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APPENDIX B-3

N90-15840

THE SOLAR POWER SATELLITE (SPS) - PROGRESS SO FAR

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INTRODUCTION

During the 1980's, public interest in large-scale alternative energy sources waned with the apparent availability of affordable fossil fuels. However, the environmental risks associated with combustion (the "Greenhouse Effect") and exploitation of non-renewable energy sources in ecologically fragile areas are a source of public concern on an international level. It is appropriate, therefore, that there be an assessment of alternative energy technologies and the potential use of extraterrestrial resources to provide decision makers with an understanding of the energy options available to them in the coming decades. One promising alternative option is the Solar Power Satellite (SPS)[1].

The objective of the SPS is to convert solar energy in space for use on Earth. Its most significant benefit is the potential for continuously generating large-scale electric power for distribution on a global basis. While, there has been no SPS development program in the United States since 1980, it has continued to be investigated in the Soviet Union, Europe, and Japan. In addition there has been very significant progress in SPS-related technologies, including solar cells, power beaming, structures and space transportation. The current and projected developments in the build up of the space infrastructure could have a positive impact on the overall feasibility of the SPS not only by supplying commodity materials from the moon[2],[3], but by developing intermediate markets for power in space (e.g., energy for the Space Station, free-flying platforms and for lunar and planetary bases).

The objectives of this review are to outline the major developments in key SPS-related technologies and to evaluate the significance of these developments to the consideration of the SPS, both as an alternative energy option for use on Earth and as a potential stimulus for space infrastructure developments, and the use of extraterrestrial resources.

BACKGROUND

In the 1970's, SPS assessments were performed by NASA and the U.S. Department of Energy, the Congressional Office of Technology Assessment, and the National Research Council, National Academy of Sciences.[4] These assessments considered technical, economic, environmental and societal issues. In preliminary studies of the SPS concept (1968 to 1972), a plan for an SPS R & D

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1 P.E. Glaser, "Power From the Sun: Its Future," Science, 162, 857-866 (1968).

2 E. Brock, Lunar Resource Utilization for Space Construction, Final Report, General Dynamics, Convair Division, NASA, JSC, Houston, Texas, NAS9-15560 (1979).

3 P. DuBose, "Solar Power Satellite Built of Lunar Materials," Space Power, Vol. 6,1986, pp. 1-98.

4 National Research Council, Electric Power From Orbit, a Critique of a Satellite Power System, July 1981.

program was outlined[5]. In 1974, a feasibility study was undertaken to evaluate an SPS design for a power output of 5 GW for use on Earth[6]. This feasibility study identified key technological, environmental and economic issues for further study and provided the foundation for more extensive system definition studies[7,8,9]. A preliminary assessment of the SPS concept resulted in the SPS Concept Development and Evaluation Program Plan[10], which had as its objective: "To develop, by the end of 1980, an initial understanding of the technical feasibility, economic practicality, and societal and environmental acceptability of the SPS concept."

THE SPS SYSTEM

As originally conceived[11] an SPS could utilize various approaches to solar energy conversion, such as photovoltaic and thermal-electric. Among these conversion processes, photovoltaic conversion was selected as a useful starting point because solar cells were already in wide use in communication, Earth observation and meteorological satellites, both in low-Earth orbit (LEO) and in geosynchronous orbit (GEO). Since then, an added incentive has been the substantial progress being made in the development of advanced photovoltaic materials, microwave and laser power beaming, and the increasing confidence in the achievement of significant cost reductions in space transportation and use of lunar materials.

In the baseline SPS concept, solar cell arrays would convert solar energy directly into electricity and feed it to microwave generators forming part of a planar, phased-array transmitting antenna. The antenna would direct a microwave beam of very low power density precisely to one or more receiving antennas, at desired locations on Earth. At the receiving antennas, the microwave energy would be safely and efficiently reconverted into electricity and then transmitted to users. An SPS system could consist of many satellites Earth orbits, e.g., in GEO, each SPS beaming power to one or more receiving antennas at desired locations.

The SPS Orbit

The most favorable orbit for solar energy conversion would be an orbit around the Sun. However, at this stage of space technology development, GEO represents a reasonable compromise because solar radiation received in GEO - unlike solar radiation received on Earth - is available 24 hours each day during most of the year. Solar radiation intercepted by a satellite in GEO will be interrupted by Earth eclipses of the Sun for 22 days before and 22 days after the Equinoxes. The

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5 National Science Foundation, An Assessment of Solar Energy as a National Resource, NSF/NASA Solar Energy Panel, University of Maryland, College Park, MD (1972).

6 P.E. Glaser, O.E. Maynard, J. Mockovciak, Jr., and E.L. Ralph, Feasibility Study of a Satellite Solar Power Station, NASA Lewis Research Center, Cleveland, Ohio, CR-2357, NTIS N74-17784 (1974).

7 ECON, Inc., Space-Based Solar Power Conversion and Delivery Systems Study, Final Report, NASA, MSFC, Huntsville, Alabama, NAS8-31308 (1977).

8 Boeing Aerospace, Solar Power Satellite System Definition Study, Final Report, Vol. I-VII, for NASA, JSC, Houston, Texas, NAS8-32475 (1980).

9 Rockwell International, Satellite Power System (SPS) Concept Definition Study. NASA, MSFC, Huntsville, Alabama, NAS8-32475 (1980).

10 U.S. Department of Energy, Satellite Power (SPS) Concept Development and Evaluation Program Plan: July 1977 - August 1980, DOE/ET-0034, U.S. Government Printing Office, No. 061-000-00031-3, Washington, D.C. (1978).

11 P.E. Glaser, "Method and Apparatus for Converting Solar Radiation to Electrical Power", U.S. Patent No. 3,781,647 (1973).

maximum period of interruption, occurring when the Earth, as seen from a GEO position is near local midnight, will be 72 minutes a day. Overall, eclipses will reduce the solar energy received in an orbital position in GEO by about 1% of the total available during a year. With this year-round conversion capability, the SPS could be used to generate base load power on Earth with minimal requirement for energy storage. Furthermore, the absence in space of environmental and gravitational constraints on the erection of light-weight, extensive, contiguous structures would permit the deployment of the SPS over large areas. Micrometeoroid impacts are projected to degrade 1% of the SPS area over a 30-year exposure period. Because of the small probability of impact, large meteoroids are not likely to affect the SPS components in GEO.

The Solar Energy Conversion Process

Several photovoltaic energy conversion processes are applicable to the SPS concept. Both flat arrays of single crystal silicon, and gallium arsenide solar cells with solar concentration[12] have been evaluated. Significant progress is being achieved in the development of mono-and polycrystalline, thin-film, multijunction and heterojunction solar cells as indicated by subjects discussed at major conferences, so that further performance improvements can be projected[13], [14].

The solar cells should have as high an efficiency as possible, a low mass per unit area, and be resistant to radiation during transit to, and operation in, GEO. To extend the lifetime of the solar cells, *in situ* annealing methods have been considered, including heating with solar concentrators to reduce the degrading effects of accumulated radiation exposure.

Power Transmission From Space to Earth

Microwave beams or laser beams could be used to transmit the power generated in the SPS to suitable receivers on Earth. Laser power transmission is an interesting possibility because of considerable advances in laser technology[15] and the ability to deliver power in amounts as low as 100 MW to receiving sites on Earth.

- **Microwave Transmission**

Microwave power transmission has received most attention, based on considerations of technical feasibility, fail-safe design, and low flux levels. Free space transmission of power by microwaves is not a new technology[16]. The system efficiencies for the interconversion (d.c.-to-microwaves-to-d.c. at both terminals of the transmission system) have already been demonstrated to be 54%; a further improvement to 70% is projected. The general belief about microwave power transmission is that it is an emerging technology which has to rely on fragile and short-lived, as well as expensive and low-power, components. In fact, the conversion of d.c.

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12 Rockwell International, Advanced Satellite Power System Concept, PD 80-61, Rockwell International, Downey, CA (1980).

13 Solar Energy Research Institute, 9th Photovoltaic Advanced Research and Development Project, May 24-26, 1989, Lakewood, CO.

14 Commission of the European Communities, 9th European Photovoltaic Solar Energy Conference, Sept. 25-29, 1989, Freiburg, FRG.

15 NASA, Langley Research Center, Second Beamed Space Power Workshop, 28 February to 2 March, 1989, Hampton, VA

16 W. C. Brown, Experimental Airborne Microwave Supported Platform, Technical Report, Rome Air Development Center, Rome, NY, TADC-TR-188 (1965).

to r.f. power at microwave frequencies has led to the establishment of a major industrial capability to produce devices to meet consumer and industrial requirements. Several microwave generators, including linear beam devices, klystrons, gyrotrons, solid-state amplifiers, and cross-field devices, amplitrons and magnetrons, could be used. Magnetron developments indicate that a microwave generation subsystem based on the magnetron would have better performance and a smaller mass.[17]

The microwave generators are incorporated in the transmitting antenna, which is designed as a circular, planar, active, slotted, phased array. Space is an ideal medium for the transmission of microwaves: a transmission efficiency of 99.6% would be achievable after the beam has been launched at the transmitting antenna and before it passes through the upper atmosphere. To generate 5 GW, assumed for the NASA SPS reference system[10], the transmitting antenna would be about 1 km in diameter and the receiving antenna would be an ellipse about 10 by 13 km at 40° latitude. A peak power density of 23 $mWcm^{-2}$ at the receiving antenna would obviate heating of the ionosphere. The microwave power beam could be shaped so that the power density at the edges of the receiving antenna would be 1 $mWcm^{-2}$, and only 0.1 mW cm^{-2} at the receiving antenna site perimeter, about 1 km beyond the receiving antenna.

The transmitting antenna is divided into a large number of subarrays. A closed-loop retrodirective array with a phase-front control system could achieve the high efficiency, pointing accuracy and safety essential for the microwave beam operation. In the retrodirective array design, a coded reference signal is beamed from the center of the receiving antenna to the transmitting antenna. With this design, it is physically impossible for the microwave beam to be directed to any other location on Earth but the receiving antenna.

The receiving antenna has been demonstrated to intercept, collect, and rectify the microwave beam into d.c. with an efficiency of 85%.[18] The d.c. output interfaces with either high-voltage d.c. transmission networks or is converted into 60 Hz a.c. The receiving antenna consists of an array of elements which absorb and rectify the incident microwave beam. Each element consists of a dipole, an integral low-pass filter, a diode rectifier and a bypass capacitor. The dipoles are d.c.-insulated from the ground plane and appear as r.f. absorbers to the incoming microwaves. The collection efficiency of the receiving antenna is insensitive to substantial changes in the direction of the incoming beam. Furthermore, the efficiency is independent of potentially substantial spatial variations in phase and power density of the incoming beam that could be caused by nonuniform atmospheric conditions. Under normal atmospheric conditions, attenuation and scattering of the microwave beam will result in a loss of about 2%. Under the worst weather conditions the total loss could be as high as 8%.

The amount of microwave power received in local regions of the receiving antenna can be matched to the power-handling capability of the microwave rectifiers. The rectifiers, which could be gallium arsenide Schottky barrier diodes, have a power-handling capability several times that required for this application. Any heat resulting from inefficient rectification in the diode and its circuit can be convected by the receiving antenna to ambient air, producing atmospheric heating

17 W. C. Brown, Satellite Power System (SPS) Magnetron Tube Assessment Study, Final Report, NASA, MSFC, Huntsville, Alabama, NAS8-331578 (1980).

18 R. M. Dickinson and W. C. Brown, Radiated Microwave Power Transmission System Efficiency Measurements, Technical Memorandum 33-727, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (1979).

which will be only about twice that of the heat release of a typical suburban area. The low thermal pollution resulting from the microwave power rectification process cannot be equalled by any known thermodynamic conversion process for power generation.

The receiving antenna could be designed to be 70% transparent to sunlight. Microwaves can be excluded from beneath the antenna by a grounded mesh enclosure. A large number of potential sites for receiving antennas can be identified. However, for each site environmental impacts will have to be assessed before constructing a receiving antenna[19]. Design concepts for offshore receiving antennas include floating structures for installation in continental shelf waters and bottom-mounted structures which could be deployed in shallow waters.[20] Offshore receiving antennas could be constructed near major population centers which are located near sea coasts in many countries around the world. They could be designed to permit secondary operations beneath the antenna, for example, mariculture with on-site docking and processing facilities to provide a significant source of fish protein. One such site could meet up to about 5% of the present US demand for fish protein.

- **Laser Transmission**

Concentrated and dispersed beams generated by continuous-wave, electric-discharge lasers with recirculating gas have been considered[21]. Gas circulation permits the removal of waste heat and minimizes consumption, thus allowing extended operations. Although carbon dioxide and carbon monoxide electric discharge lasers have reached an advanced state of development, other laser concepts, including free-electron lasers, diode laser arrays, and solar-pumped lasers, are being developed. Power may be supplied to these lasers by solar photovoltaic and nuclear thermal conversion, or through direct excitation by solar radiation.

Photovoltaic cells, compositionally tuned for high efficiency[22], could be used to convert laser beam radiation at the receiving site on Earth. If successfully developed, tuned optical diodes, which are the analog of microwave diode rectifiers but operate in the infrared portion of the spectrum, may be used to convert laser radiation into a d.c. output. Thermodynamic cycles could also be used when efficient laser heat absorption systems have been developed.

Atmospheric absorption of laser radiation would be reduced when the receiving sites are located at high elevations, but even in such locations unfavorable weather would require that the laser radiation be beamed to receiving sites with more favorable weather conditions and fed into a shared transmission grid. The dimensions of a laser radiation receiving site, including a safety zone, could be measured in hundreds of meters against the thousands of meters needed for a microwave beam receiving antenna.

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19 Environmental Resources Group, Prototype Environmental Assessment of the Impacts of Siting and Constructing a Satellite Power System (SPS) Ground Receiving Station (GRS) DOE/ER-0072, NTIS, August 1980.

20 J. W. Freeman, Solar Power Satellite Offshore Rectenna Study, Contractor Report 3348, Rice University for NASA, MSFC, Huntsville, Alabama, NAS8-33023 (1980).

21 R. E. Beverly, SPS Laser Systems Analysis and Environmental Concerns, Rockwell International Corporation, Downey, California, NAS8-3475 (1979).

22 Gilbert H. Walker, Photovoltaic Conversion of Laser-to-Electric Power, Proceedings of 18th IECEC, August 1983, pp. 1194-1199.

Although laser power transmission is still in an early stage of development, and significant technology advancements will be required, there is considerable promise in a laser power transmission system for the SPS. Environmental impacts, including heating of the atmosphere and meteorological effects, are not expected to be significant, although the plasma chemistry of the upper atmosphere and induced reactions will require further study. The potential for interference with communication links will be greatly reduced. Requirements for safety and security of laser power transmission could be adequately met, however, there would have to be safeguards to prevent misuse of laser power.

Space Transportation

To be commercially competitive, the SPS will require a space transportation system capable of placing payloads into LEO and GEO at the lowest possible cost. The space transportation system which will be available during the early phases of SPS development for technology verification and component functional demonstration will be an advanced version of the Space Shuttle, and subsequently an advanced launch system now under study.

As part of the SPS system studies, various space transportation systems concepts have been considered.[8,9] including advanced shuttles, launch vehicles utilizing shuttle components and a variety of advanced heavy lift launch vehicles, including ballistic single-stage and two-stage vehicles or winged two-stage vehicles for easy recovery. Such vehicles could transport payloads ranging from 100 to 300 tons into LEO and would be recoverable and repeatedly reusable. In the two-stage vehicles, the fuel for the lower stage would be liquid oxygen and a hydrocarbon; liquid oxygen and liquid hydrogen would be used for the upper stage.

Both offshore and onshore launch facilities have also been considered. For example, an offshore launch facility constructed near the Equator would reduce launch costs and eliminate the noise impact of frequent launches in populated regions. To achieve a projected cost of $50 per kg for launching SPS payloads would require turn-around maintenance and mission control procedures similar to those employed in commercial airline operations.

Personnel and cargo would be transported from LEO to GEO with chemically or electrically propelled vehicles which would not need to reenter the atmosphere. Ion thrusters of high specific impulse would be powered by solar cell arrays. Although the transit time to GEO would be measured in months, ion thrusters would minimize the amount of propellant to be transported to LEO.

The development of advanced space transportation systems is proceeding. The cost of orbiting payloads is projected to drop from thousands of dollars per kilogram for the space shuttle to less than a hundred of dollars per kilogram for an advanced space transportation system[23].

These cost projections appear to enhance the competitiveness of an SPS as compared to currently known energy sources. However, the transportation of the required materials from Earth on the scale required to build up a global SPS system may result in undesirable environmental effects, as propellant combustion products will be deposited at various levels in the atmosphere. Therefore, it may be advantageous to obtain commodity materials required for the construction of the SPS from the moon especially if processing and transportation of materials from the moon to GEO could be accomplished at costs comparable to launches of payloads from Earth.

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23 U.S. Department of Energy, Satellite Power Systems (SPS) Space Transportation Cost Analysis and Evaluation, DOE/ER-0086, November 1980. (NTIS)

Orbital Assembly And Maintenance

The absence of gravity and of the influence of forces shaping the terrestrial environment, presents a unique freedom for the design of extensive orbiting structures, their fabrication, assembly and maintenance in LEO and/or in GEO.

In a selected orbit the function of a structure is to define the position of components rather than to support loads. The loads, under the normal operating conditions, are orders of magnitude less than those experienced by structures on the surface of the Earth. The structure will have to be designed to withstand loads imposed on discrete sections during assembly into a continuous structure. Attitude control will be required to direct the solar energy conversion system towards the Sun and the transmitting antenna towards the receiving antenna on Earth. This configuration will require that the transmitting antenna rotate once a day with respect to the solar energy conversion system. The extensive structures envisioned for the solar energy conversion system and the transmitting antenna will undergo large dimensional changes as a result of significant temperature variations imposed during periodic eclipses. Composite materials can be considered for the structure because they have a small coefficient of thermal expansion compared to aluminum alloys.

The contiguous structure which would be required for the SPS is of a size which has never been fabricated on Earth. Therefore, automated construction methods will be required to position and support the major components such as the solar arrays forming part of the solar energy conversion system and the microwave subarrays forming the transmitting antenna. For example, an automated beam builder has already been demonstrated on Earth.

Warehousing logistics and inventory control will be required to manage the flow of material to the SPS construction facilities which will be located in LEO and GEO. The construction facility could be a space station which would also provide launch and docking facilities and a habitat for crew members.

SPS GROWTH PATH

An optimized SPS design has not yet been developed. However, to analyze technical issues, evaluate environmental effects, explore societal concerns and perform comparative assessments, an SPS reference system based on assumed guidelines was established.[24] The SPS reference system was based on the use of either single crystal silicon flat arrays or gallium arsenide solar cells in combination with solar concentrators.

The complete SPS system includes not only the satellite but also the following space construction and support systems:

- A base in LEO for electric orbit transfer vehicles, for servicing space transportation systems, and for logistics support;
- An assembly station in GEO for constructing the SPS, and
- A GEO support base for the robotic systems that provide service and periodic maintenance for an operating SPS.

24 U.S. Department of Energy, Satellite Power System Concept Development and Evaluation Program -- Reference System Report, DOE/ER-0023 (1978).

The objective of the SPS is to generate base load electrical power for use on Earth. Assuming that a global SPS system is planned to be placed in operation after the year 2010, it is most likely that at first it would be designed to replace existing power plants and to add new generating capacity to meet future energy demands in both developed and developing countries. This role for the SPS would only be possible if it could generate competitively priced electricity in the context of future energy demands.

The build up of the global SPS system would be time-phased to gain confidence in its effective performance and the realizability of projected construction costs. A modest number of SPSs could be placed in operation in the first quarter of the 21st century to demonstrate the commercial feasibility of the SPS. Only after the necessary operating experience has been obtained could a more rapid growth in the SPS contribution to future energy demands be expected. The rate of growth of a global SPS system would be determined by the development of efficient electricity demand technologies and by the economics of this system relative to alternative energy technologies.

Thus far, studies[25] have shown that there are no likely show stoppers in an SPS program. They have, however, identified technical, economic, environmental and societal issues which require more detailed definition. The cost estimates for the SPS reference system, rough as they are and subject to criticism as they may be, fall in a potentially interesting range. They are sufficiently competitive to justify, not a major commitment at this time, but a continued analysis, research and technology verification program of the SPS.

An approach can be devised for the development of the SPS that identifies the underlying generic technologies and their application to specific space power projects, as shown in Figure 1. The "terracing" of space power projects would reduce the challenges typically associated with large-scale projects, including the control of the project, the effects of technical uncertainties, maintenance of investor confidence, reduction of environmental impacts, and the difficulties associated with termination of the project if warranted. The increasing capabilities needed for planned space projects - free-flying carriers, manned space stations, and space transportation systems of higher performance and lower cost-will contribute to the industrial infrastructure that could be the foundation for SPS development.

Projects such as the SPS are unlikely to be pursued until information from space power projects at successive "terrace" levels can guide the evolution of the most appropriate design for the SPS.

The assumption underlying the "terracing" approach is that advanced technologies will be developed in support of national and international space projects. For example, some of the technologies that will be required for the SPS are already being developed for a variety of space applications.

There is every indication that advanced technologies and space infrastructure elements could lead to the development of an even more competitive SPS system, particularly if a lunar base and processing of lunar resources were to be realized.

SPS Economics

The economic justification for an SPS development program must acknowledge that it is not possible to know now the cost of a technology which will not be fully developed for at least 15 years or commercialized in less than 20 years. Justification is equally difficult to provide for other advanced energy technologies.

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25 U.S. Department of Energy, Program Assessment Report Statement of Findings, DOE/ER-0085 (1980).

Cost-effectiveness analyses alone are inappropriate because they would require the extremely difficult task to postulating credible scenarios of the future. The near-term decisions regarding the conduct of the SPS program should therefore be based on the resources allocated to the SPS research tasks and their priorities rather than the projected economics of the SPS in the 21st century.

Cost projections do not provide meaningful estimates of the potential market penetration of the SPS or alternative energy supply technologies because the uncertainties in forecasting prices are much larger than the cost differentials on which the cost comparisons among competing technologies will eventually be based. However, such cost studies provide estimates of the delivered cost of power to indicate whether the SPS has any chance of being competitive, identify the major cost elements so that program efforts can be properly focused to reduce the projected costs, develop a consistent framework to evaluate different technological options, determine the impacts of raw material requirements and availability on cost and the effects of a development program on labor costs and capital markets and assess the cost risk in comparison with alternative energy supply technologies, including environmental impacts and societal effects.

The SPS was compared with alternative energy technologies, including coal, nuclear and terrestrial photovoltaic systems, in terms of cost and performance, health and safety, environmental effects, resource requirements, and institutional issues.[26] The assessments indicated that:

- The life-cycle cost range for the SPS overlaps the competitive cost ranges of alternative energy technologies;
- All the technologies considered will have distinct, though different, health and safety impacts;
- The low-level and delayed impacts of all energy technologies are difficult to quantify and assess;
- Each technology has material requirements that could be critical, because of environmental control standards or limited production capability; however, these requirements do not appear to limit the SPS;
- The total amount of land required for the complete fuel cycle is roughly the same for all energy technologies; however, the SPS and terrestrial centralized photovoltaic systems would require large contiguous land areas;
- The SPS, fusion and other advanced energy technologies may be difficult to operate within the current regulatory environment; however, the SPS could also be subject to international regulations that do not appear to limit the other technologies.

SPS Assessment Issues

The SPS program is unique in that for the first time a technology assessment program focused not just on key technology issues but was also concerned with environmental effects, comparative economic factors, societal issues and program risks and uncertainties before any commitment to a development program was made[27]. Of these considerations the most significant non-technical issues were the SPS's environmental effects and resource requirements.

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26 M. R. Riches, A Comparative Assessment of the Reference Satellite Power System with Selected Current, Near-Term and Advanced Energy Technologies, Department of Energy, Conference Report. 800491, 66-67 (1980).

27 F. A. Koomanoff and C. A. Sandahl, "Status of the Satellite Power System Concept Development and Evaluation Program", Space Solar Power Review, 1, 67-77 (1980).

Environmental Effects

The key environmental effects associated with the SPS are those which could affect human health and safety, ecosystems, climate, and interactions with electromagnetic systems.

o **Health and Ecological Effects of Microwave Power Transmission**

At the perimeter of a receiving antenna, the public would be exposed to microwaves at a power densitv of 0.1 mW cm^{-2}. If as assumed for the NASA SPS reference system, 60 receiving antennas in the continental United States were spaced an average of 300 km apart, the minimum power density at any point would be about 10^{-4} $mWcm^{-2}$. At present, 1% of the population is potentially exposed to microwave power densities of 10^{-3} mWc^{m-2}. In the USSR, the maximum value for continuous, 24-hour, exposure of the general public is estimated to be 10^{-3} $mWcm^{-2}$. The US population is experiencing a medium exposure value of about 10^{-6} $mWcm^{-2}$ for a time-averaged microwave power density. The workers within the receiving antenna area would not be exposed to levels exceeding U.S. guidelines for occupational exposure with suitable precautionary measures.

The fact that large populations are exposed to microwave energy from communications, medical, radar and industrial processes for many decades and, more recently, from microwave cooking, without demonstrated adverse effects on human health and the ecosystem, is an indication that microwaves beaming from space to Earth is unlikely to result in undesirable health and ecological effects.

o **Non-microwave Health and Ecological Effects**

Among the various space-related activities only the exposure of the space workers to ionizing radiation appears to present a major health risk. Most of the other health and ecological effects of the construction and operation of receiving antennas and launch sites have conventional impacts which would be controlled or mitigated by appropriate engineering changes and are analogous to developing and constructing alternative energy sources.

The risks from ionizing radiation to space workers could be minimized through carefully designed shielding for space vehicles, for working and living modules and by the provision of solar storm shelters. Of greatest concern are the high-energy, heavy ions in GEO which may result in exceeding recommended exposure limits for workers. More data are required to establish the expected ionizing radiation environment in GEO to guide the design of measures to limit exposure of space workers.

o **Effects on the Atmosphere**

Weather and climatic effects of waste heat released at a receiving antenna site would be generally small, comparable to the heat released over suburban areas. The absorption of microwave power in the troposphere is expected to increase during heavy rainstorms, but even then would have only a negligible effect on the weather. The air quality effect of the launch of advanced space transportation vehicles, which would increase sulphur dioxide concentration, would not be critical. Nearly all of the carbon monoxide would be oxidized to carbon dioxide, and the amount of nitric oxides formed would be negligible. Some acid rain might occur near the launch site if there are significant quantities of sulphur in the fuel. Inadvertent weather modification by rocket effluents in the troposphere, because of cumulative effects, would be possible and would require continuing monitoring of rocket exhaust clouds and the various meteorological conditions to mitigate such effects.

Carbon dioxide emissions if carbohydrate-based propellants are used would be expected to add to the "greenhouse" effect. The change in the globally averaged ozone layer due to SPS launches would be undetectable as would the effects of nitrogen oxides. Transient clouds at stratosphere and mesosphere altitudes could be induced in the vicinity of the launch site, but they would not be expected to have a detectable impact.

The effect of rocket launches on the ionosphere could be mitigated by a depressed launch trajectory: for example, a winged booster returning below an altitude of 75 km would keep the rocket effluents in the turbulent mixing regions of the atmosphere, reduce the possibility of hydrogen diffusion into the ionosphere and prevent the formation of noctilucent clouds. Optimization of the first stage's launch trajectory would reduce the injection of water vapor into the lower atmosphere if hydrogen-oxygen propellants are used, however, water vapor deposited in the upper atmosphere will have a long residence time and may result in undesirable effects if large quantities of water are deposited over an extended time frame.

Ion thrusters controlling the position of the solar energy conversion system and the microwave transmission antenna would inject argon ions into the plasmaphere and magnetosphere. These effects are either unknown or uncertain. Their magnitude would have to be established and perhaps other ion-thruster propellants utilized to minimize any disturbance of the plasmasphere or changes in the magnetosphere interaction with solar wind.

o **Effects of Ionospheric Disturbance on Telecommunications**

The ionosphere is important to telecommunications because radio waves can be totally reflected and returned to the Earth's surface, depending on the ionospheric electron density, the frequency of the electromagnetic energy, the frequency of occurrence of electron collisions, and the strength of the geomagnetic field. Changes in the ionosphere can alter the performance of telecommunication systems, and small-scale irregularities can produce radio signal fading and result in loss of information. Ionospheric changes could result either from heating of the ionosphere by the microwave beam or the interactions with effluents from space vehicles. The effects of rocket exhaust effluents during launch can be reduced through appropriate trajectory control. However, during reentry of the winged booster and orbiter stages, ablative materials and oxides of nitrogen could affect a small portion of the ionosphere.

Experiments on the effects of microwave beam heating of the ionosphere have indicated that at a peak power density of 23 mW cm^{-2}, the microwave beam would not adversely affect the performance of telecommunication systems and that the power density could be doubled.[28] Because of equipment limitations, these experiments deposited power in the lower ionosphere comparable to the microwave beam power densities. Modified and expanded facilities would be required to simulate heating of the upper ionosphere, verify the existing frequency-scaling theories, and establish the effects of the microwave beam on the upper atmosphere. If no adverse heating effects are observed, the peak power density could be increased.

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28 W.E. Gordon and L.M. Duncan, "SPS Impacts on the Upper Atmosphere," Astronautics and Aeronautics, Vol. 18, 1980, pp. 46-48.

- **Electromagnetic Compatibility**

The SPS must be designed and operated to satisfy established national and international rules for using the electromagnetic spectrum. There is a potential for producing interference because the amount of microwave power transmitted from space to Earth would be unprecedented and the size of the microwave beam would be very large at the Earth's surface. It could interfere with military systems, public communications, radar, aircraft communications, public utilities, transportation systems communication, other satellites, as well as radio and optical astronomy. The interference potential of the microwave beam would not be especially unusual except in the extent of the geographic area affected. High-powered radar systems produce interference of similar electromagnetic intensities, but over limited areas. Shielding and radio receiver filters are commonly used to avoid interference and could be adapted for this purpose.

The dimension of SPS-caused interference by direct energy coupling to any class of equipment is part of the engineering design of the microwave power transmission system and the receiving antenna. Interference can be minimized by designing the microwave system to stringent specifications, to reduce undesirable emissions at frequencies other than its operating frequency and to constrain the size and shape of the transmitted microwave beam. Careful receiving antenna siting, including tradeoffs between locations of the antennas near energy load centers, could avoid interference with most other users of the radio spectrum. SPS will not interfere with other satellites in GEO, such as communication satellites, because the microwave beam would deliver less than one-fifth the power that would be required to produce interference.

Radio and optical astronomical observations have to measure weak signals. Such observations could be significantly inhibited by the microwave power beam, even at distances of hundreds of kilometers from the receiving antenna sites. One mitigating approach would be to construct radio telescopes on the far side of the moon, where they would be shielded from all forms of terrestrially produced electromagnetic interference. Earth-based optical observations would be hindered by light reflected from the surfaces of an SPS, which would have a brightness approaching that of Venus when it is most visible. Orbiting astronomical observatories could be constructed which would provide better observational conditions than those obtainable even in the best locations on Earth. The cost of these mitigating approaches may have to be charged to the SPS system.

- **Resource Requirements**

The physical resource requirements which could present problems are land use, materials availability, and energy utilization.

- **Land Use**

Receiving antenna siting studies[29] showed that there are suitable locations for receiving antenna sites throughout the United States. The methodology developed for determining eligible areas for receiving antenna sites is widely applicable; however, actual acquisition of specific sites may be difficult, and location of sites in some areas could, because of their topography, incur a heavy cost

29 J.B. Blackburn, et al, "Satellite Power Systems Rectenna Siting: Availability of Nominally Eligible Sites", U.S. Department of Energy, 1980.

penalty for site preparation and perhaps even modifications of the receiving antenna designs. Studies showed that there are no apparent undesirable biological effects of microwaves on birds[30], selection of sites to avoid migratory bird flyways may be possible.

The sheer size and intensity of use of the contiguous land area required for a receiving antenna site and site construction will have significant implications for environmental, social and economic impacts and these will have to be established for each specific antenna site. In addition, the secondary uses of selected receiving antenna sites for agricultural purposes or for terrestrial solar energy conversion will need to be assessed.

The alternative of locating the receiving antenna offshore may be attractive for major population centers which are located near the sea coasts not only because of their possible proximity but also because floating offshore structures may be competitive with land-based structures and provide an opportunity for mariculture[20]. For example, the Northeast region of the US has the smallest potential land area for receiving antenna sites relative to projected needs.

o **Materials Availability**

An analysis of the materials requirements for the construction of the SPS indicated that no insurmountable materials supply difficulties are evident in terms of world and domestic supply and potential manufacturing capacity[31]. Over one-half the materials for the SPS reference system are readily available, but there are potential supply constraints on tungsten, silver and gallium. The industrial infrastructure to fabricate SPS components such as ion thrusters, dipole rectifiers, microwave generators, and graphite composites will be adequate; however, solar cell arrays will require development of mass production technologies, which could be used not only for the SPS but also to meet terrestrial photovoltaic system requirements.

o **Energy Utilization**

Net energy analysis is useful in comparing alternative energy technologies in terms of the energy produced by each system per unit of energy required. When fuel is excluded, the energy ratios for the SPS reference system are marginally favorable with respect to other energy production methods. When fuel is included, the SPS energy ratios are very favorable.[32] Using the technologies of the SPS reference system and estimates based on their probable improvements, energy payback periods for the SPS would be about one year.[33]

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30 Arthur D. Little Inc., Responses of Airborne Biota to Microwave Transmission from SPS. Report to Environmental Protection Agency, Research Triangle Park, N.C., 68-02-3278 (1980).

31 P.E. Glaser and P.K. Chapman, "The Emerging Infrastructure for the SPS", SPS Program Reviews Proceedings, U.S. Department of Energy, Conf. 800491, 1980, pp. 475-478.

32 R. R. Cirillo, Comparative Analysis of Net Energy Balance of Satellite Power System and Other Energy Systems, U. S. Department of Energy, DOE/ER-0056 (1980).

33 F. R. Livingston, Satellite Power System Environmental Impacts, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, Report 900-822, Rev. A (May 1978, August 1978).

PROGRESS IN THE FUTURE

The SPS reference system that was the basis for assessments by NASA, U.S. Department of Energy, National Research Council and the Office of Technology Assessment[34] does no longer represent the current and projected state-of-the-art of space power. As Figure 1 indicates, an evolutionary development of the SPS concept to meet intermediate objectives with definable benefits is the most likely scenario for SPS development. It is possible now to project trends in technologies critical for SPS applications and to establish SPS development goals envisaged for a global SPS system. The SPS development goals are summarized in Table 1. Meeting these goals can achieve the vision of the National Commission on Space[35]: "Our ambition: Opening New Resource to Benefit Humanity".

CONCLUSIONS

- No single constraint has been identified which would preclude the resumption of an SPS program for either technical, economic, environmental or societal reasons.
- The SPS Reference System which assumed that 5 GW of base load power would be generated at the receiving antenna on Earth demonstrated that the technology for transmitting power from space to Earth is amenable to evolutionary development and that the SPS concept is technically feasible.
- Lunar resources including metals, glasses and oxygen promise to provide commodity materials for the construction of the SPS in GEO provided that the use of these resources can be competitive with terrestrial materials.
- Technology advances, performance improvements and projected cost reductions in, for example, solar cell arrays, large space structures, laser power transmission, microwave generators and rectifiers, and space transportation systems increase the technical feasibility and economic viability of the SPS concept.
- The significant progress that has been made as a result of broadly based technical, economic, environmental and societal studies on the SPS is resulting in a growing consensus that the SPS is one of the promising power generation options which could contribute to meeting global energy demands in the 21st century.
- The SPS concept has the potential, not only for baseload power generation on a global scale, but also represents an evolutionary direction for expanding human activities in space and the use of extraterrestrial materials.

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34 Office of Technology Assessment, Solar Power Satellites, OTA-E-144, August 1981.

35 National Commission on Space, Pioneering The Space Frontier, Bantam Books, 1986, p. 3.

Figure 1 POWER BEAMING GROWTH PATH

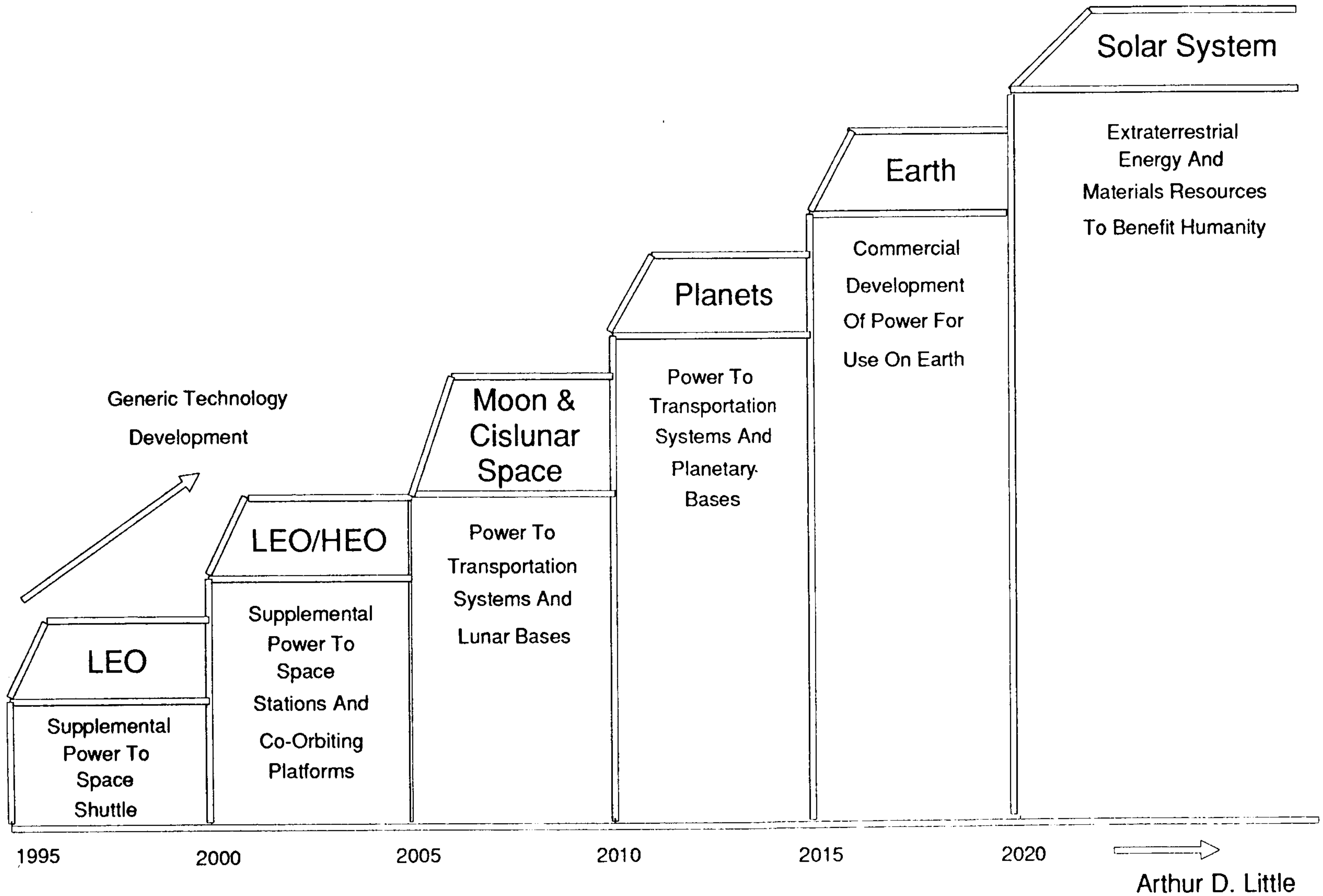

Table 1
SPS Development Goals

- o A significant contribution to meet global power demands of 25 TWyr/yr in 2030
  - 30 GW/yr
- o Microwave transmission
  - Frequency greater than 2.45 GHz
  - Efficiency greater than 70%
- o Laser transmission
  - Efficiency greater than 50%
- o Solar energy conversion with an efficiency greater than 35%:
  - Multijunction solar cells
  - Solar dynamic cycles
  - Thin Film solar concentrators
- o Structures
  - Advanced low-mass composites
  - Use of lunar resources
- o SPS mass
  - 2000 t/GW
- o Transportation
  - From Earth to GEO: $50/kg
  - From Moon to GEO: $20/kg
- o Space infrastructure: Earth to GEO
  - LEO assembly of components
  - GEO construction base
- o Space infrastructure: Moon to Earth
  - L_2 assembly of components
  - GEO construction base
  - Lunar base
- o Cost of operational SPS
  - $5000/kW ($1989) for SPS produced from lunar resources
- o Environmental Impacts
  - Within required terrestrial constraints
  - Effluents from Earth to GEO reduced through use of lunar resources for commodity materials