex than either the SPS or fusion, but is more complex than conventional nuclear systems. The main potential difficulties are the nuclear properties of the breeder core, the peculiarities of the liquid metal coolant, and the potential difficulties of the breeder fuel cycle. Although these factors are incremental additions to the complexity of a nuclear plant, they are the driving factors behind the projections that the breeder will cost 25 to 100 percent more than a light water reactor (LWR).

The solar thermal plant is also a steam system that has much of the complexity of other steam systems, such as coal or nuclear, mitigated by the reduced size of the plant and the modularity of the heliostat field. There may be special problems in having a central plant boiler at the top of a tall tower, but solar thermal plants appear to be less complex than nuclear, fusion or SPS technologies. Their complexity may be comparable to current baseload coal technologies.

Central PV plants have by far the least complexity of the alternatives discussed here, for two reasons. First, the basic technology is simple, modular, and should be manufactured cheaply if the experience with mass-produced semiconductor products holds as expected. Second, the additional technology needed for a central plant is electrical rather than mechanical or thermal, and is already proven at the appropriate scale.

Costs. –The cheapest acceptable technologies available in any future time period will be the ones deployed, so cost is the most important — and most problematic —factor. Two aspects of technology cost will be discussed. The busbar cost is the cost at which truly commercial versions of the various electric technologies will produce power. The opportunity cost is the total cost of RD&D for a technology from inception through the construction of a commercial prototype plant. It is the cost of lost opportunities in other areas for which the money could have been spent. A component of the opportunity cost is the cost of the commercial prototype itself, which is the demonstration cost.

The busbar cost is the actual cost of producing electricity with a technology when capital costs, fuel costs (if any) and operation and maintenance costs have been considered. For current technologies, these costs are well-known and therefore detailed comparisons between technologies are possible. However, even for current technologies the task can be difficult–witness the debate over whether coal or conventional nuclear is cheaper. For future technologies, the task is much more uncertain. Therefore, cost estimates of delivered electricity are of little use in deciding between technologies in early development stages. Furthermore, technologies reach commercialization at different times. Therefore, cost estimates for one technology are more reliable than for another, with the most fully developed technologies having the most thoroughly tested cost data. For example, coal plant costs are well known, but breeder costs are less so, and fusion costs are much less so. Though it is a current technology, the future costs of PV for onsite, central, or SPS plants, depend strongly on the future costs and efficiencies of PV cells and are consequently uncertain as well. A final note on busbar cost estimates is that as a technology matures, the projected cost may fall (as has happened with computers) but much more often rises. The maturation effect of costs during R&D has been particularly borne out in aerospace and energy technologies.[14 15]

Although busbar cost estimates are useful in the research phase to identify cost sensitivities and indicate preferred research directions to reduce costs, they become crucial at the

[14] U S General Accounting office, "Need for Improved Reporting and Cost Estimating on Major Unmanned Satellite Projects," PSAD-75-190, 1975.

[15] E W Merrow, S W Chapel, and C Worthing, "A Review of Cost Estimation in New Technologies Implications for Energy I'recess Plants," R-2481-DOE, Rand Corp , 1979

deployment phase. The DOE prepared cost estimates for coal, light water reactors, coal gasification systems using combined cycle systems, LMFBR breeders, peaking terrestrial PV plants, fusion and the SPS (fig. 28). " The figure indicates the high and low ends of the range of estimates for each technology in 2000. It shows that capital costs do indeed increase with complexity, rising steadily for coal, LWR, LMFBR, fusion, and SPS systems. Costs are also relatively high for the terrestrial PV. Although it is an unlikely circumstance, the chart indicates that all could cost the same in 2000.

OTA prepared estimates that considered these future electric technologies including fusion (but not combined cycles), in terms of their busbar costs in 2010. The results are given in table 17, using common financial considerations, equal capacity factors (65 percent in all cases), and the assumption of baseload operation for each technology. As noted above, these numbers may be indicative but are limited in their use because the uncertainty range represented by the range of costs means different things for each different technology. Factors that are small contributors to the estimated costs may have uncertainties that are substantial (such as nuclear waste disposal costs) but are difficult to identify and measure. Finally, baseload operation is not necessarily the most attractive operating mode for solar thermal and solar PV though it provides a basis for comparison.

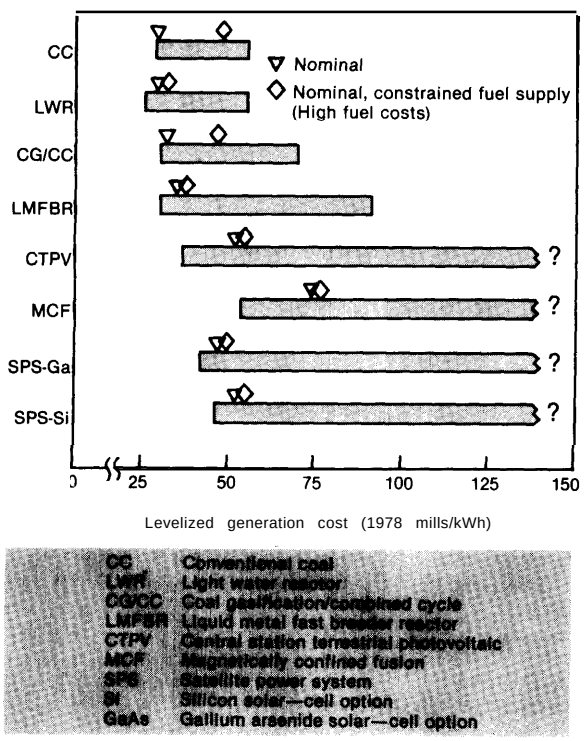
RD&D Costs. –One of the most difficult tasks in choosing the wisest course for RD&D is to maintain the proper balance between the risks and the potential payoffs associated with a particular line of research. The goal is to minimize the risk and maximize the payoff. In energy research, the risk is associated with the expenditure of RD&D funds for a project that could conceivably fail. The hoped-for payoff is cheap energy. The associated RD&D funds required to pursue some of the future electric options under consideration are so great that it is likely that not al I can be pursued at an optimum rate. By according priority to some, opportunities for payoffs from others will be foregone.

As the matrix of table 16 makes clear, SPS will have the highest front-end costs by a considerable margin, followed by fusion and the breeder. The solar thermal and solar PV systems will have lower RD&D costs, in the range of $0.5 billion to $2 billion.

The costs of the breeder will be large–in the range of $10 billion to $15 billion—assuming the United States does not change the present policy of developing domestic rather than foreign technology. But this figure is nevertheless comparable to the front end costs of other centralized energy technologies. Cumulative RD&D for light water reactors, for instance, is estimated to have total led $10 billion. Fusion's costs will be the same or somewhat higher, estimated at $20 billion to $30 billion, including a commercial prototype

"*Program Assessment Report statement of findings,* SPS **Concept and Evaluation Program, DOE/E** R-0085, 1980

Figure 28.—Levelized Lifecycle Cost of Electricity



SOURCE: *Program Assessment Report Statement of Findings,* SPS Concept and Evaluation Program, DOE/E R-0085, 1980.

Table 17.—Summary Assessment

Technology	Prospective economic-cost range[a] (1 980 $) (mills per kWh)	Relative environmental costs	Scientific	Engineering/ technical	Commercial	Commercial readiness (year)
Satellite power system	80-440	Unknown	Proven[b]	Unproven	—	2005-2015
Solar photovoltaic with storage	65-86	Negligible	Proven	Proven	Unproven	Late 1980's
Solar thermal with storage. . . .	62-89	Negligible	Proven	Proven •	Unproven	Late 1980's
Breeder reactors	58-73	Substantial	Proven	Proven	Proven	*2000*
Fusion	44-75[c]	Moderate-substantial	Unproven	—	—	?
LWR-201O	58	Moderate-substantial	Proven	Proven	Proven	Operational
LWR-1980	47	—	—	—	—	—

[a]Plant startinn in 2010.
[b]Environmental impact still unknown, other aspects generallY accepted.
CN,t, this range reflects differences between two studies' estimates (footnotes 10 and 11 On p 120).
aMassive scale-up of known technologies.

SOURCE: OTA working paper.

plant. Fusion and the breeder may thus compete with each other for R&D funds.

The costs of the SPS will be substantially higher than for any of the other options, at an estimated figure of $40 billion to $100 billion.[7] The high number assumes all space development and plant investment costs are allocated to the SPS (see ch. 5), while the lower number assumes the total cost but allocates $60 bill ion to other space programs that could benefit from the same technical capability.

The SPS RD&D cost is so high that commitment to it could foreclose fusion or the breeder. As such, a decision at some point in the future to commit to the SPS would be a decision with potentially far-reaching consequences.

In fact, the SPS is the first proposed energy option whose RD&D costs enter the budgetary range that has previously been limited to very high-technology, high-cost national defense programs such as the MX missile system. That system, as proposed, will cost" $34 billion to $50 billion. Thus, from a policy point of view, the SPS is qualitatively different from any other proposed long-range energy solution.

Institutional Impacts. — **Neither fusion nor fission requires much that is new institutionally because their size, health and environ mental impacts, and operating structure are similar to current LWR technology. As technologies used in the centralized mode, the solar technologies will not require different institutional attention than do any other peaking or intermediate plant. As dispersed plants, they are likely to be subject to a much different regulatory regime'[8] and utility structure that encompasses a much broader technological scope than is now the case.**

SPS, however, because it is a space system requiring very high capital investment, would likely involve an institutional structure very unlike those in use today in the utility industry (see ch. 9). The main point is that the utilities are unlikely to want to invest directly in satellites, or perhaps even rectennas. It will create far fewer regulatory and capital problems for the utilities for them to buy power from a single SPS corporation and incorporate It directly into their grid. A national SPS monopoly would necessarily be federally, as well as internationally regulated (see ch. 7).

National Security Risks. – Both **of the nuc l ear technologies u rider consideration (breeders and fusion) can be used to generate weapons material and therefore they carry some risk of increasing nuclear weapons proliferation. The terrestrial solar technologies**

[17]OTA **Workshop on Technical Optlons, December 1979**

"Office of Technology Assessment, U.S. Congress, "Decentralized Electric Energy Generation Systems," upcoming report, fal l 1981

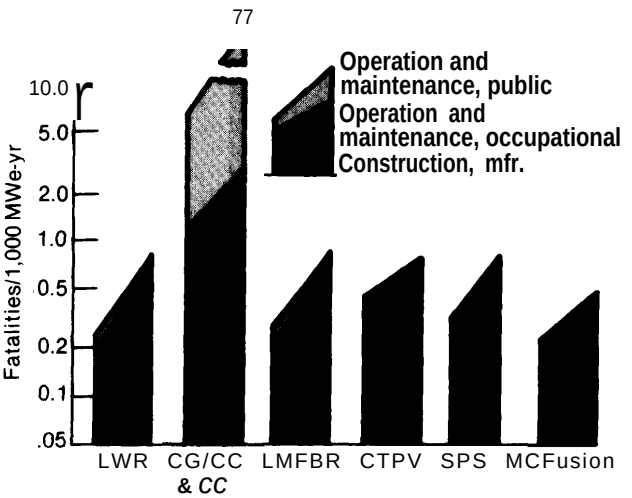
seem to have purely beneficial national security effects, however. They can be exported and used around the world for peaceful purposes. Because they would be used in relatively small units, they would be much less vulnerable than any larger unit and less of a military risk for a country selling the technology.

SPS would have indirect military potential, largely from the technology that would be developed for space transportation and space construction. However, the system itself would serve as a poor weapon. The question of vulnerability of an SPS system to nuclear or other attack is a different issue. On the whole it is little more vulnerable than any of the larger terrestrial electricity options (see ch. 7).

Economic Risks of RD&D Failure.— In general, the risks of failure are tied directly to the opportunity costs for the different central electric technologies. Therefore, the risks are higher for fusion and SPS than for any of the others. However, the financial risks of failure may be mitigated if some of the RD&D costs are recoverable for other uses. For example, the space spinoffs from developing the SPS could be significant (an upgraded shuttle, space platform technology, an orbital transfer vehicle technology, high powered microwave or laser transmission devices), which would reduce the economic risks. Here, as in the strictly research phase of an SPS program, it is very important to be cognizant of other space and energy programs that could benefit from dollars spent on SPS research and vice versa.

Safety and Health Risks. –OTA pursued no independent study of health and safety risks of the five technologies. This assessment has therefore relied on the work of Argonne National Laboratory that was funded by the SPS office of DOE. '9 The reader is referred to its report for a comprehensive treatment of the problem (see also app. D). The Argonne study attempted to quantify risks in terms of the number of fatalities that would occur per year for a specified plant output (see fig. 29). Some of the issues are unquantifiable, and for the

Figure 29.—Quantified Health Effects



SOURCE *Program Assessment Report Statement of Findings,* SPS Concept and Evaluation Program, DOE/ER-0085, 1980.

SPS and fusion, most of the issues are in this category. The difficulty of quantifying issues for SPS and fusion is a function of the uncertainties about the final configuration these technologies will take as well as the lack of experience with them upon which to base estimates of fatalities. This is an area that needs considerable further study, not only for SPS but in every other comparative study of energy technologies. The major needs are to put all the data on as common a basis as possible and to quantify risks where they are currently unquantified (see ch. 8 for a summary of SPS health and safety risks).

Environmental Risks. –As with health and safety risks, OTA attempted no independent analysis and has relied on the comparative assessment study of Argonne National Laboratory.[20] Table 18 summarizes the most important environmental effects for each of the technologies under study, plus coal. The nuclear technologies have been grouped together because their effects are common to all the nuclear technologies.

[19] G R Woodcock, "Solar Power Satellites and the Evolution of Space Technology, " presented at A I AA Meeting, May 1980

[20] L J H abegger, J R Gasper, and C D Brown, "Health and Safety Preliminary Comparative Assessment of the SPS and Other Energy Alternatives, " DOE report No DOE/E R-0053, April 1980

Table 18.—Major Environmental Risks

Coal	Nuclear	SPS
Air pollution	Catastrophic events	Atmospheric changes
Atmospheric changes (CO_2, particulate)	Land use	Bioeffects from microwaves, lasers, reflected light
Esthetic deterioration	Thermal discharge waste disposal	Electromagnetic disturbance
Land use		Land use

SOURCE: Office of Technology Assessment

Other factors. – **How well would SPS compete with other baseload electric technologies? This question can ultimately be answered only in the context of overall demand for electricity, considerations that are taken up at the end of this chapter. However, if demand for electricity is such that SPS may be needed to supply a portion of that demand, then the competitive position of SPS vis-a-vis the other technologies will depend primarily on its being cost competitive, and presenting comparable health or environmental hazards to the other technologies. Other utility concerns such as its reliability and rated capacity factor have direct and obvious economic impacts that are subsumed in the condition of its being cost competitive. It is too early to tell whether SPS can compete effectively. What is clear, however, is that factors beyond the scope of control of an SPS program may determine more effectively whether SPS is competitive than the important concerns over costs or health and environmental effects. The effects of reduced coal useage are examined below. However, before the United States needs to decide whether it is prudent to continue or expand coal burning (c 2000), it must make a decision about the use of breeder reactors (c 1990). If we institute a strong breeder program, then SPS is less likely to be needed than otherwise, simply because breeders are apparently cheaper to build and operate than the SPS. They have the further competitive advantage that they strongly resemble LWRS, both in operating characteristics and in health, safety and environmental impacts.[21] Thus, utilities are more likely to purchase breeders than to take on a brand new technology whose major resemblance to terrestrial technologies is the fact that it produces electricity. However, perhaps more important is the fact that breeders could play a significant role in supplying electricity 10 to 20 years before the SPS, thus giving them an automatic competitive advantage.**

Although the fusion program has not yet proven that it is possible to generate more energy than is fed to the fusion process, the fusion community is confident that the production of electricity from fusion is a matter of continued R&D. The costs are more uncertain than for SPS. However, fusion has a strong followlng inside and outside the fusion community. Furthermore, the utilities are already actively pursuing fusion studies. Therefore, if fusion's costs turn out to be competitive with SPS, it too may be chosen over SPS because it has a strong following and because beyond the first wall, it is similar to other nuclear options in the way in which it generates electricity. However, it may not be capable of making a significant impact on the supply of electricity until well after SPS, i.e., not until 2030 or later.

Because several proposed versions of the SPS are designed to use PV cells, a terrestrial PV system constitutes an obvious comparison to the SPS. The satellite or SOLARES ground site would receive continuous sunlight. A terrestrial system, however, receives constantly varying sunlight. Table 19 compares the peak and total annual insolation in space, at a SOLARES ground station and in Boston and Phoenix for an optimally tilted flat-plate, nontracking solar collector. Therefore, a terrestrial PV in Phoenix the size of a reference system rectenna would, in theory, be capable of producing as much electricity on a yearly basis as the reference satellite. However, the output of

[21] **E. P Levine, et al , "Comparative Assessment of Environmental Welfare Effects of the Satellite Power Sytem and Other Energy Alternatives, " DOE report No DOE/E R-0055, April 1980**

Table 19.—Terrestrial and Space Insolation Compared

	Peak insolation (per square meter)	Average annual insolation (per square meter)	Area needed to produce 1,000 MW (per continuous output on Earth (17-percent efficiency cells)
Space	1.3 kW	11,800 kWh	10 km^2
SOLARES GND Station (29° latitude)	1.3 kW	9,734 kWh	6 km^2
Boston	0.8 kW	1,430 kWh	44 km^2
Phoenix	1.0 kW	2,410 kWh	26 km^2
Equivalent rectenna area for reference system—35° latitude	—	—	28 km^2

SOURCE: Office of Technology Assessment,

such a central terrestrial system would be subject to short-term and seasonal variations in output due to fluctuations in insolation brought out by cloud cover. This effect is illustrated in table 20 for the Boston and Phoenix areas. The daily insolation for the month of December is 28-percent less than for the average month, resulting in 28- percent less PV output for the same sized array. Phoenix, by contrast, experiences average insolation values only 14 percent lower than the average in July, its month of lowest insolation.

Decentralized Electrical Generation

Although technologies that are capable of producing electricity in a dispersed mode may not be direct competitors of centralized technologies, they will compete for a percentage share of overall electricity supply in this country and the world. In 1977, the residential sector of the electrical market constituted 36 percent of this Nation's demand for electricity. If a significant portion of this demand as well as part of the demand for commercial and industrial consumption can be met by dispersed technologies such as solar PV, wind, and biomass at costs that are competitive with centralized electricity, then the demand for centrally produced electricity will drop. Low demand for centrally produced electricity will in turn reduce the need for new, large-scale generating technologies and place them in a poor competitive position with respect to proven technologies. Thus, it is of considerable interest to investigate the role that dispersed electrical technologies may play in the Nation's energy future.

Dispersed modes of generating electricity are first and foremost attractive in remote regions where the electricity grid has not yet penetrated. It is in these areas where windmills and PV, with storage, are now being installed even though their cost is high relative to the price of grid-supplied electricity.

As experience with these technologies grows, and their price decreases due to deeper market penetration and increased commensurate production, they are likely to penetrate areas that are now served by the utilities. Such a shift will be aided by the Public Utilities Regulatory Policies Act of 1978 (PURPA) that requires utilities to purchase electricity from renewable-based powerplants at their avoided cost of power. To date, State regulatory commissions have established prices that are equal to, or higher than, the retail price of electricity. If this practice should continue into the mid-1980's, onsite electrical generating systems will not only provide energy for their owner's use, but will become income generators as well.

This shift will be further aided by the attractiveness of modular units that allow a homeowner or community to become relatively self-reliant and independent of large-scale generating systems over which they have little control. Additionally, onsite systems can be erected rapidly and incrementally, allowing a close match of supply to local demand. Under such conditions, it can be expected that there would be a rapid increase in demand for small-scale systems.

The role of dispersed electrical generating technology in the Nation's electrical supply is

Table 20.—Terrestrial Insolation at Different Latitudes and Climates

Boston: Latitude 42.2

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
kWh/m^2	3.4	3.7	4.1	4.0	4.4	4.3	4.6	4.4	4.4	4.1	3.0	2.8
kWh/m^2/month	104	104	126	119	135	129	142	137	131	126	90	85

Total insolation per year 1,430 kWh/m^2
Average daily insolation: 3.9 kWh/m^2

Phoenix: Latitude 33.3

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
kWh/m^2/day	6.0	7.0	7.4	7.5	6.6	6.2	5.7	6.2	7.0	7.3	6.7	6.0
kWh/m^2/month	184	195	228	225	204	186	178	185	218	227	200	185

Total insolation per year 2,414 kWh/m^2
Average daily insolation: 6.6 kWh/m^2

SOURCE: *Solar Photovoltaics: Applications Seminar,* **Planning Research Co**

the subject of another OTA **study that will discuss the full array of dispersed electrical technologies: wind, PV, and biomass. However, because much of the technology for constructing space-rated solar cells will be applicable to terrestrial applications and vice versa, this report explores the possible role of dispersed PV systems in filling part of this country's electrical needs in the time frame of the SPS.**

Dispersed Photovoltaic Systems. —The most important single characteristic that makes PV of considerable interest for dispersed uses is their relative insensitivity to economies of scale for generating electricity because PV are modular, allowing considerable flexibility in their location. Economies of scale are very important in their production, however. The present high cost of PV (about $7/peak watt) is largely due to a very small production capacity. About 4.5 MW (peak) of terrestrial capacity were produced globally in 1979, by only a dozen manufacturers. Demand exceeds supply, however, even at $7/peak watt and thus the market will surely expand, especially as new manufacturing techniques allowing cheaper PV are developed. All indications are that continued reduction in price in line with DOE cost goals will accelerate the demand for PV cells for all applications and in particular for dispersed systems that are either connected to the utility grid or stand alone. Meeting this cost goal is important for the SPS, which in the reference design, is highly sensitive to PV array costs (34 percent of satellite costs).

The total penetration of PV and other decentralized energy technologies into the residential, commercial, and industrial sectors of the energy economy will depend on a number of interrelated factors in addition to cost. The following summary indicates the most important ones.

- *Average Available Sunlight.* **–The best areas for dispersed PV are the same ones where centralized applications are most plausible, i.e., in desert climates such as the Southwestern United States. However, the variation of regional average insolation across the continental United States is less than a factor of two. Changes from year to year are considerably less. Both effects are smaller than variations in energy consumption and price patterns. Thus, regional or annual insolation variations are not likely to be a strong determinant of PV penetration. This will be even more true in areas where biomass and wind systems can work in complementary fashion with PVs.**

- *Storage.* – **Advances in storage technology could have a significant effect on the market penetration of PV systems, particularly for remote and stand-alone applications. It is generally agreed, however, that low-priced storage, if it is ever developed, is a decade or two away.**
- **The Use of Centralized Photovoltaic Systems. — Using PV for peaking or intermediate generating capacity will enhance the development of low-priced PV cells and the auxillary equipment (mounting panels, inverters, etc.) and speed the introduction of dispersed PV systems to marginal areas (i. e., areas where the centrally generated electricity is cheaper than onsite generation).**
- *Conservation.* **–Conservation has already resulted in important reductions in per-capita energy use. In the Washington, D. C., area for example, use of electricity is increasing by only 1.4 percent a year,[22] a sharp contrast to the 7 percent yearly increase in consumption that was common in the mid-1 970's. Continued price increases for energy will increase the desire to conserve energy and make the total needs of a residence, for instance, much less. The Virginia Electric Power Co., for example, reports that in its service area all-electric homes, used about 24 MWhr/yr in the mid-1 970's, but consumed only 19 MWhr for 1979,[23] a 20-percent drop. Decreases in total consumption make it more likely that PV systems can be sized to meet the needs of the residential sector.**
- *Other Dispersed Sources of Electrical Power.* **–The acceptance of wind and biomass for dispersed electrical generation, or as substitutes for electricity, may enhance the desire for photovoltaics as individuals and the utilities become accustomed to working with dispersed sources. However, if other sources failed to make a significant impact because they were expensive or because they didn't work well, they could have the opposite effect on the use of PVs.**
- **Cost of Photovoltaics. – Single-crystal silicon cells are highly energy intensive. Thus, the energy cost of producing them is high, and if energy prices increase, the cost of the cells will be higher than the DOE goals. New production techniques for amorphous silicon or other materials, however, may lead to less energy intensive cells, and the problem could be avoided.**
- *Reliability y.* **–One of the major reasons for preferring centralized power generation is the high reliability of electrical service. Dispersed systems must be reliable in order to capture a significant portion of the electricity market. The PV themselves are extremely reliable. However, the associated equipment is subject to a higher failure rate. Market penetration will therefore depend on a highly reliable product and effective, timely service to repair failures.**
- *Institutional Effects.* – **PURPA regulations will enhance the use of dispersed-systems. If these regulations are retained and if they are carried out effectively on the local level, then they will be effective in speeding the introduction of dispersed electrical capacity. However, a number of negative effects (e. g., low reliability, high costs, etc.), could cause such regulations to be repealed if they are found to work inefficiently.**

In summary, it can be said that the future of dispersed electric systems, and PV in particular, is subject to considerable uncertainty. If cost goals are met, and the effect of the other factors is positive overall, then dispersed electrical systems could make a significant contribution especially in a future in which the demand for electricity is relatively low. As table 21 illustrates, the cost per kilowatt-hour for grid-connected PV systems, though subject to considerable uncertainty, is competitive with baseload systems. By combining several different kinds of dispersed sources of electricity (e.g., wind, PV, and biomass), the prospects for dispersed PV sales becomes even

[22] *Washington Post,* **Mar 25, 1981, P D-9**
"Washington Post, June 23,1980, p B-1

Table 21.–Costs of Onsite Photovoltaics (1980¢/kWh)

	Household				Industry			
	Without storage		With storage*		Without storage		With storage*	
	Boston	Phoenix	Boston	Phoenix	Boston	Phoenix	Boston	Phoenix
Roof replacement	3.0¢	1.8¢	9.0¢	7.O¢	—	—	—	—
Flat on roof	3.9¢	2.3¢	9.9¢	7.6¢	—	—	—	—
Columns on roof or ground	8.3¢	4.9¢	14.7¢	10.4¢	8.O¢	4.7¢	18.9¢	12.9¢

NOTE: These costs were developed assuming photovoltaic arrays costing $35/m² and 17-percent efficiency in space (18 percent on ground). Further details of the assumed systems can be found in app. B.
● Assumed a 80-percent capacity backup generator,

SOURCE: Office of Technology Assessment.

stronger than when used alone. As in the case of the baseload technologies, these figures must be seen as indicative of the range of costs that may be attained and should not be used as a basis for comparison at this time. Considerable development will be needed to determine whether the various cost goals can be met.

Implications

Introduction

The discussions just completed illustrate that the future of the SPS, assuming it can be developed technically, depends on a variety of factors. These include the future demand for electricity and how SPS compares with other supply technologies. There are two questions to be answered: 1) is the SPS necessary at all? 2) if so, when do we need it? The section on demand showed that future electricity needs are highly uncertain and are dependent on technological developments that can profoundly influence the costs of various end use technologies. The section on supply contained discussion of several technologies that would compete, partially or completely, with the SPS to supply electricity for the long term. The section gave criteria for choosing between these technologies and the range of uncertainty about their potential success. From the discussion it is clear that a variety of factors beyond purely technical success will determine which supply technology(ies) will emerge.

To see this more clearly, OTA chose three hypothetical U.S. energy futures in order to examine possible future supply mixes. They were chosen to span a wide range of possible electricity demand scenarios for 2030. The lowest assumes no change from our present end-use demand for electricity, the highest uses the 1979 **Energy Information Administration (E IA) high projection for 2020 extrapolated to 2030, and the mid-level is halfway between. These futures were chosen as an exercise to illustrate the way various technologies might be used and the constraints placed on this selection. OTA does not treat these demand levels as forecasts of what will occur, but as a plausible range of future end-use demand.**

The extremes of the three scenarios are characterized by zero growth in electricity demand for the low scenario, and an average growth of 2.8 percent per year for the high scenario from 1980 to 2030. The growth in the high scenario is not steady, however, but starts at 4.1 percent in the 1980-95 time period, and declines to 1.9 percent by the end of the scenario in 2030.

The low scenario represents a conservation-oriented energy strategy, in which the increases in industrial output and residential and commercial space are offset by improved efficiency of electricity use for industrial processes and drives, and residential and commercial heating, air conditioning, lighting, and appliances. The end-use electricity level in the low scenario, taken from the CONAES scenario A, assumed electricity demand at a constant level of 7.4 Quads for 1980 to 2010, and extrapolated the same constant level to 2030. That level is very close to the actual end-use electrical consumption in 1979 which was 7.6 Quads. The total primary energy consumption

in the CONAES scenario A is 74 Quads, compared to actual use in 1979 of 78.9 Quads.[24]

The high scenario represents a major expansion of the use of electricity in all sectors. The scenario is taken from the E 1A Series C projection from the Long-Term Energy Analysis Program. The total primary energy use in this scenario is 169 Quads. The scenario projects a major shift in residential fuel use, with electricity supplying 60 percent of all residential needs and 55 percent of residential heating. (Water and space heating alone are projected at 8 Quads end-use electricity in 2020.) Electricity is expected to provide 70 percent of the commercial energy demand in 2020. In this project ion, EIA forecasts that the industrial sector will grow faster than any other sector, and that industrial use of electricity will triple or quadruple by 2020. Total energy use in the industrial sector in the scenario is 63 Quads in 2020. Electricity's share of the industrial energy sector rises from 11 to 20 percent. The dominant supply technologies in the scenario are coal and nuclear, with coal providing 60 percent, nuclear 33 percent, and hydro and other renewable the remainder. The E 1A scenario was extrapolated to 2030, using the same electric growth rate as assumed in 2010 to 2020, namely 1.9 percent. According to the extrapolation of this scenario, the total energy use in 2030 is 196 quads and the total electricity use is 30.2 Quads (end use).

The middle scenario is chosen to be the midpoint between the high and low scenarios at each of the decades projected. The end-use figures for each of these three scenarios are given in table 22.

OTA does not suggest these demand levels as forecasts of what will occur. These futures were chosen to illustrate the way various technologies might be used and the constraints that might be placed on their selection.

[24] *Energy in Transition*, op cit

Table 22.—Range of Energy Demand in 2030

Scenario	End-use electrical (Quads)	Primary total energy (Quads)
High	30.2	196
Mid	18.8	135
Low	7.4	74

SOURCE: Office of Technology Assessment.

To characterize the mix of supply technologies possible under these scenarios, a number of questions was addressed. Among these questions were the numbers and kinds of technologies that would contribute to the supply mix under the various scenarios, the maximum reasonable SPS contribution under each scenario, the most likely technologies to replace SPS were it not deployed, and the relative implementation rates of the various technologies under different demand conditions. The exercise carried the simplifying assumption that one technology could be substituted for another These questions cannot be answered precisely, but their discussion leads to interesting insights into the potential role of SPS.

Low-Demand Future

For this case, end-use energy demand for electricity is selected to be 7.5 Quads (today's level). A zero electric growth future is likely to be the result of substantial conservation – probably resulting from high energy prices — and the failure to develop end-use technologies that use electricity at a lower net cost than technologies using liquid or gaseous fuels and direct solar. The principal feature of this future is that electricity demand can be satisfied without SPS, fusion or breeder reactors. The supply potential of coal, hydro, ground based solar (including wind) and conventional nuclear would be more than sufficient to meet demand Even if coal were to be phased out due to negative findings about the CO, buildup, its share could probably be absorbed by other sources. Zero growth in electricity demand gives the nation considerable time for developing new technologies.

In this situation utilities would only need to replace retiring plants. Therefore they would have considerable latitude in choosing technologies. Further, a zero growth rate would not favor large plants because they would add too much capacity at one time. Therefore, small-scale, dispersed technologies may play a major role in this future. If any of the new tech-

nologies under discussion are introduced they will have to appear in relatively small increments in order to maintain system reliability. For example, one could expect SPS to provide no more than 1 to 2 Quads at any given time to the 7 to 8 Quad total. This would act strongly against an SPS the size of the reference system since it would only require 7 to 15 units of 5,000 MW at a 90-percent capacity factor to supply this much energy. Therefore deployment of any SPS would depend on an international demand for electricity and/or the development of much smaller units than the reference system (perhaps on the order of 500 MW). A similar argument could be made about fusion and breeder reactors, although current development plans show the size of eventual commercial plants to be 1,000 MW or less.

In summary, a scenario that shows little or no increase in electricity demand for the next several decades does not appear to be attractive for accelerated SPS development, particularly of the reference system. At the same time, development of other central, baseload supply options ultimately competing with SPS could also be slowed. The choice among these, if needed at all, would primarily depend on which ones could most economically be developed in smaller sizes.

Middle Demand Future

In this case net electricity demand reaches about 20 Quads in 2030 representing about a 2-percent growth rate per year that is close to that which the Nation is now experiencing. Although this is about 2.5 times current electric energy demand, it too could be met without using the SPS, fusion or the breeder reactor. For example if two-thirds of the 20 Quads were produced by coal, it would require a tripling of present yearly production, which is within the Nation's capability. Current estimates of domestic uranium reserves are sufficient to supply another 6 Quads in 2030. In addition, a major contribution from terrestrial solar (wind, onsite PV) can be expected to help meet increased intermediate and peak load demands that coincide with solar peaks (space heating and cooling). If growth continues past 2030, this mix may be insufficient. Yearly coal production could probably not be expanded too much beyond this (tripled) level without straining other sectors of the economy, and by 2030 the Nation may be near its uranium resource limits. Therefore, to ensure supply beyond 2030 and to replace retiring nuclear plants, some level of new, centralized technologies would probably be needed.

If coal and conventional nuclear remain acceptable, it is not likely that all three of the major centralized technologies under development would be needed. The contribution they could make by 2030 would be small because of the time needed to bring them on line and the fact that they would be starting from a zero base sometime near 2010. A 10-percent contribution to 20 Quads would require anywhere from 60,000 to 100,000 GW, depending on capacity factor. Unlike the low demand future, this would allow SPS units of up to 5,000-MW size to be added if continued growth past 2030 is expected. A 2 percent per year growth rate means about 0.4 Quad/yr added at that time. This could be supplied by three SPS plants per year at the reference design size, in addition to baseload units to replace retired plants. This is still a small enough increment that smaller SPS plants appear to have an advantage. In addition, this demand increment is still not too large to rule out its being met by onsite solar, wind, and centralized solar. All have much lower energy densities than fusion or breeders, however, and eventually their contribution will be limited by available area. About 25 m^2 are required to supply a continuous kilowatt of solar electricity assuming PV conversion efficiencies of 20 percent. The entire 0.4 Quad could be supplied by about 125 mi^2, not an unreasonable area.

If coal is not acceptable because of $C0_2$ then there will have to be a substantially larger contribution by the newer technologies. In this case it is plausible that all three, plus substantial ground based solar, would be needed. Such a replacement could be achieved with these new technologies but it would be a sizable effort. If coal supplied just half of the electricity in the case discussed above, about

10 Quads of new electric energy would have to be found, requiring 300 to 500 GW. If new plants were on the order of 1,000 MW in size, a construction rate of 15 to 25 per year would be needed assuming they were first available in 2010. Under this future of constrained coal, then, there would appear to be sufficient demand for al l technologies to be introduced at a rate that would pay for their development in a reasonable period. Also, it is not likely that any one technology would be relied upon to supply the entire 10 Quads at the end of this 20 year phasing-in period. An even three-way split, for example, would mean that SPS would supply about 100 to 150 GW by 2030.

High-Demand Scenario

This future assumes a final demand for electricity of 30 Quads (about four times the current level), meaning a growth rate of about 2.8 percent per year. At that rate, about 0.8 Quad/yr would be added in 2030. If one assumes an increase in net conversion efficiency from today's 29 to about 35 percent and an increase in capacity factor from 42 to 55 percent, then this total demand could be met by an installed generating capacity about three times today's figure. Efficiency and capacity factor will almost certainly have to increase if a 30-Quad demand is to be met. Total system capacity would be in the range of 1,200 to 2,400 GW (1,800 GW at 55-percent capacity factor).

To be able to supply this much electric energy, all technologies would probably be needed. Further, larger plants are likely since a demand increment of 0.8 Quad/yr would require about 40,000 to 50,000 MW of new capacity per year. Therefore, addition of plants ranging from 1,000 to 5,000 MW would not cause any significant short- or long-run overcapacity problems. Because of the large amount of capacity needed, conventional nuclear and coal will probably be able to supply only about two-thirds of the total (i. e., about 1,200 GW) before they reach the limits discussed above. Thus, about 600 GW must be supplied by hydro, ground based solar, geothermal, and some combination of SPS, fusion and breeders. Breeders are likely to supply the bulk of this by 2030, provided they are acceptable, since they are the closest to commercial readiness. Even so, as much as 200 GW of SPS could be needed by 2030. The SPS development would have to be accelerated if it is to meet a goal like this. The same holds true for fusion, which could also be required to supply around 100 GW by 2030.

The mix of technologies will be determined substantially by constraints such as environmental concerns, capital, land and water availability, materials limitations and labor requirements. For example, limited water would favor SPS and ground-based solar PV. Limited capital, however, would favor the least capital-intensive technologies such as coal and act against the SPS. In any event, these constraints will be very important at this demand level because of the large number of powerplants needed

If coal must be phased down or eliminated then even larger demands will be put on the new technologies. For example, if coal and conventional nuclear could only meet one-third of the demand, an additional 600 GW of capacity would be needed. In this case it is probable that an all-out breeder program would be needed. This should not affect the SPS– in fact, more satellites may be needed– but it could actually reduce fusion's contribution since it is a competing nuclear technology. The terrestrial, onsite solar contribution will have to be large in either case but is very unlikely to be able to supply even one-half of the 30 Quads. Even 20 percent of the demand would require a very large deployment of PV systems — nearly 400 GW of dispersed generating capacity.

Conclusion

The size of future electric demand will be the major determinant in the amount of SPS capacity installed, assuming successful development and competitive price. Table 23 shows estimates of the upper range of SPS capacity available for each future for the case of full coal development and coal phaseout.

Table 23.–Upper Range of SPS Use (in GW)

Future (Quads)	With coal	Without coal
7.5	0	0-30
20.0	0-60	100-200
30.0	100-200	100-200

SOURCE: Office of Technology Assessment

In addition to determining the upper range of the contribution of SPS the demand level and rate of growth will also determine the preferred unit size. For the low scenario, smaller plants would be preferred since overcapacity problems caused by adding too much at once would probably more than offset gains made by any economy of scale. For the upper future, however, for even the largest SPS proposed plant size, it is unlikely that too much can be added at once for any reasonable construction schedule. The mid scenario, however, gives somewhat ambiguous results, although the smaller size SPS systems appear generally to be more desirable.

For the first two scenarios it is unlikely that all three major, centralized supply technologies will be needed simultaneously, even if coal cannot be used. Onsite, dispersed solar will be able to make up a larger percentage of the needed capacity and could eliminate the need for any new centralized technology in the low demand case. In all cases, coal can be the dominant source and continue in that role for several years past 2030. Finally, as the demand for electricity increases, decisions about capacity mix will become more and more dependent on physical and labor constraints because of the sheer size of the capacity requirements.

THE EFFECTS OF SPS ON CIVILIAN SPACE POLICY AND PROGRAMS

The effects of SPS development on the U.S. civilian space program would be great, though their precise type and magnitude would depend on the kind of SPS built, the overall speed of the development program and the status of space capabilities at the time. An SPS program would stimulate more rapid development of space transportation, large-structure assembly and manned-mission capabilities, and automated operations. SPS development would also have a bearing on national space policy and institutional structures, both Government and private sector. The following discussion will examine four areas: 1) space policy, 2) current and future space projects, 3) institutional structures, and 4) indirect effects and "spin offs."

Space Policy

The Nation's space policy is a reflection of broad national goals. The principles guiding the U.S. civilian program were first enunciated in the 1958 National Aeronautics and Space Act, and have been periodically reaffirmed with minor modification and changes of emphasis. The 1958 Act states that "activities in space should be devoted to peaceful purposes for the benefit of all mankind," to promote the "general welfare and security of the United States " The Act specifies that civilian activities shall be directed by NASA, and military/defense operations by the Department of Defense. The specific aims of the space program include: expansion of knowledge, improvement of space transportation, "the preservation of the role of the United States as a leader in aeronautical and space sciences," and cooperation with other nations. NASA was established to "plan, direct and conduct aeronautical and space activities. "[25]

These general goals and this framework have been reaffirmed subsequently, most recently in the "Directive on National Space Policy" and the "White House Fact Sheet on

[25] "Natlonal Aeronautics and Space Act of 1958, as Amended, " in *Space Law, Selected Basic Documents,* **Senate Committee on** Commerce, **Science, and Transportation; U.S. Government** Printing **Of flee, 1978; pp 499-503**

U.S. Civil Space Policy," both issued in 1978. In these documents the Carter administration committed the United States to increase scientific knowledge, develop useful commercial and Government applications of space technology, and "maintain United States leadership in space technology. " Establishing and maintaining satisfactory relations between the civil and military programs was recognized as a priority issue, and the National Security Council was charged with providing coordination for all Federal agencies involved in space. Cooperation with other nations, including joint programs and the development of a stable legal regime allowing all nations to use outer-space for peaceful purposes, were emphasized as important goals. The investment and direct participation of the private sector in space activities was addressed in the context of remote-sensing systems. NASA's responsibilities for the operation, as opposed to research, development, and testing, of applications systems have yet to be clarified.26

The U.S. civil space program can thus be said to have an ongoing set of policy goals:

- scientific — increasing knowledge,
- political — maintaining U.S. preeminence, and
- economic–developing useful commercial applications.

It also has a continuing policy framework:

- separation of civil and military programs (with various mechanisms for coordinating different efforts),
- cooperation with foreign countries and agencies, and
- separation of NASA R&D and prototype development programs from commercial applications (an unclear relationship).

Would an SPS program alter the basic thrust of U.S. policy? I n terms of goals, an SPS program would be primarily an applications effort for commercial purposes, and hence would further the economic goals that have been emphasized in recent policy proclamations.

The political end of U.S. preeminence in space, though no longer stressed as strongly as during the Apollo program, would also be served by commitment to an SPS. (This assumes that the project would be successful; failure of such a high-visibility effort could be extremely damaging to U.S. prestige. International cooperation might tend to mitigate this danger.)

The SPS program would not be focused on increasing basic scientific knowledge, but much of the research and experimentation required would provide some scientific gains; in addition, the infrastructure for SPS (e. g., platforms, transportation vehicles) could be used for a multitude of scientific projects in space. There is some danger, though, that focusing the national space program on such a major applications project as SPS would divert resources and attention, at least temporarily, from scientific missions.

The effects of SPS on the U.S. policy framework will depend on how it is financed and managed. Civil-military relations could be altered. Although the SPS is not technically suited to be used as a weapons system, much of SPS technology and infrastructure, especially the transportation vehicles, would have military uses (see ch. 4). Furthermore, it is unlikely that a project with the scope and impact of SPS could be approved by Congress without at least the tacit consent of the Department of Defense (DOD). In the foreseeable future, DOD requirements for aerospace expertise and facilities will be great, and SPS may be seen as a competitor for scarce resources unless direct defense benefits can be realized. Although an SPS program would not be run by the military, it might be necessary for the civil and military sectors to be more closely coordinated than has previously been the case.

Foreign cooperation and joint ventures might be encouraged not only by the desire to improve international relations but by more direct economic considerations. (see ch. 7). These considerations would be strong enough

[26]" Description of a Presidential Directive on National Space Policy, June 20, 1978, " and "White House Fact Sheet, U.S. Civil Space Policy, Oct 11, 1978," in *Space* law, pp 558-564.

to provide for a greater degree of shared responsibility than in any equivalent U.S. program to date, unless U.S. military involvement proves an insuperable obstacle. International participation might be such that the project could no longer be run as a U.S. venture with limited foreign cooperation, but would become a truly multinational effort with no dominant U.S. role.

The relation between public and private participants would be a major issue in any SPS program. Policy in this area has not been clearly established, though there is precedent for detaching applications projects, such as satellite communications and Landsat, from NASA after development is completed. NASA has conducted all U.S. civilian launches on a reimbursable basis; it is unclear what would happen if private firms wished to build and/or launch their own vehicles, as has been suggested for the shuttle. If, as is presently the case, a Federal SPS program were managed by DOE or some other agency besides NASA, NASA might be responsible for only a limited part of SPS development and NASA restrictions and policies might not apply.

Current and Projected Space Projects

SPS would be strongly affected by current space programs and capabilities, and in turn might also determine what many of those programs would be. However, since an SPS development decision is unlikely to be made before 1990, and may not be possible until 2000, (see ch. 4), SPS will not shape NASA projects conducted during the next decade (though it may affect long-range planning).

Historically, NASA has devoted the major portion of its resources to a single major project, first the Apollo lunar-landing program, and then the Space Shuttle. However, there are currently no plans for a similar "centerpiece" project to follow the Shuttle; the White House Fact Sheet asserted explicitly that: "it is neither feasible nor necessary at this time to commit the United States to a high-challenge space engineering initiative comparable to Apollo." Instead, present plans call for a number of smaller scale operations and scientific missions centered around use of the Shuttle and other components of the Space Transportation System (STS). The lack of a single, clear, overriding project goal for the civilian space program has been criticized for squandering NASA and contractor capabilities, and leaving the United States without a visionary and profitable use for the new transportation capabilities under development. This problem will undoubtedly be addressed during the 1980's, but jurisdictional and philosophical differences, as well as budgetary constraints, may make consensus difficult to achieve.

For the next 5 years, NASA plans to concentrate on a number of areas: those most directly relevant to SPS include:

1. Transportation and Orbital Operations: Transportation efforts will concentrate on meeting shuttle schedules but also include other elements of STS: the inertial upper stage, for placing payloads in geosynchronous orbit (CEO) (under development by the Air Force); Spacelab, for manned and unmanned experimentation (joint program with ESA); development of orbital transfer vehicles such as an electric orbit transfer vehicle (EOTV); systems to handle payloads outside of the Shuttle; and free-flying platforms. Each of these programs will be important for improving our capability to move and work in space, and hence directly relevant to SPS. The key element is the Shuttle, which must work and work well if these projects are to proceed during the 1980's. Delays in Shuttle operations, or in building additional orbiters, will not only retard these projects but also might prevent SPS-specific research flights as envisioned in one of the policy Options from taking place in the late 1980's (see ch. 4).
2. *Immediate Applications:* In this area, space processing experiments to be conducted on Spacelab could be important in determining the proper kinds of materials for SPS construction, as well as prospects for direct processing of raw materials in orbit. Communications and remote-se ns-

ing development will involve work with microwave transmission, lasers, and mirror systems, as well as detailed studies of the upper atmosphere,[27] which will be vital in determining the environmental effects of launch effluents and energy transmission beams.

3. Solar Radiation: The Solar Maximum Mission (launched February 1980) and the upcoming International Solar Polar Mission, scheduled for 1983, will study solar radiation and its effects on the near-Earth space environment. Such information could be important in designing SPS solar cells and in adding to our knowledge of the effects of radiation on SPS workers: ionizing radiation in CEO is a potentially serious obstacle to human effectiveness and could be decisive in determining the optimal "mix" between automated and human-controlled operations.
4 Humans in Space: The studies of Shuttle crew performance as well as specific Spacelab experiments will provide a basis for determining the long-term effects of weightlessness and cramped quarters, and for designing appropriate equipment to improve manned performance. 28

The above projects are already underway and are those for which funding or explicit planning are in place. NASA has also outlined other, longer term plans that would be important to SPS. NASA's Office of Space Transportation Systems' long-term goals are predicated on the assumption that "the growth of U.S. civilian space programs in the 1990's will probably continue to be moderate and evolutionary, rather than rapid or 'Apollo-like,' " and that "space projects will increasingly have to demonstrate significant economic return or perform essential services to obtain approval." The specific goals are: 1) routine operation of the STS by the mid-1 980's; 2) routine operation of unmanned large low-Earth orbit (LEO) platforms by the mid-1980's; 3) a permanent manned facility in LEO for research, construction, and operations, by the end of the 1980's; and 4) a permanent facility in GEO, eventually manned, by the late 1990's. Meeting goals would involve:

- augmenting the Shuttle's thrust, perhaps via a liquid booster;
- developing EOTVs, such as the low-thrust ion-propelled Solar Electric Propulsion System (SEPS) for service to geosynchronous orbit;
- equipping the Shuttle and its modules with a 25-kW add-on electrical power system; and
- carrying-on a ground and space-based effort to fabricate and assemble precision structures in orbit .29

All of these projects could have direct bearing on SPS and on any future decision to proceed with SPS development. Some of the longer term aims, such as SEPs, might overlap with an SPS development program, that would provide a strong impetus for their completion.

NASA is not the only body with plans for space. DOD goals, though largely classified, include large platforms, orbital microwave radars, and space-based lasers. DOD requirements could drive NASA projects such as Shuttle thrust augmentation, or lead to separate development of SPS-useful equipment.

Other long-range projects have been suggested by many individuals and organizations, in and out of government. In the transportation area, these include very large fully reuseable launchers; laser-propulsion; 30 lightsails, to power low-acceleration transfer vehicles or deep-space missions; [31] and mass-drivers to lift material off the lunar surface, or as a solar-powered propulsion system for space vehicles.[32] Other than the building of full-scale permanent colonies, SPS is the largest space project proposed to date, in

[27] National Aeronautics and Space Administration, *NASA Program Plan, Fiscal Years 1987 Through 1985, 1980,* p 107
[28] Ibid, pp 3-5
[29] Ibid pp 190-205
[30] A Hertzberg, K Sun, W Jones, "Laser Aircraft, *Astronautics and Aeronautics,* March 1979 p 41
[31] K Eric Drexler, "Spinoffs To and From SPS Technology: A Preliminary Assessment," OTA Working Paper, June 1980, p. 9
[32] G. O'Neill, G Driggers, B. O'Leary, "New Routes to Manufacturing in Space, " *Astronautics and Aeronautics,* October 1980 pp 4651

terms of expense, returns, timeframe, and amount of people and materials placed in orbit; if developed it would be a spur to all forms of cheaper space transportation.

SPS's effect on space projects would depend to some extent on the type of SPS that would be developed, the size of each unit, and the size of the entire system (as well as the scope and type of space program in place at the time). A geosynchronous microwave SPS similar to the reference design would require extensive transfer vehicle capacity and hence lead to accelerated development of EOTVs, chemical-powered personnel vehicles, and manned GEO construction stations. A laser-SPS in LEO, on the other hand, would require relatively little LEO to GEO transfer capacity. A mirror-system might need even less upgraded lift or construction capacity in order to be fully deployed (see ch. 5).

A large SPS system consisting of many satellites would tend to have greater economies of scale, leading to the development of more and different sorts of vehicles, and greater mass-production and automation. In-orbit processing of lunar or asteroidal raw materials would also be feasible only if a very large system were built, to justify the front-end costs of lunar mining and orbital processors.

Institutional Structures

Would an SPS program require a change in current national institutions? The completed SPS Concept Development and Evaluation Program[33] was a joint DOE/NASA effort, with DOE providing most of the management and NASA providing technical support. A decision to have further SPS research, development, and demonstration efforts managed by DOE would likely prove awkward, since the bulk of the up-front development costs would be for space systems; hence DOE would have to pass most of its SPS funding to NASA, or attempt to develop its own contractor relations and in-house space capability, which would be time-consuming and wasteful. SPS would require a much clearer and stronger coordinating mechanism than currently exists for national space programs, since not only NASA and DOE but a number of other departments and agencies would be involved. 34

Extensive NASA involvement in SPS would require clarification of NASA's appropriate role in commercial applications ventures, and perhaps modification of NASA's charter. Both underlying policy— i.e., to what extent NASA should operate applications systems, such as Landsat and communication satellites—and specific procedures for turning over patents, technology, and hardware to private industry or other Government agencies, have been subject to continuing controversy. *

It is probable that a separate public or quasi-governmental body would eventually be set up, outside of NASA and DOE, to manage an SPS program. Such a decision would be influenced by, among other things, the desired mix of public and private funding, and the degree of international involvement. Possible forms such a body might take are discussed in chapter 9, Financing Ownership and Control, and in chapter 7.

Indirect Effects and "Spinoffs"

There would be three kinds of indirect effects of SPS development:

- technology and hardware developed for SPS that could have other uses (and that otherwise would not be developed or would be developed at a much slower pace),
- uses of the SPS itself other than providing terrestrial baseload electric power (and that would otherwise not be provided for), and
- economic/technological changes and basic shifts of national attitudes

SPS developed technologies and hardware: Most, though not all, of these spinoffs would relate to space capabilities. We have already

[33] "Satellite Power Systems Concept Development and Evaluation Program, "Program Assessment Report Statement of Findings," November 1980, DO E/E R-0085

[34] DOE report on SPS and Government agencies – in press

*See OTA assessment, *Space Policy and Applications*, in preparation

seen that NASA's transportation plans include many elements directly useful to SPS, which SPS development would tend to accelerate or modify. Although the reference system calls for heavy-lift launch vehicles able to carry 400 tons to LEO, and a 5,000-ton payload EOTV, the exact types of vehicles needed cannot yet be specified. The proper mix between size, numbers, and types of vehicles depends on many unknown factors, including the type of system, its location, and the number of satellites to be built.

The combination of improved and cheaper transportation, robotics and teleoperation, possible new construction materials (such as graphite composites), and human expertise, would make possible many commercial space activities. Large communications platforms, scientific and industrial research facilities, processing plants for chemical and raw materials —these are a few possibilities. Past experience teaches that commercial exploitation follows in the wake of the development of new capabilities, and cannot be accurately foreseen. 35

Space industrialization could be greatly enhanced by the use of extraterrestrial raw materials. SPS could lead to lunar or asteroidal mining by fostering the development of transport and robotics capacity, as well as by providing a major market for processed products such as aluminum, steel, silicon, and oxygen. The most detailed studies have examined mining the lunar surface, and launching raw materials to orbiting processors via an electrically powered mass driver. Others have suggested mining or capturing a small asteroid, preferably a carbonaceous-chondrite asteroid rich in carbon and high-grade iron/nickel ore.[36] Establishing such facilities, which might be done in the later stages of SPS development, could considerably reduce the costs of transporting material to high orbits.

On the ground, SPS would require large-scale automated production of solar cells; some of this technology could also be used for ground-based solar projects.

Space or ground-based industries using SPS-developed technology or hardware could, at least temporarily, compete with SPS for scarce resources. A mechanism for allocating priorities might have to be established to resolve competing claims.

Alternative SPS uses; Depending on the electromagnetic environment (i.e., on the type of system used and the amount and type of shielding available), the SPS platform, whether in (GEO or LEO, could be used as a station for a variety of communication and remote-sensing equipment. A GEO SPS would be especially useful, due to the relatively small number of positions available. Remotely operated optical astronomy devices could be placed near or on SPS as a way of escaping the interference faced by Earth-based telescopes. Given a large amount of space traffic associated with increasing industrial and military space flights, the SPS station could become a focal point for local storage, refueling, and rest and relaxation for crews – a kind of spaceport. Living quarters for maintenance crews and construction workers could be expanded and upgraded into occasional (and, initially, very high-cost) tourist accommodations.

SPS electricity could be used in orbit, either at the satellite itself or at remote sites equipped with receiving antennas, to provide power for industrial activities. Processing, especially of extraterrestrial raw materials, could require large amounts of electrical power that might be more efficiently supplied by a central SPS than by building specific electrical capacity.

Some SPS designs, especially the mirror-systems, might produce enough power to be used for local climactic modification. This would require more precise understanding of weather systems than is now available. Orbital mirrors have also been suggested as a way of providing nighttime illumination of cities and/or of cropland to enhance growth. 37

[35] Woodcock, op cit, p 12
[36] Drexler, op. cit, pp 10-11
[37] Woodcock, op cit

Special mirror surfaces that reflect only specific wavelengths would need to be developed for such purposes.

Generic economic and social effects: A successful SPS could be instrumental in provoking an economic upsurge by stimulating new production in the aerospace and energy industries, and new industries altogether in space fabrication, solar cells, antenna construction, and so on. Specific technical advances necessary for SPS and likely to provide economic spinoffs have been mentioned. The likelihood of a revolutionary new product, comparable in effect to the transistor or microchip, resulting from SPS is unpredictable. Estimates of the aggregate economic and technical effects of large research and engineering projects, such as Apollo or nuclear reactors, vary enormously. Some credit a large portion of the U.S. economic vitality and technical leadership in the 1960's, especially increases in research, engineering, and project management skills, to Federal investments in the Space program .38

[38]Drexler, op cit , pp 8-9

SPS might prove equally stimulating. Others argue that these resources would have been available anyway, and could have been used in more efficient ways.

Arguments about long-term social vitality also often revolve around the Apollo experience. The optimism and vision that characterized the "Apollo decade" are contrasted with the pessimism, uncertainty, and sense of limits of the post-Apollo 1970's. Skeptics, however, argue that Apollo represented a misguided effort to escape from more pressing social and political problems, and that the space program lost public support when this became apparent[39] (see ch. 9). Whether the United States will regain some of its former enthusiasm for large high-technology projects will depend partly on the success of current efforts, such as the Space Shuttle, and on the magnitude and type of benefits that such projects offer.

[39]Klaus Heiss, "New Economic Structures for Space in the Eighties, *Astronautics and Aeronautics,* January 1981, p 17

CHAPTER 7

THE INTERNATIONAL IMPLICATIONS OF SOLAR POWER SATELLITES

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Chapter 7

THE INTERNATIONAL IMPLICATIONS OF SOLAR POWER SATELLITES

INTRODUCTION

The development of solar power satellites (SPS) requires consideration from the perspective of its international implications. First, as a space technology SPS would operate in a global medium, outside of any national territory, which is subject to international law embodied in existing treaties and agreements. Secondly, as a major energy project the SPS would affect supply and demand for what is by far the largest commodity traded on international markets, one that is of vital interest to all countries. Thirdly, because of its tremendous cost and technical sophistication an SPS system could have a strong effect on the economies of states involved in its construction. And finally, development of an SPS and of the launchers needed to build and maintain it may give its builders significant military and/or economic leverage over other states.

This chapter will look at the SPS primarily from a political perspective, because in the final analysis SPS development will depend on national efforts, instigated by national leaders, paid for– in large part– by public funds. The United States is the only country in which there is any likelihood that there would be significant private-sector responsibility for SPS decisions. The importance of national efforts would be especially crucial in the near future when SPS projects are in the R&D and prototype construction phases.

Actors. – If SPS is developed, Government involvement would be guaranteed because SPS would affect vital national interests in a number of areas, e.g., external security, prestige and influence, and economic growth. Energy policy in itself has become a central component of national planning in most countries.

Nonstate actors would be involved as well. On the international level these include global organizations such as the United Nations and its specialized agencies; multilateral groups such as the Organization for Economic Cooperation and Development (OECD) and OPEC; and regional groupings such as the Common Market and the European Space Agency (ESA). On the substate level there are numerous interests, including those of private companies, public utilities, and governmental agencies, that often conflict and that seek to influence national decisions. Furthermore, the role of the large multinational corporations in international relations is in some areas very great and often independent of direct government control

However, for the SPS, national decisions and interests are likely to predominate. Although the rise of energy as a major global concern has led to the formation of numerous international organizations (such as the International Energy Agency) and to intense discussion of the global dimensions of energy prices and shortages, the overall impact has been to place decisions about energy consumption and production more and more firmly in the hands of national governments. In general, it seems that the role of the state in furthering peace and security, stability, prestige, and economic well-being has not been supplanted by other entities.

Forecasting. – Because SPS is a project which, if pursued, will not reach fruition for at least 20 years, assumptions must be made about future political and economic developments. Since radical changes are by definition unpredictable, these will be unavoidably conservative. In general, it is assumed that the basic political and socioeconomic alinements of today's world are likely to continue. In the past, fundamental realinements of the international political structure have often been the

result of major wars or of deep-seated alterations in political and social expectations, neither of which can be confidently predicted. Even relatively small shifts in public support for various programs can have large effects; increasing skepticism in American and European attitudes towards the space program and nuclear energy in the late 1960's and early 1970's, for instance, has decisively affected our current space and energy capabilities.

DEGREE AND KIND OF GLOBAL INTEREST IN SPS

National and regional interest in the SPS will stem from an evaluation of the ways an SPS system would affect all the components of national interest outlined above. The degree and kind of interest shown will vary from nation to nation. In deciding what institutional structure to use for SPS development, it is crucial to take these various foreign interests into account. In this case, interest can be divided — somewhat arbitrarily— into economic and noneconomic components. The economic interest in SPS would be focused on SPS's ability to provide electricity, and hence on the local demand for electricity over the time SPS becomes available. Noneconomic concerns would include prestige and national security interests.

Economic Interest

A recently completed study by the international Institute for Applied Systems Analysis (IIASA), Energy in a Finite World,[1] provides the most up-to-date projections of long-range future global energy demand. The IIASA study uses a global model with several different scenarios, broken down on a regional basis. We will present the high and low estimates to give the entire range of predictions; it should be noted that the lower estimates are closer to those of some recent U.S. studies, such as Energy in Transition 1985-2010, by the National Academy of Sciences.[2] (See app. C.) In general the slowdown in gross national product (GNP) growth over the past several years, and the sharp rises in oil prices in 1979, have caused recent energy forecasts to be much lower than those of only a few years ago. Since OTA believes that IIASA's analysis may tend to overestimate future energy demands (see app. C), especially in the advanced industrialized countries, the following figures should be used with some caution.

The IIASA projections for primary energy demand are based on an integrated model in which supply and demand are matched on a global basis (see table 24). (See app. C.)

Historically, the rate of growth in electrical demand has been approximately twice as high as that of total energy demand. IIASA predicts that it will remain higher, but by a factor of 1.4 instead of 2.0.3

Currently, electricity accounts for an average of 11 percent of global end-use energy, ranging from 6.5 percent in developing countries to 12 percent in the OECD. By 2030, IIASA expects this figure to rise to 17 percent (in both high and low scenarios), with developing countries using 13 percent and OECD 21 percent, reflecting an annual increase in usage of 2.6 percent (low) to 3.4 percent (high).[4]

[1] Energy *in a* Finite *World,* A *Global* Systems Analysis, Energy Systems Program Group, International Institute for Applied Systems Analysis (Cambridge, Mass.: Ballinger Publishing Co., 1981).

[2] *Energy in Transition 1985-2070* (Washington, D. C.: National Academy of Sciences, 1979).

[3] Finite *World,* op. cit., p. *482.*

[4] Ibid

Table 24.—Primary Energy Demand (Quads)

	1975	2000		2030	
		Low	High	Low	High
OECD	146.8	200.3	224.5	266.3	393.4
SU/EE (Soviet Union, E. Europe)	55.0	98.9	110.3	149.4	219.1
Developing	37.7	107.0	148.9	253.8	453.1
Global Total	239.5	406	503.7	669.5	1,065.6

SOURCE: *Energy in a Finite World;* conversion to Quads done by the Office of Technology Assessment.

Electricity use is affected by many factors, including changes in end-uses, (such as heat pumps or electric cars), saturation of demand, and the cost and availability of fuel (see ch. 6). Table 25 shows the IIASA figures for end-use electricity demand.

Assuming 70-percent load factors and 15-percent losses in transmission and distribution, IIASA estimates for installed generating capacity in 2030 are shown in table 26.

Although the IIASA report is pessimistic about the possibility of extensive use of alternative energy sources, such as fusion or ground-based solar, by 2030, it points out that a breakthrough in fusion or solar-cells would change the supply and cost of electricity drastically. Cheap photovoltaics might encourage a shift towards a "hydrogen economy, ''with electricity produced in high-insolation desert areas being "stored" and transported as hydrogen. [5]

Barring such developments, future baseload electrical demand will be met overwhelmingly by coal and nuclear sources (see app. C). IIASA also predicts that coal will be used extensively for producing liquid fuels, especially in coal-rich regions such as North America and the Soviet Union — up to 55 percent of coal production in North America by 2030[6] (see app. C).

[5] Ibid., p. 163.

Table 25.–End-Use Electricity Demand (Qe)

	1975	2030	
	—	Low	High
OECD	12.5	35.3	50.2
SU/EE	3.9	15.5	25.4
Developing	1.8	23.3	41.3
Global Total	18.2	74.1	116.9

SOURCE: *Energy in a Finite World,* p. 659. These numbers should be taken as approximations, since they are based on IIASA estimates of the percent of end-use demand that will be met by electricity. For graphic presentation, see *Energy,* p. 481.

Table 26.—Amount of Global Installed Capacity (GWe)

1975	2000		2030	
	Low	High	Low	High
1,600	3,550	4,390	6,320	9,845

SOURCE: *Energy in a Finite World,* p. 483.

Regional Variations

In order to understand how different countries might view SPS, it is crucial to highlight the major regional differences that will affect demand for electricity. Foremost among them is the question of regional or national self-sufficiency.

SELF-SUFFICIENT AREAS

In the 50-year time-frame considered, it appears possible for three major consuming regions — North America, Soviet Union/Eastern Europe, and China –to achieve energy self-sufficiency. This would require rapid development of indigenous sources of North American oil shale, tar sands, and Western coal; for the Soviet Union, untapped oil, gas and coal reserves in Central and Eastern Siberia; for China, development of oil and coal deposits and expanded exploration in Western China. In all three cases very substantial growth in nuclear and/or solar, hydro, and other generating sources would also be required. With the possible exception of U.S. and Soviet coal, none of these regions is likely to export significant energy supplies, since indigenous growth will absorb most new capacity even under optimistic scenarios.

The costs of achieving regional self-sufficiency would be very high. Development of North American oil shale and tar sands, for instance, on a scale sufficient to produce oil and gas in quantities comparable to the large commercial oilfields of today, will cost hundreds of billions of dollars. Such development will also be "dirty" environmentally, involving extensive surface-mining, and hence expensive to clean up and to regulate.

In the Soviet Union, currently the world's largest oil producer, finding the capital for major energy investments during the 1980's will be difficult. Inefficiencies in central planning practices are likely to be magnified as de-

[6] Ibid , p 669,

mands for consumer goods and services increase.

China's energy production potential is not well enough known to predict future supplies with any certainty. Oil, coal, and oil shale are known to be present in large quantities. Current modernization plans call for sizable energy investments.

ENERGY-DEPENDENT AREAS

Regions without sufficient local resources will include Western Europe, Japan, and large portions of the (currently) developing world. Western Europe and Japan can be expected to invest heavily in nuclear plants, especially fast breeders.

Unfortunately neither Western Europe nor Japan is in a good position to exploit alternate nonnuclear technologies to alleviate dependence on imported oil. Except for a relatively small part of Southern Europe, average annual insolation is low—only 1,000 kWh/m^2 in Central Europe, compared to 2,500 kWh/m^2 in Arizona. ' Hydroelectric resources are limited and already extensively developed. There are no large wooded areas to provide biomass, and regional cropland in densely populated regions is scarce.

It is likely that Western Europe and Japan will try to develop assured foreign sources for future needs. This may take the form of joint development of capital-intensive North American energy projects, gaining through partial ownership an assured source of supplies. Foreign interest in U.S. coal, including investment in mines and shipping facilities, has accelerated since the 1979 rise in oil prices.[8] However, it is unlikely that national policy in the United States and Canada will permit extensive ownership of energy resources by foreign countries or enterprises, or significant exports of nonrenewable fuels, even to friendly countries. Though the size of the capital requirements may allow for foreign participation, it will not be enough to alleviate European or Japanese shortages. Investment in or legal control of foreign assets provides little insurance against price rises or expropriation, when the local government is so inclined.

The underdeveloped energy-poor regions vary greatly in their levels of development and their degree of energy dependence. In virtually all cases oil-price rises have seriously hampered economic growth.[9] In some instances the increases have spurred development of indigenous sources– nuclear plants in Brazil, Argentina, and India; biomass in Brazil; numerous small-scale hydro and solar projects suited for decentralized generation. It is in the less developed countries (LDCs) that the greatest proportional surge in energy demand and electrical usage will come over the next 50 years, rising from 12 percent'" to 31 to 35 percent of global electrical demand (see app. C). Decentralized systems can be effective in regions without developed utility grids and where demand is for small units for domestic, agricultural, and light industrial use. But the baseload power needed for extensive growth and modernization will be expensive and in short supply.

ENERGY-EXPORTING AREAS

Current energy-exporters include OPEC members as well as a few non-OPEC oil producers, such as Mexico, Malaysia, and the Soviet Union. Over the next 50 years, many current oil-surplus states will cease to export, due to increased domestic consumption and/or decreased output. The time and rate at which current oil production in exporting countries will diminish depends on the rate of consumption as well as future discoveries. IIASA predicts only small increases in exporting country production through 2030, with demand increases being met primarily by coal liquefaction and unconventional oils. The report emphasizes that: "The 'energy problem,' viewed with a sufficiently long-term and global perspective, is not an energy problem, strictly speaking, it is an oil problem, or, more

[7] K. K. Reinhartz, "An Overview of European SPS Activities," *Final Proceedings of SPS* Program Review, Department of Energy, April 1980, p. 79.

[8] See "The Coal Ships," *Washington* Post, Oct. 13,1980, p. 1.

[9] See Energy *in* the *Developing Countries,* World Bank, August' 1980, pp 3-6

[10] '"I bid , p 44.

precisely, a liquid fuels problem.''[11] As demand grows over the next 50 years, the ability of countries to import such fuels to make up for local shortfalls will dwindle, and prices will rise sharply.

In summary then, the 50-year forecast is for an increase in demand for energy of some three to four times, and an increase in demand for electricity of some four to six times with rates being somewhat higher in the currently developing regions. These forecasts are based on a declining rate of growth in GNP, averaging some 2.7 percent (in the low scenario) to 3.7 percent (high scenario) per year. (Compared to a global average of 5 percent from 1960 to 1975.) In general, energy scarcity will cause higher prices, reducing demand and increasing supply. The question is whether future supplies will be so high cost as to force a radical change in living standards and growth rates. Maintaining a moderate rate of growth in the developed countries and a somewhat higher growth rate in the developing world —to provide for population increases as well as the prospect of real increases in living standards —will place demands on energy resources that guarantee that energy costs will consume a larger proportion of national income than in the past. IIASA predicts an increase of 2.4 to 3.0 times in the proportion of gross domestic product (GDP) spent on energy. Even if IIASA's projections prove to be on the high side, future energy sources can expect to be competitive within a very high-cost ceiling.

SPS Contribution

SPS could begin to provide electricity by 2010-20 and could be a substantial source of new power within the selected 50-year period. None of the global projections to date has considered the possible impact of an SPS system on future energy scenarios. The rise in electrical consumption is expected to be met by large increases in coal-fired generators and nuclear plants. However, there are serious problems with both methods.

Coal, like oil, is abundant only in certain areas. Unlike oil, it is expensive to ship compared to the cost of mining (because of its bulk), especially overseas and in areas without extensive rail links, While oil and gas are suitable for small-scale household use, coal is expensive to store, and prohibitively dirty to use (especially in urban areas). And increased burning of coal could have disastrous environmental consequences, including acid rain and global temperature increases (see ch. 6). IIASA predicts a 10 to 1.50 C average increase, through 2030, depending on high or low growth rates,

Nuclear plants are characterized by widely publicized environmental dangers. Even if these can be resolved, public opposition to nuclear power, as well as the rapidly increasing costs of building new nuclear capacity, have already delayed the production of nuclear generators, especially in the United States (where alternative fuels are more readily available than in many other countries). Furthermore, the spread of nuclear technology, especially breeders, into more and more parts of the world will almost inevitably make it easier for more states to manufacture nuclear weapons. Since uranium is concentrated in scarce deposits, largely in North America, the Soviet Union, and parts of Africa, many areas will be inclined to depend increasingly on breeders. The safeguards and restrictions set up by the United States to prevent proliferation have been only partially successful when the main reason for building reactors has been prestige-they will be even less effective as energy needs make nuclear plants essential.

For these reasons, SPS may be attractive as an alternative to other methods of generating electricity. In addition, unpredictable factors such as a major nuclear accident or the failure of alternative energy sources could spur interest in the SPS. SPS would by no means replace coal or nuclear power within the next 50 years, but could reduce otherwise excessive reliance on these technologies.

Economic acceptance of an SPS system would depend on several factors. Overall costs of delivered power will be crucial; these must be competitive with other systems. Perhaps equally important would be the division of

[11] *Finite World,* op. cit., p. 653.

these costs between developers, owners, and users and the way these are shared between participating countries. Development of an SPS system would require large amounts of capital and a high level of technical/engineering expertise. There are three distinct areas with capital and expertise: 1) North America; 2) the rest of the OECD countries (i.e., Western Europe and Japan); 3) the Soviet Union and Eastern Europe. Assuming that extensive cooperation between the Soviet Union and other countries is unlikely (see p. 161), the two possible collaborators have somewhat different interests. North America has the requisite technical/industrial capacity in space transportation and related areas, but is potentially energy rich, while Europe and Japan have increasing expertise in aerospace and face continued large energy shortfalls. If the future interest of these possible participants were estimated, North American interest would rate as potentially moderate to high and West European and Japanese (along with some other industrialized areas–South Korea, Taiwan, South Africa, Australia) as potentially very high. In North America, capital and interest in SPS would be competing with coal and synfuel development, as well as nuclear energy; in the rest of OECD, primarily with nuclear development. In general, development of technologies using renewable or inexhaustible fuel sources, (such as SPS, but also fusion, ground-based solar, and biomass) would be preferred to depletable ones.

The possible cooperative mechanisms for SPS development and operation will be discussed later (see Advantages and Disadvantages of Multinational SPS, pp. 159-163). It is important here to see that potential SPS users with limited initial capital and expertise to contribute to an SPS system might need special incentives to participate in buying SPS power. A major economic consideration for such SPS users might be the lack of direct and indirect spinoffs from SPS participation. Ground-based antenna construction would require large amounts of unskilled labor, but would provide few technical or managerial posts. The capability to participate directly in building and deploying the satellite portion of the system is probably beyond the reach of most of the present LDCs over the next 50 years, so that relying on SPS power might be seen as undercutting efforts to develop an indigenous energy infrastructure. Payments to foreign companies for such power would be a drain on scarce foreign exchange reserves compared to development of local resources, which cause ripple effects in the economy. User governments would be sensitive about depending on a foreign high-technology energy source, even if costs and other aspects are favorable.

What is the potential global market for SPS? To date, only the studies by Maurice Claverie and Alan Dupas have attempted to estimate this in any detail. Their recent papers[12] present a possible methodology for making SPS projections. Unfortunately, their results are based on energy demand projections completed in 1976 and 1978 that are now considered to have considerably overestimated future electricity demand' [13 14] (see app. C).

From these projections Claverie and Dupas estimate the maximum demand for large electric powerplants (LEPP) (see map in app. C), and calculate SPS demand assuming either 10-percent or 50-percent market penetration by 5 gigawatt (CW) SPSs (see table 27).

Even allowing for the high estimates of the energy projections used, the Claverie-Dupas calculations must be considered very rough upper estimates of future demand; in particular, cost comparisons with alternative sources were not taken into account. Claverie and Dupas attribute much of SPS's potential attractiveness to environmental and political factors rather than strict cost advantages. [15]

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[12] M Claverie and A. Dupas, "Preliminary Evaluation of Ground and Space Solar Electricity Market in 2025," 29th IAF Congress, October 1978; "The Potential Global Market in 2025 for Satellite Solar Power Stations, " May 1979; "Possible Limitations to SPS Use Due to Distribution of World Population and World Energy Consumption Centers, " 31st IAF Congress, September 1980

[13] Edison Electric Institute, *Economic Growth in the Future (New* York McGraw-Hill, 1976), pp. 215-234

"World Energy Conference, *World Energy Demand (New* York: IPC Science and Technology Press, 1978)

'5Claverle and Dupas, "Potential Market, " op cit., p. 4.

Table 27.–SPS Market in 2020/2025 (G We)

	10% of New LEPP		50% of New LEPP	
	CWE[a]	WEC[b]	CWR	WEC
OECD.	135	75	685	365
SU/EE.		40	260	195
Developing . . .	50	85	430	435
Global	275	200	1,375	995

[a]CWR - Case Western Reserve.
[b]WEC - World Energy Conference.

SOURCE: Adapted from Claverie and Dupas, *Potential Global Market,* p. *4.*

Within the limits of this study the Claverie-Dupas estimates using the IIASA projections cannot be duplicated. However, by using IIASA'S estimates of installed capacity in 2030, a rough estimate of global demand can be made. We can assume that 20 percent of capacity will be reserve, to guard against outages, and that of the remaining 80 percent, 65 percent will be baseload. Moreover, if we accept Claverie and Dupas' estimate that 10 percent of world demand will be met by decentralized sources, then the global estimate of the maximum possible demand for installed baseload capacity in 2030 would be: 80 percent (peakload) x 65 percent (baseload) X 90 percent = (approximately) 47 percent of total installed capacity.[16] Using the IIASA estimates (table 26) of 6,320 (low scenario) to 9,845 (high) GWe, then we get 2,970 to 4,627 GWe as the potential demand for baseload capacity.

The amount of new capacity supplied by SPS would depend on the percent met by SPS as opposed to alternate generating sources. If we assume 10-percent market penetration there would be demand for 295 GWe (low) to 465 GWe (high); if market penetration were as high as 50 percent (which is not probable, at least by 2030) there would be demand for 1485 to 2315 GWe. However, it should be noted that conventional generators built from 1990-95 on will still be in operation by 2030; since SPS would not be available until 2010-15, the new capacity market will be considerably smaller than the total demand.

The number of satellites this demand represents would depend on their size; estimates range from 5 GW down to 0.5 GW (see ch. 5). Development of smaller sizes would greatly improve the market penetration of SPS by mitigating two serious obstacles: the large size of reference rectennas, and the problems of inserting large blocs of power into utility grids.

Rectenna size in the 5 GW reference design is 10 x 13 km at 350 N., including a 2 km buffer zone. Reducing the size of the design to 1.5 GW would necessitate a receiving antenna only 6.5 *X* 5.5 km, lowering costs and making siting more feasible. In European demand centers, mostly located from 450 to 650 N., rectennas would need to be much larger. Given Europe's high population densities, many experts have suggested placing rectennas offshore in shallow North Sea waters. [17] Similar problems would be faced in the Northeastern United States, Japan, Eastern China, and India. Though apparently feasible, placing rectennas offshore would add considerably to their cost.

Even more important, a reduction in size would enable SPSs to be used by smaller utility grids, since utilities in developed countries do not generally make use of single generating units supplying more than 15 percent of the utility's total capacity, because of the need to ensure against generator failure (see ch. 8). Conversely SPSs, even in less than 5 GW units, may be a spur to integration of utility grids in order to make use of the SPS's large power increments. Currently, there is widespread integration of national grids in both Eastern and Western Europe. Western Europe has an interconnected high-voltage network, with routine commercial exchanges of power, which is coordinated by organizations such as the "Union pour la Coordination de la Production et du Transport de l'Electricity."[18] In Eastern Europe, Comecon has established an integrated 150-GW grid including all of Eastern Europe and the Ukraine.

"See: "SPS—The Implications for the Utility Industry," working paper for OTA workshop, July 1980, p. 12,

[17]P Q Collins, "Potential for Reception of SPS Microwave Energy at Off-Shore Rectennas in Western Europe," *Final Proceedings,* p. 529.

[18]Arnaldo M. Angelini, "Power for the 80's: A Challenge for Western Europe," *Spectrum,* September 1980, p. 44.

Successful integration of national grids is possible only where there is an expectation of long-term stable relations with neighboring countries. Unfortunately, though LDCs could benefit greatly from regional interconnections, such expectations are rare in developing regions where integration may be necessary to accommodate large blocs of power, and to share the costs of building expensive rectennas. Countries and regions with a successful history of cooperation in other areas would be most likely to join together for SPS integration as well.

In many developing regions, where the bulk of the population lives in rural areas, the feasibility of large centralized power plants is reduced by a lack of costly infrastructure, especially transmission lines and end-use capabilities. In such an environment decentralized generating capacity is preferable to SPSs or other large plants. It has been suggested[19] that such countries may be able to make use of large amounts of electricity for producing liquid fuels, such as methanol, directly from the basic elements; such fuels can be easily integrated into economies that currently depend on kerosene or wood for cooking and heating. However, using electricity in this fashion would not be economically feasible. Methanol can be produced from coal at a projected cost of $0.50 to $1 .00/gal. But at 5q/kWhr, the cost just to separate from water the amount of hydrogen necessary to make a gallon of methanol also lies between $0.50 and $1.00. There would be the further expense of providing the necessary carbon (which could be provided from carbon dioxide taken from the atmosphere). However, producing methanol from biomass or from coal (in which the hydrogen, carbon, and oxygen necessary to manufacture methanol are already present) would be far more cost effective. A more reasonable need for SPSs might be for energy-intensive uses such as desalination of seawater or fertilizer production. 20 These projects might be coordinated on a regional basis.

Geographical location may also be an important factor to developing countries. If the SPS were located in geostationary orbit, it would cost more to beam power to areas located far north or south of the equator. Europe, as we have seen, is at a disadvantage; the Soviet Union is in a similar position. Equatorial and tropical states, on the other hand–most of them LDCs–would be in better positions to build small-size rectennas. Cheaper power could be an incentive to industrial development and foreign investments.

In addition, an equatorial position is optimal for launching payloads into orbit, since the Earth's rotational speed at the equator (approximately 1,000 mph) is higher than at other places on the Earth's surface. Spaceports for sending up SPS construction material might profitably be located near the equator, providing benefits for the countries in which they are placed in the form of rents, infrastructure investments, and training of local administrators and technicians.

Earlier it was assumed that the Soviet Union, barring some radical change in its political and social institutions, would not participate in a cooperative SPS venture, except with its East European allies. As a major space power, the Soviet Union has the ability to go it alone, though without a global market for its product the costs would be considerable. The Soviet Union has a number of economic reasons to consider an SPS system, including its increasingly remote and expensive conventional energy resources, and the large investment it has put into its space program (currently estimated at some 1.5 to 2 percent of GNP, compared to 0.3 percent in the United States[21]). The large distances involved in providing electricity to many areas within the Soviet Union are an incentive to develop a system in which power can be sent directly to the area being served, without transmission lines and without transporting fuel long distances, The Soviet Union has a penchant for big projects, especially when competing with the West. However, currently there is no firm indication that

[19] J. Peter Vajk, *Doomsday* Has Been *Cancelled,* Peace Press, 1978,

[20] D. Criswell, P. Glaser, R. Mayor, et al., The Role of Space Technology in the Developing Countries," Space *Solar Power Review, vol. 1,1980,* p. 99.

[21] Walter A McDougall, "The Scramble for Space," *Wilson* Quarterly, fall 1980, p. 81.

the Soviet Union intends to proceed with an SPS.

Noneconomic Interest

Any SPS system would have numerous noneconomic aspects relating to national prestige and security, and different national and regional interests can be expected to conflict. There are three separate "arenas" in which such conflicts might arise.

Within OECD

Although cooperation between the United States and other OECD allies is probable, there would likely be a high degree of competition centered around economic interests. Control of any joint program, the division of responsibilities between countries, and the apportionment of economic benefits to be gained from contracts let during R&D and construction, are all potential problem areas. In the case of SPS, the industries involved —aerospace and energy—are high-prestige ones in which many countries wish to develop independent capabilities. Fear of economic and technological dominance by the United States, or of U.S. failure to follow through on program commitments, may be a spur to accelerated development of European or Japanese launch vehicles and construction facilities. The ESA's Ariane expendable launcher program has been largely motivated by worries about such dependence, especially by France, Ariane's prime mover. Japan has announced plans for a new generation of launchers, and non-OECD countries such as Brazil and India have built sounding rockets and satellites. Increased competition with the United States can be expected over the period of SPS development.[22]

East-West

Development of an SPS by the Soviet Union would have major international consequences. Since Sputnik, each side has reacted to the actions and statements of the other. Although space successes may no longer be seen as proof of the superiority of one social system to another, as Khrushchev used to claim, they are still a vehicle for peaceful competition, and a way of impressing allies and potential allies with individual achievements. Because of its scope and visibility, the SPS would be a major symbol of successful efforts in advanced technology. "Visibility" here is meant literally:[23] a completed SPS, even in geosynchronous orbit, would be easily visible to the naked eye. The impact of such an effort would be direct and great. It is unlikely that the Soviets could allow a U.S. or Western SPS to go unchallenged. If they felt they could not compete successfully, they would be likely to try to block construction by emphasizing environmental dangers or supporting Third World demands for shared control over orbital positions. On the other hand, a Soviet SPS effort would encourage U.S. projects by acting as a spur to public opinion and raising fears of Soviet ascendancy.

North-South

Many Third World states would be antagonistic to SPS development, insofar as control of the system rests with industrialized countries, West or East. These states would be concerned about increased economic and technical dependence on the "North," and the limited opportunities for meaningful participation in an SPS system. The SPS could be charged with diverting funds from development projects and with increasing the gap between the developed and underdeveloped worlds. International forums such as the United Nations and its specialized agencies could be used as foci for investigations of any proposed SPS systems and for discussion of legal measures to bloc them or to give the LDCs various sorts of leverage.

Many developing countries have invested heavily in industries such as steel and oil refining in part because of the prestige value of such large and advanced sectors. Energy production is a prominent example–witness atomic reactors and hydroelectric projects such as Egypt's Aswan Dam. The SPS could be resented because it is unavailable to LDCs;

[22] Ibid., pp. 71-82.

[23] See: Jerry Grey, *Enterprise* (New York: William Morrow & Co., 1979), p 225

only the receiving antennas could be built on home territory with local resources. Conversely, large amounts of scarce capital might be spent trying to buy an SPS (if they are for sale) and the lift capacity to service it in an attempt to "keep up" with the advanced countries.

The "South" is by no means monolithic, and, if SPS were built, many states would be potential supporters, some because of the benefits of less expensive electricity and others because of the prospects for future participation. The most likely supporters of an SPS would be energy-poor countries with a rapidly developing urban-industrial base, such as Brazil, Argentina, Kenya, Turkey, India, and South Korea. Any system that reduces Western imports of OPEC oil reduces pressure on prices and means less expensive supplies for vulnerable LDC importers. It has been argued that firm plans for building an SPS would of themselves put a "cap" on oil price rises by sending a signal to exporters that Western imports will drop in the future. [24]

The oil-exporting states are in a special position. An SPS would by no means eliminate oil demand and may prove beneficial by helping to reduce pressure on exporters to increase production to satisfy rising export needs. Countries with large populations and relatively small reserves, such as Nigeria, Indonesia, China and Malaysia, may view SPS as insurance against the upcoming depletion of their oil supplies and may choose to invest some of their current earnings in the hope of long-term gains. On the other hand, exporting countries, especially those with long-term reserve potential such as Saudi Arabia, have no immediate use for an SPS and may be tempted to side with other LDCs —for political and cultural reasons — in attempts to put pressure on the West for greater LDC control. Soviet support for such measures could cause the SPS to become a highly polarized issue in which the Soviet bloc and the nonalined states seek concessions from the West— a not uncommon phenomenon in recent international affairs.

[24] House Committee on Science and Technology, *SPS Hearings on H. f?. 2335*, 96th Cong., March 1979, pp 132-180,

LEGAL ISSUES

The United States and other space-capable states are currently bound by a number of agreements that would affect SPS development.[25] Much of existing international law has been formulated at the United Nations (U. N.) by the Legal Subcommittee of the Committee on the Peaceful Uses of Outer Space (COPUOS). COPUOS has been in existence since 1959, when it began with 24 members. It now has 47, with membership expanding as international interest in space matters has increased. COPUOS decisions have been made by consensus rather than by outright voting.[26]

The most important and comprehensive of the currently applicable agreements, all of which have been ratified by the major space powers, is the 1967 Treaty on Principles Governing the Activities of States in the Exploration *and Use of Outer Space, Including the Moon* and other Celestial Bodies . In 1979, COPOUS agreed on a final version of a new treaty, the so-called "Moon Treaty, " which has so far not been signed by the United States or other major powers. The Moon Treaty applies to the Moon and other celestial bodies, but not to Earth orbit. In addition to COPUOS, important decisions on frequency allocations and orbital positioning are made by the International Telecommunications Union (ITU), a specialized U. N. agency.

[25] See Stephen Gorove, *SPS International Agreements*, DOE/NASA contract No. EG-77-C-01-4024, October 1978; Carl Q. Christol, *SPS International Agreements*, DOE/NASA contract No EG-77-C-01-4024, October 1978.

[26] Eilene Galloway, "Consensus Decisionmaking of UNCOPUOS," *Journal* of Space *Law, vol.* 7, No. 1

As a new arena of human exploration, legal norms with respect to outer space have had to be defined. This has been done through a gradual process shaped by actual usage, the extension of existing law, and the explicit adoption of common principles and regulations.

The outstanding international legal issues that might affect SPS development are:

1. the status of the geosynchronous orbit, and the source of jurisdiction over the placement of satellites;
2. provisions against environmental disturbances;
3. the military uses of space and arr- trol implications; and
4. issues relating to the c facilities and ber tion of the kind" p:

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ned. In recent years a number of states located on the Equator have claimed jurisdiction over the geosynchronous orbit on the grounds that it is not part of "outer space" but is determined by the Earth's gravitation, and is a limited natural resource requiring national control. In December 1976 eight equatorial countries issued the Bogota Declaration asserting their position and laying claim to the orbital segments lying over their respective territories.

The equatorial states' claims have been rejected by the majority of other nations—including the Soviet Union, the United States, and Western Europe—as legally and scientifically untenable. Control over the orbit by a few states would prevent free and equitable access to a crucial position by space-capable countries.

The equatorial claim must be see - - - context of various attempts by t to gain leverage over ec activities otherwise o - seven Bogota sig~ Ecuador, Indor (Brazil

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Even if parts of the orbit cannot be appropriated by sovereign states, there is still the problem of allocating positions and of deciding competing claims to scarce orbital slots. The question here is part technical and part legal: How much space is there, and what constitutes infringement? This is dependent on the state of technology, since "infringement" is not so much a problem of two or more objects trying to occupy the same place as of electromagnetic interference between nearby satellites (see ch. 8). SPS satellites would not only be very large but would, especially if using microwaves, radiate a great deal of energy at radio frequencies. Each SPS would have to be allocated a position and frequency to mini-

[27] *Space Law Selected Basic Documents,* 2d cd,, U.S Government Printing Office, 1978, p 26

[28] See Gorove, *SPS Agreements,* op. cit., pp. 14-21; and Delbert Smith, *Space Stations: International Law and Policy,* Westview Press, 1979

mize interference with a rapidly growing number of satellites (see ch. 8). Many spectrum users have worried that SPS operation would disrupt communications and sensing tasks, others that the initial SPSs would use up the available electromagnetic space, preventing exploitation by latecomers. Since the acceptable limits vary with the size and type of SPS used, the size and type of future communications satellites, and advances in transmission technology, it is impossible to say at this time how many SPSs could be built without unacceptable interference.

Allocation of frequencies and positions has to date been the province of the ITU, whose 1973 convention states that stations "must be established and operated in such manner as not to cause harmful interference of other members, or of recognized private operating agencies, or other duly authorized operating agencies which carry on radio services, and which operate in accordance with the provisions of the Radio Regulations."[29] Whether the ITU would have jurisdiction over noncommunications satellites such as SPSs is unclear.[30] In November 1979, at the ITU's World Administrative Radio Conference, the United States raised the question of allocating a frequency position for future SPS testing; the proposal was referred to a specialized study group for evaluation and future decision.

Allocation decisions by the ITU have been characterized by debate over the first-come first-served tradition, whereby first users have priority in the use of frequencies and orbital slots. Newly space-capable states as well as LDCs and others who intend to develop such capabilities in the future have urged, since 1971, that all states have "equal rights" to frequencies and positions, and the ITU has called both the radio spectrum and the geostationary orbit "limited natural resources" that "should be most effectively and economically used." A number of LDCs have proposed that space be reserved for their future use. Since there is no legal basis for permanent utilization or ownership of positions, the possibility of future reallocation clearly has considerable support among have-not states. Established users such as the United States remain opposed to a priori assignment of slots and frequencies. Again, the ITU debate is part of LDC attempts to gain leverage. SPS development could be affected by attempts of disaffected states to block development by denying frequency allocations, or by making consent contingent on concessions by states with the most interest in SPS.[31]

Environmental Considerations

The 1967 treaty states, in article VI 1, that each state is "internationally liable for damage" to others caused by its activities in space.[32] The 1973 "Convention on International Liability for Damage Caused by Space Objects" amplifies on these responsibilities.[33]

Hence, SPS developers might face lawsuits or other forms of grievance if the SPS damaged the global or local environment. The extent of various environmental effects is unknown and in need of further research (see ch. 8). Even if operation of any one SPS had no effect outside of the state making use of it, designing a globally marketable system to meet widely varying national standards could add significantly to costs. The possibility of large lawsuits could make insurance expensive or impossible to procure; large risks in the nuclear industry made it necessary for the Federal Government to provide insurance, and similar provisions might have to be made for SPSs.

Military and Arms Control Issues

The 1967 treaty commits states "not to place in orbit around the Earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction" (art. IV) and in general to carry on activities "in the interest of maintaining international peace and security and promoting international cooperation and understanding" (art. III).34 The 1977 "Conven-

[29] *Space Law,* op. cit., p. 87.
[30] Gorove, op. cit., pp. 27-33.
[31] Ibid, pp. 21-33,
[32] Space *Law,* op. cit., p. 28.
[33] Ibid, pp. 49-69.
[34] Ibid, p. 26.

tion on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques" prohibits the activities implied, with "environmental modification techniques" defined as "any technique for changing the dynamics, composition or structure of the Earth, including its biota, lithosphere, hydrosphere and atmosphere." (art. 11).35 These general principles obviously allow for criticism of some SPS designs as having weather modification potential, requiring restrictions or redesign to reduce such effects. Whether an SPS's microwave or laser capabilities would class it as a weapon of "mass destruction" and hence make it illegal under the 1967 treaty is unclear, but it is very likely that such charges would be made in the event of SPS deployment. Development of an SPS might entail renegotiation of relevant treaties or special system design to minimize its usefulness as a weapon.

Military satellites for communications and remote sensing are currently used by several countries, and presumably use of the SPS platform for such purposes would not constitute a change in accepted practice. The Soviet Union has tested antisatellite satellites on several occasions, and the United States and Soviet Union have conducted informal talks (currently suspended) on limiting antisatellite weapons. The Soviet Union has complicated matters by stating that it considers the Space Shuttle an antisatellite system, an unacceptable proposal for the United States.[36] U.S. Air Force involvement in the shuttle program and Department of Defense (DOD) plans for military missions provide Soviet negotiators with their rationale. Insofar as the Soviet Union is making this argument for bargaining purposes in the absence of a similar Soviet system (similar to Soviet proposals to ban atomic weapons in the period when it lacked its own and to prohibit satellite reconnaissance in the early 1960's) such a charge could also be made against heavy lift launch vehicles (HLLVs) used for shuttle construction. In the absence of their own SPS program, obstructionist tactics by the Soviet Union could be expected.

Although unlikely, use of the SPS for directed-energy weaponry, either directly, or as a source of energy to be transmitted to remote platforms, or for tracking, would be regulated by the 1972 Anti- Ballistic-Missile (ABM) Treaty between the United States and the US.S.R. Article V of the treaty states that "each party undertakes not to develop, test, or deploy ABM systems or components which are sea-based, air-based, space-based, or mobile land-based."

Use of the SPS for ABM purposes would hence be banned. Since any laser or microwave SPS is potentially capable of being so used, the Soviet Union (or the United States if the tables were turned) would undoubtedly insist on assurances and inspection provisions to prevent such developments. The ABM treaty provides for inspection and verification by "national-technical means, " i.e., by remote surveillance. Onsite inspection has historically been refused by the Soviet Union, although the 1967 treaty, and the "Moon Treaty," include provisions for mutual inspection of lunar and celestial facilities. SPSs would need to be monitored by Earth- and space-based reconnaissance means.

Although the ABM treaty is of "unlimited duration" there has been considerable sentiment in the United States for its abrogation or renegotiation in order to provide a defense for America's increasingly vulnerable land-based ICBMs.[37] Abandonment or substantial change in the treaty might allow for development of directed-energy weapons in conjunction with an SPS system. Renewed negotiations may have to take SPS development into account, perhaps by specifying SPS designs that make it unusable as a weapons system. An SPS that used lasers as its energy-transmission medium would be particularly destabilizing and it is possible that arms control considerations would prevent such a system from being built.

[35] *Agreement Governing the Activities of States on the Moon and* Other *Celestial* Bodies, pts. 1 and 2, U.S Government Printing Off ice, May 1980, p. 256.

[36] "Soviets See Shuttle as Killer Satellite, " *Aviation Week and Space Technology,* Apr. 17,1978, p. 17

[37] See Carries Lord, "The ABM Question, " *Commentary,* May 1980

Common Heritage and the Moon Treaty

The 1967 treaty states, in article 1, that "The exploration and use of outer space . . . shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind."[38] The draft version of the Moon Treaty adds (art. IV). "Due regard shall be paid to the interests of present and future generations as well as to the need to promote higher standards of living and conditions of economic and social progress and development in accordance with the Charter of the United Nations. "[39] The exact meaning of these provisions is unclear, beyond a negative duty not to interfere with the activities of other states or to harm their interests. A positive interpretation that "would impose on space powers the obligation either to permit other countries to use the former's space vehicles or to share the financial benefits of its space activities, "[40] has been made by some LDCs but has not received widespread support. Since 1958, U.S. policy has been to encourage international cooperation. U.S. launch capabilities have been available to all countries, on a reimbursable basis, for peaceful and scientific purposes.

In 1970, A. A. Cocca of Argentina proposed a draft treaty in UNCOPUOS which provided that the natural resources of the moon and other celestial bodies be "the common heritage of mankind." This terminology was borrowed from similar language used in the Law of the Sea negotiations in 1967 for regulating seabed resources that lie outside of national jurisdiction.

In the course of the Law of the Sea negotiations (not yet concluded) "common heritage," has come to mean common ownership, "by mankind as a whole" (art. CXXXVII), [14] with commercial exploitation to be regulated by a yet-to-be-formed "international regime" which will distribute part of the returns among participating countries. In 1970, the United States voted for a "declaration of principles" that prohibited activities "incompatible with the international regime to be established."[42] Until the regime is more clearly defined, it is impossible to tell whether current activities will be incompatible or not. The effect of this climate of uncertainty and of the possibility that future regulations may make mining unprofitable has been to keep sea-bed mining consortia —several of which were formed in the 1970's—from proceeding with the large capital investments needed for commercial exploitation.

Article Xl of the draft Moon Treaty provides for a regime (to be established sometime in the future) with the following provisions:

1, The Moon and its natural resources are the common heritage of mankind . . .
5. States parties to this agreement hereby undertake to establish an international regime, including appropriate procedures, to govern the exploitation of the natural resources of the Moon as such exploitation is about to become feasible . . .
7. The main purposes of the international regime to be established shall include . . .
   (d) an equitable sharing by all States Parties in the benefits derived from those resources, whereby the interests and needs of the developing countries, as well as the efforts of those countries which have contributed either directly or indirectly to the exploration of the Moon, shall be given special considerate ion. 43

Moon Treaty opponents have argued that the treaty, like the proposed Law of the Sea, would delay or prevent commercial investment in space activities, and would in any case substitute a state-run international body for private enterprises.[44] Because of the already developed technology for deep-sea mining (most of it U.S.), the Law of the Sea negotiations have become absorbed in detailed discussion of the regime to be established, while

[38] *Space Law,* op. cit., p. 25
39 Agreement, op. cit., pts. 1 and 2, PP 88-89
[40] Smith, op. cit., p. 92.
"Agreement, op. cit., pts. 1 and 2, p 74
"Agreement, op cit , pt. 3, August 1980, pp. 295-307
"Agreement, op cit , pts. 1 and 2, pp 91-92,
[44] See ' 1-5 Memorandum" in *Agreement,* op cit., pp. 377-378

in the Moon Treaty such details have been left to the time when exploitation of lunar or other celestial resources is "about to become feasible." The eventual outcome of the Law of the Sea may have an important bearing on the shape of a future outer space regime.

Since the Moon Treaty would not apply to objects in Earth orbit, SPS would not be directly affected. However, the Treaty could have several indirect effects. First of all, in several scenarios large-scale SPS construction beyond an initial demonstration system is economically feasible only if the satellites are built from lunar or asteroidal material (see ch. 5). Such prospects would be dependent on a regime such as is envisioned in the Moon Treaty, which would have to grant permission to mining companies to extract minerals and build facilities.

Secondly, it can be argued that solar energy is a celestial resource under the jurisdiction of the proposed regime, and that SPSs (and other space-craft) must be granted permission to use it.[45] Though such an argument is unlikely to find general acceptance, it could be used by interested states to try and gain additional leverage.

Thirdly, adoption of the Moon Treaty would provide a powerful precedent that could affect the evolution of a future SPS project. It would legitimize developing countries' claims to receive benefits on a par with states that have actually invested in launch or construction facilities, and give impetus to arguments that the geostationary orbit is a "common heritage" resource requiring explicit allocation by an international body.

In the course of the Moon Treaty negotiations the United States was a consistent supporter, along with virtually all the Third World participants, of the common heritage provisions, while their most persistent opponent was the Soviet Union.[46] The U.S.S.R. did not accede to these provisions until 1979. While the United States generally interpreted common heritage in such a way as to allow for some degree of private unilateral commercial development, the Soviet Union expressed fears that the treaty would lead to an unacceptable suprastate body. The Soviet position was that such a body would infringe on the sovereign rights of states. The Soviets have also opposed allowing private or nongovernmental bodies to engage in space activities. Both the 1967 treaty (art. VI) and the proposed Moon treaty (art. IXV) provide for state supervision of and responsibility for the activities of nongovernmental entities. This "state-centric" approach is typical of Soviet attitudes in international negotiations.

As a result of concerns generated by the Law of the Sea negotiations, as well as antitreaty lobbying by "pro-space" organizations such as the L-5 Society, U.S. support for the draft Moon Treaty has been limited. U.S signature has been discussed in the Senate Subcommittee on Science, Technology, and Space, and by a special interagency committee chaired by the State Department. Prospects for U.S. approval currently appear to be slight.

[45] "Conversation with Eilene Galloway, September 1980,

[46] "*Agreement,* op. cit., pts 1 and 2, pp 27-38

ADVANTAGES AND DISADVANTAGES OF MULTINATIONAL SPS

No matter what country or organization were to build an SPS, it is clear that construction would involve some cooperation with and accommodation of the interests of other states and regions. However, from the point of -view of any national government— and to a lesser degree of private corporations as well–it would be preferable, other things being equal,

to build the SPS as a strictly national venture and to own and operate the system on a unilateral basis.

Unilateral Interests

From a corporate viewpoint, it is much easier to do business within a country than to do so across national boundaries. Multinational ownership or control would complicate decisionmaking, reduce flexibility, and introduce a multitude of political strains that any company would prefer to avoid. To the extent that foreign markets are attractive, the company would prefer to retain domestic ownership and to sell completed units abroad, minimizing foreign entanglements.

From the point of view of governments that might consider investing in SPS, the desire to do so alone would be very strong, for reasons of prestige, security, and economics. At present only the United States and the Soviet Union could even consider such a unilateral effort. In the longer term, however, it is conceivable that a European consortium or perhaps even a single European state—most likely France– could also undertake such a project. So could Japan, with possible cooperation from China, South Korea, and other regional powers with technical expertise and financial resources.

Is it likely that the United States or the Soviet Union would build an SPS in the near future? Such a program would be undertaken only if there were serious doubt that alternative energy sources will be available in the future, or that their costs will be acceptable. This would have to mean that the $C0_2$ and environmental problems of large-scale coal use were seen to be acute and imminent, or that nuclear reactors were deemed unacceptable due to a major accident and public disapproval. In addition, alternatives to the SPS such as fusion, ground-based solar cells, and possible other future technologies, would have to fail to fill the gap (see ch. 6). In the event of some such crisis SPS studies must be sufficiently advanced to provide very high assurance that such a system would work. Given this combination of events, and if cooperation with foreign governments or corporations is rejected because of fears that it might slow down the project or otherwise reduce its domestic usefulness, it is possible that a unilateral effort would be undertaken.

There are several other factors that might increase the attractiveness of a unilateral crash project similar to the Manhattan or Apollo programs. Three requirements for such decisions are: 1) a crisis, requiring immediate action, which threatens basic national interests; 2) the existence of a workable plan to resolve the crisis; 3) decisive leadership by persons in positions to implement such plans. " In the Manhattan and Apollo cases, the crises involved challenges to national interests that placed a premium, not only on developing the atomic bomb or the ability to go to the Moon, but on doing so first.

The SPS would have important economic, prestige, and security implications. Unilateral development by the Soviet Union or the United States would provide a strong impetus for the other to do so as well, as long as the project could also be justified on other grounds. The strength of this impetus would depend on the state of future U.S.-Soviet relations. In the 1950's nuclear weapons and their delivery systems were seen as vital to the existence of the state; the space programs of the 1960's as symbolic of each state's social and economic superiority. It is unlikely that the SPS would be as crucial to East-West competition as these earlier technologies, unless the SPS or the launchers needed to build it become vital elements of military systems. For the reasons given in the next section, Nationa/ Security Implications of SPS this is possible but unlikely. Hence an equivalent desire to build the first system–an SPS "race"- is improbable.

Within the United States certain interests would favor unilateral as opposed to multilateral development. Businesses likely to benefit from development, such as aerospace indus-

[17] John Logsdon, *The* **Decision** *To Go To the* **Moon (Cambridge, Mass MI T Press, 1970), p** 181

tries or large construction firms, might prefer a unilateral effort that would provide them with most or al I of the contracts, as well as the prospect of foreign sales. However, others might fear that a unilateral development would discourage foreign buyers. Some utilities and oil companies might oppose an SPS altogether if it competes with energy sources in which they have already invested. Since unilateral development would almost undoubtedly mean a government-dominated and financed project, such businesses would be likely to argue that the SPS is unfairly competitive and to demand compensation.

In the Soviet Union there is no private sector and hence no question of public v. private development. Though it is possible that non-Communist states such as India and France, both of whom have engaged in cooperative space projects with the Soviet Union before, might participate in small ways, it would be unprecedented for the Soviet Union to engage in extensive joint planning or operations with nonallied states. Such cooperation in sensitive, high-technology areas involving space capabilities, which in the Soviet Union are run by the armed forces and considered top-secret military programs, is especially unlikely. Hence an international SPS program is not a real option for the Soviet Union, given its present political and economic institutions.

Within both the United States and Soviet Union, the military may argue for a unilateral program in order to enhance SPS's military usefulness, which would be destroyed if sensitive information had to be shared among neutral partners or partners who could not be trusted not to reveal technical or other details to unfriendly states. In the United States, resistance to military involvement is likely to be strong, partly to avoid foreign charges of aggressive intent, and also to prevent possible military interference in the project's efficiency, as with the Space Shuttle.[48] However, given the military's role in the Soviet space program, such arguments are likely to be less telling there than in the United States. Although various Soviet ministries would seek a say in SPS development, none has the technical or managerial competence to displace the military in such a project.[49]

In the United States, the Government sponsors two largely separate space programs, a civilian one run by the National Aeronautics and Space Administration (NASA), and a military one run by the Department of Defense. Both draw extensively on expertise and experience from a large number of private firms. While an SPS project in the Soviet Union could not help but be dominated by the military, a U.S. project, even one run by the Government, could be shared between the military, Government-civilian, and private sectors. Various combinations could be developed to provide a desirable mix between public and private, military and civilian authorities.[50] In the past, Government-sponsored projects that might provide guidance and precedent for an SPS program have included the Panama Canal, the Tennessee Valley Authority, and the Interstate Highway System. (See ch. 9, Financing, Ownership, and Control.) What is important is the flexibility available to U.S. planners, a flexibility not found in the Soviet Union, which, if a multinational effort is preferred, makes it possible to accommodate international partners on various terms.

Both Western Europe and Japan have more urgent requirements for reliable energy supplies than the two current space powers. The impetus for SPS development would be similar to that for the United States, but the need is more imminent, and the costs of alternatives, in the absence of indigenous fossil fuels, are higher. Could an SPS be built in an acceptable period without extensive U.S. assistance (assuming Soviet assistance is improbable)?

"The price for Air Force support of Shuttle fundin, in Congress was substantial redesign of the original Shuttle model, lowering performance and increasing costs See Jerry G rey, Enterprise (New York: William Morrow & Co , 1979), pp. 66-68.

"See *Soviet Space Programs 1971-1975,* vol. 11, ch. 2, "Organization and Administration of the Soviet Space Program, " August 1976, pp. 63-82.

"For discussions of these issues, see Peter Vajk, *SPS Financial/Management Scenarios,* DOE/NASA contract No. EG-77-C-01 -4024, October 1978, Herbert Kierolff, *SPS Financial/Management Scenarios,* DOE/NASA contract No. EG-77-C-01 4024, October 1978.

The requisite technical and financial base is available; strong aerospace industries exist; national and multilateral space programs, such as the European Space Agency (ESA), are in place. However, both ESA and Japan lack the depth of U.S. industry's aerospace expertise, its worldwide tracking and relay networks, and above all experience in and development of manned space-vehicles. The most sophisticated non-American launch vehicle is ESA's Ariane, which is still being test-flown and is scheduled to begin commercial operations in 1982.[51] The Ariane is a high-quality three-stage expendable booster, but it is far smaller than the large U.S. Saturn rockets used for the Apollo program. And it is far behind the U.S. Space Shuttle in capabilities, payloads, and cost effectiveness (at least to LEO). Since the Shuttle itself is too small and expensive for full-scale SPS construction, ESA is at least two generations of vehicles away from being able to develop an SPS unilaterally. Producing the requisite lift capabilities in an independent program would be extremely costly and time-consuming.

It is clear that any unilateral SPS program depends on a dramatic and unpredictable increase in the sense of urgency about medium and long-term energy supplies. Even if such an increase were to occur, such efforts would be very expensive for any one country or region to undertake, especially since crash programs are necessarily more expensive than ordinary ones; money is traded for time.

Multilateral Interests

There are three reasons why interested parties may wish to abandon their preference for autonomy in favor of an international effort. These are: 1) to share the high costs and risks; 2) to expand the global market; 3) to forestall foreign opposition and/or promote international cooperation.

costs

The exact costs of developing, manufacturing, and operating a SPS are unknown; NASA estimates a 22-year, $102 billion program for the reference design.[52] (See ch. 5, Costs.) Although the R&D costs would be much lower than construction costs, they would be the hardest to finance, and the ones where international cooperation would be most valuable. The number of satellites needed for a global system would clearly be much larger than for a U.S. system alone. However, the R&D/prototype costs are essentially the same whether the system is unilateral or multilateral. Since the very long 30-year period of investment before payback is the project's weakest link, it would be desirable to spread these costs between a large number of possible investors. And by widening the available pool of capital and expertise, an international effort would have less of an inflationary impact on resources, thus keeping costs down.

However, it should be realized that an international consortium, whether involving private firms or government agencies, will tend generally to increase the overall costs. Under the best of circumstances there are costs associated with doing extensive business across borders, with coordinating efforts in different languages and geographic areas, and with balancing the divergent national interests of foreign partners. Without careful management and a high degree of cooperation from the states involved, these extra inefficiencies can eliminate any advantage gained from internationalizing the project. The experience of European collaborative efforts has been that costs rise as the large number of participants increases the managerial superstructure and project complexity .53

The Global Market

We have previously discussed the SPS's potential global market. An international venture may improve the marketing prospects of the system. First of all, potential users and buyers would be less concerned about becoming dependent on a particular country or corporation, which may infringe on national sov-

"Edward Bassett, "Europe Competes With U.S. Programs, " *Aviation* Week and Space Technology, Mar 3,1980, p. 89.

[52] Kierolff, op. cit., pp. 4-5

[53] Testimony of Dr. Wolfgang Fink, *International Space Activities,* 95th Cong., November 1978, U.S. Government Printing Office, p 12

ereignty. Many states, especially LDCs, are concerned about such a situation, particularly with regard to U.S. firms. Over the past 15 to 20 years, LDCs have made great efforts to gain indigenous control over local industries and resources, often resorting to nationalization and expropriation. The accumulation of financial and legal expertise by LDC governments means that future dealings with foreign firms will be more cautious and equitable than in the past. Also, it is often politically more feasible for a neutral or nonalined state to deal with an internationally controlled consortium than with a U.S. or Japanese or West European firm, especially when internal opposition to such relationships is strong.

A consortium that offered direct participation and ownership to a large number of states would improve its marketing position even more. Such participation/ownership, even if on a small scale, would help to familiarize members with the organization's operation and finances, and assure potential buyers that they were not being deceived. A financial stake would provide an incentive to see that the system worked efficiently and was suited for the needs of a variety of users.

Widespread participation by many countries with different financial stakes and energy requirements would also present a host of problems. Even small investors could be expected to lobby for a proportionate share of the benefits, including profits and contracts, and for a say in policy and management decisions. Investors with similar interests can be expected to band together. Often, small-stake participants with less to lose are willing to use any available forum to further ideological or economic interests unrelated to the business at hand. A balance must be struck between the advantage of open participation and the danger that such participation could undermine the organization's credibility and competence.

Forestalling Opposition, Promoting Cooperation

Because of the importance of the SPS and the size of the financial stake involved, major SPS participants could expect that nonparticipants would use their leverage for concessions in unrelated political or economic areas. However, mere participation would not forestall opposition. If member interests are not mutually compatible, opposition is only moved from without to within. The best check on internal obstructionism would be for the major participants to indicate their willingness to go it alone, if necessary, rather than allow internal obstacles to destroy the project. Since organizations quickly develop their own constituencies, within and without governments, which have an interest in maintaining the organization, a credible threat to go it alone must be backed up by national leaders and by investment in the requisite systems.

Possible Models

Intelsat, Inmarsat

How might such an organization be constructed, and what are the types of problems that might be faced? Here it is helpful to look at historical examples of international organizations in the space and energy fields. We will look briefly at Intelsat and Inmarsat; at cooperative efforts in nuclear power; and at the European Space Agency (ESA).

Of existing bodies, Intelsat and its near-relative, Inmarsat, have been mentioned most often as possible models for an international SPS project. Intelsat is attractive because it has been efficient and profitable, and because it has succeeded in including a large number of participating states.

Intelsat was founded in 1964, largely at the prompting of the United States, to provide international satellite telecommunication services. The initial agreement provided for joint ownership and investment in proportion to the use of the system by each participating country, and for renegotiation in 5 years to take account of experience and new developments.[54] At first, Intelsat was dominated by the United States through its semipublic participant, Comsat; LDC participation was minimal, and the

[54] Jonathan Galloway, *The Politics and Technology of Satellite Communications* (Lexington, Mass.: Lexington Books, 1972), p 75

Soviet Union and East Bloc countries refused, to join, preferring to establish a separate organization, Intersputnik. The permanent agreements reached in 1971 reduced Comsat control and made it easier for low-use countries to participate. In 1979, Intelsat had 102 members, with the U.S. share being 24.8 percent.[55] (See app. E.)

Inmarsat is designed to provide positioning and maritime services between ships and ship-to-shore. Organized similarly to Intelsat, it is expected to begin operations in 1981, leasing its initial satellite services from Intelsat.[56] (See app. E.)

Though Intelsat has functioned relatively smoothly and has shown a good return on invested capital, serious disagreements between participants have arisen. Many of these disagreements have revolved around the allocation of procurement and R&D contracts, with member countries competing for prestigious and high-value shares. Given the predominant position of U.S. aerospace firms, much of the pressure has been for equitable shares for European and Japanese companies. However, some participants, especially LDCs and others without indigenous aerospace capabilities, have objected to distributing contracts on a geographical or political basis, charging that it drives up costs.[57] Non-U. S. contract shares have risen over time (23 percent of Intelsat 5, the latest model satellite, is foreign built),[58] and future use of ESA'S Ariane launcher and purchase of European communication satellites may raise this significantly. (See app. E.)

What do the Intelsat and Inmarsat model tell us about a possible "Intersunsat?" The relatively smooth functioning of Intelsat is largely a result of its initial organization, which had certain peculiarities not likely to be repeated in the future.

Above all, Intelsat came into being through the. dominant interest and investment of a single participant, the United States. U.S. determination to institute a global communication satellite system was due in large part to the Kennedy administration's desire, at a time when the Soviet Union seemed superior in manned and unmanned space capabilities, to achieve a space success before the Soviets that would pay off in terms of global prestige and the furtherance of U.S. national interests. The 1958 National Aeronautics and Space Act which established NASA proclaimed that space activities "should be devoted to peaceful purposes for the benefit of all mankind."[59] In addition to the scientific and commercial benefits, improved international communication was seen as a foreign policy plus for the United States, that would involve other states as participants under U.S. leadership. The technology for such activities was well advanced and judged to be superior to that of the Soviet Union.

The centralized management structure thus created, combined with U.S. technical leadership and its status as the largest single user of the system, gave Intelsat initial national support that was vital in allowing it to operate efficiently and with a minimum of delays. The promise of future renegotiations placated those, such as France, who objected to the initial phase of U.S. dominance. By contrast, the establishment of Inmarsat, despite its close adherence to the Intelsat model, took 4 years of negotiations and some 9 years before the start of actual operations.

At the outset of Intelsat negotiations in 1963, and even at the time of renegotiation in 1969-71, the U.S. position vis-a-vis Europe and the Third World was much stronger than it has been since or is likely to be again, not only in space technology but in general economic performance and military strength. This across-the-board preeminence made palatable-a U.S. position that would today probably not be tolerated.

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[55] *Comsat Annual Report 1979,* p. 23.

[56] "Operating Agreement on Inmarsat," 1976; in *Space Law,* p. 445.

[57] Joseph N, Pelton, *Global communications Satellite Policy: Intelsat,* Politics, *and* Functionalism (Mt Airy, Md.: Lomond Books, 1974), p. 76.

[58] "Intelsat Being Readied for November Launch," Aviation Week *and Space Technology,* Oct. 27,1980, p 51.

[59] "National Aeronautics and Space Act," 1958; in *Space Law,* p 499

In the foreseeable future, U.S.-European equivalence in technical and economic capabilities and the increased self-confidence of the Third World countries, who were effectively excluded from the initial Intelsat arrangements, will make a repeat of the U.S. position impossible. With regard to an SPS, the United States would not necessarily be the largest user, nor would it have a monopoly on engineering expertise. And the political impetus provided by Soviet competition, which was vital to the formation of Comsat and Intelsat, is likely to be missing or muted.

The swift and effective establishment of Intelsat depended on several other factors. One was the prior existence of international and national entities dealing with global communications. Bodies such as the ITU provided technical background and legal precedents for dealing with communication satellites, and national telecommunications agencies had long experience with short-wave and cable transmissions. No such equivalent exists for the SPS.

The initial costs of Intelsat were comparatively low; as of 1980 (through 16 years of operation) a total of somewhat over $1 billion had been invested in R&D and procurement. In addition, the basic research had already been done, and paid for, by the United States; it was a proven technology with a predictable market. The SPS would be several orders of magnitude more expensive, would take decades to produce, and is far riskier. One consequence of communication satellites' low cost—and the existence of established communication entities—was that the basic decisions, both at the beginning and later on, were made by expert bodies with little public awareness. [60] This prevented sharp polarization and allowed negotiators to give and take without risking outcries at home. SPS negotiations would not take place in this atmosphere. As one observer notes, "An SPS is not likely to come into being through the nonpolitical activities of technical agencies . . . Decisions about SPS at the international level will be made . . . by the political leaders of major nation-states in the context of international political debate. "[61] The large size and importance of SPS contracts would create strong pressures for geographical allocation; here the experience of the North Atlantic Treaty Organization (NATO) may be more relevant than that of Intelsat.

The above is not meant to dismiss Intelsat's experience. Valuable lessons from Intelsat are the importance of corporate-style independent management; weighted voting by investment share and usage; and interim arrangements that allow a project to begin work and gain experience before establishing a permanent structure. And the positive example of Intel sat and the experience gained in its operation will prove helpful in the future.

Other Models

Besides Intelsat, with its distinctive combination of state and designated-entity participation, there are other possible models for international cooperation, including: 1) joint-ventures by privately or Government-owned multinational corporations, on the model of Aramco, or the recently formed Satellite Business Systems, jointly owned by Comsat, IBM, and Aetna Insurance, 2) state-to-state agreements coordinating national space programs, such as ESA and its predecessors, ELDO and ESRO; 3) international agreements on the development and use of atomic power, such as Euratom; 4) U.S. bilateral arrangements between NASA and foreign agencies or companies.

PRIVATE CONSORTIUM

Agreements for joint financing and management by nationally based companies can provide extensive informal coordination across boundaries and facilitate the raising of capital on diverse financial markets. (See ch. 9, Financing, Ownership, and Control.) Two major difficulties would face such an attempt. From the company's viewpoint the very high initial investments and the uncertain legal and regulatory constraints would inhibit commitment without government guarantees. Many dis-

[60] Pelton, op. cit., p. 44

[61] John Logsdon, "International Dimensions of Solar Power Satellites Collaboration or Competition?" July 1980, p 3.

cussants have concluded that public sector financing would likely be essential for any SPS project. 'z From the state perspective, especially outside the United States, there would be reluctance to rely on private sector development and control of energy supplies, as well as potential antitrust problems (especially in the United States) caused by a concentration of companies.

ESA

Within Western Europe there have been ongoing efforts to coordinate national space programs so as to compete with the United States and the Soviet Union. In the early 1960's two organizations were founded: ELDO (the European Space Vehicle Launcher Development Organization), aimed at designing and building a European launch vehicle (the "Europa" rocket); and ESRO, (European Space Research Organization) to conduct basic research. Both groups, and especially ELDO, suffered from a lack of direction and from divergent national interests. '3 Allocation of contracts was based on the principle of "fair return;" contributions to the organization were in proportion to each state's GNP, and contracts were supposed to be let in similar ratios. This produced intense disagreements and delays, exacerbated by cost increases which had to be allocated evenly among the participants.

In the late 1960's Europe began to pay increased attention to the so-called "technology gap" between it and the United States. In 1967, J. Jacques Servan-Schreiber's book The *American challenge* "polemicized the U.S. economic invasion of Europe and aroused a popular interest in technology comparable to the Sputnik aftermath in the United States.''[64] Interest in joint space efforts increased; the failure of ELDO to produce a reliable Europa rocket was heavily criticized, with France and Germany claiming their willingness to produce it on their own.

The late 1960's also produced strong pressures, as in the United States, for projects with economic payoffs, rather than abstract research or prestige programs. After Apollo, the United States began to look for ways to reduce the costs of its proposed Space Transportation System. One way was increased cooperation with Europe. While France remained suspicious that such offers were designed to forestal I independent European programs, Germany welcomed NASA proposals for joint development as a way to gain access to U.S. technology and to use of the Space Shuttle. Hence, while France continued to emphasize launcher development, Germany turned to production of Spacelab for NASA.

In 1973, ESRO and ELDO were joined together as the 9-member European Space Agency. Its major projects to date have been: 1) the Ariane launcher, a $1 billion effort which is 64-percent French financed and flown from France's spaceport in Guiana, South America; [65] and 2) Spacelab, an $880 million project, 55-percent German financed, being built in West Germany. Other ESA projects have included regional remote sensing, meteorological, and maritime satellites, and a regional communications satellite (L-Sat) being developed under the guidance of Great Britain. [66]

The formation of ESA has not eliminated intra-European difficulties and the problem of coordinating national programs. A report in Interavia charges that "individual states are tiring of the paper-passing and consensus-seeking that is involved in getting programs started and keeping them alive within the framework of an international civil-service organization.''" One result may be a turn towards commercial alternatives. With the completion of Ariane a new firm called Arianespace has been formed, made up of European industries, banks, and the French National Space Agency, to market the launcher commercially and in competition

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'*See Vajk and Kierolff for further discussion

'3 See Mihiel Schwarz, "European Policies on Space Science and Technology 1960-1978, " *Research Policy,* August 1979, pp. 205-242,

"Henry Nau, *National Politics and International Technology* (Baltimore: Johns Hopkins University Press, 1974), p. 55

"'The French Space Effort, " *Interavia,* June 1979, p, 508.

"Edward Bassett, "ESA Planning New Telecommunications Satellite," A *viation* Week and Space Technology, Dec 31, 1979, p 12

"'European Space Programs: An Industrial Plea for Integrated Effort,11 *Interavia,* August 1979, p. 785,

with the U.S. Space Shuttle. [68] If successful, Arianespace will provide an example of how an internationally financed and developed spacecraft can be turned over to a commercial operating group, which could be a model for similar development of the SPS. However, all-in-all the history of European collaboration provides more "dont's" than "do's" for a future SPS effort.

NUCLEAR POWER

International nuclear cooperation is the only model that compares with the SPS in its financial and political scope, though the security aspects of nuclear power are largely unique. Like SPS, nuclear power is a baseload electricity source requiring large investments and a high degree of technical competence, with widely perceived environmental dangers.

The overall picture of nuclear cooperation shows a field where development and operation, though expensive, is not prohibitively so, and where considerations of national prestige and security are extraordinarily high. "Have" countries have had little reason to promote the spread of nuclear technology, except as a profitable export or a form of foreign aid. The expense of initial development has been justified as a military necessity (as in the U.S. submarine reactor program). Cooperation is largely motivated by the need for agreed-on international standards and regulations to prevent accidents and inhibit proliferation. Strictly economic or energy-supply considerations have played a small role, except as window-dressing, while political and competitive needs have been the prime movers. Nuclear development in Third World countries, such as Brazil and India, has been especially motivated by noneconomic considerations. [69]

Development of an SPS should not suffer from the extreme obstacles to positive cooperation faced in the nuclear field: the military uses would be less important, the costs much higher, and the economic need greater. The intense politicization of nuclear development shows an extreme case of the forces that can come into play during the development of a major new technology.

U.S. BILATERAL ARRANGEMENTS

The United States has been very successful in establishing useful bilateral arrangements with foreign governmental agencies and organizations, such as ESA. NASA has been empowered to enter into exchanges of information and services, in coordination with other parts of Government, such as the State Department. NASA has provided launch services, technical assistance, and remote sensing (Landsat) imagery to a large number of foreign customers.'" The network of relationships built up over the years could be helpful in promoting a multilateral SPS. Direct bilateral cooperation with major potential partners in Europe and Japan might be the best way to initiate foreign cooperation and create a climate conducive to the expansion of the enterprise, especially in the initial less expensive R&D stages. Such agreements would take substantially less time to negotiate than regional or global ones. "

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[68] "New Commercial Organization to Take Ariane Responsibility," *Aviation Week and Space Technology* Apr. 7,1980, p. 45.

[69] "June Sabato and Jairam Ramesh, "Atoms for the Third World, " *Bulletin of Atomic Scientists,* March 1980, p. 39.

"Stephen M. Shaffer and Lisa R. Shaffer, "The Politics of International Cooperation: A Comparison of U.S. Experience in Space and Security," *Monograph* Series *in World Affairs, vol. 17,* book *4,* University of Denver, 1980, pp. 15-26.

"Go rove, op. cit., p. 50,

NATIONAL SECURITY IMPLICATIONS OF SOLAR POWER SATELLITES

The potential military aspects of an SPS will be of major concern to the international community and to the general public. There are fears that the satellite will be vulnerable to attack, or that it may be used for offensive weapons (see ch. 9, Public Opinion). Such con-

cerns may be decisive in determining the pace and scope of SPS development, and the mode of financing and ownership that is used. There are three basic aspects to consider: 1) SPS vulnerability and defensibility; 2) the military uses of SPS launch vehicles and construction facilities; and 3) direct and indirect use of SPS as a weapons system or in support of military operations. Of these it is the second, the extensive capability of new launchers and large space platforms, that will constitute the most likely and immediate impact.

Vulnerability and Defensibility

There are two main segments of any SPS, the ground receiver and the satellite proper. Since reference-system rectennas or mirror-system energy parks would be very large and composed of numerous identical and redundant components, they would be unattractive targets; the smaller antennas of other designs would be slightly more vulnerable. The satellite segment would be vulnerable in the ways outlined below, but in general no more so than other major installations. Its size and distance would be its best defenses.

Would SPS Be Attacked?

The reasons for attacking a civilian SPS would be that it is expensive and prestigious, not easily replaceable, and that it supplies an essential commodity, baseload electricity. In determining whether to target an SPS in the event of hostilities, the crucial consideration would be how much of a nation's or region's electricity is supplied by SPS. In most developed countries, utilities maintain a reserve of approximately 20 percent of their total capacity, in order to guard against breakdowns and maintenance outages. If SPS supplied no more than the reserve margin, its loss could be made up; however, given an SPS system consisting of many satellites particular regions or industries would be likely to receive more than 20 percent. Making up for losses would require an efficient national grid to transfer power to highly affected areas. Increased use of high voltage transmission lines and other measures should increase U.S. ability to transfer power. However, in many countries, especially LDCs, SPS losses might not be easily replaceable since SPSs, if used, would be likely to provide more than 20 percent of total capacity on a national basis.

An attack on SPS would also depend on other factors. If the attacker relies on its own SPSs, it may fear a response in kind. If the satellites were owned by a multinational consortium the attacker might be hesitant to offend neutral or friendly states involved. If they were manned— it is unclear whether permanent personnel would be required for SPS — the attacker might be reluctant to escalate a conflict by attacking manned bases.

The unprecedented position of the SPS, located in orbit outside of national territory, gives rise to uncertainties as to how an attack would be perceived and responded to. If the SPS is seen as analogous to a merchant ship on the high seas, attacks would be proscribed unless war were declared and outer space were proclaimed a war zone. Otherwise, any attack would be tantamount to a declaration of war. In practice, however, experience has shown that attacks on merchant vessels have not caused an automatic state-of-war, though they have often played a crucial part in bringing one about.

It is more likely that the SPS, because of its function and/or its stationary position (for certain designs), would be perceived as similar to a fixed overseas base or port rather than a ship. An attack would then be taken more seriously, especially if lives were lost. It will be important for national leaders to clarify what status an SPS would have, particularly in times of crisis. A low priority assigned to SPS could encourage enemy states to attack it as a way of demonstrating resolve or as part of an escalator response short of all-out war.

How Could SPS Be Attacked?

There are essentially five ways the satellite portion of an SPS could be destroyed or damaged: 1) ground-launched missiles; 2) satellites or space-launched missiles; 3) ground or space-based directed-energy weapons; 4) orbital

debris; 5) disruption or diversion of the energy transmission beam.

A missile attack from the ground on a geosynchronous SPS would have the disadvantage of lack of surprise, due to the distances involved and the satellite's position at the top of a 35,000 km gravity well; missiles would take up to an hour or more to reach, geosynchronous orbit. An attack from prepositioned geosynchronous satellites would be faster and less detectable. However, a laser or mirror SPS in low orbit could be reached from the ground in a matter of minutes. Lasers or particle beams, which might be used to rapidly deface the solar cells or mirrors rather than to cause structural demage, would have virtually instantaneous effect.

Placing debris in SPS's orbital path, but moving in the opposite direction —such as sand designed to degrade PV cells or mirrors– would have the disadvantage of damaging other satellites in similar orbits, and of making the orbit permanently unusable in the absence of methods to 'sweep' the contaminated areas clean. The relative ease and simplicity of this method, however, could make it attractive to terrorists or other technically unsophisticated groups. Any explosive attack could have similar drawbacks, although since the resultant debris would be traveling in the same direction as most other satellites (which move with the Earth's rotation) the ensuing damage would be Slight.

If technically feasible, disrupting SPS's microwave or laser transmission beam, either by interfering directly with the beam or its pilot signals, or by changing its position so that it misses its receiving antenna, would be a highly effective way to attack the SPS. Since the effects would be temporary and reversible, such an attack might be favored in crisis situations short of all-out war. Disruption using metallic chaff would be ineffective against a microwave beam, due to its very large area. Laser beams could be temporarily deflected by clouds of small particles or by organic compounds that absorb energy at the appropriate frequency. Electronic interference possibilities for lasers or microwaves cannot be presently predicted.

A missile attack with a conventional warhead might be difficult due to SPS's very large size and redundancy. The most vulnerable spot on the reference and other photovoltaic designs would be the rotary joint connecting the antenna to the solar cell array. Laser transmitters would be more vulnerable due to their smaller size, though they would also be easier to harden. Attackers would be tempted to use nuclear weapons, either directly on the satellite, or at a distance. In space a large (one megaton or more) nuclear blast at up to 1,000 km-distance could cause an electrical surge in SPS circuitry (the electromagnetic pulse (EMP) effect) sufficient to damage a photovoltaic SPS[72] (though it would have no effect on a mirror-system). Such an attack would be particularly effective against a large SPS system, as it could destroy a number of satellites simultaneously. However, like an orbital debris attack, it has the problem of damaging all unhardened satellites indiscriminately within the EMP radius. Furthermore, any use of nuclear weapons would constitute a serious escalation of a crisis and might not be considered except in the context of a full-scale war.

Could the SPS Be Defended?

Defense of orbital platforms can be accomplished in three ways: 1) evasion; 2) hardening against explosive or electronic attack; 3) antimissile weaponry.

All of the SPS designs being considered would be too large and fragile to evade an incoming attack. SPSs may be equipped with small station-keeping propulsion units but not with large engines for rapid sustained movement.

Hardening against explosive or debris attack would require rigid and heavy plating. Such efforts would be prohibitively costly, except perhaps for a few highly vulnerable areas.

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[72]*Peter Vajk, "On the Military Implications of Satellite Power Systems," Lincoln Proceedings, April 1980, pp. 506-507

Hardening against EMP bursts or electronic warfare would require heavier and redundant circuitry as well as devices to detect and block jamming attacks. If incorporated in SPS designs from the beginning, these might be sufficiently inexpensive to justify inclusion. Different designs may differ in their vulnerability to such attacks —the photoklystron variation, for instance, would be less susceptible to EMP than the reference design.

Antimissile weaponry, whether in the form of missiles or directed-energy devices, could be placed on the SPS to defend against missile and satellite attack. Though potentially highly effective against incoming missiles, such weapons would be useless against long-distance nuclear bursts or remote lasers. Furthermore, they would have unavoidable offensive strategic uses against other satellites and intercontinental ballistic missiles (ICBMs), and would hence invite attack. For these reasons major defensive systems are unlikely to be placed on civilian SPSs. Attacks would be more effectively deterred by political arrangements and by the use of separate military forces.

Who Would Attack?

In most instances an attack could only be carried out by a technically sophisticated nation with its own launchers and tracking systems. Threats by such a space-capable power against other space-capable powers —say by the U.S.S.R. against the United States—are possible in the context of a major crisis or actual war where the attacker is willing to risk the consequences of its actions. Threats against inferior or nonspace-capable states, such as SPS-using LDCs, might be made at a much lower crisis threshold.

It is unclear which states will be capable of projecting military power into space over SPS'S lifetime. It is possible that technical advances will allow even small countries to purchase off-the-shelf equipment enabling them to attack an SPS, in the way that sophisticated surface-to-air missiles (SAMs) are now widely available to attack airplanes. However, it is more probable that, over the next 50 years, such capabilities will remain in the hands of the larger developed nations (including a number of countries that can be expected to enter this category in the future).

The state of technology obviously bears on the question of whether terrorists or criminals could attack an SPS. Politically motivated terrorists are generally strong on dedicated manpower, not technical expertise. The SPS would be a symbolic high-visibility target, but terrorists would be more likely to attack SPS launch-vehicles, which would be vulnerable to simple heat-seeking missiles, than to threaten the SPS directly.

However, a believable threat of direct attack by terrorists or small powers could be a spur to defensive measures such as hardening or antimissile devices, which would not stop an attack by a major power but might be effective against lesser threats.

Sabotage of the SPS through the construction force, either for political purposes and/or for ransom, could not be ruled out. Careful screening of construction workers — who would be few in number— can be expected, along with supervision while in orbit. The unavoidable conditions of life and construction in space would make it difficult, especially at first, to smuggle explosives or sabotage-devices into orbit. However, a major expansion into space involving large numbers of personnel would, in the long run, provide opportunities for sabotage that probably cannot now be foreseen.

Under current conditions any installation, in space or on the ground, is vulnerable to long-range missiles, or to dedicated terrorist groups. Reasonable measures to mitigate threats to SPS should be undertaken, but the dangers themselves cannot be eliminated.

Current Military Programs in Space

At present a number of nations use space for military purposes. The United States and Soviet Union operate the bulk of military satellites, but China, France, and a few other countries also have military capabilities. The preva-

lent uses involve satellites in low and high orbits for communications and data transmission, weather reporting, remote surveillance of foreign territory and the high seas, and interception of foreign communications. The crucial character of these satellites, especially in providing information on strategic missile placements and launches, is such that any future war between superpowers will undoubtedly include actions in space to destroy or damage enemy satellites. [73]

For these reasons both the United States and the U.S.S.R. are working to develop antisatellite (A-sat) weapons. The Soviets have in the past tested "killer satellites" capable of rendezvousing with objects in orbit and exploding on command. " 75 The United States has not yet tested A-sat weapons in space but is developing a sophisticated orbital interceptor designed to be launched from an F-15 fighter. " Neither system is capable of reaching geosynchronous satellites without being placed on larger boosters, but such development is probably only a matter of time.

The United States and U.S.S.R. have held informal talks in the past on limiting or banning A-sat weapons; the most recent such discussion took place in June 1979. These talks have been complicated by Soviet claims that the Space Shuttle is an A-sat system. The talks are currently "on hold. "

An outgrowth of A-sat concern has been the rapidly increasing interest, on both sides, in laser and particle-beam weapons. " Although some have predicted that such weapons could be deployed within a few years (especially lasers, whose technology is more advanced than particle beams), most experts say that, if at all feasible, they will not be available until the end of the decade.

High-energy lasers and particle beams are desirable because of their speed and accuracy–light speed for lasers, an appreciable fraction of that for particle beams–making them ideal for attacking fast-moving targets such as satellites and incoming missiles. They may be deployed on naval vessels, antiaircraft positions, and in space. Space-based directed-energy weapons 'could theoretically attack satellites at great distances — up to a thousand miles — since their beams would not be attenuated and dispersed by the atmosphere. Most importantly, they could also be used to engage attacking ICBMs, providing an effective ABM capability that would radically change the strategic nuclear balance. Such uses depend on attaining very accurate aiming and tracking, and extremely high peak-power capabilities.

Use of SPS Launchers and Construction Facilities

The most important military impact of SPS development would likely be military use of SPS launchers and construction facilities. In order to build an SPS it would be necessary to develop a new generation of high-capacity reusable lift vehicles to carry men and materials from the ground to low orbit. A second vehicle, such as an EOTV, would probably be used for transportation to geosynchronous orbit.

In addition, techniques and devices for constructing large platforms and working effectively in space would have to be developed, along with life support systems and living quarters for extended stays in orbit.

Improved and cheaper transportation would allow the military to fly many more missions, orbiting more and larger satellites and servicing these already in place. New construction techniques would enable large platforms for communications, surveillance, and/or directed-energy uses to be rapidly deployed. The

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[73] Clarence Robinson, "Space-Based Systems Stressed," *Aviation Week and Space Technology,* Mar. 3, 1980, p. 25.

[74] *Soviet Space Programs 1971-1975,* VOI 1, staff report for Committee on Aeronautical and Space Sciences, 1976, pp. 424-429.

[75] Craig Covault, "New Soviet Antisatellite Mission, " *Aviation Week and Space Technology,* Apr. 28,1980, p. 20.

"Craig Covault, "Antisatellite Weapon Design Advances, " *Aviation Week and Space Technology,* June 16, 1980, pp. 243-247

[77] See articles in *Aviation Week and Space Technology* of July 28, 1980; also Richard Burt, "Experts Believe Laser Weapons Could Transform Warfare in 80's, " New York *Times,* Feb. 10, 1980, p. 1.

military would have the further option of flying manned or unmanned missions.

Without SPS, advanced launch-vehicles and construction devices may not be built or, at best, be done so much less quickly. The military may hence have a strong interest in participating in their development, as they have with the Space Shuttle. Whether the military would actively support the SPS in order to benefit from such developments might depend on whether they think SPS funding would direct resources away from other military programs.

An ongoing SPS construction project with a high volume of traffic into space could provide opportunities for the military to disguise operations or incorporate them in normal SPS activities. Such a possibility would likely cause any unilateral SPS project to be closely monitored by foreign observers.

The most significant use of a fleet of military-capable SPS launchers and crews would be in providing a "break-out" capability whereby, in time of crisis, large numbers of communications and surveillance satellites, antisatellite weapons, or directed-energy platforms could be placed in orbit on short notice. This would be similar to the way a national merchant shipping or air cargo fleet is viewed as a military asset, and often supported in peacetime because of its strategic significance. Fear of such uses might be a spur to the development of antilauncher weapons, analogous to attack submarines or merchant raiders.

Military Uses of SPS

Direct Use of SPS

The energy transmission beams of the SPS could have direct military uses. A microwave system in geosynchronous orbit would not generate a beam intense enough to cause direct damage to people or installations; it might be enough to cause minor irritation or panic if used against populated areas. An intense microwave beam might be used to interfere with short-wave communications over a broad area (see ch. 5, Electromagnetic Compatibility).

Certain laser designs would be sufficiently powerful and focused to cause some immediate damage to people and structures, but would not be optimally designed for weapons-use. An SPS would use a continuous laser rather than the high peak-power pulsed lasers needed for military missions. For such uses, increased focusing of the beam would be required, as well as appropriate tracking mechanisms. If so equipped, a laser SPS could be used directly against satellites and ICBMs, and also against targets on the ground such as ships, planes, and oil refineries. Such uses would be greatly facilitated if a laser SPS were placed in low orbit, with energy relayed to the ground via geosynchronous mirrors. Since a sun-synchronous SPS in low-Earth orbit would of necessity pass directly over many different countries (including the Soviet Union), it could be seen as potentially more threatening than a geosynchronous satellite that remains fixed above one spot. A geosynchronous laser might have difficulty tracking low-flying ICBMs and satellites, due to its position 35,800 km from the target.

Since the key requirement for directed-energy weapons is a large power supply, any SPS that generates electricity directly [i.e., any design except the mirror-system) can be used to power such weapons. These weapons could be built into the SPS platform or placed at a distance in lower orbits and supplied by lasers from the SPS. The question is whether relatively small directed-energy weapons can be designed with autonomous power supplies, perhaps from nuclear reactors. Since weapons used against ICBMs must be capable of firing a large number of very rapid bursts in order to engage a fleet of 1,000 or more missiles, it may be that SPS power, if available, would be the most efficient and economical way to supply future laser or particle-beam platforms.

Direct use of the SPS in this way would of course make attack in time of war inevitable. Extensive defensive armament would have to

be built in; the offensive weaponry could also be used to defend against missile attacks.

Any testing, deployment, or use of directed-energy weapons in space is presently prohibited by the 1972 ABM Treaty and other space treaties. A proposed SPS would probably be a topic of future arms control negotiations to clarify and limit its military implications (see discussion on pp. 156-1 57).

Indirect Military Uses

In addition to these direct uses, a laser SPS could be used to supply power to military units, providing increased mobility to ground forces that could dispense with bulky fuel supplies in remote and roadless areas. Given adequate tracking capability it might even be possible to supply mobile units such as ships, planes, or other satellites equipped with thermoelectric converters, increasing their range and allowing them to carry more armaments or cargo. 78

A geosynchronous SPS is at an advantageous position for numerous communications and positioning uses, military as well as civilian. Its large size would make it easy to attach equipment to it; the military's need for redundancy makes it convenient to use all available platforms, as does future crowding of geosynchronous positions. Operation of a microwave SPS, however, could interfere with communications uses unless switched off.

SPS's power and position might make it suitable for electronic warfare uses, such as jamming enemy command-and-control links. This would require the addition of specialized equipment.

The mirror designs use reflected sunlight rather than energy transmission beams. However, it has been suggested that the reflected light could be used for weather modification or for nighttime battlefield illumination. The energy levels are not high enough, in current designs, to change weather patterns significantly (see ch. 8, Environment). Such use would be prohibited by the 1980 "Convention on the Prohibition of Military or any Other Hostile Use of Environmental Techniques."

Nighttime illumination could be significant, especially in cases of guerrilla warfare or urban terrorism where attacking forces rely on darkness and surprise as equalizers. However, fragile Solares mirrors could probably not be adjusted quickly enough to deal with sudden military developments; rapid deployment of mirrors by the military for specific uses would probably be more effective.

Ownership and Control

Any of the military uses discussed clearly depend on who owns, operates, and builds the SPS system. If SPSs are unilaterally owned by national governments, their military use is far more likely than if run by private enterprise or by a multilateral consortium. Fears of military involvement could be an incentive to establishing a multinational regime to operate or regulate SPSs, and to prohibiting militarily effective SPS designs.

A key question would be who has effective control over SPSs in a time of crisis. If a private SPS consortium, having its own launchers and crews, has a monopoly on SPS control and expertise, then governments might be hard-pressed to take over SPSs on their own. A limited defensive capability would help to deter any national takeovers. However, governments might stipulate that in an emergency they be allowed to commandeer SPSs for defense purposes.

A nongovernmental owner can be expected to resist any attempts to use SPSs for military functions rather than supplying electricity to commercial users. The threat of lawsuits or diplomatic protests at electricity interruptions caused by military preemption might help to deter such actions.

[78] See Michael Ozeroff, *SPS Military Implications,* DOE/NASA report, October 1978, pp. 13-1 *6;* also A Hertz berg, K Sun, and W. Jones, "Laser Aircraft," *Astronautics and Aeronautics,* March 1979, p. 41,

FOREIGN INTEREST

Interest in SPS has been expressed outside of the United States, especially in Europe but also in Japan, the Soviet Union, and some developing countries.

Europe

- **The first significant European study of SPS was done in 1975 by a German firm under contract from West Germany's space research organization.**
- **In England, the Department of Industry funded a study, completed in early 1979, that led to a further effort by British Aerospace to investigate the implications of SPS for British industry. "**
- **In France, the work of Claverie and Dupas on global demand for SPS has already been mentioned.**
- **The ESA began SPS assessments in 1977, publishing a-number of papers in the ESA Journal of 1978. Ruth and Westphal performed a study in 1979,[80] which examined offshore sites for rectenna placement, and in 1980 a major report on ground receiving stations was published by Hydronamic B.V. of the Netherlands.[81] In 1978, Roy Gibson, then director of ESA, said ESA was "intensely interested" in SPS,[82] and ESA has supported a group within the IAF for SPS investigation. In June 1980, an International Symposium on SPS was held at Toulouse, France, with representatives from many European countries and agencies.[83]**

In general, the European studies have focused on the European requirements for possible contributions to an SPS system. Little detailed work on the system proper has been done outside of designs to reduce the size of rectennas; European participants have relied on U.S. projects for technical information. Suspension of NASA/ DOE research efforts due to lack of fiscal year 1982 funding will have an adverse effect on foreign studies and has led to great disappointment among foreign SPS experts.[84] A major difference between U.S. and European efforts is that while in the United States SPS has attracted interest from energy experts and the DOE, European studies have been the exclusive province of organizations involved in space research .85

Soviet Union

The Soviets have initiated no major known studies of SPS, though there have been unverified claims of a Soviet SPS project. It is impossible to tell with certainty what the degree of interest or expertise is; U.S. experts feel the Soviets are relying on Western reports and are far from developing the launchers, microwave transmission expertise, and advanced solar cells necessary to consider an SPS.[86] Recent signs of interest include a paper entitled "Satellite Power Stations" published by scientists from M.V. Lomonosov State University, Moscow in December 1977.[87]88 At the 30th Congress of the IAF in Munich, September 1979, the Solar Power Bulletin reported that: "Although the Soviets were reluctant to disclose their level of commitment to a solar power satellite program, Chief Cosmonaut Beregovoy commented 'that if the United States puts up an SPS first, we will congratulate you, and if ours goes up first, we will expect congratulations from you'. "[89]

"K. K. Reinhartz, "An Overview of European SPS Activities," in *Final Proceedings of the SPS Program Review,* U.S. Department of Energy, July 1980, pp. 78-88.

[80] J. Ruth and W. Westphal, "Study on European Aspects of SPS," ESA report No CP(P) 1266.

[81] A. R. Bresters, "Study on Infrastructure Considerations for Microwave Energy G round Receiving Station," Hydronamic Project, p. 495, November 1980

'*In Jerry Grey, "The Internationalization of Space, " *Astronautics and Aeronautics,* February 1979, p 76

[83] See Peter Glaser, "Highlights of the International Symposium on Solar Power Satellites," July 1980,

"Conversation with Jerry Grey, of the Al AA, Oct. 15,1980.

[85] K K Reinhartz, op cit., p 80

""Conversations with James Oberg, Johnson Space Center, and Charles Sheldon I I, Congressional Research Service, September 1980

" *Soviet Space Programs 1971-/975, VOI 1,* staff report, Library of (ongress, 1976, p 529

[88] See statement of Peter Glaser in House *Hearings on SPS,* 96th Cong., March 1979, p 218

[89] *Space Solar Power Bulletin,* Sunsat Energy Council, February 1980), p 3

Japan

The Japanese have expressed interest and funded studies within the National Space 'Development Agency, though no permanent office for SPS exists. Japanese interest in space exploration and industrialization is strong and includes plans for several new series of Launchers. [go]

Third World

Information about SPS has been spread to the Third World by discussions at COPUOS and by sessions on SPS at international conferences such as those of the IAF. Reaction has generally been cautiously optimistic. At the International Symposium in Toulouse, Dr. Mayur of India's Futurology Commission claimed: "There is no conflict between small scale technologies and the SPS." Dr. Chatel, former Chief of the UN's Office of Science & Technology, proposed an international working party to coordinate national programs and perform assessments. " The SPS has been placed on the agenda of the upcoming U.N. energy conference in Nairobi in the summer of 1981.

[go] "James Harford, "Japan Showcases Crowing Space Prowess," *Astronautics and Aeronautics,* December 1980, pp. 120-125.

[go] Glaser, op cit

STUDY RECOMMENDATIONS

It is crucial to continue updating long-term projections as new information becomes available about developments in the space and energy fields. Close attention should be paid to: 1) future global electricity demand under various scenarios and on a detailed regional basis; 2) evaluation of the impact that possible external events —wars, oil embargoes, widespread famine— could have on U.S. and European energy needs; 3) the feasibility of a unilateral SPS System given a global market, including estimates of profitability; 4) monitoring of Law of the Sea negotiations and the resulting international regime with special attention to the implications for the Moon Treaty and other space agreements; and 5) weapons development and foreign military space programs, and arms-control negotiations.

U.S. energy and space experts often tend to pay little attention to the foreign implications of their programs. Since SPS is a system that may make sense globally but not domestically, neglect of the international dimension could lead to an unjustified foregoing of SPS development. In making plans for future R&D programs, attention should be paid to involving and informing potential partners as well as to considering the ways in which a global system might differ, technologically and institutionally, from a domestic one.

Chapter 8

ENVIRONMENT AND HEALTH

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Chapter 8

ENVIRONMENT AND HEALTH

INTRODUCTION

As a large-scale energy system operating in both the space and terrestrial environments, the solar power satellite (SPS) is unique. And because it is a new concept, our understanding and experience of a number of the environmental impacts associated with SPS are limited. The great uncertainties surrounding these effects make comparisons between SPS and other energy technologies especially difficult. While one advantage of SPS is that it would avoid many of the environmental risks typically associated with conventional energy options such as coal and nuclear, it also would generate uncommon environmental effects that presently cannot be quantified or compared to those of other powerplants. The large uncertainties also tend to provoke public debate. In light of past controversies over the siting of powerplants, transmission lines and other facilities, it is clear that environmental issues could play a key role in public consideration of SPS (see ch. 9).

This chapter will outline the environmental and health impacts of SPS that are currently thought to be most important. It will identify research needs and highlight areas of controversy. As with other aspects of SPS, the environmental effects have been evaluated most fully for the reference system. Some of this data is also applicable to the other SPS technical options, differing only in extent or degree, but information on the full range of their environmental effects is limited.

At the current stage of development, SPS environmental studies can play an important role in determining concept feasibility, technical design, and cost. For example, bioeffects research might influence the choice of frequency which, in turn, could determine hardware design and land use. Thus, many of the effects currently identified might be minimized by appropriate choices of design. However, it is also possible that one or more risks might be identified in the development process that could not be reduced to an acceptable level without jeopardizing the economic or technical viability of the SPS concept.

The SPS environmental effects and the cost of reducing them must be viewed in the context of energy technologies, energy needs, other space activities, and the incremental effect on human health and the environment. Preliminary comparative assessments indicate that, in general, those health and environmental impacts of the reference system SPS that can presently be quantified would probably be no more severe than for other large-scale electricity generating technologies although the uncertainties for SPS are high).[1,2,3,4] In fact, when compared to coal, SPS would be an order of magnitude cleaner (see app, D). However, if an SPS program is pursued, further comparative analysis between energy options would be required as more is learned about the unquantifiable impacts that could not be incorporated in the present studies A good portion of this chapter discusses these latter effects for SPS.

The discussion in this chapter relies heavily on the data and analysis generated by the Department of Energy (DOE)[5] and the National Academy of Sciences (NAS).[6,7] The reader is

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[1] L J Habegger, J R Gasper, and C D Brown, *Health and Safety Preliminary Comparative Assessment of the Satellite Power System (SPS) and Other Energy Alternatives,* **DOE/NASA report No DOE/ER-0053, April 1980**

[2] D E Newsom and T D Wolsko, *Preliminary Comparative Assessment of Land Use for Satellite* Power Systems *and Alternative Electric Energy Technologies,* **DOE/NASA report No** DOE/ER-0058, April 1980

[3] D A Kellermeyer, *Climate and Energy: A Comparative Assessment of the SPS and Other Energy Alternatives,* **DOE/NASA report No DOE/ER-0500, January 1980**

[4] **F P Levine, M J Senew, and R R** Cirillo, *Comparative Assessment of Environmental Welfare Issues Associated With the Satellite Power System and Alternative Technologies,* DOE/NASA report No DOE/ER-0055, April 1980

[5] *Environmental Assessment for the Satellite Power System Concept Development and Evacuation Program,* DOE/NASA report No DOE/ER-0069, August 1980

[6] Committee on Satellite Power Systems, National Research Council Open Committee Meetings Jan 31-Feb 1, 1980, Apr 9-10, 1980, July 1-2, 1980, Oct 1-2, 1980

[7] C H Dodge (rapporteur), *Workshop on Mechanisms Under/y-*

referred to the DOE documents for more detailed discussions. While those studies have not identified any environmental reasons not to continue with SPS development, it is very evident that much more study and research would be required before decisions could be made regarding the environmental viability of SPS. What is not clear is how long it might take before our confidence in the resolution of some environmental impacts such as microwave bioeffects would be high enough to make development or deployment decisions.

As table 28 illustrates, there is a great diversity of environmental and health impacts. Of

(continued from p. 179)

ing Effects of Long-Term, Low-Level, 2.450 MHz Radiation on People, organized by the National Research Council, Committee on Satellite Power Systems, Environmental Studies Board, National Academy of Sciences, July 17-17, 1980

Table 28.—Summary of SPS Environmental Impacts

System component characteristics	Environmental impact	Public health and safety	Occupational health and safety
Power transmission			
Microwave	—[b]Ionospheric heating could disrupt telecommunications. Maximum tolerable power density is not known Effects in the upper ionosphere are not known —Tropospheric heating could result in minor weather mod if i cat ion —[b]Ecosystem: microwave bioeffects (on plants, animals, and airborne biota) largely unknown; reflected light effects unknown —[b]potential interference with satellite communicant ions, terrestrial communications, radar, radio, and optical astronomy	—[b]Effects of low-level chronic exposure to microwaves are unknown — Psychological effects of microwave beam as weapon —Adverse esthetic effects on appearance of night sky	—Higher risk than for public; protective clothing required for terrestrial worker —Accidental exposure to high-intensity beam in space potentially severe but no data
Lasers	—Tropospheric heating could modify weather and spread the beam —Ecosystem: beam may incinerate birds and vegetation —[b]potential interference with optical astronomy, some interference with radio astronomy	—Ocular hazard? —Psychological effects of laser as weapon are possible —Adverse esthetic effects on appearance of night sky are possible	—Ocular and safety hazard?
Mirrors	—[b]Tropospheric heating could modify weather —Ecosystem: effect of 24-hr light on growing cycles of plants and circadian rhythms of animals —[b]potential interference with optical astronomy	—Ocular hazard? —Psychological effect of 24-hr sunlight —[b]Adverse esthetic effects on appearance of night sky are possible	—Ocular hazard?
Transportation and space operation			
Launch and recovery HLLV PLV COTV	—Ground cloud might pollute air and water and cause possible weather modification; acid rain probably negligible —[b]Water vapor and other	—Noise (sonic boom) may exceed EPA guidelines —Ground cloud might affect air quality; acid rain probably negligible — Accidents-catastrophic	—[b]Space worker's **hazards:** ionizing radiation (potentially severe) weightlessness, life support failure, long stay in space,

Table 28.—Summary of SPS Environmental Impacts—Continued

System component characteristics	Environmental impact	Public health and safety	Occupational health and safety
POTV	launch effluents could deplete ionosphere and enhance airglow. Resultant disruption of communications and satellite surveillance potentially important, but uncertain —[b]possible formation of noctilucent clouds in stratosphere and mesosphere; effects on climate are not known —[b]Emission of water vapor could alter natural hydrogen cycle; extent and implications are not well-known —[b]Effect of COTV argon ions on magnetosphere and plasmasphere could be great but unknown —Depletion of ozone layer by effluents expected to be minor but uncertain —Noise	explosion near launch site, vehicle crash, toxic materials	construction accidents psychological stress, acceleration —Terrestrial worker's hazards: noise, transportation accidents
Terrestrial activities			
Mining	—Land disturbance (stripmining, etc.) —Measurable increase of air and water pollution —Solid waste generation —Strain on production capacity of gallium arsenide, sapphire, silicon, graphite fiber, tungsten, and mercury	—Toxic material exposure —Measurable increase of air and water pollution — Land-use disturbance	—Occupational air and water pollution —Toxic materials exposure —Noise
Manufacturing	—Measurable increase of air and water pollution —Solid wastes	—Measurable increase of air and water pollution —Solid wastes — Exposure to toxic materials	—Toxic materials exposure —Noise
Construction	—Measurable land disturbance —Measurable local increase of air and water pollution	—Measurable land disturbance —Measurable local increase of air and water pollution	—Noise —Measurable local increase of air and water pollution —Accidents
Receiving antenna	—[b]Land use and siting—major impact — Waste heat and surface roughness could modify weather	—[b]Land use— reduced property value, esthetics, vulnerability (less land for solid-state, laser options; more for reference and mirrors)	— Waste heat
High-voltage transmission lines (not unique to SPS)	—[b]Land use and siting—major impact —[b]Ecosystem: bioeffects of powerlines uncertain	—[b]Exposure to high light intensity EM fields—effects uncertain	—[b]Exposure to high intensity EM fields—effects uncertain

[a]Impacts based on SPS systems as currently defined and do not account for offshore receivers or possible mitigating system modifications
[b]Research priority.

SOURCE: Office of Technology Assessment

most concern are: 1) the biological effects of electromagnetic radiation produced by the power transmission and distribution systems; 2) the atmospheric effects of electromagnetic radiation and launch effluents and the resulting impacts on telecommunications and air quality; and 3) the land requirements and siting considerations for ground-based receivers. The greatest environmental uncertainties are listed in table 29.

The first part of the chapter will deal with the potential environmental impacts resulting from the construction and operation of SPS systems. These and other effects will then be addressed in the second section as they pertain to human health and ecosystems. Detailed discussion of a number of impacts is found in appendix D.

Table 29.—Major SPS Environmental Uncertainties

Reference and solid-state systems
- Microwave bioeffects
  —Low-level, chronic exposure
- Launch effluent effects
  —Ions in the magnetosphere
  —Natural hydrogen cycle
  —Ionospheric depletion
  —Noctilucent clouds
- Microwave heating of the ionosphere
  Effects on telecommunications
- Land use

Laser system
- Laser bioeffects
- Tropospheric heating
- Launch effluents
- Land use

Mirror *system*
- Weather modification
- Land use
- Biological and psychological effects of 24-hr light

Systems comparisons

SOURCE: Office of Technology Assessment

ENVIRONMENT

One of the consequences of constructing and operating an energy system in space is that the extent of the environment that is directly affected by the system is much broader than for Earth-based powerplants. For example, both the transmission of SPS power and the injection of launch effluents will directly affect every layer of the atmosphere. The purpose of this section is to discuss the state of knowledge of the predominant environmental impacts of SPS, especially those that are fairly unconventional and to outline areas where further research would be needed. Biological effects, i.e., human health and safety and ecological impacts, are deferred to the second part of the chapter.

The two major environmental concerns at the present time are: 1) the effect on the atmosphere of the transportation and power transmission systems; and 2) electromagnetic interference with communications systems and astronomy.[8] With respect to the former, the effluents emitted from the launch vehicles could deplete portions of the ionosphere, alter the natural hydrogen cycle and magnetosphere dynamics and modify weather and air quality near the launch site. The effects of the power transmission system on the atmosph are a function of the frequency of the For the laser and mirror systems, the mos nificant potential impact is heating of near-Earth atmosphere, which might alter weather. If the microwave beam were to alt the ionosphere, it could disrupt telecom mu n i cat ions.

In order to understand clearly these and the other more conventional environmental impacts described in this chapter, it is worthwhile to review the properties and structure of the atmosphere as illustrated in figure 30 and discussed in box A.

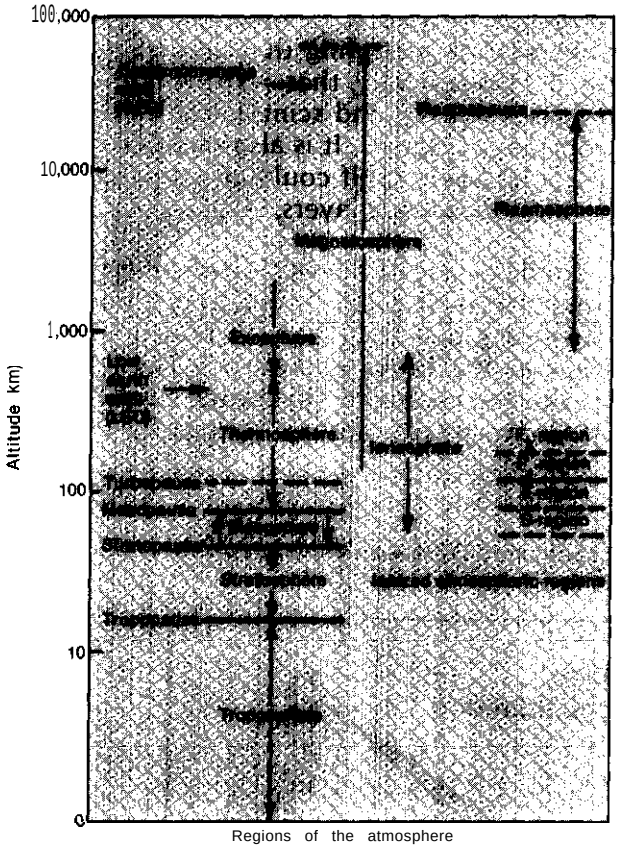
Power Transmission Effects on the Atmosphere and Weather

Current SPS designs transmit energy to Earth using microwaves, lasers or reflected light. Since the atmospheric effects of power transmission are highly frequency dependent, each

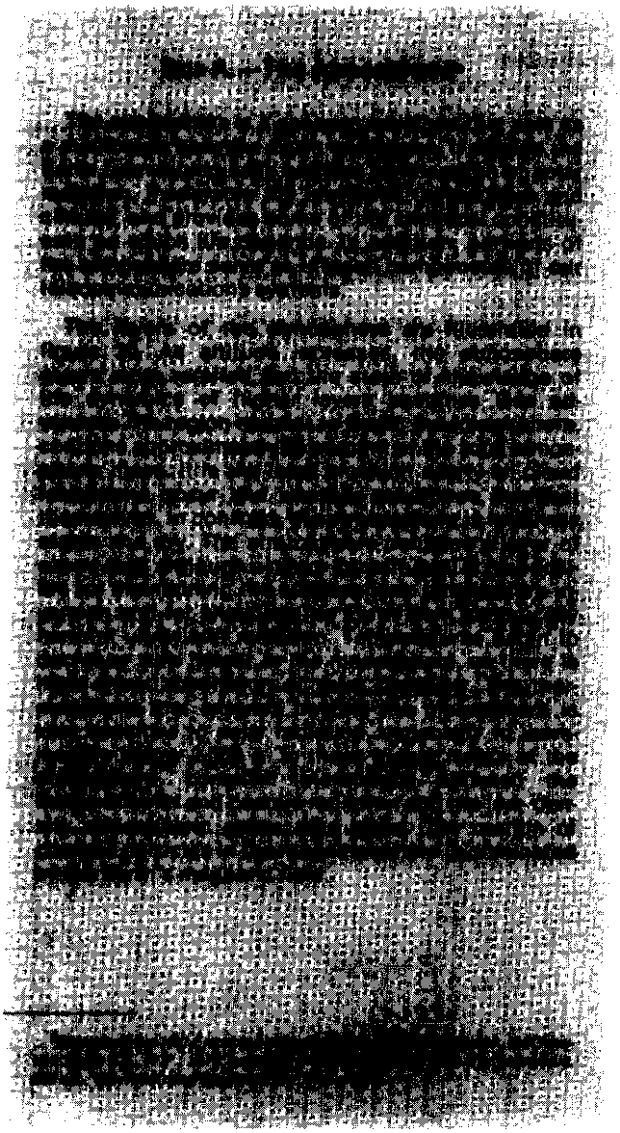
[8] *Program Assessment Report, Statement of Findings,* Satellite Power Systems Concept Development and Evaluation Program, DOE/NASA report No DO E/E R-0085, November 1980

Figure 30.— Regions of the Atmosphere

Solar radiation excites, disassociates and ionizes atmospheric constituents. The ionosphere in particular is a region of marked abundance of free electrons and ions. The properties of the ionosphere vary with latitude, time of day, season and solar activity. When electromagnetic waves enter the ionospheric plasma, they will be refracted and slowed down. Depending on the frequency of the incident wave and properties of the ionosphere, the wave can be totally reflected. It is this phenomena that makes many radio frequency communication systems possible.



SOURCE: *Program Assessment Report, Statement of Findings,* Satellite Power Systems Concept Development and Evaluation Program, DOE/NASA Report, DOE/ER-0085, November 1980



of these will be discussed separately. Table 30 summarizes the impacts of most concern.

Microwaves[8]

As the beam from a microwave satellite traveled towards Earth, it would heat the atmosphere. While attenuation of the microwave beam by clouds and rain in the troposphere could cause a slight modification of cloud dynamics and precipitation,[9] absorption

[8] See app D for details

[9] Kellermeyer, op cit

Table 30.—Power Transmission Impacts

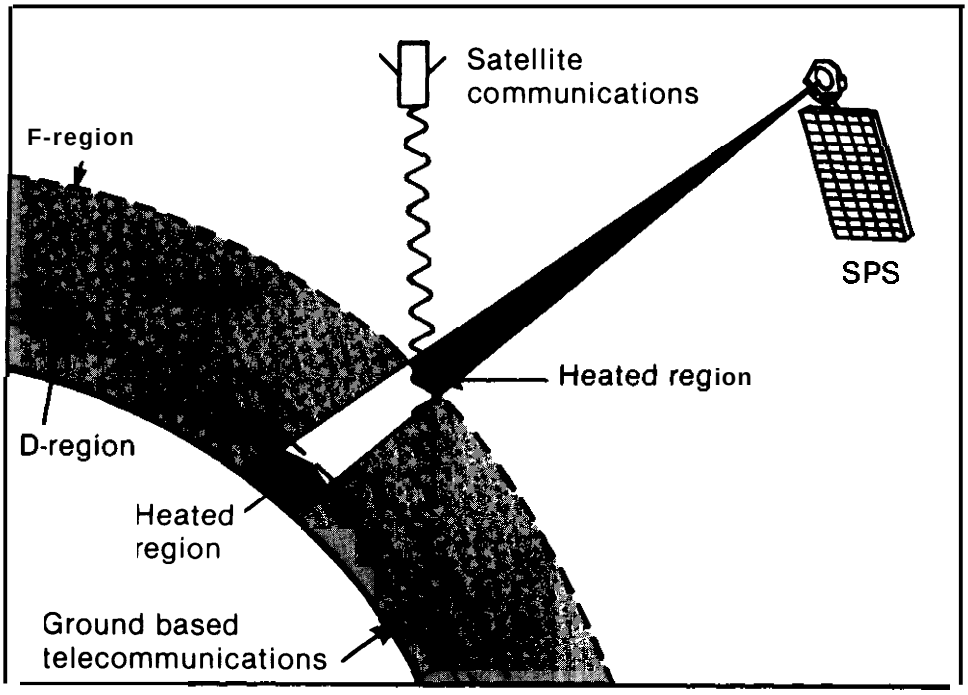
Microwaves
• Upper ionosphere telecommunications effects unknown; experiments and improved theory are needed
• Lower ionosphere impacts are thought to be negligible for a number of telecommunications systems; scaling laws must be verified and effects on telecommunication systems operating in the 3 MHz to 20 MHz range must be tested
• The maximum power density for which telecommunications effects are insignificant is not known and must be determined
• Tropospheric heating is not thought to be significant
Lasers
• Thermal blooming in the troposphere may degrade the beam
• Tropospheric heating may cause increased cloud formation, turbulence and weather modification
• Effects on the mesosphere, stratosphere, and thermosphere and continental cloud distribution and albedo are thought to be inconsequential
Reflected light
• Weather modification in vicinity of ground sites is possible, but unquantified
. Photochemistry of the ozone layer is not thought to be affected

SOURCE: Office of Technology Assessment.

of microwave energy is most important in the ionosphere. Of particular concern are the effects of ionospheric heating on telecommunication systems that rely on the ionosphere to transmit and reflect radio waves. Changes in the ionospheric properties due to heating can degrade (or in some cases, enhance) the performance of telecommunication systems by absorbing or scattering the radio signals (see fig. 31). Specifically, these effects could result in losses, fading, and scintillation of the electromagnetic signals. It is also possible that the SPS pilot beam itself could be affected by the heated ionospheric layers.

In the course of the DOE assessment several experiments were conducted to test the extent of heating and the effect on telecommunications in the lower ionosphere. These experiments demonstrated that while heating does occur the effects are not serious for the tele-

Figure 31 .—Examples of SPS Microwave Transmission Effects on the Ionosphere and Telecommunication Systems



SOURCE: *Prograrn Assessment Report, Statement of Findngs,* Satellite Power Systems Concept Development and Evaluation Program, DOE/NASA Report, DOE/ER-0085, November 1980

communication systems tested. Some researchers have even suggested that the proposed power density of 23 mW/cm^2 could be doubled without significant impact to telecommunications in the lower ionosphere. However, more research is needed in order to determine the power density threshold in the lower ionosphere, and for this the power density of the existing heating facilities will have to be increased. Additional study is also required to ascertain the effects in the lower ionosphere on telecommunication systems that operate at frequencies greater than 3 MHz (i.e., 3 to 100 MHz) range. In addition the effects of multiple microwave beams need to be determined.

Our knowledge of upper ionosphere (F region) heating is less advanced than in the D & E regions. Few underdense experiments (i. e., the beam travels through the region as opposed to being reflected, which is termed an overdense condition) to simulate SPS heating have been attempted. Recent experiments'[12] suggest that ionospheric irregularities can be created when the Platteville heater operates in an underdense mode and that these irregularities induce scintillations in very high frequency satellite-to-aircraft and satellite-to-ground transmission links. Further work would be required, however, to establish whether scintillations would occur if SPS heated the upper ionosphere. Presently, the theoretical scaling models that would extrapolate these results to SPS conditions in the F-region are very uncertain. In order to test these theories, the ground-based heating facilities will have to be upgraded

In sum, it appears that effects on telecommunications in the lower ionosphere would probably be negligible, but more study of the upper ionosphere effects is needed. By making the heating facilities more powerful, the following research can be conducted:

- Lower ionosphere: verify scaling theory; and test additional telecommunication systems (e. g., VHF, UHF, satellite-to-ground)
- Upper ionosphere: refine and verify F-region scaling laws and ionospheric physics and then test effects on representative telecommunications systems for SPS equivalent heating.

Lasers

The most significant potential environmental effects associated with the SPS laser system appear to be local meteorological changes and beam spreading due to tropospheric heating.

Tropospheric heating would result from energy absorption by aerosols and molecules and from the dissipation of receptor waste heat. Attenuation by scattering from molecules and by absorption and scattering from aerosols would be greatest for short wavelengths. Thus scattering would be only significant for visible wavelength lasers, while aerosol effects become important to infrared lasers only under hazy or overcast conditions.

The absorption of laser energy would lead to a process called "thermal blooming, " in which a density gradient acts as a gaseous lens that

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[10] *Environmental Assessment for the Satellite Power System – Concept Development and Evaluation Program – Effects of Ionospheric Heating on Telecommunications,* DOE/NASA report No DO E/ ER-10003-T1 , August 1980

[11] W E Gordon and L M Duncan, "Reviews of Space Science — SPS Impacts on the Upper Atmosphere, " *Astronautics and Aeronautics,* vol *18, No 7,8,* July/August 1980, p 46

[12] S Basu, A L. Johnson, J A Klobuchar, and C M Rush, "Preliminary Results of Scintillation Measurements Associated With Ionosphere Heating and Possible Implications for the Solar Power Satellite, " *Geophysical Research Letters,* vol *7, No 8,* August 1980, pp 609-612

can spread, distort or bend the laser beam.[13] The severity of the thermal blooming would be a function of several parameters, including the frequency and intensity of the laser, the wind velocity, atmospheric density, absorption and altitude. Laser wavelengths that have high atmospheric transmittance would be less likely to suffer from thermal blooming. Thermal blooming could also degrade and spread the beam. It is clear that if spreading did occur it would be less critical for the space-to-Earth SPS beam than for Earth-to-space transmission (i.e., laser pilot beam) that would be deflected earlier in its path.

Tropospheric heating would be likely to induce meteorological alterations. It is unlikely that global climate changes could result since the absorption of laser energy would be less than the typical natural variations of the atmosphere; it would take the deployment of 200,000 to 400,000 laser systems before the global climate might be affected. " The potential local weather effects include changes in wind patterns, evaporation of sections of ground fogs and clouds and elevated temperatures. None of these effects are expected to exceed those associated with conventional nuclear powerplants of comparable power rating. '5 The most significant potential impact would be updrafts above the receptor site, which might induce cloud formations (a problem for the beam) and severe turbulence in the lower troposphere. Increased turbulence is not necessarily an adverse effect; the upward convective air movement would promote vertical mixing and the dispersal of waste heat. [16] However, the turbulence could present a hazard to aircraft that flew in the affected region. For this and other reasons, it has been suggested that aircraft be restricted from flying through transmission areas. [7]

The laser beam would be capable of boring holes through thin clouds and fog by evaporating the water from aerosol droplets. After passing through the beam, the cloud fog would recondense. Portions of noctilucent clouds in the mesosphere might also be vaporized. The possible environmental consequences, such as alteration of the continental cloud distribution or albedo, would be slight but research would still be needed.

Preliminary analysis indicates that the potential impacts in other atmospheric regions would be negligible. [18] In the stratosphere, ozone would not be affected for wavelengths greater than 1 micron. Possible perturbations of the plasma chemistry by the laser beam in the mesosphere and thermosphere are believed to be small and inconsequential, since the interactions would be confined to the laser beam volume; ionospheric heating would also be negligible. " However, research would be needed in order to validate this conclusion.

In the near term, environmental studies could concentrate on the following areas:

- Thermal blooming — increase theoretical understanding and refine models; investigate enhancement of thermal blooming by clouds; study transmission and thermal blooming as a function of laser frequency, time of year, and receptor altitude and location.
- Induced clouds–study the extent and consequences of induced clouding.

Reflected Light

The mirror system would reflect about 0.8 kW/m^2 of light to Earth, somewhat less than the illumination due to the Sun.[20] The primary atmospheric effect of this additional light would be tropospheric heating. Coupled with the sensible heat release at the energy conversion site, the weather might be measurably modified as convection, cloud formation, and

[13] R E Beverly, *Satellite Power Systems (SPS) Laser Studies, Technical Report–Laser Environmental Impact Study,* vol 1, Rockwell International report No SSD 80-0119-1

"Ibid

[15] Ibid

"[bid

"Ibid.

'"t W Walbridge, *Laser Satellite Power Systems,* Argonne National Laboratory, AN L E S-92, January 1980

"Ilt'k erly, op cit

[20] K W' Bill man, W P Gilbreath, and S W Bowen, " Solar Energy Economics Orbiting Reflectors tor World Energy, " in *How Big and Still Beautiful Macro-Engineering Revisited,* F P Davidson, et al (eds) (Boulder, Colo American Association for the Advancement of Science, Westview Press, 1980), pp 293-339

rainfall above the site are increased. While no assessment has been made of the magnitude or consequences of this potential impact, the weather effects of other "heat islands" of the same scale, such as New York City that releases about 0.6 kW/m^2 of heat, can be used for comparison. " Weather impacts on a global scale are not anticipated since the mirror system would add less than 0.015 percent to the normal solar heat input. 22 Large-scale computations on weather models applicable to the mirror system size are needed to quantify the effects for different locations. Additionally, the heating effects of the orbiting refiector system could be simulated on the ground, using solar heated ponds or other means without the need for a demonstration satellite and hence at a relatively low cost and at an early time. [23]

Once the potential weather impacts are more clearly understood, the system design and economics could be reevaluated to accommodate possible environmental concerns. For example, one might redesign the system to reflect less light to Earth or use heat dispersion devices on the ground and in space to reject the heat into areas that would have the minimal impact. Dichroic mirrors in space for example, could selectively reflect to Earth only those wavelength bands that would be converted with highest efficiency at the receiving site. It may also be found that the weather modification induced by the mirror system heat is actually beneficial to the receiving region by preventing cloud impingement over site.

In addition to tropospheric heating, other possible environmental impacts have been suggested. The mirror system beam might perturb the photochemistry of the atmosphere, particularly the ozone layer. However, preliminary analysis indicates that the effect would be negligible.[24] Further study is needed to confirm this finding and to investigate the potential photochemistry effects if dichroic mirrors were used in space. [25]

More detailed study is required before reasonable comparisons can be made between the mirror system and the other SPS technical options. Research priorities include:

- weather modeling and large-scale computations applicable to large mirror system size,
- the effects of dichroic mirrors on the system's environmental impacts, and
- possible ground-based experiments to simulate mirror system heating.

Space Vehicle Effects*

There are two major environmental effects associated with the space transportation segment of SPS: the injection of rocket exhaust products into the atmosphere (see fig. 32) and noise generated at the launch site (see Health and Ecology). The severity of these impacts would depend on the size and frequency of launches, as well as the composition of rocket fuels and flight trajectory.

Assessment of the potential SPS effects on the atmosphere is hampered by the unprecedented scale of SPS transportation requirements as well as an incomplete understanding of the atmosphere. The reference design, for example, requires that a heavy lift launch vehicle (HLLV), five times larger than the Saturn V, be flown one to two times per day for 30 years.") The other reference system space vehicles and launch schedules are shown in tables 31 and 32.

The effects of SPS exhaust products on the atmosphere are also uncertain because much of our theory and experience with the effects of launch effluents stem from the space shuttle, which uses solid-fuel boosters. Since the SPS HLLV would be fueled with liquid propellants, the composition and distribution of the

[21] Kenneth Bi l l man, E PR 1, Private Communication

[22] KBil l man, W P G ilbreath, S W Bowen, "Solar t nergy Revisited W ith Orbit ingReflectors," N A SA, A me\

"f311 l man, privatecommunication

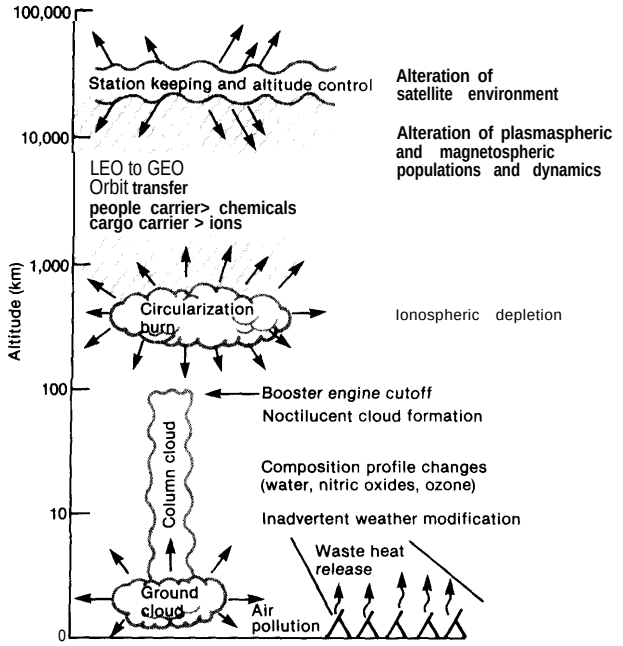
[24] Bil l man, Gilbreath, andBowen, Solar Energy Economics, ' op (-lt

[25] 1+1 l ma n, private communication

See a 1)1) D tor details

* Environmental Assessment for the Satellite Power System (Concept Development and Evaluation Program, DOEER-0069, August 1980

Figure 32.—Summary of SPS Atmospheric Effects



SOURCE: *Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program, DOEI/R-0069,* **August 1980.**

reference system launch effluents would differ from that of the shuttle.

The major space vehicle impacts of the reference system are identified in table 33. Presently, the greatest uncertainties are associated with four potential effects[27] (treated in more detail in app. D):

- **In the magnetosphere, the emission of ions from COTVS and POTVS would substantially increase the ambient concentrations of these particles. Because of our poor understanding of the complex dynamics and composition of this region, potential impacts can be identified, but the likelihood and severity of these effects are highly uncertain. Possible effects include enhancement of Van Allen belt radiation and changes in magnetospheric and plasm aspheric dynamics that could perturb ionospheric electricity, tropospheric weather, and satellite communications.**

— — —

Program Assessment Report, Statement of Findings, op cit

Table 31 .—SPS Space Transportation Vehicles

Name	Function	Propellants	Launches[b] per year	Operating altitude (km)	Main exhaust products[c]
Heavy-lift launch vehicle (HLLV)	Transport material between Earth and LEO	CH_4/O_2 (stage 1) H_2/O_2 (stage 2) H_2/O_2 (circularization/deorbit)	375 375 375	0-57 57-120 450-500	$C0_2$, H_20 H_20, H_2 H_20, H_2
Personnel launch vehicle (PLV)	Transport personnel between Earth and LEO	Details not available (probably same as HLLV)	30	0-500	C_2, H_20, H_2
Cargo orbit-transfer vehicle (COTV)	Transport materials between LEO and GEO	Argon $H_2/0_2$	30	500-35,800	Ar+ plasma H_2O, H_2
Personnel orbit-transfer vehicle (POTV)	Transport personnel between LEO and GEO	$H_2/0_2$	12	500-35,800	H_2O, H_2

[a] CH_4/O_2: liquid methane/liquid oxygen H_2/O_2: liquid hydrogen/liquid oxygen.
[b] Assuming construction of two (silicon option) 5-GW satellites/year.
[c] CO_2: carbon dioxide H_2O: water H_2: hydrogen Ar + : argon ion.

SOURCE: *Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program, DOE/ER-0069,* **August 1980,**

Table 32.—Exhaust Products of SPS Space Transportation Vehicles[a]

Atmospheric region	Altitude range (km)	Source[b]	Total mass (t)[c]	Mass of specific emission products (t)				
				$C0_2$	co	H_2O	H_2	Ar +
Troposphere	0-0.5	HLLV, PLV	650-	260	117	260	13	—
	0.5-13	HLLV, PLV	2850	1140	513	1140	57	—
Stratosphere	13-50	HLLV, PLV	3027	1210	546	1210	61	—
Mesosphere	50-80	HLLV, PLV	758	199	90	450	19	—
Thermosphere	80-125	HLLV, PLV	2031	—	—	1960	71	—
	LEO[d]	HLLV, PLV	33	—	.	443	1	—
	LEO	POTV	460	—	—	443	11	—
Exosphere	GEO[d]	POTV	153	—	—	147	6	—
	477-GE0	COTV[e]	985	—	—	0	0	985[f]

[a]Mass emissions per flight.
[b]PLV emissions would be chemically similar to those of the HLLV, but are not Otherwise determined at this time. The numbers shown are emissions Of the HLLV only
[c]t = metric ton = 1000 kg.
[d]Low earth orbit (LEO) is at 477 km; geosynchronous earth orbit (GEO) is at 35,800 km.
[e]In additio, t. mass emissions, th, argon plasma engines of the COTV would inject a significant amount of energy into this altitude range. Also argon plasma engines would be used for satellite attitude control and stationkeeping control at GEO; these em ISSIONS are unknown at present and have not been included.
[f]Ar + mass for the silicon photovoltaic cell option. For the gallium aluminum arsenide option, the Ar + mass would be 212 t.

SOURCE: *Environmental Assessment for th Satellite Power System Concept Development and Evaluation Progra DOE/ER-0069, August 1980.*

Table 33.—Space Vehicle Impacts

Troposphere
- Ground cloud nuclei and heat could have a measurable effect on weather
- NO_x emissions are small compared to typical powerplant, but in conjunction with ambient concentration could exceed projected EPA standards

Stratosphere and Mesosphere
- [a]Emission of water vapor may cause noctilucent clouds in the mesosphere; climatic effects would probably be small, but uncertain
- [a]Water and NO_x are not expected to significantly alter ozone, but uncertainties remain

Ionosphere
- [a]Formation of large ionospheric hole in F-region from water and other effluents should not adversely affect HF telecommunication signals over distances significantly larger than the ionospheric depletion, impacts on other telecommunications systems are not known; more studies are needed; long-term depletion around launch trajectory possible
- [a]D&E region effects are poorly understood; impacts on telecommunications from depletion of the ionosphere are possible
- Possibility of enhanced airglow and Perturbation of Van Allen belts, but likelihood is-unknown'

Thermosphere and Exosphere
- [a]Large increase **in water content might alter the natural hydrogen cycle and affect the dynamics of the region**

Plasmasphere and Magnetosphere
- [a]Argon ions and hydrogen atoms might enhance Van Allen belt radiation, generate ionospheric electric currents that would interfere with public utilities, modify auroral response to solar activity and affect weather and satellite communications, but probability and severity are unknown
- The effects of the satellite structures are thought to be negligible or easily remedied

[a]Research priorities.

SOURCE: Office of Technology Assessment

- **The injection of water vapor in the upper atmosphere would significantly increase the water content relative to natural levels. One possible consequence is an increase in the upward flux of hydrogen atoms through the thermosphere. If an accumulation of hydrogen results, the dynamics of the thermosphere and exosphere could be affected. Satellite drag could also be increased. Models of the natural hydrogen cycle are needed to quantify and simulate the effects of SPS on global scale.**
- **The injection of rocket exhaust, particularly water vapor, into the ionosphere could lead to the depletion of large areas of the ionosphere. These "ionospheric holes" could degrade telecommunication systems. While the uncertainties are greatest for the lower ionosphere, experiments are needed to test more adequately telecommunications impacts and to improve the theoretical understanding of chemical-electrical interact ions throughout the ionosphere.**
- **Another consequence of increasing the concentration of water in the upper atmosphere might be the formation of noctilucent clouds in the mesosphere. While global climatic effects of these clouds are thought unlikely, uncertainties remain, especially with respect to the persistence**

of the clouds as a function of temperature.

The transportation system for other SPS options could be substantially different from that for the reference system. For example, the mirror system and the bulk of the laser system satellites operate in low-Earth orbit (LEO). The magnetospheric effects associated with transporting materials to geostationary orbit (CEO) would therefore not be a problem for these systems. Environmental impacts are also determined by the frequency of launches, which depends on the size of the vehicle, and the total mass in orbit. For the same size launch vehicle and total system power, it appears that the mirror system, which is the least massive per kilowatt of the four alternatives, would require the least number of flights, whereas the laser system would require the most.

Other transportation scenarios have been proposed (see ch. 5). With respect to the reference system, some of the environmental effects could be mitigated by changing the flight trajectory of the HLLV, the rocket fuel of the COTV or other transportation characteristics that present a problem. Laser propulsion, for example, has been suggested as an option. The tradeoffs associated with these design changes would need to be studied as the SPS concept evolved.

As an alternative to the HLLV, it has been argued that economies of scale result from increasing the number and frequency of launches of a vehicle much smaller than the proposed HLLV.[28] However, it is not clear how the effects of more launches of a smaller rocket compare to the impacts of fewer flights of a larger one.

A very different approach in the construction of SPS would be the utilization of nonterrestrial materials. This could significantly reduce the amount of terrestrial materials that need to be transported to space, and hence reduce the environmental impacts associated with the frequent launch of transport vehicles.[29] While the economics and technical feasibility of this concept have been evaluated, the possible environmental impacts have not been studied and require consideration

Electromagnetic Interference

Each SPS transmission option, whether microwave, laser, or mirror, has the potential for affecting other users of the electromagnetic spectrum. In general, where such effects occur they will be detrimental to one user or another, since most systems now depend on the relative purity of the wavelength band they use.

Sharing the same air or ground space is possible by operating at different frequencies and at specified power levels. This is most obvious for radio frequencies, where the frequency band width and power levels at which systems can operate are assigned by national agencies working in accord with national and international standards. Where potential for interference occurs in the radio frequency spectrum, the power level and antenna characteristics of such interference are strictly regulated in order to keep it below the available technology's ability to filter out undesirable effects. The principle is to assure that electronic systems are compatible with one another, i.e., that interference from one system does not degrade the overall performance of a second.

Because of the large amounts of power that the microwave, laser, or mirror SPS systems transmit through the atmosphere, and the extensive area covered by a full satellite deployment, potential interference effects would be much greater than any other system which now use the electromagnetic spectrum. They would also be commensurately more difficult to ameliorate. Affected parties would include users of space and terrestrial communications and sensor systems, radar systems, various terrestrial control devices, computers, radar and radio telescopes, optical telescopes, and

[28] D L Akins, "Optimization of Space Manufacturing Systems," in *Space Manufacturing From Non-Terrestrial Materials*, J Grey and C Krop (eds) (New York AIAA, November 1979)

[29] J Grey, *Satellite Power System Technical Options and Economics* Contractor report prepared for OTA, Nov 14, 1979

microprocessors. SPS systems using microwaves for power transmission would generate the greatest potential interference because communications systems and passive receivers of all sorts share this portion of the spectrum, as well as other electronic equipment (e. g., computers, control devices, sensors) that are susceptible to microwave energy. The reference system is designed to transmit at 2.45 GHz, the center of the Industrial, Scientific, and Medical band (ISM).

This analysis focuses on the affected users on an area-by-area basis. It is based on the presumed characteristics of the three transmission options of table 34. However, it should be emphasized, that the precise characteristics of the transmission beams are as uncertain as other details of the proposed alternative systems. Not only are the characteristics of the systems and their components poorly known, the theory is inadequate to extend known data to other frequencies, angles, or distances. Nevertheless, it is possible in most cases to indicate broadly the sources of potential interference and their effects on other users of the spectrum.

Potential Affected Users of the Electromagnetic Spectrum

SPACE COMMUNICATIONS

All artificial Earth satellites use some portion of the electromagnetic spectrum, either for communication, remote-sensing or telemetering data. All would be affected in some way by the SPS.

• *Geostationary satellites.* These would be most strongly affected by the microwave systems. They would experience microwave interference from the fundamental SPS frequency (e.g., 2.45 GHz for the reference design) and noise side bands, spurious emissions in nearby bands, harmonics of the fundamental SPS frequency, and from so-called intermodulation products. All radio frequency transmitters generate harmonics and minor spurious components in addition to the desired signals. The unintentional outputs are filtered to satisfy national and international regulations about compatibility with other spectrum users. Receivers also generally include sufficient filtering to prevent degradation by the residual undesired signals. However, the magnitude of the power level at the central frequency and in harmonic frequencies for a microwave SPS would be so great that the possibility of degrading the performance of CEO and LEO satellite receivers is significant. Examples of serious interference include the 2.50 to 2.69 GHz direct broadcast satellite band, the 7.3 to 7.45 GHz space-Earth government frequency slot,'" and the S-band National Aeronautics and Space Administration (NASA) space communications channel.

I n addition to the direct effects from microwave power transmissions, geostationary communications satellites may experience "multipath interference" from geostationary power satellites due to the latter's sheer size. I n some cases, microwave signals traveling in a straight line between two communications satellites would experience interference from the same signal reflected from the surface of the power satellite lying between them. Communications satellite uplink channels would be degraded by multi path interference from the SPS vehicle during orbit periods when the SPS is at a lower altitude than the adjacent communications satellites.

These adverse effects would necessitate a limit on the spacing that a geostationary satellite must have from a power satellite in order to operate effectively. The minimum necessary spacing would depend directly on the physical design of the satellite, the wavelength at which it operates, the type of transmission device used (i.e., klystron, magnetron, solid-state device), and the satellite antenna sidelobe magnitudes, transmitted power, orbit perturbations, and intermodulation product frequency distribution and amplitudes.

Because a microwave SPS as currently configured must share the geostationary orbit with other satellites, the value of the minimum

[10]John R Juroshek, "The SPS Interference Problem – Electronic System Effects and Mitigation Techniques, " *The Final Proceedings of the Solar Power Satellite Program Review*, Conf 800491(DOE), pp 411-438

Table 34.—Summary of Electromagnetic Effects

System	Spectral region	Affected systems	Mechanism/effect
Microwave			
	Microwave		
	• Power radiation at central frequency (2.45 GHz or some other choice)	Terrestrial	Scatter in atmosphere, from rectenna
		LEO satellites	Pass through SPS beams
		Radio astonomy receivers	Scatter from rectennas, atmosphere
		Deep space communications	Direct interference
	• Harmonics of central frequency	GEO satellites	Direct interference
		Radio astonomy receivers	Direct interference
	• Spurious noise near central	GEO satellites	Direct interference
		Radio astronomy receivers	Scatter from rectennas
	• M u l i path interference	GEO satellites	Two-beam interference
	Infrared		
	• Thermal radiation from all satellite components	Radio astronomy receivers	Direct interference (raised background). Satellite appears as spurious source
		Infrared astronomy receivers	Satellite appears as spurious source
	All wavelengths (reflected sunlight)		
	• Diffuse reflections		
	• Specular reflections Ž Glints	Optical telescopes	Sky background increased. Portions of sky obscured.
Laser			
	Microwave		
	• **No** discernible effect	None	
	Infrared		
	• Central beam radiation	Infrared receivers near terrestrial receiver	
	. Thermal radiation from all components	Radio astonomy receivers	Direct interference (raised background). Satellite appears as spurious source
	All wavelengths (reflected sun/ight)		
	• Diffuse reflections	Optical telescopes	
	• Glints	Probably no effect	
Mirrors			
	Microwave		
	• No discernible effect	None	
	Infrared		
	• Thermal radiation from all components	Radio astronomy receivers	Direct interference (raised background). Satellite as spurious source
	All wavelengths (reflected radiation)		
	• Specular reflection to terrestrial station	Optical telescopes near terrestrial station	General sky brightening
	• Diffuse reflection	Optical astronomy	Sky background obscured around satellite
	• Glints from structural components	Effect probably small	

SOURCE: Office of Technology Assessment

necessary spacing has emerged as one of the most critical issues facing a geostationary SPS. However, in the absence of a specific design, it is impossible to characterize the exact form and nature of the potential interference parameters that are needed in order to calculate the minimum required spacing. In addition, even if the design parameters were known accurately, the theory of phased arrays is insufficiently developed at present to predict the

minimum spacing with any accuracy. Estimates range from ½° to 1°.[31] The lower limit would probably be acceptable. However, a minimum spacing much greater than 10 would, result in too few available geostationary slots to allow both types of users to share the orbit over the continental United States.

In 1980, some 80 civilian satellites shared the geostationary orbit worldwide, and by 1990 that number is expected to increase substantially. Even though improvements in technology will lead to a reduction in the total number of satellites necessary to carry the same volume of telecommunications services, total service demand is expected to rise dramatically. At present the minimum spacing for domestic geostationary satellites is 40 in the 6/4 GHz communication band and 30 in the 14/12 GHz band. At these spacings, a total of 90 6/4 GHz band satellites and 120 14/12 GHz band satellites could theoretically coexist at geostationary altitudes, in the absence of SPS. Additional satellites could use other frequency bands without interfering with the above satellites, though this would ultimately be limited by the station-keeping capability of the various satellites. Multiple use platforms represent one possible option to reduce contention over orbital spaces.

The laser and mirror systems in LEO would not interfere substantially with geostationary satellites. Even in the unlikely event that such a satellite were to pass precisely between a geostationary satellite and its ground station, the time of passage as well as the apparent size of the occluding power satellite would be so small as to cause only a slight diminution of the signal.

- *Other satellites.* In addition to geostationary satellites that would operate at the same altitude as the GEO SPS, there are numerous remote sensing, communications, and navigation satellites in various LEOs that may pass through an SPS microwave beam. Proposed high-Earth orbit (HEO) satellites would also be affected because of shadowing in the path from orbit to terrestrial station by the large SPS vehicles, and receiver interference thresholds that could be exceeded by the unintentional emissions from the SPS platforms. They use a range of optical and microwave sensors, particle detectors, computers, and communication devices. Although the optical sensors are not damaged by a microwave beam, increased device noise can result in microwave interference in related parts of the satellite. " A number of shielding and filtering techniques are available to ameliorate potential interference. These would need to be tested for specific satellite and deployment scenarios. Such satellites could protect their uplink communications receivers from adverse interference by shutting down for that short period (a few seconds) during SPS power beam traversal, or it might be feasible for the SPS to shut down for the satellite passage. " For short-term SPS shutdown, high-capacity battery storage would have to be Included in the ground segment (see ch. 9, sec B). This shutdown presents a severe control problem (reduce power, start up again), as well as serious network load transfer complexities. It may also be possible for some satellites to fly orbits that would not intersect the SPS beam. For example, satellites traveling in an equatorial orbit at altitudes lower than 1,000 km would not intersect SPS beams directed to rectennas at 350 latitude or greater. Computer and processing/control circuit functions can be protected by improved module shielding and interconnection noise filtering.

The laser and mirror systems might interfere with nongeostationary satellites by causing reflected sunlight to blind their optical sensors or by occluding communications beams. Of the two systems, the mirror system would be

[31] E Morrison, et al , *SPS Effects on LEO and GEO Satellites,* NTIA publication (inpress)

[32] W B Grant, E L Morrison, J r , and K C Davis, "The EMC Impact of SPS Operations on Low Earth Orbit Satellites, " *The Final Proceedings of the Solar Power Satellite Program Review,* Conf-800491(DOE), pp 411-434

[33] P K (hapman, " Encounters Between SPS Power Beams and Satellites in 1 ower Orbits, " *The Final Proceedings of the Solar Power Satellite Program Review,* Conf **-&100491 (DC) E),** p p 428-430

most problematic because of the large size of the mirrors and their orbital speed. To date, no one has calculated the possible adverse effects due to this cause.

- Deep space communications. Because deep space probes generally travel in the plane of the solar system (known as the ecliptic), they would be especially affected by a geostationary microwave SPS. As seen from the Earth, the ecliptic crosses the Equator in two places. A microwave SPS would effectively prevent ground communication with the probe when the latter happens to lie near the part of the ecliptic that crosses the Equator. This interference is especially serious for deep space vehicles because it is essential to be able to communicate with them at any time for the purposes of orbit control and for timely retrieval of stored data. The susceptibility problem is more serious than normal satellite communications links because of receiver sensitivities and the low signal-noise ratios imposed by the long distances from Earth station to probe.

It would be possible to avoid such interference by establishing a communications base for deep space probes in orbit. As we penetrate deeper into space, this may be advisable for other reasons. Such a communications station would effectively add to the cost of the SPS.

TERRESTRIAL TELECOMMUNICATIONS AND ELECTRONICS

Both civilian and military terrestrial telecommunications and electronic equipment would suffer from a number of possible effects of a microwave beam. Direct interference can occur from the central frequency and harmonic emissions. In addition, scattered and reflected radiation from the rectenna and structure intermodulation products could cause additional interference problems for terrestrial receivers. At the very least, rectennas would have to be located far enough from critical sites such as airports, nuclear powerplants, and military bases to render potential interference as small as possible. In addition, most equipment would have to be modified to permit far better rejection of unwanted signals than is now necessary. This appears to be technically feasible; primary concerns would be modifications to the shielding of sensitive circuitry. The initial estimate of the cost of modifying terrestrial electronic equipment is in the range of 0.1 to 5 percent of the unit cost (approximately $130 million for the 1980 estimate of the inventory of susceptible equipment).

The EMC evaluation program determined that most terrestrial electronic equipment would be unacceptably degraded by SPS interference for power levels possible within a 50- to 75-km distance of a rectenna site. The most sensitive equipment, such as high capacity satellite terminals and radio astronomy receivers would be adversely affected at distances of 100 to 200 km.

Mitigation techniques have been evaluated for radars, computers and processors, sensors, and multichannel terrestrial microwave communications. With the exception of the most sensitive receivers, modifying shielding and grounding procedures and using rejection filters in radar and communications receivers would allow most systems to operate with the SPS interference levels expected at the rectenna site boundary. Special mitigation techniques for more sensitive systems involving interference cancellation methods have been considered, but they must be tested to determine the range of protection possible.

EFFECT ON TERRESTRIAL ASTRONOMY AND AERONOMY

None of the proposed SPS systems could benefit astronomical research except insofar as they would indirectly provide a transportation system for placing large astronomical facilities in space. Their detrimental effects would vary depending on the system chosen. The impacts of a microwave system would likely be severe for both optical and

[14] E Morrison, "SPS Susceptible Systems Cost Factors – Investment Summary and Mitigation Cost Increment Estimates," in press

[15] P A tkstron and G M Stokes, "Workshop on Satellite Power Systems (SPS) Effects on Optical and Radio Astronomy," (ont 7')05141 (DOE)

radio astronomy. An infrared laser system[36] would have fewer detrimental effects on both forms of astronomy than the reference system. The mirror system would have its most serious effect on optical astronomy.

- *Optical astronorny.* For the reference system, diffuse reflections from the satellite structures would cause the greatest degradation for terrestrial telescopes. Because they appear to remain stationary along the celestial Equator, reflected light from a system of 15 to 60 satellites would meld together to block observation of faint objects over a large portion of the sky near the Equator for telescopes located between the longitude limits of the satellites. Some major foreign, as well as most domestic observatories would be affected. Observations of bright objects would be possible, but degraded in quality. In addition, reflected light from the LEO construction base could be expected to interfere with observations of faint sources in its vicinity. Telescopes in orbit, such as the U.S. Space Telescope, to be launched in 1984, will travel in nonequatorial orbits and therefore would not be affected significantly by a reference system SPS. The danger of pointing directly at a geostationary satellite will increase the complexity of the telescope-pointing mechanism. Astronomical photometry and spectrometry instrumentation, and high resolution telescope tracking systems would be degraded if located within 50 to 60 km of a rectenna site. The EMC evaluation program indicated the necessity of improving sensor and sensitive circuit shielding, and maintaining a minimum separation distance of 50 to 60 km between rectenna sites and telescopes using sensitive electronics to remove SPS induced degradation.

  The effect of diffuse reflections from a laser SPS in LEO could be expected to cause fewer problems for observations of diffuse objects near the Equator because the laser collection and transmission satellite would be constantly in motion. Thus, no part of the sky would be permanently blocked from view. The relay satellites located in CEO would not be likely to interfere with optical observations. However, large moving satellites would present optical astronomy with another observational obstacle. Scattered light from them would vary in intensity as the satellite passes near a celestial object of interest, making calibration of the nearby background radiation very difficult if not impossible. Photographic exposures of faint celestial objects may last from 1 to 3 hours and individual photographs cannot be added effectively. The laser satellite would interfere with infrared astronomy studies involving wavelengths adjacent to the transmission wavelength of the beam.

  The mirror system, which would involve a number of large, highly reflective moving mirrors in LEO, would have very serious effects on optical astronomy. While the precise effect has not been calculated, it would render a large area around the ground stations totally unacceptable for telescopic viewing. Because of diffuse reflections from the atmospheric dust and aerosols above the ground station, the individual mirrors would create moving patches of diffuse light that would preclude studies of faint objects that lie in the direction of the satellite paths.
- *Radio astronomy.* Radio astronomy would suffer two major adverse affects from microwave systems: 1) electromagnetic interference from the main PS beam, from harmonics, from scattered or reflected SPS signals, and from reradiated energy from rectennas; and 2) increasing the effective temperature of sky noise background, which has the effect of lowering the signal-to-noise ratio of the radio receivers. Studies of faint radio objects near the Equator would be rendered impossible. In addition, rectennas would have to be located more than 200 km from radio observatories and in terrain that would shield the observatories from reradiated microwave energy. Also of concern to radio astronomers is the possibility that expected failures of the klystron or other microwave emitting devices would result in spurious noise signals that would further disrupt radio astronomy reception.

[36]CBain, *Potential of Laser for SPS Power Transmission,* SPS CDEP, October 1978

Neither the laser nor the mirror systems would contribute to the first effect. However, they would raise the effective temperature of the sky background. Low-level measurements such as scientists now routinely conduct, for example, to measure the amount of background radiation from the primordial explosion of the universe would thus be extremely difficult if not impossible from terrestrial stations. Many other types of sensitive radio astronomy observations would be seriously degraded.

The susceptibility of radio astronomy receivers results from their high sensitivity, and the wide range of observing frequencies in the microwave spectral region. Mitigation techniques effective for other electronic equipment are only marginally useful because of the sensitivity factor and associated dynamic range. A preliminary review of interference canceling techniques indicates that this method has a high probability of providing rejection of SPS signals to a level that would allow rectenna sites to be located within a 100- to 150-km range from radio astronomy facilities. Detailed design and testing at a radio astronomy receiver is necessary because of the unique aspects of integrating a canceler function into such complicated and sensitive receivers.

Space basing of radio telescopes, especially on the far side of the Moon, would eliminate the impact of SPS and other terrestrial sources of electromagnetic interference. However, such proposals, though attractive from the standpoint of potential interference, are unlikely to be attractive to astronomers for many decades because of their high cost and relative inaccessibility.

- Optical aeronomy. Much of our knowledge of the upper atmosphere is gained by nighttime observations of faint, diffuse light. Some of the observations that are made today must be carried out in the dark of the Moon. The presence of satellites whose integrated brightness is equal to a quarter Moon would effectively end some studies of the faint airglow and aurora. Other observations would be severely limited in scope.

Terrestrial Activities

The terrestrial environment would be affected by SPS in a number of ways. The construction and operation of receivers could alter local weather, land use, and air and water quality. The mining, manufacturing, and transportation associated with SPS could also adversely affect the environment.[37]

Land Use and Receiver Siting

Land use and receiver siting are important issues for SPS, especially from a political perspective (see ch. 9, Issues Arising in the Public Arena).* This is due in part to the microwave and mirror system land requirements for large contiguous areas for receiving stations and transmission lines. In siting receivers, tradeoffs would have to be made between a number of parameters such as the topography and meteorology of the candidate locations, local population density, land and transmission line costs, electromagnetic interference, and electricity demand, as well as environmental impacts. The construction and operation of SPS receivers would have measurable effects on the ecology, soil, air and water quality, and weather of the receiver area.[38] Since many of these impacts are site-specific, an extensive program would have to be carried out in order to locate and assess each proposed site.

The severity and extent of the environmental impacts of SPS ground receivers and transmission lines would also depend on which SPS system is deployed. For example, as shown in table 7, the baseline mirror system (1) would deliver power to a few, extremely large sites, whereas the laser system might be designed to

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[37] *Satellite Power System, Concept Development and Evaluation Program,* reference system report, DOE/E R-0023, October 1978

*The majority of remarks made in this section pertain to land-based receiver sites as specified by the technical systems addressed in this report It is important to note, however that offshore receptor siting that may alleviate some of the problems associated with land-based sites is also possible

[38] *Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program,* DOE/E **R-0069,** August 1980

generate the same amount of power at a great number of sites, each of which is two to three orders of magnitude smaller than the mirror sites. Smaller mirror system (1 1) sites are also possible.

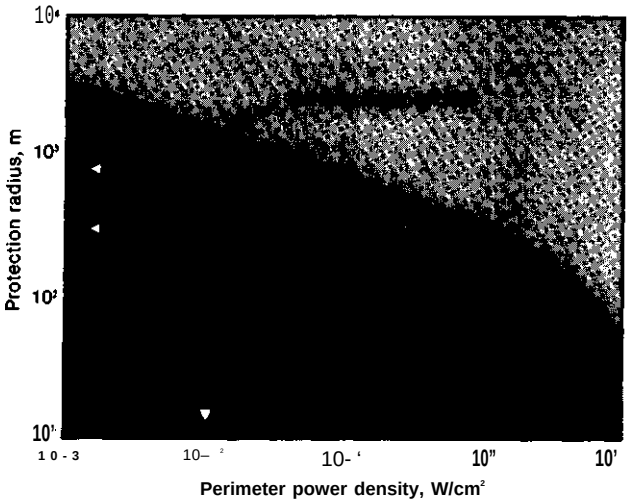
For safety purposes, buffer zones would be established around each site. For the laser design, the infrared power density at the edge of this zone would be 10 mW/cm^2 (see fig. 33). As shown in figure 34, the microwave power density at the edge of the reference system exclusion boundary would be 0.1 mW/cm^2. If microwave standards become considerably more stringent, SPS land requirements could increase. For example, if the power density at the edge could not exceed 0.01 mW/cm^2 (the Soviet standard), then each site would require almost 1,700 km^2 of land.[39]

In addition to land for receivers, about 20 to 850 km^2 would be needed for launch facilities.[40] This could be made available through expansion of the Kennedy Space Flight Center in Florida, although environmental considerations might preclude this option. Transmission line, mining, and transportation land uses are not considered in table 35. More analysis is needed to determine these impacts and to explore tradeoffs between centralized and dispersed electricity systems with respect to transmission line siting. In table 36, the SPS reference system is compared to other electricity powerplants.

[39] J B Black burn, *Satellite Power System (SPS) Mapping of Exclusion Areas for Rectenna Sites*, DOE/NASA Report HCP/R-4024-10, October 1978

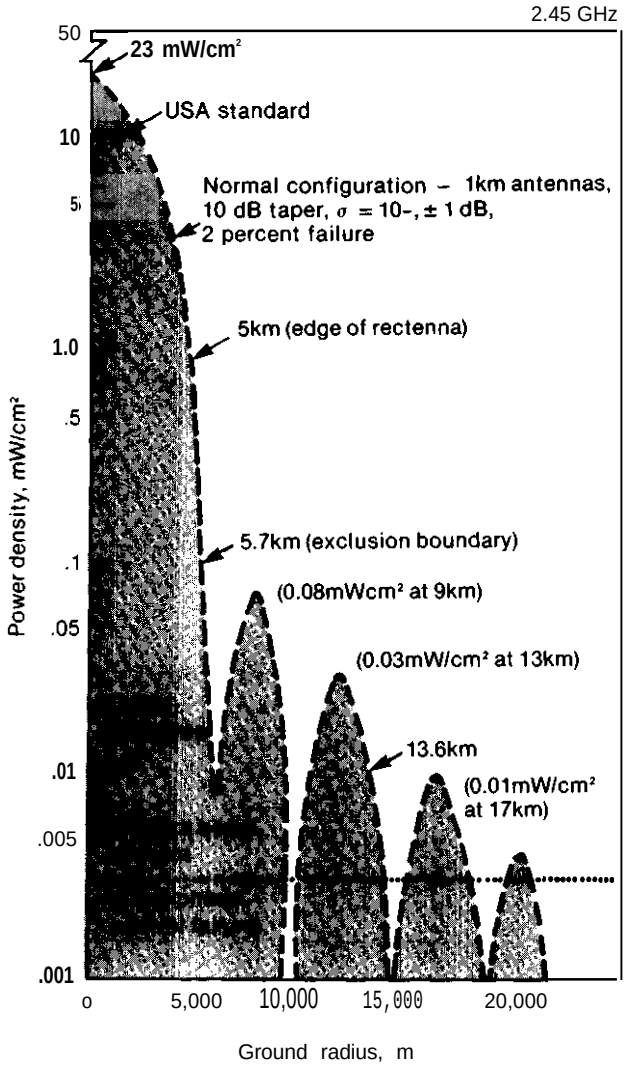
[40] Ibid

Figure 33.— Receptor Site Protection Radius as a Function of the Perimeter Laser Power-Density Level



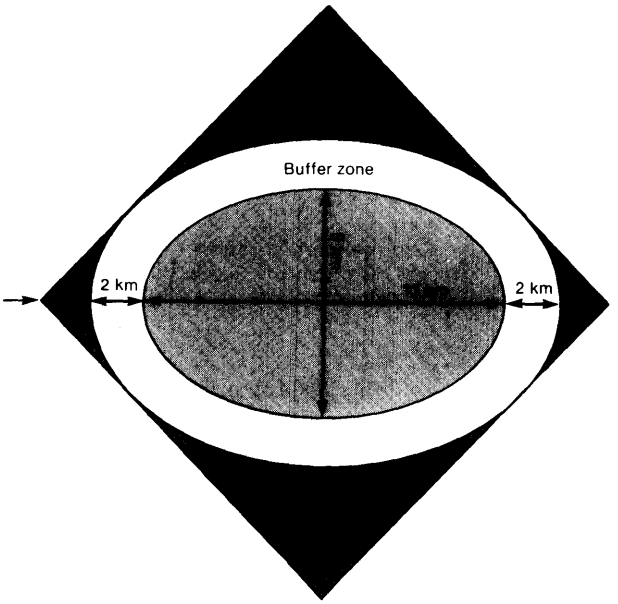
SOURCE: R. E. Beverly, *Satellite Power Systems (SPS) Laser Studies, Technical Report—Laser Environmental Impact Study*, vol. 1, Rockwell International report, SSD 80-0119-1.

Figure 34.—Microwave Power Density at Rectenna as a Function of Distance From Boresight



SOURCE Satellite *Power System, Concept Development and Evaluation Program,* reference system report, DOE/ER-0023, October 1978.

Figure 35.—Rectenna/Washington, D.C. Overlay



SOURCE: Office of Technology Assessment.

Some of the environmental, societal and institutional problems associated with land-use and receiver siting might be remedied by siting receivers in shallow offshore waters. For some land-scarce areas such as New England and Europe, this concept is particularly desirable. The taper of the solid-state power-transmission system makes offshore siting particularly attractive. A few preliminary technical studies have been conducted," including an offshore rectenna siting study,[42] (see fig. 36). However, little attention has been paid to the environmental ramifications of offshore siting. Areas of special concern include the effects on weather and ecosystems from thermal release and the effects of microwaves on aquatic life and birds that might be attracted to the receiver

Land-use problems might also be alleviated by innovative receiver designs that would permit multiple land use under the receivers, such as crop agriculture, biomass production and aquaculture.43 Again, however, until the biological effects of microwaves and reflected sun light are better understood, the environmental impacts and hence viability of these ideas are largely unknown.

[42] J Freeman, et al , *Solar Power Satellite Of fshore Rectenna Study*, contract report No **NAS 8-33023,** prepared for Marshall SpaceFlight (-enter, May 1980

[43] *Satellite Power System (SPS) Rectenna Siting A vailability and Distribution of Nor-n inally Eligible Sites,* DC) E/E R-10041-TI O, Novem ber 1980

[44] Grey, op c it

Table 35.—SPS Systems Land Use

SPS system	km²/site	km²/1,000MW	Number of sites for 300,000 MW	Total land area (km²) for 300,000 MW	m²/MW-yr[a]
Reference	174.0	35.0	60	10,400.0	1,280
Solid state[c]	50.0	33.0	180	9,000.0	1,230
Laser I[d]	0.6	1.2	600	360.0	44-35[e]
Laser II[f]	40.0	80.0	600	24,000.0	2,960-3,550[e]
Mirror If	1,000.0	7.4	- '29	2,200.0	274-329[e]
For **comparison**					
Washington	174.0				
New York City	950.0				
Chicago	518.0				

a These units are presented for comparison with table 36. The values for the reference and solid-state designs assume a 30-year lifetime and a capacity factor Of 0.9.
b Rectenna at 34o latitude covers a 9km x 13km (117km²) elliptical area, Microwave power density of edge of rectenna is 1.0 mW/cm². If an exclusion boundary is set at 0.1 mW/cm², then the total land per site is approximately 174 km² (2 km extra on each side for buffer zone). J. B. Blackburn, *Satellite Power System (SPS) Mapping of Exclusion Areas for Rectenna Sites*, DOE/NASA report No. HCP/R-4024-10, October 1978, Does not include land for mining or fuel transport.
C The solid-state sandwich design is described in J. Grey, *Satellite Power System Technical Options and Economics*, contractor report prepared fOr OTA, Nov. 14, 1979.
d Laser I and Laser II are two laser systems considered by DOE. Both deliver the same amount of power but the beam of Laser I is more narrow (and hence more intenSe) than that of Laser II. See C. Bain, *Potential Of Laser for SPS Power Transmission*, SPS CDEP, October 1978.
e The values for the laser and mirror systems assume a 30-year lifetime and Capacity factors of 0.75-09
f Mirror system parameters are defined by SOLARES System as described in K. Billman, W P Gilbreath, S. W. Bowen, "Solar Energy Revisited With Orbiting Reflectors," NASA, Ames,
g The SO LARES system is designed to deliver 810 GW to 6 sites; 2 SOLARES sites actually provide 270 GW.

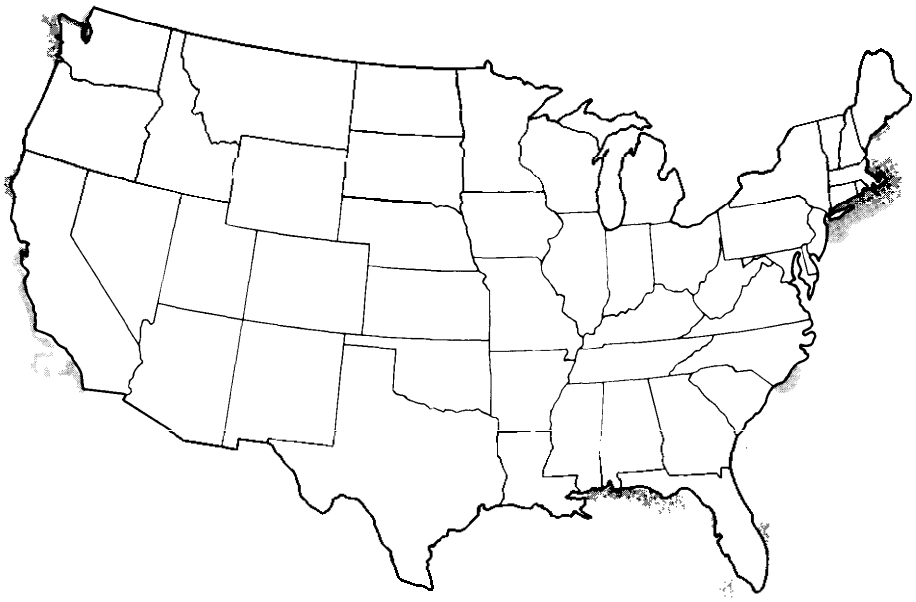
Table 36.—Summary of Land Requirements

Purpose	Construction	Plant	Fuel	Disposal	Transmission
CG/CC					
Quantity	—a	7.2-150 $m^2$1MW-yr	1,800-4,520 m^2/MW-yr	5 $m^2$1MW-yr	**300** $m^2$1MW-yr (480 km)[b]
Duration	—c	30 yr	30 yr	—c	30 yr
Location	—c	—c	—c	—c	—c
FBC					
Quantity	—a	5.2-16.8 m^2/MW-yr	—c	1.4 m^2/MW-yr	**300** m^2/MW-yr (assume same as combined cycle)
Duration	—c	30 yr	—c	—c	30 yr
Location	—c	—c	—c	—c	—c
L **WR**					
Quantity	—a	57-174 m^2/MW-yr	**31 m^2/MW-yr**	**4 m^2/MW-yr**	**225-1000 m^2/MW-yr (480-1600 km)[b]**
Duration	—c	**30-40** yrs (20 m^2/MW-yr "permanent")	**30 yr**	**1 0[e] years**	**30-40 yrs**
Location	—c	—c	—c	—c	—c
LMFBR					
Quantity	—a	76-133 m^2/MW-yr	**5** m^2/MW-yr (plant life-time) and .25 m^2/MW-yr (permanent)	—c	200 m^2/MW-yr (80 km)[b]
Duration	—c	30 yr	—c	—c	30 yr
Location	—c	—c	—c	—c	—c
TPV					
Quantity	—a	600-3,800 m^2/MW-yr (depending on cell efficiency and capacity factor)	neg 1[d]	neg 1[d]	300-3,000 m^2/MW-yr (480-4,800 km)[b]
Duration	—c	30 yr	NA[e]	NA[e]	30 yr
Location	—c	Southwest	NA	NA	—c
STE					
Quantity	—a	2,260-6,650 m^2/MW-yr	neg1[d]	neg1[d]	300-3,000 m^2/MW-yr 480-4,800 km)[b]
Duration	—c	30 yr	NA	NA	30 yr
Location	—c	Southwest	NA	NA	—c
OTEC					
Quantity	—a	neg1	neg1[d]	neg1[d]	**300** m^2/MW-yr (480 km)[b]
Duration	—c	NA[e]	NA[e]	NA[e]	30 yr
Location	—c	NA[e]	NA	NA	—c
SPS					
Quantity	20-850 km^2 (launch)	1,480 $m^2$1MW-yr[g] (rectenna)[f]	neg1[d]	neg1[d]	300-1,000 m^2/MW-yr (480-1,600 km)[b]
Duration	30 yr	30 yr	NA[e]	**NA**[e]	30 yr
Location	Florida?	—c	NA	NA	—c

approximately the sum of plant and transmission requirements.
[b]Dist[ance] to load center.
[c]Data lacking; some categories are discussed in test
[d]Negligible.
[e]NA-Not applicable
[f]Includes buffer zone, rectenna proper occupies about 50% of total.
[g]Assumes 200 km^2 per rectenna site.

SOURCE: D. E. Newsom and T. D. Wolsko, *Preliminary Comparative Assessment of Land Use for Satellite Power Systems and Alternative Electric Energy Technologies*, DOE/NASA report No. DOE/ER-0058, April 1980.

Figure 36.—Offshore Summary Map



Offshore siting study - dark areas are *not* eligible for rectenna siting

SOURCE: *Satellite Power System (SPS) Rectenna Siting Availability and Distribution of Nominally Eligible Sites*, DOE/ER-1OO41-TIO, November 1980.

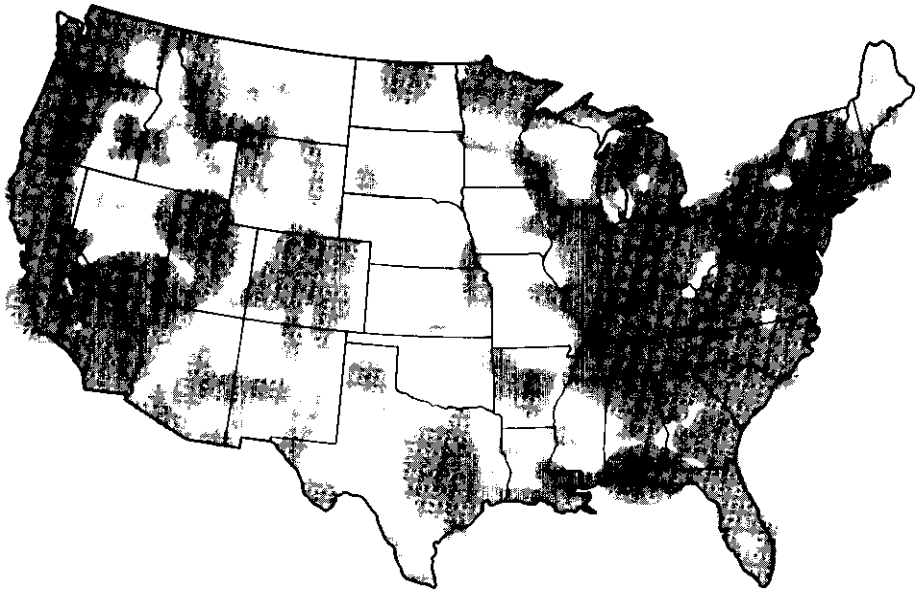
If SPS is to be deployed on a multinational scale, the siting constraints may be different from those in the United States. This is especially true with respect to microwave exposure standards, which in some countries are more stringent than in the United States (see Health and Ecology, Microwaves). The environmental standards of other nations and their effects on SPS siting requirements need to be explored in more detail.

A siting study for the continental United States has been conducted for the reference system to determine if 60 candidate sites can be found. " The United States was divided into grids, each approximately the size of a rectenna. Grid squares were eliminated from consideration if they violated a set of "absolute" exclusion variables that included inland waters, high population density areas, marshlands, military reservations, habitats of endangered species, National recreation areas, Atomic Energy Commission lands, and unacceptable topography. Sites were also excluded if they were found within a specified distance from military installations, nuclear powerplants and other facilities that might suffer from electromagnetic interference with the SPS microwave field.

In figure 37, ineligible grids were marked with an "x." In this first exercise 40 percent of the United States remained eligible. After the application of additional "potential" exclusion variables that were categorized as having an unknown or adverse, but potentially correctable impact (e. g., agricultural lands and flyways of migratory waterfowl), 17 percent of the United States remained eligible. In general, the greatest number of eligible sites was found in the West, Southwest, and in the northern regions of the Midwest; the least number of eligible sites occurred in the Mid-Atlantic States, where 3 to 10 percent of the land was eligible (31 to 83 grids, depending on the criteria for eligibility). The exclusion variables that had the greatest incremental effect in rendering land ineligible included topography, popula-

[44] J. B. Blackburn and B A Ballinger, "Satellite Power System Rectenna Siting Study, " in *The Final* Proceedings of *the Solar Power Satellite Program Review,* Apr 22-25, 1980, DOE/NASA report No Conf -800491, July 1980

Figure 37.—Satellite Power System—Societal Assessment



SOURCE: *Satellite Power Svstem (SPS) Rectenna Siting: Availability and Distribution of Nominally Eligible Sites,* **DOE/ER-1OO41-TIO, November 1980.**

tion and electromagnetic compatibility' (absolute variables) as well as private agricultural lands, flyways, and Federal dedicated and protected lands (potential variables).

The siting study also revealed an important point about the siting of smaller rectennas. Smaller site sizes could increase the likelihood that sites identified as eligible (in the first application of absolute exclusion variables) would remain so upon closer examination in a "validation" process. However, they would be unlikely to make previously excluded grid squares eligible. Therefore, it was concluded that smaller rectenna size (i. e., one-fourth or one-half the rectenna area) would not make a substantial difference in the siting process. 45

The effects of eliminating isolated sites were also considered on the assumption that local variations and the problems associated with public or private land acquisition would make siting more difficult in areas that did not contain a large number of adjacent eligible grid squares. By imposing the constraint that eligible sites had to fall within a 3 x 3 grid pattern, the amount of eligible sites dropped dramatically, especially in the Mid-Atlantic region and the Southeast. A less restrictive requirements of 2 x 2 grid patterns produces a considerably less drastic result.

The siting results (from the application of "absolute variables") were then correlated with the distribution of projected electrical demand.[46] Based on one projection of future electricity demand, it was concluded that the only potential site scarcity would occur in the Mid-Atlantic region (see fig. 38). In most other regions there would be about 100 times more eligible grids than "required" sites. Scarcity of large load centers relative to allocated rectennas could be a problem in sections of the Midwest and West.

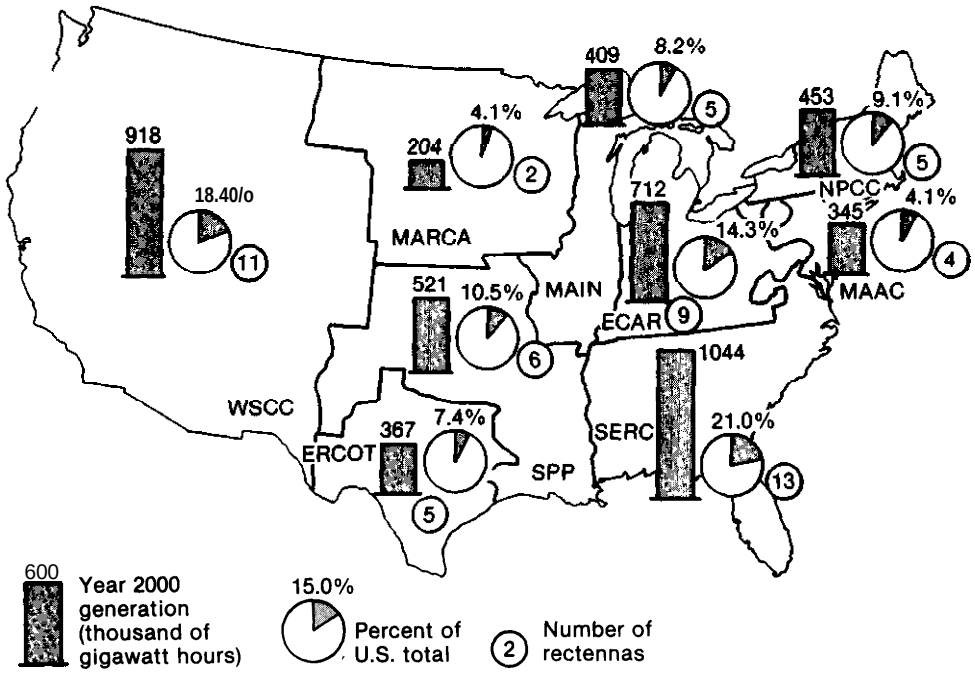
A prototype environmental assessment was conducted for a rectenna site in the California desert (Rose Valley, 250-km north of Los

***This was also an important constraint for the siting of offshore rectennas**

"Ibid

" A Kotin, "Relationship of Eligible Areas to Projected Electricity Demand, " in *The Final Proceedings of the Solar Power Satellite Program Review,* Apr 22-25, 1980, DOE/NASA report No Conf -800491", July 1980

Figure 38.—Regional Generation (2000) and Rectenna Allocations



Note: This figure is based on the EIA Leap Series C (1978) protection of electricity in the year 2000 which assumes a 4 10/. electricity growth rate per year from 1977-1995. See chapter VI or discussion on alternative electricity growth rates

SOURCE. A. Kotin, "Relationship of Eligible Areas to Projected Electricity Demand," in *The Final Proceed/rigs of the Solar Power Satellite Program Review*, Apr 22-25, 1980, DOE/NASA report No conf -800491, July 1980

Angeles)." The major environmental impacts (excluding microwave effects) and possible solutions are summarized in table 37.

The assessment emphasized that large amounts of contiguous land area must be completely committed to the project, totally displacing existing land use and completely altering the existing natural environment. investigators also noted that after the site boundaries are selected, there is no flexibility in the siting of individual rectenna structures, so that areas particularly sensitive to SPS impacts could not be avoided. To alleviate adverse effects, they recommend that land areas much larger than the minimum requirements be located in the site selection process. In addition, the study recommends that: 1) rectenna panels be light and open to allow passage of sunlight and rain; 2) natural characteristics of the site be considered in the panel and diode/ dipole design, e.g., taking account of possible attraction birds and rodents might have to the panels for resting or nesting; and 3) the design minimize the use of materials.

Finally, investigators note that the siting of receivers in the Southwestern United States will be especially hampered by land-use conflicts with other energy sources, archaeological sites and military programs. In particular it is pointed out that 15 percent of the California Conservation Area is reserved for defense purposes.

[47] *Protot ype Environmental Assessment of the Impacts of Siting and Constructing a Satellite Power System (SPS) Ground Receiving Station (GRS),* DOE/NASA report No DOE/E R-O072, August 1980

Table 37.—Summary of Environmental Impacts of Rectenna Construction and Operation at a Specific Study Site

Technical area	Rectenna construction	Rectenna operation	Mitigation
Air quality and climatology	. Probable standards violation for nitrogen oxides, particulate, and hydrocarbons. • No climatic impacts.	. No significant air quality impacts. • Unknown, but possibly significant microclimateic effects at or near ground surface	• Adequate dust suppression program during construction would mitigate particulate impacts. . Extending construction schedule would reduce emission peaks for hydrocarbons and nitrogen oxides. • Pending further research, project modifications might be needed for ground surface microclimate impact
Noise	• Substantially elevated noise levels, but in areas with low population density, • Possible impacts on noise-sensitive species.	. No significant impact.	• Improved noise control technology by construction time frame for vehicles, equipment, and processes would mitigate impacts. • During construction, noise-sensitive habitats should be avoided to maximum extent possible during breeding and nesting seasons.
Geology and soils	• Geologic impacts less important than geologic constraints. • Study area very active • seismically, but within normal range for southern California. • Soils impacts significant: large disturbed area, compaction, wind/water erosion. • Soils constraints: diversity of soils types implies variability in engineering properties (e.g., shrink/swell potential, corrosivity to metals/concrete).	• Seismicity has potential for facility destruction or loss of efficiency (alinement v. satellite). • Soil productivity impacted for project life: depends on extent and degree of construction—phase and ongoing operations disturbance.	. Thorough seismic and soils studies required as part of site-specific engineering. • Careful soil-stabilization/age/erosion-control programs required.
Hydrology and water quality	• Project requirements: 2-14 x 10^6 m^3 (depends on dust suppression methods used). • Meeting project needs from groundwater would lower water table 0.2-1.5 m/yr; would reduce underflow to adjoining valley, could lower water level in nearby lake; might contaminate usable water through hydraulic connection with unusable ground water.	. Project requirements minor unless major revegetation program undertaken. Revegetation could require 27 x 10^6 m^3/yr for 3 yr, that could cause water table drawdown.	• Careful soil stabilization/drainage/erosion-control program required. • Ground water withdrawal impacts could be alleviated by importing water from outside study area. • Proper sewage control program necessary during construct ion to prevent water quality degradation).

Table 37.—Summary of Environmental Impacts of Rectenna Construction and Operation at a Specific Study Site-Continued

Technical area	Rectenna construction	Rectenna operation	Mitigation
Flora	• Land disturbance would completely modify site's floral communities. • Possible indirect impacts on flora from hydrologic changes, air and water pollutants, and personnel activities • No endangered species present at Rose Valley/ Coso; one rare species present.	• Impacts similar to construction phase. • Microclimate changes at ground surface a key issue for severity and potential for mitigation of floral impacts.	• Reestablishment of preexisting flora problematic; major and difficult revegetation program required. • Careful placement of ancillary facilities necessary to minimize impacts on sensitive habitats. • Careful planning, design and construction/ operations practices necessary to minimize indirect impacts (e.g., water quality degradation).
Fauna	• **Land disturbance would completely modify site faunal communities.** • **Possible indirect impacts on fauna from hydrologic changes, air and pollutants, personnel activities, and loss of feeding areas for nearby fauna.** • **Surface water sources for migratory water and land birds would be lost (Playas) and jeopardized (Little Lake).** • **One protected species (Mohave ground squirrel) found in Rose Valley.**	• Impacts similar to construction phase. • Impacts closely related to flora impacts. • Microclimate changes at ground surface a key issue for severity and potential for mitigation of fauna impacts.	• Reestablishment of preexisting fauna problematic; closely linked to strategy and success of floral mitigation. • Careful placement of ancillary facilities needed to minimize impacts on sensitive habitats. • Careful planning, design, construction, O&M practices, and construction scheduling needed to avoid indirect impacts and to avoid sensitive habitats during breeding and nesting seasons.
Land use	• **Total displacement** of existing site uses (e. g., farming grazing, recreation). • Minor loss of mineral resources (cinder, pumice). • Minor indirect (growth-related impacts. • Potential land acquisitior/use conflicts with Navy (China Lake NWC), energy (geothermal), wilderness, archaeological resources, native American use and access to cultural and religious sites.	Same as construction phase	• Major impacts could not be mitigated. It might be possible to achieve joint use of rectenna sites but this remains speculative.

SOURCE: *Prototype Environmental Assessment of the Impacts of Siting and Constructing a Satellite Power System (SPS) Ground Receiving Station (GRS),* **DOE/NASA report No. DOE/ER-0072, August 1980.**

Receiver Structure: Weather Modification

Other DOE studies have investigated the potential of the rectenna for modifying local weather. They indicate that the surface roughness and albedo of the rectenna structure and the waste heat generated by rectenna operation (750 MW per site) would have a small, but detectable impact on regional weather and climate.[48] [49] In particular, rectennas would perturb the average surface heat exchange by about 10 percent. SPS land-use changes could alter temperature (on the order of 10 C), cloud density and rainfall. However, it is important to note that these effects would be no greater than those attributable to other nonindustrial urban activities. For example, the waste heat generated by typical coal and nuclear plants range from 750 to 6,000 MW. The waste heat rejected at laser receptor sites, would also produce weather effects that would be less significant than those associated with nuclear plants of comparable power. 50

Resources

The construction and operation of SPS could strain supplies of some critical materials, as shown in table 38. The most serious problems arise for the solar cell materials (e. g., gallium, gallium arsenide, sapphire, and solar grade silicon) and the graphite fiber used for the satellite structure and space construction facilities of the reference system. [51] It appears that the silicon SPS systems pose less serious problems than the gallium arsenide option, but this may be due to the immature state of gallium arsenide technology. The most serious resource strain for the gallium arsenide system is gallium; for the silicon option, large amounts of electricity might be needed to produce the cells.

[48] *Environmental* **Assessment for** *the Satellite* **Power** *System* **Concept Development and Evaluation Program, op** cit.

"Proceedings of the Workshop on Meteorological Effects *of* **Satellite Power System** *Rectenna* **Operation and Related Microwave Transmission** *Problems,* **Aug 23-25, 1978, DOE/NASA report No Conf -7808114, December 1979**

[50] Basu, **Johnson,** Klobuchar, **and Rush, op** cit

[51] **R R Teeter and W M** Jamieson, *Preliminary Materials Assessment for the Satellite Power System (SPS),* **DOE/NASA report No DOE/E R-0038, January 1980**

Table 38.—Summary of Materials Assessment Results

Parameter	Percent supplied as byproduct	World production growth rate	SPS percent of demand	Net percent imported	Percent world resource consumption	cost $/kw
Threshold value[a]	50 %	10 %	100/0	50%	200%	$50/kw
Gallium	A	A	A	—	—	—
Graphite fiber	—	A	A	—	—	A
Sapphire	—	A	A	—	—	A
Silicon SEG	–	A	A	—	—	A
Gallium arsenide	—	A	A	—	—	A
Electricity	—	—	—	—	A	—
Arsenic/arsenic trioxide	B	—	—	B	—	—
Kapton	—	B	B	—	—	—
Oxygen (liq)	–	B	B	—	—	—
Silica fiber	—	B	B	—	—	—
Silver	B	—	—	B	—	—
Silver ore	—	—	—	B	B	—
Glass, borosilicate	—	—	B	—	—	—
Hydrogen (liq)	—	B	—	—	—	—
Mercury	—	—	—	B	—	—
Mercury ore	—	—	—	B	—	—
Methane	—	B	—	—	—	—
Petroleum	—	—	—	—	—	B
Steel	—	—	—	—	—	B
Tungsten	—	—	—	B	—	—

Note: "A" signifies problem of serious concern "B" signifies problem of possible concern.
[a]Parameter value above which a potential problem exists. Materials in this table exceeded these values where an "A" or "B" is recorded.

SOURCE: R. R. Teeter and W. M. Jamieson, *Preliminary Materials Assessment for the Satellite Power System (SPS),* DOE/NASA report No. DOE/ER-0038, January 1980.

Most of the resource constraints identified stem from limitations in production capacity rather than exhaustion of reserves. SPS could compete for graphite composite with the automobile industry and, depending on its time of introduction, with terrestrial photovoltaic technologies and the electronics industry for semiconductor materials. The demand by SPS for a few materials such as gallium, tungsten, and mercury could also increase U.S. dependence on foreign sources. Further analysis would be required to determine the severity of the resource limitations identified for the reference system and possible measures that would circumvent them.

While no assessment has been made of the material requirements for any of the other SPS technical options, a few observations can be made. The solar cell, graphite, and transportation materials that are problematic for the reference design might also be used in the three other options. The solid-state design calls for silicon or gallium arsenide devices in the transmitting antenna as well as in the solar collector. While the solid-state satellites would be smaller than the reference design, the solid-state material needs per unit energy would be greater. Therefore, if the reference design were to strain supplies of semiconductor materials, the solid-state variant most certainly would tax them as well (assuming that both systems deliver the same total amount of power and use the same materials). The laser and mirror systems would require slightly less photovoltaic material per kilowatt of delivered electricity than the reference system. The quality of the photovoltaics material used in the mirror design might be different than the reference materials however, since in the mirror system they would be placed on the ground. All of the systems would require graphite for structures, and fuels for space transportation. Further analysis is required in order to compare the material requirements of the alternative designs to the reference system. Moreover, the effect on SPS material requirements of using nonterrestrial materials (lunar soil contains aluminum, titanium, iron, silicon, and oxygen) and developing space processing and industrial capacity needs to be investigated.

Mining, Manufacturing, and Transportation

The minerals extraction, materials processing, manufacturing, and transport activities associated with SPS could result in a measurable increase in air and water pollution and sol id wastes. 52 For example, the potential environmental impacts of mining include water pollution from leaching and drainage modifications, air pollution from fugitive dust and land disturbance from strip mining, subsidence and spoil piles. Manufacturing would produce stack emissions, process effluents and solid wastes. In table 39, order-of-magnitude estimates have been made of some of the environmental impacts resulting from these reference system activities. The incremental domestic processing of materials required for SPS can also serve as a rough guide to increased pollution levels.

While these exercises help identify the potential scope and extent of environmental impacts, a thorough and quantitative assessment is presently lacking. However, it is anticipated that most impacts would be conventional in nature and could probably be minimized by methods currently used in industry [53] There is no information on similar effects

[52] *Prototype Environmental Assessment of the Impacts of Siting and Constructing a Satellite Power System (SPS) Ground Receiving Station (Rev.)*, DOE NASA report No DOE ER-0072, August 1980.

[53] Ibid.

Table 39.—Annual Environmental Effects of SPS[a] (mining, processing, manufacture, and ground-based construction)

Air pollutants	Percent U.S. total[c]
Particulate	**0.8%**
Sulfur dioxide	0.04
Carbon monoxide	0.05
Hydrocarbons	0.05
Nitrogen dioxide	0.005
Nonrecoverable water[d]	0.24
Solid waste[e]	**0.70**
Land requirements[f]	0.12

[a] Based on an earlier SPS design assumes two satellites and rectennas are built per year.
[b] From mining, processing and fabrication
[c] U. S totals in 1973
[d] For propellant manufacture, launch pad coating, construction.
[e] From dun-tin urn and steel processes.
[f] For rectenna Sites as fraction Of total US. land area.

SOURCE Adapted from *Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program*, **DOE/ER-0069 August 1980**

due to the other SPS technical systems. Studies should be conducted as the design parameters become more clear. Analysis would also be needed to determine the incremental effect of SPS on the environment relative to other electricity generating facilities.

HEALTH AND ECOLOGY

Human health and safety could be affected by launch and space activities, mining, manufacturing, and transport, and the construction and operation of SPS receiving antennas and powerlines. These effects and the public concern about them are likely to be most pronounced closest to launch and receiver facilities. Long-term exposure to low-level electromagnetic radiation from SPS power transmission and distribution is a critical issue, involving potential health effects about which very little is known. For SPS space workers, exposure to ionizing radiation is of the utmost concern. Other important terrestrial impacts are shown in table 40. While the effects of some SPS activities such as mining and manufacturing are fairly conventional and could be routinely assessed, the uncertainties of other health and ecological impacts, such as exposure to microwaves, are great. When experimental data does exist it is rarely directly applicable to SPS. Furthermore, extrapolation from experimental animal to human health and safety standards is tenuous and uncertain without a good theory on which to base the extrapolation. For other impacts, such as exposure to ionizing radiation, it is not clear if existing standards should apply to SPS. More stringent standards can strongly influence SPS design, cost, and social acceptability. Ecological effects of SPS are also extremely uncertain as little attention has been paid to this complex area.

This second part of the chapter will identify the health and ecosystem impacts that presently appear most significant. The first section will address the bioeffects of terrestrial activities on the public, SPS workers and ecosystems. In the second section, the implications for the health and safety of SPS space workers will be discussed. With the exception of power-transmission effects, most of the health and safety risks described here pertain to the reference system only. There is not enough information on the personnel requirements, industrial activities and environmental impacts to treat adequately the other technical options. It is assumed that many of the effects would be similar to those of the reference system, varying only in intensity and degree. It is important to note that some of the impacts identified for the reference system could be minimized or avoided by worker training, protection devices, or changes in the system design, but the effect of these measures on concept feasibility and cost need to be examined in more detail.

Terrestrial Effects

The primary sources of potential health and ecological effects are electromagnetic radiation from the power transmission and distribution systems and noise and pollution from launches, mining, manufacturing, and construction (see table 40). The risks to the terrestrial worker are usually greater than to the general public because of the increased frequency, duration, and intensity of occupational exposure to certain hazards (although occupational exposure could be more easily controlled by protective devices). Estimates of SPS hazards have in many cases been extrapolated from other technologies, such as the space shuttle. Risk analysis would improve as the system design becomes more clear. However, the major uncertainties associated with some effects (e. g., electromagnetic radiation) rest in the state of biophysical knowledge and not SPS specifications.

Table 40.—Terrestrial Health and Ecological Impacts

Microwaves
- Effects of public and ecosystem exposure to low levels uncertain
- Occupational exposure higher; may require protective clothing

Laser **Light**
- **Hazard to people and other living organisms directly exposed to beam**
- **Hazard to slow airplanes, birds, and insects flying through the beams**

Reflected light (mirror system)
- Ocular effects not expected to be significant; potential hazard with binoculars not known
- Psychological impacts on public, effects on the photoperiod of plants and circadian rhythms, and navigation of wildlife are unknown

Reflected light (from reference system)
- Plants and animals would probably not be unduely affected, but many effects are uncertain. The human eye could be damaged if SPS reflected light were viewed for **too long or with magnifying devices.**

High-voltage transmission lines
- Effects of public and ecosystem exposure to electromagnetic fields not well demonstrated but still uncertain (not unique to SPS)

Noise
- Without preventative measures, construction **noise from certain machinery could exceed occupational standards; no significant public or ecosystem effect is anticipated**
- Launch noise and sonic booms could present problems for public and ecosystems. Workers would wear heavy protective devices

Air Pollution
- Without preventative measures, construction of rectennas could violate standards for certain emissions such as hydrocarbons and particulate
- Mining, manufacturing, and transport emissions are expected to be comparable to industrial and energy producing processes (except coal)
- Launch effluents are not thought to exceed emissions standards unless ambient levels are high but studies must be refined
- Effects on ecosystems are unclear

Water Pollution
- Construction and revegetation could deplete or contaminate local water, depending on site
- Onsite facilities would be needed to treat polluted water at launch site

Safety
- Risks to public, workers, and ecosystems from the handling and transport of toxic and explosive materials such as rocket propellants
- Occupational risk of catastrophic explosion or launch accident higher than that for public and ecosystems

SOURCE: Office of Technology Assessment.

Electromagnetic Radiation

Over the last few decades, the development and proliferation of technologies that utilize electromagnetic radiation has been astoundingly rapid and widespread. However, there is a growing concern about the biological consequences of exposure to the radiant energy these devices employ. Terrestrial life as we know it has evolved in response to a very specific spectral distribution, diurnal and seasonal cycle, and intensity of solar and terrestrial radiation. It is possible that the alteration and enhancement of the ambient electromagnetic environment brought about by modern technologies could have a profound impact on biological entities and human health.

SPS would increase the local levels of nonionizing radiation (see fig. 39) in a few areas of the spectrum, e.g., microwaves, infrared laser light, or reflected sunlight from the power-transmission system .54 The distribution of power from the receiving site via transmission lines would also increase exposure to very low frequency or static field radiation at some locations. Light reflected from the surfaces of space structures and vehicles would be visible from Earth. Space workers involved in the construction and operation of SPS could also be exposed to high levels of nonionizing and ionizing radiation in space.

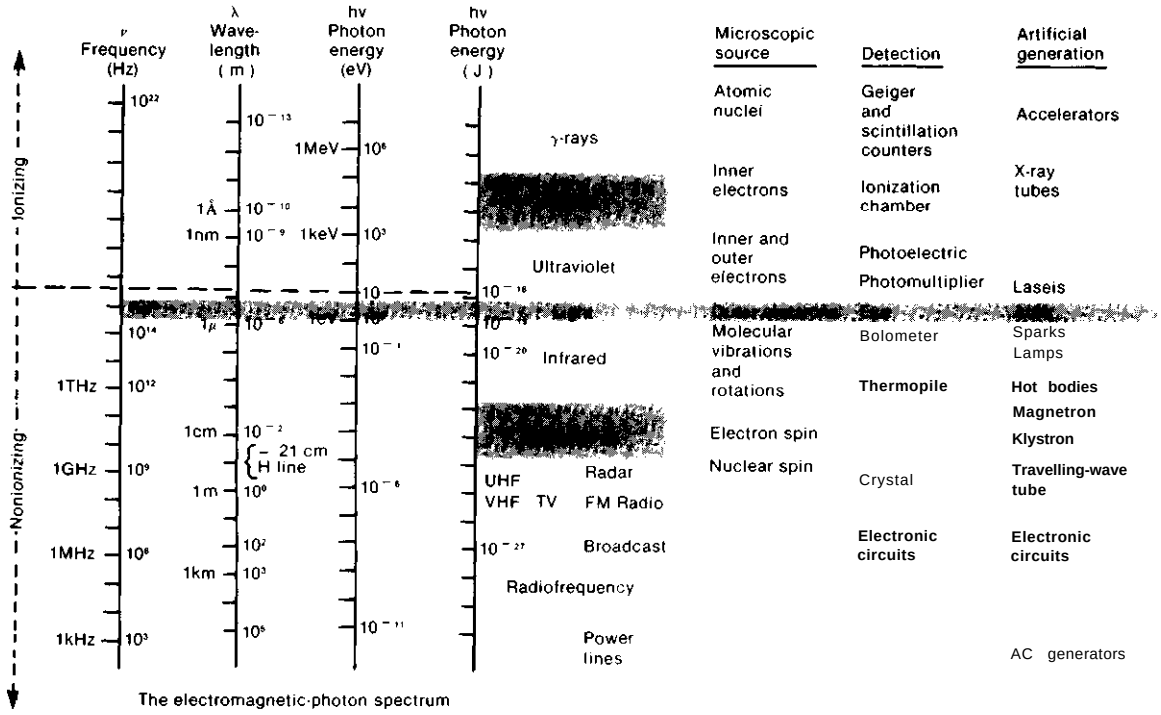
MICROWAVES

There is not enough relevant data currently available to assess reliably the biological risks to humans, plants, and animals exposed to SPS microwaves. The data base that does exist is incomplete, often contradictory and usually not directly applicable to SPS.[55] In particular,

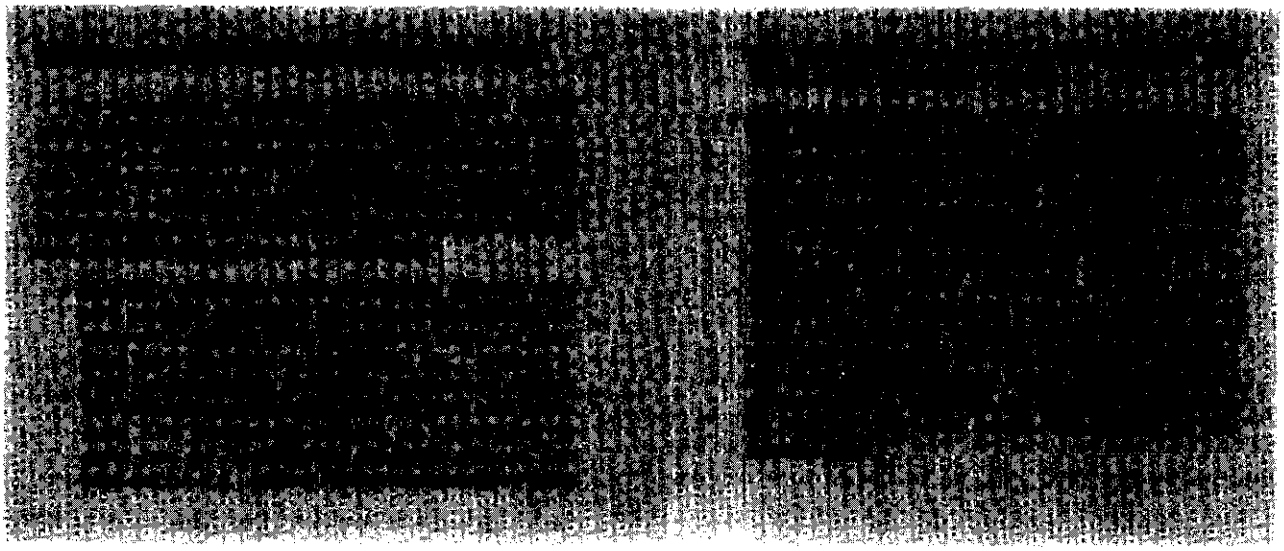
[54] P Lorrain and D R Corson, *Electromagnetic Fields and Waves* (San **Francisco** W.H **Freeman, 1970)**

[55] *Preliminary Environmental Assessment for the Satellite power System (SPS) Revision 1,* **DOE/NASA report No DOE/E R-0036, January 1980**

Figure 39.—The Electromagnetic-Photon Spectrum



SOURCE: P. Lorrain and D. R. Corson, *Electromagnetic Fields and Waves*, W. H. Freeman. San Francisco, 1970



there is a lack of information on the bioeffects of chronic exposure to microwaves at low-power densities. Data is presently lacking on empirical dose-response relationships at these low levels as well as on the theoretical mechanisms of interaction between living organisms and microwaves. Improved theory would facilitate extrapolations (which are currently tenuous and oversimplified) from experimental animal data to the prediction of human bioeffects.

This knowledge is also required for the quantification of SPS microwave risks, without which no useful assessment of the SPS microwave concepts can be made, If an SPS program is pursued, the study of microwave bioeffects should receive top priority. Microwave research and future microwave standards could play a large role in determining the design and feasibility of SPS systems.

- SPS microwave risks. The SPS reference system microwave environment is illustrated 'in figure 40. Table 41 presents the public, occupational, and ecosystem exposure levels. Since the power densities emitted by the solid-state system are lower as a function of distance from the rectenna center than the reference system, they will not be specifically addressed here.

No quantitative risk assessment for SPS workers has been performed or is currently possible. Occupational exposures would need to be controlled by adequate protective clothing and shielding, dosimeters (all of which are not presently available), and possibly changes in system design.[56] The extent of the necessary protection has yet to be determined. For occupational exposure engendering the greatest risks, (e. g., space workers and terrestrial personnel working above the rectenna) it might be necessary to shut off or defocus the microwave beam if other protective measures prove insufficient. Additional research would be required to clarify the risks and protective criteria for short-term exposure. Possible synergisms between the space environment (e. g., ionizing radiation, weightlessness) and microwaves must be explored as well as the plausibility of simultaneously shielding microwaves and ionizing radiation (see Space Environment). It is also imperative that understanding of the long-term effects improve substantially (see below) before a reliable occupational safety threshold can be determined. In addition, possible disparities between SPS microwave levels and occupational standards in this and other countries (see table 42) should be addressed, especially if SPS were to be a multinational system. The effects on system cost and feasibility of implementing protective measures, complying with safety standards, and reducing the risks of long-term effects will need to be analyzed.

Public and ecosystem exposure to SPS microwaves is presently of greatest concern. It has been estimated that the 60 satellite reference system would raise the ambient microwave level in the continental United States to a minimum of 10^{-4} mW/cm^2.[57] Although not directly comparable, this level is two orders of magnitude greater than the median population exposure to FM radiowaves.[58] (Ambient microwave and radio frequency levels are inturn 10^6 times greater than natural levels of solar and terrestrial radiation.) It therefore appears that the general population and ecosystems would be exposed to levels significantly higher than current background microwave radiation.

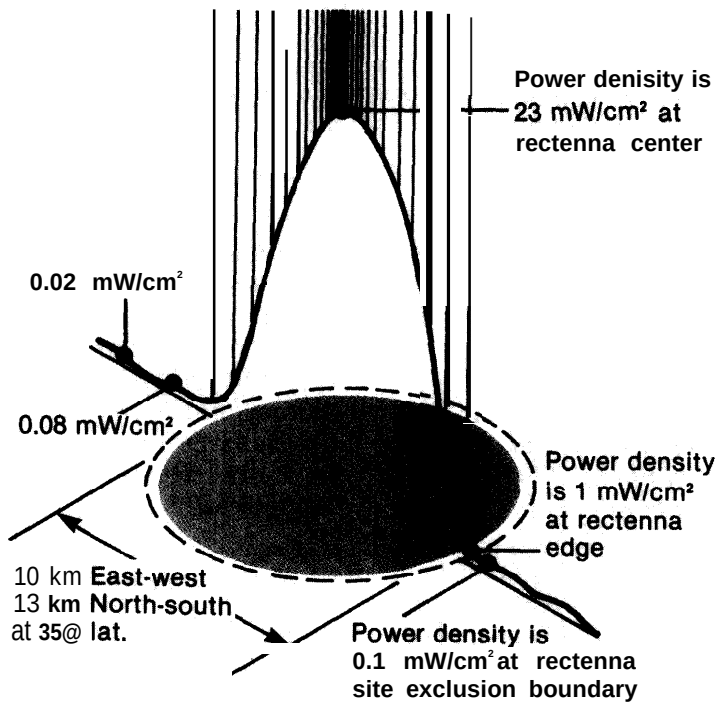
The health risks of chronic exposure to microwaves, especially at these low levels (i. e.,

[56] *Program Assessment* Report, *Statement of Findings,* op c it

[57] Ibid

[58] R A Tell and E D Mantiply, "Population Exposure to VHF and U H F Broadcast Radiation in the United States, " *Proc. IEEE,* 68(1) 6-12, 1980

Figure 40.—SPS Microwave Power-Density Characteristics at a Rectenna Site



SOURCE: *Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program,* DOE/ER-0069, **August 1980**

Table 41 .—Characterization of Exposure to Reference System Microwaves

		Outside buffer zone	Between 10^{-4} mW/cm² and 0.1 mw/cm²
Public		Airplane flying through beam	Less than 23 mW/cm² (shielding)
Terrestrial workers		Rectenna field	Up to 23 mW/cm² (may be higher if reflections occur)
Space workers		Transmitting antenna	Up to 2.2 W/cm²
Ecosystems (plants, wildlife, airborne biota)	Under rectenna	Rectenna field: Outside buffer	Less than 0.1 mW/cm²
		Inside buffer	Between 0.1 mW/cm² and 1.0 mW/cm²
		Rectenna field: above rectenna	Up to 23 mW/cm²

SOURCE: *Environment/ Assessment for the Satellite Power System Concept Development and Evaluation Program,* DOE/ER-0069, **August 1980.**

Table 42.—Microwave Exposure Limits

	Frequency (G Hz)	Occupational (mW/cm^2)	Occupational duration	Public (mW/cm^2)
United States[a]	0.01-100	10.0	No limit	None
U. S.S.R.[b]	0.3-300	0.01	Workshift	0.001
Canada[c]	1-300	5.0	8 hours	1.0
Czechoslovakia	0.3-300	0.01	8 hours	0.0001
Poland	0.3-300	0.2	10 hours	0.01
Sweden[d]	0.3-300	1.0	8 hours	1.0

[a]This is a guideline only and is not enforceable; the standards in the United Kingdom, German Federal Republic, Netherlands and France are similar to that Of the U.S. guideline; ANSI will probably recommend 5 mW/cm^2 as a new occupational exposure limit. ANSI and EPA are presently considering a new population limit.
[b]$0.1 mW/cm^2$ for rotating antennas.
[c]Canada is proposing a $1 mW/cm^2$ limit at 10 MHz to 1 GHz frequency.
d5 mW/cm^2 at 0.01 to 0.3 GHz for 8 hours.

SOURCE: Adapted from L. David, *A Study of Federal Microwave Standards,* DOE/NASA report No. DOEIER-1OO41-O2, August 1980.

less than 1.0 mW/cm^2) cannot be analyzed with the current data base. While appreciation for the complexities of the interaction between microwaves and biological systems (see app. D) has grown in recent years, the state of knowledge, particularly with respect to low-power microwaves, is immature and incomplete; hence, no assessment for SPS can be conducted at this time. However, a DOE review of the existing scientific literature identified the biological systems that might be most susceptible to microwaves. 59 For the public and ecosystems outside of the rectenna, DOE tentatively concluded that effects on the reproductive systems would be small; risks to special populations (e. g., people taking medication, children, older and pregnant people, etc.) and effects on behavior would be uncertain and effects on the immune and blood systems appear unlikely. No cancer, development or growth effects would be expected. Again, however, the data base on low level chronic exposure that supports these conclusions is incomplete and more research would be required to satisfactorily assess potential effects.

For ecosystems (and SPS workers) at the rectenna site, effects on physiology, behavior, development, reproduction and the thermoregulatory, immune and blood systems might be possible.[60] Of particular concern are the effects on insects and birds that might fly through the beam. Birds in flight are often near their thermal limit and exposure to microwaves might result in thermal overloading. " DOE has initiated three laboratory studies to test the effects on bees, birds, and small animals at SPS frequency and power densities. (See app. D.) While no significant effects have been observed to date, the research is far from completed.

- **Research needs. A workshop organized by the National Research Council (NRC) recently identified the principal research priorities for the bioeffects of exposure to low-level SPS microwaves.[63] These are listed in table 43. Basically, three kinds of laboratory studies are needed:**

  1 **animal laboratory experiments to establish effects empirically as well as dose-response relationships;**
  2 **studies of mechanisms of interaction at different levels of biological organization (e.g., atoms, molecules, cells, organs); and**
  3. **improvement of dosimetry, instrumentation and models.**

While limited resources might dictate that these studies be carried out only at the SPS reference system frequency and power densities, it is clear that research at many frequencies and power densities would help to elucidate the fundamental mechanisms of interaction that allow extrapolations to be made between frequencies, irradiance and

59A. R. Valentine, "Environmental Assessment Overview," In *The Final Proceedings of the Solar Power Satellite Program Review,* **Apr 22-25, 1980, DOE/NASA report No Conf -800491,** July **1980.**

"I bid

[61] *Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program,* op cit

[62] Ibid

"Dodge, op cit

Table 43.—Research Needs To Help Reduce Uncertainties Concerning Public Health Effects Associated With Exposure to SPS Microwave Power Densities and Frequency

Local or general thermal effects
- Long-term experiments at power densities< 0.1 mW/cm^2 at whole body, organ, and organelle levels, testing for biological endpoints such as alteration of enzyme reaction rates and cell membrane confirmational changes.
- Studies of basic physical interactions of electromagnetic fields with molecular components of living tissue, to develop models of biological effects or phenomena. (For example, biophysical experiments are required to determine the role of microwaves at SPS frequencies and intensities at the molecular level and their action on ionic conductivity. Any responses, biological, biochemical, or physical, should be investigated from the point of view of alteration of enzyme reaction rates, and cell membrane phase transitions and confirmational changes.)
- Better dosimetry techniques for calculating and measuring (such as a probe that could be used within an organism to measure in a nonperturbing way) internal field patterns.

Interactions with drugs or other chemicals
- Repeat selected experiments showing effects (including the potential of microwaves as a cocarcinogen), using carefully controlled dosimetry and statistical analysis.
- Develop and test hypotheses to explain effects.
- Long-term dose-response experiments at power densities around 0.1 mW/cm^2 and with a larger number of drugs at whole body, organ, and organelle levels.

Immunological effects
- Repeat selected Russian research at 1 to 500 mW/cm^2 levels; repeat selected U.S. work to validate it.
- Mechanistic and molecular biological experimentation.
- Long-term studies, particularly autoimmune response.

Effects on calcium ion efflum in brain tissue
- Studies to determine bioeffects using 2450 MHz as the carrier frequency or studies to determine whether the power density "windows" are carrier-frequency dependent.
- Studies to establish the interaction mechanism (the interaction site) of the modulated fields and ELF fields on calcium ion efflux.
- Studies to determine whether the phenomenon will occur under the modulation and power characteristics expected of the SPS microwave beam.
- Studies to determine whether the calcium ion efflux phenomenon correlates with Russian and East European findings of neurological/behavioral decrements in people and animals exposed to low levels of microwaves.
- Experiments to determine whether other ions—sodium, potassium, magnesium–are similarly affected.

Effects on organized structures
- Studies of changes in behavioral responses under simulated SPS conditions, using behavioral tests (such as time-based schedules of reinforcement) that are both sensitive and reliable measures of such effects.
- Studies of long-term effects.
- Neurological and blood-brain barrier experiments at low levels.
- Determine the neurological and physiological significance of behavioral responses.
- Molecular level studies on biological relaxation times.
- Consideration of long-term animal experiments at 2,450 MHz to evaluate, if possible, whether there is any trend toward life shortening in animals.

SOURCE: C H. Dodge, (rapporteur), *Workshop on Mechanisms Underlying Effects of Long-Term Low-Level, 2.450 MHZ Radiation on Peep/e,* organized by the National Research Council, Committee on Satellite Power Systems, Environmental Studies Board. National Academy of Sciences, July 15.17, 1980

species. It may also be possible that frequencies other than 2.45 GHz would be used for SPS. If a much different frequency were used, however, low-level microwave research would have to be done at that frequency as well, because different frequencies cause different responses,

In addition to laboratory experiments, epidemiological studies are also needed.[64] It has been argued that such studies are currently of limited usefulness; they are very expensive, difficult to accurately document (i.e., it is difficult to determine the dose to which individuals are exposed) and may overlook important biological endpoints.[65] In addition they have limited usefulness for exposure to low levels of microwaves because the variability of the response is small and might be masked by other effects. It is also not clear how many people would need to be observed. Nonetheless a coordinated program of prospective epidemiology (as opposed to retrospective studies that rely on medical records many years after exposures) and laboratory research is essential to bridging the gap between biological effects observed in a laboratory animal and human health standards.

Special attention must also be paid to effects on ecosystems. To date, nearly all studies have been conducted in a controlled laboratory environment on a relatively few species. Virtually nothing is known about the effects of microwaves on a complete ecosystem and no studies have been performed that even ap-

[64] Office of Science and Technology Policy, A *Technical Review of the Biological Effects of Non-Ionizing Radiation,* Washington, D C , May 15, 1978

[65] Paul Tyler, Armed Forces Radiological Research Institute, private communication, July 30, 1979

preach the projected time scale of SPS operation (i.e., 30 to 100 years). With respect to SPS, it must be determined if animals and airborne biota would be attracted to the beam or would avoid it. What impact would microwaves have on the navigational systems of birds and insects (as well as aquatic life for offshore rectennas)? What effect would exposure to microwaves have on the productivity of plants and their susceptibility to drought? How would SPS affect the local food chain? The effects on micro-organisms, such as bacteria, fungi, and algae should be invest igated. [66]

- Microwave standards. The biological consequences of exposure to low-level microwaves are poorly understood because of inadequate and sporadic support of microwave bioeffects research in general and because the bulk of research performed in this country has focused on the bioeffects at levels of 10 mW/cm^2 or greater.[67] This emphasis stemmed from a belief that the only biologically significant damage from exposure to microwaves is due to heating. In fact, occupational guidelines developed in the 1950's through the Department of Defense and its contractors in response to concerns about exposure of radar personnel were based on biological injuries (e. g., cataracts, burns) from acute exposure to microwaves on the order of 100 mW/cm^2. It was concluded that humans could well tolerate exposures to power densities 10 times smaller[68] (i. e., 10 mW/cm^2) without suffering serious or permanent damage. [69] This reasoning was accepted by the American Standards Association (now the American National Standards Institute (ANSI) which in 1966 recommended a maximum permissible exposure of 10 mW/cm^2, averaged over any 6-minute period (1 O to 100 GHz).[70] This rationale also forms the basis of the current U.S. occupational guideline (which in 1975 was ruled advisory rather than a mandatory standard") as promulgated by the Occupational Safety and Health Administration (OSHA) which adopted the ANSI recommendation in 1971. Presently, there is no official recommendation for general population exposures in this country.

The reasoning underlying the U.S. guideline is currently in dispute and OSHA and ANSI are considering new recommendations. [72 73] The conflict centers around the assumption that only thermal effects result from exposure to microwaves. While it is generally acknowledged that exposure to microwaves of 10 mW/cm^2 or greater will result in heating, the effects and consequences of exposure to lower power densities are controversial. Experiments documenting behavioral and neural changes and the enhancement of calcium efflux from brain cells[74] in particular have suggested the existance of other effects at power densities below 1.0 mW/cm^2. These phenomena are thought by some to result from direct interactions with the electromagnetic field rather than as an indirect consequence of heating. Some of the mechanisms that have been postulated for non ionizing radiation include:

1. distortion of the shapes of individual molecules or rearrangement of a group of molecules that might transiently or per-

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[66] O P Gandhi, "Biohazards of Microwave Beams From Proposed Satellite Power Stations', in *Health Implications of New Energy Technologies*, W N Rom and V E Archer (eds) (Ann Arbor, Mich Ann Arbor Science Publishers Inc , 1980)

[67] P Tyler, "Overview of Radiation Research Past, Present and Future, " in *Biological Effects of Nom Ionizing Radiation*, P Tyler (ed) (New York Academy of Science\, annals, vol 247, 1975)

[68] R Bowen\, et al , (*ommunications for a Mobile Society (Beverly H ills, Calif Sage Publ i cat ions, 1978)* (Bell Laboratories and General Electric recommended 0 1 mW/cm^2 and 1 () mW/cm^2 respectively as maximum permissible exposure limits)

[69] N H Steneck, H j Cook, A J Vander, and G 1 Kane, "The Origins of U S Safety Standard\ tor Microwave Radiation," *Science*, vol 208, pp 1230-1237, June 1 3, 1980

[70] L David, *A Study of Federal Microwave Standards*, DOE/ NASA report No DO E/E R-10041-02, August 1980

[72] General Accounting Office, *Efforts by the Environmental Protection Agency to Protect the Public From Environmental Non-Ionizing Radiation Exposures*, Washington, D C , Mar 29, 1978

[73] A W Guy, "Non-I Ionizing Radiation. Dosimetry and Interaction," in *Non-Ionizing Radiation*, proceedings of a Topical Symposium, Nov 26-28, 1979, The American Conference of Governmental I ndustrial Hygienists, Inc , 1980

"Z R Glaser, "Basis for the NIOSH Radiofrequency and Microwave Radiation Criteri a Document, " in *Non-Ionizing Radiation*, proceedings of a Topical Symposium, Nov 26-28, 1979, The American Conference of Governmental I ndustrial Hygienists, Inc , 1980

"Dodge, opcit

manently alter the function and replication process of a biological unit;[75]
2. reorientation of dipole molecules in the microwave field and polarization of molecules that control membrane permeability; [76]
3. biological electromagnetic interference in which the microwave field disrupts or enhances the transfer of biological information in the form of electromagnetic energy between molecules and cells; [77] and
4. field receptor interactions where neural tissue acts as a receptor of weak fields. [78]

The discussion of low-level effects is hampered by the experimental difficulties of isolating the various possible mechanisms. Most U.S. microwave experts acknowledge the need for research on low-level effects, but remain skeptical about their biological significance, especially at the proposed SPS single frequency of continuous radiation.

The controversy over low-level effects has been fueled by the disparity between U.S. and U.S.S.R. research and exposure standards (see table 14)—the Soviet standard is three orders of magnitude lower than the U.S. guideline. Some U.S. authors have attributed the different standards to dissimilar research philosophies.[79] For example, microwave studies thought most valid by U.S. scientists are those performed in a controlled laboratory environment, whereas Soviet researchers rely on clinical and "subjective" data as well.[80] In fact, based on the complaints of radar personnel, "microwave sickness" has been isolated as a distinct occupational disease in the U. S. S. R." It has also been argued that the Soviet exposure levels are based on the occurrence of a biological effect whereas the U.S. guideline reflects levels of known biological damage (with a safety margin). " Moreover, it has been claimed that the Soviet standard has been set without regard to the practical feasibility of meeting such low levels. It is further argued that in any case the standards are not enforced, especially in the military sector, although this would be difficult to substantiate.

For many years the flow of information between East European and Western researchers was restricted. Translation problems sometimes also contributed to misunderstandings.[83] This situation has improved considerably, and attempts are being made in the United States to replicate many of the low-level experiments performed in other countries (although the United States still has not sponsored any clinical studies). Western literature is also beginning to acknowledge the possibility of behavioral response and selective sensitivity of organs to low levels .84 Partly for these reasons, it is anticipated that new ANSI guidelines will be established that are more stringent than the present exposure levels (see fig. 41). At the SPS frequency of 2.45 GHz, the maximum occupational exposure that is now being considered is 5 mW/cm². * EPA is also considering

"K D Straub, "Molecular Absorption of Non-Ionizing Radiation in Biological Systems" in *The Physical Basis of Electromagnetic Interactions With Biological Systems: Proceedings of a Workshop, University of Maryland, June 15-17, 1977,* L Taylor and A Cheung, (eds), US DHEW, 1978, report No [FDA) 78-8055, Washington, D C , April 1978

"A S Pressman, *Electromagnetic Fields and Life* (New York Plenum Press, 1970)

[77]Ibid

[78]D R Justesen, et al , "Workshop on Radiation: Scientific, Technological, and Sociological Implications of Research and on Biological Effects of Radio-Frequency Electromagnetic Radiations," in *Proceedings of the 1978 Conference on U.S. Technical Policy* (New York. IEEE, 1979)

"W C Milroy and S M Michelson, "The Microwave Controversy, " *International Journal of Environmental Studies,* VOI 4, p 123, 1973

[80]D R Justesen, Veterans' Administration, private communication, J u ly 16, 1979

[81]C H Dodge and Z R Glaser, "Biomedical Aspects of Radio Frequency and Microwave Radiation A Review of Selected Soviet, East F u ropean, and Western References" in *Biological Effects of Electromagnetic Waves: Selected Papers of the USNC/URSI Annual/ Meeting,* L L Johnson and M Shore (eds), Boulder, Colo , October 1975, USDHEW, (report No (FDA) 77-8010/8011), Washington, D C 1976

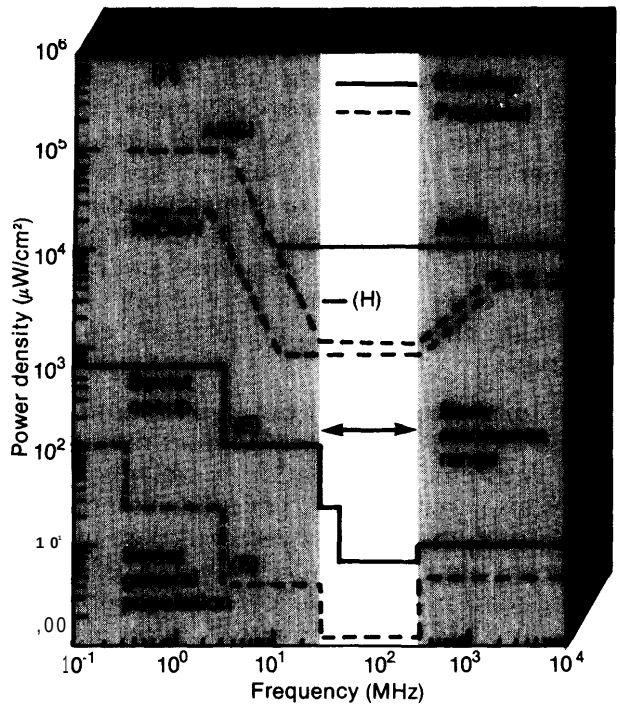
[82]D Michaelson, in *Symposium on the Biological Effects and Health Implications of Microwave Radiation,* S Cleary (ed), Richmond, 1969, USDHEW, report No BRH/DBE 70-2, 1970, pp 76-81

"F'rzemyslaw Czerski, Department of Genetics, National Research I nstitute of Mother and C h ild (Poland), private commu n ication Sept 5, 1979

[84]C H Dodge and Z R Glaser, "Trends in Non-ionizing Electromagnetic Radiation Bioeffects Research and Related Occupational Health Aspects," *Journal* of Microwave *Power,* vol 12, No 4 1977, pp 319-334

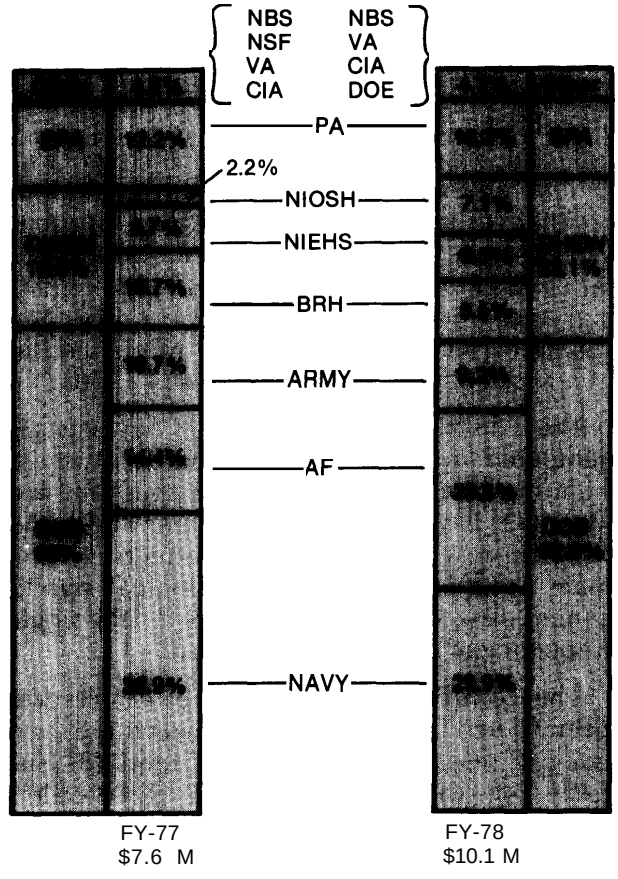
*This level has been criticized by the National Resources Defense Council as being arbitrary and not found with any recognition of possible nonthermal effects, see ch. 9, *Public Issues*

Figure 41 .—Comparison of Exposure Standards



SOURCE: A. W. Guy, "Nonionizing Radiation: Dosimetry and Interaction," in *Nonionizing Radiation,* **Proceedings of a Topical Symposium, Nov. 26-28, 1979, The American Conference of Governmental Industrial Hygienists, Inc., 1980.**

Figure 42.— Program Funding



SOURCE: *Fifth Report on "Program for Control of Electromagnetic Pollution of the Environment: The Assessment of Biological Hazards of Nonionizing Electromagnetic Radiation, "* **NTIA report No. 79-19, U.S. Department of Commerce, March 1979.**

the development of exposure guidelines for the general population, although it does not have the jurisdictional authority to enforce standards. It is conceivable that future public standards could be established at 1.0 mW/cm² or below.[85] The impact of more stringent standards on SPS design and concept viability should be addressed.

Agencies. **At present, the study of the bioeffects of nonionizing radiation falls under the jurisdiction of 13 Federal agencies.[86] The allocation of funds (currently about $15 million per year) is shown in figure 42. The agencies primarily responsible for regulation and the establishment of microwave guidelines[87] include the Department of Health and Human Services (the Bureau of Radiological Health/ Food and Drug Administration, for example, sets emission standards for electronic products such as microwave ovens); the Department of Labor (which sets occupational guidelines); and EPA (which sets environment guidelines for other Federal agencies).**

The Federal effort has been coordinated at various times by other Federal agencies, but a clear, dedicated, well managed and adequately funded national program in microwave bioeffects research is currently lacking. To some extent, the ineffectiveness of the agencies responsible for the management of the Federal program is due to lack of control

***'David,** op. **cit.**

[86] *Fifth Report on "Program* **for** *Control of Electromagnetic Pollution of the Environment: The Assessment of Biological Hazards of Nonionizing Electromagnetic Radiation, "* **NT I A report No 79-19, U.S. Department of Commerce, March 1979.**

[87] David, op cit

over the allocation of research funds .88 It is also often the case that within each of the research and regulatory agencies, microwave research receives low priority on the agency's agenda. jurisdictional ambiguities have caused some agencies to take a limited approach to research and protection. Multiagency effort has also made public participation and education difficult.

Often, the most cohesive and vigorous research and evaluation of microwave bioeffects take place in conjunction with one particular technology such as a radar facility. This is not always the best arrangement since in the past, user agencies with vested interests have often been responsible for the assessment of health and environmental impacts. Moreover, fundamental research is needed in order to elucidate the mechanisms of interaction; technoiogy-specific research is helpful but usually does not contribute significantly to basic understanding. In addition, long-term continuous studies are needed and project-specific research is sporadic and unpredictable.

Nonetheless, unless the Federal research effort is consolidated into fewer agencies and given greater support, it is likely that an SPS program would be required to sponsor microwave bioeffects studies as it did in the DOE assessment. If the current climate continues, this research would not only gather information specifically relevant to SPS, but would probably be quite fundamental in nature. If a microwave SPS program is pursued, the development of SPS would entail the involvement of the Federal agencies shown in table 44. State agencies might also be affected.

Conclusion. DOE-sponsored microwave studies stimulated thinking about the design of microwave bioeffects experiments, tended to clarify research needs and obstacles and con-

[68] Tyler, op cit

Table 44.—SPS Development

SPS development phase	Microwave aspect	Agency involvement
Basic research	Environmental and public health effects evaluation MPTS technology	DOE, EPA, HEW/FDA, NASA
Applied research	Conduct experiments and further define health and safety risks of MPTS to public, the environment and SPS workers	DOE, NASA, HEW/FDA, Department of Labor/OSHA EPA
Exploratory development	Preliminary standards development radiation exposure standards occupational health and safety standards development	HEW/FDA, DO E/EV, EPA, HEW/FDA, Bureau of Radiological Health, Department of Labor/OSHA
Technology development	Final standards for MPTS chosen occupational health and safety standards finalization	HEW/FDA, DOE/EV, EPA, DOL/OSHA
Engineering development.	Preparation of environmental impact	Council on Environmental Quality
Demonstration	Guidelines for health and safety (worker) enforcement	Department of Labor/OSHA
	Guidelines for public health and safety environmental impact statements	HEW/FDA-Bureau of Radiological Health, EPA, Council on Environmental Quality
Commercialization.	Review guidelines for worker health and safety	Department of Labor/OSHA
	Review guidelines for public health and safety	HEW/FDA, EPA
Production	Enforcement of guidelines for worker health and safety	Department of Labor/OSHA
	Enforcement of regulations for public health and safety	EPA
Operations	Enforcement of guidelines for worker health and safety	Department of Labor/OSHA
	Enforcement of guidelines for public health and safety	EPA

SOURCE: L. David, *A Study of Federal Microwave Standards,* DOE/NASA report No DOE/ER-10041-02, August 1980.

tributed to an increased study capability. While the results of these studies are useful, the time and resource constraints of the SPS assessment program precluded a thorough research agenda; in particular, no studies on long-term exposure to low levels of microwaves could be initiated and little more could be done to improve our theoretical understanding. In spite of the general acknowledgment by the microwave community of the need for studies of chronic, low-level exposure, practically no such studies are underway or planned. Clearly, if many of the fundamental questions about the bioeffects of microwaves are to be resolved within the next one or two decades, a more comprehensive, dedicated national research program will be needed.

LASER LIGHT

The biological risks associated with the laser system have been assessed only to a very limited degree. The power density of the focused laser system beam would be sufficiently great to incinerate biological matter."' Safety measures (such as a perimeter fence and pilot beam system) would have to be devised in order to avoid beam wandering and the direct exposure of the nearby public and ecosystems. Less easy to protect would be birds and insects flying through the beam; without some sort of warning device they would be incinerated.[90] It is not known if air-borne biota would be aware of the beam, and if so whether they would be attracted to or avoid it. Siting studies should consider migratory flyways and local bird populations.

It has been suggested that aircraft be restricted from the power beam area.[91] While it is not expected that jets and their passengers would suffer any damage in traversing the beam due to their high speed and infrared reflectivity, slower flying, less reflective aircraft could be affected. More important, laser light specularly reflected from an airplane would present an ocular hazard to the public.[92] A radar warning system might be devised to defocus the laser beam if a plane did happen to fly through it.

The primary risk to the public and nearby ecosystems outside of the direct beam would be due to laser light scattered from clouds, dust and the receptor site. This "spill over" of laser power (less than 1 percent) would necessitate establishing a buffer zone surrounded by an opaque, tall fence.[93] As shown in figure 33, it has been estimated that a protection radius of 300 to 800 m would be required in order to limit public exposure at the perimeter to 10 m W/cm a recommended maximum whole-body irradiance limit.[94] More research would be needed to verify this exposure guideline and to investigate the effects of chronic exposure to low level laser radiation. For visible laser beams, the risk of ocular damage could be increased at the receiving site if magnifying devices were used. Prolonged occupational exposure at infrared power densities greater than 10 mW/cm^2 would be of particular concern, especially for the cornea. Workers at receiving sites would probably be required to wear protective clothing and eye goggles.

Hazards outside of the site have not been assessed. It is unlikely that wildlife or vegetation at the receptor site would survive.[95] The etfects of the low level laser light on ecosystems outside of the receptor area are not known It is possible that certain infrared sensitive Insects would be attracted to the laser beam, but this requires further study .9'

The bulk of research on the biological effects of lasers is not directly applicable to the infrared lasers that have been suggested for SPS Most studies have concentrated on the effects on the eyes and skin of visible and near infrared lasers in a pulsed mode. The standards that have been promulgated pertain predominantly to short-term occupational exposure to

"'Beverly, op cit
[90] Walbridge, op cit
[91] Beverly, op cit
[92] Walbridge, op cit
' 'Beverly, op cit
[94] D H Sliney, K W Vorpahl, and D C Winburn, "Environmental Health Hazards From High-Powered Infrared Laser Devices" Arch Environmental Health, VOI 30, April 1975, pp 174170
"'W~Ihridge, op cit
[96] Ibid

lasers operating in a controlled indoor environment such as a laboratory or medical facility. Few studies have examined the effects of chronic exposure at SPS-like power densities and under SPS environmental conditions. A summary of known effects on the skin and eyes is presented in appendix D.

REFLECTED LIGHT FROM THE MIRROR SYSTEM

The light reflected by the mirror system to Earth would be visible at night as a general glow at up to 150 km from the receiving site. " The potential health impact of most concern is ocular damage from either the scattered light or from direct exposure to reflected light as the mirror image sweeps across the Earth during orientation maneuvers. Since the Collective intensity of all the mirrors at one site would be equal to that present in the desert at noon, it appears that the intensity of light would be too low to be of danger to the observer. One investigation revealed that under the worst conditions (i.e., staring, no blinking) it would be safe to view the mirrors directly for at least 2.4 minutes. " No information is available regarding the ocular effect produced when an individual views the mirrors with a binocular or telescope. The psychological effects of a "24-hour day" or alterations of the sky near the sites also needs to be studied.

The ecological impacts have not been assessed. It is known that the polarization, frequency and intensity of light as well as the percentage of daylight hours influence the behavior, navigation, and lifecycle of many species of wildlife and vegetation; many species have inherent biological clocks or circadian rhythms that are triggered by the diurnal and seasonal variations of sunlight.[99] However, ecosystems in the area surrounding the receiver site would be exposed to low levels of incremental sunlight and so it does not appear likely that significant biological effects would occur. Nonetheless, research should be conducted in this area. The effects of changing the night sky also need to be studied for ecosystems both near and distant from the site. Ecosystems could also be indirectly affected by weather modification induced by the mirror system.

LIGHT REFLECTED FROM REFERENCE SYSTEM

The transportation vehicles, construction and staging bases, and the satellite structure of the orbiting satellite systems will reflect sunlight, discernible on Earth. Some specular reflections from reference system components may be exceptionally bright due to their large size, low altitude, and reflectivity.[100] Most specular reflection would be restricted to small, fast moving spots or "glints" as the structures and vehicles change orientation. The worst cases, which may exceed acceptable limits, occur for reflections from the solar panels of the OTVS while in LEO, and the back of the solar panels in CEO. Diffuse reflections, brighter than most stellar sources would make the LEO OTV staging base visible during the day It may be possible to reduce most of these reflections by controlling the orientation, surface curvatures, solar panel alignment and surface quality of the vehicles and structures. Reflection of visible light from the components of other SPS technical options may be similar to the reference system depending on the orbit and size of transportation vehicles and space structures.

The effects on the public and ecosystems have yet to be evaluated in depth. One study found that the reflections from the reference system would be bright but not dangerous to the human eye[101] unless viewed for too long or with a magnifying device. Studies would be further needed to evaluate the ground illumination in terms of human exposure limits and to explore any possible psychological effects While DOE has tentatively concluded that plants and animals would not be unduly

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[97] Billman, private communication, op cit

[98] M T Hyson, "Sunlight Reflections From a Solar Power Satellite or SOLARES Mirrors Should Not Harm the Eyes, " in *The Final Proceeding of the Solar Power Satellite Program Review,* Apr 22-25, 1980, DOE/NASA report No Conf -800491, July 1980

"McGraw-Hi/l Encyclopedia of Science and Technology, VOI 10 (New York McGraw-Hill Book Co , 1977)

[100] D L Iiemohn, D H Tingey, and B R Sperber, "Characterization of Reflected L ight From the Space Power System, " in *The Final Proceedings of the Solar Power Satellite Program Review,* Apr 2225, 1980, DO E/NASA report No Conf -800491, July 1980

[101] Hyson, op cit

affected by the reflected light, ecosystem effects are largely uncertain. More research would be needed to investigate how alterations of the day and night sky could influence behavior, navigation, and lifecycles of wildlife and vegetation.

Noise

Noise is generated during rocket launches and the construction of receiving stations. With respect to the latter, the highest noise levels would result from heavy equipment used to prepare the site and build the support structure. The DOE prototype siting study concluded that it would be unlikely that significant noise-related impacts on the public and most animals located 2 km or more from the prototype construction site would occur. '[102] For some machinery, occupational noise standards would be exceeded. Mitigation measures include ear protection devices, mufflers for machinery, and special insulation in factories.

Very high noise levels would be associated with launch vehicles during ascent and reentry. Table 45 presents the estimated noise produced by the HLLV. Table 46 is exhibited for comparison. A preliminary assessment indicates that the OHSA standard of 115 db(A) would be exceeded within 1,500 m of the launch pad, and the EPA guideline violated within 3,000 m.[103] Using the Kennedy Space Center as a prototype launch site, the study concluded that launch noise would not interfere significantly with speech (interruption for 2 minutes at 30 km twice a day), but that interference with sleep could occur 30 km from the site Table 47 presents an estimate of the number of people annoyed by the noise as a function of distance. Sonic booms would also be generated; pressure levels are shown for HLLVs and PLVs in table 48. The HLLV sonic booms would not cause injury but would invoke gross body movements and might interfere with sleep. It has been suggested that the trajectories of launch vehicles should avoid population areas.

The effects of noise on wildlife include startle responses and disruption of diurnal and reproductive cycles that could be particularly significant in endangered species habitats. It has been suggested that wildlife would adapt to the noise, but this is not clear. '[104] While the noise generated by the space shuttle is not expected to be serious, the effects of HLLVs would be greater because of the increased fre-

[102] Protot ype Environmental Assessment of the Impacts of Siting and Constructing a Satellite Power System (SPS) Ground Receiving Stat Ion (GRS), op c it

[103] Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program, op cit

[104] Ibid

Table 46.—Representative Noise Levels Due to Various Sources

Source or description of noise	Noise level (db)
Threshold of-pain	120
Riveter	95
Elevated train"	90
Busy street traffic.	70
Ordinary conversation	65
Quiet automobile	50
Quiet radio in home	40
Average whisper	20
Rustle of leaves.	10
Threshold of hearing	0

SOURCE Environmental Assessment for tire Satellite Power System Concept Development and Evaluation Program, DOE/ER-0069, August 1980

Table 45.— Estimated Sound Levels of HLLV Launch Noise

Sound level and duration	Distance from launch pad				
	300 m	1,500 m	3,000 m	9,000 m	30,000 m
OASPL[a] (dB)	149	136	130	120	109
A-level[b] [db(A)]	130	114	105	89	72
Duration(s)	12	42	54	77	77

[a] OASPL: overall sound pressure level expressed in decibels (db) above the level corresponding to a reference pressure of 20 pa (pa= pascal=1 N/m²)
[b] A-level: Weighted average sound level over the frequency spectrum in accordance with the Performance of the human ear

SOURCE: Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program, DOE/ER-0069, August 1980

Table 47.–Community Reaction to HLLV Launch Noise

Distance from launch point (m)	Percent of people highly annoyed[a]
300	90
1,500	45
3,000	24
9,000	5
30,000	1

[a]Based on a 24-hr average of the noise

SOURCE *Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program* DOE/ER-0069, August 1980

Table 48.—Sonic Boom Summary (Pa)

Vehicle	Launch	Reentry
HLLV booster	1,200	190
HLLV orbiter	—	140
PLV booster	770	140
PLV orbiter	—	70

SOURCE *Environmental Assessment–for the Satellite Power System Concept Development and Evaluation Program* DOE/ER-0069, August 1980

quency and level of noise, due especially to sonic booms.

Terrestrial workers would be exposed to noise levels higher than the general public and would require hearing protection.[105] Possible hearing damage and pyschological effects should be studied in light of the unprecedented frequency and size of launches.

Other Risks

Quantitative studies are needed to determine SPS impacts on air and water quality and the generation of solid wastes. It is currently assumed that these impacts would be comparable to typical industries and powerplants (except coal) and that unusually high risks would not be encountered by the public and terrestrial workers that could not be minimized or corrected.[106] The effects on ecosystems are less certain.

DOE has concluded that acid rain from the SPS launch ground cloud would be localized, temporary and minimal. Because of the consequences of ozone depletion, i.e., a l-percent decrease in ozone corresponds to a 2-percent increase in biological harmful ultraviolet radiation that reaches the Earth,[107] the effects of SPS on the ozone layer has been studied. preliminary analysis concludes that the change in ozone brought about by SPS launch effluents would be negligible, but further study is requ i red.[108]

The deployment of SPS would also require the mining, production, and transport of certain toxic materials. Some toxic materials such as hydrocarbons could also be released from fuel burning in the launch and recovery of space vehicles. Rocket propellants such as liqu id hydrogen are of special concern because they are toxic, flammable, and explosive.[109] A spill of liquid oxygen would adversely affect local ecosystems. However, no information is available to quantify the exposure or risk to the public, workers or ecosystems. An incremental increase in the risk of catastrophic explosions or fire is thought possible, especially because of the large amount of fuels involved; the occupational risk, of course, being considerably higher than that for the public. Launch and recovery accidents are not likely to have any more impact on the public than conventional aircraft accidents, although it has been suggested that flight trajectories avoid populated areas. The noise and shock waves from a catastrophic explosion of an HLLV could possibly blow out windows and doors in buildings up to 15 km from the launch pad.[110]

Space Environment

Many space workers would be needed to construct and maintain an SPS system. The reference design, for example, requires 18,000 person-years in space;[112] workers would serve ten 90-day tours over 5 years. Other SPS designs may have different personnel requirements, but they will not be specifically ad-

[105]Ibid
[106]Ibid
[107]S Hamer, "Ozone Controversy, " Editor/a/ Research Reports, vol 1, No 11, 1976
[108]Ibid
[109]Ibid
[110]Ibid
[111] Ibid
[112] *'Program Assessment Report, Statement of Findings,* op cit

dressed here. The health effects of the space environment are potentially serious, but highly uncertain; experience with people in space is limited to a few highly trained astronauts who lived mostly in LEO for a maximum of a few months. [113] NASA's current ground-based program as well as future activities with the space shuttle and space operations center will yield information relevant to SPS space worker health and safety. DOE does not consider the potential health effects an obstacle to continued planning and development of SPS, [114] but if this and other space projects are to be considered, the health and safety of space personnel should be a high-priority research task,

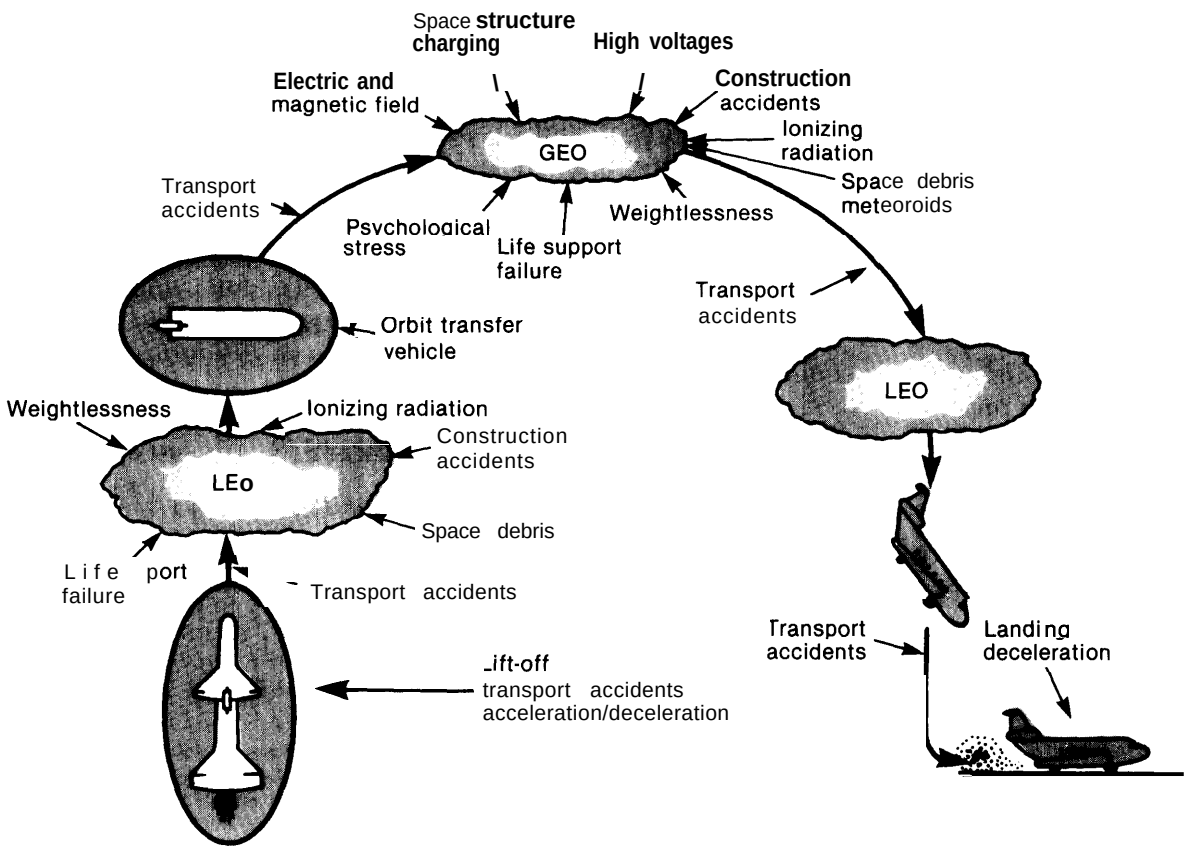
The principal health and safety risks of the space segment of SPS are illustrated in figure 43. Effects on the general health and safety of space workers such as acceleration and weightlessness are discussed in appendix D.

The most serious potential health risk of the space environment is exposure to ionizing radiation. The types of radiation found in the different SPS orbits are listed in table 49. Exposure to radiation in CEO and in transit between LEO and CEO are of most concern because, under the reference system scenario, workers spend approximately 91 percent of

[113] Ibid.

[114] *Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program*, op. cit.

Figure 43.— Factors Pertinent to Space Worker Health and Safety



SOURCE: Program Assessment *Report Statement of Findings* Satellite Power Systems Concept Development and Evaluation Program, DOE/NASA report No. *DOE/E R-0085* November 1980

Table 49.—Types of Radiation Found in the Different SPS Orbits

GEO
- Radiation belts
  - —Electrons—dominant when shielding is less than 3gm/cm² aluminum
  - —Bremsstrahlung —produced by electron interactions with shielding—dominant when shielding is greater than 3 gm/cm² aluminum
  - —Protons—low energy—stopped by minimal shielding
- Galactic cosmic rays
  - —Protons
  - —Helium ions
  - —High-energy, heavy ions
- Solar particle events— i.e., particles accelerated to high energies during a solar f l are
  - —Protons
  - —Heavy nuclei

Travel **Between Orbits**
- Radiation belts
  - —Bremsstrahlung radiation produced by electrons
  - —Protons

LEO
- South Atlantic Anomaly
  - —Protons
  - —Electrons—low energy—stopped by minimal shielding

SOURCE: Margaret R. White, Lawrence Berkeley Laboratory, private communication, Feb. 12, 1981

their time in the higher orbit where the radiation environment is the most severe.[115] In GEO, except under the unusual circumstance of a large solar flare, the major part of the radiation dose in the reference system would be due to bremsstrahlung produced by the interaction of high-energy electrons with the shielding material. The biological effects of this kind of radiation are reasonably well understood, and innovative shielding might reduce this dose. However, radiation from the high-energy, heavy ions (HZE) in galactic cosmic rays cannot be stopped by conventional shielding and their biological effects are currently very poorly understood. From theoretical considerations and preliminary experiments it appears that they may be much more effective in causing biological damage than other types of ionizing particles. Thus, though they contribute a small fraction of the total radiation dose in the reference system, they are of major concern with regard to the health of space workers.[116]

Estimates of the radiation dose for exposed SPS space workers are uncertain. Few measurements have been made of the radiation flux in GEO.[117] It is also difficult to quantify the radiation levels at any one time because solar storms that significantly increase the levels are currently impossible to predict. Moreover, there is considerable controversy over the models that are used to estimate the amount of energy absorbed in the human body as well as the biological consequences of the absorbed radiation.[118] The most significant long-term effect of ionizing radiation is cancer. Cancer risk depends on a number of factors including the total I-fetime dose-equivalent; dose rate; duration of exposure; and the age, sex, and susceptibility of the exposed person.[9]

DOE has estimated that space workers for the SPS reference design (which includes modest shielding— 3 g/cm² aluminum for habitat and work stations and 20 to 30 g/cm² for the storm cellar, used during solar particle events) would receive 40 reins per 90-day tour or 400 reins for the planned 10 tours.[120] This estimate could be inaccurate (probably too high) by a factor of 5 or 10.2' However, the biological impacts could actually be higher than this dose would indicate if HZE bioeffects are taken into account and/or a solar particle event occurs. In spite of the large uncertainties, it is almost certain that reference system exposure **would exceed current limits for radiation workers as recommended by the National Council on Radiation Protection and the International Commission on Radiological Protection.[122] For comparison, the general population receives about 0.1 rem/year on the average;[123] occupa-**

[1] *"ionizing Radiation Risks to Satellite Power Systems (SPS) Workers, LBL-9866,* **November 1980, advance copy**

[116] **M R White,** *Environmental Assessment for the Satellite Power System, Non-Microwave Health and Ecological Effects,* **DOE, in press (1981)**

[7] Margaret R White, Lawrence Berkeley Laboratory, private communication, Feb 12, 1981

[8] **"Program** *Assessment Report, Statement of Findings,* **op. c** it

[9] JT **Lyman, "Hazards to Workers From** Ionizing **Radiation** in the SPS **E** nvironment, **"** in **The** *Final Proceeding of the Solar Power Satellite Program Review,* **Apr 22-25, 1980, DOE/NASA report No Conf -800491, July 1980**

[120] *Ionizing Radiation Risks to Satellite* **Power** *Systems (SPS) Workers,* op cit

[1] **" Program Assessment Report, Statement of Findings, op** cit

[2] **"Zlbld**

[3] Committee **on the** Biological **Effects of** Ionizing **Radiation, The F f** *fects* **on Populations of** *Exposure to Low Levels of Ionizing Radiation (BE/R III),* **National Academy of** Sciences, **1980,** typescript edition

tional exposure limits (for blood terming organs) are 3 reins for 90 days and 5 reins over 1 year;[124] and the NAS maximum recommended exposure limit (for bone marrow) for astronauts is 35 reins for 90 days, 75 reins over l-year period and 400 reins for life.[125] If space worker careers were 5 years, with 90 days in space alternated with 90 days on Earth, it would be expected that for each 10,000 workers in space, between 320 to 2,000 additional cancer deaths in excess of normal cancer mortality would occur.[126] An issue critical to SPS design and economics is whether the radiation standards developed for astronauts should be applied to SPS workers.[127]

Risks could be reduced in a number of ways. For example, the time per tour and the number of tours per worker could be decreased. Robots and teleoperation could be used to reduce the number of people required in space. It is also essential that accurate, quick and rugged dosimeters be developed that monitor the real-time radiation flux and energy levels to which each individual is exposed.[128] instruments would also have to be developed to warn personnel in GEO of solar storms or other unforeseen high radiation events so that they can move to shelters. Considerable improvements in dosimeter technology are needed since present devices are not very accurate and take a long time to display radiation levels. Shielding is also crucial Some of the risks associated with the reference system could be reduced with additional or innovative shielding. Analysis is needed to determine if better shielding techniques can be devised that would not incur a greater weight or cost penalty. Studies are also needed to examine to what extent additional shielding mass will incrementally reduce risks of exposure to most radiation (because secondary radiation can be produced as the thickness is increased),[129] or if shielding materials can be developed to stop HZE particles.

DOE has concluded that as presently designed, the reference system construction scenario is unacceptable.[130] Risks could be reduced if personnel spent more time in LEO. More study is required to improve the current assessment and to explore the impacts on the system Cost and feasibility of modifications of the reference system in order to minimize ionizing radiation hazards.

In sum, research priorities include:

- measurements of radiation flux in CEO. This can be done with CEO satellites; the space shuttle and space operations center will provide data on LEO;
- study of the bioeffects of HZE particles;
- continued study of radiation bioeffects and refinement of models;
- improvement in dosimetry techniques and shielding technology; and
- for SPS, improved analysis of exposure risk, and shielding techniques, consideration of exposure limits, and assessment of the viability of workers in space: tradeoffs between human health, system feasibility, and economics.

[124] W Schimmerling and S Curtis (eds.), Workshop on the Radiation Environment of the Satellite Power System (SPS), Sept 15, 1978, DOE, Conf -7809164, December 1979

[125] 1251b;d

[126] Whke, Environment/ Assessment for the Satellite power System, Non-Microwave Health and Ecological Effects, op cit

[127] Program Assessment Report, Statement of Findings, op cit

[128] Environmental Assessment for the Satellite Power System Concept Development and Evacuation Program, op cit

[129] Program Assessment Report, Statement of Findings, op cit

[130] Ibid

Chapter 9
INSTITUTIONAL ISSUES

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Chapter 9

INSTITUTIONAL ISSUES

FINANCING, OWNERSHIP, AND CONTROL

The questions of who would finance, own, and control a solar power satellite (SPS), and to what extent, are interrelated. As a project that would involve the Nation's space and energy sectors, as well as several Government agencies, there are numerous issues to be considered regarding the proper allocation of risks and responsibilities. The following discussion will examine: 1) current policy and structure of the space and energy sectors; 2) the relation between Government and private-sector activities; 3) the importance of distinguishing between the different phases of SPS development and operation; and 4) possible historical and hypothetical models for an SPS project.

Space and Energy Sectors

Space

In the United States, space capabilities have been primarily instigated and funded by the Federal Government (with much of the actual development and construction done by private firms under contract to the National Aeronautics and Space Administration (NASA)). Launchers, launch facilities, and tracking networks are currently Government monopolies that may be leased to private companies, Government agencies, or foreign countries for specified purposes. Only certain payloads are built and owned by nongovernmental bodies. Within the Government, NASA is responsible for R&D of civilian space-systems that, when development is completed and the operational stage begins, are turned over to another part of Government or to the private sector. Scientific missions, such as deep-space probes, are run by NASA, as are launch facilities such as Cape Canaveral. Military and intelligence operations are largely separate even in the R&D phases, with control exercised by the Department of Defense (DOD) or specific intelligence agencies.

Energy

Electricity is provided by public and private utilities, which are regional monopolies regulated by State authorities. R&D and construction of generating equipment—turbines, nuclear reactors, switching gear— is done by private firms, who sell to utilities. The utilities operate and maintain equipment, build transmission lines, and market electricity to end-users Due to severe capital constraints and a lack of expertise in space operations, utilities are unlikely to own and operate SPS in the way they currently do with other types of powerplants, though they may well be responsible for the ground-receivers. In the case of SPS, there is a question as to who would carry out these various activities,

Although energy production in the United States has traditionally been handled in a decentralized manner by private industry, increased sensitivity to the importance of energy issues since the 1973 oil embargo has led to various attempts at formulating a national energy policy, centered in the newly created Department of Energy (DOE). DOE's scope and responsibilities in areas such as basic research and engineering have yet to be determined; funding is being provided for projects in photovoltaics, conservation, nuclear power, synfuels, and other areas. DOE can be expected to have a prime role in any SPS project.

Government-Private Sector Relations

What would be the degree of Federal involvement with the SPS at different stages, such as R&D, construction, and operation; and in different areas, especially financing, transportation and transmission, and marketing?

The arguments for Federal involvement center around fears that the private sector will not be able to undertake an SPS project, because

of the very high costs and risks, and the long and uncertain payback period. There is also concern that private-sector development, even if economically feasible, might be detrimental because of monopoly by a single firm or consortium, and environmental and international policy considerations requiring public control.

Cost estimates for different SPS scenarios are very imprecise; the most comprehensive estimates have been done by NASA for the reference design and call for a total investment of $102 billion (1977 dollars) over 22 years for construction of the first 5-GW SPS, i.e., before any return on investment (see ch. 5). The key questions are whether the private sector can or would raise these amounts of capital, and how investment costs and management responsibilities might be shared between Government and industry.

Though the reference figures are highly tentative, the general magnitude of the project and its division into discrete stages are likely to be similar regardless of what design is used. None of the alternatives has been examined in nearly the detail of the reference design, largely because the technologies are less well-developed. The following discussion will focus on reference figures but should be applicable to any SPS system of similar magnitude.

Difficulties With Private Involvement

A total investment of $40 billion to $100 billion over 22 years–with additional much larger investments to build a complete system —would be unprecedented for private-sector financing of a single project.

Private capital can be raised by borrowing, issuing bonds or stocks for sale to the public, or from profits. Especially in the first years, borrowed funds would be available, if at all, only at prohibitively high interest rates. Stocks and bonds would be unlikely to attract large investors when profitability lies some 30 years in the future. Both institutional investors and large corporations allocate only a small proportion of their funds for high-risk long-term projects; in some cases, such as pension funds, there are legal limitations on high-risk investments. Uncertainty, whether technical, political, or economic will deter potential investors.

The incentives required to spur any private interest would in themselves involve drawbacks. A company taking a major risk on SPS would expect to be compensated by exclusive patents and other guarantees, in effect with a monopoly. Government regulation would have to take risks into account by allowing a very high rate of return, i.e., allowing the owners to charge high rates for SPS electricity. A private monopoly charging above-average prices could prove to be politically embarrassing.

An SPS system will require a great deal of political support both locally, nationally, and internationally: land-use conflicts, monopoly considerations, environmental standards, tax incentives, and radio frequency allocations are a few of the political issues that SPS will need to confront. Private development and ownership may be seen as leading to an excessive concentration of power outside effective public control

Difficulties With Federal Involvement

Any large long-term project, public or private, dealing with advanced technology may suffer from financial and management problems: lack of coordination between parts of the program; inadequate supervision of contractors; financial and production bottlenecks in specific areas that delay other parts of the program; inaccurate initial estimates of costs and completion times, and so on. However, Government programs often have special constraints that need to be taken into account. Without a profit motive and the discipline of responsibility to owners and stockholders, there is less incentive to reduce costs. Civil service regulations can interfere with hiring and firing and limit salary ranges, decreasing flexibility and making it difficult to retain personnel Annual Government funding produces uncertainties and leaves programs vulnerable to political pressures and pork-barrel compromises. Government-funded R&D in the public domain requires special supervision, since without the incentive of exclusive rights to patents and processes, firms doing research

may tend to inflate costs and draw out delivery schedules.[1] Any extensive Government funding could divert funds from other space, energy, and R&D programs, whose backers might ask for compensation.

Explicit Federal involvement may increase the probability of military participation in some or all SPS activities, complicating most forms of international cooperation and possibly leading to detrimental changes in the SPS design or operating characteristics.

Finally, a federally financed or owned SPS would increase centralized control over an important sector of the economy and would lead to greater politicization of America's energy industry.

Phases of SPS Development

Federal v. private investment is not an either/or proposition. I n general, Federal involvement would be necessary in the early stages, and become increasingly less so, assuming the system remains technically and financially feasible, as the project becomes operational. The basic problem is how to differentiate between the various and overlapping stages and ensure adequate management and continuity throughout.

SPS development can be divided into successive stages (as described in ch. 5): research, engineering, demonstration, and so on. Federal financing and management of the research and engineering phases might turn into a combined Federal-private program as more directly commercial phases were undertaken. The question is at what point and to what degree private investors will be willing to enter the project. On the one hand, investors would prefer to see as much as possible paid for by the Government; but early investors would have an advantage in setting program priorities and establishing a dominant position. Involvement of owners and operators at the earliest possible stages would help to ensure that the completed system is suited for commercial operation, that internal procedures and structure are appropriate to private ownership, and that the transition from development to operation proceeds smoothly.

The SPS would consist of a number of distinct systems, each of which must be developed separately and simultaneously: e.g., transportation, energy conversion and transmission, orbital construction, and ground stations launchers and solar cells, for instance, may be useful and profitable regardless of whether SPS is built or not. Should their development be charged to SPS? If so, their use and sale might help to offset the risks of the program as a whole; on the other hand, their development adds considerably to the SPS cost. It can be argued that public funding should be reserved for those parts of the project that private investors will not handle and that segments with near-term commercial applications should be left to the private sector. As in any complex program, there is the question of internal apportionment of risks and benefits. Successful items can help to subsidize less profitable projects, provided funds are transferable from one division to another, allowing for risky high-return investments, but also for Edsels.

In the case of SPS it is essential that each component be developed on time and to the proper specifications for the system as a whole to function. Management must be given sufficient authority to produce appropriate products., even if particular divisions suffer; say, if SPS solar cell designs are not optimal for ground-based users. Major investors in a privately funded SPS will have their own particular interest–aerospace companies in launchers, electronics firms in microwave hardware, utilities in delivered power — that could compromise the project's overall goals. Government supervision, whether by partial ownership, regulatory oversight, or appointment of d i rectors, may mitigate certain conflicts but is no guarantee of smooth sailing. Federal concern for a broadly conceived public interest may be affected by a desire for continued control and supervision, or by the interests of particular agencies. For instance, DOD may place

[1] I Mark Gersovitz, "Report on Certain Economic Aspects of the SPS Energy Program," OTA contract No 03 3-26700, 1980, pp 1719

emphasis on booster and LEO to CEO transport development for its use (see ch. 7), perhaps affecting launcher design or the allocation of program funds. NASA may wish to emphasize and prolong the R&D phase. Annual budget review may increase costs by creating uncertainty and requiring project managers to spend large amounts of time drawing up and justifying annual budgets.

Possible Models

Perhaps the best way to further examine possible financing and management scenarios is through historical and hypothetical models that might be applicable to SPS. In each instance there are several questions to be asked: 1) Is it complete: can this model support an SPS program from start to finish, or is it applicable only to certain phases or components? 2) How are risks apportioned: who pays, and who reaps the benefits of a successful project? 3] How efficient and flexible is it: can it adapt to changing economic and technical circumstances, and can it attract support from a variety of sources, particularly foreign investors?

Historical Models

NASA

NASA is an independent Government agency with a general mandate to engage in R&D and testing and to conduct launches for civilian space activities. Although NASA has in the past centered its efforts on high-visibility manned projects, such as Apollo and the Space Shuttle, it has also conducted major programs in telecommunications, remote-sensing, and the sciences, such as the Viking and Voyager interplanetary probes.

NASA is funded by general tax revenues appropriated annually by Congress. NASA funds are overwhelmingly—90 to 95 percent— spent on outside contracts with private firms, research centers, and other Government agencies, foreign as well as domestic. NASA itself helps to set priorities and policies, oversees and coordinates contractor performance, and operates specific facilities (on a cost-reimbursable basis) for research and launches.

- *Advantages.* – NASA is already in place, with 22 years of experience. It has well-established relationships with private contractors, other parts of the Government, and foreign. companies and Government agencies. It has the technical and administrative expertise to evaluate most of the major components of the SPS, many of which— interorbit transfer vehicles, assembly and construction facilities — are part of current NASA plans.
- *Disadvantages.* –Annual funding for NASA projects creates difficulties in implementing long-term plans that are likely to go in and out of political favor. It also hampers agreements with foreign firms and agencies, that have had problems in the past when NASA budget cuts have forced cancellation of joint programs. Legislative changes to permit ongoing funding would greatly improve NASA's position.

  NASA's emphasis on R&D and prototype development (NASA's ability to participate in commercial ventures is unclear and subject to restrictions) could create problems in developing a commercial product such as SPS; NASA might have to relinquish control after the demonstration phase. There is often reluctance to complete R&D phases, since completion means loss of the project. Coordination with eventual users and owners may be underemphasized. Amending NASA's charter to allow for beginning-to-end development and operation would alleviate this problem, but might be harmful to the agency's R&D mission.

  The broad scope of NASA activities has meant that, within and without the agency, there have been conflicts over the relative priority of scientific v. applications, or manned v. unmanned missions. The SPS could be criticized for diverting funds and attention from competing programs; intra-agency squabbling might interfere with the project. Excessive concentration on SPS could prevent NASA from accomplishing other tasks, although many aspects of SPS

development would be applicable to other space activities.

Funding all, or even a large part, of the SPS through general tax revenues would produce strong pressure for continued Government control. Since the risks are borne, involuntarily, by the general public, justification in the form of visible public benefits may have to be provided. These benefits could take the form of electricity-rate reductions, tax-reductions, or other types of returns. Turning SPS or SPS technology over to private profitmaking firms may be unacceptable. Such a prospect could discourage private interest; this difficulty is common to all publicly financed ventures.

TENNESSEE VALLEY AUTHORITY (TVA)

TVA, the Nation's largest utility, was established in 1933 to provide power for a region that commercial utilities were not willing to develop. Until 1959, TVA received annual Federal appropriations; since then it has raised capital by issuing bonds, the amount of which is subject to congressional approval, as well as by charging customers for its services. At that time, TVA was forbidden from expanding its service area, in order to avoid competition with private utilities. In 1978 TVA's borrowing authority was raised to $30 billion.[2] A TVA-type independent authority, initially financed by tax revenues and authorized at some point to issue self-backed bonds, could be a possible model for SPS development and operation.

- *Advantages.* — Initial Federal financing would allow for pursuit of R&D and prototype development. Adoption of TVA practices, such as the absence of civil service requirements, would free the authority from certain Government inefficiencies. Issuing bonds would subject the issuer to the financial judgments of investors and make the risks of the project more palatable, since much of the investment would be voluntary rather than by congressional or executive decision. The concentration of a newly established authority on a single-project would avoid the internal conflicts inherent in having it undertaken by an established agency.
- *Disadvantages.* — It is not clear at what point private financing would become available on a large scale, and hence how much must be spent out of general taxes. The larger the public part of the investment, the more likely are the public-interest problems outlined previously.

  Financing through bonds does not provide for the type of accountability available through congressional appropriation, or through public ownership via the stock market Specific arrangements for public oversight, given the monopoly position of such an entity, would have to be made. Ownership of patents and products generated by public investment would have to be clarified, given the possibility of competition between private firms and the authority in the latter stages of development and operation.

HIGHWAY TRUST FUND

Since 1956 the Federal Government has spent over $7.5 bill ion (in current dollars) to finance the Interstate Highway System and a number of other road and highway programs. The money for these investments has been channeled through the Highway Trust Fund, which receives revenue from taxes on gasoline and diesel fuels, on heavy trucks, and other sources. These funds are not spent by the Federal Government, but apportioned to the States to pay for their share of highway systems.

The rationale for Federal financing was that an improved road-system would aid the Nation's defenses, as well as improve commerce by decreasing transportation costs. The system was planned on a national scale, but takes advantage of existing State highway departments to implement the proposed network. No central construction or maintenance firm was needed [3]

The distinctive feature of the system is its use of specific taxes on a commodity directly related to the project. Through the tax on gaso-

[2] "'increasing the TVA Bond Celling, " hearings before Senate Environment and Public Works Committee, Feb 23, 1979

[3] 'Porter (' wheeler, *Highway A ssistance Programs A Historical Perspective,* Congressional Budget Of flee, February 1978

line and diesel fuel, transport users have contributed in proportion to their total transportation expenditure. An additional tax on heavy commercial trucks has ensured that large users, who were responsible for a high proportion of maintenance costs, would contribute appropriately. Unlike tolls or direct fees for highway usage, revenue could be collected before the roads themselves were completed. An analogous tax to finance a fund for SPS might be levied on current domestic and commercial electricity consumption (though from a strictly financial point of view the tax need not be directly related to energy consumption.)

- *Advantages.* —The use of a designated tax provides more assured and predictable funding than general revenue taxes that need to be reallocated on a yearly basis. By taxing electricity consumption the costs would be borne by the future beneficiaries of SPS. If desired, taxes on other forms of energy could also be imposed; all energy taxes would have the added benefit of encouraging conservation. As private investment was found, the tax could be reduced, or revenues could be spent elsewhere.

  The size of the tax, if levied on electricity alone, would not have to be large to generate significant revenue. A tax of 2 mills/kWh would produce over $4 billion per year (at current consumption rates) while raising consumer costs by less than 5 percent.[4]

- Disadvantages. — A tax on electricity may cause consumers to switch to other forms of energy, harmin, utilities Higher electricity costs will inflate prices of electricity-intensive products, such as alum inure.

  The organizational framework to manage the SPS will have the same difficulties as other Government agencies, especially in handling the transition to private ownership.

U.S. SYNTHETIC FUELS CORP.

The Synfuels Corp. was established in June 1980 with a specific mandate to produce the equivalent of 2 million barrels per day of crude oil by 1992. The corporation is instructed to do so by, in decreasing order of preference: 1) price guarantees, purchase agreements, or loan guarantees; 2) loans; 3) joint ventures. The corporation's goal is to facilitate private-sector synfuel production, and to produce synfuels itselt only as a last resort. Initial funding was set at $20 billion, with total funding of up to $88 billion envisioned. Funds are to be provided from the windfall-profits tax on domestically produced oil. [5]

A possible SPS corporation would resemble the Synfuels Corp. in being a high-cost energy production plan with a specific goal and timetable It would differ in that it would involve creating a single firm rather than funding numerous private enterprises.

- Advantages. — The Synfuels Corp. has the advantage of a discrete goal and timetable, with maximum flexibility as to achievement. The etmphasis on price and loan guarantees to encourage rather than replace conventional financing arrangements should reduce the cost, assureing projects are successful. Direct Government control will be avolded, unless no private ventures whatever are forthcoming.

- Disadvantages. – It is far too early to tell whether the Synfuels Corp. will accomplish Its goal, or will do so without exorbitant costs Critics fear that an indiscriminatory 'shotgun" approach may result in funding numerous uncompetitive ventures, in the hope of finding one that works; while the revenue taken from the oil companies in taxes may prevent the development of additional fuel sources. The promise of "easy" Government money and soft loans may discourage efficient financial and managerial practices.

  While the Synfuels Corp. can pick and choose from a number of relatively well-developed and predictable projects, the SPS Corp would have to generate its own organization. The SPS Corp. could not, especially at first, simply be a channel for funding to private firms, or for loan guarantees.

'Peter Vajk, *SPS Financial Management Scenarios*, DOE contract No EG77-C-01 -4024, October 1978, p36

~ *nergy Security A et*, Publ ic Law 96-924, 96th Cong., June 30, 19H() ptB

COMSAT

Comsat was founded in 1962 as a federally chartered corporation to establish and run satellite communications (see ch. 7). Comsat did not receive direct Federal funding, but was given the fruits of extensive and continuing NASA research on telecommunications satellites,[6] as well as the right to use NASA launch services on a reimbursable basis (which does not reflect R&D costs). The Government retained a measure of control through Comsat's operating charter and by appointing board members, who were initially divided between Government, communications common carriers, and private investors. Capital was raised by issuing stock, which from the outset was well-received by investors. As of 1979, Comsat stock was held overwhelmingly by noncommon carriers; 3 of 15 Board members were Presidential appointees, the rest being elected by stockholders.

- *Advantages.* — A Comsat-styled SPS corporation would be independent of direct Government control and free to operate as a private, profitmaking corporation. Government supervision would be provided without the need for onerous restrictions. Comsat has been highly successful internationally via its participation in Intelsat, and a "Solarsat" corporation might find it easier to engage in international activities than would a Government agency. Such an organization could inherit the results of Government-financed R&D and engineering with less of a political outcry than if control were to be turned over to established private firms such as aerospace or oil companies; Comsat was established in large part to prevent AT&T from gaining a satellite communications monopoly.
- *Disadvantages.* — Issuing common stock would not suffice to raise capital for the early development stages. The transition from Government to private funding would have many of the difficulties already mentioned.

PRIVATE JOINT-VENTURES

A private SPS project could be undertaken either by an established firm, a new company, or a joint-venture of existing companies and financial institutions. For the reasons mentioned (high cost, uncertainty, long period before payback, and too many eggs in one basket) no single firm, whether new or established, is likely to undertake SPS development unaided

A joint-venture or consortium is formed when a single project or enterprise is of interest to several parties, no one of which is willing to finance or manage it on its own, as with the Alaskan pipeline. Or, companies may be legally prevented from exercising sole ownership for antitrust reasons, while a single system may be technically desirable. For instance, the Federal Communications Commission (FCC) required Comsat and IBM to add a third partner (Aetna Insurance) when forming Satellite Business Systems (SBS). In any consortium, partners are likely to have a particular interest in the consortium's success above and beyond immediate profitability. In SBS's case, IBM Corp. and Aetna intend to be major customers of the system, and IBM Corp. will supply operating equipment. [7]

- *Advantages.* — Potential major partners in an SPS consortium would be: aerospace companies, oil/energy firms (including possible emergent industries in photovoltaics, synfuels, or other energy sources); and electric utilities. A consortium that could draw on the resources of firms in these major industries would find it easier to borrow money, sell stocks and bonds, and use profits for SPS investment. According to most estimates, the utility industry alone will be spending hundreds of billions of dollars over the next 30 years to replace old generators and build new capacity; an SPS project would not constitute an unmanageable proportion of total industry investment,

[6] NASA communications research was phased out under the Nixon administration, which looked to Comsat and the private sector to maintain U S preeminence in communication satellite technology However, in 1978 the Carter administration reinstated NASA's leading role in communications R&D, largely to offset foreign government R&D efforts

[7] Court Upholds SPS," *Aviation Week and Space Technology*, March 1980, p 22

• *Disadvantages.* – However, there would still be difficulties in funding the initial phases. While aerospace and electronics firms would begin to benefit relatively early in the project, oil/energy companies and utilities (that have the bulk of the resources) will see returns only towards the end. utilities in particular, as part of a publically regulated industry, will find it difficult to set rates so as to raise funds for R&D or speculative purposes, as opposed to purchase of more established technologies. For instance, the $2 billion Great Plains coal gasification project was to be financed by a surcharge on gas rates charged by consortium members. Although DOE approved the rate hikes, customers — such as General Motors—and State officials protested against being asked to subsidize synfuels investments.[8] The Federal district court then disallowed DOE's action, effectively blocking the project.

  Consortia are more likely to arise in the investment and operation phases, when individual members' interests are more clearly defined, and risks have been reduced. The very high costs and large size of a full-scale SPS system, as well as the monopoly dangers of a system under the control of single company, may make inter- or intra-industry consortia attractive.

Hypothetical Models

In discussing possible SPS financing scenarios, some writers have proposed completely novel methods with no historical precedent. Foremost among them are the Taxpayer Stock Corp., a new form of Government financing; and a private approach, the staging company.[9]

TAXPAYER STOCK CORP.

Under this method, taxpayers would receive shares in a public corporation, financed by general tax revenues, in proportion to the percent of taxes used to finance SPS. Shareholders could then trade their shares on the market, as with any other corporation. Those who did not wish to support SPS could sell their stock for immediate returns.

Although such a scenario has the advantage of diffusing SPS ownership, it is difficult to see how SPS shares would retain their full value on the market; if they did, funding via taxes would not have been necessary in the first place. Shareholders would instead be left with devalued pieces of paper, unless they are purchased by the Government—with tax dollars — to maintain a reasonable price. This would amount to a straightforward Government subsidy.

STAGING COMPANY

The staging company is essentially a bootstrap operation whereby sufficient revenues are generated during the R&D phase to attract further capital. The firm would invest its initial funds in existing aerospace and high technology companies, gaining patent rights and new technology—via joint ventures—as well as conventional investment returns. The success of the company's first investments, and its increasing expertise, would attract further speculative investors; the staging company is in effect a mutual fund. Eventually, the company would begin to finance SPS R&D directly, concentrating on those aspects with near-term returns. At some point conventional financing would become available for the investment and operation phases.

Such an approach is unlikely, unless its first investments turn out to be in budding Xeroxes or IBMs, to raise the $33 billion estimated to be necessary for the reference design R&D and prototype phases. In 1978 Christian Basler established International Satellite Industries, Inc., to test his concept; it failed when neither New York nor California would allow ISI stock to be sold. [10]

Conclusions

It is clear from the review of possible models that there are many ways to finance the latter stages of a successful SPS program, but that

[8] Robert D Hershey, "Gasification Plant Rising Amid Many Snags," New *York Times, Nov 17, 1980,* p 1

[9] For further discussion see Vajk, op cit, pp 32-40

[10] Conversation with Stephen Cheston, President, Institute for the Social Science Study of Space, December 1980

the initial phases would in all likelihood have to depend on some sort of Federal funding. Some combination of the suggested methods may prove attractive.

In establishing an SPS organization, attention should be paid to several factors. First, there should be provisions for stopping the project if it becomes unfeasible. Large initial investments will create considerable momentum, which may cause wasteful development to continue unless authority is given to terminate. This is especially true for Government enterprises.

[11]Gersovitz, p 36

Second, at all phases careful attention must be given to public policy concerns: environmental protection, regional interests, and military involvement. Private companies must not think SPS can be developed in secrecy or without reference to a wide public environment (see ch 8, Issues Arising in the Public Arena).

Third, early and continuous efforts should be made to involve and inform potential international partners to attract investment aid, forestall competition, and ensure that the global market for SPS is kept in mind when technical and managerial decisions are made. A narrow focus on domestic concerns, by Government or industry, may jeopardize SPS unnecessarily. (see ch. 7, International Implications).

THE IMPLICATIONS FOR THE UTILITY INDUSTRY

Introduction

The interest of the utilities in the SPS would depend on technology related factors such as stability and reliability, as well as those more directly related to the economics of electricity generation and distribution (i. e., siting, capital investment and Government regulation). Each of these factors would require more study as more is learned about the various SPS alternatives. From what is now known, it appears that the technical barriers to integrating SPS into the utility grid are solveable, particularly if the units of SPS generated power are of the order of 1,000 MW or less. It is also apparent that for the utilities to develop sufficient confidence in SPS, one or more units would have to be tested over time.

More troublesome are the economic risks of SPS. When considering adding a new plant, utilities must plan far ahead of actual system integration for the associated transmission lines and other generating capacity (i.e., intermediate or peaking plants to supplement the baseload powerplants). Failure of the SPS to meet expected implementation deadlines would result in severe economic loss for the utility. The need for extensive trials and testing of a new plant render it highly unlikely that the SPS could become part of utility grids until several years after a commercial prototype were built. Although SPS could force some regulatory changes, there seem to be no strong regulatory barriers to implementing SPS.

Table 50 summarizes the projected characteristics of the SPS that would be of interest to the electrical utilities.

The Utilities' Planning Process

The Current Situation

Because of the recent rapid rise of all energy costs and subsequent efforts to conserve, the utilities find themselves in an uncertain position for the future. In the past, the utilities experienced fairly steady, high peakload growth rates, resulting in a correspondingly high rate of growth (7 percent) of generating capacity, a rate that leads to a doubling of capacity every 10 years. Recently, however, average peakload growth has fallen sharply. Lower economic growth rates and price-induced conservation efforts have had a strong effect on consumption I n response, the average growth of installed generating capacity has also fallen. The

Table 50.—Characteristics of the SPS Systems

System characteristics	The reference system"	Solid-state sandwich design"	Laser system"	Mirror system (baseline SOLARES)[15]
Delivered power from each satellite (at the busbar)	**5,000 MW**	*1,500* MW	**500 MW**	**135 GW (10 GW possible)**
Total system of.	**300 GW**	Not projected	**Not projected**	**810 GW over 6**
Implementation rate	**2 per year for 30 years**	—	—	**7**
Start of deployment.	**A.D. 2000**	2010-2020 (estimate)	2010-2020 (estimate)	2010-2020 (estimate)
Lifetime of each satellite	**30 years**	30 years	30 years	?
Transmission frequency ... ,	**2.45 gigahertz (i.e , microwave)**	2.45 gigahertz	10 microns (infrared)	Reflected sunlight — I.e., continuous spectrum
Designed capacity factor .,	**90 percent**	**90 percent**	70-80 percent	?
Rectenna size.	**10 km x 13 km at 35° lat. plus 1 km buffer**	**6.5 x 5.5kw at 35° lat. plus 1 km buffer**	36 meter diameter	39-km diameter
Terrestrial conversion mode.	**Microwave dipole** antenna-rectifier and inverters	Microwave dipole antenna-rectifier and inverters	Thermal conversion	Thermal, photovoltaic conversion
Major potential causes of interruption.	Maintenance, satellite eclipses (max. 21/2 hr near equinoxes)	Maintenance, ecilpses Of Satellite? (max 2 ½ hr near equinoxes)	During any thick cloud cover, maintenance	During any thick cloud maintenance

[12]"'Sa,ellite Power System Concept Development and Evaluation Program Reference System Report DOE report No DOE/E R-0023, October, 1978

[13]G. M. Hanley, et al , "Satellite Power Systems (SPS) Concept Definition Study, " First Performance Review, Rockwell International Report No SSD79-0163, NASA MSFC contract No NAS8-32475, Oct. 10, 1979

[14]W. S. Jones, L L Morgan, J. B. Forsyth, and J P Skratt, "Laser Power Conversion System Analysis: Final Report, Vol. I I," (Lockheed Missiles and Space Co , report No LMSC-D673466, NASA report No CR-159523, contract No NASA ;-211 37, Mar 15, 1979

K W Bill man, W P G I I breath, and S W Bowen, "Orbiting Mirror\ for Terrestrial Energy Supply, " in 'Radiation Energy Conversion in Space, *Progress in A stronautics & Aeronautics Series*, K w Billman (ed), VOl 61 (New York Al AA, July 1978), pp 61 80

SOURCE: Off Ice of Technology Assessment

U.S. total of installed electrical generating capacity in 1978 and 1979 rose by an average rate of 3.1 and 3.2 percent respectively, rates that cause a doublin, of capacity every 22 years. Growth rates in some sections of the country have been zero or negative in the same time span.

As the high growth rate of electricity demand and subsequent expansion of the utility industry has subsided, the industry has had to rethink its posture with respect to adding new capacity, I n addition to the uncertainties of future demand, increasing costs for fuel, more stringent environmental standards, public opposition to nuclear powerplants and technological changes are also affecting the planning process. What is perhaps of most concern, however, is the increasing difficulty private utilities face in raising the large amounts of capital needed for building new capacity or replacing old, inefficient plants

In response, the utilities are placing more emphasis on understanding the interaction between reserve margins, types of capacity, and reliability requirements. They are also sharply reducing the amount of new capacity, delaying Installation of some plants, canceling others, Although on average the difference between total capacity and average annual load is greater than ever before, some industry executives have expressed concern that these planned reductions in generating capacity wi ll leave the United States seriously deficient if the current trend towards lower growth of peak demand reverses itself. others, generally outside the industry, have suggested that increased conservation measures can bring the need for new generating capacity to zero or less, leaving the industry, on the average, in the posit ion of simply replacing or refurbishing outmoded plants

Planning Process

U S generating capacity in 1980 was about 600 gigawatts. * The peak load that this capaci-

*A gigawatt (GW) of power is equal to 1,000 megawatts

ty is expected to serve is about 410 GW. To meet this load, the generating capability is composed of about 10 to 15 percent of peaking units, 20 to 25 percent of intermediate and 60 to 65 percent of baseload generating units. A planning reserve margin of 20 to 25 percent above peak demand is required to allow the utility to continue to serve the customer when any of the operating units fails and when unusual load peaks occur.

For a given utility system, the reserve is related directly to the expected reliability of the total system. Although the exact amount of reserve needed is currently debated within the industry, [16] the rule of thumb that most utility systems use to calculate their necessary reserve is that they must have no more than one generating outage or failure to meet expected demand in 10 years, a failure that may be as short as a minute or as long as several hours. I n practice, this criterion results in some days of line voltage reductions and a few days of appeals to customers for conservation, but a very low probability of outage in any one year.

A utility is not simply a set of generating plants, transmission lines, and transformers. It is a complicated interactive network in which individual components affect each other through an intricate set of feedback loops. A failure in one part of the system may set off a failure in another part. Adequate reliability is ensured by building enough redundancy into the system to meet most contingencies, whether from system failure or from unexpected surges in demand.

The amount of redundancy required for a given system depends heavily on the reliability of the equipment in the system and the utilities' experience with them. To calculate the necessary reserve, the utilities generally use several methods, the simplest of which, called the contingency outage reserve criteria, will serve to illustrate the most important features of reserve planning.

After projecting the peak load requirements of the system, utility planners add an amount of generating capacity equal to that which might be unavailable because of scheduled maintenance. System reliability will then be achieved if sufficient excess capacity over and above this amount is available to cover one or more of the sorts of contingencies I isted in table 51.17 This method tends to treat the system in gross terms and does not generally allow for important details of a given system such as the variations of peak load throughout the year or the percentage of time it will be capable of generating given levels of power at different seasons. For this, a more sophist i- (ated analysis would be needed.

Planning for New Technologies

The SPS is one among many new technologies that the utilities are considering in planning for the future. These include *regional* technologies such as ocean thermal energy conversion and geothermal; *intermediate or peaking* technologies such as wind, solar thermal and solar photovoltaic without storage; and *baseload* possibilities such as advanced coal, breeder reactors and fusion. I n addition, some utilities are considering grid connected dispersed technologies such as solar thermal, solar photovoltaics, wind, and fuel cells. Planning for such a mixed bag of technologies is a complicated and time-consuming process. As figure 44 illustrates, the time from the initial conception of a new technology to actual integration into the utilities' grid can be extremely long– up to 40 years or more. Not only must utility suppliers develop the components of the individual technology, they must make it technological ly and economical ly attractive to

[16] A Kaufman, L T Crane, J r , B M Daly, R J Profozich, and S J Bodily, "Are the Electric Utilities Gold Plated?" committee print, 96-1 FC 12 Committee on Interstate and Foreign Commerce, United States House of Representatives, 1979

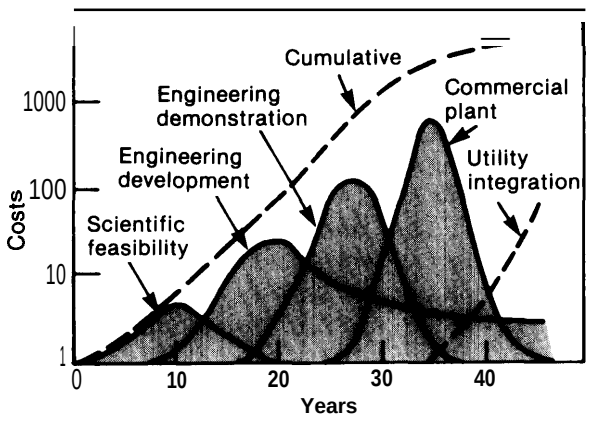
' Ibid

Table 51 .—Major Grid Contingencies

1. Loss of the largest generating unit in the system
2. Loss of the two largest generating units in the system
3. A failure in the largest transmission facility in the system
4. A combination of the above
5. An error of a specific magnitude in load projection

SOURCE A Kaufman, L T Crane, Jr., B. M. Daly, R J. Profozich, and S. J. Bodily, "Are the Electric Utilities Gold Plated?" committee print, 96-IFC 12. Committee on Interstate and Foreign Commerce, United States House of Representatives, 1979.

Figure 44.—Phases of R&D



SOURCE: R L Rudman and C. Starr, 1978 "R&D Planning for the Electric Utility Industry," in *Energy Technology v* Government Institutes, Inc, Washington

the utilities and, in addition, develop a large supportive infrastructure. Thus, the vast bulk of the time spent in the long chain of technology development is in the phases following scientific feasibility— newly conceived technologies are not likely to fill near-term supply deficiencies.

Assuming that an engineering demonstration of a new technology is successfu 1, its ultimate fate would depend on several factors whose influence can only be seen dimly at the time when scientific feasibility is proved. Comparative costs are a prime consideration, but public acceptance, the complexities of the technology, and the ease with which it can be integrated into the existing utility infrastructure are also important (see ch. 6). The utilities use some or all of the following criteria to judge a new technology: [18]

ECONOMIC CRITERIA

- Cost *to the User.* — Bus bar costs are important but an expensive long-distance transmission and distribution system may price a technology that is otherwise competitive at the busbar out of the market. This problem could apply to any very large, highly central ized faci l ity.
- *Reliability.* – Plants that are highly capital intensive must operate at high capacity factors in order to minimize electricity costs. Thus, numerous forced or unplanned shutdowns for a given plant would make its technology less desirable. In general, a new technology can be expected to sustain a higher rate of forced or unplanned shutdown than a more mature one. Current mature nuclear plants and coal plants with scrubbers sustain forced outage rates as low as 15 and 19 percent of their total availability respectively. As the industry gains even more experience, it wil l probably be able to reduce this rate even more.
- *Ease of Maintenance.* — It is extremely important to be able to maintain and repair components of the generating system quickly and easily. Nuclear and fossil fuel plants currently experience planned outage rates of 15 and 10 percent, but utility experts believe that these rates can be reduced by several percent. Here again, mature technologies fare better than newer ones. However, the percentage of maintenance doesn't tell the whole story. The timing of the maintenance is also important. If it is possible to plan maintenance during periods when electricity peak loads are lower, the adverse effect on the utility is thereby reduced.

RESOURCE AVAILABILITY

Here, fossil or other depletable energy sources wil l suffer in competition with renewable sources such as wind-, solar-, fusion-, or breeder-generated fissile material. Further, because the Sun or wind are more available in some regions of the country than in others, terrestrial renewable technologies wil l vary in their attractiveness.

SYSTEM CAPABILITY AND FLEXIBILITY

- *Control and Operating Characteristics.* — The more stable a power system, the better. Short-term transient outages must occur under conditions that allow the utility grid to accommodate them as a matter of course.

[18] R L Rudman and C Starr, "R&D Planning for the Electric Utility Industry," in *Energy Technology V* (Washington, D C Government Institutes, Inc, 1978)

[19] Ibid

- *Ability to Tolerate Abnormal Events.* –A system that is otherwise acceptable to the utilities may fail to be adopted because it is easily disturbed, i.e., small perturbations in operating mode lead to wide swings of electrical output.
- *Unit Rating.* –Although economies of scale are very real in generating equipment, smaller capacity units may often be desirable, because they are easier to repair and replace than the large ones.
- *Environment/ Issues.* — Environmental impacts produce an economic cost that, while often impossible to specify, have a strong effect on the acceptability of a given technology. In addition, some technologies may have environmental side effects that are unacceptable no matter what price the utility is willing to pay (e. g., the potential effects of the addition of large amounts of carbon dioxide to the atmosphere).

LICENSING

"Licensing . . . is currently the largest single issue facing all new technologies. "[2]° The issues that will affect the licensing procedure such as siting, health and safety, and environmental concerns must be identified and reckoned with early in the development of the technology. They also have a direct effect on the cost of a technology.

Once a generating technology has proven its commercial feasibility, it generally takes another 20 years or so for it to be used significantly. The complexity of the technology, institutional barriers, market growth (housing, industry, etc.) market initiative (dispersed v. central use), and system size will all have their effects on the rate at which a given technology will penetrate the total utility market.

Engineering Implications of the SPS for the Utilities Grid

The SPS would make numerous special demands on the utility grids. Some are related to the fact that the primary generator or collector would be based in space. Others are characteristic of all large-scale baseload technologies. In this section, we will proceed through each technology, citing the most important effects each alternative will have on the utilities.

The Reference System

- **5,000-MW Capacity.** – Because of the grid reliability requirements, the large size of the reference system plant would limit the number of individual utilities or utilities' systems that could accommodate it. As a rule of thumb, a utility generally will not purchase a single unit that would constitute more than 10 to 15 percent of the utility's total generating capacity. " In other words, a single plant must be no more than one-half of the system's total reserve capacity of 20 to 25 percent.

  If a utility could accommodate a first SPS of 5,000 MW, it could accept another provided it met a less stringent application of the penetration rule. In other words, the system would benefit somewhat by redundancy of generating units *provided* there was a low probability of both failing at once.

  As an example, for a utility to accept a 50,000-MW satellite, it must have a system capacity of 5,000/0.13 = 38,000 MW. This exceeds the capacity of any single current utility. Assuming current average rates of growth of 3.2 percent for the industry, it would exceed the capacity of all utilities save TVA in the year 2000. It might, of course, be possible for a group of several utilities with the appropriate total capacity and adequate grid interconnections to take on 5,000 MW of power. According to the rule for reserve capacity, for the group to then assume another 5,000 MW, its total capacity would have to be large enough for the two satellites together to constitute 20 percent or less of a system capacity of 50,000 MW. The exact percentage any given consortium of utilities would be willing to

[2] "I bid

[2] P J Donalek and J L Whysong, "Utility Interface Requirements for a Solar Power System, " Harza Engineering Co, DOE contract No 31-109-38-4142, report No DO E/E R-0032, September 1978

accept would depend on its view of the probability of two SPS units and another unit or transmission line failing at the same time (see table 52).

As an additional consideration, it should also be noted that supplying 5 GW of reserve power from elsewhere in the system would put a great strain on the dispatching capability of the utility.

- *Lack of Inertia in SPS Power Generation.* — The frequency stability of a utility system is directly related to the rotating mass or mechanical inertia of its collection of generators. It is, in effect, analogous to a giant flywheel kept in motion by numerous small driving elements on its rim. Just as a flywheel adjusts only slowly to a sudden removal or addition of individual driving elements, the utility network takes several seconds to adjust to the loss or gain of megawatts of power. A generator added to the system adds additional mechanical inertia as well as power. Because the SPS reference design would add power but no additional inertia, i.e., it might come on or go off line virtually instantaneously, it would create surges that would be difficult for the system to accommodate. In order to use SPS-generated power, the utilities would have to develop new modes of ensuring frequency stability and control since the present operating mode depends implicitly on the mechanical inertia of the system. One possibility is to add short-term (15 minutes to 1 hour) battery storage capacity to the rectenna. Such an adjustment would add a small amount to the cost of SPS power.

- *Variations in SPS.* – Rectenna power output would vary seasonally because of the eccentricity of the Earth's orbit. As currently designed, the SPS would deliver 5,000 MW when the Earth is at maximum distance from the Sun. At its closest approach during the northern winter, each rectenna will deliver about 10 percent more power, or 5,500 MW. However, because the variation has a yearlong period, it would be relatively easy to adjust for it continually.

Short-term variations would be much more serious. Around the equinoxes, the satellite would lie in the Earth's shadow for a short period each night around midnight. These "eclipses" of the satellite would vary trom a few seconds duration at the start of the 31-day eclipse period to a full 72 minutes at the equinox and then decrease again to zero. Because the antenna array would require a warmup period of 15 to 60 minutes, outages at the rectenna would vary from 30 to 140 minutes. Because the eclipses would be highly predictable and would occur at midnight in late March and September when loads are often low (typically 40 to 60 percent of the peak for summer peaking systems), they would be unlikely to constitute a problem for the system's reserve capacity. * However, following the load swing during the shortest eclipses *would* place a strain on the ability of the utility to respond because of the need to replace 5,000 MW very rapidly unless storage were in place.

Without short-term storage, the rate at which SPS power would decrease during an eclipse would undoubtedly pose control problems for the grid. As the satellite entered the Earth's shadow, it would lose power at the rate of 20 percent per minute, too fast for the grid to respond. In general, the maximum power fluctuation a grid can accommodate is about 5 percent per minute. However, it would be possible to shut down the satellite at an acceptable rate somewhat ahead of the eclipse.

The satellites and rectennas would require replacement or maintenance of numerous components (klystron amplifiers, solid-state amplifiers, laser components, photocells, dipole antennas, etc.) several times a year. Normally the outages associated with routine maintenance could be scheduled during periods of low electricity demand and are estimated[22] to constitute a loss of

* The demands on different utility systems vary regionally Thus, the truth of this statement must be examined on a region-by-region basis

[22] I Grey "Satellite Power System Technical Options and Economics," OTA working paper, Solar Power Satellite Assessment, 197'4

120 hr/yr of SPS power. Assuming maintenance could be scheduled during eclipse periods, the total time the satellite would be unavailable due to maintenance could be considerably less than this.

Boeing[23] has summarized the various losses of power to which the referenced SPS might be subject (table 52). Conspicuously missing, however, is the possibility of satellite equipment failure. It will be of considerable interest to everyone concerned to identify as many potential sources of *unplanned* SPS shutdown as possible.

Other possible variations in the amount of transmitted power have to do with the mechanism for controlling the position of the beam on the rectenna, which would be accomplished by a pilot beam directed from the rectenna to the satellite in space. Because of the finite time of travel in space for an electromagnetic signal, the time between sensing a position error at the rectenna and correction of it at the rectenna would be about 0.2 see, causing an oscillation in power output at a frequency of 5 Hz. Again, the 5,000 MW nominal output would strain the capabilities of the utility grid to follow the resultant load variations if short-term storage capacity were not made a part of the SPS system.

- *Power Reception, Transmission, and Distribution.* –At the rectenna, the power collec-

[23] "SPS/Utility Grid Operations," sec 14 of DI 80-25461-3, Boeing Corp

Table 52.—Potential for Power Variations From the Reference System SPS

Source of power variation	Range percent	Frequency of occurrence per year	Average duration of outage per occurrence min/yr	Total outage hr/yr	Maximum power reduction GW	Average yearly energy loss GW hr	Time to maximum power loss	Scheduled Yes	Scheduled No
Spacecraft maintenance	0-100	2	2 x 3,600	120	5	600	6 min	X	
Eclipse	0-100	62	3,376 total 71 maximum per/occurrence	56.26	5	281.3	1 min	X	
Eclipse with shutdown and startup			5,270	87.8		439	1 min	X	
Wind storm	75-100	0.01	5,260	87.6	1.25	109.5	5 min		X
Earthquake	90-100	0.01	1,800	30	0.5	15	10 sec		X
Fire in rectenna system	80-100	0.01	840	14	1	14	30 min		X
Meteorite hit of spacecraft equipment	90-100	0.01	1,200	20	0.5	10	100 ms		X
Rectenna equipment failure	91.5-100	1	50	0.833	0.425	0.35	100 ms		X
Precipitation	93.3-100	50	1	0.833	0.335	0.28	1 m		X
Pointing error	94.8-100	5,000	0.6	0.833	0.29	0.24	1s		
Ionosphere	98.5-100	20	10	3.32	0.15	0.24	I s	X	
Ground control equipment failure	95-100	5	3	0.25	0.25	0.06	0.3 s		X
Aircraft shadow	99.99-100	20	20 m 1 m maxi occurrence	0.3	0.0005	0.0015	1s		X
Total without shutdown/startup: 331 hour (3. 77%)			1,030.8(2.350/~)						
Total without shutdown/startup: 362 hour (4.1 20/.)			1,188.5(2.71 %)						

SOURCE: "SPS/Utility Grid Operations", sec 14, D180-25461-3, Boeing Corp.

tion system would be divided up into units of 320 MW or less. The loss of any one or even a combination of several power blocks would present few problems for the grid because they would be relatively small compared to 5,000 MW. Transmission would be over four to five 500 KV lines or eight 345 KV lines. The loss of one of the transmission lines should not affect the stability of the system or the operation of the SPS. In the event of decreased load requirements, some excess power could be absorbed by the rectenna as heat. *Sharp* drops in power demand (e. g., an open circuit due, say, to a loss of several transmission lines) might cause overheating of the rectenna diodes if the system were unable to dissipate the excess power quickly enough. Hence, protective measures would be required.

Maintenance of the dipole antennas and rectifiers in the rectenna might present a major expense for the utility. Although the mean time to failure is projected to be 30 years,[24] this would mean that on the average, 7 to 8 diodes (in the rectifier circuit) could be expected to fail every second, [25] leading to an overall failure rate of 3 percent per year. Increased quality control of the manufactured components might mitigate some of the replacement needs by decreasing the failure rate. This procedure, though more expensive per unit, might be less expensive than replacing failed components.

Operating Capacity Factor. – In order to maximize capital investment, the SPS, if developed, should be operated as close to its "nameplate rating" as possible, i.e., 5,ooO MW. However, during periods of very light load (e.g., at night during the spring and fall) even current baseload nuclear and coal units must sometimes be run at less than fu ll capacity in order to follow the load swing. Such factors would make the real operating capacity of the reference SPS less than its maximum capacity, thereby causing it to be more expensive.

- *Rectenna Siting.* — The land requirements for the SPS reference system are "large (see ch. 8). At 350 latitude the rectenna plus its exclusion area would cover an elliptical area some 174 km^2 in extent. By comparison, the city of Chicago is 57o km^2, and Washington, D. C., 156 km^2. Finding available land far enough from population centers and military installations (to make potential electromagnetic interference slight) and near enough to the load centers to make transmission costs acceptable would not be a trivial exercise. Rectenna siting would involve the various regulatory agencies and wou ld have to be addressed by uti l ities very early in the overal l planning process.

  Utilities in far northern latitudes would generally find siting more difficult because the necessary rectenna area and rectenna exclusion area increases with increasing latitude. Some of the most acceptable locations are in the Southern and Southwestern United States where terrestrial photovoltaics and solar thermal devices will also be most economic to operate. Offshore siting wou ld also be possible, though this option wou ld require extensive study.

The Solid-State Variation

The sol id-state sandwich appears to be more economical to build and place in orbit in smaller units (about 1.5 GW),[26] mitigating-automatical [y problems arising from the control of 5 GW of power from the reference system ı n addition, a smaller rectenna would make it possible to place the rectenna closer to load centers or in offshore locations.

Because it is a microwave system, it would share the same stability problems that the reference system wou ld experience.

Laser System

The laser system would present a different set of challenges and opportunities for the

[24] R Andryczyk, P Foldes, J Chestek, and B Kaupang "Solar Power Satellite Ground Stations, " *IEEE Spectrum,* July 1979, "Satellite Power Systems Utility Impact Study," EPRI AP-I 548 TPS 79-752, September 1980 J GBohn, J W Patmore, H W Faininger

[25] A D Kotin, "Satellite Power System (SPS) State and Local Regulations as Applied to Satellite Power System Microwave Receiving Antenna Facilities," DO E-H CP/R-4024-05, 1978

[26] H a l ey, op c it

utilities. Because it can generate electricity by employing infrared radiation to heat a boiler, it could perhaps be used to repower existing coal, oil, or nuclear facilities. A ground-based thermal collector would generate steam that could be used directly to drive a turbine. In addition, the scale of the proposed satellite/ground system (100 to 500 MW) would fit existing utility capacity quite wel 1. For cases where the laser were used for repowering an existing facility, no new transmission lines would be needed.

On the other hand, several intrinsic limitaions of the proposed laser system would make it difficult for the utilities to integrate it into their grid:

- *Weather Limitations.* — Although lasers of the overall power and power density of the proposed laser system could burn through light cloud cover, heavy clouds would make it unusable. Thus, it would be unsuitable in areas where clouds cover the region for more than a few percent of the year. It might be possible to use it in regions where there are more receiving stations than lasers to support them. Then, if station A were covered by clouds, for example, the laser feeding that station could be redirected to station B that was under no cloud cover. The resulting extra laser radiation at station B could then be used to generate more electrical power at that station to compensate for the loss of power at station A, assuming that B had the necessary extra capacity. This arrangement could work wel I for selected parts of the country, i.e., where the likelihood of cloud cover forming simultaneously over several stations was smal 1. However, since cloudy conditions tend to occur over large sections of the Nation at one time, the practicality of this notion would be limited.

Mirror System

A mirror system would be the most highly centralized technology of the four alternatives. Its proposers envision a few energy parks in which the increased daylight would be used to generate electrical energy — or perhaps, hydrogen. How it might be integrated into existing uti I ities is unclear. As an electrical system, it would require long transmission lines leading from the energy parks to the point of end use. However, hydrogen generated at the site could be transported by vehicles to other destinations.

This concept appears to require a national grid in order to make effective use of the large generating capacity of the site (from 10 to 135 GW). Stability would be much less of a problem for SOLARE S than for the microwave system because of the large number of satellites that would reflect sunlight, the inclusion of storage in the system, and because of the independent blocks of ground-based photovoltalcs or solar thermal plants at the site.

The SO LARES proposal would be subject to similar problems with clouds as the laser concept. However, the additional radiant energy *might* be great enough to dissipate clouds that would form in the region. For this reason, large mirrors have also been proposed for weather modi fic at ion.[27]

Regulatory Implications of SPS[28]

Although this area has received only a cursory investigation at this time, it is clear that the potential for new forms of financial support and management structures for the SPS might engender new regulatory modes. I n general, the SPS is I ikely to lead to greater centralization of the Nation's utility structure, leading in turn to a strong need for coordination between neighboring Public Utility Commissions or perhaps to completely new structures for regulating utilities.

Local v. Regional Control

Utilities have generally entered into a greater degree of cooperation with utilities in other States than have their associated regulatory agencies. This state of affairs will

[27] Vajk, op cit

[28] MGersovitz, "Report on Certain Economic Aspects of the SPS Energy Program, " OTA Working Paper, SPS Assessment, 1980

have to change with increasing use of high-capacity generating units and greater grid interconnections. A move toward regional planning and control will likely also come about because of the current disparity between States in siting and other regulations, making it more attractive for utilities to build in States where regulations are not as stringent or to purchase power from utilities that have a surplus of generating capacity.

In order to regulate their processes, new regional regulatory agencies are likely to be set up long before SPS could be part of the utility grid, leading to greater grid interties. The introduction of an SPS would undoubtedly hasten the process because the larger the grid, the more easily outages from a single rectenna or a laser receiver could be handled. The intermediate-scale sol id-state system would fit into this kind of structure easily, but a larger scale SPS such as the reference system or SOLARES would necessitate an even more widespread system than is now envisioned. Although the laser system might be used to repower inter mediate-s i zed generating facilities, the ever present possibility of massive cloud cover would require system interties in order to make the most efficient use of the available laser satellites.

Site Decisions*

Siting would be a major issue for each one of the alternative technologies and would also require the development of regional cooperation. A major question in SPS siting decisions is who would have the control; local, State, regional, or national entities? Currently, State or local regulatory boards make the ultimate decisions concerning plant siting. The Nuclear Regulatory Commission and the Environmental Protection Agency review these decisions. Except for Federal or State land, the planning for a 174 km' rectenna would likely involve several local jurisdictions, one more of whose land use regulations may not be compatible with an SPSrectenna. However, if the need for SPS power were great, there might be adequate reason to supercede local regulations in siting a rectenna. A single 5,000-MW rectenna could serve a large population, one which is very likely to be distributed across State I ines. Coordination of regulatory authority could come from voluntary interstate agreements or from federally mandated regional planning.

The current debate about energy parks would be instructive in identifying and resolving some of these issues. Along with this, the trends toward regional izing economic control on energy facilities and instituting a national power grid could provide the institutional framework for addressing siting issues for a rectenna or SOLARE S energy park.

Rate Structure

The magnitude of the capital investment that SPS and other future technologies would require wou ld certainly cause some alteration of the utility rate structure. Just what form these alterations might take is currently unclear because they depend heavily on the form that the SPS companies would take and how they might be f inanced.

For example, if the utilities were to own individual SPS plants, they would wish to include their capital costs during construction (current work in progress) in the current rate base. Most States are presently unwilling to allow this. However, the extraordinarily high capital costs of other sorts of new generating capacity may make this scheme a necessity. On the other hand, if SPS power were to be bought directly from an SPS corporation and sold to the customer, the concern about adding capital costs during construction to the rate structure would be eliminated for the utility regulatory agency and shifted to another sector of the economy (though they would still be reflected in busbar costs).

SPS Corporations and the Utilities.

Currently, the utilities purchase equipment and knowhow from competing corporations who build and service generating equipment. Because of the scale of investment necessary to supply the supportive infrastructure for building an SPS, the SPS corporation might well evolve as a monopoly, requ i ring

*See also chs 8 and 9, pt C

monopoly-type regulation on the Federal level. Whether generating plants or power are sold, it is likely that the Federal Government would be heavily involved in the regulation of SPS rates and in siting, reliability, and other aspects of integrating the SPS into the utilities' structure. Such a state of affairs would be likely to lead to a greater degree of centralization of the electrical industry whether a national power grid were instituted or not.

General Implications for the SPS

Centralization v. Decentralization

Two opposing forces currently affect the utilities industries—a move towards greater centralization and an opposite trend towards greater decentralization. On the one hand, economies of scale, shared facilities, and the benefits of regional planning make greater centralization attractive. On the other, the desire of individuals, communities, and many companies for a greater degree of energy self-reliance for economic or social reasons suggests that the utilities will have to adjust to an increased demand for grid-integrated dispersed systems.[29] The utilities are just beginning to address these issues squarely. Market pressures may make dispersed units increasingly more attractive (see ch. 5, *Energy in Context)* at the same time that the Federal Government supports the development of new central technologies. The main issue for the utilities to address is how to accommodate both ends of the scale in their planning.

Market Penetration

From the point of view of the utilities that would either purchase SPS generated power for distribution in a grid or purchase receiver installations to incorporate directly into their own systems, the ultimate total volume of SPS generated power would depend on a number of factors in addition to cost. Even if the busbar cost of SPS electricity was highly competitive with other future options, SPS market penetration could be limited by reliability requirements and by the technical difficulties of grid-dispatch that we have already discussed.

- *Reserve Requirements.* –The criterion that any two units (e. g., transmission l ine, generating plant, etc.) in a utility system must constitute less than 20 percent of the total system capacity leads to a minimum size for any single utility system for a given SPS capacity (see *Planning* Process). Thus, two 5,000-MW plants could be accommodated by a utility system with total capacity of 33,000 to 50,000 MW or greater. Smaller utilities' systems could accommodate appropriately smaller SPS plants. But in making decisions about whether to proceed with SPS or not, it is important to estimate how much total SPS capacity the U.S. utilities grid overall could accommodate. The projected total capacity of the reference system is 300 GW. Could the utilities grid in 2030 or 2040 accommodate that capacity?

  Simply scaling up from the individual utility or utility grid, using the 20 percent criterion, 300 GW total SPS capacity implies 1,500 GW total electrical capacity in 2030 or 2040, about 2'A times current capacity.

  It is clear that under these stringent conditions, a low electricity demand would preclude development of SPS from the utilities point of view. The 20-percent requirement is certainly overly stringent, since in effect, it implicitly assumes that the entire SPS fleet would fail at one time (i. e., no reserve power would be available from other utilities). On the other hand, satellites that would be subject to eclipse (i. e., all those in geostationary orbits) would be eclipsed in groups, not singly. For a few days around the equinoxes, approximately 18 satellites would be eclipsed at once. * Roughly speaking this means that a band of Earth some 1,250-miles wide in longitude would suffer SPS power outage at one time. Thus, there is a distinct limit to the amount of lost generating capacity that nearby utilities could supply during the eclipse period. Utilities and their regulatory commissions would only be I ikely to in-

[29] "D Morris and J Furber, "Decentralized Photovoltaics" OTA Working Paper, SPS Assessment, 1980

'A satellite placed at each degree of longitude corresponds to 15satellites per hour of time

crease their proportion of SPS beyond the 20 percent or so of reserve capacity if they were consistently able to draw power from beyond the "shadowed" region, or if the March/September night peaks are low enough to offset this difficulty. In other words, the larger the grid served by SPS the smaller the reserve capacity that would be required in any one region.

For the country as a whole then, a 20-percent penetration for the reference SPS or any geostationary SPS must be seen as an average limit. Utilities with appropriate backup could accept more. Others, because of their size, location, or special needs would only accept less than 20 percent.

A 20-percent penetration of SPS would constitute 120 GW in the low scenario and about 490 GW in the high one. At a 90-percent capacity factor, the contribution of electrical energy from SPS would be 3.2 Quads in the low scenario and 13 Quads in the high scenario (44 percent of the total electrical energy consumed in both cases).

- *Vulnerability.* –Another aspect of SPS that the utilities would certainly investigate in comparison with other generating options is its vulnerability to hostile actions[30] (see ch. 7), and to unforeseen technical failure.

  Of perhaps far more concern to the utilities would be any vulnerability to technical failure (especially common mode failure) or to human error. As noted earlier, the utility grid would experience some difficulties in adjusting to planned outages from the reference SPS. Unplanned ones would be far more difficult to adjust for, though they are a common feature of utility operation. The potential for unplanned failure of any of the alternative SPS options would only be fully known if a decision is made to proceed with one option and a full-scale demonstration were built and tested extensively.

  Perhaps the most technically sensitive component of the satellite system is the beam-focusing apparatus. In the microwave design, a pilot beam sent from the rectenna to the satellite antenna would control the phasing of the beam transmitters. With the loss of the pilot beam, the SPS power beam would quickly defocus, a safety feature that would prevent accidental or intentional wandering of the beam. The laser beam would be controlled in a similar manner. It would be important to design this apparatus to be insensitive to minor perturbations in operating mode, yet sensitive enough to maintain its safety qualities. Orientation of the reflecting mirrors of the SOLARES system would be entirely mechanical and would be controlled by built-in thrusters. Because the mirror system would be highly redundant, the loss of one mirror would not be catastrophic. It would also be essential to design the SPS to be as free as possible from human error. As the nuclear industry realizes, designing a technologically complex system in which the potential for human error is small is a difficult and complex task. Here again, experience with operating systems would be essential to utility acceptance.

System Comparison

The most acceptable SPS option for the current utilities to pursue may be the solid-state or a similarly sized microwave. It would provide baseload power with minor weather interference at a scale more in keeping with current utility practice (i.e., 1.5 GW). If future utility systems develop the capability and the experience to handle larger increments of generating capacity, an SPS similar to the reference system would be more acceptable, though siting problems might be very great.

The laser and mirror concepts, though offering some interesting potential, suffer from severe weather constraints. The possibility that laser SPS could be used to repower fossil fuel plants would make it of particular interest in regions of relatively low cloud cover. One of the significant drawbacks of the mirror concept is that it would require the utility and overall energy industry to make a radical

[30] P. Vajk, "The Military Implications of Satellite Power Systems" NASA/DOE SPS Program Review Meeting, April 1980, Lincoln, Nebr.

change from its current structure because of its very high degree of centralization (10 to 135 GW per site). This would be particularly true for an SPS system operating in other countries where the grid system is either nonexistent or very small (see ch. 7, International Issues).

Timing of Grid Integration.

If SPS followed the pattern of other new energy technologies it would take a long time to be integrated into the utilities structure. The reference system scenario[31] suggests that the first SPS could be deliverig power to the grid in about 20 years time. But nuclear power, which has been used for generating steam for 30 years, and became an active option for the utilities in 1960 still constitutes only 9 percent of the country's total capacity (54,000 MW). *

In the face of this past experience, it seems more likely that the demonstration and testing phases of the SPS would be longer and therefore involve higher costs than can presently be envisioned. The utilities are faced with providing reliable power to their customers. Looking at SPS from a utilities standpoint, it seems highly unlikely that the first SPS would be part of the utility grid before 2010.

This estimate is based on technology similar to the reference system technology. Developing a laser SPS might take considerably longer because we simply have less experience with high-powered lasers. The SOLARES system would be technically easier to build, but the institutional and political barriers to creating the associated large energy parks could well slow its development to beyond 2020.

Rate of Implemental ion

The reference system assumes additions of 10,000 MW per year to the grid. Assuming electricity demand makes feasible 10,000 MW additions to U.S. generating capacity, it is unlikely that the rate would begin at that high level. Again, the utilities would want to have considerable experience with the first SPS before they would be willing to invest in additional units. Thus, it is more likely that the annual rate of implementation would begin at less than 5,000 MW on the average and build to higher levels as utilities gain experience and (onfidence in SPS.

Planning for SPS

Acceptance of SPS by the utilities would depend on a number of factors, not the least of which would be utility involvement in planning for SPS. But for the utilities to invest their time and money in such an effort, they would have to be convinced that it is worth their while. Thus, SPS must be considered to be economically, environmentally, and socially acceptable compared with the other future energy options. Much depends on a comparative analysis of the available options. And because comparative assessment is necessarily a process carried out over many years, the utilities must Involve themselves in all phases of that process. A comparative assessment done today, though instructive, is as a snapshot compared to a motion picture. As we know more about each technology in the comparative group, the particular parameters will change, leading to a reassessment of the desirability of each technology.

""Satellite Power System Concept Development and Evaluation Program Reference System Report," op cit

* Nuclear power actual ly produces 13 percent of the electricity sold

ISSUES ARISING IN THE PUBLIC ARENA

SPS Debate

Public involvement in the development of technologies has grown significantly in the last two decades. Debate has focused on the environmental. health and safety. economic and military issues surrounding new technologies, The supersonic transport, nuclear powerplants, PAVE PAWS radar facilities and high-voltage transmission lines are examples of technologies that have been subject to recent public controlversy. Since SPS would probably be a

federally funded technology (at least in the research, development, and demonstration — RD&D phases) with long-term and widespread ramifications, public input in the development process is crucial, especially in the early stages. Moreover, the potential effectiveness of public resistance to technological systems, and the public's interest in direct participation makes public understanding and approval imperative for the development of SPS.

The assessment of likely public attitudes towards SPS is difficult, however, because SPS is a future technology. At present, public awareness of SPS, while growing, is minimal. Even if opinions about SPS were well-formed today, it is likely that these attitudes would change with time. Public thinking could be influenced by the other energy and space technologies, perceived future energy demand and general economic and political conditions.[32] The state of SPS technology and estimated SPS costs could also be important determinants. In addition, the degree of public participation in the SPS decisionmaking process could play a part in future opinions about the satellite.

Most public discussion on SPS has been confined to a small number of public interest and professional organizations. OTA has drawn heavily on the views of these groups because they represent selected constituencies that could play a key role in influencing future public thinking and motivating public action. While OTA cannot determine whether or not the public would ultimately accept SPS, these interest groups can help identify the issues and philosophical debates that may arise in the future.

Interest Groups

A small number of public interest and professional organizations have expressed their views on SPS. In general, many of the individuals and groups that support the development of SPS also advocate a vigorous space program. SPS proponents, represented by organizations like the OMNI Foundation, view the exploitation of space in general, and SPS in particular, as important means in overcoming terrestrial energy and resource limits.[33] To the L-5 Society, which has been the most vocal SPS lobbyist, the satellite system is "a stepping stone to the stars, "[34] an important milestone towards the society's goal, the colonization of space Groups like the Aerospace Industries Association of America[35] and the SUN SAT Energy Council, a nonprofit corporation established to explore the SPS concept,[36 37] believe that SPS is one of the most promising options available for meeting future global energy needs in an environmentally and socially acceptable manner. Professional organizations such as the American Institute of Aeronautics and Astronautics[38] and the institute of Electrical and Electronics Engineers[39] support continued evaluation of the concept.

Opponents of SPS characteristically support terrestrial solar and "appropriate" technologies and are often concerned about environmental issues. The Solar Lobby[40 41] and the Environmental Policy Center,[42] for example, fear that an SPS program would drain resources and momentum from small-scale,

"Solar Power Satellite Public Opinion Issues Workshop, A Summary, Feb 21-22, 1980, Office of Technology Assessment

"Ibid

"C Henson, A Harlan, and T Bennett, "Concerns of the L-5 Society About SPS," The Final Proceedings of the Solar Power Satellite Program Review, Apr 22-25, 1980, DOE, Cent-800491, July 1980 p 542

"Aerospace Industries Association, Statement submitted for the record in Solar Power Satellite, hearings before the Subcommittee on Space Science and Applications, U S House of Representatives, Mar 28-30, 1979, pp 241-242

"P G laser, "Solar Power Satellite Development – The Next Steps, Apr 14, 1978, in Solar Power Satellite, hearings before the Subcommittee on Space Science and Applications, U S House of Representatives, Apr 12-14, 1978, No 68, pp 165-178

"J Freeman (ed) Space Solar Power Bulletin, VOI 1, No 1 and 2, SUNSAT Energy Council, 1980

"Solar Power Satellites, AIAA Position Paper, Nov 29, 1978, prepared by the AIAA Technical Committee on Aerospace Power Systems, and the AIAA Technical Committee on Space Systems

"'H Brown, "Statement on 'Solar Power Satellite Research, Development, and Evaluation Program Act of 1979,'" in Solar Power Satellites, hearings before the Subcommittee on Space Science dnd Applications, U S House of Representatives, Mar 28- 30, 1979, No 15, pp 4-8

"Citizens Energy Project, Solar Power Satellites News Update, Solar Power Satellite Fact Sheet, Coalition Against Satellite Power Systems Statement (newsletters), 1980

"G DeLoss, ' Solar Power Satellite, " Sun Times, July 1979, p p 4-5

"G De Loss, testimony in Solar Power Satellite, hearings before the Subcommittee on Space Science and Applications, U S House of Representatives, Mar 28-30, 1979, No 15, pp 109-114

ground-based, renewable technologies. They argue that compared to the terrestrial solar options, SPS is inordinately large, expensive, centralized, and complex and that it poses greater environmental and military risks. The Citizen's Energy Project has been the most active lobbyist against funding SPS and has coordinated the Coalition Against Satellite Power Systems, a network of solar and environmental organizations.[43] Objections to SPS also have been raised by individuals in the professional astronomy and space science communities that see SPS as a threat to the funding and practice of their respective disciplines.[44,45] While there is a wide spectrum of support for SPS in the advocates' community, ranging from cautious support of continued research to great optimism about the concept viability and deployment, almost all opponents object to Government funding of SPS research, development, and deployment.

If the SPS debate continues in the future, it is likely that several other kinds of groups would take a stand on SPS.[46] For example, antinuclear groups could oppose SPS on many of the same grounds that they object to nuclear power: centralization, lack of public input, and fear of radiation, regardless of kind. Antimilitary organizations might also object to SPS if they foresaw military involvement. It is likely that community groups would form to oppose the siting of SPS receivers in their locality if the environmental and military uncertainties were not adequately resolved or if public participation in the siting process was not solicited. Rural communities and farmers in particular could also strongly oppose SPS on the grounds that, like highways and high-voltage powerlines, it would intrude on rural life.

Issues

The issues that repeatedly surface in the SPS debate are shown in table 53. It should be noted that in most of the discussion, it is assumed that SPS would be a U.S. project (at least in the near term). If the question of SPS were posed in an international context, it is possible that the flavor of the following arguments would be altered considerably. Currently, public discussion is focused on the question of R&D funding. It is anticipated that as public awareness grows, the environmental, health, safety, and cost issues will receive more public attention. Questions of centralization, military implications and the exploitation of space could also be important.

R&D PROGRAMS

The primary purpose of an SPS R&D program in the near term would be to keep the SPS option open. However, opponents argue that it makes little sense to investigate this complex, high risk technology when other more viable alternatives exist to meet our future energy needs.[47] In particular, they fear that SPS would divert funds and valuable human resources from the terrestrial solar technologies, which they perceive as more environmentally benign, versatile, less expensive to develop, and commercially available sooner than SPS.[48] Opponents also argue that a Government R&D program for SPS would fall easy prey to bureaucratic inertia, and that no matter what the results of R&D, the program would continue because the investment and attendant bureaucracy would be too great to stop.[49] Moreover, opponents believe that political inertia will be generated from the relatively large amount of money that is presently allocated to organizations with a vested interest in SPS as compared to those groups opposed to SPS. In addition, they are concerned that studies evaluating SPS for the purpose of making decisions about R&D funding do not compare SPS with decentralized solar technologies; they argue that without this kind of analysis, the public would be unwilling to make a commitment to SPS funding.

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[43] "Citizen's Energy Project, op. cit.

[44] "Solar Threat to Radioastronomy, " New Scientist, Nov. 23, 1978, p. 590.

[45] "Peter Boyce, Executive Officer of the American Astronomical Society, prwate communication

[46] "Solar Power Satellite: Public Opinion Issues Workshop, A Summary, Feb. 21-22,1980, Office of Technology Assessment

[47] "K Bossong and S. Denman, "A Critique of Solar Power Satellite Technology, " INSIGHT, March 1980

[48] Citizen's Energy Project, op. cit

[49] "Solar Power Satellite: Public Opinion Issues Workshop, A Summary, Feb 21-22, 1980, Office of Technology Assessment

Table 53.—Major Issues Arising in SPS Debate*

Pro	Con
R&D funding	
• SPS is a promising energy option	• SPS is a very high-risk, unattractive technology
• The Nation should keep as many energy options open as possible	• Other more viable and preferable energy options exist to meet our future energy demand
Ž An SPS R&D program is the only means of evaluating the merit of SPS relative to other energy technologies	• SPS would drain resources from other programs, especially terrestrial solar technologies and the space sciences
• SPS R&D will yield spinoffs to ether programs	• No matter what the result of R&D, bureaucratic inertia will carry Government programs too far
cost	
• SPS is likely to be cost competitive in the energy market	• SPS is unlikely to be cost competitive without Government subsidy
• Cost to taxpayer is for R&D only and accounts for small portion of total cost; private sector and/or other nations will invest in production and maintenance	• Like the nuclear industry, SPS would probably require ongoing Government commitment
• SPS will produce economic spinoffs	• Projected cost are probably underestimated considerably
	Ž The amount of energy supplied by SPS does not justify the cost.
Environment, heath, and safety	
• SPS is potentially less harsh on the environment than other energy technologies, especially coal	Ž SPS risks to humans and the environment are potentially greater than those associated with terrestrial solar technologies
	. Major concerns include: health hazards of power transmission and high-voltage transmission lines, land-use, electromagnetic interference, upper atmosphere effects, and '(sky lab syndrome"
Space	
• Space is the optimum place to harvest sunlight and other resources	• SPS is an aerospace boondoggie; There are better routes to space industrialization and exploration than SPS
• SPS could be an important component or focus for a space program	• SPS is an energy system and should not be justified on the basis of its applicability to space projects
• SPS could lay the ground work for space industrialization and/or colonization	
• SPS would produce spinoffs from R&D and hardware to other space and terrestrial programs	
International considerations	
• One of the most attractive characteristics of SPS is its potential for international cooperation and ownership	• SPS could represent a form of U.S. and industrial nations' "energy imperialism," it is not suitable for LDCs
• SPS can contribute significantly to the global energy supply	• Ownership of SPS by multinational corporations would centralize power
• SPS is one of few options for Europe and Japan and is well suited to meet the energy and resource needs of developing nations	
• An international SPS would reduce concerns about adverse military implications	
Military Implications	
• The vulnerability of SPS is comparable to other energy systems	. Spinoffs to the military from R&D and hardware would be significant and undesirable
• SPS has poor weapons potential	. Vulnerability and weapons potential are of concern
• As a civilian program, SPS would create few military spinoffs	

Table 53.—Major Issues Arising in SPS Debate* —Continued

Pro	Con
Centralization and scale	
• Future energy needs include large as well as small-scale supply technologies; urban centers and industry especially cannot be powered by small-scale systems alone	• SPS would augment and necessitate a centralized infrastructure and reduce local control, ownership, and participation in decisionmaking
• SPS would fit easily into an already centralized grid	• The incremental risk of investing in **SPS** development is unacceptably high
Future energy demand	
. Future electricity demand will be much higher than today	. Future electricity demand could be comparable or only slightly higher than today with conservation
. High energy consumption is required for economic growth	• The standard of living can be maintained with a lower rate of energy consumption
• SPS as one of a number of future electricity sources can contribute significant y to energy needs	• There is little need for SPS; future demand can be met easily by existing technologies and conservation
• Even if domestic demand for SPS is low, there is a global need for SPS	• By investing in SPS development, we are guaranteeing high energy consumption, because the costs of development would be so great

*Arguments mainly **focus** on the SPS reference system.

SOURCE: Office of Technology Assessment.

Advocates, on the other hand, view SPS as a potentially viable and preferable technology. [50] They argue that an R&D program is the only means of evaluating SPS vis-a-vis other energy technologies. Moreover, if the Nation can afford to spend up to $1 billion per year on a high-risk technology like fusion, it could certainly afford SPS research that would be much less expensive. [51] proponents maintain that SPS research will yield many spinoffs to other technologies and research programs whether or not SPS is ever deployed. [52 53] They also respond to claims of bureaucratic inertia by citing several cases in which large projects, such as the SST and the Safeguard ABM **system, were halted in spite of the large investment. 54 They argue that at the funding levels currently discussed for R&D, the risk of program runaway is very low.**

COST

Economic issues have played center stage in the SPS debate. Almost every journal account of SPS (particularly those critical of the satellite) has highlighted its cost. [55 56 57] The

[50] P. Glaser, **"Solar Power From Satellites, "** *Physics Today*, **February 1977,**

"Solar Power Satellite: *Public Opinion Issues Workshop, A Summary,* **Feb. 21-22, 1980, Office of Technology Assessment**

[52] P Glaser, **"Development of the Satellite Solar Power Station," in** *Solar Power* **from** *Satellites,* **hearings before the Subcommittee on Aerospace Technology and National Needs,** U S **Senate, Jan 19,21,1976, pp 8-35**

[53] T A. Heppenheimer, *Colonies in Space* (City, State: Stackpole Books, 1977)

"Solar Power *Satellite: Public Opinion Issues Workshop, A Summary,* **Feb. 21-22, 1980, Office of Technology Assessment.**

"J Marinelli, **"The** Edsel **of** The Solar Age," *Environmental Action,* **July/August 1979,**

"R Brownstein, "A $1,000,000,000 Energy Boondoggle; Science Fiction Buffs Will Love It, " *Critical* **Mass** *Journal,* **June 1980.**

"L Torrey, **"A Trap to Harness the Sun," New** *Scientist,* **July 10, 1980**

predominant questions revolve around R&D priorities and capital and opportunity costs. In addition, the calculation of costs themselves and cost comparisons between technologies could be subject to extensive scrutiny and debate.

Proponents argue that the only cost open for public discussion is the cost of RD&D to the taxpayer. 5859 The bulk of the SPS investment would be carried on by the private sector in competition with other inexhaustible energy alternatives. Furthermore, much of the RD&D cost could be returned from other space programs such as nonterrestrial mining and industrialization that build upon the SPS technological base. '" Advocates also contend that an SPS program would produce economic spinoffs by providing domestic employment and by stimulating technological . innovation for terrestrial industry.[61] Some proponents also argue that as an international system, SPS could lead to the expansion of world energy and space markets. [62 63] In addition, in a global scenario, the United States would bear a smaller portion of the development costs. Finally, advocates believe that in spite of the large investment costs, SPS would be economically competitive with other energy technologies. [64 65]

Opponents argue that the present cost estimates are unrealistically low.[66] They expect that like other aerospace projects and the Alaskan pipeline, the cost of SPS would significantly increase as SPS is developed. Furthermore, the U.S. taxpayers would be required to support this increase and to maintain an ongoing commitment to SPS above and beyond the RD&D costs, just as they have for the nuclear industry. " The National Taxpayers Union, in particular, sees SPS as a "giant boondoggle that will allow the aerospace industry to feed its voracious appetite from the federal trough."[68] Opponents argue that SPS would not alleviate unemployment substantially because it provides unsustainable jobs to the aerospace sector alone.[69] Most opponents also do not believe that SPS will be cost competitive and argue that the amount of energy produced by SPS would not justify its large investment cost. 70

The most critical issue for opponents is the question of opportunity cost, i.e., the cost of not allocating resources for other uses.[71] They argue that a commitment to SPS R&D would jeopardize rather than stimulate the development of other energy technologies. Opponents also argue that SPS might foreclose opportunities for alternate land use, Federal nonenergy R&D funding, allocation of radio frequencies and orbital slots, resource uses and jobs.

ENVIRONMENT, HEALTH, AND SAFETY

Opponents contend that the environmental risks and uncertainties of SPS far exceed those of the terrestrial solar options.[72] They are most concerned about the effects of microwaves on human health, airborne biota and communications systems. Critics of SPS also argue that it would severely strain U.S. supplies of certain materials, thereby increasing our reliance on foreign sources. 73 In addition, opponents ques-

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[58] *Solar Power Satellite: Public Opinion Issues Workshop, A Summary,* Feb. 21-22, 1980, Office of Technology Assessment.

"K Heiss, testimony in *Solar Power Satellite,* hearings before the Subcommittee on Space Science and Applications, U S House of Representatives, Mar 28-30, 1979, pp 132-158

[60] G. Driggers, letter and statement submitted for the record in *Solar* Power *Satellite,* hearings before the Subcommittee on Space Science and Applications, U S House of Representatives, pp 407-416

[61] Glaser, "Solar Power Satellite Development–The Next Steps," op cit

[62] *Solar* Power *Satellite: Public* Opinion Issues Workshop, A Summary, Feb. 21-22, 1980, Office of Technology Assessment

"Heppenheimer, op. cit

"P. Glaser, "The Earth Benefits of Solar Power Satellites, " *Space Solar* Power Review, vol 1, No 1 &2, 1980

[65] R. W Taylor, testimony in *Solar* Power From *Satellites,* pp 48-51.

[66] K. Bossong, S. Denman, *Solar* Power *Satellites* or How to Make *Solar* Energy Centralized, Expensive and *Environmentally* Unsound, report No. 40, Citizens Energy Project, June 1979

"Solar Power *Satellite: Public Opinion Issues* Workshop, A *Summary,* Feb 21-22, 1980, Office of Technology Assessment

[68] J Greenbaum, National Taxpayers Union, letter to the Senate Energy and Natural Resources Committee, expressing views on H R 12505, July 7, 1978

"Richard Grossman, Environmentalists for Full Employment, private communication, July 25, 1979

[70] Bossong and Denman, op cit

7. *Solar* Power *Satellite: Public* Opinion *Issues* Workshop, A Summary, Feb 21-22, 1980, Office of Technology Assessment

[71] Citizen's Energy Project, op cit

[73] J Hooper, Star Gazer's *Alert,* update to "Pie in the Sky" (newsletter), The Wilderness Society

tion putting Earth resources in space where they cannot be recycled or retrieved. " Opponents also cite the large amount of land needed for receiver siting, high-voltage transmission lines, the effects of launches on air and noise quality, the potential for unplanned reentry of LEO satellites ("Skylab Syndrome"), reflected sunlight from the satellites and potential adverse effects on climate and ozone as serious problems. [75]

Advocates, on the other hand, maintain that compared to other baseload or large-scale energy technologies, SPS would incur less environmental risk. [76] [77] [78] In particular, its climatic effects would be far less severe than those of fossil fuels and its bioeffects would probably be much less hazardous than those of coal and nuclear. Proponents claim that the principal advantage of SPS as opposed to terrestrial solar and hydroelectric is that it would ueless land per unit energy.[79] Most advocates are confident that while electromagnetic interference and some atmospheric effects could be a problem, acceptable methods can be found to mitigate most of the environmental impacts of SPS. Some proponents also argue that one of the major benefits of SPS is that it transports to space many of the environmental impacts typically associated with the generation of power on Earth.[80] Moreover, air and water pollution and resource strains could be alleviated if the Nation mined the Moon or asteroids. Some advocates have also stressed the importance of weighing environmental concerns against the needs for inexpensive energy.[81] A few contend that while environmental issues have ranked high in the public mind, convenience and the cost of energy are becoming more important. Opponents, on the other hand, contend that environmental concerns will remain predominant and that the public perception of environmental risks will ultimately dictate costs.

Historically, public involvement in technological controversies has often been spurred by concerns about the environmental risks. Environmental issues could be very important in future public thinking about SPS as well.[82] It is also likely that SPS would serve to bring controversies over the impacts of other technologies to the forefront, most notably the bioeffects of microwaves and high voltage transmission lines (60 cycle). While the public might be concerned about all environmental impacts (see table 28), those that most immediately affect people's health and well-being would dominate discussion. Moreover, environmental issues would be most focused and amplified at the siting stages of SPS development (see Siting section). Public acceptance of SPS will depend strongly on the state of knowledge and general understanding of environmental hazards. It will also depend on the institutional management of the knowledge; who determines the extent and acceptability of the public risk may be just as important as the data itself.

The most critical environmental issue for the reference system at present is the biological effect of microwaves, not only because the uncertainties are so great, but also because of the existing controversy over microwave bioeffects in general. As the proliferation of microwave and radio frequency devices has increased dramatically, this issue has received considerable attention in the public arena. A great many newspaper and journal articles,[83] as well as television segments on 60 minutes and 20/20,[84] and Paul Brodeur's book, The Zapping of America: Microwaves, Their Deadly Risk and the Cover-Up[85] signal growing public

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"DeLoss, "Solar Power Satellite, " op cit

[75] *Solar Power* Satellite: *Public Opinion Issues Workshop, A Summary,* Feb 21-22, 1980, Office of Technology Assessment

"C laser, "Solar Power Satellite Development–The Next Steps." op cit

[77] Heppenheimer, op. cit

"G. O'Neill, *The High Frontier: Human Colonies in Space* (New York William Morrow & Co , Inc , 1977)

[79] Glaser, "The Earth Benefits of Solar Power Satellites, " op cit.

[80] G W Driggers, "SPS Significant Promise Seen, " *The Energy Consumer,* September 1980, pp 39-40

[81] *Solar Power Satellite: Public Opinion Issues Workshop, A Summary,* Feb. 21-22, 1980, Off ice of Technology Assessment

[82] Ibid

[83] S Schiefelbein, "The Invisible Threat, " *Saturday Review,* Sept 15, *1979,* pp 16-20

[84] A Bachrach, *Satellite Power System (SPS) Public Acceptance,* October 1978

[85] Paul Brodeur, *The Zapping of America* (New York W W Norton & Co Inc , 1977)

concern over the increase of "electronic smog."

The press has been particularly suspicious of the motives and conclusions of the apparently small, closed community of microwave researchers and decisionmakers in the 1950's and 1960's. Suggestions of vested interests, conspiracy, and coverups stem from the confidential classification of microwave research by radio frequency users such as the military and the microwave device industry and the lack of attempts to solicit public input.[86] Whether or not such motives in fact existed, the public and press, fearful of the word "radiation," have expressed little confidence in "official" claims that microwaves are as safe as they are purported to be.

The political edge of the scientific controversy has also been sharpened by several incidents over a 10-year period of microwave irradiation of the U.S. embassy in Moscow. The peak power of the modulated field was 18 microwatt, far below the U.S. guideline.[87] Although neither electronic jamming or surveillance seemed to be the purpose of the waves, there was concern about attempted behavior control and health hazards that led to Project Pandora and other studies. These investigations tended to conclude that the embassy workers did not encounter health hazards traceable to their exposures.[88] Few follow-up studies have been conducted however, and suspicions still exist. Public opinion seems to have been influenced by the extensive publicity these episodes have received. Articles questioning the ethics and motives of the State Department leave the reader feeling that the issues were never adequately resolved.

Most recently the proposed American National Standards Institute and National institute of Occupational Safety and Health (NIOSH) microwave standards have been criticized. The Natural Resources Defense Council (NRDC) claims that the NIOSH criteria document that will form the basis of the NIOSH standard, fails to provide a scientifically and medically sound standard; while it admits the existence of many low-level effects, it proposes a thermal standard and fails to adequately address low-level non-thermal effects.[89] NRDC argues that the proposed standard was arbitrarily chosen, just like its predecessor. NRDC recommends that the criteria document be recommissioned, that a balanced team of experts work with NIOSH and another review the document and that a temporary emergency standard of 1 mW/cm^2 for 10 MHz to 300 GHz, be promulgated.

In spite of the proliferation of microwave ovens, public resistance to the siting of technologies that use the radio frequency portion of the electromagnetic spectrum has been strong and often effective. Local residents have opposed the construction of broadcasting towers and radar installations, as well as high voltage transmission lines (ELF radiation). (See Siting section.)

SPACE

SPS would represent a giant leap in our present commitment to space. To some, this space component and its supporting infrastructure would be an unnecessary and expensive commitment,[90] while others enthusiastically embrace SPS as the first step towards an extraterrestrial future for human kind.[91] Others argue that a commitment to space is desirable, but that SPS would be the wrong route to get there. It is likely that the discussion of the SPS concept would precipitate extensive debate over national priorities, domestic space policy and the international and military implications of space.

Proponents of SPS argue that space is the optimum place to harvest sunlight[92] and other resources that are needed for an Earth plagued by overpopulation, resource limitations, and a threatened environment. Many envision a

[86] Ibid.
[87] Schiefelbein, op. cit.
88A. Lilienfeld, et al , Foreign Service *Health* Status *of Foreign Service* and Other Employees From *Selected* Eastern European *Posts Final Report,* Department of Epidemiology, the John Hopkins University, July 31,1978
[89] Lou is Slesin, letter to Dr Anthony Robbins, NIOSH, from NRDC, July 11, 1979
[90] Citizen's Energy Project, op cit
[91] Henson, Harlan, Bennett, op cit
[92] Brownsteln, op clt

future in which the U.S. mines, industrializes and colonizes space as a hedge against these limits to growth.[93 94 95] SPS is one step in this vision, for it not only would deliver energy to Earth but would also spur the development of hardware, management, expertise and energy for use by other space activities. In fact, some proponents have suggested that without SPS, the space program will atrophy;[96] that SPS would give NASA a clear context in which to plan other space projects. Some advocates see SPS, like Apollo, as a way to restore the frontier spirit by dispelling the gloom associated with limits to growth.[97 98]

Many opponents, on the other hand, call SPS an aerospace boondoggle. " They argue that SPS, as an energy system, should not be justified on the basis of its applicability to other space pro jets. Moreover, it is argued that it is not necessary to go to space in order to generate technological spinoffs; the Nation can encourage technological competence and innovation in more direct and less expensive ways. [100] Some critics of SPS also argue that SPS would serve to escalate and accelerate confrontations in space.

In the future, public opinion about space and SPS in particular will be influenced by the relative status of space programs in this and other countries.[101] For example, the pursuit of SPS programs in other nations might act as an impetus for the United States to participate in or develop its own SPS. In light of the experience with Skylab, it is clear that the success or failure of U.S. space projects such as the space shuttle will have a marked effect on public thinking. Grassroots organizations supportive of space, and the popularity of science fiction and space-oriented entertainment, could also play a role in determining attitudes toward the exploitation and exploration of space. A growing public interest in space utilization or exploration and increased appreciation of the pragmatic benefits of space could put SPS in a favorable light.[102] Equitable international agreements about the use of space could also spur support for SPS. On the other hand, ambiguous space agreements, international conflicts, or the escalation of space weaponry could turn public opinion away from SPS. Negative public thinking about space activities and SPS could also stem from the technical failure of a major space vehicle or satellite.

INTERNATIONAL CONSIDERATIONS

Beyond its immediate implications as a space system, there are other international issues associated with SPS. The satellite system is seen as a possible focus for either global cooperation or global conflict by advocates and opponents alike. '03 However, opponents are especially skeptical of the feasibility of a multinational system; they doubt that international cooperation would occur until most of the existing conflicts on Earth are resolved. SPS opponents are most concerned that SPS would represent U.S. "energy imperialism" by dominating the cultural and technical development of lesser developed countries (LDCs).[104] Reliance on the industrial nations would impinge on third world attempts at energy independence. Furthermore they argue that SPS would do little to alleviate the near term energy needs of LDCs, whereas most terrestrial solar technologies could. Opponents also fear that control of SPS by multinational corporations would accelerate the movement of economic and political power away from individuals and communities.[105]

The characteristic of SPS that is most attractive to some proponents, on the other hand, is the potential for multinational cooperation. [106 107] In fact, a few contend that

[93] Glaser, "Development of the Satellite Solar Power Station, " op. cit.
[94] Heppenheimer, op. cit.
[95] O' Neill, op. cit.
[96] Peter Glaser, private communication.
[97] Glaser, "Solar Power Satellite Development–The Next Steps, " op. cit.
[98] Heppenheimer, op. cit.
[99] Greenbaum, op. cit.
[100] Office of Technology Assessment, op. cit.
[101] Ibid.
[102] Ibid.
[103] Ibid.
[104] Ibid.
[105] Bossong and Denman, "A Critique of Solar Power Satellite Technology, " op. cit.
[106] Glaser, "The Earth Benefits of Solar Power Satellites, " op. cit.
[107] Glaser, "The Solar Power Satellite Research, Development and Evaluation Program Act of 1979, " testimony in *Solar Power Satellite, 1979,* pp. 215-224.

this is the only feasible arrangement for SPS;[108] a multinational SPS would alleviate many of the problems associated with a unilateral SPS, e.g., military implications and high costs. Proponents also argue that SPS would enhance the economies and industrial development of LDCs by meeting their primary energy needs.[109] They maintain that electricity from SPS could be used to produce methanol, transported to rural areas in labor intensive pipelines for heating, cooking, and small industries.[110] SPS might also be used for mariculture to provide food. SPS advocates maintain that for oil- and sun-poor Japan and Europe, SPS is one of the very few energy options available. Some also argue that the deployment of SPS would slow the proliferation of nuclear technology in the third world. [2]

MILITARY IMPLICATIONS

Military issues are intimately related to space and international considerations. Proponents stress that SPS microwave and mirror systems would be ineffective weapons and no more vulnerable than a terrestrial powerplant. ' While some believe that a military presence in space is unavoidable, it is clear that there are better ways to achieve military competence than with SPS. A primary concern for opponents is that SPS would provide a technological base that would further military capabilities and serve to escalate military conflicts.[114] Many opponents feel that, like the shuttle, military involvement with SPS is inevitable and that because of its vulnerability, SPS would accelerate the need for a military presence in space. Opponents are also concerned that because of their highly centralized nature, SPS satellites and receiving stations would be targets for attack from terrorists and hostile nations.

[t is likely that the military issue will be of great concern to the public, although it is not apparent how the military implications of SPS would be viewed. For example, a perceived military potential of SPS and its supporting infrastructure might be seen as a real benefit to a public concerned about both national security and energy needs. [5] Many might even expect a military presence in space. The laser system would probably engender more concern over military applications than the microwave or mirror designs. Clearly, future opinion will be influenced by the state of space weaponry in this and other nations, future agreements about the use of space, and the state of terrestrial weapons as well as arms limitations and the perceived military stature of the United States relative to the rest of the world.

CENTRALIZATION AND SCALE

Debate over future energy strategies often involves questions of general social values rather than a narrow choice of specific technologies. One of the issues fundamental to this debate is that of centralization of energy production. The degree of centralization underlies many of the other issues discussed here including siting, ownership, public participation, military implications, and the choice between terrestrial solar and SPS.

Opponents of large-scale technologies object to society's increasing reliance on complex technologies and centralized infrastructures that, they argue, tend to erode the viability of democratic government by concentrating economic and political power in the hands of a few, and reducing individual and community control over local decisions.[116] Critics of SPS argue that it would augment and necessitate centralization by requiring a massive financial-management pyramid.[117] Utility, energy, and space companies and Federal agencies would combine into a simple conglomerate, in which small business would play little or no part. They reason that decisions about local energy development, receiver and transmission line siting and economic and environmental planning would necessarily be made by Federal

[108] Glaser, private communication, op cit
[109] Heppenheimer, op cit
[110] D Criswell, P. Glaser, R Mayur, B O'Leary, G O'Neill, and J Vajk, "The Role of Space Technology in the Developing Countries," Space Solar Power Review, VOI 1, No 1 & 2, 1980
[111] Bachrach, op cit
[112] Driggers, op cit
[113] Office of Technology Assessment, opcit
[114] Ibid
[115] Ibid
[116] "Bossong and Denman, "A Critique of Solar Power Satellite Technology, " op cit
[117] Citizen's Energy Project, opcit

and industrial decision makers at a national or perhaps multinational level.[118] Many opponents argue that decentralized solar technologies are preferable to SPS because they employ a wider range of skills, encourage participation of small firms, are more directly accessible to the individual consumer and equitably allocate their negative environmental impacts to the same people who receive the benefits. In addition, unlike SPS that must be built in large units to be economic, terrestrial solar technologies can flexibly accommodate large or small variations in energy demand. ' Moreover, unlike SPS, they do not require large contiguous land areas, a large initial investment, large energy backup units or a national utility grid to ensure adequate reliability. Dispersed energy technologies are also considered more appropriate for lesser developed nations because they are better matched to end-use needs, produce relatively small impacts on local culture and environment and don't require foreign financing, materials, complex infrastructures or hardware.[120] Opponents of SPS also view its scale as a severe detriment from an energy planning perspective because the incremental risk of investing in an SPS development program would be unacceptably high; a case of "too many eggs in one basket.[121]

Most proponents of SPS argue that the Nation's energy future will be characterized by a mix of centralized and dispersed energy generating systems, but that only centralized technologies like SPS will be able to meet the needs of industry, large cities, transportation and fuel production.[122] In addition, the centralized nature of SPS facilitates its adoption into the existing electricity infrastructure.[123] Some organizational centralization may result, but this will occur in the utility and aerospace sectors, already strongly centralized, and so it will not cause a significant new concentration of power.

In general, advocates of large-scale technologies like SPS maintain that centralized systems are more reliable and easier to implement than dispersed technologies. Centralized powerplants also produce environmental impacts that are localized and hence directly affect fewer people. It is argued that dispersed power generation does not reduce centralized decisionmaking; in order to be economic these systems will require mass production, standardization, and regulation and an extensive distribution and service network.[124] Centralized technologies, at least, are more convenient from the user's perspective. Advocates also contend that centralized technologies and infrastructures are a better means of ensuring equity among the Nation's citizens.[125] For example, many people, predominantly in the inner cities, will continue to rely on centralized delivery systems because they cannot afford the capital costs to do otherwise.

While the public might not couch the problem in terms of "centralization, " it is clear that people will be concerned about technologies and systems that appear to prevent them from directly influencing the conditions of their own lives.[126] Public thinking about SPS will then be determined by the extent of public participation in the planning and decisionmaking process, experience with centralized and dispersed technologies, attitudes towards energy, space, and utility conglomerates as well as the perceived influence and benefits (e g., convenience) of centralized technologies.

FUTURE ELECTRICITY DEMAND

Those in favor of SPS tend to foresee an energy future characterized by high electricity consumption and an expanded power grid.[127] Many equate economic well-being to high energy growth rates.[128] Even if the United States is not able to absorb all of an SPS

[1] "Office of Technology Assessment, op cit
'"DeLoss, testimony in *Solar Power Satellite,* op cit
""Off ice of Technology Assessment, op cit
"'DeLoss, "Solar Power Satellite, " op cit
"'Office of Technology Assessment, op cit
[123]R Stobaugh and D Yergin, *Energy Future (New* York Random House, 1979)

[24]H Brooks, "Critique of the Concept of Appropriate Technology", in *Appropriate Technology and Social Values — A Critical Appraisal,* F Long and A Oleson (eds) (Cambridge, Mass Ballinger Publishing Co , 1980)
[25]Office of Technology Assessment, op cit
[26]Ibid
[27]Office of Technology Assessment, *The Energy Context of SPS Work shop, A Summary,* September 1980
"Off Ice of Technology Assessment, *Solar Power Satellite Public Opinion Issues Workshop, A Summary,* Feb 21-22, 1980

system, they argue that on a global scale there will always be high demand.[129] [130] Proponents also argue that if SPS is able to provide relatively cheap, environmentally benign and plentiful energy, then it will be consumed and demand will be high. '3' Some argue that no matter which demand scenario is finally realized, we need to investigate every possible electricity option today, so that we have adequate choices in the future.

Most opponents, on the other hand, envision an energy future dominated by conservation and solar technologies.[123] Some believe that electricity should play a minor role in our energy supply mix because of its thermodynamic inefficiency.[133] Furthermore, most opponents contend that even if electricity demand were to increase somewhat, it could be satisfied with existing technologies.[134] They argue that by developing large-scale energy systems such as SPS, we are guaranteeing high energy use because the investment in their development is so great.

Public attitudes about SPS will depend on the relative cost and availability of energy, the advancement and proliferation of electrical end-use technologies, attitudes towards energy companies and forecasters of electricity demand, and the sense of energy security as determined by domestic supply v. reliance on foreign sources. 35

SPS Technical Options

How might future public reaction to alternative SPS systems differ?[136] Table 54 identifies some of the relative benefits and drawbacks of the proposed SPS systems as they might be perceived by the public.

Siting

Historically, public debate over the introduction of a technology has been most pronounced at the siting stage. It is during the siting phase that public opposition to a technology has been most vocal, organized, and effective. Citizens have taken direct action against the siting of powerplants, airports, prisons, high-voltage transmission lines and military facilities by forming local and national groups, publicizing their cause through the media, taking legal action, demonstrating, and occasionally resorting to civil disobedience and violence.[137] In general, siting controversies revolve around issues of environmental effects, health and safety risks, reduced land values and fair compensation, private property rights, opportunity costs, vulnerability to attack, and public participation in land-use decisions.[138] It is clear that in the absence of national land-use policies, conflicts over land-use priorities will escalate as the population grows, and friction between rural and urban America and local communities and regional or national decision makers will increase "9

For SPS, siting is a major issue. * SPS would be particularly prone to siting difficulties because of its large contiguous land requirements, its potential military implications, and its use of nonionizing electromagnetic radiation (e. g., microwaves or lasers) in power transmission and distribution. This last factor is most important because of considerable uncertainties associated with the environmental and health risks of electromagnetic radiation as well as possible interference with electromagnetic systems. These uncertainties and

[129] O'Neill, op cit.
[130] Glaser, private communication, op cit
[131] Office of Technology Assessment, The Energy Context of SPS Workshop, Op. cit
[132] Ibid
[133] A B Lovins, "Energy Strategy The Road Not Taken?" - Foreign Affairs, October 1976
[134] "Office of Technology Assessment, The Energy Context of SPS Workshop, op. cit
[135] "sOffIce of Technology Assessment, Solar Power Satellite: Public Opinion Issues Workshop, op cit
[136] Ibid
[137] "L Caldwell, L Hayes, and I MacWhirtey, Citizens and the Environment Case Studies in Popular Action (Broom ington, Ind IndianaUniversity Press, 1975)
[138] Office of Technology Assessment, op cit
[139] Ibid

*It is assumed that SPS receivers would be sited on land Offshore locations are also possible and might alleviate many of the SPSland-use problems, but are not specifically addressed here Also not considered here are possible multiple land uses If it can he shown that land can safely and economically be used for siting S PS receivers and other uses (e g , agriculture, pasture land) simultaneously, then siting on private land might not be a problem However, in the absence of detailed assessments on the costs and environmental impacts of multiple uses, it is assumed in this section that land is dedicated to SPS receivers alone

Table 54.—Potential Benefits and Drawbacks of SPS Technical Options

Advantages	Disadvantages
Laser system	
. Does not use microwaves . Of SPS systems, requires less land area per site and can deliver smaller units of energy	• Possible weapon • Health and safety impact of beam wanders • Weather modification
Mirror system	
• Most environmentally benign of SPS systems • Least weapons potential of all SPS systems • Least complex to demonstrate, most immediately reliable system • Possibly least expensive system	• Largest land requirements per site • Illumination of night sky • Weather modification . May fall out of low-Earth orbit
Solid state	
. Can deliver smaller units of power than mirror or reference system • Land per site is smaller than mirror or reference system . Satellites in GEO (in vulnerable to unplanned reentry) and can be placed over the ocean • Less weapons potential than lasers . Fairly well-developed technology	• Microwave bioeffects • Electromagnetic interference
Reference system	
• Satellites in GEO (invulnerable to unplanned reentry) and can be placed over the ocean • Less weapons potential than lasers • Fairly well-developed technology	. Microwave bioeffects • Electromagnetic interference

SOURCE: Office of Technology Assessment

their institutional management have been responsible **in part for controversies over the siting of a great many other technologies that utilize the radiowave spectrum. Community resistance to the siting of radar installations, broadcasting towers, and high-voltage transmission lines, for example, has been particularly strong and unexpectedly effective.**

Citizens groups have actively opposed transmission lines in a number of States including Oregon, New Hampshire, lowa, and Montana.[140] As a result of public action in New York, the State Public Service Commission has expanded the minimum right-of-way for new lines and established an Administrative Research Council to study and assess health risks."' The legislatures of a few New York counties have adopted resolutions opposing the construction of 765 KV lines. '42 In Minnesota, farmers battled with the public utilities over the construction of a powerline through 8,000 acres of prime farm land. '43 After attending public hearings and installing solar and wind devices in their homes to reduce their dependence on the utilities, some became frustrated with what they perceived as the unresponsiveness and dishonesty of the utilities and finally resorted to demonstrations, destroying utility towers and equipment.

The siting controversies most relevant to the SPS microwave systems are the disputes over the Navy's Project SEAFARER (Surface ELF* Antenna for Addressing Remotely-Deployed Receivers), a 25,600-mi^2 underground radio antenna for communication with nuclear submarines; and the Air Force's PAVE PAWS (Precision Acquisition of Vehicle Entry Phased Array Warning System), a radar system.'" When the Navy attempted to locate SEAFARER at different times in Wisconsin, Texas, New Mexico, Nevada, and Michigan, it encountered vehe-

[140]" **The New Opposition to High-Voltage Lines, "** *Business Week,* **November 1977**

'41A. Marino and R **Becker, "H igh Voltage Lines. Hazard at a Distance,"** *Environment,* vol **20, No 9, p 6-15**

[142]K **Davis, "Health and High Voltage, "** *Sierra Club Bulletin,* July **1, August 1978**

[143]H Nuwer, **"Minnesota Peasant's Revolt, "** *Nation,* vol **227, Dec 9, 1978**

*** E 1 F (extremely low frequency) radio waves**

'[44]P Brodeur, *The Zapping of America, Their Deadly Risk and Cover-up (New* **York W W Norton & Co , 1977)**

ment local opposition. Residents in these communities were concerned about the health hazards of ELF radiation. Ranchers in Texas were also worried about the effects on livestock. Opponents raised other issues including vulnerability to nuclear attack, private property rights, and decreased land values. 45 Referenda defeated SEAFARER's construction in several counties in Michigan, and in an unprecedented action, the Governor of Michigan rejected the military program.[146] The Governor of Wisconsin also accused the Navy of suppressing environmental impact studies that reported possible environmental and health hazards.[147] Although the ELF program is still being funded, it has yet to find a new site.

Legal action has also been taken against the Air Force's plans to build PAVE PAWS in Cape Code, Mass., and Yuba City, Calif.[148] Fear of adverse microwave bioeffects, especially long-term, low-level effects, sit at the heart of the controversy. While the Air Force stressed that health risks were negligible and emphasized the need for national security, local groups argued that the data did not support the claim that PAVE PAWS will not jeopardize their health.[149]

Several key observations can be made from these disputes. First, farmers, ranchers, and rural Americans are becoming an increasingly active social force working against the intrusion of urban America on their rural quality of life. As one OTA workshop participant familiar with powerline siting controversies remarked, "Developers say that high voltage transmission lines wouldn't make any more noise than a highway would and the reaction of people is 'What do you mean? –That's why we're out here. We don't want to be near the highways' . . , . (Rural Americans) are sacrificing the kind of life they are out therefor, for the energy excesses of urban America.[150] In many cases, communities would prefer to leave a site overgrown than consent to any kind of development. For SPS as well as other powerplants, dumps, mines, and military installations, siting in remote areas could be a difficult task, especially in parts of the country where residents have already mobilized against other large-scale projects.[151] According to another workshop participant, one farmer, when asked about the SPS proposal, responded, "I've had enough. I'm ready to get my gun out."[152]

Another factor that emerges from siting controversies is that while concerns over the environmental and health risks of a technology are very important to nearby residents, this issue may mask related concerns such as unsightliness and devaluation of local property values[153] that may be more important to the local community. For example, in the Minnesota powerline dispute, the fundamental issue for many of the farmers was the question of land-use, i.e., farmland v. right-of -way. '54 However, this issue was channeled into environmental and health concerns that had greater political leverage in the courts and to which the utilities and the general public were more responsive. While the health effects of ELF radiation were the most frequently articulated concern of communities opposing SEAFARER, it is clear that to some residents, economics really lay at the heart of the controversy [155] These people were primarily concerned that land values might decrease if potential buyers worried about the health effects, and might not have opposed the siting if they had been justly compensated. Other residents were most concerned that the presence of SEAFARER would make their land more vulnerable to military attack; this would threaten their safety and could also reduce the value of their land.[156]

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[145] G Ellis, "Sanguine/SEAFARE R," *Sierra Club Bulletin*, vol 61, No 4, April 1976

[146] Brodeur, op cit

[147] S Schiefelbein, "The Invisible Threat, " *Saturday Review*, Sept 5,1979, pp 16-20

[148] Brodeur, op cit

[149] S. Kaufer, "The Air Pollution You Can't See, " New *Times*, Mar 6,1978

[150] Office of Technology Assessment, op cit

[151] Ibid

[152] Ibid

[153] Ibid

[155] Joseph Thiel, Texas State Department of Health, private communication, Nov 28, 1979

[156] P Boffey, "Project SEAFARER Critics Attack National Academy's Review Group," *Science*, vol 192, June 18, 1976, pp 1213-1215

This second observation also points to the complex interrelationship between environmental and health risks, costs, land and air use, private property rights, esthetics, and public control over local decisions. For SPS, it is clear that the choice of transmission frequency and power distribution as well as public radiation standards could have a great bearing on the area of land that would be required as a buffer zone, the number of people potentially affected, compensated, and/or relocated, and hence the cost of developing SPS. In addition, the size of each SPS unit and its location could determine the extent, number and therefore cost of transmission lines that would have to be sited. The cost of a proposed energy facility such as SPS can also be increased if developers do not solicit public participation and disputes and court battles delay construction. Siting should therefore be considered as early as possible in the development process; public input is an essential element in the development and design strategy.

Finally, it is clear that many of the siting disputes might have been resolved earlier and more easily if the channels of communication between developers and the local community had been more open. Public participation should be solicited whenever and wherever possible, ideally even before the siting stage. Too often, residents become frustrated and resentful towards developers and officials who make inadequate and occasionally dishonest' attempts to involve the public in meaningful decisionmaking. This practice has led the public to seek other forums to voice complaints, thereby delaying decisions and driving up costs. SPS developers must be well-informed about the environmental, economic, and military implications of SPS and should arrange for open dissemination and discussion of that information. In addition, no matter what objective research findings are, public perceptions of potential hazards are largely influenced by public confidence (or lack thereof) in "official" interpretation of that data (see Environment, Health, and Safety). Whether justified or not, the public is considerably more cautious and fearful of the biological effects of microwaves and other electromagnetic radiation than are many representatives of Government and industry. But until the uncertainties are resolved to the public's satisfaction, the past cases strongly suggest that local resistance to SPS receivers could be substantial.

APPENDIXES

Appendix A

ALTERNATIVES TO THE REFERENCE SYSTEM SUBSYSTEMS

Solar-Thermal Power Conversion

The basic operational principle involved in solar-thermal-electric power systems is identical to that of virtually al I conventional ground-based powerplants, with a solar furnace replacing the fuel-fired furnace or nuclear reactor normally used to heat the power-cycle working fluid. The 10-MW demonstration plant at Barstow, Calif., is such a solar-powered thermal cycle. Virtually all components of such power systems have been extensively used and/or tested on Earth, and hence solar-thermal systems for potential space applications in the SPS time frame would enjoy the availability of a large body of applicable technology, hardware, and experience. Significant problems are foreseen, however, in reducing the mass and complexity of space-based powerplants to levels that make them competitive with the reference system photovoltaic power source.

The basic rationale for considering thermal power cycles is their inherently high energy conversion efficiency. High-performance thermal cycle power generators on Earth routinely attain overall efficiencies of more than 40 percent, as compared with the 17-percent projected efficiency for the reference-system photovoltaics, and it is quite probable that material and component developments during the next decade or two could extend overall operational thermal-cycle efficiencies for terrestrial units to over 50 percent. Unfortunately, however, the space environment is such that these efficiency levels, even with advanced-technology power-conversion hardware, are extremely difficult to achieve. The fundamental problem is that of heat rejection; that is, in accordance with the dictates of the Second Law of thermodynamics, it is necessary that any heat engine reject to its environment some of the energy it receives (the ubiquitous "thermal pollution" of Earth-based powerplants). On Earth, effective heat rejection at the low temperatures needed for high thermal efficiency is readily accomplished by using vast quantities of cool water or air. In space, on the other hand, all heat rejection must be accomplished solely by radiation, a process that depends on the fourth power of the radiator's temperature. Hence efficient heat rejection in space can be accomplished only at high temperatures, which **by the Second Law results in reduced thermal efficiency. The radiators of the space-based thermal powerplant therefore become the key limitation on performance, and counteract the beneficial effect of potentially high-cycle efficiency. The most effective space-based thermal power cycle, then, is generally the one that minimizes the radiator mass.**

The Brayton and Rankine Cycles

The two "simple" solar-thermal cycles considered for SPS are the Brayton and Rankine cycles—the cycles used on Earth for gas turbines and steam turbines, respectively. In the Brayton cycle, a compressor compresses a gaseous working fluid, that is then heated by solar energy concentrated into an "absorber" by large, diaphanous thin-film solar mirrors having a concentration ratio of perhaps 2,000-to-l, then discharges its waste heat to a radiator. It then returns to the compressor and repeats the cycle.

The Rankine cycle utilizes the same basic energy **source as the Brayton cycle —typically, a 2,000-to-l solar concentrator mirror focused on an absorber – but employs a condensable liquid, or, frequently, ordinary steam. The solar energy impinging on the absorber boils and superheats the steam, which then drives a turbine. The steam then condenses in the radiator at constant temperature. The condensed water is then pumped back up to high pressure and forced into the boiler (absorber) to complete the cycle.**

The Brayton and Rankine cycle options were rejected for the reference system, despite their relatively high efficiencies, because of the high radiator mass, the lower projected reliability of rotating machinery, and relative complexity of orbital assembly operations as compared with the photovoltaic options. However, recent developments in high-temperature heat exchangers and turbines, [1] and particularly innovative designs of heat-pipe and other radiators[2,3] now make Brayton-cycle turbines more attractive.

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[1] "Review Study of a Brayton Power System for a Nuclear Electric Spacecraft, J PL contract 955-008, Garrett-AIResearch report No 31-1288A Oct 9, 1979

[2] Yale G Eastman, "A Study of the Appl ication of Advanced Heat Pipe Technology to Radiators for Nuclear Spacecraft, " Thermacore, Inc , Lancaster Pa Dec 3, 1975, a l so see Yale G E astm an, "Advanced Heat Pipes in Aerospace Power System s,' A IAA paper No 77-501, St l. ouis, Mo , Mar l -1, 1977

[3] John Hedgepeth and K Knapp, "Preliminary Investigation of a Dust Radiator tor Space Power System s," Astro Research Corp report No ARC-TN 1054 Mar 1978

Other Thermal Cycles

Other thermal cycles have also been considered,[4,5] to be used independently or in conjunction with the Brayton or Rankine cycles in a combination. The most likely prospects are the thermionic[6,7] and the magnetohydrodynamic (MHD)[8] cycles or the wave-energy exchanger.[9,10,11,12,13]

None of these seems particularly well adapted for use in an independent mode in space, although any one of them may have potential when used in combination with either the Rankine or Brayton cycle. **The primary consideration for these cycles is the tradeoff between high efficiency and high radiator mass. Principal areas requiring research and/or additional development are in the high-temperature solar collection and absorption portions of all systems and high-performance heat-rejection devices, as well as extensive testing and pilot operations to establish the required levels of reliability and reductions in cost uncertainties.**

Photovoltaic Alternatives

Alternative Materials

Alternative photocell materials considered before selecting the reference system options of single-crystal silicon and gallium aluminure-arsenide were amorphous silicon, polycrystalline silicon, cadreium sulfide, copper iridium selenide, and polycrystalline gallium arsenide. Although all these materials cost less than either of the two selected materials, their efficiencies are low and there is little experience in their production. Other factors considered by the National Aeronautics and Space Administration before selecting the two reference system options were total system mass, materials availability, susceptibility to radiation damage, development status, manufacturing processes, and energy payback. Other potential photovoltaic materials that were rejected due to obvious problems with one or more of the above factors include selenium and various selenides, cadmium telluride, copper sulfide, gallium phosphide, iridium phosphide, and a number of higher order inorganic compounds.

Concentration

Another important parameter is the concentration ratio (CR). The selection of CR = 2 for the reference-system gallium arsenide option was strongly Influenced by cell temperature considerations.[14] Should cell technology develop that would retain high efficiency at elevated temperatures, higher concentrations might prove cost effective, since both the mass and the cost of reflector materials are considerably less than those of photocells.

There is good experimental evidence that the gallium aluminum-arsenide/gal lium-arsenide cells selected for the SPS could utilize much higher concentration ratios to gain higher overall efficiency. There has been considerable development in concentrating photovoltaic subsystems for terrestrial use during the past 2 years, and it is possible that passive rather than active cooling may be possible.

Multicolor Photocell Systems

Photocells respond to only a part of the available solar spectrum that impinges on them. It is **possible to achieve more efficient utilization of the solar spectrum by: 1) manufacturing a single photocell from various materials, each responding to a different wavelength band;[15] or 2) using separate cells, each optimized for a different spectral region and using an optical system to split the incident light into the corresponding spectral ranges.**

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[4]Daniel L Gregory, "Alternative Approaches to Space-Based Power Generation, " *Journal of Energy 1,* **March-April 1977, pp 85-92**

[5]William P Gilbreath **and Kenneth W** Billman, **"A Search for Space** Energy **Alternatives, "** in "Radiation **Energy Conversion** in **Space, "** *Progress in Astronautics & Aeronautics, vol 61,* **Al AA, N Y ,** July **1978, pp 107-125**

[6]G **O , Fitzpatrick and E** J Britt, "Thermionics **and** its Application **to the** SPS, **" Ibid, pp 211-221**

[7]**(For example), W** Phillips **and J Mondt,** "Thermionic **Energy** Conversion **Technology Development Program, " Progress report No 630-36 (for June-September 1978), Jet Propulsion Laboratory, Pasadena,** Calif , **Nov 15, 1978**

[8]**'C V Lau and R Decher, "MHD Conversion of Solar Energy, "** in "Radiation **Energy Conversion** in **Space, " K W** Billman **(ed), Progress** in *Astronautics & Aeronautics, vol 61,* **Al AA, N Y , July 1978, pp 186-200**

"Robert T Taussig, **Peter H Rose, John** F Zumdieck **and Abraham Hertz berg, "Energy Exchanger Technology** Applied **to Laser Heated Engines, " Ibid, pp 465-478**

[9]**"W E Smith and R C Weatherston, "Studies of a Prototype Wave Superheater** Facility **for Hypersonic Research ' report No HF-1056-A-I, contract AFOSR-TR-58-I 58, AD207244,** Cornel **I Aeronautical Laboratory, Buffalo, N Y , December 1958**

"Abraham Hertzberg and Chan-Veng **Lau, 'A High-Temperature** Rankine **Binary Cycle for Ground and Space Solar** Applications, " in **"Radiation Energy Conversion** in **Space, " K W** Billman **(ed),** *Progress in Astronautics & Aeronautics, vol 61,* **Al AA, N Y ,** July **1978, pp 172-185**

"Arthur T Mattick, **"Absorption of Solar** Radiation **by Alkali Vapors, "** Ibid, **pp 159-171**

[10]**'A** Jay **Palmer,** "Radiatively **Sustained** Cesium **Plasmas for Solar E** lectric **Conversion," Ibid,** pp 201-210

[11]**W** James, and R L Moon, "GaAs Concentrator Solar Cells, " *Proceedings of the 11th Photovoltaic Specialists Conference,* 1975, **pp 40,? 408**

Richard J Stirn, **"Overview of Novel** Photovoltaic **Conversion** Techniques **at H igh I ntensity Level s,"** in "Radiation **Energy Conversion** in Space **K W** Billman **(ed),** *Progress in Astronautics & Aeronautics, vol 67 I* **Uly** 1978 **pp 136-151**

[12]**" I aan,** Jurisson, "Multicolar **Solar** Cel **I Power System for Space, 'r Ibid, pp** 152 **158**

Although the technology for both approaches is known, it is far from having been proved practical, and will require considerable research and development effort before being considered for future operational systems. The second approach appears to be the most promising in principle. However, it suffers from a lack of basic data on the photovoltaic materials that might be used for it. Despite their attractiveness from the standpoint of efficiency, both systems also require either higher mass or concentrator systems, which may require active cooling. Again, vastly more research is needed to determine the overall effectiveness of these concepts.

Alternative Microwave Power Converters

In addition to the klystron, several other devices may be capable of converting satellite electric power to microwaves and transmitting them to Earth. The solid-state amplifier, based on semiconductor technology, could result in a significant and beneficial change of the entire system. The latter serves as one of the four systems considered in this assessment.

- *Crossed-Field Amplifier.* This device in the term of an "amplitron," was originally suggested for the reference system in place of the klystron (linear beam amplifier). Another form of this device, the magnetron, appears to have considerable merit, * particularly in reducing the spurious noise and harmonics generation of the microwave antenna. In smaller form (1 kW), this is the familiar unit that powers microwave ovens. The latter devices are reliable and cheap. Whether working devices of the 70-kW capacity needed for the reference system antenna will prove to be cost effective and possess the required signal characteristics must await design and testing, individually and in a phased array.
- *Solid-State Devices.* The principal motivation for considering solid-state devices" is their extremely high reliability;[17,18] projected failure rates are 100 times lower than those of the reference-system vacuum-tube klystrons or amplitrons.[19] A secondary advantage of solid-state devices is their potential for lower mass per unit area than the vacuum-tube devices. Further, their small size and potentially low unit cost facilitate convenient research and development activities.

  The basic problem with solid-state devices is their low-temperature capability, which implies low power, coupled with their low-voltage output. Additional potential problem areas are uncertain efficiency, current high cost for high-performance units, and a host of as yet unresolved transmission, control, and power distribution complexities.[20] However, these devices are still in the early stages of being evaluated for the SPS application, and it is likely that studies of the extent devoted to vacuum-tube devices during the past few years can reduce the present uncertainties associated with sol id-state power conversion and transmission.

  A major area for concern with the solid-state devices is the paucity of data and experience on phase control. Although the same generic type of retrodirective control is projected as for the reference system, much research, analysis, and technology advancement will be needed to define its phase control capabilities to the necessary level of confidence.

Photoklystrons

The photoklystron combines the principles of a conventional klystron transmitting tube and the photoemitter in a single device. Sunlight falling on a photoemissive surface generates a current of electrons oscillating in such a way as to emit radio frequency electromagnetic waves. If used on the SPS, the resultant microwaves could be beamed to Earth by using a resonator waveguide.

Potential advantages of the photoklystron over the photovoltaic array/klystron are that it could increase the useful portion of the photoelectric energy spectrum as compared with photovoltaics (it may reach efficiencies as high as 50 percent[21] as compared with 15 to 20 percent for conventional photovoltaics), and that it would greatly simplify the entire space segment of the SPS[22] as compared with the reference system, by (a) eliminating the solar cell arrays altogether, (b) eliminating the need for on board power distribution, (c) eliminating the rotary joint and sliprings, (d) reducing the individual klystron power and heat dissipation requirements (there would now be many more klystrons

*W C Brown, Microwave Beamed Power Technology Improvement PT-5613 J PL contract 955-104, May 1980

"G M Hanley et al , "Satellite Power Systems (SPS) Concept Definition Study, " First Performance Review, Rockwell International report No SSD79-0163, NASA MSFC contract NAS8-32475, Oct 10, 1979

"Gordon R Woodcock, "Solid-State Microwave Power Transmitter Review, " Boeing Aerospace CoDOE SPS Program Review, June 7, 1979

[19] Ibid

[20] Ibid

[21] Gibraeth and Billman, op cit

[22] John W Freeman, William B Colson and Sedgwick Simons, "New Methods for the Conversion of Solar Energy to R F and Laser Power, " In Space Manufacturing 1 I I,' Jerry Grey and Christine Krop (eds) Al AA, New York November 1979

distributed over a much larger area), thereby increasing the lifetime of individual klystrons, (e) reducing individual klystron cost, and (f) reducing rectenna area requirements, since the transmitting antenna is much larger than that of the reference system.

One suggested system (fig. 10) consists of a large elliptical array of photoklystrons, constituting the collector and antenna. A large mirror (that could also be a concentrator) would reflect sunlight to the photoklystrons. Note that even though the mirror and antenna must rotate with respect to each other to maintain proper Sun-facing and Earth-facing attitudes, as in the SPS reference system, there is no need for a mechanical connection between them; in fact, their relative alinement is not at all critical.

Small working models of photoklystrons exist, but have not yet demonstrated any of the system characteristics needed for a practical and cost- effective SPS. Hence the concept still remains just that: a highly interesting and promising prospect for further intensive study.

Offshore Rectennas

Because siting a rectenna near the coastal population centers that will have most of SPS-generated baseload electricity may prove extremely difficult, it has been suggested that rectennas be located in shallow offshore waters. * The costs of such siting would certainly be higher for a given area than for comparable land-based sites, but the system costs might be cheaper overall because of cost reductions in rectenna size. The considerable body of relevant experience that was developed for offshore airports would be useful for studying this possibility. The land areas that have been considered for offshore airports are comparable to the needs of SPS rectennas (e. g., 50 to 20 km^2).

It may be possible to reduce the necessary area of an offshore rectenna by eliminating most of the buffer zone and "flattening" the power distribution of the beam across the rectenna. Though potentially costly, the option may be taken very seriously by the European community for whom rectenna siting on land would prove most difficult. It may also find uses along the shores of densely populated areas in the United States.

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*Rice University, Solar Power Satellite Offshore Rectenna Study NASA CR 3348, November 1980

Appendix B

DECENTRALIZED PHOTOVOLTAIC MODEL

Estimating the busbar costs for a house or industrial plant power station, whether connected to the grid or stand-alone, may involve somewhat different assumptions than for a central power station. For one thing, the homeowner's access to capital is different than that of the utility. In addition, the tax liabilities are different and arise from a different conceptual framework.

In order to compare most directly the busbar costs of a decentralized photovoltaic technology with the centralized terrestrial case and with the solar power satellite, OTA has adopted the case of decentralized systems leased by a utility to an individual owner. The choice to calculate the costs this way represents neither a preference nor a prediction on the part of OTA for the way in which dispersed photovoltaic systems will be marketed in the future. The costs so calculated are the costs to the utility and do not reflect the price to the consumer. They therefore are directly comparable to the busbar costs of electricity from the solar power satellite.

For homeowners who would prefer not to continue to rely on a central structure for their power, leasing equipment from a utility may not be an acceptable arrangement. Many, however, will not wish to accept the relatively high capital investment and subsequent maintenance which an in stallation requires and will prefer leasing to purchase.

Household and Industrial Photo voltaics: costs and efficiencies

System assumptions:

Array efficiency–18 percent*
Degradation – 5 percent first year, stable thereafter
Systems life– 30 years*
Inverterefficiency—90 percent
Battery efficiency– 75 percent round trip
Array cost — $35 m^2*
Additional installation costs assuming roof replacement — $0.0
Additional installation costs assuming array flat on roof — $1 3/$m^2$
Additional installation costs assuming array on ground – $80/$m^2$
Operation and maintenance–1 percent of initial costs per year
Lightning protection:
Household – $500
Industry– $0
Inversion and power conditioning–$82/kW
Battery lifetime **(deep cycles) –2,000**
Battery initial costs ($/kWh capacity)–$49/kWh
Battery O&M cost (¢/kWh discharged) –O.038¢/kWh
Battery total cost (¢/kWh discharged): 4.3¢/kWh
Battery housing and related costs ($/kWh capacity)– $6.4/kWh
Backup generator, residential –$306/kW
Industrial cogenerator steam turbine–$1,446/kW
Percent backup in system with storage–60 percent

Sample Calculation

The following equations apply, assuming there are no variable O&M costs and no fuel costs.

Busbar costs (¢/KWh) = levelized capital cost/levelized output + levelized fixed O&M/levelized output
Levelized capital cost = FCR X initial capital cost ($/100$m^2$) x 100 ¢/$
FCR (fixed charge rate)= CRF (i/N) + T

$$\text{CRF (i/N) = capital recovery factor} = \frac{1}{1-(1+i)-N}$$

where:

I = weighted cost of capital
N = economic life = book life
T = levelized income taxes =(t/(l-t))(CRF(i/N) -1) x P – (TD – 1/N)
TD = tax allowance for accelerated tax depreciation**
= CRF (i/N) x ((2 x (M – (1/CRF(i/M)))/(M X (M+ 1)X i))
M = tax life
Levelized output = kWh/year/100m2 array
Levelized fixed O&M= O&M($/100m2/yr)X1000/$ X AF(e,i,N)
AF(e,i,N) = CRF(i/N) X (1 – ((1 + e)/(1 + i))N)/(i – e)) X (1 + e)
where e = apparent escalation rate (inflation rate)
Financial assumptions:

I = 0.10
t = 0.30
e = 0.06
N = 30 years for array
= 6 years for batteries
M = 20 years

Example–

A household 100m^2 array mounted on the roof in Boston generates *22,017* kWh/yr:

Cost of array	**.$3,500**
Lightning protection	**$ 500**
Power conditioning ., ...	**$ 650**
Structural support ., ..	**$1,300**
Total ... .,	**.$5,950**

'Assumptions of SPS reference system

**Assumes sum-of-the-years digits depredation method

83-316 0 - 81 - 19

O&M costs/year = 1 percent capital costs = $59.56
FCR = 0.12504
Levelized capital cost= 0.125 X 5,956 X 100
= 74,450 ¢/l00m^2/year
Levelized fixed O&M = 9,705 ¢/100m^2/year

Busbar costs (¢/kWh) =

$$\frac{74{,}450}{22{,}017} + \frac{11{,}233}{22{,}017} = 3.9\text{¢/kWh}$$

GLOBAL ENERGY DEMAND FORECASTS

1. **IIASA's predictions were influenced by several factors: 1) most of the analysis was done prior to the 1979 rise in oil prices; 2) there was an optimistic view of the growth of nuclear capacity (to some 50 to 60 percent of global generating capacity by 2030); 3) participation in the study by the Soviet Union and other centrally planned economies, who for political reasons projected very high economic and energy-use growth rates; 4) low expectations for conservation and alternative energy sources.**
2. **Predictions of future energy demand are based on estimates of underlying economic and demographic factors, and of the relation between overall economic and population growth and energy demand. IIASA's population and GDP growth rate projections are as follows:**

Population projections by region, high and low scenarios (10' people) (Finite *World, p.* **429)**

Region	*Population base year 1975*	*Projection 2000*	*2030*
I (NA)-North America	237	284	315
II (SU/EE)-Soviet Union/East Europe .....,	363	436	480
III (WE/JANZ)-West Europe/Japan, Australia	560	680	767
Iv (LA)- Latin America	319	575	797
v (AF/SEA)-Southern Africa& Asia	1,422	2,528	3,550
VI (ME/NAF)-Middle East/North Africa	133	247	353
VII (C/CPA)-China/Central Planned Asia	912	1,330	1,714
World .	3,946	6,080	7,976

NOTES: 1975 data are mldyear estlmates from Unlted Nations Monthly Bulletin of Statistics Januar~ 1978

Historical and projected growth rates of GDP, by region, high and low scenarios (percent/yr)

High scenario

	Historical		*Scenario projection*			
Region	**1950-60**	**1960-75**	**1975-85**	**1985-2000**	**2ooo-15**	**2075-30**
I (NA)	3.3	34	43	33	24	20
II (SU/EE).	10.4	65	5.0	40	35	35
III (WE/JANZ)	50	52	43	34	25	20
Iv (LA)	5.0	61	62	49	37	33
v (AF/SEA).	39	55	58	4.8	38	3.4
VI (ME/NAf)	70	98	72	5.9	42	38
VII (C/CPA)	8.0	61	50	4.0	35	30
World	5.0	50	47	38	30	27
I + III (OECD).	4.2	44	4.3	34	2.5	20
IV + V(Developing)	47	6.5	6.3	51	39	35

Low scenario

	Historical		*Scenario projection*			
Region	*1950-60*	**1960-75**	*1975-85*	*1 985-2000*	*2000-15*	*2015-30*
I (NA)	3.3	34	31	20	11	1.0
II (SU/EE).	10.4	65	45	3.5	2.5	20
III (WE/JANZ).	50	52	32	2.1	1.5	1.2
Iv (LA)	5.0	6.1	47	3.6	30	30
v (AFI/EA)	39	55	48	36	28	24
VI (ME/NAf)	70	9.8	56	4.6	27	21
VII (C/CPA)	8.0	61	33	3,0	25	20
World	50	50	3.6	27	19	17
I + III (OECD)	42	44	3.1	21	13	11
IV + V + VI (Developing)	47	65	5.0	38	29	26

SOURCE *Energy in a Finite World, A Global Systems Analysis,* Energy Systems Program Group International Institute **for** Applied Systems Analysis **(Cambridge, Mass** Ballinger Publishing **Co , 1981)** p 433

3. **In general, the IIASA study places great emphasis on the development of nuclear power, and especially on an explosive growth in fast breeders after 2000. Although a number of countries, including France, Japan, and the Soviet Union, have announced aggressive plans to install breeders over the next several decades, it should be remembered that questions still remain as to breeder reactor safety, reliability and operating costs. (See ch. 6 for a comparison of breeders and other baseload power sources.) IIASA's high expectations for breeder development are by no means universally shared.**

Percent of global secondary electrical demand met by nuclear power–IIASA

	1975	2000		2030	
		Low	*High*	*Low*	*High*
Conventional reactors	20	271	294	19,2	22.9
Breeders	0.0	044	067	40,6	38,2
Total	20	275	303	498	611

SOURCE *Energy* in *a Finlte* World, p 580

4. **These higher estimates for the amount of coal used for synfuels depend on a number of assumptions, including the greatly increased use of nuclear power to replace coal in electricity generation.**
5. **The following CONAES study estimates for the U.S. should be compared with the IIASA estimates for North America (see No. 1, p. 271 for population and economic figures; assume Canadian population is approximately 10 percent of total),**

Population in 2070—279 **million (Bureau of Census Series I I projection, with no allowance for illegal immigration).** [2]
Average growth in GNP, 1980-2010—2 **percent per year** [3]

Primary energy demand (Quads)
CO AfAES[4] *[United States on/y - 2010)*

Low [A]	*Medium [B]*	*High (C)*
70	*90*	130

IIASA[5] **(North America-Canada approximately 10 percent of total)**

	2000	2030
Low	99	131
High	120	180

Direct comparisons are difficult because of the different time frames and geographical areas examined. The CONAES A projection, no growth in energy demand over the next 30 years, has no parallel in the IIASA study. The IIASA low scenario is slightly higher than the CONAES series B projections; the high scenario is approximately equal to CONAES C. Population estimates are compatible; however, CONAES' 2 percent per year average GNP growth rate is much lower than IIASA's high scenario. It is approximately equal to the low scenario forecast.

Insofar as the two studies are comparable, CONAES' estimates are somewhat lower than IIASA's, with the more radical CONAES A projection much lower. The difficulty lies in determining what this might mean on a global scale. Lower estimates for the United States may hold true for other Western industrialized areas, but cannot be extended to developed centrally planned economies or to the developing world, where growth rates are expected to be higher than in the OECD. The CONAES report itself states that: "Even if energy conservation in the United States accomplishes a great deal domestically, it will be more than offset by demand growth in countries at the 'takeoff' stage of development " Global energy consumption in 2010 is estimated to be probably three to four times what it is now, with electrical consumption rising at even faster rates. [b]

6. **The Case Western Reserve and World Energy Conference estimates for future energy and electricity use are as follows:**

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[1] **Energy** *in Transition, 1985-2010* **(Washington, D C , National Academy of** Sciences, **1979), p 626**
[2] **I bid , p 643**
[3] **Ibid , p 645**
[4] **Ibid , p 668**
[5] **Energy** *in a Finite World A Global Systems Analysis,* **Energy Systems** Program **Group, I nternational I nstitute for** Applied **Systems** Analysis **(Cambridge, Mass** Ballinger Publishing Co , **1981), p 44o**
[a] *Energy In Transition,* **p 626)**

Energy demand (Quads

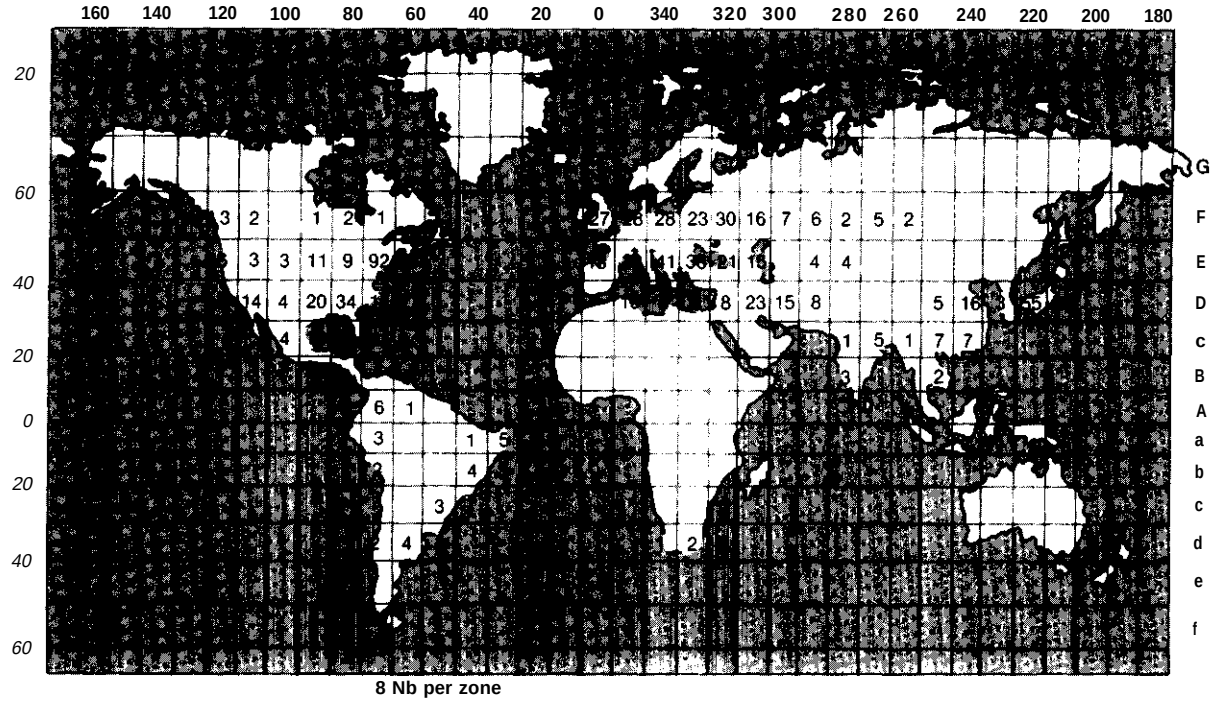
	1975	2000		2025/2020	
		CWRU	*WEC*	*C WRU*	**WEC**
OECD	146.8	3453	266.2	618,8	395.1
SU/EE	55.0	98.3	126,1	205.7	235.0
Developing, ...,...	37.7	103.0	174.0	296,8	434.2
Global.	239.5	5466	566.3	1,121.3	1,064.3

End-use electricity demand (Quads electric) (estimated by Clav. and Dupas from model data)

	1975	*2000*		2025/2020	
		CWRU	**WEC**	*CWRU*	*WEC*
OECD .,	12,5	55.8	386	106,9	66.1
SU/EE :	3.9	152	216	353	353
Developing .,	1.8	102	135	40.2	465
Global, ...	18,2	812	737	182,4	1479

Compare these figures to the lower IIASA estimates in figure C-1. The worldwide distribution of LEPP in 2025 for the CWR model is:

Figure C-1 .—Large Electric Powerplants in 2025



8 Nb per zone

SOURCE: From Claverie and Dupas, "Preliminary Evaluation of Ground and Space Solar Electricity Market in 2025, " 29th IAF Congress, October 1978

7. The World Bank report on Energy in the DevelopingCountries projects energy use and demand over the next decade. From 1973-78, growth in electricity consumption in developing countries averaged 8 percent per year, compared to 3.5 percent in developed countries; the Bank estimates this will continue through the 1980's. The Bank reports that in 1980 Oil-Importing Developing Countries (OIDC) invested $18.5 billion in electric power (70 percent for generation, 20 percent for distribution, 10 percent for transmission) out of a total of $24.6 billion invested in all forms of energy—over 75 percent. This is expected to more than double, to $39.7 billion/year, by 1990.

The amount of installed capacity is estimated to be 241 gW in 1980, rising to 523.7 in 1990. Large increases will be made in gas and nuclear fired generators though absolute levels will remain relatively low; hydro power will remain the largest single source, at approximately 40 percent of the total, with **oil generation declining rapidly from 37 to 25 percent. '**

'*Energy in the Developing Countries,* **World Bank, August 1980, pp 42-49**

ENVIRONMENT AND HEALTH

DOE Comparative Environmental Assessment

The Department of Energy (DOE) has sponsored comparative environmental assessments between the following energy technologies: conventional coal (CC), coal gasification/combined cycle (CG/CC), light water reactor (LWR), liquid metal fast breeder reactor (LMFBR), magnetically confined fusion (MC F), central station terrestrial photovoltaics (CTPV), and the reference system solar power satellite (SPS). An analysis was performed to quantify and compare the effects of these technologies on environmental welfare (i. e., effects that are not directly related to health and safety such as weather modification, resource depletion and noise), health and safety and resource requirements. Unquantifiable health impacts were also identified, but were not ranked (see table D-l). The major conclusions include:[1]

- **With respect to effects on the environmental welfare, all of the energy options except for coal (because of CO_2 climatic alterations and acid rain) are roughly comparable in magnitude, while different in nature.**
- **As shown in figure D-1, it is apparent that the quantified public and occupational health risks of all the technologies except coal are about the same in magnitude, but different in cause. The health effects that were not included in this analysis are listed in table D-1.**
- **Land use comparisons indicate that the land area required for SPS would be similar to that for CTPV. Coal utilizes slightly less total land area. This is distributed among many mining sites as opposed to the large contiguous land space needed for SPS and CTPV. The nuclear technologies require the least total land area.**
- **While each technology would encounter material constraints, none appear insurmountable. Water requirements are listed in table D-2.**
- **All technologies considered are not energy producers when operating fuel requirements are excluded from the calculations. Otherwise, only the inexhaustible technologies are net producers.**

Microwaves—Ionosphere Interaction

While only a small fraction of the incident microwave energy is absorbed by the ionosphere, the resultant heating at microwave frequencies could significantly alter the thermal budget of the ionosphere. In the lower ionosphere (D & E regions) a phenomenon called "enhanced electron heating" can occur if the microwave heating overwhelms the natural cooling mechanisms of the ionosphere. The resultant heating can then affect electron-ion recombination rates, changing ionospheric densities, or drive additional interactions. Furthermore, in the E region it is possible that the microwave heating could enhance natural density irregularities called "sporadic E" that can cause scintillations or scattering of radio frequency signals particularly in the very high frequency (VHF) band, e.g., citizen-band and some television bands.[2]

New experiments and theories were needed to understand the effects of an SPS microwave beam traveling through the ionosphere (an example of

[1] *Program Assessment Report, Statement of Findings,* Satellite Power Systems, **Concept Development and Evaluation Program, DOE/E R-0085, November 1980**

[2] W E Gordon and L M Duncan, "Reviews of Space Science–SPS Impacts on the Upper Atmosphere," *Astronautics arid Aeronautics,* July/August 1980, vol 18, NoS 7,8, p 46

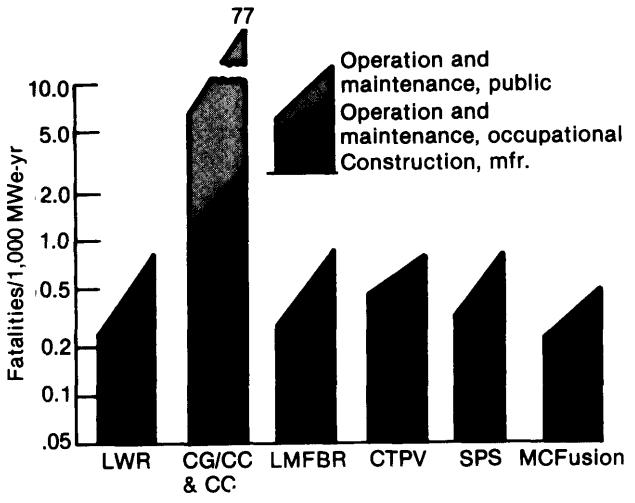
Table D.1 .—Unquantified Health Effects"

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.

SOURCE: *Program Assessment Report, Statement of Findings,* Satellite Power Systems, Concept Development and Evaluation Program, DOE/ER-0085, November 1980.

Figure D-1.—Quantified Health Effects



SOURCE: *Program Assessment Report, Statement of Findings,* SPS Concept and Evaluation Program, DOE/ER-0085, 1980.

Table D.2.—Water Requirements for Alternative Energy Technologies

Technology	Cubic meters per gigawatt year
Conventional coal	77x 10^6
Light water reactor	37x 10^6
Liquid metal fast breeder reactor	32X 10^6
Coal gasification/combined cycle	14x 10^6
Magnetically confined fusion	39x 10^6
Satellite power system	= 1 x 10^3
Central station terrestrial photovoltaics	= 1 x 10^4

SOURCE: *Program Assessment Report, Statement of Findings,* **Satellite Power Systems, Concept Development and Evaluation Program, DOE/ ER-0085. November 1980.**

what is called "underdense" heating) because almost all of the data generated in the past has focused on the "overdense" case, i.e., where the ionospheric density is great enough to *reflect* the incident heating frequency.

Two high frequency (HF) ground-based heating facilities have been used to simulate SPS heating in the lower ionosphere. At Arecibo, Puerto Rico, ionospheric physics and heating mechanisms have been studied. The Platteville facility in Colorado has tested the effects on specific radio frequency navigation and broadcasting systems, namely VLF (3 to 30 kHz, OMEGA), LF (30 to 300 kHz, LORAN-C), and MF (300 kHz to 3 MHz, AM).[3] However, neither Arecibo nor Platteville is equipped to generate a beam of SPS frequency and power density. Instead the experiments were performed at lower frequencies and power densities and the results extrapolated to SPS conditions using the scaling law:

$$\frac{P_{SPS}}{f^2_{SPS}} = \frac{P_{HF}}{f^2_{HF}}$$

where P_{sps} and P_{HF} are the power of the SPS beam (i.e., 23 mW/cm^2) and heating facility beam respectively, and f is the frequency of the beam (i. e., f_{sps} = 2.45 GHz).[4] This extrapolation is thought to be valid only if the primary heating mechanism is ohmic (i. e., heating by Collisions between ions). This assumption has been verified over a limited range of frequencies. By increasing the Platteville and Arecibo power densities and maximum frequency, confidence in the sealing theory could be improved. Experiments are also needed to test the effects of localized ionosphere heating on telecommunication systems operating at frequencies above 3 MHz.

In the upper ionosphere (F region), effects on telecommunications and on the SPS pilot beam stem primarily from a phenomenon called "thermal self focusing" which results **when an electromagnetic wave propagating through the ionosphere is focused and defocused as a result of normal variations in the index of refraction. As the incident wave refracts into regions of lesser density, the electric field intensity increases. Thermal pressure generated by ohmic heating drives the plasma from the focused areas, thereby amplifying the initial perturbation. Although the heated volume in the D and E regions is confined essentially to that of the beam, the heated particles in the F region will traverse magnetic field lines so that large-scale field-alined striations or density irregularities form. These striations reflect VHF and UHF radiowaves specularly, causing interference and the abnormal long-range propagation of the signals.**

Less is known about the effects of SPS-type heating in the F region than the D and E layers. The power scaling law in the upper ionosphere may differ from that in the lower regions (i.e., the scaling law for thermal self-focusing instability may follow a $1/f^3$ dependence rather than the $1/f^2$ dependence valid for ohmic heating). Experimental data is

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Environmental **Assessment for the** *Satellite* **Power System – Concept Development and** *Evaluation* **Program – Effects of** *Ionospheric* **Heat/rig on** *Telecommunications,* **DOE/NASA report, DOE/E R 10003-TI, August 1980**

[4] *Environmental* **Assessment for the** *Satellite* **Power** *System* **– Concept** *Development and Evaluation Program,* **DOE/E R-0069, August 1980**

needed to improve theory and test the effects on telecommunications.

A single SPS would cause the indicated ionosphere perturbations within a Volume approximately equal to the power beam dimensions. For muitiple SPS deployments (e.g., the 60 systems defined in the Reference Design) the cumulative effects of the perturbed volumes must be determined. One important question obviously concerns the possibility of coupling between adjacent volumes, and determining beam separation constraints to eliminate mutual coupling. [5]

The Effects of Space Vehicle Effluents on the Atmosphere

SPS reference system rocket exhaust products would affect every region of the atmosphere. In table D-3, the atmospheric effects of most concern are listed. As part of its assessment, DOE has also identified possible means of resolving these uncertainties in the event that an SPS program is pursued.

Troposphere [6]

SPS launch effluents injected into the troposphere could modify local weather and air quality on a short-term basis. These changes would be due primarily to the formation and dispersion of a launch site ground cloud that consists of exhaust gases, cooling water, and some sand and dust. While sulfur dioxide, carbon dioxide, and carbon monoxide concentrations would not be significant, nitrogen oxides and water vapor are of concern.

Nitrogen oxides (NO_x, especially NO, in the ground cloud, might under certain conditions, present problems for air quality. The projected ground cloud concentrations themselves are not thought to violate the short-term national ambient air quality standards that are expected to be promulgated in the near future, but if ambient concentrations are already high, a violation could occur. NO_x and SO_x in the ground cloud could contribute to an increase in localized acid rain but this is expected to be small.

The ground cloud will also contain about 400 to 650 tons of water. While having a negligible impact on air quality, water vapor, especially in association with launch-generated heat and condensation nuclei could have a measurable, although short-term effect on weather. In particular, under certain meteorological conditions, heat and moisture could enhance convective activity, and induce precipitation. While the frequency and degree of such effects are uncertain, none of the projected weather effects are thought to be serious. Cloud-condensation and ice-forming nuclei would also be produced in the ground cloud. The effects of the latter on weather cannot be reliably estimated at this time. The high abundance of the former in the ground cloud is thought to be meteorologically important; cloud-condensation nuclei could change the frequency and persistence of fog and haziness. It has been suggested that because of the large size and frequency of HLLV launches, cumulative effects might occur. More research is needed not only for SPS, but of weather and climate phenomena in general.

Research needs include:

- refine and test ground-cloud formation and transport predictive models as well as weather and climate models,
- update ground-cloud composition as systems are developed; conduct appropriate observations of rocket launches,
- study effects on local weather of prospective launch sites including possible cumulative effects, and
- consider NO_x effects and possible ways to reduce levels given a range of likely future standard levels and meteorological conditions; refine and validate theoretical models for simulating NO_x dispersion,

Stratosphere and Mesosphere

The upper atmosphere has received considerable public attention in the last decade, largely as a result of a number of studies examining the effects on the stratospheric ozone layers (which shield the Earth from biologically harmful ultraviolet radiation) of the supersonic transport, fluorocarbons, and the biological generation of nitrous oxide etc. [7,8] There is concern that while the potential effects on climate and terrestrial life of altering the upper atmosphere could be serious, our understanding of the physics and chemistry of the region is Incomplete. For example, it is known that the chemical composition of the upper atmosphere plays a key role in maintaining the Earth's thermal budget and is directly linked to the dynamics, cir-

[5] E Morrison, National Telecommunications and Information Administration, private communication, Feb 17, 1981

[6] Most of this section is derived from *Environmental* Assessment for *the Satellite* Power *System,* Concept Development and *Evaluation* Program, DO E/ ER-0069, August 1980

[7] The Aerosol Threat, " Newsweek, Oct 7, 1974, pp 74-75

[8] Climatic Impact Committee, NRC, *Environmental Impact of Stratospheric Flight* NAS, Washington, D C 1975

Table D-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 characterize better 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 NO_x 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 or anticipate 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.
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 percent 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 to 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.

SOURCE: *Program Assessment Report, Statement of Findings,* **Satellite Power Systems Concept Development and Evaluation Program,** DOE/ER-0085, **November 1980.**

culation and climate of the troposphere, but the mechanisms that couple the two regions are extremely complex and not well understood.[9] The SPS assessment relies mostly on theoretical models [10] One dimensional models predicting global average vertical transport of atmospheric constituents are used most extensively, although less-refined two **and three dimensional models are also**

[9] *Encyclopedia of Science* **and Technology** vol **1 (New** York McGraw-Hill **Book** Co **, 1977]**

[10] Supra **note b**

available. High-altitude experiments are needed to improve atmospheric theory and the data base for the SPS assessment.

The most significant SPS impacts would arise from the injection of rocket effluents, especially water vapor and reentry NO_x directly into the stratosphere and mesosphere. SPS vehicles emit CO, into the upper atmosphere but the amount is extremely small relative to existing levels and to the quantities generated by the consumption of fossil fuels. The effects of any impurities in the rocket fuel, such as sulfur would be negligible. Thermal energy is also injected by HLLV and PLV launches, but the effects are thought to be minor and transient.

Increases in water vapor would be of concern because its natural abundance in the upper atmosphere is very low. The most recent estimates indicate that the increase in the globally averaged concentration of water vapor due to 400 HLLV flights per year would be about 0.4 percent in the stratosphere (30 km) and 8 percent in the upper mesosphere (80 km). [2] Increases near the latitudes at which the water vapor was emitted could be higher due to a so-called "corridor effect" with increases in water content up to 15 percent above 80 km. " At 120 km and above, it is estimated that the global water content could be increased by a factor of 100 or more. [4]

The production of nitric oxide from the reentry of HLLVS is expected to increase significantly the naturally occurring NO_x concentration and to exhibit a pronounced long-term corridor effect in the NO_x distribution of the mesosphere. [5] Stratospheric NO_x levels would also be altered due to downward diffusion from the mesosphere, but would be confined mostly to the lower stratosphere where their impact would be negligible.

In the mesosphere, the injection of water could induce luminous, thin, or "noctilucent" clouds of ice crystals in the vicinity of the rocket exhaust. It is estimated that the cloud would expand from a size of 1 to 1,000 km^2 over 24 hours. [16] This finding is based on theoretical calculations and observations of other rocket launches that deposited far less water into the mesosphere than that which is projected for the HLLVS. The clouds are not thought to alter significantly the global climate, but in view of the poor understanding of the coupling between the mesosphere and troposphere, this expectation requires further analysis. A large unknown is the effect of the excess water content on temperature that may affect the likelihood and persistence of the clouds. [7]

In the stratosphere, detectable depletion or enhancement of the ozone layer from the emission of water and nitric oxide would be unlikely. While water vapor tends to decrease ozone, nitric oxide tends to increase it. The net effect of SPS reference system effluents is thought too small (i. e., either a decrease or increase on the order of 0.01 percent) relative to the natural fluctuations of the ozone concentration. [8] This conclusion requires further verification as it is based on one-dimensional models.

In addition to the formation of noctilucent clouds and perturbations of the ozone layer, the water vapor deposited in the stratosphere and mesosphere might contribute to a chronic partial depletion of the ionosphere. However, this is expected to be very small in comparison to the local depletions caused by rocket emissions directly into that region. '9 Climatic effects might occur from changes in the chemical composition of the upper atmosphere, although at present it is not possible to assess reliably any potential effects. Research priorities for SPS upper atmospheric effects include

- update emissions inventory and estimates of reentry NO_x;
- estimate magnitude of corridor effect and study possible temperature feedback mechanisms;
- identify and augment existing experimental programs to make high-altitude measurements of water and NO_x concentrations, study high-altitude water release data;
- assess the possibility and climatic impacts of noctilucent clouds;
- develop scenarios of SPS impacts on a number of different background conditions including future increases of $C0_2$;
- document and verify effects of effluents that are now thought to have a minor impact on the upper atmosphere; and
- determine telecommunicate ions effect of chronic, partial depletion of ionosphere (from water vapor injected in the stratosphere and mesosphere).

[4] Ibid

[5] Ibicl

[6] 'Program Assessment Report, Statement of Finding>, Satellite Power Systems Concept Development and Evaluation Program, DOE/NASA Report, DOE/E R-0085, November 1980

[7] "Environmental Assessment for the Satellite Power System – Concept Development and Evaluation Program – Atmospheric Effects, DOE/E R-0090, November 1980

[8] Supra note 9

[9] Supra note 6

[10] Supra note 6

Ionosphere

The ionosphere is used extensively in telecommunication systems to propagate and reflect radio waves. The injection and diffusion of SPS launch propellants into the ionosphere could alter the density of the electrons and ions that are responsible for the unique properties of the ionosphere, thereby degrading the performance of the telecommunications systems. Other effects might also occur, such as enhanced airglow and increased electron temperature, but the likelihood and consequences of these impacts are yet to be determined. 20

A reliable assessment of the effects of launch effluents on the D-region of the ionosphere cannot be made at this time. However, two apparently counteractive effects have been postulated. [21] The emission of water vapor into the D-region is likely to deplete the ionospheric plasma density. This would reduce radio wave absorption in the daytime ionosphere and result in propagation anomalies. On the other hand, NO_x, produced by frictional heating during reentry, could engender the formation of ions in the D-region. It is believed that enough NO_x would be deposited in the region to compensate for the reduction of the plasma due to water vapor. A recent lower ionosphere experiment suggests that anomalies in the propagation of VLF signals were due to the effects of rocket effluents. " While the experiment was not conclusive, it is clear that detectable effects might occur that warrant further study.

As in the D-region, current understanding of the launch effluent effects on the E-region is not very advanced. Rocket propellants would be directly injected only into the lower E-region because HLLV engines would be shut off at 124 km.[23] Some effluents would enter the upper E-region by upward diffusion. Exhaust products emitted above the E-region in LEO by PLVS, POTVS and HLLV could also diffuse and settle downwards. The impacts of these effluents on the E-region, however are very uncertain. It is possible that the deposition of ablation materials during reentry could augment a radio signal altering phenomenon called "sporadic E" in which regions of greatly enhanced electron concentration are created. In addition, the coupling between the ionosphere and magnetosphere, the ozone layer, air conductivity, and hence climate could be affected by the effluents but no reliable conclusions can be made at this time.

The effects of rocket exhaust products are better understood in the F-region, but the impact of SPS effluents is still not certain. This region is dominated by oxygen atoms that recombine more slowly with electrons than their molecular counterparts in the lower ionosphere. Exhaust products such as water, hydrogen and $C0_2$ emitted in the F-region become quickly ionized by charge exchange reactions with the existing atomicions.[24] These molecular ions rapidly recombine with the ionospheric electrons, thereby causing a region of pronounced depletion known as an "ionospheric hole." It has been estimated that for each POTV launch (which would occur once or twice a month), an ionospheric hole with an area two to three times the size of the continental United States[25] would be formed and persist for 4 to 16 hours. [26] Each HLLV launch (one or two per day) would produce a hole about one-tenth the size,[27] lasting 4 to 12 hours. It has been suggested that a long-term low-level depletion on the order of 10 percent would develop in a ring around the launch latitude as a result of multiple launches .28 The probable consequence of this depletion ring is a small perturbation of VLF, H F, and possibly VHF wave propagation.

These findings were based on a number of theoretical models of the ambient and perturbed F-region as well as several observations of rocket effluent-induced ionospheric holes. The models are fairly well developed and theoretical mechanisms are well understood, but care should be taken in scaling up radiowave propagation effects. Further study is required in order to predict accurately the location, size, movement, and lifetime of the hole as well as the cumulative effects of multiple launches.[29] An observation of ionosphere depletion inadvertently took place after a 1973 skylab flight that produced a hole 1,000 km in radius.[30] In 1977, experiments were conducted to purposefully produce an ionospheric hole.[31] The experiments, named Project LAGOPEDO tended to confirm the

[20] Supra note 9

[21] Ibid

[22] G Meltz and J A Darold, "VLF OMEGA Observations of the Ionospheric Disturbance produced by an Atlas HEAO-C Launch, " in *Proceedings of the* Workshop/Symposium *on the Preliminary* Evaluation of *the Ionospheric Disturbances Associated With the HEAO-C* Launch, With *Applications to the SPS Environmental* Assessment, M Mendillo and B Baumgardner (eds), DOE/NASA report Conf 7911108, August 1980

[23] Supra note 9

[24] E Bauer, *Proceedings of the Workshop on the Mod/ f/cation of the Upper Atmosphere by the Satellite Power System (SPS) Propulsion Effluents,* DO E/NASA Report Conf -7906180

[25] Supra note 14

[26] Supra note 6

[27] Supra note13

[28] Ibid

[29] Supra note 9

[30] M Mendillo, C Hawkins, and J Klobuchar, *An Ionospheric Total Electron Content Disturbance Associated With the Launch of NASA Skylab,* Air Force Cambridge Research Laboratories, July 1974

[31] Pongratz, et al , *Lagopedo-Two F-Region Ionospheric Depletion Experiments* Los Alamos Scientific Laboratory, LA-U R-77-2743

theory. Recently, DOE took advantage of the launch of NASA's High Energy Astrophysical Observatory (HEAO-C) by an Atlas/Centaur rocket in order to monitor the resultant large-scale (1 million to 3 million km^2) effluent-induced ionospheric hole, which persisted for approximately 3 hours.[32] The preliminary finding indicates that no severe long-term impacts on HF radio signals occured as a result, but that VLF transmissions (14 KHz) could have been affected.[33] On the whole, not enough is known about SPS-induced ionospheric holes to make conclusions about their impacts on telecommunications.

In addition to telecommunication effects, other potential effects of SPS rocket effluents deposited in the F-region have been suggested .34 Enhanced airglow emissions could affect astronomy, remote sensing, and surveillance systems. Past observations have noted enhancements on the order of 10 kilorayleighs for certain visible and near infrared emissions.[35] The magnitude and significance of SPS airglow emissions warrants further study. The injection of water vapor in the F-region might also perturb the thermal budget of that region. This would increase the ratio of cooling by radiation and perhaps alter the Van Allen belts and the amount of ionizing radiation in space. Also, as noted previously, the number of hydrogen atoms emitted by HLLV launches in the upper thermosphere and exosphere could be comparable to the number naturally present. This could increase satellite drag, alter the Van Allen belts, and affect radio communications. The water budget of these regions is not well understood however, and so the probability of these effects is not known.

Research should focus on the following areas:

- improve understanding of D&E region effects;
- refine studies of F-region ionospheric holes in order to predict location, size, movement, and lifetime;
- test effects on telecommunications systems using D, E, and F regions; and
- assess airglow effects perhaps with the involvement of the remote sensing and astronomy communities. [36]

Thermosphere and Exosphere

As discussed above in the *Stratosphere and Mesosphere* summary, HLLV flights are predicted to substantially increase the natural water content above 80 km. One consequence of this excess could be an increase and, perhaps, doubling of the upward flux of hydrogen atoms that result from the breakdown of the molecular water vapor as well as molecular hydrogen emitted above 56 km by HLLVS, PLVS and POTVs.[37] While it is fairly certain that an increase in the hydrogen flux would result, the consequences of a perturbed hydrogen cycle are quite uncertain. The hydrogen escape rate into outer space could increase. Accumulation of hydrogen above 800 km might also occur, thereby possibly altering thermospheric and exospheric dynamics and enhancing satellite drag.

Research is needed to:

- improve understanding of the natural hydrogen cycle and dynamic processes of the thermosphere and exosphere; and
- design models to quantify hydrogen increases and simulate SPS effects on a global scale.

Plasmasphere and Magnetosphere

SPS reference system effects on the plasmasphere and magnetosphere result primarily from the emission of COTV argon ions and POTV hydrogen atoms as the vehicles move between LEO and GEO. [38] The impacts of these effluents could be great, because the energies and number of ions and atoms injected would be substantial relative to the ambient values. Unfortunately, the magnetosphere and plasmasphere are poorly understood. While some potential SPS impacts have been identified as shown in table D-4, their probability and severity cannot be assessed since no experimental data relevant to SPS exists for these regions. I n particular, the consequences and the mechanism of interaction between the argon ions and the ambient plasma and geomagnetic field must be explored.

In addition to the exhaust products, the satellites themselves could also have an impact on the magnetosphere by obstructing plasma flow, or producing dust clouds, electromagnetic disturbances, space debris, visible and infrared radiation, and high-energy electrons.[39] Little emphasis has been placed on these potential effects, however, because they are thought to be minor and easily reinedied.

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[12] M Mendillo and B Baumgardner, *Proceedings of the Workshop/Sumposium on the Preliminary Evaluation of the Ionospheric Disturbances Associated With the HEAO-C Launch, With Applications to the SPS Environmental* Assessment, DOE/NASA Report Conf 7911108, August 1980

[13] Ibid

[14] Supra note 9

[15] Supra note13

[16] Ibid

[17] Supra note 6

[18] Supra note 9

[19] Ibid

Table D-4.—Satellite Power System Magnetospheric Effects

Effect	Cause	Mechanism	System/activities impacted
1. Dosage enhancement of trapped relativistic electrons	**O + and Ar + in magnetosphere due to exhaust and plasmasphere heating**	**Thermal heavy ions suppress ring-current-ion cyclotron turbulence, which keeps electron dosage in balance in natural state**	**—Space equipment —Modification of human space activity**
2. Artificial ionospheric current	**Ionospheric electric field induced by argon beam**	**Beam induced Alfven shocks propagate into ionosphere**	—Powerline tripping —Pipeline corrosion (probably unimportant)
3. Modified auroral response to solar activity	Neutrals and heavy ions in large quantities	Rapid charge-exchange loss of ring-current particles	—May reduce magnetic storm interference with Earth and space-based systems
4. Artificial airglow	3.5 keV argon ions	Direct impact on atmosphere from LEO source	—Interference with optical Earth sensors
5. Plasma density disturbance on small spatial scale	Plasma injection	Plasma instabilities	—Signal scintillation for space-based communications

SOURCE: *Environmental Assessment for the Satellite Power System, Concept Development and Evaluati Program—Atmospheric Effects,* DOE/ER-0090, November 1980.

If an SPS program is conducted, it is clear that the design of transport vehicles for the outer regions of the atmosphere and the environmental assessment of their impacts in these regions will be closely linked. Possible methods of reducing adverse effects include the use of both chemical and argon ion engines or an alternative propulsion system in the COTV, and lunar mining.

Near term studies include:

- **design and implement experiments in the magnetosphere and the laboratory to test SPS effects and increase theoretical understanding of magnetospheric phenomena.**

The Electromagnetic Characteristics of the Alternative SPS Satellites

Microwave Satellites

The satellite would generate microwave power at a frequency of 2.45 GHz or some other central radio frequency, thermal radiation, and reflected sunlight at all solar wavelengths. In addition, it would generate some power at multiples of the central frequency (harmonics), and also spurious noise on either side of the central frequency. Because the reference system is the only system for which an attempt has been made to characterize a system completely, this report will use its characteristics as an illustrative model for all microwave systems.

The space antenna would radiate a total of 6,720 MW of microwave power towards Earth. The reference system design calls for the power distribution over the face of the satellite antenna to be gaussian with a 10-d B taper. The resulting beam pattern is shown in figure 40, p. 211. Atmospheric scattering and attenuation due to absorption, in addition to losses at the rectenna would reduce the usable power at the rectenna to 5,000 MW. The following radiative effects are the most important for the reference system (fig. D-2):

- *Out-of-band radio frequency* **emissions. The reference system's klystrons are estimated to radiate energy at the following harmonic frequencies:** [40]

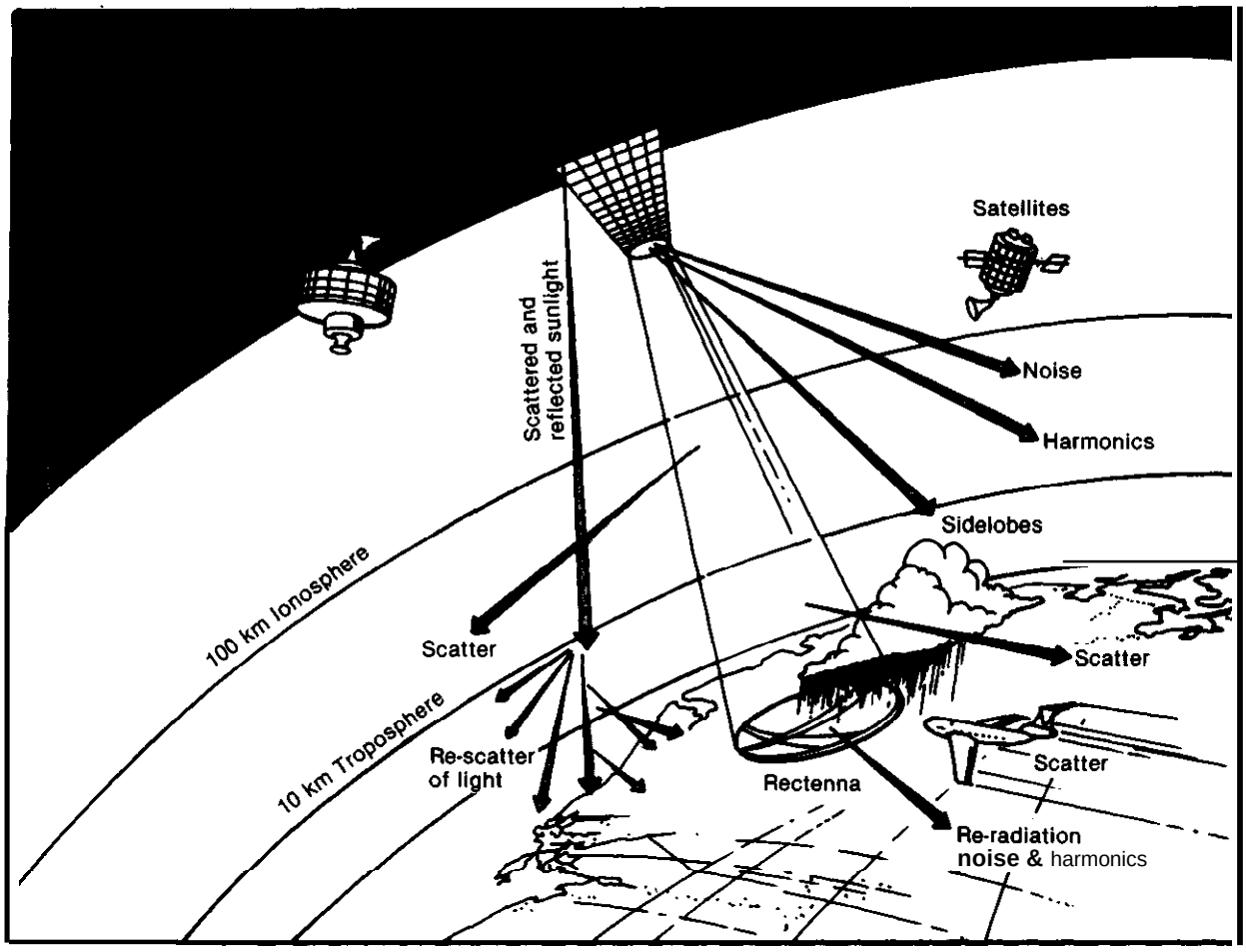
Frequency (C HZ)	*Power level (times 6,720 MW)*
245- **(central frequency)**	1
490- (second harmonic)	**-50d B(10-^{5})**
7 35- (third harmonic)	**-90d B(10-^{9})**
980- (fourth harmonic)	**-lOOd B(10 ^{10})**

Although it is known that the antenna patterns for these frequencies would be rather different from that of the reference system, current antenna theory is inadequate to predict a detailed spatial pattern.

Spurious sideband noise generation from the klystrons outside of the central frequency is estimated to be no greater than – *200* **d B of the central frequency at a separation of 8 to 10 MHz from the center frequency. Filtering may be able to reduce this to levels which would not cause appreciable interference in most cases This is one constraint in the separation necessary between an SPS frequency assignment and the boundaries of the 2.45 GHz International Scientific and Medical band. These considerations apply after the klystron tubes have warmed up. Since, on the average the**

[4] G D Arndt and L Leopold, "Environmental Considerations for the Microwave Beam from a Solar Power Satellite," *13th Intersociety Energy Conversion Engineering Conference,* San Diego, Calif , August 1978

Figure D-2.–Overview of Potential SPS Electromagnetic=Compatibiiity **impacts**



SOURCE: *Environmental Assessment for the Satellite* Power *System (SPS),* Concept Development and Evaluation Program (CDEP). DOE/ER-0036/1, p. 43,

100,000 klystrons in the antenna can be expected to fail at a rate of five per day, out of band radiation as they fail and as they warm up after being replaced may be greater than during their operating period.

The reflected beam at 2.45 GHz, at the harmonics, as well as at other frequencies generated by the rectenna structure itself, would result in a complicated power spectrum which would change in time as the rectenna ages. The radiation patterns are expected to be 100 or broader and partially directive. A capability to monitor and locate rectenna intermodulation emissions is required to allow timely structural repair to assure no interference with sensitive terrestrial and aircraft equipment.

- Optical and thermal emissions. The reference satellites would reflect sunlight in three major ways[41 42] 1) diffuse reflections from the solar arrays, the antenna and the underlying structure; 2) specular mirror-like reflections from the solar arrays and the antenna; 3) glints or specular reflections from the underlying structure. Diffuse reflections would cause each satellite to appear as bright as the planet Venus at its brightest phase (magnitude – 4.3). Specular reflections would occur near the equinoxes just at local sunrise or sunset (i. e., on the same meridian as the satellite) and would cause a 330-km wide spot of light several times brighter than the full Moon to sweep

[41] P A E kstrom and G M Stokes (eds), "Workshop on Satellite Power Systems(SPS) Effects on Optical and Radio Astronomy, " CON F-7905143 (DOE], 1980

[42] J L I ivingston, "Apparent 1 uminosity of Solar Power Satellites, " *SpaceSolar Power Review1, 1980,* pp 175190

across the affected area in a few minutes. Glints from components of the satellite's structure are not expected to be as serious as the diffuse or specular reflections and in any event, may be significantly reduced or eliminated by proper structural design.

In addition to reflecting sunlight, the satellite would also emit thermal radiation of an estimated intensity of 6.3 $\times 10^{6}$ watts per square meter at the Earth. The precise wavelength peak depends on the details of the characteristics of the satellite's components (e.g., type of cell, type of antireflection coating, etc.) but would likely fall in the 5 to 10 micron band. The thermal radiation is expected to exceed Slightly current interference levels.

Laser Satellites

As with the other characteristics of laser systems, the electromagnetic characteristics of the laser satellite are ill defined. However, the following general radiation effects can be expected. Quantitative data will be available only after the systems become more highly defined.

In general, laser systems would reflect sunlight from the laser platform and from the relay mirrors in LEO and CEO, if any. I n addition, they would radiate thermal energy, most probably in the 5 to 10 micron region of the infrared. They would also be detectable as a thermal source of microwave power.

- *Reflected sunlight.* The brightness of laser satellites at CEO or LEO would depend on the mode of power Collection and conversion (e. g., photovoltaic or direct solar pumped) and the overall size of the satellite. Optically, the most important differences are that the LEO satellite would be brighter and perceived as moving slowly by terrestrial observers.

  Because they would be smaller than the reference system satellites, individually they would also be less bright. However, there will be more of them. (If laser satellites could be made to operate with the same efficiency as the microwave designs, five 1,000-MW or ten 500-MW satellites would be needed to equal reference system capacity.) Laser relay mirrors in LEO and GEO would contribute both stationary and moving sources of light. However, because of their small size (several meters), they are not expected to be readily visible from Earth.

- *Heat radiation.* Because an appreciable amount of the sunlight which is intercepted by the laser satellite would be absorbed and re-emitted as heat, the satellite, whether in CEO or LEO, would be a diffuse infrared radiator and would radiate some energy at microwave frequencies as well.
- *Laser beam characteristics.* The two major present laser alternatives operate near 5 microns (CO laser) or 10 microns (CO^2 laser) infrared wavelengths. Because the beams are highly directive, they would be only slightly observable in the infrared except for receivers placed very near the laser ground stations. Scattered light from the beam would be detectable in the lower part of the atmosphere.

Mirror Satellites

Because the mirrors are designed to reflect sun light only, their emissions would be only slightly altered from the original solar spectrum (i. e., they wouldn't radiate appreciable infrared or microwave radiation). Those emissions would be large, however, for the ground base into which the sunlight is directly reflected (i.e., the equivalent of one Sun).

- Terrestrial observers away from the ground site would see moving patches of light about 0.5 min arc across surrounded by an aureole of scattered light. The precise apparent brightness of the mirrors will depend on a number of factors, e.g., the orientation of the mirror with respect to the observer, the relative position of the Sun from both the mirror and the observer, the albedo of the reverse side of the mirrors, and the atmospheric conditions above the ground station. Low-intensity scattered sunlight from aerosols and dust high in the atmosphere would be observable at up to 150 km from the ground station.

The Interaction Between Biological Systems and Electromagnetic Waves

Microwave radiation is a form of electromagnetic energy which is used in numerous commercial, industrial, military, and medical devices including microwave ovens, radar, diathermy equipment, and sealing instruments. The microwave band accounts for frequencies ranging from 300 MHz to 300 GHz,

The extent and consequence of exposure of biological systems to microwaves depends on the following characteristics of the incident energy, the biological organism, and surrounding environment:[43]

- *Frequency of electromagnetic radiation.* — The *frequency* of radiation is the number of complete oscillations per second of an electromagnetic wave. The energy of the radiation is directly proportional to the frequency. Although the frequency of microwaves is high, it is not high enough for the quanta to ionize, i.e., to eject an electron from a molecule or atom; hence microwaves are called "nonionizing. " The bioeffects of X-rays and other ionizing radiation are known to be more severe than those resulting from the nonionizing portion of the spectrum.

  The frequency also determines the depth of *penetration* when an electromagnetic wave is incident on biological material. In general, the lower the frequency, the greater the depth of penetration. For example, infrared waves penetrate no deeper than human skin, whereas microwaves (which are lower in frequency) penetrate through the skin and fat and into human muscle.[44] The relationship between frequency or wavelength (frequency is inversely proportional to wavelength) and the size of the irradiated body is also important. *Resonance* (i. e., most efficient absorption) will occur when the length of an organism measures approximately half of a wavelength of the incident electromagnetic field. For example, the resonance frequency at which the absorption rate is maximized for the male human body is on the order of 70 to 100 MHz, whereas the maximum absorption rate for rats occurs at 2.45 GHz.[45] Thus, an electromagnetic wave may elicit a very different response from organisms of two different sizes (assuming that the amount of energy absorbed is the dominant determinant of a biological response).

  Understanding of the functional dependence of bioeffects on frequency is not complete. The existence of frequency windows, i.e., effects observed over one specific range of frequencies is not well-understood.
- Intensity of incident wave. –The energy carried by an electromagnetic wave per unit area and time is called its power density and is measured in units of milliwatts per square centimeter (mW/cm^2). Heating or thermal effects are generally thought to occur at power densities greater than 10 mW/cm^2. Effects at much lower power densities have been postulated but the existence and consequence of "*nonthermal*" phenomena remains in dispute. Power density *windows* have been observed experimentally in which bioeffects are noted only over a specific range of power densities and not above or below.

  Recently, the microwave community has adopted the specific absorption rate (SAR) as a measure of the energy absorbed by a biological organism. The SAR is expressed in units of milliwatts per gram (mW/gm). It is a function of the power density and weight of the irradiated organism. While the SAR provides more information about the bioeffects of microwaves than it does of the power density alone, it cannot be used to entirely predict the effects of exposure to microwaves. The SAR is averaged over the entire body; it does not consider energy absorbed differentially in specific body parts. It also does not account for possible nonthermal effects. Furthermore, it does not measure the "biological effectiveness" of a microwave, i.e., its ability to induce an effect which is dependent on parameters such as the relation between the frequency and size of subject or body part.
- *Duration of exposure.* – For thermal effects, the length of exposure may influence the body's ability to cool. Heating resulting from long duration exposure of high-intensity waves may overwhelm the natural cooling system. At lower power densities, i.e., "nonthermal" levels, the cumulative or long-term effects are not known.
- *Waveform.* – It is thought that the biological consequences of exposure to continuous wave radiation is usually less severe than from that which is pulsed or modulated, although basic appreciation of the mechanisms of interaction is lacking,
- *Subject characteristics.* – Bioeffects are species-specific, primarily because the factors which determine energy absorption such as size, structure, body, insulation, and heat dis-

[43] 'For a more detailed discussion of the biophysics of microwave interactions with biological systems, see S Baranski and P Czeiski, *Biological Effects of Microwaves,* Dowden, Hutchinson and Ross, Inc , Pennsylvania, 1976

[44] R D Phillips, et al , *Compilation and Assessment of Microwave Bioeffects A Selective Review of the Literature on the Biological Effects of Microwaves in Relation to the Satellite Power System (SPS),* final report, DOE/NASA, May 1978

[45] E Berman, "A Review of SPS-Related Microwaves on Reproduction and Teratology", in *The Final* Proceedings of *the Solar Power Satellite Program Review,* Apr 22-25, 1980, DOE/NASA report Conf -800491, July 1980

sipation, and adaptive mechanisms vary with species. The composition and geometry of biological matter also determine the depth of penetration and wave characteristics; tissue, muscle, and fat each exhibit different dielectric and conductive properties. Thus, without adequate theories of interaction, extrapolations from animal studies to human bioeffects are extremely difficult. The sex, age, and state of health of an irradiated subject may also be an important factor, since size and susceptibility to certain kinds of effects may differ with respect to these parameters. It also appears that electromagnetic radiation may act synergistically with drugs. The differential absorption of energy may result in hotspots. This relatively increased energy deposition in cells, organs or parts of the body relative to its surroundings could lead to very specific biological effects after exposure.

The orientation of the organism with respect to the electric field component of the wave is also important—the most energy is absorbed when the electric field is parallel to the long axis of the body. In animal experiments, physical restraints or sedation might influence study results. Measurement devices such as implanted probes could also alter the field distribution. The prediction of bioeffects may also be complicated by movement of the subject in the field which changes the absorbed energy dosage and may result in modulation of the field.

The effects of whole body irradiation may differ from partial body exposure. In addition, for either whole or partial body irradiation, smaller body parts could resonate if the frequency used was in resonance with that part of the body.

- Environment. –The humidity, temperature, and air circulation of the surrounding environment will affect the ability of a heated biological entity to cool. Objects near the electromagnetic field could also enhance, reflect, absorb or distort it. For SPS, the effects of the space environment on the biological response to microwaves are not known.

SPS-Related Microwave Bioeffects Experiments (conducted by DOE, EPA)

In conjunction with the SPS DOE assessment, three studies were initiated and managed by EPA.[46]

- Exposure of bees to 2.45 GHz at 3, 6, 9, 25 and 50-mW/cm^2. No statistically significant effects on behavior, development, or navigation have been observed following short-term exposure. Long-term exposures are planned and should clarify this possible effect. It has also been proposed that tests of effects on bee navigation be carried out in the absence of sunlight (which may possibly mask microwave induced effects).
- Immunology and hematology studies of small mammals exposed for short durations to about 20 mW/cm^2, 2.45 GHz microwaves. No effects have been reported so far.
- Experiments testing the effects on the behavioral and navigational capability of birds subjected to acute and chronic exposures of 2.45 GHz fields. Some mortality has resulted from exposure to 130 to 160 mW/cm^2 microwaves and has suggested that species and body geometry determine tolerance levels. Generally, no statistically significant effects have been detected at power densities of 0.1 to 25 mW/cm^2. Some birds chronically exposed to 25 mW/cm^2 have exhibited an increase of aggressive behavior, although the number of birds is statistically insignificant.

Laser Bioeffects

Lasers are unique among light sources because of their capacity to deliver an enormous amount of energy to a very small area at a great distance.[47] The primary biological consequence of this property is heating. However, nonthermal mechanisms

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[46] C H Dodge, Rapporteur, *Workshop on Mechanisms Underlying Effects of Long-Term, Low-Level, 2450 MHz Radiation* on People, organized by the National Research Council Committee on Satellite Power Systems, Environmental Studies Board, National Academy of Sciences, July 15-17, 1980

[47] E. Klein "Hazards of the Laser," *Hospital Practice*, May 1967, pp 48-53

have also been suggested.[48] For example, photochemical reactions are thought to be responsible for damage of biological organisms exposed to ultraviolet lasers.[49] High laser power densities may also cause injury from shockwaves or high electric field gradients.[50] Biological electromagnetic interference effects have also been proposed.[51] Clearly, the mechanisms of interaction between laser light and biological entities are not completely understood. Like microwaves, little is known about the cumulative or delayed effects of chronic exposure to low levels of laser light.[52] In general, the higher the power and the shorter the period, the greater the damage.[53] The extent of the effect also depends markedly on the characteristics of the irradiated biological material. Of primary importance is a tissue's absorptivity, reflectivity, water content, and thermal conductivity.

The organ of the body most sensitive to laser radiation is the eye. The ocular media of the human eye transmit light with wavelengths between 400 and 1,400 nm.[54] There are two transmission peaks in the near infrared at 1,100 and 1,300 nm. Light in the visible and near infrared spectrum is focused towards the retina. The refraction of the laser beam by the ocular media amplifies the light intensity by several orders of magnitude.[55] As a result, in this spectral region the retina can be damaged at radiation levels which are far less than those which produce corneal or skin damage.

For lasers that emit wavelengths outside of the visible and near infrared range, the ocular effects are quite different. At ultraviolet wavelengths, for example, light is absorbed primarily by the cornea, which can be injured by photochemical reactions. Infrared radiation is not focused on the retina either, but is absorbed by the cornea and lens. Most of the radiation from the $C0_2$ laser is absorbed in the 7 nm tear layer of the cornea.[56] Continuous irradiances of the order of 10 W/cm^2 could produce lesions within the blink reflex.[57] Corneal damage may be reversible or repairable but severe damage may result in permanent scarring, blurred vision, and opacities.[58] The lens is particularly susceptible to injury because of its inability to eliminate damaged cells. Lenticular damage characterized by cataracts or clouding may occur at irradiance levels that do not produce corneal injury. For example, "glassblowers cataracts" are thought to result from chronic exposure to 0.08 to 0.4 W/cm^2 infrared radiation.[59] Proposed thermal limits for pulsed $C0_2$ lasers range from 0.2 to 1.0 W/cm^2, '0 but this recommendation requires further study.

Effects on the skin from absorbed radiation may vary from mild erythema (sunburn) to blistering and/or charring.[61] The principal mechanisms of injury by infrared radiation are thermal and are a function of tissue reflectance, spectral depth of penetration, and the size of irradiated area. Since thermal burns are produced at temperatures higher than that which causes pain, in most present occupational situations the pain can serve as warning. A definite sensation of warmth is produced from $C0_2$ lasers at 0.2 W/cm^2 over an irradiated area only 1-cm diameter, or 0.01 W/cm^2 for full body exposure.[62] Heat stress should not be overlooked. More research is needed to determine the effects of chronic or repeated exposures.

As was the case for exposure to microwaves, the determination of laser thresholds and standards is exacerbated by problems of detection and measurement, instrument sensitivity, dosimetry, interspecies and interfrequency extrapolation, and lack of complete knowledge of physiological systems, mechanisms of interaction, and synergistic effects.

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[48] V T Tomberg, "Non-Thermal Biological Effects of Laser Beams," *Nature*, vol 204, Nov 28, 1964, pp 868-870

[49] "Department of the Air Force, *Health Hazards Control for Laser Radiation*, AFOSH Standard 161-10, May 30, 1980

[50] Ibid

[51] M Zaret, "Laser Application in the Field of Medicine," *ZAMP*, vol 16, 1965, pp 178-79

[52] M L Wolbarsht and D H Sliney, "Needed More Data on Eye Damage," *Laser Focus*, December 1974, pp 11-13

[53] Supra note 47

[54] W T Ham, et al, "The Eye Problem in Laser Safety," Arch *Environmental Health*, vol 20, February 1970, pp 1 56-160

[55] D H Sliney and B C Fresier, "Evaluation of Optical Radiation Hazards," *Applied Optics*, vol 12, No 1, january 1973, pp 1-24

[56] US Army Environmental Hygience Agency, *Laser and Optical Hazards* Course *Manual*, Aberdeen Proving Ground, Md, 8th ed, January 1979

[57] D H Sliney, K W Vorpahl, and D C Winburn, "Environmental Health Hazards From High-Powered Infrared Laser Devices," *Arch Environmental Health*, vol 30, April 1975, pp 174-179

[58] Supra note 47

[59] Supra note 55

[61] Supra note 49

[62] Ibid

[63] Supra note 55

Experiments also make clear that the extent of the superficial or immediate lesion is no gage of total damage. '3

The exposure limit for continuous wave infrared lasers as recommended by ANSI is 100 mW/cm^2 for exposures over 10 seconds and for small spot sizes on the skin or eyes.[64] A whole body irradiance limit of 10 mW/cm^2 has been suggested .65 It should be stressed that the protection standards for repetitive and chronic exposures and for wavelengths outside the visible band are based on a considerable amount of extrapolation. Data obtained from non-laser sources, such as bright, small-source lamps and high luminance extended sources cannot accurately and wholly represent the effects of laser radiation in determining injury thresholds for ultraviolet and infrared lasers directly.

General Health and Safety of SPS Space Workers*

The human body's tolerance to acceleration depends on the duration and magnitude of the acceleration, the positioning of the body relative to the accelerating force, the restraint and support systems of the spacecraft and the time spent in a weightless state. " Research is needed to quantify effects as a function of these parameters and to determine the tradeoffs between short duration, high acceleration and longer duration, lower acceleration effects. Studies should also evaluate the tolerance in the population that may fly in space (since variation in individual response levels are great) and explore possible ways to reduce harmful effects. "

Weightlessness is known to induce a number of physiological responses such as decreased heart rate, shifting of fluids to the upper body, decrease of muscle mass and loss of bone minerals .68 Most of the observed effects have been temporary; only bone calcium loss appears to require a long period of recovery following return from space.[69] For SPS, however, the effects of periodic weightlessness over a long time period need to be investigated. Moreover, ameliorative measures suitable for a large number of people with broad physiological characteristics must be investigated .'"

Workers would be exposed to electric fields generated by the collection and transmission of large amounts of electricity across the solar panel and antenna, but effects of electric and magnetic fields on biological systems are not well-understood.[71] Research is needed to determine the bioeffects of magnetic fields generated by satellite electric currents, as well as to assess the effects of field absence over extended stays in orbit, as CEO is largely outside of the Earth's magnetic field. Some space workers could also be exposed to high levels of microwaves. The effects of microwaves in a space environment deserves special attention. It is known, for example, that microwaves can work synergistically with ionizing radiation to increase the biological effectiveness of the latter. " Research would be required to determine bioeffects and if possible, to develop suitable exposure limits and protective clothing.

Psychological impacts must also be assessed, especially since there is little information on large, mixed gender groups working in close confinement for prolonged periods. Studies should also consider the effects on workers' families and friends and possible mitigation measures such as careful worker selection, recreation facilities, social management, etc.

Space workers could be prone to greater safety risks than their terrestrial counterparts because of the possible awkwardness of working without gravity.[73] Risks also stem from the high-voltage equipment and handling of toxic materials. There is a danger that spacecraft charging could produce electric shocks great enough to injure or kill workers, although this might be avoided by a judicious choice of spacecraft material. Catastrophic Collisions with meteoroids or space debris are also possible, given SPS's large size. Extravehicular activity may also create hazards.

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[*] Supra note 47

[64] *American National Standard for the* Safe *Use of Lasers,* ANSI (R) Z136 1-1979, American National Standard Institute

[65] D H Sliney and D L Conover, "Nonionizing Radiation" in *Industrial Environmental Health,* L V Cralley and P R Atkins (eds) (New York Academic Press, 1975), pp 157-172

*See text for discussion of ionizing radiation effects

[66] *Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program,* DOE/E R-0069, August 1980

[67] Ibid

"*Program Assessment Report, Statement of Findings,* Satellite Power System Concept Development and Evaluation Program, DOE/E R-0085, November 1980

[69] Ibid

[70] Ibid

[71] Supra note 66

[72] Baranski and P Czerski, *Biological Effects of Microwaves,* Dowden, Hutchinson and Ross, Pennsylvania, 1976

[73] Supra note 66

Appendix E

EXAMPLES OF INTERNATIONAL COOPERATION

Part 1

Intelsat was preceded by the formation of a domestic company, Comsat. In 1962 the Federal Government, after extensive debate over the proper degree of Federal involvement, chartered Comsat Corp. to provide a commercial communications satellite system "in conjunction and cooperation with other countries . . which will serve the communication needs of the United States and other countries, and which will contribute to world peace and understanding.'" Comsat was not directly owned or run by the Government; it issued shares of voting public stock (which were immediately over-subscribed), with 50 percent of these reserved for "common carriers"—AT&T, ITT, Western Union, and others. The Board of Directors consisted of three Presidential appointees, six common carrier representatives, and six elected at large. However, although Comsat was not directly financed by the Government, it received and continued to receive the benefit of extensive NASA-sponsored development of communication satellites and launch-vehicles, free of charge–some several billion dollars worth. (NASA research on communications satellites was cut back under the Nixon administration but reemphasized in the Carter administration's October 1978 White House Fact Sheet, largely as a result of increased competition from Japan and Western Europe.)

Under its charter, Comsat was allowed to enter directly into negotiations with foreign entities with the supervision and assistance of the State Department. In 1963, a U.S. negotiating team proposed a framework for an international telecommunications satellite organization: Intelsat. In a series of meetings details were agreed on: 1) that Comsat would be the consortium manager[2] and majority owner, with an initial 61 percent of the shares; 2) that ownership and utilization charges, as well as voting, would be in proportion to the use of the system by each participant, readjusted on an annual basis, and that membership would be open to all ITU member nations, with a minimum 15-percent share needed for representation and voting; 3) there would be two levels of agreement, one directly by nations, the other by designated agencies ("signatories"), one per nation; 4) that Intelsat would be restricted to providing services between countries, not within countries; 5) the interim agreements would last 5 years, at which point permanent arrangements would be agreed on.

One immediate result was the refusal of the Soviet Union and East Europe to participate. The Soviets used only a miniscule amount of global communications traffic, some 1 percent, and would not join an organization dominated by the United States and West Europe. They began developing their own domestic system (Molniya), which later formed the core of their international system, Intersputnik, covering the Soviet Union, East Europe, Cuba, and Mongolia.

When the interim agreements were renegotiated, from 1969 to 1971, the basic structure was retained. However, a number of changes were made, many of them designed to reduce U.S. dominance and to increase the direct role of national governments.[3] Comsat was phased-out as the manager, management being turned over to a Director General, responsible to a Board of Governors composed (in 1979) of the 27 largest participants or groups of participants, representing a total of 83 signatories. A new voting structure was established to prevent de facto U.S. veto power. The minimum participation was lowered to 0.05 percent. All signatories and states parties were entitled to receive free, technical information generated by Intel sat contracts. Intel sat was allowed to provide services to domestic and regional satellite groups. Net property in 1980 is valued at $663 mill ion, with $523 million of that in the space segment proper. Return on investment in 1979 was better than 14 percent.[4]

Part 2

Like Intelsat, Inmarsat is a commercial, profit-making venture with a corporate structure and independent legal personality. Comsat is the U.S. signatory, holding the largest original share at 17 percent; Great Britain is second with 12 percent, the Soviet Union third with 11 percent. ' Initial capitalization was set at $200 million.

Because it could participate on a more equitable basis, the Soviet Union joined Inmarsat; one conse-

[1] "Communications Satellite Act of 1962, in *Space Law, Selected Basic Documents*, Senate Committee on Commerce, Science, and Transportation, Dec 1978, p 523

[2] Joseph N Pelton, *Global Communications Satellite Policy Intelsat, Politics and Functionalism* (Mt Airy, Md Lomond Books, 1974), p 76 (p 55)

[3] Richard Colino, *The Intelsat Definitive Arrangements (Geneva* European Broadcasting Union, 1973), p 11-12

[4] *Intelsat Annual Report 1980* Intelsat, Washington, D C , p 21

[5] "Operating Agreement on Inmarsat," 1976, in *Space Law*, p 445

quence was Soviet insistence that nongovernmental signatories —e.g., Comsat and Japan's Kokusai Denshin, Ltd.—be guaranteed by their governments. It has been pointed out that the Soviet Union "is disinclined to enter mixed organizations involving states and private enterprise, " preferring to deal only with other states. [6]

Part 3

The vast majority of Intelsat signatories were government communications agencies. Only in a few instances, such as Comsat for the United States, and Interspazio for Italy, were the signatories separate corporate entities designed for communication satellite operations. One result was a conflict of interest within agencies that were involved in other communication systems, especially underwater cables. Differences of opinion also developed between Comsat, which wanted to expand Intel sat into as many other areas, including domestic communications, as possible; and agencies that wanted Intelsat's scope restricted to international telephone and television relay.

At the beginning, Comsat, with headquarters in Washington, D. C., was the managing agency; American launchers were used through NASA; and the satellites themselves were built by U.S. firms — (Hughes for Intelsat I, II, IV, and IV-A; TRW for Intelsat III; Ford Aerospace for Intel sat V). The initial agreement was structured in such a way that U.S. participation could never be less than 50.6 percent. [7]

Initially, participation by lesser developed coun- in numbers, tensions developed between LDCs, Europeans, and the United States over the distribution of benefits. One issue concerned the relative investment between satellites and ground stations. Since users were responsible for building their own Earth stations, LDCs and others with fewer resources and lower usage urged Intelsat to increase the size and complexity of the satellite component in order to reduce Earth-station costs.

As European aerospace capabilities matured, members began to lobby for larger shares of Intelsat R&D and procurement contracts. Even when European bids were higher than U.S. ones, it was argued that these were necessary to develop competition for the United States, and that it was unfair for U.S. firms to reap all the financial benefits. Over time, U.S. firms began to subcontract extensively abroad in an effort to reduce criticism of U.S. contract dominance.

In the permanent agreement, procurement policy was established with emphasis on the "best combination of quality, price and most favorable delivery time." However, in the event of equivalent bids "the contract shall be awarded so as to stimulate in the interests of Intelsat, worldwide competition" (art. 13).8 This loophole gave Intelsat the option of allocating contracts on a geographic basis as long as it determined that they were roughly equivalent. In recent years, approximately 15 percent of the dollar value of Intel sat procurement contracts has been spent outside the United States [9]

Part 4

Unlike ESRO, which had its own facilities, ELDO was entirely a coordinating body for separate national efforts. The initial planning called for a British first stage, a French second stage, a German third stage, and so on. Launches were to take place in Woomera, Australia. The major countries had widely differing interests. France was interested in an across-the-board capability to compete with the superpowers and demonstrate French independence and prestige, an aim directly connected with French military programs in nuclear submarines and intermediate range ballistic missiles. France feared that the United States would not provide launch services for French military satellites or for programs that promised to compete commercially with the United States.

Germany was more interested in private commercial ventures, and was much more willing to cooperate with the United States. Great Britain, faced by the mid-1960's with severe financial constraints and enjoying a close relationship with the United States, preferred less expensive programs in telecommunications and remote sensing.

[6] Stephen Doyle, "Inmarsat Origins and Structure, " 1976
[7] Pelton, op cit , p 58
[8] "Intel sat Organization Agreement, " 1973, in *Space Law,* p 214
[9] Conversation with John Donahue, Intelsat procurement office, October 1980

ACRONYMS, ABBREVIATIONS, AND GLOSSARY

AF – audio frequency
AIAA – American Institute of Aeronautics and Astronautics
ANSI — American National Standards Institute
A-sat — antisatellite
Aramco – Arabian-American Oil Co.
BBB — blood brain barrier
BRH – Bureau of Radiological Health
Btu — British thermal unit
bui – brain uptake index
CB — citizens' band
CEP – Citizen's Energy Project
— centimeter
CMEA — Council of Mutual Economic Assistance (Comecon) (East Europe, Soviet Union, Cuba)
CNS – central nervous system
CONAES – Committee on Nuclear and Alternative Energy Sources (National Academy of Sciences)
COPUOS – Committee on Peaceful Uses of Outer Space (United Nations)
COTV — cargo orbital transfer vehicle
Comsat – Communications Satellite Corp.
cpm — counts per minute
CW — continuous wave
dB – decibels
dc – direct current
DOD — Department of Defense
DOE – Department of Energy
DMSO – dimethyl sulfoxide
EDL — electric discharge laser
EEG — electroencephalogram m
EKG — electrocardiogram
ELDO – European Space Vehicle Launcher Development Organization
ELF — extremely low frequency
EMF — electromagnetic fields
EMP — electromagnetic pulse
EMR — electromagnetic radiation
EOTV — electric orbital transfer vehicle
EPA — Environmental Protection Agency
ER — evoked response
ESA – European Space Agency
ESRO – European Space Research Organization
FCC — Federal Communications Commission
FDA — Food and Drug Administration
FEL — free electron laser
CDL — gas discharge laser
GNP – Gross National Product
GHz – gigahertz (10^9 cycles per second)
Gw – gigawatt (10^9 watts)
GEO – geostationary orbit
HEAO-C – High Energy Astronomical Observatory-C
HEL – high-energy laser
HEW – Department of Health, Education and Welfare
HF – high frequency
HFAL – high frequency auditory limit
HLLV – heavy-lift launch vehicle
HRP – horseradish peroxidase
HVTL – high-voltage" transmission line
Hz — hertz: a unit of frequency equal to one cycle per second
HZE — high-atomic-number, high-energy particles
IAF — International Astronautical Federation
ICBM — intercontinental ballistic missile
IEA — International Energy Agency
IEEE — Institute of Electrical and Electronics Engineers
ISM — industrial, scientific, and medical
ITU — International Telecommunication Union
kg — kilogram
km — kilometer
k w — kilowatt (10^3 watts)
laser — light amplification by stimulated emission of radiation
LEO – low-Earth orbit
LMFBR – liquid metal fast breeder reactor
LORAN – long-range navigation
MHz – Megahertz (10^6 cycles per second)
MPTS — microwave power transmission system
M W — megawatt (10' watts)
mW/cm^2 — milliwatts per square centimeter
NAS — National Academy of Sciences
NASA – National Aeronautics and Space Administration
NATO — North Atlantic Treaty Organization
NBS – National Bureau of Standards
NIEMR — nonionizing electromagnetic radiation
NIOSH – National Institute of Occupational Safety and Health
NRDC – Natural Resources Defense Council
OECD – Organization for Economic Cooperation and Development (United States, Canada, Japan, West Europe)
OMEGA — generic name for long-range navigation
OPEC – Organization of Petroleum Exporting Countries

OSHA	– Occupational Safety and Health Administration
OTA	– Office of Technology Assessment
PLV	– personnel launch vehicle
POTV	– personnel orbital transfer vehicle
prf	— pulse repetition frequencies
Q	– Quad (quadrillion BTUS)
Qe	– Quad, electric
R&D	— research and development
rem	– Roentgen equivalent man, the quantity of ionizing radiation whose biological effect is equal to that produced by one roentgen of X-rays
RFP	— radiofrequency radiation
SAM	— surface to air missile
SAR	— specific absorption rate
SEPS	— solar electric propulsion system
SPS	— solar power satellite
SRBC	— sheep red blood cells
SSTO	— single stage to orbit space vehicle
STS	— space transportation system
t	— metric ton (tonne); 1,000 kg
TVA	– Tennessee Valley Authority
UHF	— ultra high frequency
VER	— visually evoked electrocortial response
VHF	— very high frequency
WHO	— World Health Organization

Ablate—to remove by cutting, erosion, melting, evaporation, or vaporization.

Aerosol—a suspension of insoluble particles in a gas.

Albedo–the fraction of incident light or electromagnetic radiation that is reflected by a surface or body.

Ambient—the natural condition of an environmental factor.

Amplitude–the maximum departure of the value of an alternating wave from the average value.

Artifact— a product of artificial character due to an extraneous agent.

Attenuation– a reduction in amplitude of electromagnetic energy.

Beam width–the angular width of a beam of radiation, measured between the directions in which the power intensity is a specified fraction, usually one-half, of the maximum.

Bias current–the electric current applied to a device (e.g., a transistor) to establish a reference level for operation.

Biota—the plants and animals of a region.

Brayton cycle— a method of driving a turbine in which a gas is compressed and heated. The most familiar use is for aircraft gas turbine engines. An alternative to the Rankine cycle.

Bremsstrablung radiation– radiation from charged particles that are decelerated in a magnetic field.

British thermal unit-quantity of heat needed to raise one pound of water one degree Fahrenheit at or near 39.2 'F.

Circadian–pertaining to events that occur at approximately 24-hr intervals, such as certain biological rhythms.

Cloud condensation nuclei (CCN)–particles on which water vapor condenses to form water droplets, that in turn form clouds and fogs.

Convection-circulatory motion that occurs in the atmosphere due to nonuniformity in temperature and density, and the action of gravity.

Cortical tissues–tissue from the outer layer of gray matter of the brain.

Cosmic ray–atomic nuclei of heterogeneous, extremely penetrating character that enter the Earth's atmosphere from outer space at speeds approaching that of light.

Coupling–the mechanism by which electromagnetic energy is delivered to a system or device.

CW laser–continuous wave laser, as distinguished from a pulsed laser. A laser emitting for a period in excess of 0.25 second.

Cytogenetics– a branch of biology that studies heredity and variation by the methods of both cytology and genetics.

Cytology– a branch of biology dealing with the structure, function, multiplication, pathology, and life history of cells.

Decible– a unit for expressing the ratio of two amounts of electric or acoustic signal power equal to 10 times the common logarithm of this ratio. A ratio of 10 is 10 dB, a ratio of 100 is 20 dB, a ratio of 1,000 is 30 dB, etc.

Diffuse reflection— reflection of a beam incident on a surface over a wide range of angles.

Dosimeter– a device for measuring doses of radioactivity.

Ecliptic–the circle formed by the apparent yearly path of the Sun through the heavens; inclined by approximately 23.50 to the celestial equator.

Electromagnetic energy– energy in the entire range of wavelengths or frequencies of electromagnetic radiation extending from gamma rays to the longest radio waves and including visible light.

Electron— a subatomic particle with a negative electrical charge.

Endocrinology– a science dealing with the endocrine glands, which produce secretions that are distributed in the body by way of the bloodstream.

Energy dose– the quantity of electromagnetic energy (in joules) that is imparted per unit of mass to a biological body.

Energy dose rate— the amount of electromagnetic energy that is imparted per unit of mass and per unit of time to a biological body.

Epidemiology-a branch of medical science that deals with the incidence, distribution, and control of disease in a population.

Extended source—an extended source of radiation that can be resolved into a geometrical image in contrast with a point source of radiation, that cannot be resolved into a geometrical image; a source that subtends an angle greater than one arc min.

Exosphere–the outer fringe region of Earth's atmosphere.

Field intensity–the magnitude of the electric field in volts per meter or the magnitude of the magnetic field in amperes per meter.

Flux–the rate of transfer of particles or energy across a given surface.

Frequency—the number of complete oscillations per second of an electromagnetic wave, measured in hertz (Hz). One hertz equals one cycle per second.

Geostationary Earth orbit (GEO)– the equatorial orbit at which a satellite takes 24 hr to circle the Earth so that it is stationary as viewed from Earth; altitude approximately 36,000 km.

Geosynchronous Earth orbit–the orbit at which a satellite takes 24 hr to circle Earth. (The satellite may or may not appear to be stationary above a point on Earth.)

Harmonic frequency– a component frequency of an electromagnetic wave that is a multiple of the fundamental frequency.

Heliostat– a mirror device arranged to follow the Sun as it moves through the sky and to reflect the Sun's rays on a stationary collector.

Hematology-a branch of biology that deals with the blood and blood-forming organs.

Heavy-lift launch vehicle (HLLV)– a proposed launch vehicle used to transport large masses of material from Earth to low- Earth orbit.

Illuminance– irradiance; rate of energy per solid angle measured at a given point.

Immunology— a science that deals with disease resistance and its causes.

Intermodulation –the mixing of the components of a complex wave with each other in a nonlinear circuit. The result is that waves are produced at frequencies related to the sums and differences of the frequencies of the components of the original waves.

Intrabeam viewing– viewing the laser source from within the beam. The beam may either be direct or specularly reflected.

Ion—an atom or group of atoms that carries a positive or negative electrical charge as a result of having lost or gained one or more electrons.

Ionizing radiation– radiation capable of producing ions by adding electrons to, or removing electrons from, an electrically neutral atom, group of atoms, or molecule.

Ionosphere—the part of Earth's atmosphere beginning at an altitude of about 5 km extending and outward 500 km or more, containing free electrically charged particles by means of which radio waves are reflected great distances around the Earth.

Irradiance (E)– radiant flux density arriving at given surface in units of watts-per-square-centimeter (W/cm^2); illuminance (as measured by a detector).

Joule (J)– unit of energy (1 watt-see) under the international system. As a thermal unit, 1 joule equals 0.239 calories. Since the calorie is defined as the energy required to heat 1 gram of water from 40 to 50 C, 4.184 joules is the equivalent of one calorie.

Kapton — lightweight, tough plastic film.

Klystron— an electron tube used to generate and amplify microwave current.

Laser– a device for generating coherent light radiation.

Low-Earth orbit (LEO) –altitude approximately 500 km.

Luminance–brightness on a light source, equal to luminous flux per unit solid angle emitted per unit area of the source.

Magnetron— a magnetically control led tube used to generate and amplify microwave radiation; the power sources for microwave ovens.

Magnetosphere– a region of Earth's outer atmosphere in which electrically charged particles are trapped and their behavior dominated by Earth's magnetic field.

Mass driver– an apparatus for accelerating material in an electromagnetic field.

Mesoscale–on or relating to a meteorological phenomenon approximately 1 to 100 km in horizontal extent.

Mesosphere– a layer of the atmosphere extending from the top of the stratosphere to an altitude of about 80 km.

Microwave– a comparatively short electromagnetic wave, especially one between 100 cm and 1 cm in wavelength or, equivalently, between 0.3 and 30 GHz 'in frequency.

Modulation–when a continuous series of waves of electromagnetic energy is modified by pulsing, or by varying its amplitude, frequency, or phase, the waves are said, respectively, to be pulse-, amplitude-, frequency-, or phase-modulated. In order to convey information by radiating electromagnetic energy, it must be modulated,

Morphology-a branch of biology that deals with the form and structure of animals and plants.

Multibiotic– having or consisting of many plants and animals.

Multipath radiation— in contrast with a so-called plane wave, that flows in a straight line through space, an area or volume where electromagnetic waves arrive from different directions because of reflection or multiple sources is said to be the site of multipath radiation.

Neuroendocrine-of, relating to, or being a hormonal substance that influences the activity of nerves.

Neutral particles– molecules, atoms, or subatomic particles that are not electrically charged.

Neutron–an uncharged elementary particle that has a mass nearly equal to that of the proton

and is present in all known atomic nuclei except the hydrogen nucleus.

Noctilucent cloud— a luminous thin cloud seen at night at a height of about 80 km.

Nonionizing radiation— radiation of too low an energy to expel an electron from a molecule or atom.

Ohmic heating-a heating mechanism in a plasma or other conducting medium. The free electrons in the medium are accelerated by an applied electric field and give up kinetic energy by collision with other particles.

Phase—the measure of the progression of a periodic wave in time or space from a chosen instant or position.

Phased array– an array of antennas that is aimed as a group by adjusting the phase of the signal it sends or receives.

Photoionization– ionization (as in the ionosphere) resulting from Collision of a molecule or atom with a proton.

Photoklystron — a device for directly converting visible light to microwave radiation.

Photon— a quantum of radiant energy.

Photoperiod – the interval in a 24-hr period during which a plant is exposed to light,

Photovoltaic cell– a cell composed of materials that generate electricity when exposed to light.

Plasma–a collection of charged particles exhibiting some properties of a gas but differing from a gas by being a good conductor of electricity and by being affected by a magnetic field.

Polarization–the electric (E) and magnetic (H) fields that comprise a propagating electromagnetic wave may be fixed in relation to Earth's horizon, or they may rotate. By convention, the vector of the E field is related to Earth's horizon: if the two are perpendicular, the wave is said to be vertically polarized; if parallel, horizontally polarized. When the E and H fields are continuously rotating with respect to the horizon, the wave is said to be elliptically polarized.

Power–the quantity of energy per unit of time that is generated, transferred, or dissipated. The unit of power, the watt (W), is defined as one joule per second (j/s).

Power density-the quantity of electromagnetic energy that flows through a given area per unit of time. Formally, power density is specified in watts per square meter (W/m^2), but by tradition in biological effects studies it is usually expressed in milliwatts per square centimeter (mW/cm^2).

Propagation —the transmission of electromagnetic wave energy from one point to another.

Proton– an elementary particle that is identical with the nucleus of the hydrogen atom, that along with neutrons is a constituent of all other atomic nuclei, that carries a positive charge numerically equal to the charge of an electron.

Pulsed laser– a laser that delivers its energy in short pulses, as distinct from a CW laser; a laser which emits for less than 0.25s.

Radiation pressure– all propagating electromagnetic waves exert a very slight pressure on an absorbing object.

Rankine cycle– a liquid gas cycle used often for steam turbines. A working fluid is heated until it expands and drives a turbine.

Rectenna– a coined term for the SPS reference system receiving antenna that also converts the microwave power to direct-current electricity.

Rectification-the conversion of an alternating current to direct current.

Refraction– a deflection from a straight path undergone by a wave in passing obliquely from one medium into another in which its velocity is different.

Root-mean-square—for an alternating voltage, current, or field quantity: the square root of the mean of the square of the quantity during a complete cycle.

Scattered power– power that is reflected or dispersed as the result of an obstruction in the path of the primary power flow.

Side lobe— refers to power radiated from an antenna in a direction other than the desired direction of transmission.

Slipring–a metal ring to conduct current in or out of a rotating member of a machine.

Solar flare– an explosion on the Sun which generates fast elementary particles.

Solar wind–a stream of particles generated by a solarflare.

Solid-state amplifier– an amplifier whose operation depends on a combination of electrical effects within solids, e.g., a transisterized amplifier for electromagnetic waves.

Specific absorption rate (SAR)–the quantity of electromagnetic energy that is absorbed by a body per unit of mass during each second of time; expressed formally in watts per kilogram (W/kg); often, informally as milliwatts or watts per gram (m W/g or W/g). "Specific absorption rate" is being considered by the National Council on Radiation Protection and Measurements as the

official nomenclature for expressing the dose rate of radio-frequency electromagnetic radiations. Synonymous with energy dose rate.

Specular or regular reflection– a mirror-like reflection.

Spurious power or frequency–electromagnetic energy produced at frequencies that are not easily related to a specified operating frequency.

Stratosphere– an upper portion of the atmosphere above approximately 10 km (depending on latitude, season, and weather) and in which temperature changes little with changing attitude and clouds of water are rare.

Sun-synchronous orbit– a near polar orbit which keeps the satellite in full sunlight all the time while Earth rotates beneath it.

Susceptibility—the sensitivity of an electromagnetic receiver to undesired electromagnetic waves that may result in interference.

Symptomatology– a branch of medical science concerned with symptoms of diseases.

Teratology-the study of malformation or serious deviations from the normal development of fetuses.

Thermosphere–the part of Earth's atmosphere that begins about 80 km above Earth's surface, extends to outer space, and is characterized by steadily increasing temperature with height.

Troposphere– the portion of the atmosphere below the stratosphere, which extends outward about 15 km from Earth's surface, and in which temperature generally decreases rapidly with altitude.

Van Allen belt— a belt of intense ionizing radiation that surrounds Earth in the outer atmosphere.

Wave guide– a device for transmitting and guiding radio-frequency waves

O