



Electric Power From Orbit: A Critique of a Satellite Power System (1981)

Pages
365

Size
8.5 x 11

ISBN
0309031834

Committee on Satellite Power Systems; Environmental Studies Board; Commission on Natural Resources; National Research Council

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Electric Power from Orbit: A Critique of a Satellite Power System

81-0097

National Research Council, Washington, DC.*National Science Foundation, Washington, DC. (019026000)

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G6092L3 Fld: 10B, 97N*, 97I, 97E GRA18207

1981 350p*

Grant: NSF-PRM79-19687

Monitor: NSF/PRM-81004

Abstract: As a basis for assessing feasibility and projecting costs, this study focuses on the elements of a reference system which includes conceptual designs of various space vehicles and construction bases. The system uses photovoltaic devices for energy conversion in space and microwave devices for energy transmission to earth. The concept of a satellite power system (SPS) is presently faced with problems concerning technological readiness, costs, competing technologies for generating electricity, magnitude of the enterprise, and international concerns. It is felt that no funds should be committed during the next decade to pursue development of a satellite power system. In addition to the major conclusions of the study, a number of detailed findings, and recommendations are presented. These cover important technological aspects of a satellite power system--economic analyses; environmental concerns; sociopolitical aspects of development; and a comparison of a satellite power system with potentially competing technologies that have prospects for meeting very long-term needs for electricity.

Descriptors: *Solar power generation, Economic analysis, Environmental impacts, Social effect, Evaluation, Technology

Identifiers: *Orbital solar power plants, Microwave power transmission, NTISNSFRA

PB82-133083 NTIS Prices: PC A15/MF A01

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ELECTRIC POWER FROM ORBIT: A Critique of a Satellite Power System

*A Report Prepared by the
Committee on Satellite Power Systems*

**Environmental Studies Board
Commission on Natural Resources
National Research Council**

**NATIONAL ACADEMY PRESS
Washington, D.C. 1981**

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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This study was supported by the National Science Foundation with partial funding by the U.S. Department of Energy and by the National Aeronautics and Space Administration under Contract No. PRM-7919687.

International Standard Book Number 0-309-03183-4

Library of Congress Catalog Card Number 81-83080

Available from:

NATIONAL ACADEMY PRESS
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Washington, D.C. 20418

Printed in the United States of America

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PREFACE

Electric Power from Orbit: A Critique of a Satellite Power System is the work of the Committee on Satellite Power Systems of the National Research Council (NRC) of the National Academy of Sciences. The Committee was organized in the summer of 1979 to make a critical appraisal of the comprehensive study of the concept of a satellite power system (SPS) being conducted by the U.S. Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA).

As explained in detail in the chapters that follow, an SPS would capture energy from the sun's rays: platforms positioned in orbit about 36,000 kilometers (22,300 miles) above the equator would collect and convert the energy to a form in which it could be relayed, day and night, to earth-based receivers that would distribute it to the electrical power networks of the country. The idea is simple and attractive; its realization would be without parallel in human experience in the design, construction, and operation of systems of any sort. A hypothetical SPS, as it has been postulated by DOE and NASA, is estimated to require expenditures on the order of \$100 billion over a period of at least 20 years before any useful demonstration of the system could be achieved. It would require 30 more years, constructing one unit at a time, to bring the system to its full capacity. Why, then, do we entertain the concept at all, let alone analyze it in the detail represented by the conceptual satellite power system--called the reference system--with which this report is so largely concerned?

The answer is that circumstances could develop in which some type of SPS could be important in the nation's or the world's energy future. Projections of future demand for and supply of energy vary greatly, but most show total demand in the United States increasing during the next 50 years, with electricity a growing share of the total. Projections for the power requirements of the world by the year 2030, for example, run as high as 3000 gigawatts--that is, 3000 billion watts--of nuclear capacity alone. The hypothetical SPS described in the DOE/NASA study would eventually generate 300 gigawatts of electrical energy for the U.S. alone. This potential combined with the uncertain aspects of our current and projected energy sources creates a context which readily justifies attention to a future SPS option.

Our program included several tasks: (1) to identify critical scientific and technical issues affecting the SPS concept, including the feasibility of using the moon and the asteroids as sources of materials for construction; (2) to identify gaps in the DOE/NASA assessment program; and (3) to examine the results of that program. We

focused, of necessity, on the reference system, for which a substantial amount of analysis had been performed during the DOE/NASA study. However, if any system is deployed 25 or 50 years from now it will certainly be different from any system currently envisaged, and for that reason we did not restrict our judgments to the reference system alone. We projected advances in space technology and sought to identify features likely to be critical in future systems derived from current concepts, remembering that entirely new concepts cannot be ruled out.

We undertook our task in a number of different ways. We familiarized ourselves with the SPS concept and related issues through briefings by experts in DOE, NASA, and elsewhere. We examined published reports of work that had been accomplished during the DOE/NASA project. We then conducted our own studies of critical issues, using experts not included in the DOE study and commissioning papers on various topics. We obtained advice from professional organizations, employed consultants, and organized study groups and workshops on aspects vital to our study. (Some of the results of these activities are contained in this report's appendixes; others are available in limited supply, upon request, from the Environmental Studies Board of the National Research Council.) Finally, we examined the document--Program Assessment Report: Statement of Findings--the final report of the DOE/NASA program concerned with SPS concept development and evaluation.

Our report is addressed primarily to the sponsors of this study--the U.S. Department of Energy, the National Aeronautics and Space Administration, and the National Science Foundation. In addition, because of the enormous implications of the SPS, which are referred to above, we hope the report will also be useful to the Office of Management and Budget, to the Congress, and to the public.

ACKNOWLEDGMENTS

Early in the study the Committee organized its work around several major task areas. For many of them, Working Groups were formed, chaired by a Committee member and composed of members of the Committee and other experts. Members of the Working Groups served by attending subgroup meetings, providing expertise and information, and voluntarily contributing to Working Group written reports. The Working Groups were an integral and essential part of the Committee's study, and the Committee acknowledges with thanks the work of the individuals who served on them (see Appendix B).

The Committee also wishes to thank those who participated in workshops or served as consultants, subcontractors, or advisers to the study (see Appendix B). Their contributions were often essential and always useful to the Committee in preparing its report. We particularly thank The Aerospace Corporation for its analyses of space operations, and the American Institute of Aeronautics and Astronautics for its projections of probable advances in space technologies.

We are grateful to the many individuals who provided written comments, reviews, and information, or who addressed the Committee or its subgroups at meetings. They include persons from government, environmental and public interest organizations, consultants, members of business and industry, and other concerned individuals.

We are especially indebted to Mr. Frederick A. Koomanoff of DOE and Mr. F. Carl Schwenk of NASA and their staffs. They assisted the Committee in obtaining information essential to its task, were routinely available to attend meetings and to give briefings, and responded rapidly and graciously to the Committee's numerous requests for documents and data on the SPS.

On behalf of the Committee, I would like to thank John M. Richardson, Principal Staff Officer, for his excellent day-to-day management of the study. I also wish to thank Adele King Malone and Myron F. Uman of the National Research Council's professional staff, and Nancy Fairfax, Deborah Faison, Sally Murphy, and Connie Reges of the support staff for their special contributions in managing the project and preparing the report. Others who provided valuable assistance include staff members Raphael G. Kasper, Estelle H. Miller, and Robert C. Rooney, and Philip and Dorothy Sawicki.

Finally, I wish to express my personal thanks to each member of the Committee for his devoted and enthusiastic efforts in bringing the study to completion.

Dale R. Corson
Chairman, Committee on
Satellite Power Systems

SUMMARY

This report examines the concept of a satellite power system (SPS) and provides a critique of an evaluation of the concept made by the U.S. Department of Energy (DOE).

If it were to be built, an SPS would consist of a number of huge satellites moving in orbit, each over a fixed point on the earth, and collecting solar energy for conversion into a concentrated form for transmission to earth day and night. There, receiving antennas would collect it and convert it into electricity to be fed into the nation's power distribution network.

In 1977, DOE, assisted by the National Aeronautics and Space Administration (NASA) and a number of contractors, undertook a three-year program to develop and evaluate this concept. In 1978, the National Science Foundation (NSF) was authorized to consider the feasibility of constructing such systems using extraterrestrial material. In 1979, NSF, with the concurrence of DOE, asked the National Academy of Sciences (NAS) to address important issues in the SPS concept, including the potential for using extraterrestrial materials; identify gaps in the DOE assessment; and prepare a critical review of the results of the DOE program. Subsequently, NASA asked NAS to expand its evaluation of critical issues in space transportation that affect the technical feasibility of the SPS concept. This report contains the findings, conclusions, and recommendations of the resulting study.

To evaluate the SPS concept, DOE developed a hypothetical system of rather specific design with the help of NASA and its contractors. This so-called "reference system" included conceptual designs of various space vehicles and construction bases and used photovoltaic devices for energy conversion in space and microwave devices for energy transmission to earth. The reference system was not intended to be an ultimate design but a basis for assessing feasibility and projecting costs. Our study necessarily focused on the elements of the reference system, but wherever possible we extended our view to more general problems and principles.

Perceptions of future need for an SPS depend on estimates of supply and demand for electricity and on projections of costs and environmental consequences of an SPS and alternative sources of electricity. Several studies of supply and demand suggest that,

between the early 1980s and the first decade of the next century, the bulk of the nation's supply of electricity will be derived from coal and uranium (using light water reactors). Toward the end of this period, other sources such as photovoltaic devices and geothermal resources may begin to contribute substantial quantities of electricity to the national supply. Early in the next century, additional sources including advanced breeder reactors, thermonuclear fusion reactors, and an SPS may have been demonstrated to be practical and ready for introduction.

There are uncertainties concerning the availability of large-scale sources of energy for electricity beyond the early part of the next century. The use of coal is, of course, technically feasible and may set the standard for economic competition; but concerns about global effects of carbon dioxide emissions and other environmental effects could constrain coal's development. The nuclear breeder reactor is also technically feasible, but it faces problems of political acceptability because of concerns about reactor safety, waste management, and the potential for proliferation of nuclear weapons. Even though rapid advances are being made in terrestrial photovoltaic cells, the technology must await progress in large-scale electrical storage capacity if it is to substitute appreciably for baseload power. Fusion, with the potential of substantial benefits as a long-term source, has yet to be shown to be technologically feasible.

If constraints are placed on the use of coal or uranium (in conventional or breeder reactors) and if a practical fusion reactor is not achieved, an SPS could become an attractive option for deployment in the next century. However, it should be noted that the technological and economic feasibility of an SPS has not been established. The concept probably presents technological problems that rival those involved in realizing terrestrial photovoltaics or solving the problems of carbon dioxide emissions, nuclear reactor safety, and radioactive waste management.

MAJOR CONCLUSIONS AND RECOMMENDATIONS

One of the tasks of the Committee was to analyze issues critical to future decisions about developing an SPS. Specific results of the analyses reveal the existence of major problem areas, which are identified elsewhere in the Summary and explained more fully in the report. As we considered our conclusions as a whole, our overall views about future attention to SPS emerged. First, we concluded that:

- The concept of an SPS is presently faced with sufficiently serious difficulties--in technological readiness, cost, competing technologies for generating electricity, magnitude of the enterprise, and international concerns--that no funds should be committed during the next decade to pursue development of an SPS. (Entire report)

On the other hand, there is a possibility that some future combination of high demand and constrained supply could make a more advanced SPS an important option in the more distant future. How might the option for a future decision on development of an SPS be kept open if the need arises? What research effort is best matched to the option?

We believe that the uncertainties that will probably remain associated for some years with the future need for and form of the SPS option are great enough that a specific program of research justified in terms of SPS would not now be warranted. However, where areas relevant to SPS technologies may be investigated in pursuit of goals of other programs, research should be vigorously conducted and the results evaluated for their implications for the SPS concept.

The most important areas requiring vigorous research in order to clarify future decisions on SPS are the following: low cost, efficient, space-qualified solar cells; low cost space transportation systems, both from earth to low earth orbit (LEO) and from LEO to geosynchronous earth orbit (GEO); space construction techniques; the GEO environment, including both the assessment of the problems in living and operating there and the development of means to mitigate the problems; and biological effects of low-level microwave radiation. We believe that the next decade will see vigorous pursuit of these areas for purposes other than the SPS and the results will be vital to future consideration of SPS.

By contrast, an SPS conceived in the next century will likely be much different from SPS as presently conceived; and research and development specific to the present form of the concept may well be irrelevant in the future.

These considerations bring us to our second overall point. We recommend that:

- In the absence of a program of research and development specifically for an SPS, the Administrator of NASA, in consultation with the Secretary of Energy, should periodically review progress in new concepts and technologies that would be important to the practicality and timeliness of a satellite power system and should report his findings to the Congress.
(Entire report)

The types of technologies needed to build an SPS--for example, space transportation, manned operations in space, photovoltaic energy conversion, generation and transmission of microwave power--have been demonstrated; the technical requirements and scale of the system, however, are far beyond our experience. Building large structures in space has not yet been attempted, but it appears to be technically feasible. For the most part, building an SPS requires advances in materials and techniques and systems development on a large scale rather than the discovery of new science. Several decades of technological advance may be needed before an effective design can be assured. We conclude that:

- Some type of SPS would be technically possible if costs were not a consideration, but the technical challenges are formidable on the basis of present scientific and engineering knowledge or its predictable extensions within the next decade. (Chapter 2)

Cost, however, is a consideration and an essential one. For SPS to be competitive, large reductions are required in current costs of lifting mass to LEO, transferring mass from LEO to GEO, and converting energy through photovoltaic cells. The costs of large-scale construction projects in space remain highly uncertain because experience is lacking. We conclude that:

- There are serious doubts that the technological requirements for several critical subsystems of the reference SPS can be met at acceptable costs through developments that can reasonably be foreseen. Examples are low cost transport from earth to low earth orbit, space-qualified solar cells, electric orbit transfer vehicles, and automated construction in space. (Chapters 2, 3)

The best data for projecting potential costs of the reference SPS are those obtained from recent and current space development experience. On the basis of data from the Apollo program and from work to date on the space shuttle extrapolated to the heavy-lift launch vehicle described in detail in the DOE/NASA assessment, we believe that the actual cost for this aspect of the space transportation system (from earth to LEO) will exceed the cost goals by a factor of two or three. Costs of transportation to LEO were estimated by NASA contractors to comprise roughly one-fifth of the total cost of building reference system. We also believe that the costs of solar cells based on 1990 technology and available for deployment in the year 2000 (which represented about 15 percent of the total reference system cost) are likely to be at least 10 and more likely 50 times higher than the cost goals assumed in the reference system. In addition, several decades could be required to develop cost-saving technological advances and transfer them into an industrial infrastructure of sufficient capacity to meet the demands of an SPS.

Given these estimates, the costs of electricity from an SPS is not soon likely to be competitive with costs of electricity from existing and potential alternative sources. Circumstances that might, in some combination, create an economic need for an SPS are high demand for electricity, together with constraints on established coal or nuclear technologies and failure of other advanced technologies, such as fusion, to develop economically. Such an exigency during the next 3 or 4 decades seems to us unlikely, particularly since reduced supply would lead to higher prices and lower demand. We conclude that:

- Based on an examination of cost estimates for the reference SPS and on recent studies of the energy outlook, an SPS will not become a cost-competitive source of electrical energy in

the next 20 years, and radical advances in technology will be required if an SPS is to become competitive in the next 40 years. (Chapter 3).

Developing and building an SPS on the scale contemplated would be by far the largest, most costly, and most complex undertaking--civil or military--ever attempted. Current technological capability would have to be extended and supported by a large industrial infrastructure. For example, space transportation systems would require logistical support and reliability typical of commercial airline operations. Total costs for research, development, demonstration, and deployment of an SPS like the reference system, capable of delivering 300,000 megawatts (300 gigawatts) of electricity, are likely to exceed \$3000 billion in 1980-year dollars, incurred over a period of about 50 years. The large initial capital investment, the long lag between investment and revenue, and high technological risk would inhibit private financing. We conclude that:

- The size and complexity of an SPS would strain U.S. abilities to finance and manage such an enterprise and, indeed, the governmental machinery for making the decisions necessary to initiate and sustain it. (Chapters 2, 3, 5)

The geosynchronous orbit is currently extensively used for worldwide communications services of substantial social and commercial value to all nations. The allocation of positions in GEO and microwave frequencies for SPS-type uses has become a concern of the cognizant international organizations. The attitudes of other countries about the possible military threat or vulnerability of an SPS may be of great importance, but so far these attitudes are only a matter of conjecture. It is also apparent that public concerns about the potential effects of exposure to microwave radiation produced by an SPS will have to be resolved if an SPS is to be pursued. We conclude that:

- On the basis of current technology, there are serious questions of international legal and political acceptability that could make an SPS difficult or impossible for the United States to achieve unilaterally. Allocations of orbital positions and microwave frequencies are examples. There are also issues of political and social acceptability such as those related to the fear of possible hazards to health from exposure to microwaves. (Chapter 5)

An SPS would affect the interests of many other countries. The electromagnetic spectrum and geosynchronous orbit may be viewed as global resources, perhaps subject to such international principles for useful exploitation as those expressed in the Moon Treaty or in drafts of the Law of the Sea Treaty. Mineral resources needed for an SPS project would have to be acquired in the international market. While the electricity from a domestic SPS would not be likely to supply a relatively large portion of U.S. demand, a worldwide SPS could supply

substantial benefits to other nations. These factors must be taken into consideration along with the costs and complexity of the undertaking. We conclude that:

- The worldwide ramifications are so extensive that a multilateral approach with the participation of other countries would probably be the only viable one if an SPS were ever to be established. (Chapter 5)

DETAILED FINDINGS AND CONCLUSIONS

In addition to the major conclusions, which integrate the analyses of the report, a number of detailed findings, conclusions, and recommendations are presented throughout the various chapters. Chapter 2 addresses important technological aspects of an SPS. Economic analyses are presented in Chapter 3. Environmental concerns are reviewed and assessed in Chapter 4, and Chapter 5 discusses sociopolitical aspects of the development of an SPS. In Chapter 6 we address the problem of comparing an SPS with those potentially competing technologies that have prospects for meeting very long-term needs for electricity. Chapter 7 presents our critique of the DOE assessment. Key findings, conclusions, and recommendations concerning these subjects are summarized by chapter below.

Technological Aspects (Chapter 2)

Space Transportation

1. Space transportation systems represent a major portion of the cost of an SPS. We believe that costs for delivering mass to LEO using the heavy-lift launch vehicle (HLLV) of the reference system are more likely to be \$130 per kilogram to \$180/kg (about \$60 per pound to \$80 per pound) than the \$44/kg to \$102/kg (about \$20 per pound to \$45 per pound) in 1980-year dollars projected by NASA contractors. Low cost transport of cargo between LEO and GEO using ion engines to propel an electric orbit transfer vehicle (EOTV) requires types of vehicles and systems that have never been used; until such systems are demonstrated, major uncertainties will remain. In the reference system, the HLLV accounts for about 65 to 85 percent (depending on contractor design) of all space transportation costs, but the EOTV presents by far the greater technical uncertainty.

Space Structures and Their Construction

2. Building large structures in space entails technologies about which little is known and with which we have almost no experience. There is no sound way now to estimate either the cost or the time

required to build large structures in space, but the costs projected by DOE and NASA and the six-month schedule for constructing SPS units appear to be optimistic. Primary reliance will undoubtedly have to be placed on automation which will require extensive development of robotics and teleoperators for space applications.

3. Construction and operation of large structures in space, such as EOTVs and power satellites, present problems in control of attitude and position that are far beyond current experience.

Energy Conversion

4. Any deployment of SPS by the year 2000 would necessarily have to rely on single-crystal silicon solar cell technology. DOE cost estimates for space-qualified silicon solar arrays used in the DOE assessments appear to be optimistic by at least an order of magnitude. Furthermore, there is no demonstrated technology for preventing radiation damage to silicon solar cells without seriously affecting the mass of the solar array, and neither the science nor the technology exists for restoring the efficiency of glass-covered cells by annealing. Radiation damage can be minimized in high-purity single-crystal silicon, but not without even higher costs and attendant production problems. For applications beyond the year 2000, there may be developments in the next decade or two in solar cell technologies, such as gallium arsenide cells, that hold more promise of meeting SPS requirements.

Energy Transmission

5. Currently the klystron tube is the preferred choice as the converter from direct current to microwave power for the reference SPS. The lifetimes of existing klystrons, however, are inadequate, with cathode life the limiting factor. Development aimed at improved performance is important to a future SPS. High-powered klystrons have not been tested in space; and until there is appropriate testing, problems of heat transfer and high voltage insulation, among others, cannot be assessed reliably. More data are also needed to compare alternative approaches to the power transmission problem, such as use of magnetrons or solid state devices.

6. The transmission of power from space by means of lasers is unlikely in the near future because of inefficiencies of energy conversion--or perhaps ever because of the fundamental limitation imposed by the opacity of clouds.

Energy Reception and Interface with the Utility Grid

7. No insurmountable technological problems are anticipated in integrating an SPS of the type described by the reference system with the U.S. electrical power grid.

Use of Extraterrestrial Resources to Build an SPS

8. Development of an SPS should not depend on the use of extraterrestrial resources, at least in the initial stages of deployment. Recovery and use of lunar and asteroidal resources require development of new technologies and space capabilities that may be more difficult to achieve than building an SPS. Even when the capability of using extraterrestrial resources exists, many critical resources of earth will still be needed for an SPS. Programs for developing extraterrestrial resources, as those for developing an SPS, would take several decades of concentrated work and require major advances in robotics.

Economic Aspects (Chapter 3)

SPS Costs

9. Any attempt to estimate the cost of a system as complex as the reference SPS at a time so far from its possible deployment is beset by uncertainties. We examined some of the capital cost estimates for the reference system prepared by NASA contractors, and we conclude, based on the work of experts in space technology, that the estimates are substantially low. For example, estimates of costs for transportation from earth to LEO are probably low by a factor of 2 or 3. Our analysis suggests that single-crystal silicon solar cell arrays alone would cost at least 10 and more likely 50 times the cost goals in the reference system. The resulting increase in system cost, by a factor of about 2 to 8, would be so great that a more advantageous solar-cell technology would have to be found before an SPS could be seriously contemplated. Radical new SPS concepts and technological developments that would change the scientific and technological base of the system are needed to achieve lower costs. Costs per unit of electrical energy provided (that is, mills/kWh) would be nearly proportional to capital costs, because operation and maintenance costs are expected to be small compared with capital costs and the solar energy is free. Consequently, no purpose would be served by trying to discuss costs of electrical energy separately from the capital costs and their uncertainties noted above.

Financing an SPS

10. Conventional financing of development and initial deployment of an SPS by electric utility companies is unlikely; public sector financing, direct or indirect, would be required. Major institutional changes in the regulation of utility rates would be required for private financing to help meet system costs in the latter stages of deployment.

Future Demand for and Supply of Electricity

11. The costs, availability, and acceptability of other sources of electricity during the next four decades are likely to be such that the chances of an SPS becoming competitive are small.

12. The capacity of an SPS is an important factor in the consideration of its attractiveness as a source of electricity. A system smaller than the reference SPS may entail higher unit costs that would adversely affect its competitiveness. There are other factors--availability of orbital positions and land requirements for receiving antennas, for example--that could limit the size of either a domestic or an international SPS. The decision to invest in a future SPS would require careful evaluation of the projected demand for electricity and the ultimate capacity of the SPS.

Net Energy Analysis

13. The total amount of energy to be produced over the lifetime of the reference system appears to be substantially greater than the total amount of energy that would be consumed in its construction and operation, provided that fabrication of its solar cells and transportation from earth to LEO can be accomplished at the expenditure of energy implied by the dollar cost estimates of Boeing and NASA. However, our own estimates of these dollar costs imply a less favorable comparison between energy produced and energy consumed. If we allow for the typical discount rates that society appears to attach to future energy generation, the energy balance becomes still less attractive.

Environmental Effects (Chapter 4)

Effects on the Biota

14. The flux of ionizing radiation outside the protective cover of the earth's magnetic field is high. Under the reference SPS design, the predicted rate of excess cancer mortality likely to be induced by radiation in space workers in GEO is on the order of 10 percent, a risk much greater than in other occupations. It would be necessary to establish some level of risk for SPS workers lower than now predicted and to design measures to stay within it. Moreover, additional radiation doses in GEO arising from solar flares may be so high that all personnel would need to take refuge in even more heavily shielded areas (storm shelters) during flares. Without an improved capability to forecast solar flares, the warning period would be less than two hours. More accurate radiation dose measurements in GEO are needed because the dose estimates are so high that errors of a factor of two or more would affect several percent of the work force. Reliable dose measurements with and without shielding are needed before satisfactory storm cellars and shielding for space workers in GEO can be designed.

15. The current established limits on ionizing radiation exposures are appreciably higher for astronauts than for terrestrial workers. The exposure limits for astronauts, however, were established with the assumption that a small number of people would be exposed. The reference SPS would require a much larger work force in space. Until ionizing radiation exposure limits for space construction and maintenance workers are established, the design of any satellite power system must remain uncertain.

16. Low-level microwave radiation outside the boundary of the receiving antenna on earth may affect, or be thought to affect, the general population. Although there are no demonstrated harmful effects of microwaves on humans at SPS power levels (0.001 to 1 watts per square meter or 0.1 to 100 microwatts per square centimeter), no reliable theory exists on which to base an understanding of possible or alleged effects at these nonthermal power levels. Hence, while there is no evidence to suggest that such low power levels are not safe, neither is it possible now to prove that they are.

Effects on the Lower and Upper Atmosphere

17. None of the concerns about lower atmospheric effects produced by the reference SPS is likely to present an insuperable problem.

18. There are several ways that the ionosphere can be affected by the reference SPS. Rocket effluents of HLLVs can lead to the recombination of ions and electrons, leaving a neutral hole in the ionized medium. Observations to date, supported by available theory, indicate no serious impact on communications from a single HLLV launch, although the impact of repeated launches, day after day, is unclear. The ionosphere can be heated by the microwave power beam, and such heating could also change the structure of the ionosphere in a way that might have an impact, either positive or negative, on radiocommunications. In tests to date, however, no interfering effects have been observed. Large numbers of heavy ions will be injected into the region of the Van Allen belts by the electric engines of an EOTV; the effects of this disturbance are unknown. Before there can be any sound decision about SPS deployment, further research is needed on the physics of the ionosphere and on radiowave propagation in an ionosphere disturbed by intense microwave beams or by effluents of many space vehicles.

Effects on Electromagnetic and Electronic Systems

19. Satellite station-keeping tolerances, together with the intense microwave radiation from a reference system satellite would make a length of the orbital arc around its orbital position unusable to other electromagnetic systems, such as communication satellites. The minimum length of that arc would appear to be the portion traced out diurnally by the satellite under the influence of the solar wind, gravitational force, and other forces, which has been calculated to be

about one-fifth of a degree. The length ascribable to electromagnetic interference is as yet not well-determined but such estimates as can be made using available information are of the order of one degree. The expected growth in the use of geosynchronous satellites in the next 20 to 50 years makes it likely that an SPS of 60 separate satellites would be incompatible with other uses of the geosynchronous orbit existing at that time.

20. Electric fields in the vicinity of receiving antennas in the reference system are in excess of 1 volt per meter (corresponding to a power flux density of 2.7×10^{-3} watts per square meter), which is the specification recommended by the American National Standards Institute for avoiding interference in general electronic equipment. Although many electronic devices can withstand considerably larger field strengths without degradation of performance, the mitigation costs to protect all other electronic devices could be substantial.

21. If any SPS concept is identified for implementation, additional study of electromagnetic compatibility problems is desirable.

Optical and Radio Astronomy

22. The reference SPS would deny a band of night sky, different for each observatory, to optical or radio astronomical measurements of faint objects from most observatories on earth. For optical astronomy, the most serious interference would be produced by an increase in the diffuse brightness of the night sky concentrated in a band on either side of the satellite arc. For radio astronomy, the major problems would arise from overloading of sensitive terrestrial radio astronomy receivers operating at frequencies near the SPS power transmission frequency and from spurious SPS radiation within radio astronomy bands.

Sociopolitical Factors (Chapter 5)

International Legal, Political, and Military Questions

23. On the basis of current technology, deployment of the reference system would be incompatible with current international obligations to avoid interference with recognized telecommunication uses of the electromagnetic spectrum. Deployment would probably be feasible only on the basis of an international decision to dedicate a portion of the spectrum and adequate space in the geosynchronous orbit to an SPS on the ground of general international benefit.

24. The military implications of an SPS need not constitute a significant obstacle to its development. A multilateral approach would reduce SPS vulnerability to attack and allay fears of potential conversion to weapons uses.

Social Acceptability in the United States

25. There is no way to forecast reliably public reaction to an SPS. The evolution of public opinion about acceptable forms of electrical energy production in the future will depend on developments in alternative sources of electricity. Public reaction, however, could make an SPS politically impractical.

Comparison with Other Long-Term Technologies (Chapter 6)

26. We did not attempt detailed cost and performance comparisons with long-term alternative technologies for a number of reasons: (a) an SPS could not be deployed for decades; (b) fusion may never reach the operational stage; (c) coal and nuclear fission may be constrained for environmental or political reasons; and (d) a terrestrial photovoltaic system is not directly comparable with systems that provide baseload power, except under detailed assumptions of how it would be integrated into the electrical utility system. It is thus too early to attempt to pick future winners and losers. The possibility exists that an SPS could become an interesting option at some time in the twenty-first century, provided that the system can be made competitive in cost, and acceptable in environmental, international, and social terms. In our current circumstances, the prudent course for the next few decades is to keep a variety of options open through research or development efforts in rough proportion to their expected promise. For SPS, whose promise is both uncertain and far in the future, periodic review and evaluation of relevant advances in related programs would serve the purpose.

Examination of the Concept Development and Evaluation Program and Final Report (Chapter 7)

27. The Satellite Power System Concept Development and Evaluation Program of DOE and NASA was a well-conceived and well-managed study in which an exhaustive number of aspects of an SPS were examined. The program provided valuable material for policy-making, as well as for other, purposes.

28. The document, Program Assessment Report: Statement of Findings, a final report summarizing the Concept Development and Evaluation Program, does not do justice to the work accomplished by DOE, NASA, and their contractors. Consequently that document must be taken together with other material from the study to provide an adequate basis for making judgments on the future development of an SPS. The usefulness of the document for this purpose would have been enhanced if its findings had been accompanied by conclusions and recommendations.

29. In general, we believe that the NASA contractors were substantially more optimistic in their estimates of schedule, performance, and cost than available data and analyses can support.

CHAPTER 1 INTRODUCTION

During the past 10 years it has become increasingly apparent that the world must develop new sources of energy. Two of the most convenient sources, oil and natural gas, are rapidly being depleted. A third, uranium, is being consumed at a slower pace, but it seems evident that as oil and natural gas reserves decline there will be increasing pressure to use more uranium. It has also become evident that two other major sources of energy in the world, hydroelectricity and coal, have limits--hydroelectricity because of the limited availability of suitable sites, coal for a number of reasons ranging from the safety of miners to the possibility that the earth's atmosphere may become overloaded with carbon dioxide as a result of hydrocarbon combustion.

As awareness of these problems has grown, so too has the number of ideas for conserving present resources by using them more efficiently, for reviving older and largely ignored methods of producing energy, or for finding entirely new ways of producing energy. Active research on many of these proposals is now being carried on throughout the world. To the extent that major sources like coal or nuclear may be constrained by environmental or political considerations, the need to develop other options increases.

This report is a survey of a possible option for producing large amounts of electricity in the future, a concept called a satellite power system, or SPS. As an idea, an SPS has an appealing simplicity. Briefly, huge satellites, covered with solar cells and orbiting in continuous sunlight high above the earth, would collect solar energy and beam it to earth in concentrated form day and night, where special receiving stations would convert the energy into high-voltage electric power and feed it into regional transmission systems. Thus, an SPS might provide a reliable and continuous supply of the highest-grade energy for use on earth.

Yet, as the rest of this report will point out, any nation, or group of nations, that attempted to build and deploy an SPS would be presented with wide-ranging technological, economic, environmental, and sociopolitical problems. These problems should become more evident in the next section of this chapter, in which more detail is provided about one such SPS--namely, the "reference system", a conceptual model developed by the National Aeronautics and Space Administration (NASA)

between 1977 and 1980 at the request of the U.S. Department of Energy (DOE).

WHAT A PARTICULAR SPS MIGHT BE LIKE

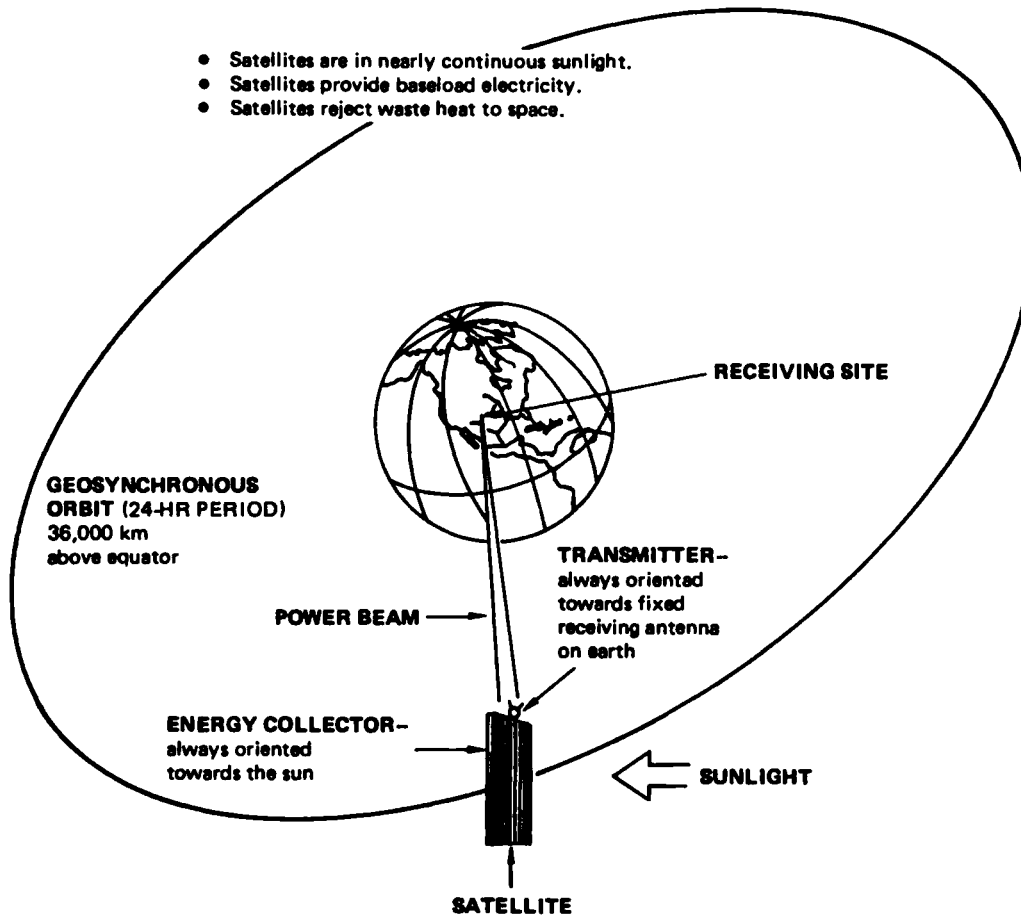
The reference system postulated by NASA would comprise 60 power satellites, each in geosynchronous earth orbit (GEO) at an altitude of 36,000 kilometers (km), or about 22,300 miles, above the equator and each continuously beaming power to its own receiving antenna, or "rectenna," on earth (Figure 1.1).

These satellites would be by far the largest structures ever placed in space (Figure 1.2). Each would be 10 km long, 5 km wide, and 0.5 km deep; each would weigh roughly 50,000 metric tons; and each would have to be precisely controlled to maintain its orientation and orbital position. A planar surface of each satellite (the surface that would constantly face the sun) would be covered with a "blanket" of solar cells that would intercept radiation from the sun and convert it, using the photovoltaic effect, into direct electric current. The current would be conducted to an array of approximately 100,000 klystron tubes that would transform it into electromagnetic waves at the frequency of 2450 megahertz (MHz) in the microwave region of the spectrum. The microwaves would then be beamed continuously to the rectenna by a transmitting antenna having a diameter of about 1 km, mounted on the satellite. At each rectenna the microwaves would be converted into electric power at a frequency of 60 hertz (Hz) and supplied to conventional electric power networks. In the reference system each rectenna would have an output of 5 gigawatts (GW), or 5000 megawatts.

Each rectenna would be elliptical in shape, roughly 10 km wide and 13 km long. A rectenna would be composed of some 10 billion half-wave dipoles, each about 6 centimeters (cm) long, placed equidistant from each other on panels tilted toward the satellite, and supported by a frame. Construction of the rectennas is assumed to be a straightforward matter, since the technology that would be used is conventional, although it has never been used on this scale before.

The construction of the satellites of the reference system and supporting orbital bases would be a much more complex undertaking, involving operations in both low earth orbit (LEO) and GEO (Figure 1.3). A staging base would be assembled in LEO at a few hundred kilometers in altitude. Once the base was assembled in LEO it would be used for the construction of cargo vessels that would carry materials to GEO for a construction base there. The staging base would remain in LEO as a logistics center, transshipment terminal, and maintenance station.

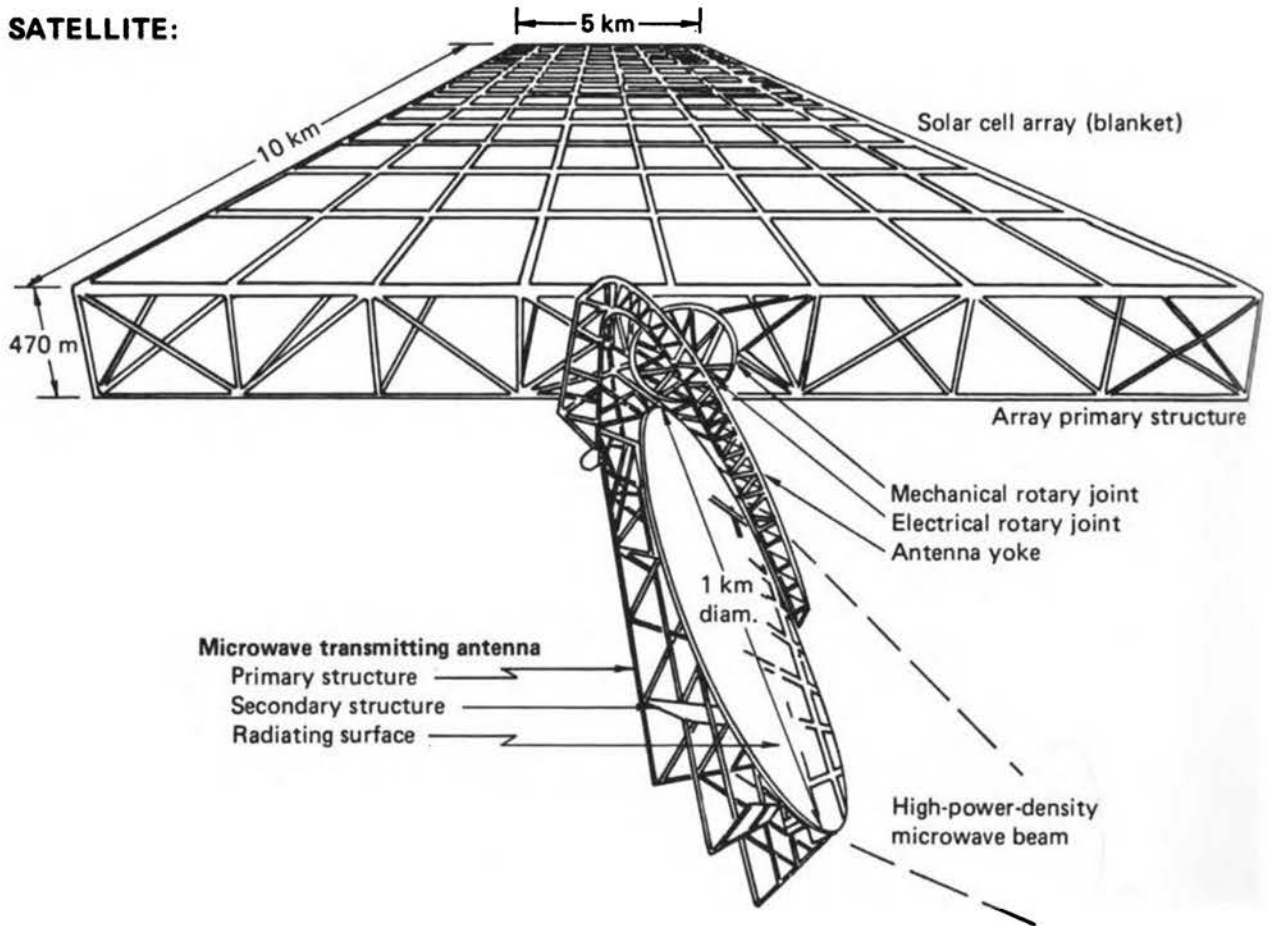
Each of the 60 power satellites would then be assembled at the construction base in GEO. Lightweight, triangular beam sections built of aluminum or some composite material would be assembled into trusses, to which would be attached the blanket of photovoltaic cells. Equipped as well with an antenna bearing the array of klystron tubes and with a control system for maintaining its proper altitude and position in orbit, each satellite would then be moved from the GEO construction base to its final orbital position.



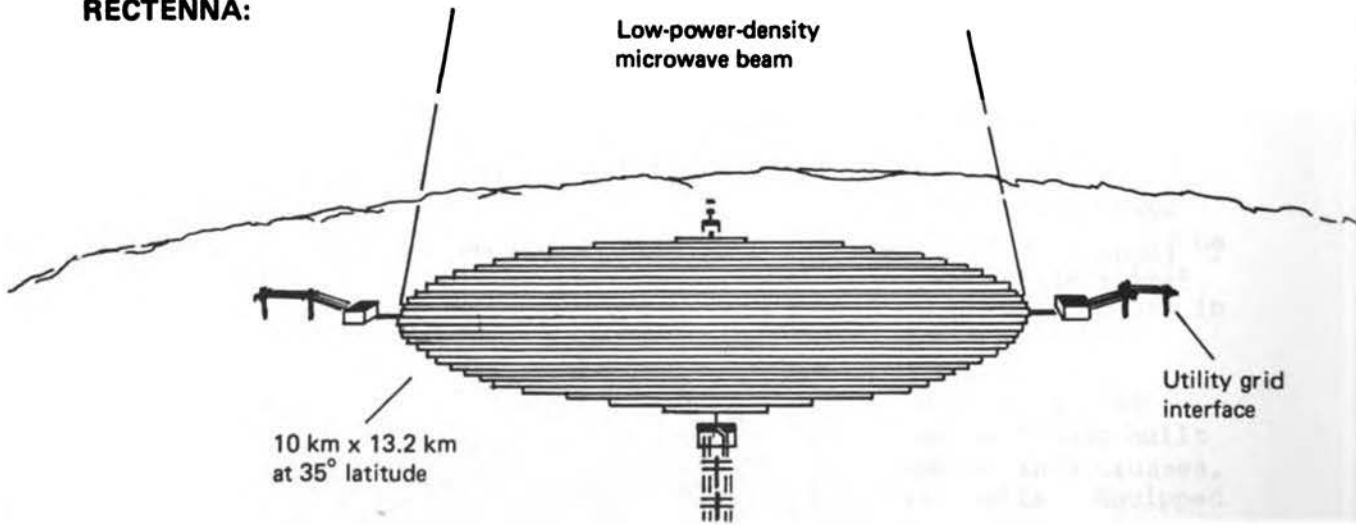
SOURCE: U.S. DOE (1980d).

FIGURE 1.1. Satellite power system concept (not to scale). The system would comprise multiple satellites and receiving sites.

SATELLITE:

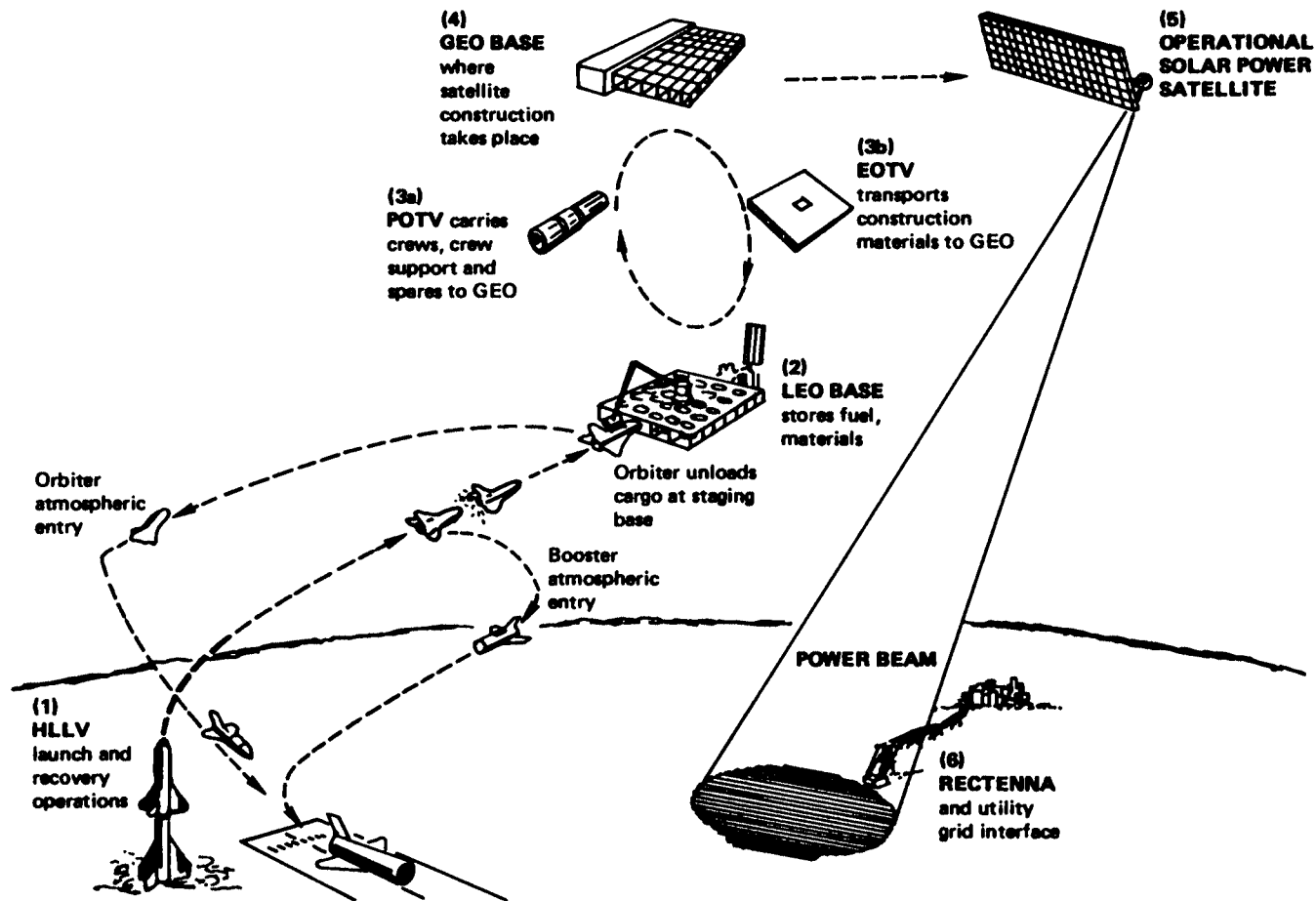


RECTENNA:



SOURCE: Adapted from U.S. DOE (1980d).

FIGURE 1.2. Reference SPS satellite and rectenna.



SOURCE: Torrey (1980). This first appeared in *New Scientist*, London, the weekly review of science and technology.

FIGURE 1.3. SPS operational system: (1) Reusable HLLV, heavy-lift launch vehicles, take people and hardware to (2) LEO, low earth orbit, where the first stage of construction takes place. (3a) POTVs, personnel orbital transfer vehicles, and (3b) EOTVs, electric orbital transfer vehicles, then transfer people and cargo to (4) GEO, geosynchronous earth orbit. The satellites are assembled at the GEO construction base. (5) The operational solar power satellite transmits solar energy to (6) a rectenna, or receiving antenna, on earth by way of a microwave power transmission system.

The construction of the SPS satellites would require the development of a complex system of space transportation, both for materials and for space workers. The first stage of transportation, from earth to LEO, would require the development of a heavy-lift launch vehicle (HLLV) that would be reusable. The reference system postulates the development of an HLLV capable of carrying about 400 metric tons. Since these vehicles would have to carry about 4 million metric tons of materials from earth to LEO over a period of 30 years, it would be necessary to construct a fleet of 40 to 50 HLLVs to make more than 10,000 flights, an average of more than one HLLV launch per day.

At the staging base in LEO a second-stage transportation vehicle called an electric orbital transfer vehicle, or EOTV, would be constructed. This vehicle would be used to carry materials from LEO to GEO. The EOTV would be more than 1 km square and 0.5 km thick, and it would be capable of carrying 4000 metric tons of cargo from LEO to GEO during a slow but efficient trip that would last 6 months. The surface of the EOTV would be covered with solar cells that would collect solar energy to power the vehicle's electric ion engines.

Construction of the entire reference SPS would require about 20,000 space workers, about 1500 of whom would be in space at any one time. These workers would be transported from earth to LEO in a special module attached inside an HLLV or in a totally separate personnel launch vehicle (PLV). Another vehicle, called the personnel orbital transfer vehicle (POTV), would be equipped with a chemical propulsion system to provide fast transit through the Van Allen radiation belts to carry workers from LEO to GEO. While in GEO, workers would spend most of their time within heavily shielded enclosures designed to protect them from the ionizing radiation of space. In these enclosures they would operate the mechanized and robotic equipment that would perform most of the construction work. Other, smaller vehicles, would be needed to transport workers between the GEO base and the power satellites.

The reference system plan calls for the construction of two SPS satellites per year beginning in the year 2000. Meeting this schedule would mean that by the year 2000 both the LEO and the GEO construction bases would have to be in place; that a fleet of HLLVs, EOTVs, POTVs, and possibly PLVs, would have been constructed; and that at least several thousand space workers would have been trained.

THE TASK OF THE COMMITTEE

Like most proposals for making use of new sources of energy or reviving older ones, the concept of an SPS began to receive serious attention following the 1973-1974 embargo of oil shipments by the Organization of Petroleum Exporting Countries. The idea of an SPS was first proposed as a technically feasible enterprise by Glaser (1968). Although some preliminary studies of the SPS concept had been done by NASA in the late 1960s, the first thorough assessment was conducted between 1977 and 1980. Sponsored by DOE's Office of Energy Research, the assessment was conducted under a joint DOE/NASA Satellite Power System Concept Development and Evaluation Program (CDEP). In 1978, the

National Science Foundation (NSF) was authorized to assess the feasibility of an SPS that would make use of extraterrestrial materials--that is, raw materials taken from the moon or from asteroids, the orbits of which lie mainly between those of Mars and Jupiter in our solar system.

By 1979 all three federal agencies involved in developing the SPS concept agreed that there was need for an independent look at the work being conducted under the CDEP because of the large scale of both the concept and its implications. Consequently the NSF, with the concurrence of DOE, asked the National Academy of Sciences:

1. To identify and analyze the scientific, technical, and other issues most critical to future decisions about developing an SPS, including the feasibility of using the moon and the asteroids as sources of materials.
2. To identify any scientific and technological issues that might have been neglected or given inadequate attention during the DOE/NASA assessment program.
3. To examine the results of the CDEP conducted by DOE and NASA.

The NAS, through the National Research Council, asked the Committee on Satellite Power Systems to undertake these tasks. Subsequently, NASA asked that the Committee expand its evaluation of critical issues in the space transportation aspects of SPS.

As it sought to carry out its work, the Committee operated with a set of underlying assumptions, which only time will show to be appropriate. It is therefore important for the reader to know what the assumptions were.

The first assumption was that existing estimates of the future demand for, and supply of, energy in the United States were satisfactory for the Committee's purposes. With few exceptions, these estimates suggest that the demand for energy in this country will grow steadily, and that the demand for electrical energy will increase faster than that for other forms of energy. The Committee, however, made no independent determination of the amount of growth, either in total energy demand or in the demand for electrical energy alone. As a corollary, we assumed that the demand for electric power in the years after 2000 will be neither so large that SPS would comprise only a negligible component of supply (and hence possibly not be worth its complexity) nor so small that the SPS output could not be fully used.

A second assumption was that by the year 2000, the time for the start of deployment of the reference SPS, the generation of electricity by oil and natural gas will have declined substantially. As of 1978, fuel oil and natural gas together were being used to produce about 35 percent of the electricity generated in the United States.

A third assumption--and one that is probably more generally accepted than any of the others--was that the United States must, and ultimately will, change from using fossil fuels (oil, natural gas, and coal) for the bulk of its energy to using virtually unlimited sources of energy--solar power, the recycling of uranium in breeder reactors, thermonuclear fusion, or some other process not yet developed or even conceived.

A fourth assumption was that while the transition from fossil fuels to other energy sources is inevitable, it will also be gradual. In other words, we assumed that during the next 20 or more years there will be no crisis in the supply of energy severe enough to require the crash development of an SPS for the purpose of meeting electrical energy needs either in this country or in the other nations of the world.

The fifth assumption (always carefully made by DOE and NASA as well) was that any SPS that might be deployed in the future will differ substantially from the reference system postulated by DOE and NASA, but that the reference system can be used as a device to examine and analyze the issues that the SPS concept raises.

The sixth assumption was that our examination of the reference system and the more general SPS concept should be based on foreseeable advances in SPS-related science and technology and that estimates of cost should be based on conceivable projections of current trends. Remarkable and unexpected advances in science and technology can occur, of course, leading to enhanced performance or reduced costs. Yet it was our view that it would be prudent not to count on future advances and economies without a reasonable idea of how they might be achieved, so that a realistic idea of an SPS undertaking could be formed.

THE CHALLENGES OF AN SPS

The research and development necessary to provide the technological base for an SPS, followed by the construction, deployment, operation, and maintenance of such a system, would present substantial challenges to any nation or group of nations that embarked on the venture. Apart from the scientific and technological challenges, the projected deployment of an SPS would also present economic, environmental, and sociopolitical questions, many of which would have to be resolved before construction began. Assuming that all the major questions raised by an SPS were satisfactorily answered, however, it would still be necessary to determine whether an SPS would be an advantageous choice as a source of electric power in comparison with other advanced technologies.

The Scientific and Technological Challenge

Of all the challenges presented by an attempt to construct and deploy an SPS, the scientific and technological ones are perhaps the most striking. First of all, it would be necessary to develop and build at least two different types of spacecraft, the HLLV and the EOTV--the one far larger and capable of carrying far heavier loads than any spacecraft developed so far, including the space shuttle, and the other an entirely new departure in space vehicles.

Both the HLLV and the EOTV would be smaller, however, than the SPS satellites. Each of the 60 power satellites postulated by the reference system would be built in space, and each would require an

on-board control system to keep it stable during construction and operation. NASA has not built structures of any size in space, and the robotic and mechanized equipment that has been proposed for automated construction is completely undeveloped.

Further, it has yet to be determined just which materials and manufacturing processes would achieve acceptable results in the construction and operation of the satellites. Photovoltaic cells for the "solar blanket" present particularly challenging problems.

Chapter 2 discusses these scientific and technological problems, and others, in greater detail.

The Economic Challenge

An SPS would be the most expensive technological venture ever attempted. DOE has estimated that the total cost of the reference system over 30 years would be about \$1300 billion in 1980-year dollars. To place the DOE estimate in a clearer perspective, it may be useful to point out that as of 1980 the replacement cost of the entire U.S. electric generating capacity of about 600 GW is roughly \$600 billion.

Estimates of costs up to 50 years in the future are highly uncertain, particularly for such a preliminary and complex system as the reference SPS. The DOE estimate is based on optimistic projections of future technology and costs. Many of the projections already assume large decreases from current costs. Many others are more accurately described as goals than projections--especially in cases where technology such as the EOTV has not yet been developed. Space transportation and photovoltaic cells, as larger elements of SPS costs, deserve critical review in this respect.

An investment of \$100 billion and a period of about 20 years without any financial return is estimated by NASA for research, development, and production of the first operating reference system satellite and rectenna. Thereafter, the new capital that would be needed each year for 30 years to construct the remainder of the system would be in competition with other capital requirements in the U.S. economy, including those of alternative sources of electric power.

Over the next few decades and into the next century, dynamic change will characterize the demand for electrical power, the economic equilibrium of the various conventional and advanced technologies that would supply the demand, and the energy returned by the energy invested in building new power systems. The SPS concept needs to be examined in the context of this changing scene.

The substantial economic challenges that an SPS would raise are discussed at greater length in Chapter 3.

The Environmental Challenge

The construction and operation of an SPS would entail numerous environmental effects, a term used broadly here to include effects on

human beings and on important human activities. For example, certain types of radiocommunications and all of the conventional methods of astronomical observation would be affected. An SPS might also have some environmental effects that are as yet unknown, such as effects of low-level, long-term microwave radiation on human beings outside rectenna sites.

Of the various environmental issues of an SPS, a critical one is the question of the effects of ionizing radiation on human beings working in space, particularly in GEO, on the construction of satellites. Another is the potential radio interference of power satellites with other types of satellites that would also need to use the limited geosynchronous orbit.

An SPS would also create other environmental problems. For example, the exhaust emissions from the HLLVs that would be launched into space anywhere from 375 to 500 times a year, would affect the different atmospheric regions in various ways, including possible weather modification and changes in the chemical composition of the atmosphere. The seriousness of these and other potential HLLV effects is unknown at this time.

The environmental problems mentioned above, as well as some of similar concern, are dealt with in Chapter 4.

The Sociopolitical Challenge

An attempt by the United States--or, for that matter, any other nation or group of nations--to build and deploy an SPS would be complicated by a web of international and domestic sociopolitical considerations that might prove hard or impossible to resolve.

For example, potential interference with other types of satellites would pose international problems of sharing the orbit and the microwave spectrum compatibly with the satellites of other nations. An SPS might also raise military issues, concerning both its convertibility to weaponry and its vulnerability to attack, that might have to be resolved in an international forum.

An SPS would pose certain domestic political questions. As we have seen, SPS satellites would beam microwaves to rectennas on earth. Although the strength of these microwaves outside rectenna sites would be about 100 times less than a present guideline for occupational human exposure limits in the United States, the safety of low-level, long-term microwave radiation is still not proven. This public health concern, along with a variety of other concerns--ranging from the possible impact on land values to the alteration of existing terrain--might pose local political problems related to the siting of rectennas.

Finally, there is the possibility that a project as large, technologically intensive, expensive, centralized, and unprecedented as an SPS might raise, in the population at large, unspecified fears about its consequences or general doubts about its wisdom.

These sociopolitical questions are treated in Chapter 5.

The Challenge of Other Advanced Methods of Producing Electricity

During the coming decades the countries of the world will be making decisions about the mix of sources of electrical energy they will rely on over the long term--that is, beyond the next 40 years. Some, it seems clear, may rely heavily on breeder reactors, while others may opt for expanded use of solar energy in its various forms. Coal will remain a major source of electricity over the next century or longer, and there will also be enhanced efforts to prove that fusion can become an economic source of energy.

It is difficult to predict whether an SPS could become an achievable and economic source of electrical energy in comparison with other potential technologies more than 40 years from now. The best that can be done, under the circumstances, is to make educated guesses about favorable and unfavorable prospects for the various known methods of generating electric power, and to qualify those guesses with suggestions about the exploration of barely known or not-yet-invented technologies.

Hence, Chapter 6 is devoted to a brief analysis of the various possibilities for producing electrical energy over the long term and a brief comparison of certain of those methods with an SPS.

Finally, Chapter 7 reports our examination of the DOE/NASA Concept Development and Evaluation Program and its final report, in view of the many challenges of SPS.

CHAPTER 2
TECHNOLOGICAL ASPECTS

Capturing solar energy in space to provide electricity on earth would entail the development and use of a variety of technologies. Since solar energy is diffuse, large satellites would be needed to intercept enough power to make the project worthwhile. The construction of these large satellites would mean that the technologies for building, positioning, and operating them would have to be developed, as would transportation systems for delivering personnel and materials to orbit, where the satellites would be built. Once collected, the solar energy would then have to be converted into a form suitable for transmission to earth, where it would have to be converted once more into conventional electric power and injected into utility grids.

In this chapter we examine the basic technological requirements for a satellite power system (SPS): space transportation, satellite and space vehicle construction in space, energy conversion, energy transmission, operations and maintenance in space, and energy reception by rectennas (receiving antennas) feeding power into the conventional transmission systems on earth. The reference system--the conceptual model developed by the National Aeronautics and Space Administration--is necessarily the focal point of this examination, but where appropriate we also discuss proposed alternatives for achieving the various objectives. In addition, we examine the prospects for using materials from the moon or asteroids in the construction of an SPS.

SPACE TRANSPORTATION

The space transportation system that would be needed for deploying and maintaining the SPS satellites postulated by the reference system would dwarf that of any other civil or military project (see Appendix C). When fully operational, the space shuttle, which reflects the technology of the 1970s, will have the capacity to lift about 30 metric tons to low earth orbit (LEO) at a cost between \$700 per kilogram (kg) and \$1200/kg with a launch rate of once every 2 weeks. Shuttle capacity is expected to grow to 50 metric tons, with proportional economies. The construction of two SPS satellites per

year, however, would require the movement of more than 100,000 metric tons of material per year to geosynchronous earth orbit (GEO). The reusable heavy-lift launch vehicles (HLLV) proposed in the reference system would each have a payload to LEO of about 400 metric tons and a launch rate of about 400 to 500 flights per year, at a cost goal in the neighborhood of \$50/kg to \$100/kg. This large number of HLLV flights would require a substantial fleet of economical vehicles with low turn-around costs. A second new vehicle, the electrical orbital transfer vehicle (EOTV) of the reference system, would transport a payload of 4000 metric tons from LEO to GEO at a cost goal of about \$20/kg. In contrast, the current cost of launching a small payload from earth to GEO using conventional one-shot rockets reflecting the technology of the 1960s is about \$50,000/kg.

Transportation Between Earth and LEO

To meet the requirements of the reference system for transportation of cargo from earth to LEO, a new and fully reusable HLLV is proposed. This vehicle would require a major extension of today's technology, but no new breakthroughs. A principal development requirement for the HLLV is a reusable, high-pressure booster engine that would burn hydrocarbons for first-stage propulsion instead of hydrogen, as the shuttle does. Other major requirements to achieve the performance and reusability planned for the HLLV would include a new thermal protection system (TPS), reusable cryogenic fuel tank insulation, advanced control systems, new high-temperature alloys for engines, and lightweight composites for structural members (Wolfe 1981, NASA 1980b).

Critical factors that would affect the performance of an HLLV fleet include maintenance and the refurbishment required after each flight. The work required in scheduling and coordinating the packaging of construction materials and delivering them for launch would be comparable to that of major airport operations today. HLLV operations would represent almost two-thirds of estimated transportation costs to LEO.

Thus, high reliability and reusability would have to be designed into the HLLV to keep costs down. For example, total system costs are sensitive to how much of the thermal protection system, which protects against the heat of reentry, would have to be replaced after each flight (see Chapter 3). Just how much refurbishment would be required between flights, particularly for the engines and the TPS, is not known at this time. Refurbishment was not a consideration in the days of expendable space vehicles, but experience with the shuttle in the 1980s should lead to a better understanding of the problems to be faced in improving the performance of future generations of reusable vehicles. For example, the initial flight of the shuttle Columbia showed little degradation of its thermal protection tiles.

Estimates of the weight of the HLLV, made independently (Wolfe 1981) by applying established weight-estimating relationships to each HLLV subsystem, were 12 to 15 percent higher than those derived by the NASA contractors.

Although the HLLV appears achievable, it would be expensive (see Chapter 3). Independent cost estimates (Wolfe 1981) are higher than the estimates of the NASA contractors by a factor of two or three. It would be important to pursue every opportunity to provide higher performance and lower costs than those offered by the HLLV. New fuels, engines, materials, and structures could be important as well as new vehicle and operational concepts. Alternative concepts need not evolve from the design of the shuttle but could be entirely new ideas. For example, a single-stage vehicle capable of flying to LEO from earth might be compared with a two-stage vehicle such as the HLLV to see whether advantages of the former in terms of ground-based logistic operations would offset its greater cost (Reed et al. 1979).

Transportation of personnel from earth to LEO in the reference system is proposed to be done by a separate personnel launch vehicle (PLV) derived from the space shuttle. The vehicle would include a passenger module which might also be used in transporting personnel from LEO to GEO. The PLV appears to be readily achievable, but the alternative of carrying the personnel module within the HLLV, in lieu of developing a separate PLV remains an open question.

As a result of its review the Committee concludes that:

- The technology for a reusable HLLV capable of delivering payloads on the order of 400 metric tons to LEO appears to us to be achievable in the not-too-distant future, and certainly by the year 2020. The HLLV of the reference system, however, would weigh about 15 percent more than NASA's contractors have estimated, with associated increase in cost.

Transportation Between LEO and GEO

Transportation between LEO and GEO would have to be of two types. One type would be for rapid transfer of personnel and limited high priority cargo in a personnel orbital transfer vehicle (POTV), probably using the passenger module from the PLV, propelled by high energy chemical rocket engines. Safety is an important concern for the POTV, but the plan appears manageable.

The other type of LEO to GEO transportation would provide slow but inexpensive transfer of large cargo shipments. Chemical rocket engines are not practical for this purpose because the costs would be prohibitive. An electric orbital transfer vehicle (EOTV), which uses electric ion engines, is proposed instead. Electric ion engines much smaller than those called for by the EOTV are being tested by NASA and, although the ability to scale up the NASA version to EOTV size is not clear, ion engine propulsion appears achievable.

Difficulties more serious than those involving the engines appear to lie in the design and integration of the major subsystems of the EOTV and in its operational characteristics. The EOTV of the reference system, for example, would use photovoltaic technology to supply electrical energy to its argon ion engines. That is, the vehicle would have an array of solar cells on its external surface to collect solar

energy. These cells, like those of the power satellites, would be exposed to potential radiation damage; they would also be exposed to additional radiation during the EOTV's repeated passages through the Van Allen radiation belts. A liquid hydrogen-liquid oxygen control system is proposed for navigation and attitude control of the kilometer-sized EOTV on its 6-month trip from LEO to GEO, including periods in the earth's shadow. Other integration requirements include those for the on-board electrical systems and propellant storage and transfer systems. An EOTV or similar vehicle to provide low cost transportation of heavy cargo from LEO to GEO is absolutely essential to an SPS. If solar cells appear to be impractical as a power source, nuclear power or solar thermal power might be considered as alternatives.

The Committee concludes that:

- The development of an EOTV would represent a major advance in low-cost transport from LEO to GEO. However, the proposed propulsion, power source, control system, and integration requirements of the EOTV would make it a development of high technical risk. The importance to future space operations of a capability like an EOTV makes the concept a likely objective for development whether or not an SPS program is undertaken.

SPACE STRUCTURES AND THEIR CONSTRUCTION

No experience exists on which to base judgments about the technical feasibility of building large structures in LEO and GEO. So far, in fact, no structures of any kind have been constructed in space. Thus, experience in building progressively larger structures would be needed before the technical and economic feasibility of building construction bases, EOTVs, or power satellites could be asserted with confidence.

Each of the power satellites of the reference system would be an open structural frame 10 km long by 5 km wide by 0.5 km high, with a solar cell blanket covering the top and a transmitting antenna about 1 km in diameter attached to the frame by means of a rotating collar. The capability to analyze and design such structures, with their unusual loads and configurations, appears to be achievable. There would, however, be many challenging design problems in integrating structural and configurational requirements with thermal and other environmental conditions, with the characteristics of the construction materials, and with the construction system to be used. Other structural concepts, using more innovative, light-weight approaches and taking better advantage of the space environment could offer important gains over the reference system structures.

A control system would be needed to maintain the stability of each satellite during its construction and operation, as well as to keep it positioned in its orbital location and pointed in the right direction. This system would have to accommodate varying loads caused by gravitational forces, the pressure of solar radiation, the thermal environment and transient loads during construction. It would have to

keep the surfaces of the satellite's solar cells perpendicular to the sun's radiation while keeping the antenna pointed at its rectenna on earth. These are demanding requirements, well beyond current capabilities. Hence, the design of such a control system would require new analytical approaches. Modeling and dynamic analysis would have to be substituted for laboratory investigation, since the physical forces in GEO cannot be reproduced on earth. Although some observers have expressed concern about the status of current progress on SPS control systems (NASA 1980a), we believe that the requirements are essentially major extensions of existing technology and could be met, although not without some difficulty.

The construction of SPS satellites in space would require the development of an entirely new technology. Except for machines that extrude beams from metal ribbons or graphite composite, which have been tested on earth, the techniques and hardware for construction in space are only in the conceptual stage. The techniques of space construction described in the reference system plan would rely heavily on robotics, but there is neither experience in robotics for construction nor a program to develop this capability. Hence, major efforts to develop a robotics capability would be required. We believe that the combination of requirements for other types of space platforms and planned construction experiments in the shuttle will lead to development of a space construction capability before the end of this century. Whether this capability would be adequate for constructing the various parts of an SPS is hard to predict at this time.

We are not optimistic about the possibility of building one SPS satellite every 6 months, as scheduled in the reference system plan. The problems of joining large numbers of long beams in space should not be underestimated. The natural modes of oscillation of beams several hundred meters in length, for lack of convenient means for grounding or damping them, may well attain relative displacements of one or two meters with respect to each other (Mosich 1981). The lightweight cranes that would be used to move and align the beams would themselves be subject to oscillation. Mosich analyzed one beam-joining operation and found that it might take 50 to 150 times longer to accomplish than estimated under the reference system plan.

The Committee concludes that:

- Space structures of the kind that are contemplated in the reference system could probably be designed and built in orbit by the early part of the next century, given adequate development of robotics. However, it appears to us that innovative designs capable of taking advantage of the environment of space are likely to be more practical than conventional beam-and-truss designs used on earth and modified for space.

ENERGY CONVERSION

The function of the power satellites is to convert solar radiation into a form of energy, like microwaves, suitable for transmission to earth. Both thermal and photovoltaic methods for performing the initial step in the conversion have been discussed in the literature. Direct optical excitation of lasers is another, though more remote, possibility. Only photovoltaic conversion is considered here, however, since this is the technique proposed in the reference system.

Solar Cells

The technical feasibility and the economic practicality of the solar cells that would be required for the satellites of the reference system are examined in detail in Appendix E. A number of important considerations would determine the feasibility and practicality of the concept. These considerations include beginning-of-life (BOL) efficiency, radiation and particle damage in GEO, methods of annealing damaged solar cells in GEO, end-of-life (EOL) efficiency, mass, cost, and the future period of time under consideration.

There are two major existing single-crystal photovoltaic technologies, silicon and gallium arsenide, that should be considered for application to an SPS. Of these, silicon has the advantage of much longer technological development and operational experience in space. (Polycrystalline, or thin-film, solar cells have unsuitably low conversion efficiencies today compared with single-crystal silicon or gallium arsenide cells.) Silicon cell arrays have been used successfully in GEO on communications and other satellites during the last two decades, and their advantages and disadvantages are both well understood. The development of gallium arsenide cells, which are potentially capable of higher conversion efficiency through the use of graded heterojunction cells, is yet in its infancy. Hence we believe that:

- Given the differences in technological development between silicon and gallium arsenide cells, and the necessary intervals between the discovery of new science and full-scale manufacturing, solar cells made of silicon would be the only choice if an SPS were to be deployed by the year 2000. In the next century better options will probably become available.

The reference system assumes that the solar arrays of each satellite would have to produce a nominal output in the neighborhood of 10 gigawatts (GW) in order for each rectenna to produce 5 GW--after allowing for losses in conversion to microwaves, transmission to earth, reception, and further conversion to conventional power. NASA (H.L. Benson, NASA Johnson Space Center, personal communication, April 11, 1980) uses a cost goal of about \$0.22 per watt (peak) in 1977-year dollars (or about \$0.30 per watt (peak) in 1980-year dollars) for these arrays, which would account for roughly 15 percent of the system's

total cost. For the reference system, both silicon cells and gallium arsenide cells were considered. However, for the reasons already given, we based our analysis on the prospects for using silicon technology for deployment beginning in the year 2000. That analysis, shown in Appendix E, led us to the conclusion that:

- If the cost and mass of solar arrays were not constraining factors, the technology needed for the fabrication of otherwise satisfactory space-qualified silicon solar cells for an SPS by the year 2000 could be developed.

The several considerations listed above are not unrelated, however, and it appears unlikely to us that all the necessary improvements in all of these considerations, including cost, can be attained for silicon at the same time. It would be possible, for example, to increase the resistance of the cells to penetrating radiation, but this could bring with it the disadvantages of greater mass and higher cost. Then again, it would be possible to reduce the mass of the solar cells, but this could reduce EOL efficiency.

Damage to Solar Cells from Particle Radiation

Damage to the solar cells in orbit from low-energy electrons and protons (from the sun) would gradually reduce the conversion efficiency of the cells; intense episodic solar flares would hasten the reduction in efficiency. The rate of damage could be slowed but not eliminated by using silicon of ultrahigh purity. Thicker glass covers on the cells would also help to reduce the damage. The former would add to the cost of silicon, however, while the latter would add to the mass of the satellite and hence also to the cost.

Thus, if the solar cells are to have a long life span, it would be necessary to anneal damaged cells in space to restore their efficiency. Currently, radiation-damaged cells are annealed in ovens, but lasers or electron beams would have to be used for this purpose in space. No data now exist on the possibilities of annealing solar cells protected by glass covers. Even for cells without covers, after repeated cycles of exposure to radiation and annealing in an oven, cells have failed to recover their original efficiency. Thus, the Committee concludes that:

- In situ annealing of glass-covered silicon solar cells is probably a major problem.

The frequency of in situ annealing would depend on the rate of radiation damage and the need to prevent the formation of complexes of radiation-induced defects in the cells (Appendix E). Defects would form at a slower rate in high-purity silicon, but in situ annealing of the high-purity silicon currently in use (especially during sun spot cycles) might be necessary too frequently for laser annealing to be energy-efficient. It would also be possible to forgo in situ annealing

and accept the reduced efficiency of the cells. This would mean a higher initial cost for the photovoltaic arrays because of the need for a larger array to compensate for the reduced EOL efficiency. Because the direct bandgap of gallium arsenide allows efficient operation with much thinner cells than does the indirect bandgap in silicon, the former is much more resistant to radiation damage. In addition, the annealing of gallium arsenide cells would be possible at a lower temperature than that required for annealing silicon cells.

Mass of the Solar Cell Array

The reference system design assumes a reduction in the mass of current silicon arrays by a factor of seven without sacrificing other important characteristics. Given other requirements, such as cost, long life, and resistance to radiation, this requirement appears to be difficult to realize.

Cost of the Solar Cell Array

The cost of the solar cell array is intimately bound up with its performance requirements. Therefore, cost is analyzed in that context in Appendix E, and the conclusions on cost are noted here with the discussion of technical characteristics.

For an SPS to be cost-effective, the cost of photovoltaic arrays would have to be drastically reduced. Currently available photovoltaic arrays suitable for use in space cost about 2000 times the unit cost assumed for the reference system. Many of the processing and manufacturing costs, of course, could eventually be reduced by increased automation and improved technology.

Cost reductions may be achieved through foreseeable technological advances in various areas. These include raw materials, crystal growth, junction formation, metallization, interconnection, array fabrication, and inspection. Estimates of how costs might be lowered in each of these areas, and with what likelihood, are at best educated guesses. But using professional judgment, estimates for each area can be examined in combination to give a very rough overall measure of the likelihood of attaining a particular cost level. In Appendix E these rough measures were considered, and from this work the Committee concludes that:

- There is virtually no likelihood that the technical requirements of single-crystal silicon cell arrays for the reference system can be met within their cost goal by the year 2000. The chances are quite small (say, of the order of 1 percent) that even a cost 10 times higher than the goal could be attained by the year 2000. The chances are moderate (say, 15 to 20 percent) that a cost 50 times higher than the goal could be attained by the year 2000.

In spite of these discouraging conclusions for single-crystal silicon solar cell arrays for the reference system by the year 2000, photovoltaic technology gives promise of significant advances beyond that time. Furthermore, this technology is vital for virtually all aspects of a national space program. Hence the Committee recommends that:

- The technical problems associated with the production of low-cost, space-qualified photovoltaic arrays should be studied in association with programs of research and development on solar cells that are mounted in pursuit of goals other than SPS. In view of continuing technological developments in the possibility of using direct-bandgap materials, such as gallium arsenide, and in developing continuous methods of solar cell fabrication, a reevaluation of solar cell technology for SPS should be made within a decade.

ENERGY TRANSMISSION

To transmit energy from GEO to earth, it would be necessary to design a system in which energy was concentrated into a well-defined beam. The beam would have to transmit enough energy to be economically practical, but it would also have to be of low enough intensity to avoid adverse environmental consequences. On the other hand, the power density of the beam could not be too low, or the receiving antenna would be unreasonably large.

The reference system postulates the use of microwaves at 2450 megahertz (MHz) to transmit energy to earth. To convert the direct-current output of the solar cells to microwaves, on the order of 100,000 klystron amplifier tubes would be needed, each rated at about 70 kilowatts (kW). To produce a well-collimated beam, the transmitting antenna on the satellite would have to be about 1 km in diameter. The beam from the antenna would be focused by controlling the electrical phase of the wave being emitted from each klystron. The klystrons would have to have high efficiencies, in the range of 80 to 85 percent, and would need to have a long average operating life to minimize expensive replacement in GEO. Because of transmission losses and losses in conversion at the rectenna site, the transmitting antenna would have to radiate about 6.7 GW for the rectenna to deliver 5 GW to the utility grid.

In connection with energy transmission, we noted with interest a suggestion of Rogers (1981). Photovoltaic energy conversion would be accomplished at optimum sites on earth, however remote. Power would be relayed by microwave beam to continental or intercontinental distances by means of a passive satellite reflector. Thus most of the complexity of an SPS would be put on earth at the expense of additional land and additional power losses incurred in two-way transmission. The suggestion illustrates that quite different concepts for an SPS will arise.

Microwave Power Generators

Three types of microwave power generators for an SPS have been examined. One is the array of high-powered klystron amplifiers described in the reference system. The second would be an array of magnetron oscillators, with the frequency and phase of the output wave controlled by a reference signal supplied to each magnetron oscillator from an external source. Since the output of each magnetron would probably be only 3 kW to 5 kW per tube, more than a million magnetrons would be needed to transmit power to a 5-GW rectenna. A third possibility would be an array of solid-state amplifiers, probably gallium arsenide field-effect transistors (FET), operating at perhaps 10 W each. In such a case, the power output would have to be scaled down because of limitations on operating temperature of the solid-state devices. A satellite capable of delivering 1 GW would require something on the order of 100 million FETs, which could be mounted on the opposite side of the satellite from the solar cells. In other words, a power satellite could be covered with solar cells on one side and with microwave generating devices on the other. Because the microwave devices must always be oriented toward the same spot on earth, movable mirrors would be needed in this design to maintain illumination of the solar cells. More detailed discussion of the various technical aspects of klystrons and magnetrons is contained in Appendix F.

Of these three, the only one that can seriously be considered for deployment in the year 2000 is the klystron. It would be the only choice in the near term for undertaking the design and fabrication of a prototype that could meet all of the specifications, with the possible exception of tube life. Detailed designs for such a klystron tube have been given by independent sources (Boeing Aerospace Company 1977, LaRue 1980, Nalos 1980). The proposals are similar and are based on an established design procedure that has been applied successfully over a period of almost three decades to a variety of high-powered klystron tube amplifiers. Such klystrons have operated in both pulsed and continuous-wave modes over a wide range of frequencies, in many cases with higher power output than would be required for an SPS. However, some shortfall, perhaps 5 percent, from the desired efficiency of 85 percent might have to be accepted in the final design. Currently, microwave systems that require very high, continuous-wave power and high gain with controlled frequency and phase use klystrons similar to those proposed for SPS satellites.

Phase control has also been adequately demonstrated in klystron systems of large spatial extent. The Stanford Linear Electron Accelerator, for example, uses 200 pulsed klystrons distributed over a distance of about 3 km, each delivering peak power of more than 30 megawatts (MW). These klystrons operate under more stringent phase control than would be required in an SPS. The accelerator has been in operation for 12 years.

The major uncertainty in using klystrons in an SPS is their anticipated working life, which is largely determined by their cathode life. Insufficient experience exists to guarantee 30 years of life. A

limited amount of data exists on klystron tubes used in the Ballistic Missile Early Warning System (BMEWS) radar (400 MHz; 75 kW (average), 1 MW (peak)); those tubes have been operating up to 14 years. Recently, however, a great deal of effort has been devoted to a new class of thermionic emitters, the so-called matrix-type cathodes, which seem likely to be able to meet the lifetime requirements for an SPS. These cathodes operate at lower temperatures for a given current and should have longer life than the conventional cathode with a barium oxide-coated surface that has been used for many years.

Data on the other alternatives for microwave generation are so rudimentary that it is not possible now to project the implications of those systems for an SPS. Since possible advantages have been claimed for each system, however, further study appears to have merit.

The Committee concludes that:

- Klystron tubes would be the preferred choice for transmitting power from space to earth in an SPS to be deployed by the year 2000, but further work would be required to develop tubes with sufficiently long lifetimes. Alternative designs for deployment in the next century might be able to use magnetrons or solid-state microwave generators for this purpose.

Controlling a Microwave Beam

One of the problems posed by an SPS is to achieve precise collimation and directional control of the microwave beam. Such control would be necessary not only to transfer the most power but also to prevent significant amounts of microwave radiation from reaching areas other than the rectenna.

Three methods of beam control have been suggested, and engineering studies of all three have been made. The methods are (1) retrodirectivity, (2) inverse radio interferometry, and (3) coherent multitone ground-based phase control. All three are sound in concept but would ultimately require detailed mathematical analysis followed by laboratory testing of key components and subsystems. The three methods are discussed in detail in Appendix F (see also NASA 1980c).

The retrodirective array postulated by the reference system is a method for automatically phasing the separate modules in the transmitting antenna so that each radiates power with a carrier phase that is the negative of the phase of a pilot signal received at the module. If the pilot signal originated at the rectenna, the components of the main power beam emanating from the many modules would arrive in phase at the rectenna, because the phase on each down path would advance by an amount just equal and opposite to the emitted carrier phase at each module.

Although pilot beams have been used to direct microwave beams on earth, there are two important areas of uncertainty in SPS application. The first involves the possible degradation of the pilot beam by the ionosphere as a result of disturbance created by the microwave power beam. Microwave transmissions through the ionosphere

have been found to scintillate strongly under certain unusual conditions (Taur 1974, 1976). If the power beam disturbed the ionosphere enough to degrade the performance of the phase control system, one obvious solution would be to reposition the pilot beam transmitter so that the beam would avoid the heated ionosphere and to introduce compensating phase corrections on the satellite.

The second question involves possible interference with the pilot signal by the high-powered transmitter on the satellite. If the high power caused nonlinear effects in the pilot signal receiver, the phase information essential for properly collimating the microwave beam might be distorted.

Laser Transmission

The possibility of using laser radiation rather than microwaves to transmit electrical power from an SPS satellite depends on a number of factors, some of which are discussed below. First, we enumerate some of the potential advantages.

The shorter wavelengths of laser radiation would permit the use of much smaller transmitting and receiving antennas. For example, the wavelength of the carbon dioxide (CO₂) laser (10 micrometers (μm)) would be shorter than the wavelength (about 0.12 m) of SPS microwave radiation by four orders of magnitude. Savings in costs would result from smaller antennas and rectennas. In addition, the short wavelength of laser radiation makes it possible to shape the profile of the beam accurately enough to keep the side lobes negligible, reducing the radiated power outside the rectenna zone compared with what would occur with microwave transmission. Finally, the problem of interference with existing communications systems of all sorts would be nonexistent if laser radiation was used.

These potential advantages, however, are more than offset by major problems associated with laser transmission, including the fact that attenuation of laser radiation by clouds makes laser transmission undependable. There is no place in the optical spectrum, including the infrared portion, where clouds are transparent. Switching the laser beam among alternative rectennas might be a solution to this problem, but meteorological studies indicate that large areas of the continental United States are covered by clouds during certain seasons. In these circumstances, having a diversity of rectennas for each satellite would not be of much help.

The argument that laser radiation could continuously "burn" a hole through the clouds does not have merit. A straightforward calculation shows that for average cloud thickness and a cloud velocity of 1 mile per hour, a laser intensity of greater than 1 MW/m² would be required to pierce the cloud cover. For safety reasons alone, laser radiation of such an intensity cannot be considered acceptable. Furthermore, thermal "blooming" at an intensity of that magnitude might make laser power transmission quite unreliable. (Thermal blooming is caused by the heating of the atmosphere by the passage of the laser beam, with consequent reduction of the refractive index nearer the axis, which in turn causes divergence of the beam.)

Moreover, the beam of a CO₂ laser using natural isotopes would be partially absorbed by atmospheric CO₂. Absorption of the strongest optical component of the CO₂ laser radiation would amount to about 30 to 50 percent. The use of rare isotopes in CO₂ lasers would alleviate this situation, since the laser wavelength for different isotopes of CO₂ is different. However, the cost of using rare isotopes would probably be prohibitive.

The electrical efficiency of practical, continuous-wave lasers is far lower than that of klystrons or magnetrons. For example, even the CO₂ laser, a prime candidate, has a demonstrated conversion efficiency just above 10 percent and a theoretical efficiency of only about 40 percent (Patel 1964, 1968).

Furthermore, the direct conversion of infrared radiation to electricity (at the rectenna) is not as well developed as the conversion of microwaves. Proposals have been made to reabsorb laser energy using the same kind of system that generated the laser radiation. However, this scheme would be applicable only to laser systems using gases, and then only to gases in which the molecular energy level of the laser gas was close to the ground state and hence appreciably populated at ambient temperatures. An appropriate example would be CO₂. The CO₂ laser emits in the 9- μ m to 10.8- μ m region, where the "heat" gained by the gas from absorption of the infrared radiation could be used to drive gas turbines for electrical generation. It might eventually be possible to make this process highly efficient (Christiansen and Hertzberg 1973), but substantial additional work would be required to do so.

Based on the discussion of laser transmission in this section, the Committee concludes that:

- The transmission of power from space to earth by means of lasers appears unlikely in the near future because of inefficiencies of energy conversion or perhaps ever because of the fundamental limitation imposed by the opacity of clouds.

OPERATIONS AND MAINTENANCE IN SPACE

Although some experience has already been gained in operating and maintaining satellites and vehicles in space, and much more experience will be gained during the shuttle program, operating and maintaining an SPS in GEO involve substantial uncertainties. It is not that the problems themselves are not understood, but that there are so many tasks for which the required base of technical knowledge has not been defined. For example, SPS operations would require the routine transfer of fluids, especially cryogenic fuels, over large distances in space. Although this capability has been identified for some time as important in future space programs, the United States has little experience in the design, development, or testing of systems for doing so. The USSR has successfully transferred liquids in orbit, however.

Another example pertains to the maintenance of the SPS transmitting antennas. Since each antenna would have about 100,000 klystrons,

several thousand klystrons per satellite would have to be repaired or replaced each year, even if the klystrons had an average lifetime of 25 years. Under the reference system, a work force of several hundred people was proposed for the task of repairing klystrons in GEO, since it apparently would be less costly to repair them than to replace them. Although the problem of servicing failed klystrons is not so fundamentally hard as some other technical aspects of SPS, there is no experience from which to judge how best to approach such an operation. Accordingly, the task cannot yet be considered solved. A general rule of thumb for operations in GEO, obviously, should be to minimize the number of people on site, either through alternative designs or through far more use of robotics for servicing than visualized in the reference system.

One important reason for minimizing the number of personnel in GEO is to reduce the extent of their exposure to ionizing radiation (see Chapter 4). The heavy shielding needed to protect workers in GEO under ordinary circumstances and the need for workers to be close to a more heavily shielded storm shelter during solar flares can be expected to hamper maintenance operations. If our analyses are correct, however, it might also be necessary to restrict the length of time spent by workers in GEO, thereby increasing the number of people who would have to be recruited and trained for the work. Consequently, the fewer the tasks performed by people in GEO, the better.

A critical task that would be performed in LEO under the reference system is the repair and refurbishment of the ion engines used in the EOTV. It is anticipated that the electrodes in the engines would have to be replaced frequently. These electrodes have very close tolerances for positioning and alignment, and how they would be replaced in space has not been specified.

The reference system deals with problems of operations and maintenance by postulating ideal solutions. Yet past experience has shown that unanticipated compromises in idealized designs are a distinct possibility, and that such compromises will result in delays and added costs. One area where the ideal and the practical may not coincide is in the extensive docking, stevedoring, and warehousing facilities and operations that will be needed in LEO to keep up with 400 HLLV launches a year. Experience in LEO and GEO is needed to gain an improved understanding of the problems of maintenance in space and to demonstrate techniques for resolving them.

ENERGY RECEPTION AND INTERFACE WITH THE UTILITY GRID

The ground facilities of an SPS would consist of receiving antennas (rectennas), to convert the microwaves received from the satellites to high voltage 60-hertz (Hz) power without intermediate storage, and transmission lines, to transmit the power to existing electric utility transmission grids.

The rectenna postulated under the reference system would account for about 20 percent of the cost of each satellite-rectenna combination. About 10 billion half-wave dipoles feeding semiconductor

diodes at each rectenna would be used to convert the microwave energy into low-voltage, direct-current (dc) electricity, which would then be converted to alternating current (ac) by conventional means. All of the technology necessary to build the rectennas is at hand; the major problem is that of scale. At 35° latitude, the field of dipoles would cover an elliptical area approximately 10 km by 13 km. Building such a rectenna and installing its electrical components, while technically feasible, would be a challenging task that would certainly take several years.

If an SPS were to be built, there would be no insuperable problems in connecting the 5-GW output of each rectenna to the integrated utility grid systems of the United States. By the time an SPS could be built, we believe that domestic grids will certainly be large enough to accommodate a single 5-GW block of power. The power from each additional rectenna would be easier to integrate into the grid system because the total amount of power feeding into the system would be larger. If the load centers were a considerable distance from a rectenna site, the ac voltage could be stepped up to a suitable level for transmission; and conventional considerations would determine whether the transmission would be by ac or dc. If it were feasible, however, to locate the rectenna adjacent to or within a large load center, the rectenna design might be modified to permit direct injection of its low-voltage power into the system. It is more probable, however, that some of the energy would be used locally, while the rest of it was transformed to a higher voltage for transmission to other load centers.

Considerations of Utility Reliability

A rule of thumb in the electric power industry is that no more than 10 percent of the power of a given system should come from any single generating station. For this basic tenet to be observed, the power system or systems receiving the energy would need to have a baseload demand of at least 50 GW. Furthermore, if the rectenna is considered a baseload source, the demand of 50 GW would have to occur during off-peak periods. Otherwise, an unscheduled outage of the SPS during a light-load period (i.e., a period when demand was less than 50 GW) might well lead to a failure of power systems using SPS energy.

Furthermore, any single transmission line from a rectenna to a power system should not be expected to deliver more than 10 percent of that system's load. Hence, if a utility served by a rectenna had an off-peak load of 10 GW, the transmission line connecting the rectenna with the system should transmit no more than 1 GW.

These criteria are not as restrictive as they may appear, however, since the power from one 5-GW rectenna could be connected to more than one grid if need be. The eastern and western U.S. grids of today would have no problem integrating the power from 5-GW baseload units.

Finally, a limitation on the length of a transmission line is set by the economic feasibility of capital cost and power losses. Experience has shown that this limit is on the order of several hundred miles.

The Committee concludes that:

- If suitable sites for rectennas could be located within a few hundred miles of large, integrated power networks, no insurmountable problems would arise in building microwave rectennas and integrating their power output into the U.S. electric grid system.

USE OF EXTRATERRESTRIAL RESOURCES TO BUILD AN SPS

Because a high percentage of the cost of an SPS would be incurred to lift large amounts of material from earth to GEO, it has been suggested that the use of extraterrestrial materials might be less costly. Since delivering a payload from the surface of the moon to GEO requires only about one-twentieth of the energy needed to move the same payload from earth to GEO (Criswell and Waldron 1978), the potential savings in energy and costs have prompted proposals to use extraterrestrial materials to build an SPS.

Expectations of potential savings, however, appear to us to be premature. First, not all of the elements that would be required for an SPS are found on the lunar surface or on asteroids. Aluminum, magnesium, and silicon are available on the moon; but concentrated deposits have not been located. Zinc, molybdenum, and other metals important for making alloys are rare. Oxygen is plentiful in lunar soils, but hydrogen is very scarce. It therefore appears necessary to import water from earth for industrial activities on the moon.

It is clear that many complications would be introduced into the construction of an SPS through the mining and beneficiating of extraterrestrial materials to produce raw stock, followed by the fabrication of finished products, and their transport from the moon to GEO. It is not at all clear that the various steps in the extraction and manufacturing processes could be accomplished in space with net energy savings or at net costs less than those that would be incurred by delivering materials directly from earth to orbit on HLLVs and EOTVs.

Developing the capability to recover resources from the moon or asteroids for use in space construction projects would require a long-range program not unlike an SPS program itself. It would take several decades to achieve the necessary technological expertise. The mining, processing, and fabricating of materials from lunar sources and the development of an efficient means of transporting these materials from the moon to an earth orbit would impose technological demands well beyond those involved in building an SPS from resources on earth. These technologies will probably become technically feasible in the next century, however, starting with the extraction of oxygen from lunar resources to refuel spacecraft. But there is no way to predict at this time whether extraterrestrial materials for space construction projects in GEO will become competitive in cost with materials from the earth. Appendix C discusses the steps that would have to be taken to achieve lunar resource capability.

To sum up, development of an SPS should be based on the use of earth-based resources if it is desired to follow the path of least cost and complexity. Once space-based construction is demonstrated, it may be practical to fabricate materials in space from resources recovered from the moon or asteroids. Accordingly, the Committee concludes that:

- A decision to proceed with an SPS should not invoke a concurrent decision to develop the capability to use lunar or other extraterrestrial resources. For the next several decades, it would be more practical to use materials from earth, thus minimizing the new technologies that would have to be developed to construct an SPS.

THE TECHNOLOGY AS A WHOLE

We have surveyed the technologies associated with the various subsystems of the reference system in the preceding sections. It remains to capture those discussions and conclusions in a brief overall statement about the technology of an SPS as a whole.

We have seen that photovoltaic conversion of solar energy in space on a large scale appears to be technically possible, although such serious difficulties attend the single-crystal silicon technology that alternatives must be sought to meet acceptable goals of cost, mass, and life. While space construction is not beyond our knowledge of how to go about it, it is beyond our experience and hence beyond our ability to make realistic estimates of construction times and costs. The ability to transport heavy loads to LEO can be extrapolated with reasonable confidence from space shuttle experience. However, the cost estimates for transportation in the reference system appear to be optimistic by a factor of two or three. Considerable technological risk attends the EOTV, but the concept is valid. Transmission of power to earth by microwaves appears possible provided that difficulties of scale and device lifetime are overcome. There appear to be no fundamental scientific obstacles, either of transport, safety, or habitation, to the establishment of the work force needed for orbital construction and operation, although further development of robotics is clearly needed to reduce the high technical risk of space operations. No insurmountable problems appear to be associated with the microwave receiving antennas on earth and their interface with the electric utility grid.

There are many technical areas where the details cannot yet be seen and where much further development would have to be done. These uncertainties will very likely delay the technical readiness of the SPS concept well beyond the year 2000 postulated for the reference system.

The present costs of performing functions similar to those of various SPS subsystems are extremely high compared with the cost goals of the reference system. Our ability to predict future costs with confidence is limited. The cost of overcoming the remaining technical problems is not well known. These considerations, more fully discussed in Chapter 3, suggest that the technical feasibility of the concept and its economic feasibility are different aspects of a broader question.

Weighing all the foregoing points, the Committee reaches the general conclusion that:

- Some type of SPS would be possible from a technical point of view within the foreseeable future. Even so, formidable technical problems remain in many areas of development and operation, and these probably could not be overcome within economically feasible limits on cost.

CHAPTER 3
ECONOMIC ASPECTS

The question of how to assure long-term energy supplies at affordable cost has received great attention in the United States during the past decade. It is this concern, in fact, that has prompted interest in various forms of solar energy, including an SPS.

This chapter seeks to answer the following questions that relate to the economic aspects of an SPS:

1. What are the probable costs of an SPS per unit of installed generating capacity or per unit of electrical energy output?
2. Would these costs favor the introduction of an SPS in the normal course of events? That is, given a modest growth in demand, could an SPS be substituted economically for other sources of supply at the time that an SPS could go into operation?
3. Would these costs favor the introduction of an SPS in unusual circumstances? That is, given a high rate of growth in demand or severe constraints on the use of coal or nuclear energy, would an SPS be cost-competitive with alternative technologies that are themselves likely to be costly?

The chapter deals first with the cost of an SPS as central to its economic aspects. We then discuss several related issues: the prospects for financing an SPS, the demand for and supply of electricity in the United States over the next four decades, and a "net energy analysis" that compares the amount of energy that an SPS would produce with the amount of energy that would be needed to build it.

The approach taken here is that an SPS would have to make economic sense--based strictly on cost-effectiveness, (including costs of environmental protection--before the Nation could consider committing itself to the development of such a huge, high-technology system.

SPS COSTS

Projecting the technological capabilities of a satellite power system that would come into existence two or more decades from now, as is done in Chapter 2, can identify trends and fields in which major advances are likely to occur. Such projections are necessary for

long-range planning, but they are not suitable for estimating costs. Therefore, the approach taken here was to adopt 1980 price levels and a 1990 technology baseline--that is, to assume that scientific, technical, and systems capabilities now in the research and development (R&D) phase will be available by the 1990s at 1980 prices.

This approach avoids questions of inflation and real increases in prices. The disadvantage is that it probably underestimates the effects of long-term technological advances. The advantage is that it can be done readily.

Prior Estimates of Costs

Four different measures of cost of the reference SPS are useful. These are the cost of the initial phases, the cost per unit of installed generating capacity (dollars per kilowatt), the cost per unit of electrical energy output (mills per kilowatt hour), and total system cost.

The costs of the initial phases, or "front end," have been estimated by the National Aeronautics and Space Administration (NASA), and published by the U.S. Department of Energy (DOE), as \$102.5 billion in 1977-year dollars (\$128.3 billion in 1980-year dollars¹). These costs are distributed among research, engineering, demonstration, investment in plants and facilities, and production of the first satellite-rectenna unit (Table 3.1).

The cost per unit of generating capacity may be obtained from an estimate of the cost of the average 5-gigawatt (GW) SPS unit (after the first one). An unofficial NASA estimate for the latter is \$11.5 billion in 1977-year dollars, giving \$2,300 per kilowatt (kW) as the result (Table 3.2). Of more interest than the dollar amount of this particular estimate, however, is the distribution of the total cost among major categories, such as the satellite-rectenna unit and space transportation. For example, in Table 3.2, about 15 percent of the cost is ascribed to the solar cell array and about 17 percent to the heavy-lift launch vehicle (HLLV). These percentages were important in connection with the cost review made by the Committee.

Using an approach similar to that of NASA, DOE made its own estimates of the range of capital costs per unit of generating capacity that would be incurred in building two different kinds of reference SPS--one whose satellites used photovoltaic cells made of silicon and the other, of gallium arsenide. These estimates are shown in Table 3.3 and are taken as the most representative ones. (Table 3.3 retains the degree of precision given in the source, although this may be greater than is really meant.) The "nominal" estimate for the silicon system is \$4253/kW in 1980-year dollars, although a high estimate of \$19,478/kW is also given. In Table 3.4 we applied the percentage distributions of Table 3.2 to the DOE nominal figure to produce estimates for the various principal components of cost, in anticipation of comparing them with the results of our own cost review. For example, the HLLV component appears as \$723/kW in 1980-year dollars by this procedure.

TABLE 3.1. A NASA estimate of costs of the initial phases of the reference SPS program (in billions of dollars).

Major Initial Program Phase	1977-year Dollars	1980-year Dollars
Research	0.4	0.5
Engineering	8.1	10.1
Demonstration	23.0	28.8
Investment	57.5	72.0
First Satellite-Rectenna	13.5	16.9
TOTAL	\$102.5	\$128.3

NOTE: Cost as given by NASA in 1977-year dollars has been converted to 1980-year dollars by multiplying by the ratio of the implicit price deflators for gross national product for 1980 and 1977, given in Note 1.

SOURCE: Adapted from U.S. DOE (1980d, Figure 3.6).

TABLE 3.2. A NASA estimate of the cost of the average 5-GW capacity satellite-rectenna unit after the first one, for the silicon solar cell option of the reference system (in billions of 1977-year dollars).

Cost Element	Cost	Percent
Satellite and Rectenna		
Solar array portion	1.7	14.8
Other satellite portions	2.3	20.0
Rectenna portion	2.2	19.1
Other	<u>0.3</u>	<u>2.6</u>
Subtotal	6.5	56.5
Space Construction	1.0	8.7
Space Transportation		
HLLV portion	1.95	17.0
Other	<u>0.85</u>	<u>7.4</u>
Subtotal	2.8	24.4
Management and Integration	<u>1.2</u>	<u>10.4</u>
Total	\$11.5	100.0%

NOTES:

1. Capital cost per unit of generating capacity is \$2300/kW (\$11.5 billion ÷ 5 GW).
2. To convert to 1980-year dollars, multiply by the ratio of the implicit price deflators for gross national product for 1980 and 1977, given in Note 1.

SOURCE: Adapted from Piland (1980) and H.E. Benson, NASA Johnson Space Center, personal communication, 1980.

TABLE 3.3. DOE capital cost estimates per unit of generating capacity for 5-GW capacity satellites, for two solar cell options of the reference system.

Year; Level of Estimate ^a	Solar Cell Option			
	Silicon (1978 \$/kW)	Gallium Aluminum Arsenide ^b (1978 \$/kW)	Silicon	Gallium Aluminum Arsenide ^c (1980 \$/kW)
1978				
Nominal	3,340	3,079	3,896	3,592
2000				
Low	3,139	2,874	3,662	3,352
Nominal	3,646	3,362	4,253	3,922
High	16,698	15,398	19,478	17,961

^aLow and high figures are indicators of uncertainties around the nominal value.

^bGallium aluminum arsenide ($\text{Ga}_x\text{Al}_{1-x}\text{As}$), also referred to as gallium arsenide.

^cCost as given by DOE in 1978-year dollars has been converted to 1980-year dollars by multiplying by the ratio of the implicit price deflators for gross national product for 1980 and 1978, given in Note 1.

SOURCE: Adapted from U.S. DOE (1980d, Table 3.7).

TABLE 3.4. Distribution of DOE capital cost estimates per unit of generating capacity, for the silicon solar cell option of the reference system.

Cost Element	Percent of System Costs	Nominal Capital Cost Estimate in Year 2000	
		1978 \$/kW	1980 \$/kW ^a
Satellite and rectenna			
Solar array portion	14.8	540	630 ^b
Other satellite portions	20.0	729	850
Rectenna portion	19.1	696	812
Other	2.6	95	111
Subtotal	56.5	2060	2403
Space Construction	8.7	317	370
Space Transportation			
HLLV portion	17.0	620	723 ^c
Other	7.4	270	315
Subtotal	24.4	890	1038
Management and Integration	10.4	379	442
Total	100.0%	\$3646	\$4253

^aCost as given by DOE in 1978-year dollars has been converted to 1980-year dollars by multiplying by the ratio of the implicit price deflators for gross national product for 1980 and 1978, given in Note 1.

^bThis Committee concluded that these estimates for the solar array portion are at least 10 to 50 times too small.

^cThis Committee concluded that a better estimate for the HLLV portion would have been around \$2000/kW.

SOURCE: Tables 3.2 and 3.3 of this report.

NASA also made estimates of the cost per unit of electric energy (in mills per kilowatt hour) based on capital costs, operation and maintenance, plant factor, system life, and rate of return on investment. The agency's calculations for the average SPS unit (after the first) are shown in Figure 3.1. Corresponding to its assumption of capital cost of \$2261/kW (consistent with the rounded unit cost derivable from Table 3.2), NASA arrived at 49.2 mills per kilowatt hour (mills/kWh) in 1977-year dollars (or \$2830/kW and 61.6 mills/kWh, respectively, in 1980-year dollars). Corresponding estimates by DOE are shown in Figure 3.2. The nominal value is comparable to the NASA estimate, but a broad range of uncertainty has been included by DOE.

The cost per unit of electrical energy is tied closely to capital costs because the solar energy is free and costs for operation and maintenance are assumed to be small compared with capital costs. An assumption sufficiently accurate for our purposes was that the cost of electricity would vary in proportion to the capital cost of installed capacity, as different base-year dollars are used or as different estimates of capital cost are considered.

Finally, the cost of the entire reference SPS is of interest. A figure sufficient to show the general scope of the venture under various cost assumptions can be obtained by multiplying the system capacity of 300×10^6 kW (i.e., 300 GW) by some particular unit capacity cost in dollars per kilowatt. For example, by using the DOE nominal figure of \$4253/kW we obtain about \$1300 billion for the whole system. Front-end and capitalization costs may be added or not, depending on specific assumptions about the means of financing and recovering these costs.

Review of Selected Costs

Transportation to LEO

The contractors who have performed studies of the reference system for DOE/NASA estimated that transportation costs would constitute 24 to 27 percent of the cost of deploying one satellite. Of this portion, some 66 to 85 percent (depending on contractor design) would be for transportation from earth to low earth orbit (LEO) by means of the HLLV. Since prior space programs have produced a substantial amount of knowledge on which to base both design and cost projections, the Committee arranged for an examination of this subject by The Aerospace Corporation (Wolfe 1981, reproduced as Appendix D in this report).

The Aerospace study first reviewed the characteristics of the HLLVs and cost estimates developed for NASA by Boeing Aerospace Company and Rockwell International. As the next step, the study identified high-cost items in the contractors' transportation designs and reestimated their costs using an independent data base that included cost information on a long series of civilian and military rockets and on the space shuttle (Space Transportation System). Finally, the study modified the contractors' designs where it was deemed necessary (for example, payload, number of flights, fleet quantity, cost per flight,

$$\text{CAPITAL RECOVERY} = \left[\frac{R}{1 - \left(\frac{1}{1+R}\right)^Y} \right] \left[\frac{CC}{E} \right],$$

where R = rate of return = 15%,
 Y = plant lifetime = 30 yr,
 CC = capital cost = \$2261/kW
 (\$11,305 million per satellite),
 E = 0.9 plant factor x
 8760 h/yr.

$$\text{CAPITAL RECOVERY PER SATELLITE AFTER THE FIRST} = \left[\frac{0.15}{1 - \left(\frac{.1}{1.15}\right)^{30}} \right] \left[\frac{2261}{0.9 \times 8760} \right] = 44 \text{ mills/kWh.}$$

$$\text{MAINTENANCE} = \frac{206 \times 10^6}{5 \times 10^6 \times 0.9 \times 8760} = 5.2 \text{ mills/kWh.}$$

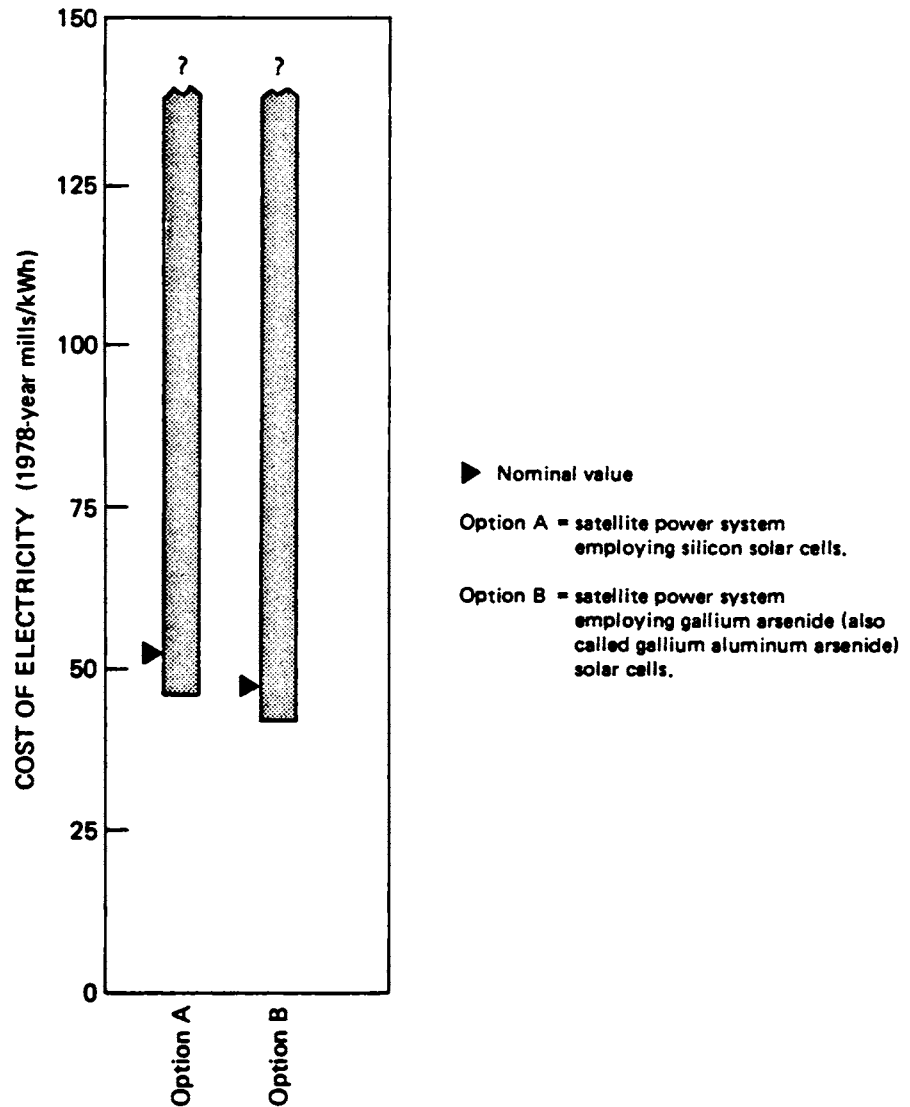
Maintenance = \$206 x 10⁶
 per satellite-year
 Rated capacity = 5 x 10⁶
 kW per satellite

COST OF ELECTRICITY = CAPITAL RECOVERY + MAINTENANCE

$$= 44 + 5.2 = 49.2 \text{ mills/kWh per satellite after the first.}$$

SOURCE: H. E. Benson, NASA Johnson Space Center, private communication, 1980.

FIGURE 3.1. NASA estimate of the cost of electricity from the reference SPS (in 1977-year dollars; to convert to 1980-year dollars, multiply by the ratio of the implicit price deflators for gross national product for 1980 and 1977, given in Note 1).



NOTE: To convert from 1978-year dollars to 1980-year dollars, multiply by the ratio of the implicit price deflators for gross national product for 1980 and 1978, given in Note 1.

SOURCE: Adapted from U.S. DOE (1980d, Figure 3.5).

FIGURE 3.2. Estimated range of the cost of electricity from two reference SPS options using silicon or gallium arsenide solar cells, respectively. Cost is "levelized" to a constant amount, taking into account estimated capital costs, operating costs, and production output over the life cycle of each option.

and operations) and again reestimated the costs. Table 3.5 gives the results of the Aerospace study of the Rockwell design. A similar analysis of the Boeing concept appears in Appendix D.

Table 3.6 summarizes the results, retaining for perspective the lesser elements (unaltered in cost) of the entire transportation system. The contractor estimates of HLLV costs were about \$200 billion to \$300 billion; the reestimates are closer to \$600 billion. The Committee therefore concludes that:

- Costs of transportation from earth to LEO in the reference system should be estimated at about \$600 billion in 1980-year dollars, or roughly two to three times the cost estimates of contractors in the SPS study, even if quite optimistic assumptions about foreseeable advances in technical capabilities in the 1990s turn out to be correct.

The figure of \$600 billion covers most of the cost uncertainties of the HLLV. The principal exception is whether the necessary refurbishing of the thermal protection system (TPS) after each flight would increase operations cost. Aerospace (Wolfe 1981) has estimated a 12 percent increase in total system cost for every 10 percent of the thermal protection system that is replaced per flight. The initial space shuttle flight showed little degradation of the TPS, and any remaining uncertainty about this question should be resolved in the 1980s.

Our conclusions on earth-to-LEO transportation costs are both encouraging and discouraging. The positive side is that the technological developments now under way in the space shuttle program, and developments that are likely to follow from it, should allow the United States to transport heavy loads to LEO by about the year 2000. Massive space projects would then become technically feasible for costs substantially lower than in the past. The negative side is that transportation costs to LEO alone would approximately equal the replacement cost of the total U.S. electric generating capacity--about \$600 billion and 600 GW as of 1980.

Transportation Costs from LEO to GEO

The cost goals postulated by the reference system for transportation from LEO to geosynchronous earth orbit (GEO) can only be met through a revolutionary advance in space transportation such as an electric orbital transfer vehicle (EOTV). The difficulty and cost of placing satellites in geosynchronous orbit are great. The Soviet Union achieved this capability only a few years ago, and the United States, using conventional one-shot rockets, is still limited to payloads of a few metric tons per flight at a cost of about \$50,000/kg from earth. Yet the reference system assumes that transportation costs from LEO to GEO would be only a small fraction of the total system cost, and that payload capability per mission will be advanced to 3600 metric tons. The cost of moving cargo by EOTV from LEO to GEO is estimated to be

TABLE 3.5. Cost comparisons for transportation from earth to LEO, based on the Rockwell heavy-lift-launch-vehicle (HLLV) design (1980-year dollars).

Item	Estimates for Rockwell Design by:		Estimates by Aerospace for Aerospace-Modified Rockwell Design
	Rockwell	Aerospace	
System Characteristics			
Dry weight (000 lb)	1,773	1,773	2,012
Payload weight (000 lb)	500	500	396
Total flights	13,849	13,849	17,486
Flights per vehicle	300	300	300
Fleet quantity	47	47	59
Vehicle Unit Cost (billion \$)	2.2	2.8	2.9
Operations Cost per Flight (million \$)			
Propellant	3.6	2.4	2.4
Manpower		3.6	3.4
Spares and overhaul	11.2	14.1	14.3
Subtotal	\$14.8	\$20.1	\$20.1
System Costs (billion \$)			
DDT&E ^a	12	27	29
Fleet of 47 vehicles	103	132	169
Operations	205	278	352
Total	\$320	\$437	\$550
Unit Cost to LEO ^b			
(\$/lb)	46	63	79
(\$/kg)	102	139	175

^a Design, development, test, and engineering.

^b Low earth orbit.

SOURCE: Adapted from Wolfe (1981, Table 4-8, in Appendix D of this report).

TABLE 3.6. Summary of cost estimates for various transportation system designs of the reference system (in billions of 1980-year dollars).

System Element ^a	Design and Estimate by:		Aerospace Estimates for Aerospace Modification of Design by:	
	Boeing	Rockwell	Boeing	Rockwell
HLLV (to LEO)	211	320	610	550
EOTV	60	28	60*	28*
PLV	35	4	35*	4*
POTV	4	1	4*	1*
PM	2	2	2*	2*
IOTV	NA	1	NA	1*
GSF	7	21	7*	21*
Total	\$319	\$377	\$718	\$607

Mass to LEO				
(10 ⁹ lb)	10.48	6.92	10.48	6.92
(10 ⁹ kg)	4.75	3.14	4.75	3.14
Unit Cost to LEO				
(\$/lb)	20	46	58	79
(\$/kg)	44	102	128	175

NOTE: The Boeing and Rockwell satellite power systems and The Aerospace Corporation modifications are described in the Aerospace report (Wolfe 1981) which is reproduced as Appendix D of this report.

^aHLLV = heavy-lift launch vehicle; LEO = low earth orbit; EOTV = electric orbital transfer vehicle; PLV = personnel launch vehicle; POTV = personnel orbital transfer vehicle; PM = personnel module; IOTV = interorbital transfer vehicle; GSF = ground support facilities.

*Not examined.

NA = not applicable.

SOURCE: Wolfe (1981), in Appendix D of this report.

between \$10 per kilogram (kg) and \$20/kg by Boeing and Rockwell. A comparison of this amount with the cost of transportation from earth to LEO--\$128/kg to \$175/kg as reestimated by Aerospace (Table 3.6)--emphasizes how important the EOTV is for attaining low unit costs. The EOTV is the most speculative element in the cost of transportation for an SPS, and without the capability assumed in the reference system an SPS would be totally uneconomic.

Solar Cell Array

Uncertainties in the cost of the solar cell array on SPS power satellites are addressed in detail in Appendix E. From that work, the Committee concluded that Boeing's 1977 cost goal of \$0.22 per peak watt (W (peak)) in 1977-year dollars--about \$0.30/W (peak) in 1980-year dollars--could not be met in the year 2000 for arrays of space-qualified silicon solar cells based on 1990 technology (see Chapter 2). Furthermore, there seems only a slight chance (on the order of 1 percent) that current costs can be reduced to even 10 times the Boeing goal. A better estimate (discussed in Appendix E) was taken to be 50 times the Boeing cost goal--that is, in the range of \$16/W (peak) to \$20/W (peak) in 1980-year dollars. There is only a modest chance (say 15 to 20 percent) that even these figures can be achieved for single-crystal silicon by the year 2000. As shown in Table 3.2, NASA has estimated the solar array cost at \$1.7 billion per satellite, or 15 percent of the estimated cost of \$11.5 billion for one satellite-rectenna combination. A factor of 10 applied to NASA's estimate would more than double the system cost, while a factor of 50 would raise the system cost by a factor of 8. The Committee therefore concludes that:

- The probable cost of a space-qualified solar cell array deployed for an SPS in the year 2000, based on single-crystal silicon technology of 1990 as it may reasonably be foreseen to develop, suggests that the cost goal of about \$0.30/W (peak) (in 1980-year dollars) is too low by a factor of at least 10 and possibly low by a factor of 50. The resulting increase in system cost by a factor of about 2 to 8 would be so great that a more advantageous solar cell technology would have to be found before an SPS could be seriously contemplated.

Solar cells made of gallium arsenide (or related crystals, such as gallium aluminum arsenide) are under intensive development in many laboratories, and appear more advantageous. As research into these materials proceeds in other programs, the possibilities of using them for an SPS should be watched closely. Nonetheless, the usual lag of 10 to 15 years between scientific advances and large-scale exploitation of those advances probably would delay the initial deployment of an SPS satellite to at least 2010.

Satellite Structure

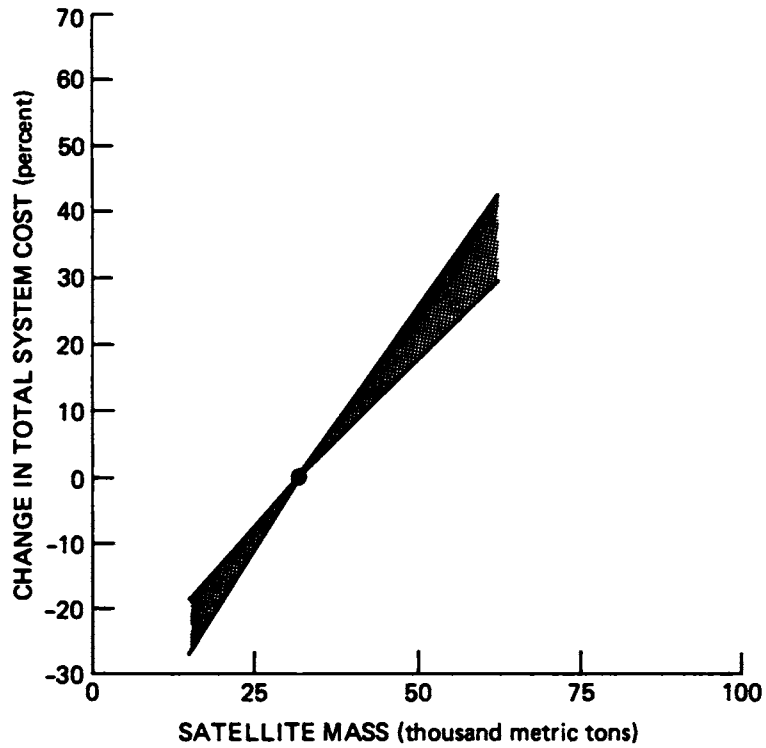
An independent cost assessment of an entire SPS satellite or its ground receiving station was not undertaken by the Committee. The reason was, in part, that the limited resources available for this study made it desirable to select a few issues for examination in some depth. More importantly, fundamental uncertainties about our ability to assemble, deploy, control, and maintain space structures the size of an SPS satellite preclude accurate cost estimates. There is no experience in building large space structures from which to extrapolate. Structures a few tens or hundreds of meters in dimension, however, will be tested in the 1980s using the space shuttle as an experimental construction base.

The requirements for protective measures to shield space workers from ionizing radiation in GEO and the effect of such protective measures on worker productivity are unknown. Further, the solution of problems in construction, spacecraft attitude control, stabilization of large structures, automation, and remote control (robotics, artificial intelligence) are not now foreseeable. These and related issues would have to be addressed before meaningful estimates could be made of the cost of the power satellites (perhaps 40 percent to 50 percent of the costs of the entire system).

The history of aerospace activities suggests that uncertainty often leads to growth in system mass. In the past, the growth in mass of major, relatively well-understood projects has been anywhere from 20 to 30 percent between time of original commitment and first-unit operation. Indeed a mass growth of 25 percent has been estimated in the reference system. However, enough technical uncertainty exists about an SPS to suggest that growth in the mass of the SPS satellites could be much larger than in past aerospace projects.

For example, the design goal for the mass per unit of power output of the solar cell array (1.5 kg/kW to 2.0 kg/kW) is some seven times less than that of arrays being deployed on today's satellites (12.5 kg/kW), and today's satellite owners have a much greater incentive (because of the \$50,000/kg earth-to GEO transport costs) to reduce the mass of solar cells. Difficulty in meeting the goals of end-of-life efficiency or radiation protection could prevent achievement of the optimistic design mass. The design mass of the solar array constitutes about one-half of the total mass of the satellite, so that doubling the mass of the solar array would increase the satellite mass by half. Uncertainties in the end fittings for assembling the satellite's structural beams easily and securely, the power conditioning and distribution equipment, and the klystron amplifiers in the transmitter might also lead to considerable increase in mass.

The Aerospace Corporation estimated that satellite mass was one of the two largest contributors to uncertainties in total system cost, the other being replacement of the thermal protection system on the HLLV. Although we have not tried to provide a detailed estimate of the increase in mass, we believe that it is not unreasonable to assume that the mass could double. As shown in Figure 3.3, a doubling of satellite mass of the Rockwell design from about 35,000 metric tons to 70,000



NOTE: The cost estimates are based on Aerospace procedures (Wolfe 1981) using the Rockwell gallium arsenide solar cell satellite design. Shaded areas indicate satellite cost uncertainty.

SOURCE: Wolfe (1981, Figure 4-4). (Wolfe [1981] appears as Appendix D of this report.)

FIGURE 3.3. Percent change in satellite power system cost as a function of satellite mass.

metric tons might lead to a 40 percent increase in the system cost of \$1300 billion (in 1980-year dollars) estimated by DOE. That increase would be about \$500 billion, a figure comparable to the estimated cost of transportation to LEO.

These observations lead the Committee to conclude that:

- Major technical uncertainties exist regarding the design construction, deployment, control, and operation of SPS satellites. For the designs of the reference system, these uncertainties are likely to lead to a growth in satellite mass. A doubling of satellite mass, which cannot be ruled out, would lead to an increase of 40 percent in total system costs.

Comparison with Prior Estimates

A NASA estimate (Piland 1980) of total reference system costs of \$781 billion in 1977-year dollars (i.e., \$102.5 billion through the first satellite and \$678.5 billion for the next 59 satellites, at \$11.5 billion each) translates into a capital cost per unit of generating capacity of about \$2300/kW (excluding R&D) to \$2600/kW (including R&D). The corresponding amounts in 1980-year dollars are \$978 billion and about \$2900/kW to \$3300/kW. The DOE nominal estimate for an SPS whose satellites used photovoltaic cells made of silicon is \$3646/kW in 1978-year dollars or \$4253/kW in 1980-year dollars. We have adopted \$4000/kW as a figure representative of the results of the DOE/NASA study.

Our examination of potential costs of transportation to LEO and solar cell arrays in the reference system concluded that costs are likely to be higher in at least these areas. Expressed as cost per unit of installed capacity in the 300-GW system, the increase of about \$300 billion for transportation to LEO, discussed above, would be \$1000/kW. Our most optimistic view of the solar cell costs would lead roughly to a doubling of system costs, as discussed above, or an increase \$4000/kW over the basic \$4000/kW figure. In addition, accounting for potential increases in mass of the satellite could increase the basic \$4000/kW figure, by up to 40 percent, or \$1600/kW. These increases, added to the representative DOE/NASA figure, and rounded, suggest a nominal cost of at least \$10,000/kW for the reference SPS. We adopt this figure for the purpose of assessing the economic promise of the reference SPS. The figure falls within DOE's "high" estimate of \$19,478/kW, in 1980-year dollars, shown in Table 3.3 but exceeds that estimate if a more realistic cost of solar cells is used.

The cost of electrical energy corresponding to \$10,000/kW would be about 200 mills/kWh. An SPS would avoid fuel costs, typically in the range of 20 mills/kWh to 40 mills/kWh, incurred by coal and nuclear systems. However, for these technologies, the capital and fuel costs together, per unit of electrical energy, still lie far below 200 mills/kWh.

All of the cost estimates discussed above are estimates of the direct costs of the reference SPS. The estimates do not include interest on borrowed capital, which could be one of the most important cost factors given the long period between inception and revenues. At this time, however, these costs are not counted because our main purpose is to compare SPS costs only roughly with the costs of other technologies and to identify areas where there is the greatest need to reduce costs by research and development.

This cost analysis focuses on the reference system and reemphasizes its role as a model to be analyzed but not necessarily to be built. Indeed, the reference system would certainly not be built given its capital costs, as developed in the analysis, compared with costs of about \$1000/kW projected for current types of generating plants. A viable SPS, in the energy future that seems most likely, would require new concepts radically different from those of the reference system.

Based on the foregoing analysis, we conclude that:

- The capital costs of the reference system would be likely to exceed the typical cost of \$1000/kW of today's other alternatives for generating electricity by so much that, even taking into account the fact that it has no fuel costs, its introduction should not be considered further. New concepts and major advances would be needed to achieve cost reductions that would make a future, advanced SPS economically viable as a substitute for other sources of baseload electricity.

FINANCING AN SPS

As long as the estimated cost of an SPS remains at the level of \$10,000/kW discussed in the previous section, it is academic to consider the question of how to finance it. The system simply would not be built.

If an SPS became cost-competitive as a result of future technological advances, financing problems would still be severe. Current regulatory and economic conditions have presented electric utilities with substantial difficulty in financing conventional generating plants. An SPS would exacerbate these problems. The unit of capacity in the reference system would produce 5 GW. The capital cost of each such unit would almost certainly, even under the most optimistic assumptions, exceed five times the cost of 1 GW of conventional capacity, the largest-sized plant we normally finance today. Thus the smallest increment of investment in SPS would have to come in larger packages than we customarily handle--a characteristic rather graphically called the "lumpiness" of the SPS investment. Furthermore, an SPS would need to have a total capacity of several hundred gigawatts in order to be economically competitive. Reasonable assurance of financing for the total system would therefore be a prerequisite for private financing of individual parts of it. The need for a large initial capital investment and the long lag between investment and salable output, combined with the high technological

risks in the early stages, would make the enterprise less than attractive to potential private investors. Utility financing would be absolutely precluded if no way were found to insure against the risks. The Committee therefore concludes that:

- Financing of an SPS by the investor-owned utilities could not be relied upon. Public sector financing--direct or indirect--would be required for research and development and also, in the absence of major changes in the regulation of utility rates, for most of the construction work in the early years of deployment.

Since it is our judgment that an SPS will not be built for decades, institutional changes that might alleviate the financing problem may well occur in the interim. Large regional power generating entities, for example, whether public or private, unregulated or federally regulated, would be in a much stronger position to participate in the financing of an SPS than smaller, state-regulated utilities. Another possibility would be to entrust the financing of an SPS to a public or quasi-public corporation that would sell power from the rectennas to individual utilities or to consortia of utility companies. Some initial federal appropriations, loan guarantees, or insurance provisions for the utilities might well be necessary in either case. Or, the corporation might be multilateral, with nondomestic companies or other governments participating in its establishment and financing.

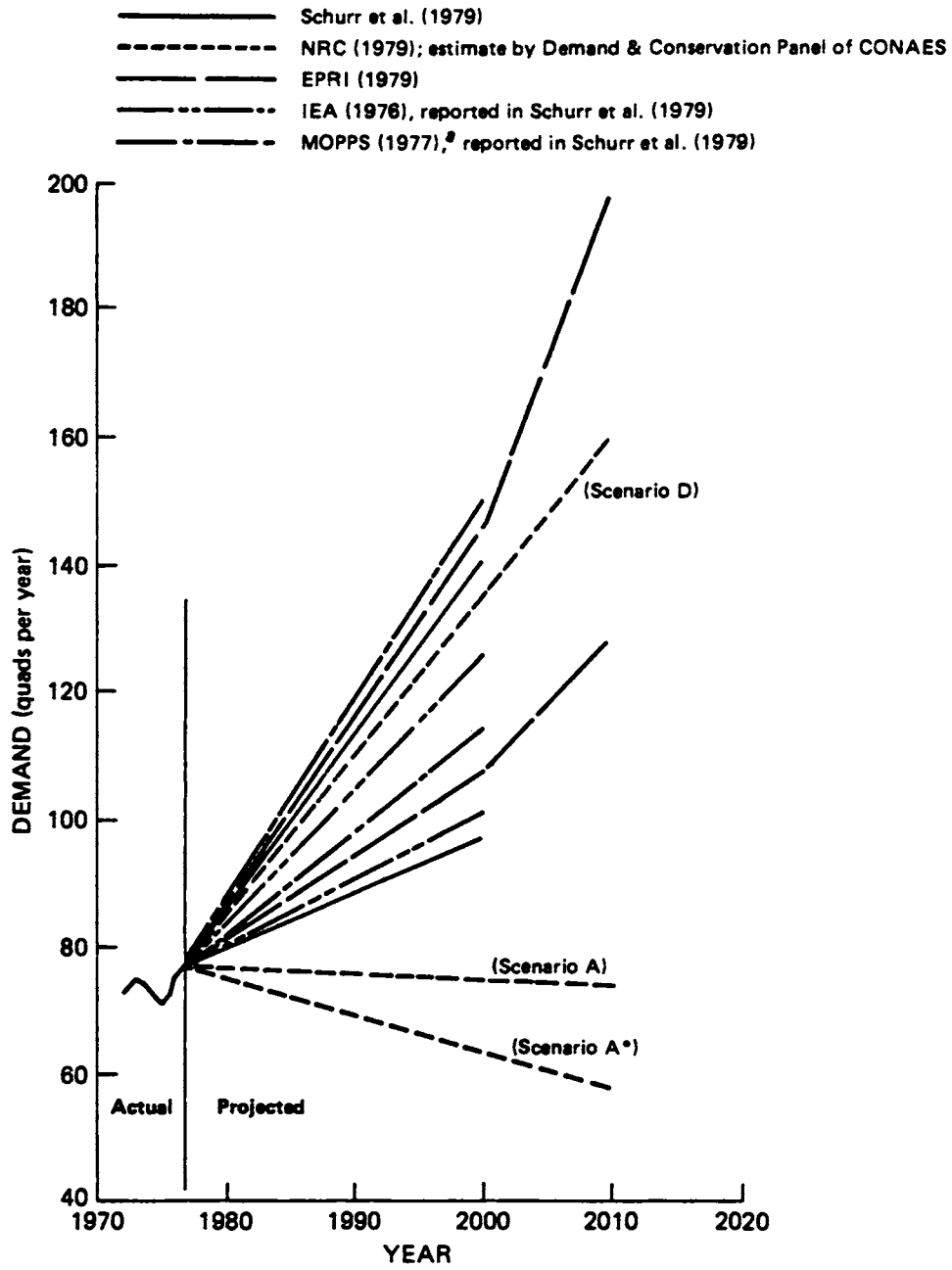
FUTURE DEMAND FOR AND SUPPLY OF ELECTRICITY

The likelihood that an SPS will be needed to help meet the future demand for electricity will depend on (a) the magnitude of future demand, and (b) the availability of alternative methods of generating electricity, which will be determined by their costs, safety, consequences for human health and the environment, and other factors affecting public acceptability.

Demand in the Next Four Decades

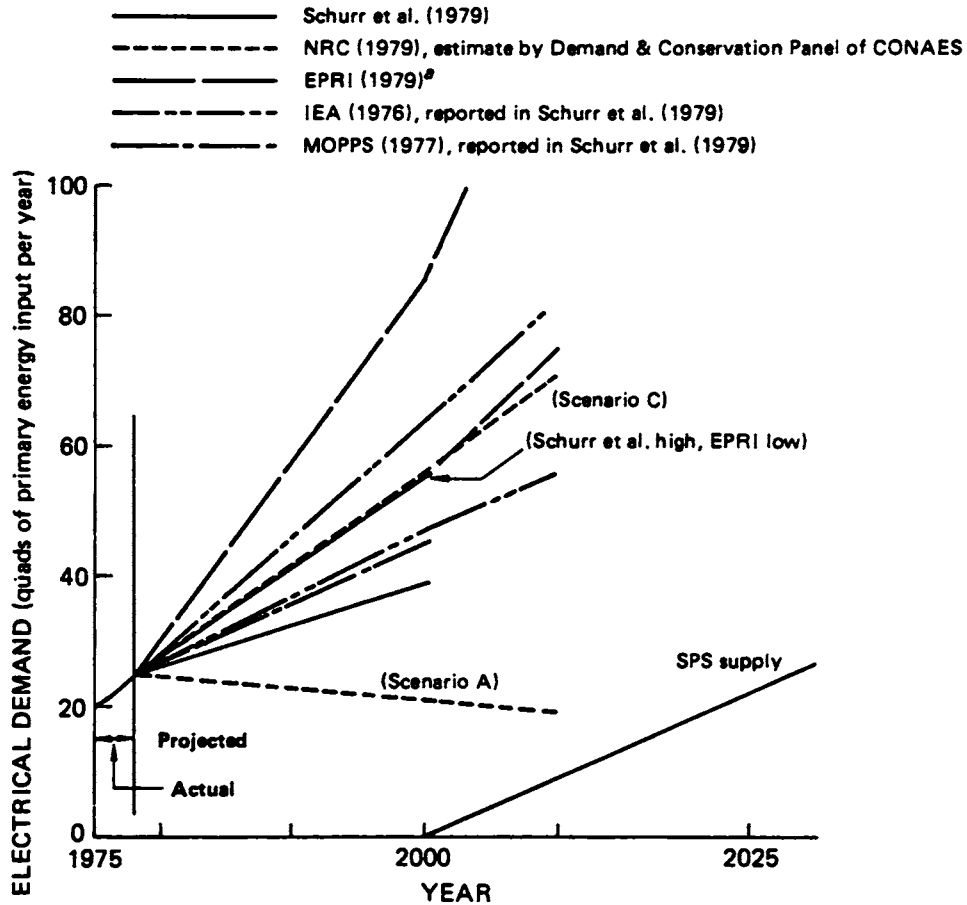
The reference SPS, when completed at the end of a 30-year construction period, would produce 300 GW of electrical generating capacity. The question arises whether U.S. demand for baseload electricity will be great enough in the future to require that much additional capacity.

No one can answer that question with great confidence as far as the United States is concerned. Projections of the future demand for all types of energy in the United States are highly variable, as are projections of electricity's share of the total energy demand (see Figures 3.4 and 3.5). The critical unknowns in any attempt to project total energy demand are how much conservation will be achieved as a result of higher energy prices and regulation of energy use and what



NOTE: Assumed economic growth rates in the five studies cited vary from 1.8 to 3.7 percent per year.
^aTop MOPPS line is the high range of a nominal, reference-case estimate.

FIGURE 3.4. Comparison of estimates from five recent studies, showing high and low primary energy demand projections from each.



NOTES:

1. The reference SPS is designed to have a 300-GW capacity. Assuming a 0.9 load factor and 30 percent efficiency in converting from primary energy input to electricity (see note a), SPS would provide an average of 27 quads per year in 2030.
2. Assumed economic growth rates in the five studies cited vary from 1.8 to 3.7 percent per year.

^aIn converting from electrical energy to primary energy input, it was assumed that electrical energy output = 0.3 x primary energy input, to be consistent with CONAES.

FIGURE 3.5. Comparison of estimates from five recent studies, showing each study's high and low electrical demand projections in quads of primary energy input per year.

impact new technologies such as an electric automobile might have. As shown in Figure 3.5, some projections of demand (NRC 1979) suggest that the United States will not require an additional 300 GW (equivalent to 27 quadrillion British thermal units, or quads, of primary energy input per year at an assumed SPS plant availability factor of 90 percent²) of capacity in the second quarter of the twenty-first century, which we believe to be the relevant period. Other projections, however, indicate a higher demand that would make 300 GW from an SPS a desirable addition to capacity³ (EPRI 1979, NRC 1979, Schurr et al. 1979).

Furthermore, Häfele (1980) projects that by 2030 the world may need about 150 quads of primary energy input per year from nuclear power generation (corresponding to roughly 3000 GW of generating capacity at an assumed average plant availability factor of 50 percent) in addition to 500 quads per year from other sources of primary energy.⁴ Thus, an SPS might be used to replace part of the demand that would otherwise be met through the construction of additional nuclear power plants.

The higher projections show total U.S. demand for energy continuing to increase for the rest of this century and during the early part of the twenty-first century, although at a significantly lower rate than in the past.⁵ They also show that electricity's share of the total demand will continue to increase for a combination of reasons. First, the price of electricity has increased (and is expected to continue to increase) more slowly than the prices of oil and natural gas. Secondly, electricity produced from domestic resources (coal, uranium, and others) is a proven way of reducing dependence on oil from the Middle East. Finally, societies prefer to use energy in its cleanest and most convenient form as they become more affluent.⁶

If it becomes apparent by the year 2000, however, that the lower projections were more accurate, the United States would have three alternatives:

1. To reduce the size of an SPS to 100 GW or 200 GW and thus accept a substantial increase in the cost per unit of installed capacity;
2. To cancel any research and development program that might have been started to maintain an SPS option;⁷ or
3. To continue to develop an SPS but to make it a multilateral program instead of a U.S. program.

In view of uncertainties about the size of U.S. and world energy demand over the next 50 years, the Committee concludes that:

- Better information about larger or smaller satellite power systems than the reference system would be important in evaluating the concept. For example, if an SPS producing less than 300 GW were built, how much would the system's cost per unit of capacity increase? If it were determined that an SPS producing more than 300 GW should be built, what factors might limit its capacity? For example, would the amount of land required for rectenna sites or the amount of space required for SPS satellites in geosynchronous orbit prevent the construction of an SPS capable of producing more than 300 GW?

Although we believe that there would be no insurmountable technical obstacles to building the 60 rectennas postulated by the reference system, an SPS would have certain characteristics that would probably make it desirable to place some limits on its size. For example, some U.S. electric utilities have indicated that they would not want to rely on electricity from such a technology for more than 25 percent of their baseload.

In summary, the Committee concludes that:

- The existence of some low projections of demand for electricity in the twenty-first century should not be a decisive factor in deciding whether to continue research and development to maintain an SPS option. It is reasonable to believe that an additional generating capacity of 300 GW, more or less -- characteristic of the scale of an SPS -- could be used at some time in the twenty-first century.

Supply in the Next Four Decades

In attempting to determine the potential need for an SPS, it is helpful to distinguish between what the competitive sources of electrical energy will be in the next few decades and what they will be in the long run. We discuss the next four decades here and consider the long run in Chapter 6, which is a comparative assessment of an SPS with other advanced technologies. Although the level of demand will certainly influence the mix of supply, the uncertainties surrounding both do not permit a much more precise discussion than is given below, nor is one needed for our present purposes.

Table 3.7 shows the distribution of U.S. energy consumption and electric energy production in 1978 by source of energy. These figures can be expected to change considerably over the next four decades, because the real costs of oil and natural gas will continue to rise and because of deliberate efforts to avoid dependence on unpredictable foreign supplies of petroleum.

The prospects for meeting U.S. energy demands over the next 20 to 30 years have been thoroughly studied (Landsberg 1979, NRC 1979, Schurr et al. 1979, Wilson 1980; also see Keeny 1977). Based on its examination of these sources of information, the Committee concludes that:

- The use of oil and natural gas to generate electricity will decline irreversibly in the United States, and between now and the year 2000 an increasing amount of electricity will be produced by coal-fired generating plants and by light water nuclear reactors.

By about 1990 new technologies will have evolved in which coal⁹ should become a much more efficient producer of electric energy, while at the same time producing less air pollution. The introduction of more advanced systems for generating electricity with coal will be

TABLE 3.7. U.S. energy consumption in 1978 (in quads).

Source	Total Energy	Primary Energy Input to Electrical Generation
Coal	14.9	11.5
Petroleum	36.1	4.1
Natural Gas	20.0	3.2
Hydropower	3.0	3.0
Nuclear	3.0	3.0
Geothermal and Other	<u>0.1</u>	<u>0.1</u>
Total	77.1	24.9

NOTE: 1 quad = 10^{15} Btu.

SOURCE: Landsberg (1979, p. 82).

determined by economic and environmental considerations that need not be considered here. The cost of coal is likely to continue to increase as the demand rises for use in producing both electricity and synthetic fuels. Nonetheless, the U.S. supply of coal is expected to be sufficient to meet domestic demands for at least another century. The one potential obstacle to the growing use of coal would be evidence that the carbon dioxide (CO₂) produced by combustion of coal is accumulating in the atmosphere--along with CO₂ from other sources--in amounts large enough eventually to cause an unacceptable change in the world's climate. In the absence of effective preventive measures, this potential problem might make it necessary to restrict the burning of coal in the twenty-first century.

Use of nuclear power in the United States will probably continue to grow, but its growth is likely to be limited by public concerns about the safety of nuclear power plants and the disposal of nuclear wastes.

Generating plants powered by light water nuclear reactors and coal-fired plants have provided electricity at comparable costs up to the late 1970s. Projections vary from continued comparability (Wolsko, et al. 1981) to a faster cost increase for nuclear plants because of more stringent safety regulations (Komanoff Energy Associates 1981). Within these divergent projections, there remains the possibility of an increase in nuclear generation for a while, which, however, may be constrained by cost at some point.

Another potential obstacle to the growth of conventional nuclear power is the limited supply of domestic uranium. If approximately 400 light water reactors are built in this country, the resource base of uranium, estimated at 2.4 million tons, would all be needed to supply fuel for these reactors over their 30-year life spans. As a result, this country would begin to run out of uranium in the middle of the next century.

If, on the other hand, breeder reactors were used to generate electricity the available supply of uranium would last indefinitely. There are, however, several concerns that have thus far resulted in delaying the development of breeder reactors for generating electricity, at least on the United States. These concerns revolve around the fact that breeder reactors produce plutonium, a highly hazardous element and one that can also be used for the manufacture, and hence the possible proliferation, of nuclear weapons.

If it is assumed that the United States will need additional electric generating capacity of up to several hundred gigawatts early in the twenty-first century, it still seems likely that the total demand for electricity could be met at acceptable cost through the use of advanced coal-fired plants and breeder reactors (and advanced converters).

As indicated in the section on SPS costs earlier in this chapter, the Committee believes that the DOE/NASA estimates of what it would cost to deploy the reference SPS early in the next century are much too low. But even if the DOE/NASA figures were correct, an SPS would still be a far more expensive way to generate electricity than coal-fired power plants, equipped with pollution-control devices, or light water nuclear reactors. We therefore conclude that:

- Electricity generated by coal and nuclear energy will be so much less expensive than an SPS over the next four decades that the prospect of an SPS becoming an economic source of supply during that time will be close to nil.

This is not to say, however, that it will be possible to provide an adequate supply of electricity by means of coal and nuclear power with no difficulties. The financial problems that electric utilities will face in raising adequate capital, in combination with governmental regulation of the rates charged to electric customers, may well limit the construction of both new and replacement generating plants, and these financial problems may be exacerbated by the need to deal with the problems of environmental protection (in the case of coal) and plant safety and radioactive waste disposal (in the case of nuclear power). Even if, the increased costs associated with these problems should turn out to be greater than expected, an SPS would not offer a competitive alternative over the next four decades because of its extremely high capital costs alone.

Meanwhile, work is steadily progressing on a variety of ways to make use of solar power by means of terrestrial facilities, either to produce heat (and thus reduce the use of fossil fuels and electricity for that purpose) or to generate electricity. The report of the Committee on Nuclear and Alternative Energy Systems (NRC 1979), hereafter called the CONAES report, estimates that as much as 11 quads per year may be displaced by solar heating by 2010. Solar energy may also be used to generate electricity if the cost of terrestrial photovoltaic cells can be reduced by at least a factor of 10. Programs and cost reduction goals have been established aimed at the generation of electricity by terrestrial photovoltaic cells. Biomass is already being used at a rate of about 1.5 quads per year (2 percent of total U.S. energy demand), and it has been projected that biomass may account for 4.5 quads per year to 5 quads per year by the year 2000 (OTA 1980). Solar ponds may contribute between 1.5 quads per year and 2.5 quads per year of primary energy, with perhaps 0.2 quads per year to 0.6 quads per year being used to produce electricity.

There are other potential sources of electric power. The techniques for producing electricity from geothermal energy are well known, although the development of methods of doing so on a large scale and at acceptable cost has not yet progressed very far. The use of wind power to produce electricity is also being developed, and the wind could provide as much as 2 quads per year of primary energy input for electric power generation by 2010.

In view of these developments, the Committee concludes that:

- The domestic demand for electricity over the next four decades can be met without an SPS. Even if it becomes necessary to restrict the construction of coal or nuclear power plants, the various methods for converting solar, wind, and geothermal energy by means of terrestrial facilities into other forms of usable energy can be considered in their entirety as an emerging, large-scale technology that may produce as much as

20 quads per year of energy for domestic needs by 2010. All have the great advantage over an SPS that they can be introduced incrementally on a small scale as needs develop.

NET ENERGY ANALYSIS*

Since the construction of an SPS would clearly be an energy-intensive process, it is prudent to examine the ratio of the usable energy that would be produced by an SPS to the energy that would be required to build and maintain it. Others have also examined this question (Herendeen, et al. 1979; Cirillo, et al. 1980). We assume that, other things being equal, the higher this ratio the better--e.g., 5 Btu of electrical output is preferable to 4 Btu from the same expenditure of energy for construction. The energy used for construction and maintenance will be diverted from other uses by society, some of which might be to produce electricity by other means. In the formalism used here we do not assign any explicit energy value to input fuels not yet extracted from the environment, such as fossil fuels, uranium, geothermal, or solar energy. Therefore, the questions to be answered are:

1. Would an SPS be a net source of energy or a net consumer of energy over its lifetime?
2. If an SPS was a net source of energy, how would it compare with other available systems for producing large amounts of electricity?

We attempt to answer these questions in this section, fully realizing that a net energy comparison cannot by itself determine whether an SPS would be desirable. We might exclude petroleum, for example, as a source of electricity for reasons of national policy, thus preempting any net energy analysis favorable to that fuel. Although it is easier to understand the net energy concept without assigning any time value to energy, we also derive a useful net energy ratio for an SPS and its major competitors based on the concept of present value, borrowed from finance.

Several sets of energy ratios are calculated in this chapter for the reference SPS whose satellites would have photovoltaic cells made of silicon. Each set is based on certain assumptions:

1. The feasibility of laser annealing of solar cells. Up to now, SPS studies have usually assumed that the degradation of solar cell

*Statement by Charles J. Hitch: A disaggregated energy flow analysis can provide useful information which cannot be derived from financial or cost analyses. But I do not believe that a net energy analysis like the one reported in this section, which aggregates different forms of energy on the basis of Btu content (with or without "thermodynamic weighting"), while ignoring the Btu content of input fuels as well as all other valuable productive inputs, can throw any significant light on the relative desirability of energy conversion technologies.

efficiency due to damage from ionizing radiation could be corrected by laser annealing. The analysis of Appendix E, however, indicates that laser annealing may not be available by the year 2000, the year in which the first satellite postulated under the reference system would begin operation. This chapter analyzes the energy ratio of an SPS with and without the benefit of laser annealing.

2. The energy cost of the satellite solar cell array. Cost estimates of the solar cell array now vary by a factor of 50 or more. Our analysis considers several possible costs to determine their effect on the energy ratio through the coefficients that relate energy to cost.

3. The temporal value of energy. If we assume that society "spends" or "invests" energy just as it spends or invests money, a discount rate should be used in estimating the value of future energy consumption or production. An energy discount rate is the mechanism by which society implicitly expresses its willingness to divert presently available energy into an energy-producing process so that a greater quantity of energy can be created in the future. This analysis considers three different discount rates.

Finally, some analysts argue that research and development expenditures for a current project should not be attributed solely to it because that effort will benefit future projects as well. The counterargument is that, under this same view, any current project has already benefited from the research and development of many previous projects, so that the costs incurred are always in rough balance with benefits received. The results reported here do not include energy consumption in the initial, or front-end, phases of preliminary research, engineering verification, demonstration, and initial plant investment.

Method

Net energy analysis provides information about the physical usefulness of a proposed system that traditional financial analysis cannot provide. This is particularly evident when a discount rate on energy use is assumed. A financial analysis cannot indicate whether the new system will increase or decrease the total amount of available energy.

As a help in understanding the concept of net energy ratio, a general energy-producing system is defined in Figure 3.6. This system receives fuel in its raw form and converts it into a form of energy that is presumably more useful to society. In a coal-fired electric generating plant, for example, a portion of the energy contained in the input coal is transformed into electrical energy. The processing energy consists of all the energy (apart from the fuel input) required to build, operate, and maintain the system, converted into the same quality of energy as the output. The usable output will always be less than the energy content of the fuel because the conversion process is inherently less than perfectly efficient. A certain amount of energy is always lost in any practical conversion process because of thermodynamic limitations.

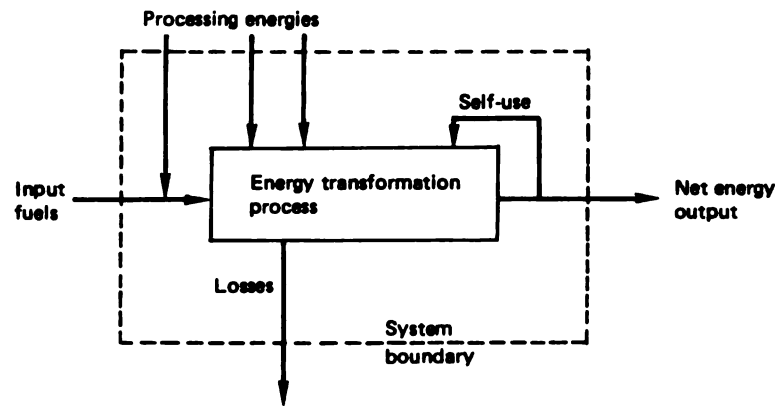


FIGURE 3.6. Diagram of a typical energy-producing system. (Net energy output is the gross output of the energy transformation process net of losses and self-use.)

Net energy analysis does not focus on thermodynamic efficiency, however. Instead, it takes the view that the fuel is an energy resource available for conversion into another form and asserts that the important point is whether the energy output is greater than the energy required to build, operate, and maintain the system, apart from the fuel input. Otherwise, the conversion process would, in effect, consume all of its own output and energy from other processes as well.

The net energy ratio, R , can be defined as

$$R = (\text{net energy output})/(\text{processing energies}).$$

In other words, the net energy ratio is the net energy output (that is, the gross output of the energy transformation process net of losses and self-use) divided by the energy required to build, operate, and maintain the system (except for the fuel input). Both output and processing energies are measured in terms of identical energy quality in the thermodynamic sense.

Six cost estimates for the reference SPS solar cell array were considered in our analysis (Hannon and Naughton 1980), four of which are reported here. All of the cost figures are in 1980-year dollars. The most optimistic of the estimates, \$0.256/W (peak),⁹ was made by NASA (Harron and Wadle 1981). The least optimistic figure, \$20/W (peak), is within the range of our conclusions, reached by analyzing the improvements that appear to be possible in space-qualified solar cell technology (Appendix E). The two remaining estimates (\$1/W (peak) and \$5/W (peak)) were chosen as intermediate values of this parameter.

The discount rate on the future use of energy is somewhat analogous to a discount rate on the future use of money. An investor of money makes choices based on the possibilities of future value, and his choices hinge on the money discount rate, r , at which it is equally preferable to him to receive one dollar today or $1 + r$ dollars a year from today. It is the behavior of millions of investors of money that allows us to infer a typical money discount rate.

We assume that an investor of energy, such as a utility that uses energy to construct a new energy-producing process, will also choose among various possibilities of energy flow. For any particular process there will be positive and negative energy flows associated with the construction and operation of a generating plant. The internal rate of return on these energy flows is the discount rate at which the net present value of the energy flows is zero, or equivalently, the discount rate at which the (discounted) net energy ratio equals unity. This discount rate is presumably acceptable to that investor. Thus, the behavior of "energy investors" allows us to infer a typical energy discount rate. Net energy analysis might, by this view, more accurately be called net energy flow analysis analogous to net cash flow analysis in financial use.

Three energy discount rates were considered in our analysis. The zero discount rate represents the traditional approach to energy analysis: that is, energy is valued the same regardless of time of use. The 8 percent discount rate represents the lowest return on a small-scale energy investment that today's investor of energy appears

willing to accept. This rate has been found empirically to correspond to a light water nuclear reactor that will generate electricity for electric heating (Hannon and Naughton 1980). The 19.6 percent rate represents the lowest return that today's investor of energy will accept on a large-scale investment. This rate has been found empirically to apply to a light water nuclear reactor that will generate electricity for home appliances and lighting (Hannon 1980).

The net energy ratios were calculated first on the assumption that the reference SPS would have a laser annealing system that would repair solar cell damage. The ratios were then calculated on the assumption that annealing would not be available.

All of the ratios were calculated by means of a Monte Carlo simulation. In other words, certain key variables (such as the parametric solar cell cost and the energy content per unit of cost for various materials) were assigned uncertainties. The calculations were then made by computer several hundred times; and these key variables were allowed to take on a value each time within their bounds of uncertainty, according to a normal probability distribution. The result was a distribution of numbers that characterized the net energy ratio. Each distribution was described in terms of its mean and standard deviation, as shown in Table 3.8 and Figures 3.7 and 3.8.¹⁰

The energy costs of some SPS subsystems were derived from their estimated dollar costs. These dollar costs were the Boeing/NASA estimates, except for the cost of the solar cell array, which was parameterized. To the extent that the cost estimates are optimistic, the results for the net energy ratio are optimistic.¹¹

Results

The net energy ratios obtained when laser annealing is assumed to be used are given in Table 3.8 and are shown graphically in Figure 3.7. At a zero discount rate, and excluding front end energy, the ratio is 18.9 at a solar cell cost of \$0.256/W (peak). In other words, under the most favorable conditions the reference SPS would generate nearly 19 times the amount of energy it took to build it (in energy of equivalent quality). If the solar cell cost were \$20/W (peak), however, implying correspondingly greater energy input to the solar cells, the ratio would be only 2.02.

At a discount rate of 19.6 percent and a solar cell cost of \$0.256/W (peak), the ratio is 2.96, about one-sixth the value for an energy discount rate of zero. From these results the Committee concludes that:

- Allowing for the typical discount rates that society appears to attach to future energy generation, the net energy ratio of the reference SPS becomes less attractive than it would be under a discount rate of zero.

If laser annealing is assumed not to be practical, the output of the reference SPS would decrease to half its original amount by the end

TABLE 3.8. Mean and standard deviation of net energy ratios for the reference system with and without laser annealing.

Energy Discount Rate (%)	Ratios and Standard Deviations ^a , at solar array cost (\$/@(peak)) of:			
	0.256	1	5	20
With Laser Annealing				
0	18.9 (0.64)	14.3 (1.33)	6.24 (1.21)	2.02 (0.50)
8	8.14 (0.32)	5.95 (0.61)	2.44 (0.50)	0.77 (0.19)
19.6	2.96 (0.08)	2.28 (0.20)	1.02 (0.20)	0.33 (0.08)
Without Laser Annealing				
0	13.5 (0.44)	10.2 (0.94)	4.45 (0.86)	1.43 (0.35)
8	6.61 (0.24)	4.82 (0.49)	1.97 (0.40)	0.61 (0.15)
19.6	2.63 (0.08)	2.03 (0.18)	0.90 (0.17)	0.29 (0.07)

NOTE: Front-end energy consumption is not included in these calculations.

^aStandard deviations are in parentheses.

SOURCE: Hannon and Naughton (1980).

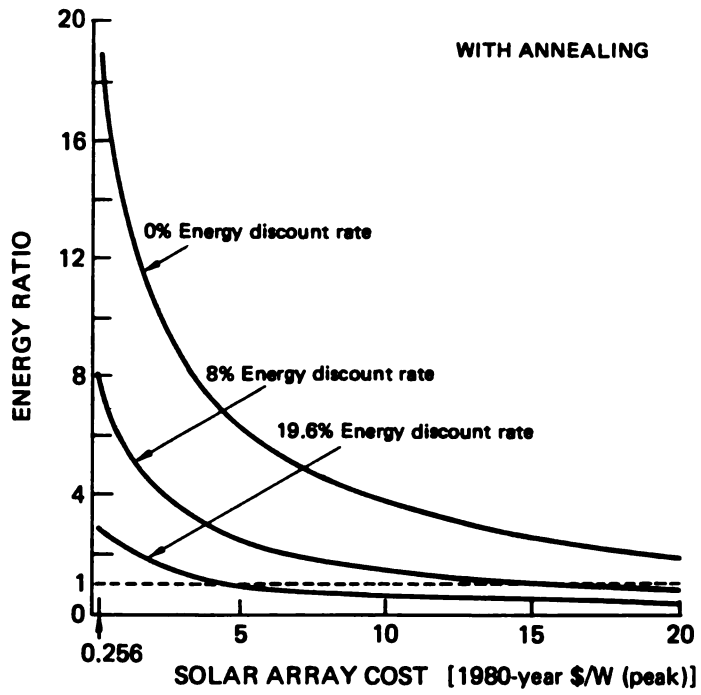


FIGURE 3.7. Mean value of the net energy ratios for the reference SPS with laser annealing of the solar array and without front-end energy consumption.

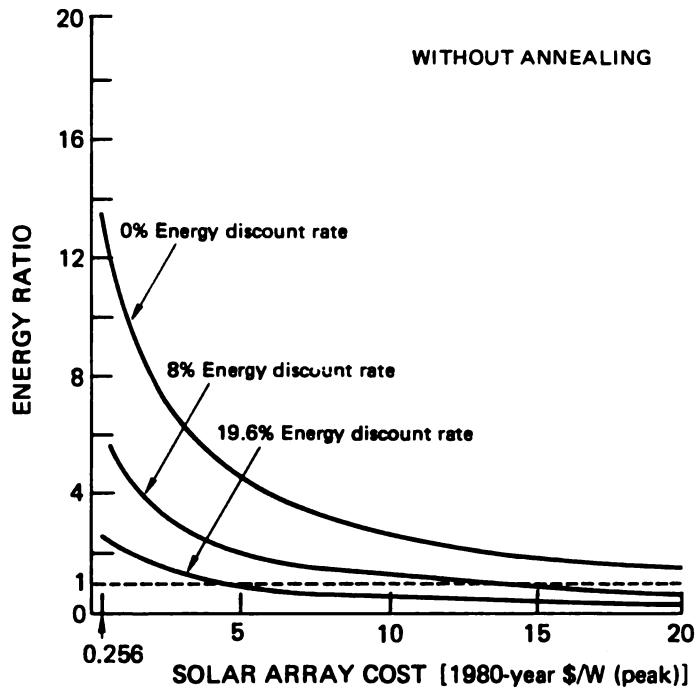


FIGURE 3.8. Mean value of the net energy ratios for the reference SPS without laser annealing of the solar array and without front-end energy consumption.

of the system's lifetime and result in lower energy ratios (see Table 3.8 and Figure 3.8). At a solar cell cost of \$0.256/W (peak) and a zero discount rate, the elimination of annealing changes the ratio from 18.9 to 13.5. At a discount rate of 8 percent, the elimination of annealing changes the energy ratio from 8.1 to 6.6. At a 19.6 percent discount rate, the omission of annealing changes the ratio from 3.0 to 2.6. Thus in analogy with the characteristics of net present monetary value:

- At higher energy discount rates, long-term power generation in the reference SPS becomes less significant relative to near-term power generation. This result is favorable for the omission of annealing the solar cells because long-term power generation is affected more severely than near-term by the absence of annealing.

The Desirability of an SPS in Comparison with Two Conventional Technologies

An undiscounted net energy analysis of an SPS can be used to determine whether the system would be feasible in terms of energy production--that is, whether it would be capable of producing more energy than was required to build and maintain it. Moreover, the desirability of an SPS in energy terms can be assessed by comparing its net energy ratio to the energy ratios of other technologies.

In Table 3.9 the net energy ratio of the reference SPS is compared with the net energy ratios of a coal-fired power plant equipped with scrubbers (to reduce sulfur emissions) and with a conventional nuclear power plant. The ratios for the two plants (data from Hannon 1980) do not include research and development energy and therefore may properly be compared with SPS ratios that exclude front-end energy consumption. The two sets of SPS ratios are for different assumptions about the level of technological development--that is, whether laser annealing and low-cost solar cell arrays will be achieved by the year 2000 or not. All ratios were calculated once without an energy discount rate and once with a discount rate.

Assuming that silicon cells will cost \$0.256/W (peak) and that they can be annealed in space according to the design of the reference system, an SPS would be highly desirable from an energy viewpoint if the future value of energy is not discounted. That is, the SPS energy ratio of 18.9 is much higher than that of the coal-fired or nuclear power plants. For a discount rate of about 19 percent, however, an SPS becomes less desirable than a coal-fired plant but more desirable than a light-water reactor facility. It would then have a ratio of 3.0, compared with a ratio of 1.0 assigned to a nuclear plant and a ratio of more than 5.0 for a coal-fired plant. (The reader will recall from the earlier section on "Method" that when the discounted net energy ratio of a large scale nuclear plant is set equal to unity the associated energy discount rate is empirically found to be 19.6 percent.)

TABLE 3.9. Comparison of net energy ratios for three electric power generation technologies.

Generating Plant	Ratios Discounted at:		Comments
	0%	19%	
Coal ^a			Surface mines; limestone-based stack gas scrubbers; includes distribution losses
Eastern U.S.	10.6	5.8	
Western U.S.	10.0	5.4	
Nuclear ^a	6.8	1.0	Light water reactor; includes distribution losses
Reference SPS ^b			
With annealing	18.9	3.0 ^c	Array cost = \$0.256 (1980 \$/W (peak))
Without annealing	1.4	0.3 ^c	Array cost = \$20 (1980 \$/W (peak)) ^e

^aData for these conventional technologies were obtained from Hannon (1980).

^bBoth scenarios include distribution losses; R&D energy costs are omitted.

^cDiscount rate = 19.6%.

^dNASA estimate.

^eEstimate of this Committee.

SOURCE: Hannon and Naughton (1980).

If, on the other hand, we take our estimate of cost for the solar cell array, (\$20/W (peak)), the reference system would be much less advantageous in terms of its net energy ratio, with or without energy discounting.

Clearly, the conclusions drawn from this analysis are highly dependent on the notion of net present value of future flows of energy (i.e., discounting) and on the assumptions made about the level of technological development. Further research on laser annealing and on solar array fabrication would be necessary to clarify the level of technology that would actually be available for an SPS over the next 20 years. The Committee therefore concludes that:

- A highly developed SPS technology that used low energy inputs and maintained high energy outputs would result in favorable energy ratios for an SPS at low energy discount rates. However, if the technologies of solar cell fabrication and annealing should not reach levels favorable to these objectives, the energy ratio of an SPS would be inferior to that of conventional power plants.

NOTES

1. Conversion from current dollars of a given year to current dollars of another year is accomplished by multiplying by the ratio of the implicit price deflators for gross national product. This index is published by the U.S. Department of Commerce in Survey of Current Business as follows (index for 1972 equal 100.00):

<u>Year</u>	<u>Index</u>	<u>Issue, page</u>
1977	141.70	July 1979, p. 61
1978	152.05	July 1979, p. 61
1979	162.77	March 1981, p. 14
1980	177.36	March 1981, p. 14

2. The electrical energy output, E_{out} , of a generating plant of conversion efficiency, η , and primary energy input, E_{in} , is

$$E_{out} = \eta E_{in}$$

Also, the energy output of a plant of nominal power capacity, C , and plant availability factor, f , expressed as a fraction of a period of time, T , is

$$E_{out} = fCT.$$

Therefore, E_{in}/T and C are related by the expression,

$$E_{in}/T = fC/\eta,$$

where, of course, E_{in} , T , and C are to be expressed in the same system of units.

Often, however, it is convenient to express E_{in}/T in quads per year (quads/yr) and C in gigawatts (GW). To convert C to its physical equivalent in quads/yr, it must be multiplied by the conversion factor, 1 (quad/yr)/33.4 GW. The conversion factor derives from the fact that 1 quad = 10^{15} British thermal units (Btu), 1 year = 31.56×10^6 seconds (s), 1 GW = 10^9 watts (W), and 1 Btu = 1.055×10^3 W*s.

Accordingly, the appropriate numerical relationship between E_{in}/T and C is

$$E_{in}/T(\text{in quads/yr}) = (f/\eta) C(\text{in GW})(1 \text{ (quad/yr)}/33.4 \text{ GW}).$$

For the typical values, $f = 0.50$ and $\eta = 0.30$, the relationship becomes (to two significant figures),

$$E_{in}/T \text{ (in quads/yr)} = (1/20) C \text{ (in GW)}.$$

For illustration, if C is 20 GW, E_{in}/T is equal to 1 quad/yr, expressing the fact that 20 GW of nominal power capacity in plants of typical characteristics will consume 1 quad of primary energy input in the course of a year, taking into account conversion losses and

operation at less than rated capacity (that is at less than full plant availability).

3. The study of the Committee on Nuclear and Alternative Systems (CONAES) (NRC 1979), Energy in Transition 1985-2010, examines scenarios, produced by its Demand and Conservation Panel, of energy demand ranging from 53 quads to 134 quads (Btu content of primary fuels) in the year 2010 compared with 71 quads in 1975 (pp. 82-83). The share of purchased electricity in the total varies from 24 percent to 55 percent, compared with 28 percent in 1975; and total primary energy input for electricity ranges from 19 quads to 71 quads, compared with 18 quads in 1975 (p. 558). The corresponding values of capacity are approximately 380 GW (for 19 quads/yr) and 1420 GW (for 71 quads/yr). (Here 20 GW of capacity is taken to correspond to a primary energy input of 1 quad/yr, assuming an overall average availability factor of 0.5. This factor depends on load patterns and the mix of different modes of generation with their respective plant availability factors.) Clearly the 300 GW of the reference SPS (or an alternative) could not be accommodated at the lower levels, and could easily be accommodated at the higher. Presumably the higher projections would be still higher in the second quarter of the twenty-first century, although the CONAES study expects the growth in demand to taper off even during the period it examines.

4. The CONAES study (NRC 1979, p. 521) reaches qualitatively similar conclusions. It expects world energy demand in 2010 to be 3 to 4 times as large as now, and world demand for electricity to grow even more rapidly to 3 to 5 times present levels (over 60 quads of primary energy) in 2010.

5. Schurr and his coworkers (1979) analyze several projections. Their midrange projection for the year 2000 is 114 quads (primary energy) of which 40 percent (45 quads, or a capacity of at least 900 GW) is electric.

6. CONAES (NRC 1979, p. 521) cites the first and third of these reasons. The direct combustion of coal is an alternative to the conversion of coal to electricity as a means of saving oil, but has not yet begun to penetrate the market to a significant extent.

7. Many analysts believe we are now spending a disproportionate amount on electric options.

8. We are using coal in this section as shorthand for solid fossil fuel.

9. The figure of \$0.256/W (peak) used here is for all practical purposes equivalent to the figure of \$0.30/W (peak) mentioned in the section "Solar Cell Array" earlier in this chapter. The difference is ascribable to consulting slightly different sources.

10. Note that in the net energy analysis calculations, SPS output is converted to the same thermodynamic quality as the energy used in construction and maintenance. Specifically, 1 Btu (electric) is equivalent to 4 Btu (thermal), or, the number of Btu (thermal) is equivalent to 4 times the number of Btus (electric).

11. For example, The Aerospace Corporation (Wolfe 1981, reproduced as Appendix D in this report) recently estimated that the Boeing/NASA estimates of the cost of transportation to LEO were too low by a factor

of 3. The new estimates may be considered in principle to introduce a second value for the HLLV dollar cost parameter. However, rather than to try to express results in terms of too many parameters, we simply note that the effect would be to lower the net energy ratio for the reference SPS by a factor of slightly less than 3 (assuming that the energy content per unit of transportation cost remains constant and restricting the conclusion to the lower ranges of the photovoltaic array cost parameter). These recent Aerospace cost analyses were not available when the net energy calculations were made.

CHAPTER 4
ENVIRONMENTAL EFFECTS

An SPS would have various consequences for the earth's environment, including effects on the biota, on the upper and lower atmosphere, on man-made electromagnetic systems, and on optical and radio astronomy.

EFFECTS ON THE BIOTA

The Committee initially identified five types of effects of a reference SPS that might pose unique and serious risks for human health or for ecosystems: (1) the effects of ionizing radiation on persons working on SPS satellites in space; (2) the effects of zero gravity on persons working on SPS satellites in space; (3) the effects of microwave radiation from SPS satellites on ecosystems in the vicinity of the rectenna; (4) the effects of microwave radiation on persons working on either a power satellite in space or on a rectenna; (5) the effects of low-level microwave radiation on humans outside the rectenna.

Of the potential effects on workers in space, those of ionizing radiation were chosen as a focus. The effects of zero gravity were deemed to be less significant, since the data appear to be more certain, and mitigation of the effects is more easily accomplished. In addition, many of the effects of zero gravity on human beings appear to be reversible, whereas the effects of ionizing radiation may not be.

Of the potential effects of microwave radiation, the question of human exposure outside rectenna sites was chosen as a focus. As for the effects on ecosystems, the Committee agrees with the U.S. Department of Energy (DOE) that the data now available are insufficient for a valid assessment of the ecological impact of microwave radiation from reference SPS satellites to earth. A substantial amount of additional work needs to be done to obtain a more definitive assessment of effects on ecosystems within and close to rectenna sites. However, although ecosystem effects are uncertain, they are expected to be small. The Committee therefore considers an assessment of the potential effects on humans more critical to an imminent decision on whether to proceed with a research and development program to maintain a future SPS option. Further, the exposure of workers at the rectenna site or at the satellite antenna would be intermittent and could be controlled by having workers wear protective clothing and by using

operational safeguards, while the exposure of the general population outside rectenna areas would be both involuntary and continuous. Also, potential effects are more uncertain at the lower levels, of exposure that might be experienced by the general population than that by workers on the system.

A great deal is known about the effects that ionizing radiation has on people at the levels of exposure anticipated in geosynchronous earth orbit (GEO). Little is known about the effects of microwave radiation at the low power levels anticipated outside rectenna sites. The two types of radiation are completely different in their mode of physical interactions with and their effects on the components of biological systems. Ionizing radiation releases amounts of energy large enough to eject electrons from atoms and thus to ionize water and the molecules of living cells. Such ionizations have a high probability of destroying the enzymatic activity of proteins in the body and the biological activity of deoxyribonucleic acid, or DNA, the genetic material in cell nuclei.

In general, the ionization of molecules in living tissue has a much more devastating effect than does the absorption of nonionizing radiation such as light or microwaves. For example, if an electron in a molecule is not ejected but only raised to an excited energy level, say by the absorption of a quantum of ultraviolet light (energy approximately 200 x average thermal energy), the probability that the molecule's biological activity will be affected is approximately 100 times less than the probability of its being affected by an ionization. Microwave quanta do not even have sufficient energy to excite the electronic energy states in an atom or, for that matter, to change the vibrational or rotational states of molecules in solution. Thus, it is more appropriate to approach the interaction of microwaves with biological material as that of electromagnetic waves with the electric dipoles in water or on macromolecular structures. The energy transmitted during these interactions is dissipated as heat or results in configurational changes in membranes or other macromolecular structures.

The Ionizing Radiation Environment in Space

For our assessment of ionizing radiation we have drawn extensively on four sources of information: (1) A DOE report issued in December 1979, Workshop on the Radiation Environment of the Satellite Power System (SPS) (Schimmerling and Curtis 1979). (2) A working paper by Harald Rossi (Appendix G) of Columbia University estimating the radiation doses that space workers might receive by reviewing the estimates given in (1) above. (3) A working paper contributed by Charles Land (1980) of the National Cancer Institute in which he calculates the expected excess cancer mortality among space workers exposed to either 30 rads or 50 rads per 90-day tour of duty in geosynchronous orbit, and for the total of 10 tours of duty over 5 years. These calculations use the latest values given in The Effects on Populations of Exposure to Low Levels of Ionizing Radiation (NRC

1980) (hereafter referred to as BEIR-III). (4) A working paper by Paul Todd (1980) of Pennsylvania State University surveying the biological effects of energetic particles of high atomic number (high Z), since there are appreciable numbers of these particles in space.

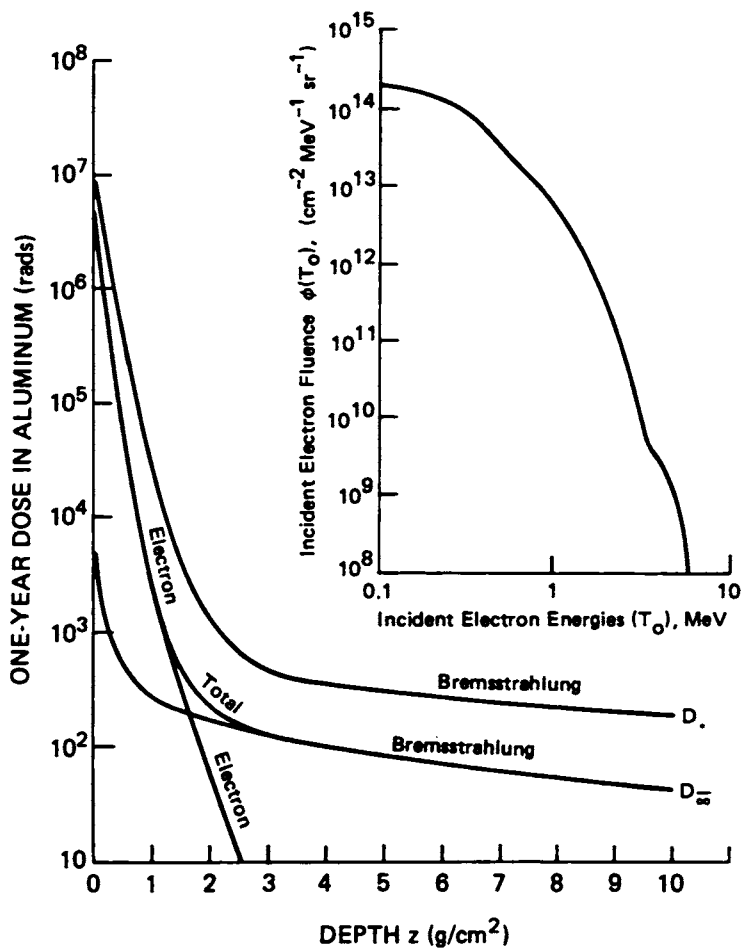
Radiation of Low Linear Energy Transfer (LET) and Cancer

Since the doses of ionizing radiation in space would be substantial, workers would have to be shielded in some way. The dose estimates reviewed here and in Appendix G are those contained in Madey's (1979) summary of a DOE-sponsored workshop held in September 1978 (Schimmerling and Curtis 1979) and assume shielding of 2 grams per square centimeter (g/cm^2) of aluminum. (The doses given by Madey (1979) and by most subsequent DOE reports are doses in aluminum targets and must be increased by about 30 percent to show the dose that would be received in tissue.) Although less shielding would result in appreciably greater dose rates, and 3 g/cm^2 would lower the dose rates by 2-fold to 3-fold, more than 3 g/cm^2 of aluminum shielding would not further decrease the dose rates appreciably (Schimmerling and Curtis 1979). This is because secondary radiation produced in the shielding itself dominates the dose behind aluminum thicknesses greater than 3 g/cm^2 . Composites would have to be used to provide more shielding. In more recent reports (U.S. DOE 1980c, 1980d) doses to SPS space workers are estimated assuming 8 g/cm^2 of shielding.

The largest doses would be received by workers in geosynchronous earth orbit. In GEO the geomagnetically-trapped electron flux and the resultant bremsstrahlung are high. Estimates of the dose that would be received, depending upon the longitude of the satellite, vary from 30 rads to 60 rads (in aluminum) for a 90-day tour (Madey 1979; Seltzer 1979; U.S. DOE 1980c, 1980d). The agreement between the various estimators is in part fortuitous. Madey describes a dose behind an infinite slab of 2 g/cm^2 of aluminum, whereas Seltzer and DOE estimated the dose at the center of an aluminum sphere of radius corresponding to a shielding of 8 g/cm^2 (3 g/cm^2 of shielding from the habitat and work stations and 5 g/cm^2 of aluminum equivalent shielding from human tissue). Despite the high shielding, the latter estimates agree with the former because Seltzer used a different geometry and seems to have made a more sophisticated estimate of the effects of bremsstrahlung. For Seltzer's method of calculation, the dose for a 90-day tour estimated at the center of a sphere of radius equivalent to 2 g/cm^2 aluminum would be approximately 350 rads; for a 3- g/cm^2 , 110 rads; and for a radius equivalent to 8- g/cm^2 , 60 rads (Figure 4.1).

Radiation doses in low earth orbit (LEO) would also not be negligible. They would come mainly from trapped protons and would range from about 20 rads during minima in solar activity to 10 rads during solar maxima for a 90-day tour (Madey 1979).

Workers passing from LEO to GEO and back would cross the Van Allen belts. The traverse time would be relatively short, however, and a person shielded by 2 g/cm^2 of aluminum could expect to receive a dose of approximately 3 rads on each one-way trip (Madey 1979).



SOURCE: Seltzer (1979, Figure 12).

FIGURE 4.1. Depth-dose distributions in aluminum targets for the radiation encountered from trapped electrons during 1 year in geosynchronous orbit at 160° W longitude. Insert shows incident electron fluence. Results are given for the dose D_∞ at depth z in a semi-infinite slab and for the dose D_0 at the center of a sphere of radius z .

At the doses estimated for GEO, effects are manifested months or years following exposure (and are called late or delayed effects). The effect of greatest concern is cancer induction. Estimates were made for us of the cancer mortality that would result from one tour of 90 days in geosynchronous orbit and from a 5-year career of 10 tours of 90 days each (Land 1980). Such estimates are uncertain, since the precise relationship between dose and response at these dose rates is not well known. The risk of dying from cancer increases dramatically as age at first exposure is lowered, since the individual would have more time to develop cancer before dying of some other cause. Land provides estimates based on two dose-response models (linear and linear-quadratic) and two risk-projection models (absolute and relative) developed for the BEIR-III report (NRC 1980). The estimates were also calculated by age at exposure and by sex.

We use here the linear-quadratic, relative-risk model. For a dose (in tissue) of 50 rads per tour to workers exposed for the first time at age 30 and working 10 tours, the excess cancer mortality above that otherwise occurring would be about 6 percent for males and about 8 percent for females. (The higher value for females is due to the higher risk of breast cancer.) The other models give values ranging from about 3.5 percent to about 18 percent.

The outlook might be even more serious than the Land estimates would suggest, however. In the most detailed calculations (Madey 1979, Stassinopoulos 1979) reviewed for us of ionizing radiation doses to workers in GEO shielded by 2 g/cm² aluminum, it appears that some secondary and higher-order radiations produced in the shielding have been underestimated, resulting in a dose estimate low by a factor of 4 (Appendix G). This is probably because a semi-infinite slab geometry was assumed. Dose estimates based on a spherical shield model, which is more appropriate in spacecraft applications, would be about 4 times greater at the center of the sphere than in a slab of thickness equal to the radius of the sphere (Seltzer 1979). As noted above, assuming a shielding in the reference SPS of 8 g/cm² instead of 2 g/cm² would reduce the estimated dose to workers somewhat. However, the increase in the dose estimate when a spherical model is used in place of a semi-infinite slab model overrides the reduction resulting from thicker shielding--an overall increase in the dose estimate results. Furthermore, all of the estimates are an additional 30 percent too low because the dose rates are given for aluminum targets rather than human tissue. Since the dose estimates of 30 rads to 60 rads in GEO depend critically on geometrical factors, the amount of shielding, and the tissue irradiated, they could be low by an appreciable factor.

Thus, if the doses were approximately 100 rads per tour, the estimates of excess cancer mortality obtained by using the linear-quadratic, relative-risk model would be approximately 10 percent for males and 15 percent for females. That is, for a worker population of 1000 males approximately 100--or for 1000 females, approximately 150--would be expected to die of cancer from exposure to the ionizing radiation environment in GEO, in addition to cancer deaths from all other causes. Note that these numbers refer to deaths from cancer. In BEIR-III, a ratio of incidence to mortality for radiation-induced

cancers was calculated separately for males to be 1.54 and for females to be 2.00 (NRC 1980). Thus, the rates of incidence of cancer could be as much as 2 times greater than the mortality rates discussed above. The Committee concludes that:

- The predicted excess cancer mortality in space workers exposed to the ionizing radiation environment in GEO associated with the SPS reference design is on the order of 10 percent, a risk much greater than that in other occupations. It would be necessary to establish some level of risk for SPS workers lower than now predicted and to design measures to stay within it.

The hazard from ionizing radiation might be mitigated by changing the number or the length of tours of duty, by new shielding designs, by shifting construction to LEO, or by arranging to have most of the construction done by robots.

The estimates of excess cancer mortality discussed above indicate that an increase in the individual dose per tour, from 50 rads to 100 rads, would result in almost a doubling--from 6 percent to 10 percent for males and from 8 percent to 15 percent for females--of the risk associated with a career of 10 tours. The Committee therefore concludes that:

- Accurate dosimetry in geosynchronous orbit is absolutely necessary as a prelude to designing manned systems in GEO, since the dose estimates are so large that errors of even a factor of 2 would affect several percent of the work force.

Solar Flares

In addition to the doses of radiation caused by the trapped electron flux in GEO, workers in space would be subject to aperiodic radiation caused by solar flares. The magnitude of solar flares and the time at which they will occur cannot now be predicted. The data indicate, however, that flares could be lethal to space workers. It has been estimated that a flare that occurred in August 1972 would have delivered 300 rem over a short time despite shielding of 10 g/cm² of aluminum (Stassinopoulos 1979). Such a dose will produce early health effects, i.e., effects that occur within hours, days, or a few weeks, such as damage to bone marrow, white blood cell formation, and testes, and an expected mortality on the order of but not more than 10 percent within 30 days. Workers in low earth orbit would be shielded from solar flares by the earth's magnetosphere.

The Committee concludes that:

- Radiation doses from solar flares may be so high in geosynchronous orbit that workers must be able to get into a heavily shielded area (storm shelter) within an hour or two of warning.

- Accurate measurements of radiation doses in geosynchronous orbit with and without shielding would be needed in order to determine the appropriate types of storm shelters that would have to be constructed. Continued research on how to predict the magnitude and the time at which solar flares will occur is also needed.

High-Z Particles

Workers in space would also receive doses of energetic particles of high atomic number (high-Z particles, $Z > 2$), most of which would come from cosmic radiation. The most significant characteristic of a high-Z particle is its ability to inactivate a large number of cells in its path. Since a high-Z particle loses energy rapidly after it strikes tissue, the physical event is sometimes called a thin-down hit, and the corresponding biological event, a microlesion. A microlesion can be thought of as a core of dead cells surrounded by some nonlethally damaged cells.

Although microlesions occur during exposure, macroscopic effects can be expected to show up only some time after a 90-day mission. In an assessment of several earlier studies (Arcos et al. 1968, Malachowski 1978, Tobias and Grigor'yev 1975), Todd (1980) suggests that small decrements in visual acuity might result from damage to the cones in the retina and to ganglion cells, and that late cataracts could develop as a result of the tremendous energy deposited locally by these particles. There is also reason to believe that the microlesions produced by high-Z particles in the liver and the lungs might be carcinogenic (Todd 1980), although there are no direct data on this question. The carcinogenic risk will depend on the probability of a microlesion inducing a malignant focus. This probability remains to be determined in laboratory experiments. The Committee therefore concludes that:

- More accurate quantitative data are needed on the biological effects of high Z-particles.

Due to the very high energy of high-Z particles, it would be more difficult to shield against them than it would be to develop protection against energetic electrons or protons. A shield for high-Z particles would have to be 10 g/cm² of aluminum to be between 25 and 40 percent effective. It is impossible to say what biological effects might result given this amount of shielding, without better information.

Consequences for Mutagenesis

The BEIR-III report estimates that a radiation dose of between 50 rem and 250 rem results in a doubling of spontaneous mutations in human beings (reaching an equilibrium in perhaps 10 generations after exposure) (NRC 1980). Space workers in the reference SPS would be

exposed to much larger doses. A single 90-day tour alone could expose a worker to a doubling dose.

The number of space workers postulated in the reference system would be only a small fraction of the total U.S. population and, hence, the average mutagenic load of the entire U.S. population would not double. The increase would be confined to the descendants of the exposed workers. Nevertheless, the prospect of mutagenesis in the descendants may present a serious problem in terms of costs to the descendants and to a responsible society as a whole. Before an SPS was deployed, the extent of this problem, its implications, and possible mitigating techniques would have to be further examined.

Exposure Guidelines for Space Workers

A number of Federal agencies presently have authority to set radiation protection standards. The Occupational Safety and Health Administration (OSHA) and the Mine Safety and Health Administration in the U.S. Department of Labor were created to regulate worker safety in areas not otherwise covered. A space work force, which in the case of the reference SPS would include tens of thousands of workers, would fall into this "not otherwise covered" category. While the National Aeronautics and Space Administration (NASA) has set limits for the exposure of astronauts, it is unclear whether NASA, OSHA or a group of agencies should be responsible for setting the exposure limits for a space work force. Nor is it clear what the exposure limits should be. It is possible that the Radiation Policy Council, established in 1980 by former President Carter, might be used for this purpose. The Council is composed of representatives from 13 federal agencies and, among other things, is intended to provide advice on radiation protection policy and to assist in the resolution of disagreements.

The current OSHA and Nuclear Regulatory Commission exposure limits for ground-based workers are 3 rem in 90 days or 5 rem per year (Schimmerling and Curtis 1979). The accumulated whole-body dose over a lifetime must not exceed $5(N - 18)$ rem (where N is the individual's age). NASA astronaut limits range from 6-fold to 22-fold higher for 90-day or yearly exposures than the ground-based worker limits. The average exposure per person with measurable exposures in each of the four covered categories for Nuclear Regulatory Commission licensees is roughly 0.7 rem per year (U.S. NRC 1977). In 1966, the occupational limit in the naval atomic propulsion program was reduced to 5 rem per year. Should similar limits apply to a large work force in space, or should space workers have different guidelines because other risks in space work may be dominant?

The ionizing radiation exposures estimated by the Committee for the reference system represent a many-fold increase over the exposure limits for terrestrial workers. The Committee therefore recommends that:

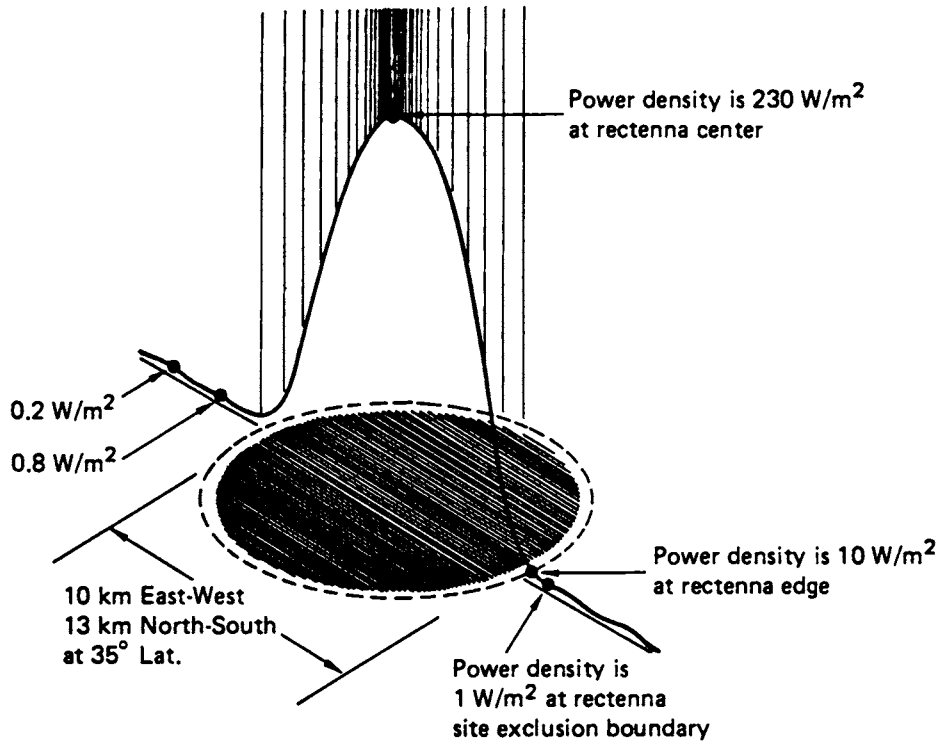
- OSHA and NASA should begin joint discussions, possibly using the offices of the Radiation Policy Council, to decide how exposure limits might be established and what such limits might be for space workers on future space projects.

The Microwave Environment Beyond the Rectenna Site Boundaries

Our assessment of the hazards of the microwave environment associated with the reference SPS to the general population comes from three sources: (1) A report prepared for DOE by the Environmental Protection Agency (EPA) entitled Environmental Assessment for the Satellite Power System--Concept Development and Evaluation Program--Microwave Health and Ecological Effects (U.S. DOE 1980b) that summarizes the available information published up to that time. (2) A workshop held under the Committee's auspices on July 15-17, 1980, at which 17 experts in the field addressed the subject "Mechanisms Underlying Effects of Long-term, Low-level, 2450 MHz Radiation on People." A summary of the workshop prepared by Christopher H. Dodge of the Library of Congress is contained in Appendix H. (3) Comments on the summary of the workshop solicited from interested parties.

In the reference system, solar energy would be transmitted from satellites to rectennas by means of microwave radiation (Figures 1.1 and 1.2). As the system is designed, the power level immediately outside the boundary of a rectenna site would be slightly less than 1 watt per square meter (W/m^2) (0.1 milliwatts per square centimeter-- mW/cm^2), and would decrease rapidly with distance from the site (Figure 4.2). The minimal background power level to which the total U.S. population would be exposed would be about $0.001 W/m^2$ ($10^{-4} mW/cm^2$) for 60 rectennas. Tell and Mantiply (1980) measured ambient electromagnetic power densities for 15 U.S. cities--representing 20 percent of the total U.S. population--and found that these populations were exposed to electromagnetic fields with a median power density of $5 \times 10^{-5} W/m^2$ (mostly FM radiobroadcasts at 88 megahertz (MHz) to 108 MHz). DOE concluded from those measurements that the reference system would expose nearly all of the U.S. population to "levels significantly greater than the current background levels" (Valentino 1980, p. 13). Accordingly, it is necessary to analyze potential health effects.

It is not now possible to determine the effects, however, since no satisfactory theory at the macromolecular or microstructural level exists for extrapolating from observed effects to effects expected at levels of $0.001 W/m^2$ to $1 W/m^2$. The mechanisms of interaction at power levels below $1 W/m^2$ are unknown, and data at these levels, where they exist, are controversial. Animal studies at power levels well below $1 W/m^2$ would require so many animals to observe a small effect, if one exists, that the experiments could become not only prohibitively expensive but impossible to carry out because of variations in the experimental system. Epidemiological experiments to detect the effects of power levels ranging from $0.001 W/m^2$ to $1 W/m^2$ would be close to impossible, because the very small expected effects require the use of huge human populations that would have two inherent variations that would confound the results--variations in the exposure levels of different individuals and variations in the response of different individuals to fixed exposures. Even though a great deal is known about the mechanisms and effects of ionizing radiation (NRC 1980, U.S. GAO 1981), so far it has not been possible to extrapolate



Location	Power Density (W/m ²)
Center of rectenna	
Malfunction	1000
Normal operation	230
Edge of rectenna (5 km from center)	10
At exclusion boundary around rectenna site,	
5.7 km from center	1.0
Beyond exclusion boundary	
9.0 km (first side lobe) ^a	0.8
13.0 km (second side lobe).	0.2
17.0 km (third side lobe)	0.1
Grating lobe levels (at spacing of 440 km) ^b	0.1

^aSide lobe power-density patterns are concentric rings, about 2 km in width, around the rectenna.

^bGrating lobe power-density patterns are isolated spots arranged in a grid surrounding the rectenna.

SOURCE: U.S. DOE (1980b, Figure 1-1).

FIGURE 4.2. Reference SPS microwave power density characteristics at rectenna sites.

with confidence its effects on people from high levels of exposure to low levels. It is likely to be all the more difficult to extrapolate from the effects of high-level microwave radiation to low-level exposures.

Hence, the Committee concludes that:

- Although it has not been demonstrated that microwaves at levels of from 0.001 W/m² to 1 W/m² have harmful effects on human beings, without good theory and knowledge of mechanisms it is not now possible to prove that exposures at such low levels are safe.

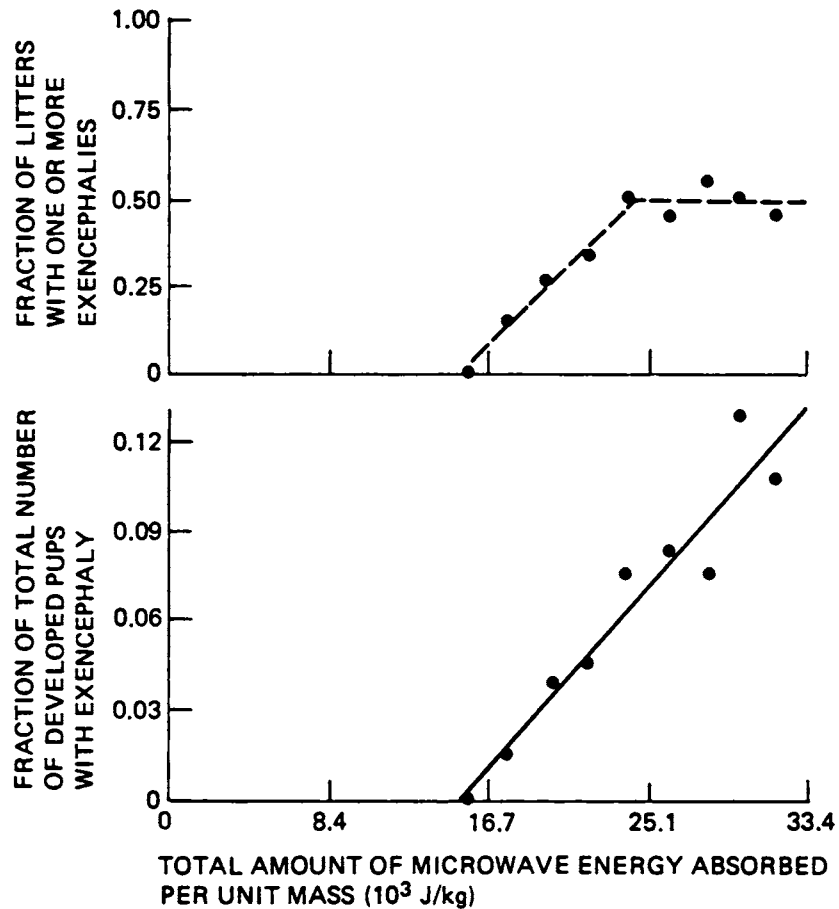
Thermal Effects

Most of the experiments in which animals have been exposed to microwaves have been performed at power levels high enough to create heat stress on a specific organ or on the whole body. The extent of the thermal effect depends on the energy absorbed per unit of weight compared with the basal metabolic rate. The energy absorbed is in part a function of the microwave wavelength relative to body or organ size. For example, an adult exposed to 10 W/m² of energy at 2450 MHz would absorb energy at the rate of 0.04 watts per kilogram (W/kg), a small value compared with the basal metabolic rate of 1.2 W/kg for human beings. The exposure of rats to the same power level would result in 5 times more absorption because rats are of a size close to the wavelength of 2450 MHz radiation (0.122 m or about 5 inches).

For biological effects that obviously have a large thermal component, such as those observed at power levels appreciably greater than 100 W/m², there is a threshold below which no effect can be demonstrated even if subjects are exposed for long periods of time (for example, see Figure 4.3). Because the threshold for gross thermal effects in humans is well above 100 W/m², the thermal effects of an SPS such as the reference system on the human population outside the rectenna sites would not be a matter of concern.

Mutagenic Effects

Bacterial and yeast cells used extensively to assess potential mutagenic effects of chemicals have also been used to determine whether microwave radiation would cause mutagenic effects. No effects have been observed from exposure to microwaves ranging from 10 W/m² to 450 W/m² (Appendix H, Dutta 1980). McKee et al. (1981) investigated potential mutagenic bioeffects of 2450 MHz radiation by measuring sister chromatid exchange in bone marrow cells of mice and found no statistically significant increase.



SOURCE: U.S. DOE (1980b, Figure 6-1), as adapted from Rugh et al. (1975).

FIGURE 4.3. Production of fetal exencephalies in mice by exposure to 2450-MHz microwave radiation. Environmental conditions were: (1) temperature, 25°C; (2) relative humidity, 50%; (3) airflow, 38 liters per minute; (4) forward power at all times, 7.37 W (1230 W/m²); (5) exposure time, between 2 minutes and 5 minutes to obtain various absorbed doses; (6) preexperimental conditioning of animals, 30 minutes.

Effects at Power Levels Below 10 W/m^2

At power levels below 10 W/m^2 , microwave radiation is reported to have had effects on (a) immunological systems, (b) reactions to drugs, (c) the efflux of calcium from brain tissue, and (d) behavior of animals (see Appendix H for details). The latter two effects were not observed with continuous waves but only with waves modulated at frequencies between 4 hertz (Hz) and 30 Hz. The microwave pattern that would occur in the reference system would be modulated by frequencies in this range because of interference between the beams of different satellites (Ott and Rice 1981); such effects on humans are therefore conceivable. However, the change in the average power level due to such modulation is estimated to be appreciably less than 0.1 W/m^2 , and hence it is doubtful that one could observe such effects in experimental systems.

The Committee concludes that:

- What is needed is a good way of extrapolating from observations to predicted effects at low power levels. If these effects occurred at the low power levels (below 1 W/m^2) and waveform characteristics of microwave radiation outside rectenna sites, it would then be necessary to determine if such effects were harmful.

The research necessary to reduce uncertainty in our understanding of the possible health hazards of low-level microwaves is shown in Table 4.1. This research should establish with reasonable certainty whether the phenomena discussed above would occur in human beings, and if so, the extent of the risk. Because of increasing public exposure to and awareness of microwaves (e.g., microwave ovens), research into the effects of frequent or continuous exposure to low levels of microwave radiation will probably continue independently of an interest in an SPS. Conversely, data from research into SPS microwaves would also be applicable elsewhere.

International Exposure Standards

There is no international agreement on microwave exposure standards for the general population; a number of countries currently have national standards (see Table 4.2). East European and Soviet standards are significantly more stringent than those of western countries. The United States has a standard for exposures in the workplace but not for exposures to the general population, although such a standard has been proposed. An SPS consistent with currently proposed U.S. guidelines could expose parts of the U.S. population to levels of microwave radiation that are unacceptable in other countries. The result--whether founded on scientific evidence or not--would be a large, environmental health concern in the United States and, just as important, a conceptual barrier to making such an SPS an international system.

TABLE 4.1. Research needed 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 animal experiments at power densities $\leq 1.0 \text{ W/m}^2$ at whole body, organ, and organelle levels, testing for biological endpoints such as alteration of enzyme reaction rates and cell membrane conformational 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 conformational 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

- Repetition of selected animal experiments showing effects (including the potential of microwaves as a cocarcinogen), using carefully controlled dosimetry and statistical analysis.
- Development and testing of hypotheses to explain effects.
- Long-term dose-response animal experiments at power densities around 1.0 W/m^2 and with a larger number of drugs at whole body, organ, and organelle levels.

Immunological Effects

- Repetition of selected Russian research at levels of 0.01 W/m^2 to 5.0 W/m^2 ; repetition of selected U.S. work to validate it.
- Mechanistic and molecular biological experimentation.
- Long-term animal studies, particularly autoimmune response.

Effects on Calcium Ion Efflux 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 extremely low frequency 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 levels of microwaves below 1.0 W/m^2 .
- 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 SPS power levels.
 - Determination of the neurological and physiological significance of behavioral responses.
 - Molecular-level studies of biological relaxation times.
 - Consideration of long-term animal experiments at 2450 MHz to evaluate, if possible, whether there is any trend toward life-shortening in animals.
-

SOURCE: 1980 Workshop on Mechanisms Underlying Effects of Long-term, Low-level, 2450 MHz Radiation on People (Workshop Summary is in Appendix H of this report).

TABLE 4.2. Comparison of major microwave exposure standards or guidelines.

Country, Date, Source of Standard	Frequency (in GHz)	Comments	Occupational Exposure		Public Exposure (Continuous)
			Limit	Duration	
Canada, 1966 Canadian Standards Association	0.01 - 100	Continuous wave	100 W/m ²	No limit	None
	0.01 - 100	Pulsed	10 W h/m ²	0.1 h	None
Canada, Proposed Health & Welfare	0.01 - 300		10 W/m ²	No limit	10 W/m ²
Czechoslovakia, 1970 Government	0.3 - 300	Continuous wave	0.25 W/m ²	Working day	0.025 W/m ²
	0.3 - 300	Pulsed	0.10 W/m ²	Working day	0.01 W/m ²
Poland, 1972 Government	0.3 - 300	Stationary antenna	2 W/m ²	10 h	0.10 W/m ²
Sweden, 1976 Worker Protection Authority	0.3 - 300		10 W/m ²	8 h	None
United States, 1974 ^a American National Standards Institute (ANSI)	0.01 - 100	Continuous wave	100 W/m ²	No limit	None
	0.01 - 100	Pulsed	10 Wh/m ²	0.1 h	None
United States, Proposed ANSI	0.3 - 1.5		Frequency (in MHz)/30	Averaged over 0.1 h	Frequency (in MHz)/30
	1.5 - 300		50 W/m ²	Averaged over 0.1 h	50 W/m ²
U.S.S.R., 1977--Occupational; 1970--Public Government	0.3 - 300	Antenna sta- tionary for occupational; either for public	0.1 W/m ²	Working day	0.01 W/m ²

NOTE: The International System of Units (SI) is used in this table, as in text. To express W/m² numerically in mW/cm², divide by 10, e.g., 100 W/m² = 10 mW/cm².

^aWith slight modification this line also applies to the United Kingdom, the Federal Republic of Germany, the Netherlands, and France.

SOURCE: Adapted from Health & Welfare Canada (1978).

Further, there appears to be a trend for western countries to make their standards more stringent. Even though there is no proof that microwave radiation at power levels below 1 W/m^2 constitutes a hazard to human health, scientists have conjectured that future U.S. public exposure guidelines might be as low as 0.1 W/m^2 to 1 W/m^2 (Appendix H). This would affect the design and cost of an SPS, the design power level at the boundary of a reference system rectenna being 1 W/m^2 .

Taking these issues into consideration, the Committee concludes that:

- It would be desirable to examine the various criteria that have been employed to establish microwave exposure standards in countries around the world in order to design an SPS that would be acceptable to the international community, if at any time in the future an SPS is a viable energy option.

EFFECTS ON THE LOWER AND UPPER ATMOSPHERE

Rocket Effluent Effects in the Troposphere, Stratosphere, and Mesosphere

Impacts on the troposphere, stratosphere, and mesosphere (which are also referred to here as the lower atmosphere) from the reference SPS are expected to be due mainly to effluents from the heavy-lift launch vehicle (HLLV). The effects of rectenna operation and absorption of microwave power in the lower atmosphere are expected to be small and of little consequence. The rectenna structure itself would modify the thermal and radiative properties of the ground on which it was built and its operation would generate some waste heat. However, the influence of these effects on weather and climate is not expected to be much different from that of a typical suburban development (Valentino 1980). Construction modifications and careful rectenna site selection can be used to minimize effects. The microwave absorption coefficient of atmospheric air is well known and predicts that absorption of microwave energy in the lower atmosphere will be negligible in clear air. During rain storms, the absorption will increase somewhat, but the effects of microwave heating are still expected to be smaller than the natural variance of cloud and storm phenomena (Valentino 1980). The impact of personnel launch vehicles (PLV), if used, will be much smaller than that of the HLLV because of the PLV's smaller size and less frequent launch rate.

After consultation with several experts in the field, the Committee concluded that DOE's identification of the major lower atmosphere issues was sound. These issues include:

1. The air quality impacts of nitrogen oxides produced by afterburning of HLLV rocket effluents in the HLLV ground cloud.
2. Temporary local weather modification by HLLV rocket effluents and cumulative effects that might impact climate (a) by producing cloud-condensation nuclei (CCN) and ice-forming nuclei (IN) that could

alter the microphysical processes of clouds, and (b) by contributing heat and moisture that could enhance convective activity.

3. Chemical composition changes in the mesosphere and, to a lesser extent, in the stratosphere due to rocket effluents and to the production of nitric oxide (NO) and ablation products on reentry. The extent of the effects of changing the chemical composition of the stratosphere and mesosphere, e.g., climatic effects and noctilucent cloud formation, are unknown because of the many uncertainties in our current understanding of stratospheric and mesospheric chemistry.

None of these issues can be assessed with any confidence at this time, given the current state of knowledge and paucity of data. For the first two issues, which involve effects of ground cloud formation, there are some useful data from an Atlas/Centaur rocket launch in November 1978. A number of parameters were measured during that launch, including the concentrations of several gases and CCN and IN. These data have been used in predicting concentrations of these products from HLLV launches. From these calculations it is predicted that an HLLV launch could contribute a significant fraction of the proposed federal standard for the maximum hourly concentration of nitrogen dioxide (0.25 parts per million by volume). Measurements of CCN and IN production from Titan III and Atlas/Centaur launches indicate that the formation of these nuclei during HLLV launches might have meteorological significance, and a potential for cumulative effects and climate modification exists since from 375 to 500 HLLV flights would be required each year for 30 years to construct the reference SPS.

No experiments have been conducted in the stratosphere and mesosphere specifically in connection with the SPS; chemical composition changes and noctilucent cloud formation were predicted using models. However, better models reflecting improved understanding of atmospheric chemistry are needed to make more confident predictions of HLLV effects. The consequences, if any, of these effects for climate or in other areas need elucidation. Nevertheless, the Committee concludes that:

- None of the lower atmosphere issues is likely to present insurmountable problems in the planning or development of an SPS. In fact, these issues are less critical than SPS impacts on the ionosphere and on telecommunications. However, further study of all three issues listed above would be necessary before an SPS should be built.

SPS Impacts on the Ionosphere and on Telecommunications

The microwave beam of the reference system would heat that part of the atmosphere through which it passed. In this section we consider the effect that the microwave beam would have on that part of the upper atmosphere known as the ionosphere. There are four critical issues (apart from the possible degradation of the control of the SPS power beam by the ionosphere, which is discussed in the section of Chapter 2 on "Energy Transmission"):

1. The effect on the design--and cost--of the system of a change in the power density of the microwave beam.

Original predictions of the ionospheric heating that would be caused by the microwave beam resulted in a reference system design limit of 230 W/m^2 for the beam. Recent theoretical and experimental studies, however, indicate that the design limit could probably be increased to between 400 W/m^2 and 500 W/m^2 . Such an increase would have a ripple effect throughout the system design and the system cost.

2. The cumulative effect on the ionosphere of repeated launches of large rockets.

Emissions from the large rockets (HLLVs) that would be needed to carry materials for an SPS into space would cause the electrons and ions normally in the ionosphere to recombine, leaving a "hole" in the ionosphere. The size and duration of the hole calculated from models are in general agreement with observations from a single launch, but unanswered questions remain about the consequences of repeated launchings. Such repeated launchings would be necessary if the materials for an SPS were sent from the earth as recommended.

3. The effect on the ionosphere of emissions from an orbital transfer vehicle.

An orbital transfer vehicle would emit certain quantities of contaminants, such as argon ions in the case of the reference system, into the outermost region of the atmosphere known as the magnetosphere. It is possible that the persistence of these ions might modify the physics of the magnetosphere, but little information is available on this subject.

4. The impact on radiocommunication and radionavigation systems of an SPS-disturbed ionosphere.

Many radiocommunication and radionavigation systems make use of signals propagated through all or part of the ionosphere. Thus, the question arises as to whether the ionosphere would be sufficiently disturbed by an SPS microwave beam to affect performance of those other systems. So far, telecommunications tests at frequencies below 3 MHz using a simulated SPS microwave beam have indicated that the beam would have little or no effect.

Description of the Issues

Increasing the power of the microwave beam. There are three aspects to the problem of the interaction between the microwave beam and the ionosphere. The first is that changes in electron temperature and density would occur in the lower ionosphere (Perkins and Roble 1978), the second is that thermal self-focusing would occur in the upper ionosphere (Perkins and Valeo 1974), and the third is that parametric instabilities might be generated in the ionospheric plasma by the microwave beam (Carlson and Duncan 1977, Gurevich 1978).

A theoretical limit of 230 W/m^2 was originally set on the power flux density to avoid "thermal runaway" in the lower ionosphere. Thermal runaway occurs when the ionosphere is heated sufficiently, e.g., by the energy in the SPS power beam, to saturate the operating

heat-dissipation mechanism before another comes into play. Thermal runaway can cause changes in the temperature and density of electrons that may interfere with the normal propagation of electromagnetic waves. However, refinements in theory, particularly better understanding of certain cooling rates, and experimental studies now indicate that the expected changes in electron temperature and density would not have a significant effect on telecommunications systems.

Self-focusing of the microwave beam would be caused by natural irregularities in ionospheric density acting as lenses. These "hot spots" in the beam would produce additional lenses through thermal expansion and spatial amplification of the effect, leading to large-scale striations of electron density in the upper atmosphere. Little is known either theoretically or experimentally about the extent to which thermal self-focusing would occur at SPS frequencies. Neither frequency scaling nor the thresholds for the onset of these striations have been validated experimentally.

Finally, a microwave beam can pump energy into pairs of resonant frequencies occurring in an ionospheric plasma when the frequencies satisfy certain matching conditions; the result is an amplification of plasma waves. The process is a form of parametric instability that is observed when the heater frequency is less than the ionospheric plasma frequency. The microwave beam of the reference system is not expected to produce this type of instability, since the beam frequency is about 2 orders of magnitude higher than the plasma frequency. But this question and related ones--such as the possibility of induced scattering instabilities, and interaction between an SPS transmitter's center frequency and noise bands--need further attention.

The original prediction, based on early heating theory (Holway and Meltz 1973), that the microwave beam should be limited to a flux density of 230 W/m^2 has been changed as a result of revised theory and new experiments in the lower ionosphere (Duncan and Gordon 1981). Heating theory on the upper ionosphere is still unsettled. Progress will require tests of the frequency scaling laws and more powerful heaters, but the impact on telecommunications of a 230 W/m^2 beam would not be significant (U.S. DOE 1980a). The following questions remain to be answered: (a) How powerful would a microwave beam have to be in order to cause unacceptable effects on telecommunications? and (b) What are the system design and cost impacts on an SPS of using a flux density of 400 W/m^2 or 500 W/m^2 ?

Rocket emissions in the ionosphere. Rockets used in heavy-lift launch vehicles emit large quantities of water and other exhaust products. The water reacts with atmospheric gases, including the ionized gases in the F-region of the ionosphere, in such a way that the free electrons and the positive ions recombine so rapidly that the recombination becomes locally complete (the ionosphere goes away, in a limited volume) (Zinn and Sutherland 1980). The recombination continues until the water is used up and photoionization resulting from solar radiation replaces the electrons and ions.

The spatial and temporal scales of ionospheric depletion are influenced by the diffusion and convection of exhaust products from

their initial point of deposition. A portion of the water deposited in the F-region of the ionosphere forms ice and falls to the D-region (65 km to 90 km altitude), where its presence is much less serious. When the concentration of water along the rocket trajectory has decreased by diffusion to levels below the normal ion concentration of 10^{12} per cubic meter in the F-region, local ionization would probably be replaced by sunlight-induced photoionization of atomic oxygen in about 4 hours.

The launch of Skylab I in 1973 involved an unusually long second-stage "burn" through the F-region, and nearly simultaneous observations of a large ionospheric hole were reported (Mendillo et al. 1978). The depletion was apparently approximately 2000 km in diameter. The ionosphere may have recovered within 4 hours, or the hole may have drifted beyond the observational line of sight. In either case, the large depletion in ionospheric electron density can be attributed directly to the rocket emissions during launch. Observation of this effect was also reported after a 1979 launch of an Atlas/Centaur rocket. These observations confirm the earlier measurements and are in agreement with theoretical models of the atmospheric chemistry.

Although the basic processes that affect the size, depth, and lifetime of ionospheric holes seem to be understood (Zinn and Sutherland 1980), there are potentially important details (e.g., striations and their extent in the upper ionosphere) which are not understood. Nor are the possible effects of persistent and repeated depletions understood.

Emissions from orbital transfer vehicles. Orbital transfer vehicles may emit large quantities of materials that would interact in an unknown way with the local plasma (F.W. Crawford, Institute for Plasma Research, Stanford University, personal communication, 1980). For example, argon ions emitted by such vehicles would remain in the plasma long enough to change its local properties. Experiments in the plasma would be necessary to make reliable predictions about the extent of the change and its impact.

Telecommunications impacts. Many telecommunications systems depend on the reflection of radio signals by the ionosphere to establish a path, or on propagation through the ionosphere to or from a communications, navigation, or information-gathering satellite. Thus, the question arises as to what might happen to telecommunications if the ionosphere were changed by an SPS microwave beam. The effect of such a microwave beam has been simulated by directing high-frequency radiowaves vertically over Platteville, Colorado, and Arecibo, Puerto Rico (Duncan and Gordon 1981). Studies under way are providing answers to many questions about the lower ionosphere, but questions about the upper ionosphere do not appear to be amenable to study with the facilities presently available.

Recent experiments at Platteville (U.S. DOE 1980a), in which the reference SPS beam was simulated in the lower ionosphere, show that an SPS with a peak power density of 230 W/m^2 would not adversely affect

the performance of telecommunications systems of very low frequency--3 kilohertz (kHz) to 30 kHz; low frequency--30 kHz to 300 kHz; and medium frequency--300 kHz to 3000 kHz. The remaining issues to be studied are (a) the scattering of higher frequency waves in the lower ionosphere by electron clouds that behave like natural sporadic E clouds; (b) the scattering of radiowaves by magnetic field-aligned striations in the upper atmosphere, should striations be produced; and (c) the effect of ionospheric holes. These holes might be avoided by rerouting telecommunications traffic.

Additional Work Needed

Of the four issues discussed above, the potential effect on telecommunications or navigation systems is probably the most important. Tests so far have been limited to interactions in the lower ionosphere (the D and E regions) and, therefore, to frequencies below a few megahertz. Before the effects of a microwave beam on the upper atmosphere can be predicted with a high degree of certainty, testing would have to be done simulating the SPS frequency and power density. Testing interactions in the upper ionosphere (F-region) would require more powerful simulators than are presently available, a careful development of the physics, and the test diagnostics to scale confidently the simulation. Such testing would require antenna apertures of thousands of square meters, transmitter power in the megawatt range, and a substantial research effort. Another approach would be to assume various levels of ionospheric disturbance and ask what measures that could be incorporated into the communications systems of two to four decades from now would allow us to avoid disruptive effects.

The next most important issue is the impact of changing the intensity of the microwave power beam. If the intensity is changed, the effects of the change will propagate through the entire satellite power system. These effects, including cost impacts, would have to be determined.

The problem of emissions from the heavy-lift launch vehicle would probably be a localized problem. If so, any degradation of communications could be avoided by alternate routing of the transmission. The cumulative effects of a series of launches would have to be established by theoretical models and by experiments. The impact of emissions from the orbital transfer vehicle is essentially unknown, but we believe that it is not likely to present a major difficulty.

The Committee concludes that:

- If an SPS were pursued, some important questions about its effects on the upper atmosphere would require further study. The most important of these are (1) consequences for telecommunications systems, (2) the system impacts of changing the power density of the microwave beam, and (3) the effects of emissions from the orbital transfer vehicle. These

questions, however, are unlikely to present insurmountable obstacles to an SPS.

EFFECTS ON ELECTROMAGNETIC AND ELECTRONIC SYSTEMS

An essential task in the evaluation of an SPS is to determine its compatibility with other users of the electromagnetic spectrum and the geosynchronous orbit. We therefore examined the potential effects of the reference SPS on terrestrial telecommunications systems and electronic devices, and on space systems, especially on those in neighboring positions in the geosynchronous orbit. Appendix I reports the results of this examination and provides the basis for the following discussion.

The Compatibility of SPS with Terrestrial Communications and Electronic Systems

Susceptibility of General Electronic Equipment

Studies sponsored by the Department of Energy on the effects of the reference SPS on communications and electronic equipment suggest that these would be concentrated within about 50 km of a rectenna, and that mitigative action would permit operation of these devices at the boundary of a rectenna (approximately 7 km from the center of the rectenna).

Recently, however, the Federal Communications Commission (FCC) initiated an inquiry into the susceptibility of general electronic equipment to radiofrequency interference. At about the same time, the American National Standards Institute (ANSI) held consultations with representatives of various interested parties in the communications and electronic industries and recommended, as a minimum design objective, that equipment be able to withstand interfering fields of 1 volt per meter (V/m) (corresponding to a power flux density of 2.7×10^{-3} W/m²). To avoid fields larger than this, terrestrial telecommunications and electronic equipment would have to be farther than about 200 km from a rectenna; to be able to operate at the boundary of a rectenna, such equipment would have to be able to operate in fields up to 20 V/m.

Although DOE-sponsored studies suggest that shielding, filtering, nulling, and other mitigation techniques are available that could possibly facilitate operation in fields up to 20 V/m, in view of the substantial difference between the standard recommended by ANSI and field strengths in the reference system, the Committee concludes that:

- Further study is necessary to determine how to mitigate the potential effects of an SPS on terrestrial telecommunications and electronic systems, with particular attention to the cost and practicality of such mitigating measures.

Susceptibility of Terrestrial Telecommunications Systems

The effects of SPS on terrestrial radiocommunications systems are similar to those on electronic equipment in general, but require even closer controls. Any proposed SPS design must include a fundamental requirement that there be no out-of-band emissions at a level that could cause interference to terrestrial communications systems.

Earth terminals of satellite communications systems are among the most sensitive types of telecommunications equipment in use today. Because these antennas are directed toward the geosynchronous orbit, they would be particularly vulnerable to SPS emissions, especially any out-of-band SPS radiation that fell in the reception band of the terrestrial station. Such radiation might originate as a harmonic of the SPS power beam, as noise sidebands of the microwave power frequency extending to the adjacent Fixed-Satellite and Broadcasting-Satellite bands at 2500 MHz to 2690 MHz, or as spurious radiations resulting from the nonlinear mixing of SPS signals with other radiations incident on the SPS. Unfortunately, estimates of the intensity of such radiations from an SPS satellite (or a system of 60 satellites) are extremely uncertain.

The Committee thus has reached the following conclusion:

- Detailed information on the emission of adjacent channel noise, harmonics, and spurious radiations from an SPS will be required before the effects of such radiation on terrestrial and space telecommunications systems can be estimated.

Rectenna Siting

The rectennas are of necessity nonlinear devices and are therefore likely to be major sources of signals at harmonics of the SPS power frequency. In addition, out-of-band interference may also be caused by the nonlinear mixing of the SPS power signal with other electromagnetic signals present at the rectenna site.

Preliminary studies on where to locate rectennas have not included adequate consideration of the effects of such rectennas on civil communications systems in the continental United States. Any radiocommunications systems (for example, the microwave relay links now used by telephone systems) located within a rectenna site would have to be relocated, and for considerations stated earlier it is possible that those within 200 km would have to be substantially altered through shielding, redesign, or relocation. This could seriously affect the availability and cost of essential communications services.

In view of these concerns, the Committee concludes that:

- No studies on the location of rectenna sites can be considered to be conclusive unless they include a thorough examination of the effects of rectennas on civil communications systems.

The Compatibility of SPS with Other Satellite Systems

Use of the Geosynchronous Orbit

The geosynchronous orbit is the only orbit where satellites remain in a fixed position in relation to points on earth. Placing communications satellites in this orbit permits the use of fixed antennas with high gain to transmit and receive communications via the satellite. Even more important, using this orbit reduces the number of satellites and antennas required to provide continuous service. Without the use of the geosynchronous orbit, the cost of international satellite communications would probably rise to prohibitive levels. Meteorological satellites in GEO are able to maintain a continuous watch on the hemisphere's weather below. In the future, direct television broadcast satellites will join today's communications and meteorological satellites in GEO.

Because of the unique advantages of the geosynchronous orbit, it represents a significant, though limited, international resource. Morgan (1980) lists 30 satellites that are now on station in the geosynchronous arc that is proposed for use by the U.S. reference SPS (i.e., between 65° and 135° W longitude) and identifies 26 more that are planned for launch to this region in the near future. It is extremely difficult to estimate the number of satellites of all types that will be on station in this section of the geosynchronous orbit in the year 2000, but it seems likely that this number will be within a factor of 3 of 300. It is possible that this number may be reduced by increasing the capacity per satellite rather than just increasing the number of satellites. Since there are already some difficulties in finding enough positions for new geosynchronous satellites, any new system that would use up a significant amount of this resource will face considerable competition.

There are at least six reasons to believe that an SPS would be a uniquely large user of both the electromagnetic spectrum and orbital space, and would therefore produce severe problems of compatibility with other types of satellite systems:

1. The number (60) of reference SPS satellites postulated for U.S. use is considerably more than the number now used in GEO for any other single service. Sixty SPS satellites would at least double the number of geosynchronous satellites of all types currently active or planned for the longitude sector appropriate the United States.
2. The power radiated by each reference system satellite would be some 30 million times larger than that now radiated from any other single geosynchronous satellite.
3. The directivity of each reference system transmitting antenna would be some 10,000 times greater than that of any other geosynchronous satellite now operating at frequencies of 1000 MHz to 5000 MHz.
4. The combination of high radiated power and high antenna directivity would mean that the intensity of the main beam would be more than a hundred billion times greater for a single SPS satellite

than for any other geosynchronous satellite operating near this frequency.

5. Each reference SPS satellite would be more than 100,000 times larger in cross-sectional area than any other current or envisioned geosynchronous satellite. It would therefore be a much greater potential source of scattered electromagnetic radiation (including sunlight) and a much larger radiator of thermal radiowaves than other satellites.

6. An SPS might also become a major source of interference outside of its own frequency band (produced by the nonlinear mixing of the SPS carrier frequency with other electromagnetic signals) because of the large amount of power radiated, the variety of materials used, and the huge size of the SPS satellite and rectennas.

We therefore conclude that:

- An SPS is likely to preclude use by other satellites of a significant fraction of the limited geosynchronous orbit and associated electromagnetic spectrum resources. Hence, obtaining international acceptance of a purely U.S. SPS is likely to be difficult not only in the administrative sense but also in the broader context of political decisions.

Sharing the Electromagnetic Spectrum

The electromagnetic waves used to transmit radio signals would become worthless if those who transmit radiowaves failed to coordinate their operations to avoid electromagnetic interference. This fact was realized at the turn of the century, when several countries began working together to establish institutions and procedures to guarantee that all who use the radio spectrum do so harmoniously. The primary treaty governing the use of the radio spectrum is the International Telecommunication Convention, to which the United States is a party. This convention established the International Telecommunication Union (ITU), which is now one of the specialized agencies of the United Nations. The Radio Regulations annexed to the International Telecommunication Convention set forth the services for which the radio spectrum can be used and allocate certain portions of the spectrum to each service. The regulations also stipulate the procedures to be followed by all member nations in notifying each other of their intent to establish new radio services. The ITU has no police powers and achieves its mission by gaining accommodation among users.

The relationship between an SPS and the frequency bands allocated to various radio services is illustrated in Figure 4.4. Since an SPS would convey no signs, signals, writing, images, sounds, or intelligence of any nature, it does not fall within the ITU definition of "telecommunications." Consequently, it may be appropriate to consider it (in ITU terminology) as an industrial, scientific, and medical (ISM) device. Such devices are recognized by the ITU, and a number of specific frequency bands have been designated for them. One

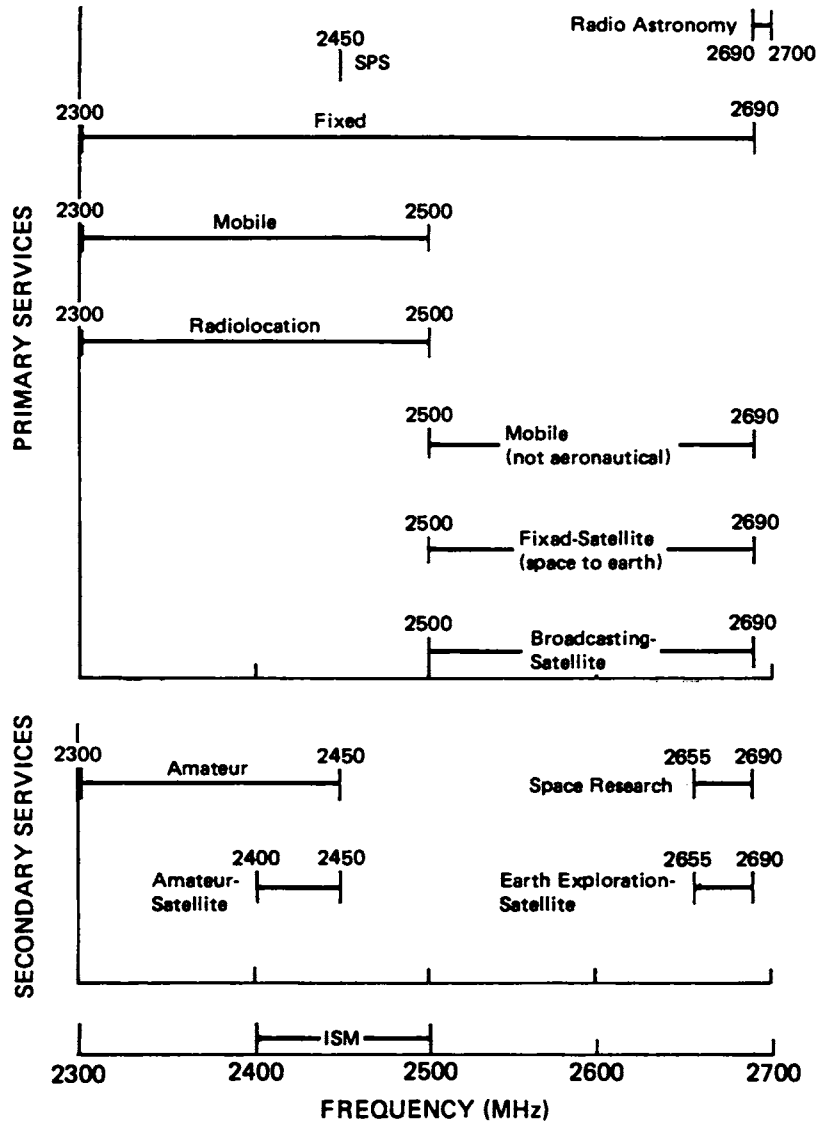


FIGURE 4.4. The reference SPS transmitting frequency and nearby International Telecommunication Union radio services pertaining to Region 2 (Western Hemisphere). (See Appendix Tables I.1 and I.2 for definitions of the various services.)

of these bands is the frequency range 2400 MHz to 2500 MHz, in which the reference SPS is postulated to operate. Within these bands, other radio services must accept harmful interference from ISM devices. In the words of the Radio Regulations,

Administrations shall take all practical and necessary steps to ensure that radiation from industrial, scientific and medical equipment is minimal and that, outside the bands designated for use by this equipment, radiation from such equipment is at a level that does not cause harmful interference to radiocommunication services and, in particular, to a radionavigation or any other safety service operating in accordance with the provisions of these Regulations. (ITU 1980, paragraph 5002 A)

As a safeguard against interference, the Radio Regulations contain quantitative limitations on power flux density at the earth's surface from space stations of the Fixed-Satellite Service and certain other protected space services, but those limitations are only appropriate for the named services when they operate in bands allocated for coequal sharing by specific space and terrestrial services. An SPS using the 2400 MHz to 2500 MHz ISM band would not, under the current Radio Regulations, be operating in such a coequal, shared allocation. Thus the limitations would not apply to the power flux density of an SPS at 2450 MHz. Only the general prohibition against harmful interference would be applicable, as it is to all users of the spectrum.

It is important to recognize, nevertheless, that the limits on power flux density given for cochannel operation do not mean that space stations (such as the SPS) operating in other bands are permitted to produce spurious emissions in the protected bands up to such densities. The International Radio Consultative Committee (CCIR) of the ITU is studying this issue, and states in a recent report that spurious emissions would have to be 10 decibels (dB) to 20 dB below the cochannel limits. One of CCIR's assumptions, however, is that the satellites in question would have differing characteristics. In the case of SPS, where all the satellites would be of the same type, it seems likely that the power flux density of the spurious emissions from a single SPS satellite might have to be 30 dB to 40 dB below those required for cochannel operation.

Interference Between SPS and Other Satellites

The power level at which a reference SPS satellite at a frequency of 2450 MHz would interfere with a typical communications satellite can be quantitatively estimated, given appropriate assumptions. This estimate must take into account the 6.7 GW radiated from the SPS satellite antenna, an estimate of the SPS antenna gain in the direction of the communications satellite, an estimate of the effective aperture of the communications satellite antenna at 2450 MHz, and the inverse square law.

This power level from a reference system satellite is much greater than the in-band noise level for the typical communications satellite, even at an orbital separation of 10° . The SPS signal is, however, out-of-band interference for the communications satellite receiver, and therefore is potentially less of a problem than the in-band noise level. In certain circumstances, however, nonlinear frequency-mixing processes may transform a strong out-of-band signal into in-band interference of sufficient intensity to degrade the satellite's communication capability.

At a longitudinal separation of 1° the power level from an SPS satellite could well equal the intentional saturation flux density level of the transponder on a typical communications satellite. Thus, until detailed interference mechanisms are known, SPS power levels of the same order as the intentional saturation flux density must be regarded as potentially harmful.

Regardless of the uncertainties as to detailed mechanisms mentioned above, the interfering power level of an SPS satellite is bound to decrease inversely as the square of the separation between an SPS and a communications satellite. This is a relatively slow variation expressed in decibels. Thus, greater separation between the two satellites along the orbital arc may not be sufficient by itself to reduce the electromagnetic interference caused by an SPS satellite to acceptable levels.

An SPS satellite could also interfere with a communications satellite through indirect coupling. In this case the coupling would occur as a result of penetration by the SPS power radiation into the internal circuitry of the communications satellite--that is, by bypassing the antenna of the communications satellite.

The potential for this type of interference can be estimated by assuming that the commonly-used level of 1 V/m for the immunity of well-designed electrical equipment to interference is applicable to this case. For a field strength of 1 V/m or less, the separation between the two satellites might have to be 2° or more, depending upon the design of the SPS. If the angular spacing were reduced to 0.1° , the communications satellite might have to be designed to operate in field strengths up to 20 V/m.

In view of the above, the Committee concludes that:

- The electromagnetic compatibility of SPS power satellites and communications satellites is a significant problem. International cooperation would be necessary to resolve the problem, since satellites from many nations use the geosynchronous orbit.

Amount of Geosynchronous Orbit Required Exclusively for SPS Use

Studies conducted by NASA have concluded that each satellite in the reference SPS would have a 24-hour elliptical motion of $\pm 0.11^\circ$ about a stationary position in the geosynchronous orbit. Given the size of the SPS satellites, however, it would be prudent to create a guard

space for them in the event of random drift or unforeseen control problems. Thus, if it were decided, for example, that the distance between the nominal position of an SPS satellite and any other type of satellite should be no less than 0.3° , the net effect would be to reduce the total arc of 70° currently available for non-SPS satellites to an available arc of 34° , assuming 60 SPS satellites in orbit.

Any attempt to use closer spacing would increase the possibility of collisions between satellites, particularly between SPS and smaller satellites. It might therefore be necessary to equip all types of satellites with additional propellant in order to enable them to maneuver in order to avoid collisions.

The Committee thus concludes that:

- The main question to be resolved with respect to sharing the geosynchronous orbit is the unknown length of the orbital arc around the nominal orbital position of an SPS power satellite that would be rendered unsuitable for use by other satellites, either because of the risks of collision, or of excessive radiofrequency interference from the SPS.

Lesser Priority Problems

Several problems of perhaps lesser priority will also affect the electromagnetic compatibility of SPS with itself and with other satellites. These are (a) the generation of spurious electromagnetic radiations by its power generation, rectification, and associated subsystems; (b) the creation of additional propagation paths on satellite-relayed communications circuits through scatter or reflection; (c) excessive illumination of satellites in lower orbits that may traverse the SPS power beam, and (d) the compatibility of SPS with its own power beam command and control systems (discussed in Chapter 2). In addition, the huge size of each SPS satellite means that the possibility of satellite collisions must be taken seriously, even though it has been appropriate hitherto for ITU to ignore the possibility of such collisions.

Additional Work Needed

It has not been possible to reach quantitative conclusions concerning the magnitude of the electromagnetic compatibility problems SPS would produce, or the costs of finding and implementing strategies to avoid them. Such conclusions will require a detailed assessment of electromagnetic compatibility based on knowledge of the scattered and radiated fields produced by the SPS and the sensitivity of all systems that might be interfered with. For example, an SPS design change to a much higher microwave frequency would profoundly alter the considerations of electromagnetic compatibility. The following four points identify the types of information that would be required if the combined effect of other studies indicates that further detailed analysis of an SPS is warranted.

1. The electromagnetic fields resulting from the operation of an SPS satellite would have to be determined as a function of frequency, distance, and direction.

- Frequency -- at the SPS power beam frequency, in adjacent bands where noise sidebands of the microwave power frequency will exist, at harmonics of these frequencies, and at any additional frequencies produced by nonlinear mixing of SPS and non-SPS signals. Also included must be any incident fields scattered by SPS.
- Distance -- in the near, transitional, and far fields.
- Direction -- in all directions, including angles near 90° to the main beam, and in the rear hemisphere.

Progress toward this goal, as required, should be made in a series of successively more detailed approximations as the configuration of an eventual SPS is more fully defined.

2. The field distributions and electromagnetic compatibility of the total system of power satellites (60 in the reference system) would have to be identified.

3. The susceptibility of all relevant classes of terrestrial electronic devices to SPS radiation fields would have to be determined quantitatively. In many cases carefully documented tests would be required involving pickup of SPS radiation via the antenna (if any) of the affected system, as well as coupling of SPS radiation into the device by other routes.

4. In cases where the use of mitigation measures is proposed to avoid adverse effects, the total costs involved would have to be carefully determined. These will include component, installation, additional servicing, and lost revenue costs.

OPTICAL AND RADIO ASTRONOMY

Optical Astronomy

There are two principal ways in which sunlight falling on an SPS satellite could modify or confuse astronomical observations and measurements on the earth. The first is by diffuse scattering of light incident on the satellite. The second is by specular reflection from the flat mirrorlike surfaces of the solar blanket or the microwave antenna structure (Figure 1.2).

The diffuse scattering would consist of a small amount of scattering from the solar cells themselves and specular reflection from individual facets of the solar blanket structure, the magnitude of which can only be estimated. Ekstron and Stokes (1980) estimate that the albedo (reflectivity) of a reference system power satellite would be 4 percent, compared with about 7 percent for the moon. The 4 percent figure is low, probably the lower limit. A satellite's reflectivity would be apt to increase over time as the satellite

surface became contaminated with local waste products and as the solar cells deteriorated.

Specular reflection from either the solar blanket or the satellite's transmitting antenna would produce a spot of light that would be visible on earth. The spot of light reflected from a satellite's solar blanket would be some 330 km in diameter. If the solar blanket were kept facing the sun exactly, the spot would be visible on earth only at local sunset and sunrise for a brief period. Since it would not be necessary to maintain the alignment of the solar blanket with the sun with more precision than was required for the efficient collection of energy, however, the reflected spot could fall within a much larger portion of the earth's night side.

The transmitting microwave antenna would face its companion rectenna with precision at all times, and the path of the spot of light that would be reflected from the antenna to the earth can be predicted accurately. It has been calculated that a location on earth would be illuminated for perhaps two successive nights in the spring and two in the summer for periods of up to 2 minutes (Ekston and Stokes 1980). Calculations have been made indicating that the specular brightness of the solar blanket of a single reference SPS satellite would be 10 times that of the full moon, while that of the antenna would be about 4 times that of the moon (Ekston and Stokes 1980).

For optical astronomers, the continuous, diffuse scattering of light by the satellites is of greater concern than the flashes of light from specular reflection. Scattered light from an SPS satellite would enter a telescope on earth whenever the telescope was pointed in the general direction of the satellite, or even to some degree when it was pointed away from the satellite. In other words, there would be a diffuse sky brightness, which would be greatest near the satellite and which would decrease with increasing angular distance from the satellite.

To the degree that the well-understood model of enhancement of sky brightness near a star can be applied, the effect produced by a single satellite can be estimated. The effect of each additional satellite is then superimposed to produce an estimated overall effect for the 60 satellites in the reference system. The result is a band of visible light centered on the string of satellites and extending outward on either side and from each end. Close to the band--say, within a third of a degree on either side--the sky would be perhaps 10 times as bright as the dark night sky. Serious effects would be apt to extend 15° or 20° on either side, and detectable effects as far as 30° on either side, of the band. Consequently, optical astronomy observations in a region of the sky from 30° to 60° wide in declination and from 70° to 90° in right ascension would be interfered with to a greater or lesser extent (Ekston and Stokes 1980).

Astronomical measurements are made with photographic plates and photon detectors. Photographic plates are not able to improve the measured "signal-to-noise ratio" through increased exposure. They must be exposed long enough to record a measurable image, but exposure beyond that time increases both the signal and the background noise.

Photon detectors, on the other hand, can increase discrimination between signal and noise by means of longer counting or integrating times, and the precision of the measurement is limited by statistical considerations. Photon detectors can be used to measure extremely weak signals, but they are highly sensitive to the diffuse background illumination of the sky.

To understand the seriousness of the problem that would be caused by an SPS, one must realize that advances in astronomy usually come through observations made at the extreme limits of signal detectability. An increase in diffuse sky brightness by even a factor of 2 could prevent astronomical measurement of faint objects. For photon detectors, which are being used to an increasing extent, an increase of 10 to 30 percent in diffuse sky brightness produces noticeable effects, an increase of 30 to 100 percent produces demonstrable loss of sensitivity, and an increase of more than 100 percent means a significant loss of otherwise retrievable astronomical information (Ekstron and Stokes 1980). Most optical objects of cosmological interest in astronomy are fainter than 3 percent of night sky brightness.

As an example of the effects on astronomical observations, for the Kitt Peak National Observatory in Arizona, the reference system would produce a significant contamination zone from $+4^\circ$ to -16° in declination for photon detectors; for photographic-plate detection there would be significant contamination from perhaps $+14^\circ$ to -28° (Gallagher and Faber 1980). The Orion nebula, one of the most important areas of the sky for studies of stellar formation, would be permanently lost to Kitt Peak for faint-source observation, even using photon detectors. This area of the sky, however, and almost all other areas would not be totally lost for studies of faint objects, since observatories at other latitudes in other countries would be able to observe objects lost to Kitt Peak; other observatories would be denied other areas of the sky. The area denied to photographic detectors at Kitt Peak would extend close to the galactic pole and would seriously limit faint-object observations of the large-scale structure of the universe.

In summary, the Committee concludes that

- The diffuse night-sky brightness produced by the reference SPS would interfere seriously with optical astronomical measurements from the earth. This interference would be concentrated in an area on either side of the satellite arc and would prevent the measurement of weak astronomical objects in those areas.

Radio and Radar Astronomy

There are also two principal ways in which an SPS using microwave transmission could interfere with the operation of radio telescopes. The first is through radiation that was close in frequency to the bands assigned to radio astronomy; the second is through radiation within the astronomy bands.

Radiation close to the bands would lead to the overloading of sensitive receivers used in radio astronomy, while radiation within the bands would lead to general degradation of the performance of a radio telescope and to the masking of radio signals of astronomical interest. These problems would loom large because the substantial amounts of power transmitted by a satellite power system would lead to hundreds of megawatts of power in unwanted modes and because radio astronomy receivers are extremely sensitive, being able to measure power levels as low as 10^{-21} W.

As with all antennas, energy at the SPS power frequency could be radiated in directions other than the intended ones through many mechanisms. For example, a considerable amount of power would be scattered into the side lobes due to electrical and mechanical tolerances within the antenna (Arndt 1980). Even minimal errors could mean the transmission of hundreds of megawatts of off-axis power, some of it at large angles to the axis. There are also so-called grating lobes, which could cause relatively large "spikes" (fractions of a watt per square meter) of radiated power in particular directions. These spikes would appear on earth at spacings of about 440 km and could occur many hundreds of kilometers from the rectenna. Finally, the rectenna itself would be capable of reradiating signals at significant power levels (tens of megawatts), more or less in all directions.

Harmonics of the power frequency would also be generated by the SPS transmitting system, and these too would be radiated over a broad area. Unless special measures were taken, these harmonics would probably be no more than 30 dB to 60 dB below the power level of the microwave beam. The rectenna also could generate harmonics and radiate them in all directions.

The side lobe pattern in the receiving antennas of radio telescopes is another complicating factor. Just as an antenna transmits attenuated signals in unintended directions, it also receives signals from unintended directions; this characteristic is a function of frequency and geometry and is described by its side lobes. So, even when a radio telescope is pointed away from an SPS satellite, it could receive scattered SPS radiation through its side lobes at the power transmission frequency. Although the received radiation is at the SPS transmitter frequency and a radio telescope would be tuned to operate at another frequency, the effect could be to overload the telescope. As little as 0.003 microwatt (μ W) of unwanted signal would begin to cause serious overloading problems in state-of-the-art radio telescopes.

Among the existing radio astronomy bands are the 2690 MHz to 2700 MHz and the 4990 MHz to 5000 MHz bands. The former is close to the reference SPS power frequency, while the latter is near the second (and strongest) harmonic of the reference system. Receivers operating in both bands would therefore be likely to experience serious problems of overloading due to the SPS. In addition, there would be SPS interference with observation of important molecular radiofrequency spectral lines that lie outside the designated bands, such as those of formaldehyde at 4830 MHz.

Radiation from an SPS at frequencies far from the SPS power frequency but within the radio astronomy bands could arise through many

mechanisms. For example, "blackbody" thermal radiation--that is, continuous radiation over a wide range of frequencies with intensity characteristic of the temperature of the emitting object--from an SPS would be likely (depending on the actual emissivity of the satellite) to exceed the interference levels proposed for radio astronomy by recommendation number 224-4 of the CCIR.

Other potential interference mechanisms include noise generated by the microwave transmitting system; intermodulation in nonlinear devices of scattered radiation with radiation from radio, television, and communications systems; and radiation from rectennas. Except for thermal radiation, it is difficult to estimate the power levels of these various forms of radiation. In view of the large power in the primary SPS beam and the extraordinary sensitivity of radio astronomy receivers, however, these radiation sources would be likely to be troublesome.

It is difficult to make reliable estimates of the degradation in performance of radio telescopes that would be caused by SPS radiation. One can conclude, however, that the reference system would produce an area in the sky--its width might be as much as 30° --where radio astronomy observations with single antennas would be impossible, even with cryogenic filters designed to exclude unwanted radiation. From important U.S. radio observatories, this band includes some of the most interesting radio astronomical objects in the sky, for example, in the Orion nebula.

The reference system would also pose a problem for radar astronomy, in which signals are transmitted from earth and reflected from the object of interest back to earth. The Arecibo Observatory in Puerto Rico, for example, is one of the major radar astronomy observatories; it operates on a principal frequency of 2380 MHz, which is only 70 MHz from the reference SPS power frequency. Overloading of the 2380-MHz receiver caused by SPS radiation would be likely to be severe and would probably reach intolerable proportions if a rectenna were placed in Puerto Rico. Furthermore, most of the objects of interest in the solar system lie close to the plane of the ecliptic. During certain times of the year, at least, the closeness of an object of interest to the satellite arc might prevent any observation at all. However, earth-based radar studies of the planets are likely to decrease in importance as deep-space mission capability grows.

An SPS would also present problems for so-called synthesis arrays, such as the Very Large Array in New Mexico, and for very long baseline interferometer systems. For these systems, however, the width of the precluded zone would be substantially narrower than for single telescopes and, in general, the interference problems would probably be less severe. In fact, use of synthesis arrays and very long baseline interferometer systems has been regarded as a mitigating strategy where such systems can be used.

Certain aspects of an SPS, particularly its continuous operation and its relative inaccessibility for modification once in orbit, would make the interference it produces much more serious for radio astronomers than interference from earth-based transmitters, which is usually relatively limited in both time and space. Thus, the Committee concludes that:

- The overloading of sensitive radio astronomy receivers operating at frequencies close to the SPS power transmission frequency and spurious SPS radiation within radio and radar astronomy frequency bands would confuse and obscure faint-object signals. Efforts to make radio astronomy measurements of faint objects in certain parts of the sky from most earth-based observatories would be seriously hampered.

Some of the problems discussed in this section can probably be mitigated to a considerable degree through various techniques, such as the use of special filters, nulling of the interfering signal, and the siting of telescopes to provide the maximum amount of shielding by the terrain. Shielding from radiation coming directly from an SPS satellite cannot be achieved, however. SPS satellite design and maintenance standards of the highest quality would be vital in minimizing interference. No matter what measures were taken, SPS satellites would preclude certain measurements in certain portions of the sky.

Implications

An SPS in this hemisphere would cause interference in varying degrees with astronomical observations and measurements throughout the North and South American continents. An international SPS with satellites in orbit over Africa and Asia as well would mean worldwide interference with astronomy.

How seriously should we take these potential problems? That is a question which we find impossible to answer now. Optical and radio astronomy have been rich sources of information about our cosmic surroundings. Any development which significantly limited our ability to observe, to measure, and to understand our universe would diminish the spirit of human inquiry and should be guarded against. On the other hand, the world has a serious energy problem. If a satellite power system were critically needed as a source of energy, astronomy might necessarily have to suffer some setbacks to its progress. As both astronomy and the SPS concept evolve, assessments and adaptations should be considered, including investments in advanced astronomical observation techniques, instruments, and stations (e.g., in space) that might compensate to some degree for observational losses caused by an SPS.

CHAPTER 5
SOCIOPOLITICAL FACTORS

INTERNATIONAL LEGAL, POLITICAL, AND MILITARY QUESTIONS

Serious international issues would be raised if the United States decided to build a satellite power system (SPS). These would include the allocation of positions in the geosynchronous earth orbit (GEO) and the allocation of radiofrequencies. In addition, an SPS has global economic and strategic implications that also must be taken into consideration.

The Orbit

Use of the limited amount of space in the geosynchronous orbit is an international issue that has not yet been resolved. In 1976, seven equatorial countries--Brazil, Colombia, Ecuador, Indonesia, Kenya, Uganda, and Zaire--issued the Bogota Declaration, in which they claimed that the segments of GEO directly above their national boundaries were an integral part of their territory and that they therefore had complete and exclusive sovereignty over those parts of the orbit. Consequently, the Bogota Declaration said, any other nation that wished to place satellites in GEO above the territory of any of the signers of the declaration would have to obtain express permission to do so. This claim of sovereignty, however, was subsequently rejected by the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS). In 1977, a COPUOS working paper expressed the view that geosynchronous orbits are included in the term "outer space" as that term is defined in the 1967 United Nations Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies. Article I of this treaty states:

The exploration and use of outer space, including the moon and other celestial bodies, 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.

At the present time, designation of parts of the geosynchronous orbit for the use of specific satellites is a task performed on an informal basis by the International Telecommunication Union (ITU). The ITU, however, does little more than collect and publish the uses of specific positions in GEO by satellites already placed there. Technically the designation of slots in GEO does not fall within the jurisdiction of the ITU, and it is possible that in the future the allocation of orbital positions may be decided by some other agency of the UN.

In any event, a serious international issue might then have to be resolved if the United States wanted to place SPS satellites in orbit for periods of as long as 30 years. The issue would be whether such long-term occupancy met the definition of "use" under the 1967 treaty, or whether it constituted an "appropriation" of geosynchronous space. Any appropriation of space would be a violation of the treaty.

Under the international legal principle of res communis, which applies to such unlimited or renewable "resources" as the high seas, all countries have unrestricted access to the resource. In other words, no country can legally claim to exercise national sovereignty over a portion of the high seas.

But for resources that are limited or depletable--for example, minerals in the deep-sea bed--the international legal principle of the "common heritage of mankind" applies. Under this principle, use of the resource is subject to international regulation for the purpose of ensuring equitable distribution of the resource among different nations and also of ensuring that the resource will be preserved to the greatest possible extent for the benefit of potential future users. Although the legal subcommittee of COPUOS has recognized that the rule of equitable distribution in the "common heritage" principle applies to the geosynchronous orbit, it is not clear at this time whether the res communis or the "common heritage" principle would ultimately prevail for SPS satellites.

Potential international legal issues would arise from the fact that a U.S. SPS would have a serious practical impact on use of GEO at longitudes coincident with North and South America by other types of satellites--i.e., the 70 degrees of arc between 65° and 135° W longitude. Fifty-six satellites will be using this portion of the orbit within the next few years (Table I.4), and in subsequent years the other nations that share this longitudinal band with the United States--for example, Canada, Mexico, and Peru--are expected to want to make increased use of it. Furthermore, recent steps taken by the Federal Communications Commission (FCC) are expected to mean that the geosynchronous orbit at longitudes coincident with the continental United States will be populated to an increasing degree by domestic telecommunications satellites, eventually including direct television broadcast.

It is difficult to predict the actual number of satellites (excluding SPS satellites) that will be in GEO between 65° and 135° W longitude by the year 2000. A straightforward projection of past growth in the number of satellites yields an estimate of as many as 2000 in the relevant arc by the year 2000 (Appendix I). Such a figure

may be unrealistically high in view of need, cost constraints, and improved technological performance in future satellites. A more conservative estimate, given in Chapter 4, is on the order of 300.

Whether the actual number approximates either of these estimates, there is little doubt that the addition of a large number of very large SPS satellites would lead to crowding in GEO. Although a conclusive determination of the necessary distance between an SPS satellite and other types of satellites has yet to be made (see the section, "Effects on Electromagnetic and Electronic Systems," in Chapter 4), estimates of the minimum necessary distance--a substantial fraction of a degree--would severely constrain the room for the many satellites of other types that will be occupying the orbit at the same time. Future improvements in technology may make it possible to reduce the necessary distance between SPS satellites and other types of satellites and to aggregate communications satellites into large antenna complexes, but that possibility is not yet firm enough to be relied upon.

This discussion of orbit congestion was limited, for specificity, to consideration of the orbit over U.S. longitudes. It will be sufficient to note qualitative rather than quantitative changes in the discussion if a global rather than national SPS is contemplated. The number of satellites elsewhere in orbit can also be expected to increase. Orbit positions over land masses rather than over oceans will be most useful for both SPS and most other satellites. Thus GEO slot scarcity can be expected to develop around the world, although perhaps not quite as severely as at the longitudes of its highly developed regions.

The placing of SPS satellites in orbit might also raise international issues because of their interference with optical astronomy and radio astronomy equipment (see the section, "Optical and Radio Astronomy," in Chapter 4). Any astronomical investigations at SPS longitudes conducted by other nations would be affected no less than those of the United States. How these international problems would be resolved, should they occur, cannot be predicted at this time. A process of continual assessment and adaptation of future system designs by both the astronomy and the SPS communities would be a natural approach.

The demands placed by an SPS on scarce geosynchronous orbital space, together with the attention being given to clarifying the status of an SPS in international law, lead us to the following conclusions:

- The requirements of the reference SPS for use of segments of the geosynchronous orbit are greater than can be accommodated under even a conservative projection of the requirements of other types of satellites using the orbit. Furthermore, the interests of other countries in the geosynchronous orbit as a whole are strong. Accordingly, the United States or even a group of countries seeking to establish an SPS would have to consult with other states and international bodies to obtain agreements accommodating the proposed use of the orbit.

The Spectrum

An SPS would also raise international problems because of its potential interference with use of the electromagnetic spectrum by other countries (see the section, "Sharing the Electromagnetic Spectrum," in Chapter 4). Legally, an SPS would have to operate within the terms of the International Telecommunication Convention (ITC). An Annex to the 1973 ITC defines telecommunications as "any transmission, emission or reception of signs, signals, writing, images and sounds of intelligence of any nature by wire, radio, optical or other electromagnetic systems." While it seems at this time that the use of microwaves to transmit power would not constitute "telecommunications" and therefore would not fall under ITU jurisdiction, it is clear that the necessary communications between SPS satellites and SPS ground controls (for example, the pilot beam) would be within ITU jurisdiction, and that frequencies for such communications would have to be in accord with ITU and national allocations.

The International Frequency Registration Board (IFRB), formed by the ITU, registers individual users of radiofrequencies and seeks to minimize interference between them. Registration is based upon prior use and international law. In requesting registration of a frequency assigned to a satellite in GEO, an applicant must notify the IFRB of the power flux density likely to result from the satellite's transmissions. Like the ITU, however, the IFRB has no enforcement authority and can only register users of GEO.

Annexed to the ITC are Radio Regulations that establish the types of services for which the radio spectrum may be used and allocate portions of the spectrum to each type of use. The current regulations do not contain any category that would clearly include the microwave power transmission of an SPS. The frequency band of 2400 megahertz (MHz) to 2500 MHz, within which the reference SPS would operate is set aside for industrial, scientific, and medical (ISM) applications. While it might be argued that SPS power transmission would be covered under the ISM category, it is very possible that the Radio Regulations would have to be amended to embrace an SPS, because the current version urges that radiation from ISM equipment should be minimal.

A number of actions taken at the 1979 World Administrative Radio Conference (WARC), which dealt with international issues concerning use of the electromagnetic spectrum, would also affect an SPS. Resolution 3 (BP) calls for the convening of another WARC not later than 1984, in order to guarantee in practice that all countries have equitable access to the geosynchronous orbit and to the frequency bands allocated to space uses. Resolution 2 (AY) states in part that all countries have equal rights in the use of both the radiofrequencies allocated to various space services and the geosynchronous orbit. Resolution 4 (BY) suggests that frequency assignments for space communications be limited to the design lifetime of the satellite network, as a concept which could promote the rational and efficient use by all countries, with equal rights, of the spectrum/orbit resource.

The WARC's Recommendation 3 (XO) recommends that the International Radio Consultative Committee (CCIR) study all aspects of SPS radio

transmission on other radiocommunications services. This recommendation was forwarded to the UN Secretary-General, who has referred the matter to the UN Outer Space Committee. In addition, Resolution 63 (AG) urges the CCIR to continue its study of the effects of electromagnetic waves from ISM equipment on the entire spectrum of radiofrequencies and to make recommendations to ensure the protection of radiocommunications services. This would affect an SPS if it was classified as an ISM application.

Finally, Recommendation 66 (L) urges the CCIR to study spurious emissions from the transmission of signals from space and to develop recommendations for maximum permissible levels of spurious emissions. Work on this topic is already under way, and CCIR's recent Report 713 concluded that spurious emissions would have to be subject to rigorous limits, as explained more fully in Chapter 4. In light of the above, the spectrum/orbit aspects of an SPS would surely trigger complex and multi-faceted international considerations. Much evidence already exists indicating that an SPS would constrain other users of the radio spectrum (see Chapter 4). It remains problematical whether the reference SPS could comply with current and future international noninterference regulations.

Since the international institutions involved in arbitrating among users of the electromagnetic spectrum have no enforcement powers, the United States could, in principle, choose to build an SPS regardless of whether or not the system threatened to interfere with use of the spectrum by other countries. This would be a self-defeating and unacceptable course of action, however, in light of the very strong interest of the United States in the continued vitality of the ITU. Any decision on the part of the United States to abandon the ITU would have dire consequences for global telecommunications.

To sum up, the impact of an SPS on worldwide users of the electromagnetic spectrum is bound to be extensive although its fine detail cannot yet be ascertained. The nature and scale of the SPS concept strains the only international machinery available for addressing SPS spectrum issues. Given these circumstances, the Committee concludes that:

- On the basis of present technology, U.S. deployment of the reference SPS would be incompatible with our international obligations to avoid interference with recognized telecommunications uses of the electromagnetic spectrum. To accommodate the unusual use of the spectrum contemplated by SPS would require design improvements in SPS itself, design improvements in telecommunications systems, and some revision of the international arrangements for spectrum management in order to make room for an SPS.

Global Energy Demand

Although the reference system postulates that the United States would be the builder and beneficiary of an SPS, a different scenario

may unfold in the future. Some projections indicate that the demand for additional sources of energy in the United States may not grow significantly over the next 50 years (see Chapter 3, section on "Future Demand for and Supply of Electricity"). There would then be no need to make the large investment that would be required to build the reference SPS. Furthermore, it is likely that the demand for additional energy in other parts of the world, particularly in the developing countries, will increase over the next 50 years.

Thus, it is conceivable that in the future the United States might find itself promoting preservation of the geosynchronous orbit and the electromagnetic spectrum for telecommunications use while other countries that possessed access to the technological capability sought to use the orbit and the spectrum for an SPS. All of this is highly conjectural, of course, and reliable predictions cannot be made without a much more detailed study of future global energy demand. The subject is raised here only to illustrate the need for much additional study before either a national or international requirement for an SPS can be established.

Military Implications

Another international question raised by the SPS involves the potential military implications of such a development. Would an SPS be considered an attractive, vulnerable target? Would it be feared as a potential power source and site for new weapons?

Like other types of satellite systems, an SPS could become vulnerable to attack or to being held hostage by a technically advanced, hostile nation. Indeed, there is a difference between attack on installations in the physical territory of another country versus an attack on installations in space. The USSR has been developing an antisatellite weapon that is presently operational at relatively low earth orbits--about 1000 kilometers. Such a weapon will become technologically possible at geosynchronous orbit by the time an SPS could be developed. Terrorist action in space, however, is unlikely since major antisatellite technology and facilities would be needed to launch an attack.

Hardening of commercial satellites for defense against attack does not seem a useful approach. As in the case of merchant ships, the hardening costs would be disproportionate. The principal protection of an SPS would be the deterrent effect of potential retaliation. There would be no symmetry of retaliation, though, unless the attacking power also possessed an SPS or other space investments. Without this, deterrence outside the attacking nation's boundaries would have to depend on the attacking nation's merchant marine or other such assets being considered vulnerable and available for retaliation. Questions of the attractiveness of an SPS as a target for attack would diminish to the extent that an SPS had international sanction and was a multilateral enterprise.

Large bases for operations in space are planned for low earth orbit by several nations during the next three or four decades. Such bases

would be vulnerable to low-altitude antisatellite weapons. While SPS ground manufacturing, launch, and rectenna sites would be vulnerable to military or terrorist attack, the entire system would be so extensive and dispersed that the damage from such attacks would likely be no more than that in the case of attacks on conventional terrestrial generating systems.

The fact that an SPS could conceivably be adapted as a potential source of power and a site for military and weapons uses might lead to fears or charges that an SPS could constitute a military threat, and to allegations by unfriendly countries that this was in fact planned by the United States. Laser or ion beams powered by an SPS might be developed for antisatellite weapons, for antiearth-target weapons, or for antimissile weapons. This last would be in violation of the Antiballistic Missile Treaty of 1972, in which the parties agreed not to deploy antiballistic missile systems in space. The 1967 Outer Space treaty's prohibition on weapons of mass destruction would probably not preclude the use of lasers or conventional weaponry in space. Specific military systems would be more likely, however, than overt or covert adaptations of a commercial SPS.

The fear that an SPS would be used for military purposes would decrease significantly if other nations were mutual stakeholders in an SPS venture, after the requisite international approval for use of GEO slots and a segment of the electromagnetic spectrum were secured.

The Committee concludes that:

- The military implications of an SPS need not constitute a significant obstacle to its development. A multilateral approach involving other participating nations would be effective in reducing SPS vulnerability to attack, and in allaying fears of potential conversion to weapons uses, or allegations of such conversion by unfriendly nations.

The Multilateral Approach

Any decision to develop an SPS would raise such questions as who would pay for it and own it, who would control its operations, who would receive its benefits, and who would be liable for any harm that might be caused by it. As seen, a number of problems in international relations would probably arise if the United States decided to build and operate an SPS primarily for its own benefit. However, many of these problems might be avoided by taking a multilateral approach. For example, a multilateral approach would give all countries some reason to find ways to use the geosynchronous orbit for the production of energy as well as for telecommunications.

A multilateral approach might be particularly attractive because of the potential liability problems that might arise from an SPS. The 1972 Convention on International Liability for Damage Caused by Space Objects holds that any country that launches a satellite or other object into GEO is liable for any harm sustained on earth as a result, and no monetary limit is placed on potential claims. Harmful microwave radiation from an SPS would fall within the purview of the treaty.

In addition, the Outer Space treaty of 1967 contains a provision requiring all of the signers of the treaty to avoid "adverse changes in the earth's environment." Since this phrase is not defined in the document, it is not clear whether a phenomenon such as microwave exposures resulting from SPS operations would come under that provision. This particular problem is complicated by the fact that the Soviet Union supports much more stringent standards for acceptable microwave exposure than the United States (Table 4.2).

Even assuming that a multilateral approach was adopted, a private international enterprise (e.g., one similar to the International Telecommunications Satellite Organization--INTELSAT) would still face formidable financial and administrative obstacles. Construction of an SPS would be a far more complex and more expensive venture than deep-sea mining under the proposed Law of the Sea Treaty, and it may prove particularly difficult to establish a sound institutional framework and management in order to raise the necessary capital and to achieve equitable participation by the intended beneficiaries (see Chapter 3, section on "Financing an SPS"). There is also the problem of long-deferred and, possibly, speculative returns on investment.

Although a multilateral approach would face considerable institutional hurdles, taking into consideration the benefits of international cooperation in terms of orbit use, spectrum allocation, future global energy needs, and potential military significance, leads the Committee to the conclusion that:

- A multilateral approach involving the participation of other countries is probably the only viable one if an SPS is ever to be established. The questions of who would manage, finance, own, control, operate, maintain, receive the benefits of, and assume liability for an SPS would have to be decided prior to the commitment of significant resources.

SOCIAL ACCEPTABILITY IN THE UNITED STATES

It is difficult to predict with any degree of certainty public reaction to a future solar power satellite system. The reference system, for example, is postulated for construction during a period 20 years to 50 years from now. Before then there may be significant changes in the growth of demand for electricity and new constraints on the supply. Public opinion about technological innovations that promise to increase the supply of energy will evolve over time as the effects of changing demand and constraints on traditional sources of supply become clearer. The direction in which public opinion evolves will depend to a great extent on external events that may or may not occur--the foreclosure of nuclear power for example, a breakthrough that makes fusion a valid way of producing energy, development of cost-competitive solar cells and energy storage systems, or a demonstration that the continued accumulation of carbon dioxide in the atmosphere will have disastrous effects. Dramatic changes with regard to any of the traditional sources or applications of energy will have a

correspondingly strong effect on public perception of the attractiveness of an SPS.

There are, however, several points that can be safely made regarding probable public concerns about an SPS. Most of these matters are dealt with at greater length elsewhere in the report, but here we focus attention on their relation to public opinion. The issues of the greatest relevance appear now to be concerns about the effects of an SPS on health, land use for rectennas, regional and international relations, and attitudes toward large-scale, capital-intensive "high technology."

Concerns about Public Health

Scientific opinion about the possible health hazards associated with the deployment of SPS satellites and the beaming of microwave radiation to earth stations will strongly influence public opinion. As microwave ovens have become more commonly used in the home, the public has become more familiar with microwave radiation and the attendant questions about the safety of long-term exposures to low levels of radiation. Nonetheless, public knowledge about the difference between ionizing and nonionizing radiation appears to be low. The term "radiation" is usually associated in the public's mind with x-rays, atomic bombs, and nuclear power, and the different question of exposure to microwave radiation is not likely to be readily understood without an extensive educational campaign.

Although there is no scientific documentation to show that long-term, low-level (0.001 watt per square meter (W/m^2) to $1 W/m^2$) exposure to microwave radiation has harmful effects on human beings, without good theory and knowledge of mechanisms of molecular biology we cannot now rule out all possibilities of harm (see Chapter 4). Scientific opinion is divided about the guidelines for exposure that should be adopted nationally. We are thus left in the uncomfortable position of considering a huge investment in a large-scale enterprise without any certainty about its possible long-term health risks. In such circumstances, it is to be expected that reasonable people will disagree about the extent of the risk they are willing to accept.

Our inability to determine the long-term health risks of an SPS is not unique. Many other technological advances may also pose long-term risks to human health, and in recent years the public has become more aware of these risks. Since the reduction of risk is often associated with an increase in scarcity and costs, the public is also becoming aware that at some point questions about the need to reduce these risks, given the cost of doing so, will have to be answered. Since people differ in their understanding of and willingness to take risks, and since the people who would enjoy the reduced risks will not always be those who would have to pay to reduce them, we can expect the debate over relative risks and costs of taking or not taking them to be sharp and prolonged. While science can contribute to the debate by providing sound theories and data on the relative levels of risk associated with different technologies, it will not by itself be able to settle the

debate unless it can show that the risks are below the minimum acceptable level or that protection can be achieved at an acceptable cost. There will not be many such cases.

Rectenna Siting

The rectenna sites envisioned in the reference system are large (approximately 10 km x 13 km), but even 60 of them would occupy only a minute portion of the total land surface of the United States. From a local point of view, however, the sites are apt to be considered unacceptably large, especially if they are near concentrated populations where the demand for electricity is highest. The history of past efforts to find sites for analogous installations--large radar stations and Project Sanguine/Seafarer with its 25,600-square-mile underground radio antenna--suggests that strenuous local opposition to such projects can effectively stop them. If, on the other hand, rectennas were placed at a distance from the areas where the electricity was used, citizens in the distant areas may argue that they are bearing the esthetic, ecological, or economic costs while others are obtaining the benefits. If the sites were located in the wilderness or in areas with a fragile ecology--coastal marshes, for example--opposition from conservationist groups would be strong. In short, even if there were strong general support for an SPS, strong local opposition to particular rectenna sites would be likely. A good thing might be deemed good only if it were somewhere else.

Regional and International Problems

We have already mentioned that the costs and benefits of an SPS may be distributed unequally. This is also true of generation by coal, oil, nuclear, hydroelectric, and natural gas facilities. A major portion of the output of each of these facilities is consumed in places remote from the point of origin of the resource. When energy supplies were plentiful there was no serious divergence between regional and national interests. Lately, however, regional needs and preferences have come into conflict and tensions have been developing between different regions of the country. Many of the western states, for example, possess large deposits of coal but do not need the coal themselves. They may not be willing to allow the extensive strip mining necessary to extract the coal, or they may raise the price of their coal so high that it may not be competitive. If regional rivalries over energy supplies continue to grow, an SPS might possibly become attractive as a national program that circumvents regional rivalries, assuming that local siting of rectennas did not become an insuperable problem.

Serious consideration of an SPS would also mean paying attention to public opinion regarding the relationship of the United States to other nations. If it were possible to develop an SPS only in a context of international control and use, for example, would the American public

be willing to finance the developmental costs? Or would there be sufficient political support for an SPS if its primary benefits were intended for other countries? These are the international aspects of the general problem stated above, namely, those who bear the costs of an SPS may not be the people who enjoy its benefits, at least in a direct sense.

General Attitudes Toward Technology

Public debate about energy problems has given rise to a more general debate about "appropriate technology" and about "hard" and "soft" paths toward solutions to the energy problem. To some extent this is an ideological debate that challenges the belief that modern science and large-scale technology have or will continue to improve the lot of humanity. While recent evidence on public attitudes in the United States (Miller et al. 1980) indicates that the belief in the benefits of science and technology is still very strong and that future benefits are expected, the public is also becoming more aware of potentially negative consequences of scientific development, particularly with respect to nuclear power, food additives, new pharmaceuticals, and chemical wastes. For that reason, we can expect general attitudes toward new technology and the implications for other aspects of society to become a more important part of the energy debate.

It is difficult to say more at this point except to note that value judgments on such issues as economic growth, social equity, and centralized versus decentralized energy systems will play a role in the debate over the desirability of developing an SPS. Even if there were no technological problems, the development of such a system would require a commitment to massive government financing over a long period of time before a substantial payoff made its appearance. It is a large investment in a centralized power system. The issues discussed in this chapter will be important in determining the public's response to the concept of an SPS, and acceptance of the desirability of such a system will have to precede the appropriation of funds for the necessary development.

In summary, we can conclude only that:

- There is little evidence that questions about the desirability of an SPS are matters of wide public concern now, but it is impossible to predict whether or not they will become so in the future. The evolution of public opinion about acceptable forms of electrical energy production in the future will depend on developments in alternative sources of energy. Negative public reaction, however, could make an SPS politically impractical.

CHAPTER 6
COMPARISON WITH OTHER LONG-TERM TECHNOLOGIES

The technical, economic, environmental, and sociopolitical aspects of a satellite power system (SPS) are described at some length in the preceding chapters. At this point the question arises as to how promising an SPS would be in relation to other technologies for the generation of electrical energy that may become available in the long run--that is, beyond the next four decades. An answer to that question, however imperfect, is needed to provide some basis for choosing a future strategy for research and development on alternative sources of electricity, including an SPS.

APPROACH TO THE COMPARISON

The Period of Comparison

For the reasons that follow, we concluded that SPS is most appropriately compared with other advanced technologies for long-run electrical generation that might be employed after the next four decades. Enormous amounts of time, labor, and capital have been invested in the present system of producing electricity, and its costs--in economic, environmental, and social terms--are reasonably well understood. Because those costs are reasonably well understood, it has been possible to make reasonably accurate predictions of what proportion of electricity will be produced by what methods in the near-term future, and how much that electricity is likely to cost. It is on that basis that this report concludes in Chapter 3 that the United States will not need to introduce an SPS as a source of electric power over the next 40 years or so.

Most of the electricity now used in the United States is produced by processes burning one of three major fossil fuels (coal, oil, and natural gas), by hydroelectric facilities, and by nuclear power plants fueled by uranium. The mix of sources arose from the fact that each of these five methods offered certain advantages--in terms of cost, availability of primary resources, public acceptability, or environmental protection--depending on the circumstances of when, where, and how a particular type of generating plant was built and operated.

The scope of the national system of electric generation, transmission, and distribution necessarily means that it cannot be transformed quickly. Institutional and social inertia, together with the time for physical construction and the problem of raising large amounts of new capital, prevent that, even in the face of sudden change, such as a rapid increase in the price of foreign oil. Thus, any new methods that prove to be acceptable will necessarily be introduced slowly in response to changing circumstances in science and technology, cost of materials, fluctuations in electric demand, and so on. This process may well go on for several decades before a markedly different equilibrium of supply develops.

Nonetheless, it is evident that the economic, social, and political forces that have kept the various methods of producing electricity relatively competitive in the past are undergoing far-reaching changes. There is no doubt that the system is now in a process of transition toward an era when this country, as well as the rest of the world, will come to rely much more heavily on more permanent sources of energy for the production of electricity. Domestic supplies of oil and of natural gas have been steadily depleted over the last 100 years, and it is apparent that the availability of these resources will continue to diminish despite increased exploration and drilling. Meanwhile, U.S. dependence on oil and natural gas from politically unstable regions overseas has become increasingly risky. As a result, there will be both economic and social pressures to replace oil- and gas-burning plants with conventional coal-fired generating plants, light water nuclear reactors (LWR), and hydroelectric facilities.

Yet coal, light water reactors, and hydroelectricity all have drawbacks, especially as sources of electricity for the long-run. Although coal is still an abundant fuel in the United States, any large-scale increase in its extraction, transportation, and combustion is bound to raise serious, social and environmental problems, the solution of which will tend to make coal more expensive. The construction and operation of larger numbers of light water reactors would mean the eventual depletion of domestic supplies of uranium. It appears as if there remain no additional sites in the United States where large-scale hydroelectric facilities can be built; future expanded use may be limited to small dams or to artificially built (pumped storage) facilities. These problems with conventional energy sources will become more sharply defined over the next few decades.

Because of problems of the kinds mentioned above, the Federal Government, utility companies, industrial firms, and the technical community are now investigating alternative methods of producing electricity for the future. The best known of these methods are the nuclear breeder reactor (a reactor that produces more fissile material than it uses) and solar energy transformed into electricity at terrestrial facilities. In addition to an SPS other prospects are being pursued as well: advanced methods for extracting energy from coal more efficiently, advanced reactor designs that would make more efficient use of uranium, thermonuclear fusion, wind power, and geothermal energy. Considerable effort is being directed at developing these technologies; others, such as photosynthetic production of fuels, are just beginning to be explored in the laboratory.

Many of the advanced methods of producing electricity, including an SPS, may need several decades of research and development before becoming capable of meeting large-scale demands. This requirement will determine the length of the transition from our current mix of energy sources to an era that is expected to be more stable because of the use of resources that are either renewable or available in amounts sufficient for centuries.

The Approach of the DOE Comparison

Under the auspices of the U.S. Department of Energy (DOE), the Argonne National Laboratory undertook a series of studies to develop an initial understanding of the reference SPS in comparison with six basic technologies (U.S. DOE 1980d): (1) improved conventional coal technology; (2) the pressurized water nuclear reactor; (3) coal gasification/combined cycle; (4) the liquid metal fast breeder reactor (LMFBR); (5) central station terrestrial photovoltaic systems; and (6) magnetically confined fusion. To quantify the analysis, a reference system that could be precisely characterized in each case was defined, even though in some cases technical and economic practicality has not been demonstrated. The hypothetical systems were compared in terms of cost and performance, health effects and safety, environmental welfare, use of resources, macroeconomic and socioeconomic considerations, and institutional problems. Three different projections of energy demand were used as a basis for side-by-side comparison of the technologies.

The Approach of the Committee

It did not seem useful to us, however, to attempt to compare all of the reasonable alternative technologies in all respects. Some of them, such as coal, LWRs, and hydroelectricity are well known and fully characterized. Their use in the future can be projected reasonably well by extrapolation from present performance. Others, such as fusion, are at such an early stage of development and so poorly characterized that conclusions about their ultimate form, performance, or cost are speculative.

Moreover, circumstances will never permit a de novo selection of energy technologies. The present combination of technologies will change only slowly as new technologies are introduced. The questions to be dealt with now are (a) whether enough is already known to decide which of these technologies merit further development, and if so, at what pace and on what scale, and (b) if not enough is known, what public expenditures are justified to provide a timely base for subsequent decisions. The pace of development of future energy sources and the manner in which the development is approached will help to determine the structure of the system 30 to 50 years from now.

Since some of the technologies now under study are likely to take 30 years or more to mature, our comparative assessment relates to the extent to which research or development is likely to advance the time

of commercialization. Therefore, the first question is whether, on the basis of what we know now, any of the systems have decisive advantages or decisive liabilities. When decisive advantages or liabilities cannot be discerned, the task is to identify the critical questions that must be answered or the critical technical problems that must be solved before future decisions can be made.

Such comparisons cannot be static, since choices made at one time may preclude other choices at a later time. The comparisons must also take into account the possibility that some technologies (e.g., nuclear power or an SPS) may turn out to be unacceptable for political reasons. The ideal approach is to look at a range of ways in which the energy situation may unfold and to make comparisons that will define the options available and courses of action that will make the best options available when they may be needed.

The features important to the comparison are, not surprisingly, the same as those in terms of which the reference SPS has been discussed: the readiness of the technology, its costliness, its capacity, its environmental effects, and its social or political acceptability. We did not make detailed assessments of the several technologies as we did for the SPS, but we did characterize them broadly, if not quantitatively.¹

ALTERNATIVE TECHNOLOGIES FOR PRODUCING ELECTRICITY IN THE TWENTY-FIRST CENTURY

The principal methods of producing electricity with which an SPS is likely to compete in the twenty-first century are:

1. Advanced coal systems (gasification/combined cycle, fuel cells, magnetohydrodynamic generators).
2. Advanced nuclear systems (the liquid metal fast breeder reactor or other types of breeders, advanced converters, fusion).
3. Solar-electric systems (solar-thermal conversion, terrestrial photovoltaic conversion, ocean-thermal energy).
4. Geothermal energy.

Coal Systems

Coal seems certain to play an expanded role in the production of electricity and other forms of energy during the rest of this century and probably for well into the twenty-first century as well. Since this country's reserves of coal greatly exceed those of oil and natural gas, coal is likely to be used to an increasing extent both to produce electricity and to serve as a substitute for oil and natural gas in industrial processes through liquification and gasification. A variety of technological methods for making coal more versatile, as well as cleaner and easier to use, are now in various stages of research and development; these methods will gradually find their way into commercial use if favorable costs are achieved.

Studies do not suggest that greater use of coal will be painless or inexpensive. The United States already exports substantial amounts of coal, and it is possible that future world demand for this fuel may be 3 to 5 times what it is today. An expansion of that magnitude in the amount of coal mined in the United States would produce even more severe problems of land degradation, since the cheapest and most accessible coal is available by surface mining. New rail and slurry pipeline facilities would have to be built and ports expanded. Burning much larger amounts of coal in this country to produce electricity would exacerbate the problems of preventing air pollution, disposing of enormous quantities of ash, and preventing the leaching of metal salts from the ash into soils or water supplies. Burning coal also produces atmospheric emissions of heavy metals, whose long-term effects on human health are not known. Controlling these environmental effects will cost money.

Over the very long run, however, the greatest obstacle to use of coal may be emissions of carbon dioxide (CO₂) from burning coal. Although coal combustion is not the only source of atmospheric CO₂, it is one of the major sources, and there is no doubt that the amount of CO₂ in the atmosphere has increased substantially over the last 100 years. It has been predicted theoretically that ultimately the increase in atmospheric carbon dioxide may cause a so-called "greenhouse effect" on earth--that is, preventing the reradiation into space of solar energy reaching the earth--thereby increasing the earth's average temperature. One prediction is that the average world temperature might rise by as much as 2 °C to 3 °C by the year 2050 as a result of increasing CO₂ concentrations (Thompson and Schneider 1981). This, in turn, might lead to melting of the polar ice caps and a rise in water levels sufficient to threaten coastal cities. It should be noted that the greenhouse effect has not yet been demonstrated as inevitable in this time period, either theoretically or experimentally. If it were, it would undoubtedly mean that worldwide constraints would have to be placed on the use of coal, although at some point it may become technically and economically feasible to dispose of atmospheric CO₂ in the ocean depths or to store it in geologic reservoirs. The Committee concludes that:

- Despite its actual and potential problems, coal is likely to be the Nation's basic source of electricity for another century. The technologies for using coal to produce electricity are well developed, and advanced systems for doing so more efficiently should become available for commercial use over the next several decades. With the possible exception of unacceptable carbon dioxide build-up in the earth's atmosphere, the safety and environmental problems arising from the use of coal can be managed by present and future technologies. Excessive accumulation of carbon dioxide in the atmosphere, however, is eventually likely to require a curtailment in the use of coal.

Nuclear Power Systems

Fission Reactors

Light water reactors similar to those now in use will be an important source of electric power through much of the twenty-first century. Gradually, however, the natural supply of uranium (U) for such reactors will diminish. At some point in the future, then, the present generation of LWRs will be replaced by more efficient "advanced converter" reactors and breeder reactors. In an advanced converter the amount of ^{238}U converted to fissile material is almost as large as the amount consumed. In a breeder reactor more fissile material is produced than is consumed from the mixtures of uranium and plutonium oxide that it uses. The result in either case is to allow the use of ^{238}U , which is some 150 times more abundant than ^{235}U . The use of uranium for fuel will also be extended by the use of thorium in either advanced converter or breeder reactors.

The scientific and technological knowledge necessary for building and operating the LMFBR currently exists; a reactor of this type is now being tested in France. One expectation is that the capital costs of breeder reactors will be more than those of LWRs, but less than twice as much.

One objection to the development of the LMFBR in the United States has been that this type of reactor produces significant amounts of plutonium. The plutonium separated in reprocessing spent nuclear fuel is suitable for use in nuclear weapons. Because breeders produce more plutonium than ordinary reactors, the United States in recent years has unilaterally reduced its effort devoted to breeder reactors and has tried to prevent the reprocessing of spent fuels elsewhere, on grounds that the material might be stolen by agents for other countries or by terrorist groups seeking to build their own nuclear weapons. Another objection is the higher cost of electricity from breeders compared to LWRs, at the current price of uranium.

Other than the weapons issue, breeder reactors are neither more nor less safe than LWRs. Since breeders require much less uranium, the amount of mining necessary to obtain uranium would be reduced, as would the amount of radioactivity in the environment from mine tailings. On the other hand, breeder reactors also produce high-level wastes, and these wastes would have to be safely stored just as the wastes from LWRs. The Committee's Working Group on Comparative Assessment (Appendix B) accepted prior estimates that safe geologic storage could be achieved without undue technical difficulty (NRC 1979, p. 221).

Advanced converter reactors would reduce the possibility of plutonium being diverted into weapons production, and their capital costs would be significantly less than those of breeder reactors. Advanced converters, however, would use a great deal more uranium than breeder reactors. Thus, advanced converters are likely to be seen by utility companies as cost-effective ways to produce electricity only if demand increases slowly and the price of uranium remains within a range of about \$100 per pound to \$200 per pound. The Committee concludes that:

- Breeder reactors can be developed that can supply electric energy on a large scale and at competitive cost far into the future.

Controlled Thermonuclear Fusion

Controlled thermonuclear fusion for the production of electricity, on the other hand, is still the subject of research. Although considerable progress has been made in this work, a technique has yet to be developed for confining the plasma of the fusion reaction for a sufficiently long time and at a sufficiently high temperature to produce more energy than the reactor uses. In other words, the technical feasibility of a fusion system has not yet been demonstrated. However, recent increases in the capabilities of experimental equipment for magnetically confining the reaction have been achieved, and scientists working in the field are optimistic that a laboratory demonstration of an actual sustained reaction will occur within the next decade.

Meanwhile, the engineering design of a fusion reactor, or its capital costs, remain matters of pure speculation. Much less speculative is the matter of the preferred fuel for the fusion reactor--deuterium and tritium. The supply of deuterium is unlimited, and tritium depends on the supply of lithium, a common substance that would be available far into the future. The radioactivity produced by the fusion reaction is 10 to 100 times less than that of a fission reactor. Also, the problem of dangerous wastes containing long-lived α -active actinides would be avoided in the fusion process because the principal fusion reactant, tritium, has a half-life of only 12 years. Thus, the Committee accepts the view that:

- Even though fusion's technical success and economic practicality have not yet been demonstrated, its attractiveness is that it holds the prospect of becoming a boundless source of energy that would produce relatively little harmful waste material. In its current early stage of research however, fusion can only be considered a dark horse in the competition to produce electrical energy in the twenty-first century.

Terrestrial Solar Energy

The terrestrial solar technologies for producing electricity that can be compared with an SPS are solar-thermal generation, terrestrial photovoltaic systems, and ocean-thermal energy conversion. Each of these is discussed separately in the following subsections. Other terrestrial solar technologies are discussed briefly in a fourth subsection.

The immediate conversion of incident solar energy to electricity, as accomplished by solar-thermal and terrestrial photovoltaic systems,

although attractive in many ways, is not by itself a source of baseload electrical power. Sunlight reaches the various parts of the earth for only part of each day, and even then many parts of the globe are under a cloud cover that screens out much solar energy. A related constraint is that, unlike fossil fuel, directly incident solar energy cannot be stored for use at a later time, although research is being conducted into indirect methods of storing energy from the sun--for example, using compressed gases, pumped water, and electrochemical batteries, photolysis of water with subsequent recombination in fuel cells. None of this research has progressed to a point where it can be determined whether any of these methods of storing solar energy will become economically practical, however.

In the absence of storage, terrestrial solar energy could supplement the basic supply of electricity, since it tends to be available during that period of the diurnal cycle when the demand is greatest. It would be useful for supplying about 10 to 15 percent of the demand at peak levels. Beyond this contribution, storage would be required.

Solar-Thermal Electric Power

The construction of solar-thermal electric systems would present no unusual technological or environmental problems, since such systems are relatively simple, using mirrors to collect solar energy, a boiler in which solar heat turns water into steam, and an electric generator. Demonstration projects are in various stages of development. There is insufficient information available thus far to make reliable estimates of future costs, but it has been estimated that the first successful demonstration plant will produce electricity at a cost of between 5 and 10 times that of the current busbar cost of electricity from conventional generating plants. Since the technology for building solar-thermal electric power plants is well known, large-scale reductions in the cost of these plants appear unlikely.

Terrestrial Photovoltaic Cells

In the long run, terrestrial photovoltaic cells probably offer greater promise of producing substantial amounts of electricity from solar energy than do solar-thermal facilities. Terrestrial photovoltaic conversion of solar energy into electricity has been demonstrated in many specialized installations (Ehrenreich 1979), and with adequate efficiency (16 percent) and reliability.

In particular, the semiconductors that are being pursued for further development include silicon (Si), gallium arsenide (GaAs), cadmium zinc sulfide with copper sulfide (CdZnS/Cu₂S), and copper indium selenide with cadmium sulfide (CuInS/Cds). It is expected that photovoltaic efficiencies can be improved by tailoring the semiconductor structure to the spectral distribution of the incident radiation. Further progress is expected from improved control of the

charge production, recombination, and collection processes within the solar cell through ingenious design of materials and dimensions. Concentration of the incident radiation by reflectors and useful recovery of rejected heat can lead to more efficient systems. In short, the readiness of the technology appears to exist.

At present, however, the cost of electricity from terrestrial photovoltaic cells is more than 20 times the prevailing cost of residential electricity. Thus the critical objective of research and development is to develop methods of reducing the cost of photovoltaic systems. DOE is already pursuing such a program with cost goals of \$0.70/W (peak) in 1980-year dollars by 1986 and \$0.15/W (peak) to \$0.50/W (peak) in 1980-year dollars by 1990. Reduction of the cost of terrestrial photovoltaic cells may be easier to achieve than that of space-qualified cells for several reasons. Terrestrial cells are not constrained by the requirement of low mass per unit power. There are not such rigorous standards of reliability and lifetime. Because terrestrial cells are not exposed to damage from penetrating radiation, high purity is not critical. Finally, terrestrial cells are not subject to the extreme temperature cycles that SPS cells would experience. Such novel processes as dendritic web growth of crystalline silicon have already been shown to be capable of reducing the cost of photovoltaic cells, but large-scale use of such cells would require even greater cost reductions. Such reductions may be achieved by using cells of amorphous silicon with an efficiency of between 8 percent and 10 percent, and projections in the range of \$1.00/W (peak) have been made recently by manufacturers.

The generating capacity that could be provided by terrestrial photovoltaic cells of sufficiently low cost could be introduced in broadly distributed increments of manageable size. The equivalent of many hundreds of gigawatts could be achieved by using a combination of centralized stations and widespread rooftop installations. However, at any such total capacity, the susceptibility of terrestrial photovoltaic systems to diurnal, meteorological, and seasonal variations becomes basic. As terrestrial photovoltaic capacity is introduced, its initial uses will be for supplying peaks in daily demand, thus displacing more expensive plants now allocated to this need. However, since the peak variation in the daily load about its average is only about 5 percent to 10 percent, the amount of photovoltaic generation that can be used for this purpose is limited. Another application is for fuel saving at central plants, but this saves only fuel and not plant investment.

Hence it appears that there will be a period when the development of terrestrial photovoltaics will occur independently of SPS and will penetrate the market to a limited degree. Further penetration will depend on the development of storage technology at acceptable costs. Opportunities for the independent parallel development and the staged sequential introduction of various storage technologies are recognized. The extra cost imposed on electricity storage depends greatly on details of the storage methods and how they are incorporated into utility system design and operation. In discussing the long-term prospects of terrestrial photovoltaics, we can note only the broadest features of the problem. Reliance on terrestrial photovoltaics for

baseload electricity will require storage of the order of several days to bridge unfavorable meteorological conditions. For storage times of this magnitude the cost is dominated by the capital cost per kilowatt hour, typically \$50/kWh now and possibly \$25/kWh in the future. It can be seen that a 20-hour storage requirement adds significantly to the system cost per unit of generating capacity, and a 100-hour storage requirement does not look economic in comparison with available alternatives.

Solar sources of energy must be investigated seriously because circumstances may bring us to reliance on them in the long run. A comparison of the promise of terrestrial photovoltaic systems with SPS is especially interesting because of the clearcut similarities and differences in the two. Given the basic technology of photovoltaics, the terrestrial system must add storage to supply an important portion of electrical demand. SPS must go to orbit to do the same. Hence the important comparison is between the cost of storage on the scale of the billions of kilowatt hours involved and the cost of those features of the SPS that make storage unnecessary. Both costs are very high and uncertain, though susceptible to reduction by future technological advances. We do not see a basis for ruling out one or the other at this stage, and we believe that continued research in the various component technologies will be fruitful. Such research can easily be related to valid interim goals short of establishing either an SPS or a terrestrial photovoltaic system with storage.

Environmentally, the main consideration in terrestrial photovoltaic systems is to manage the manufacturing and waste disposal processes carefully to avoid harmful effects from toxic materials like arsenic and selenium. Large capacity storage by means of underground pumped water or compressed air will require attention to their environmental effects, but these methods are more promising than prospects for finding additional surface reservoirs for pumped hydroelectric storage.

Sociopolitically, terrestrial photovoltaic systems seem to present no critical issues. Site selection for central stations seems to be the most likely problem. The amount of land required within the perimeter of an array of photovoltaic cells is about 5 hectares per megawatt, so that a sizeable installation of, say, 200 MW would require a site of about 10 km².

Ocean-Thermal Energy

Ocean-thermal energy recovery is based on the difference in temperature of approximately 20 °C (36 °F) between surface water and deep water. The principal technical problems involve the pumping of enormous quantities of water, corrosion of equipment, fouling of heat transfer mechanisms by biological organisms, and distribution of the power. The conversion of ocean-thermal energy to electricity would be feasible chiefly in coastal areas in the tropics, such as Hawaii, Florida, or Puerto Rico. There is no current basis for making plausible cost estimates. As a result of the conversion process, certain environmental problems are likely to occur, including plankton growth in the "upwelling," change in the albedo of the ocean, and

possible climatic effects. The conversion of ocean-thermal energy might contribute the equivalent of 1 quadrillion British thermal units (quad) per year or so of primary energy input to the generation of electricity by the year 2000, and perhaps more eventually; but no sound prognostication can be made at this time.

Other technologies for producing electricity, based on ocean waves and currents or gradients in salinity, may make contributions under special circumstances; but they do not appear likely to add to our future energy supply in any substantial way.

Other Terrestrial Solar Technologies

Other solar technologies appear less promising, lack sufficient information for even speculative comparison, or are expected to contribute only a minor amount to the future electricity supply. The Committee on Nuclear and Alternative Energy Systems, referred to here as CONAES (NRC 1979), judged that new dams are so destructive of ecosystems as to make hydroelectricity a poor candidate for further development, and we did not consider it further.

CONAES also estimated that biomass fuels might eventually be used to produce 5 quads per year from organic municipal and agricultural wastes, from plants grown on otherwise useless land, and from seaweed. Reliance on biomass, however, would compete for land, water, and other inputs that could be devoted to uses of greater value, such as growing food. This conclusion is disputed by some, but we did not explore this question further.

In addition, CONAES considers the photosynthetic production of fuels--for example, by way of the photodissociation of water on catalytic surfaces--to have great potential. The primary goal is to generate liquid fuels, but the hydrogen and oxygen stored in the process might be used in fuel cells to generate electricity. However, present conversion efficiencies are so low (e.g., 0.02 percent) and the process is in such an early stage of research that data are insufficient for even speculative comparison with other technologies. The thermal dissociation of water using nuclear, solar, or other heat sources to produce inexpensive hydrogen and oxygen is also under investigation in several laboratories.

Wind power has been used throughout the world on a small scale for centuries. One of the principal technological challenges in making wind power more accessible is to make this type of power plant cheaper and more durable, especially in areas with very high winds. Wind power also presents some environmental and safety problems. Facilities that use the wind to produce electricity are noisy, interfere with the reception of television signals, and require large amounts of land. It would take from 500 square kilometers (km^2) to 1300 km^2 (about 200 square miles to 500 square miles) to produce 1000 MW, from windmills, although the land would not be lost to other purposes such as agriculture. Nonetheless, despite its decentralized character and rather small capacity, wind power will probably make some contribution to the production of electricity in the future, especially where

intermittent production is valuable in saving fossil fuels or where energy storage capability is available.

The Advantages of Terrestrial Solar Systems

In many ways, terrestrial facilities that would make use of solar energy efficiently would be an ideal way of producing electricity. Solar energy produces low pollution, and it will always be available. Most of the terrestrial solar technologies can be used economically on a small scale and are thus amenable to private-market decisions. They can be installed incrementally. Solar powered electric facilities can be built for various outputs up to 100 MW or 200 MW and can therefore be well matched to various local end uses. Yet another advantage of terrestrial solar power is that it is available during the day, when demand for electricity is highest. Thus, solar power facilities are particularly useful for saving fossil or nuclear fuels during peak and intermediate periods of electric energy use.

However, most terrestrial solar electric technologies require significantly more land area than coal or nuclear technologies because of the relatively modest power flux density of sunlight (about 1 kW/m²) and the unavoidable conversion losses. It happens that the land requirements for terrestrial photovoltaic systems are comparable with those of the reference SPS for reception at 2450 MHz. Both take of the order of 5 hectares per megawatt. If an SPS were to go to shorter wave-lengths and higher power beam intensities, its land requirements could be reduced.

On the basis of the conversion processes described above, the Committee concludes that:

- There are a number of solar technologies for generating electricity that do not pose fundamental technical questions but that are characterized by engineering and economic problems. As these problems are overcome, solar energy will likely become an important source of energy per year and could replace fossil fuels in some applications. Solar power produces little pollution, can be incrementally installed and poses few sociopolitical problems.

Geothermal Production of Electricity

The technology has been developed for producing electricity from underground geothermal steam, and natural steam is now used to produce about 900 MW of electricity in the United States. There are few prospects for increasing the amount of electricity from natural geothermal steam, however, since about 99 percent of all geothermal energy in this country is contained in hot--but dry--rock underground.

To extract heat from hot dry rock, the rock has to be fractured and then water circulated through the rock to produce steam. The current technology for doing this is too expensive to be practical, although

projections have been made indicating reduced costs in the future. At the moment, however, the possibility of large additional amounts of electrical energy from geothermal sources remains speculative. The Committee notes that:

- There is a substantial amount of geothermal energy that may eventually be used, but geothermal resources will probably make only a minor contribution to national production of electricity well into the twenty-first century.

AN SPS IN RELATION TO OTHER ADVANCED TECHNOLOGIES

In this section we make a brief comparison of an SPS with the other advanced methods of producing electricity already discussed.

The first point of importance is that the technical readiness of an SPS is low. Like a terrestrial photovoltaic system for producing electricity, an SPS would use large numbers of photovoltaic cells. Unless these cells can be manufactured to achieve high performance at costs that make them practical, neither an SPS nor a terrestrial photovoltaic system will be economically feasible. It should be noted, however, that cells for use in SPS satellites would have to meet more stringent requirements than cells for use on earth. The SPS cells, for example, would have to be much more efficient; precluding the use of amorphous silicon as the cell material. Furthermore, cells in satellites at geosynchronous orbit are damaged by energetic electrons and protons. Thus cells in SPS applications would have to be annealed periodically. We concluded that silicon cells are probably unsuitable for SPS satellites, (see Chapter 2 and Appendix E); therefore, the development of other cells would be critical to the successful development of an SPS.

As mentioned earlier, a terrestrial photovoltaic system could become cost-competitive--at least for producing about 15 percent of the country's demand for electricity--through a single technological advance, namely, about a 10-fold to 20-fold reduction in the cost of terrestrial photovoltaic cells. A much larger reduction in the cost of space-qualified solar cells and comparable reductions in the costs of space transportation, coupled with sufficiently low costs of manufacturing of satellites in space, is required to make an SPS competitive. In short, an SPS would depend to a much higher degree on many expensive, high-risk technologies than a terrestrial photovoltaic system. An SPS, of course, would have the advantage of producing electricity continuously and steadily without storage capabilities, unlike some other solar-based methods. At this time, however, it would appear that storage costs would have to be very high indeed to make a terrestrial solar energy system anywhere nearly as expensive as an SPS.

An SPS would also present a variety of environmental, health, and political problems that differ from those of other advanced methods of producing electricity. As discussed in other chapters of this report, an SPS would have effects on the earth's upper and lower atmosphere, the severity of which is as yet unevaluated. Although available data

do not now indicate it, the microwave beam might have adverse effects on human beings and other biological systems near ground rectennas. Steps would have to be taken to minimize the interference of SPS satellites with communications satellites using the geosynchronous orbit and with ground-based optical and radio astronomy.

It appears injudicious for the United State unilaterally to put an SPS into operation. Respect for the rights and sensitivities of other nations would require the United States to gain international agreement to such a system, either initially or at some time in the future.

THE LONG-TERM OUTLOOK

During the twenty-first century the United States will be making a transition to the large-scale use of renewable, or very long-lasting, energy resources for the production of electricity. Each of the prospective methods for doing so has disadvantages in terms of cost, feasibility, or acceptability.

Coal may prove to be acceptable over the long term if alarm over the so-called greenhouse effect turns out to be unwarranted, or if we learn how to control the release of carbon dioxide into the atmosphere. The use of uranium as fuel in breeder reactors may prove to be acceptable if the dangers of plutonium can be greatly reduced. Controlled thermonuclear fusion may become attractive if it proves to be technically and economically feasible. A system using terrestrial photovoltaic cells may be found to be advantageous if the cost of the cells can be substantially reduced and practical electric storage is achieved. It is also conceivable that some new, long-term method for producing large amounts of electricity--such as photosynthetic production of fuel--may emerge from future research and development.

The circumstances which, in some combination, would favor the deployment of an SPS include a high demand for electricity, the imposition of severe restrictions on the use of coal and uranium, an inability to achieve practical controlled thermonuclear fusion, and major reductions in the cost of an SPS that would at least approach the marginal costs of alternative methods.

It is clearly desirable to keep pursuing a number of alternative technical options for producing electrical energy in the long run, in rough proportion to their promise. In a dynamically changing situation no study of a single option--such as an SPS--can tell us which options to keep open or how much to spend on each one. In other chapters we have attempted to identify the critical advances in particular technologies relevant to the concept of an SPS.

As a by-product of our comparison of the promise of an SPS with other long-term technologies, a number of methods displayed characteristics indicating that they should be classified as "more promising" than others for large-scale, baseload electric power generation. Particularly attractive are advanced coal systems and breeder reactors.

Terrestrial photovoltaic and solar-thermal systems might be accorded a fallback position. So far, the storage problem for such

systems has not been solved and they appear likely to be of limited capacity and high cost; but they might be brought into operation if the need were great enough.

Uncertainty surrounds an additional number of possibilities, including SPS and nuclear fusion. Ocean-thermal energy conversion, wind energy and geothermal energy are of more limited potential as well as uncertain.

In view of the circumstances reviewed here, with all the uncertainties about need, performance, cost, and the effects on the environment and society, the Committee concludes that:

- It is too early for haste in achieving the capability to deploy an SPS. However, there will certainly be a need for new technologies some decades from now. Since an SPS may be one of them, it would be equally premature to discard the concept totally.

Consequently, the Committee also concludes that:

- The prudent approach to meeting the need for electricity in the long run (beyond the next four decades) is to continue to explore all of the prospective methods with the expectation that some of them will prove to be acceptable for the long-term, large-scale production of electricity.

NOTE

1. We have relied largely on published material (Landsberg 1979, Keeny 1977, NRC 1979, Schurr et al. 1979, Wilson 1980). In addition, and more importantly, we assembled a Working Group on Comparative Assessment (Appendix B). The group was composed of experts on five energy-producing technologies--coal (conventional and advanced), breeder reactors, fusion reactors, centralized and decentralized terrestrial solar technologies (including wind, biomass, and ocean-thermal energy conversion), and geothermal--plus three members of our Committee. This group assessed the character of each technology in 30 to 50 years with respect to (a) the likely state of the technology, (b) associated environmental (including health and safety) questions, (c) economic aspects, and (d) institutional or political aspects.

CHAPTER 7
EXAMINATION OF THE CONCEPT DEVELOPMENT AND EVALUATION PROGRAM
AND FINAL REPORT

The principal objective of the Satellite Power System Concept Development and Evaluation Program (CDEP) was "to develop, by the end of 1980, an initial understanding of the technical feasibility, economic practicality, and the social and environmental acceptability of the SPS concept." At the time the objective was established the likely outcome was also conjectured:

It must be realized that this effort is unlikely to achieve a firm recommendation to implement the SPS concept. Rather, if no insurmountable barriers are found, one would expect recommendations concerning the direction of the SPS program after fiscal year 1980 toward further laboratory experimentation and field testing. It is conceivable that some space testing recommendations as a companion to the [space] shuttle program might result. On the other hand, a recommendation based on identification of a major barrier might be to discontinue further research and development. (U.S. DOE 1980d, p. 1.)

The results of the program were summarized in Program Assessment Report: Statement of Findings (U.S. DOE 1980d). The DOE report (hereafter called the Report) is the statement on the accomplishment of the objectives of the CDEP.

THE CONCEPT DEVELOPMENT AND EVALUATION PROGRAM

The Committee reviewed the objectives and results of the Concept Development and Evaluation Program through informal briefings provided by DOE, NASA, and their contractors; through published reports on parts of the program; and through the formal 4-day public review of the program held in Lincoln, Nebraska in April, 1980. As a result of our examination, we believe that the three-year DOE/NASA study was surely one of the most thorough ever conducted so far in advance of the possible deployment of a technology. The program's method and structure were well conceived, encompassing broad classes of issues and specific issues in those classes. The execution and documentation of

the assessment was thorough. We commend Mr. Frederick A. Koomanoff of DOE for his competent direction of the study and Mr. F. Carl Schwenk of NASA for his equally competent management of the supporting investigations of NASA.

The CDEP included studies of the technical, environmental, economic, social, and political aspects of an SPS as well as comparisons of the SPS concept with other potentially competing technologies for generating electricity. These evaluations were carried out using a detailed model, the "reference system", of what an SPS might look like. The purpose of defining a reference system was to provide a concrete basis for study so that performance and cost goals might be set, areas of uncertainty and concern might be discovered, and research needs might be identified in a systematic and quantitative manner. A reference system is a legitimate tool to use for developing an initial understanding, but using it can create pitfalls. A too-detailed reference system may convey the erroneous impression that we are technically ready to deploy such a system or that such a system is likely to be the preferred one when that time comes. With the advantage of hindsight, we believe that the CDEP reference system may have been more detailed than was justified in some areas and not sufficiently detailed in others. Nonetheless, it was an effective tool and almost all of the data now available on the SPS concept were developed using the reference system as a basis for study.

The CDEP follows the recent practice of examining to the degree possible the consequences and impact of major decisions by the Federal Government. It is, however, unique in the scope of its assessment, in its attention to detail, and in its attempts to perform the required analyses so far in advance of the availability of economically practical technology. The result of this effort has been an improved understanding of the advantages and disadvantages of the SPS concept, from which we and others can make recommendations about whether to proceed with its development and, if so, how. In this sense, for all the criticisms that may be laid against it, the CDEP was a success.

The Committee concludes that:

- The Satellite Power System Concept Development and Evaluation Program of the U.S. Department of Energy and the National Aeronautics and Space Administration was a thorough study and provides valuable information for policy-making purposes.

The remainder of this chapter does not deal with the entire DOE/NASA program. Instead, we focus on the Report, because it is this final product that will be most widely read.

GENERAL VIEW OF THE FINAL REPORT*

The Report unfortunately consists only of a series of findings on the SPS concept. No conclusions are drawn, and no recommendations are made. Nor is the reader given a framework within which the findings might be interpreted and evaluated. Each reader may assign varying significance to the findings and interpret them according to his own views. In the end, the reader is left with an unclear impression of what has been done so far with respect to the SPS concept and what direction should be taken in the future.

The problem is that it is risky to make generalizations about future satellite power systems from findings that concentrate on the reference system. If the reference system is a viable approach to translating the SPS concept into concrete terms, then one concludes that at least one viable system exists. If the reference system is not viable, one should not conclude that no viable SPS is ever likely to exist.

The Report recognizes many problems that would have to be overcome in order to establish and operate an SPS to meet part of the Nation's energy needs. In fact, the Report identifies 47 problem areas and briefly discusses each, usually in terms of what is currently known, what the uncertainties are with respect to our understanding of the problems, and what types of research would be required to clarify these uncertainties.

The Report pays little attention, however, to the fact that future research may not provide the answers to problems in all 47 areas. In some cases, future research may only lead to determinations of the extent of the problems. Nor does the Report point out that many problems not foreseen now are almost certain to arise in a technological endeavor as complex and costly as an SPS, which requires development of many technologies far beyond their current states.

In reviewing the Report, the Committee was particularly struck by the complexity of most of the 47 problem areas and the extent of

*Statement by Dale R. Corson:

After the Committee's last meeting and after the final version of its report was accepted by the Committee, we received single copies of each of several final topical assessment reports from DOE. Each of these reports is comparable in length to the Program Assessment Report: Statement of Findings (U.S. DOE 1980d) and each is devoted to a single area of SPS concern. I have examined three of these reports and I find them more useful than the Program Assessment Report: Statement of Findings submitted to the Committee as the DOE/NASA summary report last December. Each summarizes the relevant factors bearing on the area of concern, distinguishes what is known from what is not known, draws conclusions and, in some cases, makes recommendations. These assessments provide the reader with a better view of the SPS than does the Program Assessment Report: Statement of Findings.

These topical assessment reports in no way change the Committee's conclusions regarding SPS.

information still to be obtained to quantify the uncertainties about an SPS, let alone to resolve them. Although a number of technical groups have spent millions of dollars in addressing these uncertainties, the Report conveys the impression that their clarification and resolution have hardly progressed beyond the point of formulating a set of intelligent questions that must be answered before the feasibility of the concept can be properly assessed. Nor does the Report estimate the additional costs of answering those questions.

Another problem presented by the Report is that the 47 problem areas are not ranked in terms of such important dimensions as cost, technical feasibility, amount of time likely to be required for solution, and likely degree of public acceptance.

Finally, the Report implies that none of the problems identified raises an insurmountable barrier to the deployment or operation of a reference SPS. As pointed out elsewhere in this report, this implication may be unjustified. Of the 47 major problem areas identified, many are likely to raise problems of far greater severity than suggested in the Report.

The Committee therefore believes that:

- The Program Assessment Report: Statement of Findings must be augmented by the material in the separate technical, environmental, societal, and comparative assessment reports to provide a framework for the development of policy on the future of the SPS concept.

SPECIFIC TOPICS IN THE FINAL REPORT

We believe that the Report's treatments of alternative SPS concepts and the atmospheric effects that would arise from the construction and operation of the reference system are well balanced statements of the possibilities and problems. A number of other important topics, however, pose major difficulties and deserve treatment beyond that given in the Report. The topics include the cost of solar cells; space transportation, construction, and maintenance; comparative assessment and costs; international considerations; the hazards of microwave and of ionizing radiation; future electrical energy demand; and limitations on the potential growth of an SPS. These topics are discussed briefly below in the rough order of their importance, as we see it, to SPS.

Solar Cells

The Report does not discuss the dramatic reduction that would be needed in the cost per unit of peak power from today's single-crystal silicon cells to make an SPS economically viable, although this need is described in supporting documents. Neither present nor future SPS solar cell costs are cited. Current costs are more than \$500 per peak watt (W (peak)). Currently known science and technology of silicon cells might be able to reduce this figure to about \$20/W (peak) in

large-scale production by the year 2000, but reductions below this range are unlikely by that date (see Appendix E). Even a cost of \$20/W (peak) is nearly two orders of magnitude above the cost assumed in the DOE/NASA program. The Report does not suggest how the assumed cost reductions would be achieved. Without entirely new scientific and technological developments, which cannot be predicted, the cost of solar cells alone would seem sufficient to make the reference SPS (or any variant using single-crystal silicon solar cells) prohibitively expensive. Further, development of gallium arsenide solar cells is at such an early stage that no sound basis currently exists for predicting costs of space-qualified cells of that type.

In addition, the efficiency of solar cells is degraded by penetrating radiation in geosynchronous orbit (GEO). The feasibility of projected means for limiting this loss in efficiency by various methods of annealing in space has not been shown.

Space Transportation, Construction, and Maintenance

The Report barely identifies the elements that would be needed for the space transportation part of the reference system. The extent of the increase over current space shuttle performance that would be required for the heavy-lift launch vehicle is not adequately described, and the challenge that would be presented in developing a transportation vehicle capable of moving massive cargoes from low earth orbit to GEO is given only a brief reference (U.S. DOE 1980d, p. 51). In short, the Report implies that the SPS transportation system would be an extension of current NASA work (mainly, the development of the Saturn V and space shuttle), with some supplemental work to meet SPS goals. A proper appreciation of the technological challenges of the electric orbital transfer vehicle (EOTV) and other transportation requirements of the reference system is not communicated.

Although automation of space construction is referred to, its importance is not stressed. The construction schedule outlined for the reference system would involve the construction in space of a power satellite every 6 months, using a technology which as yet is completely undeveloped. The stringency of this goal is not acknowledged or addressed, however. Although the Report does mention robotics, its importance in both the construction and maintenance of SPS satellites is passed over, as is the current embryonic state of that technology.

Finally, the Report does not clearly emphasize that control system requirements for SPS satellites and EOTVs are well beyond current capabilities; and the operation and maintenance of the reference system as a whole, which would require extensive manpower, facilities, and equipment, are hardly discussed except from the viewpoint of health and safety.

Comparative Assessment and Costs

The Report's attempt to compare the cost and performance of the reference SPS with six alternative energy technologies was not

realistic, because the reference system assumes the launch of the first satellites in the year 2000. This goal almost certainly cannot be achieved at any cost, and certainly not at the nominal value of capital cost assumed in the comparison, namely, around \$3600/kW in 1978-year dollars for the silicon option (U.S. DOE 1980d, Table 3.7) or around \$4300/kW in 1980-year dollars.

The SPS capital cost is compared in the Report with the following--a "nominal" capital cost for magnetically confined fusion in the year 2000, which is approximately equal to that of the reference SPS in dollars per kilowatt; the cost of terrestrial photovoltaics, which is only a third as high (presumably because storage for baseload power was not included); and the cost of coal and nuclear fission systems.

Because neither the SPS nor controlled fusion will be operating in the year 2000, and because the costs of terrestrial photovoltaics by then are uncertain by perhaps an order of magnitude, it is difficult to attach meaning to these cost estimates. Accordingly, it did not seem worthwhile to analyze them in detail. In the two cases in which the Committee examined costs in some depth (space qualified photovoltaics and transportation from earth to LEO) we found the nominal costs assumed in the comparison unrealistically low. The Report does give a range of estimated capital cost for the reference system with a high estimate of approximately \$16,000/kW (in 1978-year dollars), which would make it unacceptably expensive in any readily conceivable circumstance.

High capital cost per unit of installed power capacity is not the only deterrent to SPS deployment. The complexity of the system, its "all or nothing" character, and the necessity of investing on the order of \$100 billion before the first unit can begin operation would all strain our ability to introduce an SPS into the mix of electrical generation in the U.S. economy. On the other hand all six of the systems with which the SPS is compared can be deployed and financed selectively and incrementally. These critical issues receive sketchy treatment in the Report.

International Considerations

The Report correctly states that the allocation of positions in geosynchronous orbit for SPS satellites would constitute a problem requiring extensive international negotiations. We disagree with the Report's tentative judgments that there would be sufficient space in GEO for 60 reference SPS satellites serving the United States and that the problem of compatibility with other uses of the electromagnetic spectrum is manageable (see Chapter 4). In addition, the Report does not mention the probability of competition for orbital positions at longitudes common to the United States and other countries.

Although the Report briefly discusses the problems of compatibility with neighboring geosynchronous satellites as well as with terrestrially based radio astronomy systems, the radio interference that would be caused by an SPS is not discussed. Various CDEP studies,

however, show that microwave radiation from an SPS could impair the performance of a wide range of terrestrial electronic devices as well as that of satellites in nongeosynchronous orbits. Hence, mitigating such interference could be an important environmental consideration.

The Report's assertion that the reference system would be no more vulnerable to advanced weapons than terrestrial baseload energy systems fails to take account of the greater concentration of SPS facilities and of the difference between an attack on installations in another country's territory and an attack on installations in space. Moreover, SPS satellites might be tempting hostages, since a substantial fraction of the U.S. energy supply could be put in jeopardy.

Ionizing Radiation

Instead of taking account of the most realistic current assessments, the Report tries to put the best face possible on the effects of ionizing radiation on human beings who would work on the SPS satellites in GEO. The Report assumes a dose of 40 rem over a period of 90 days spent in GEO (U.S. DOE 1980d, p. 16), but no emphasis is placed on the fact that exposure would depend critically on the type and amount of shielding. The Report suggests that 40 rem is probably an overestimate of the likely dose, possibly by a factor of 5 or 10 (U.S. DOE 1980d, p. 16). Data available to the Committee indicate that 40 rem may instead be an underestimate, probably by an appreciable factor (see Chapter 4 and Appendix G). If the dose were actually about 100 rem, the excess over the normally expected number of deaths from cancer among workers would be about 10 percent for males and 15 percent for females. These risks are far in excess of risks in other occupations. Further, neither the DOE figure of 40 rem nor our estimate of 100 rem includes radiation from aperiodic solar flares, which might rapidly deliver 300 rem or more to workers in space, unless storm cellars with thick shielding were readily available.

The Report may give the wrong impression in stating that the present limit for workers on earth over a period of 90 days is "less than 10 rem" (U.S. DOE 1980, p. 16). The actual limit is 3 rem (Schimmerling and Curtis 1979). Thus, doses in space might be as much as 30 times (100-rem dose divided by 3-rem limit) above the present limit for terrestrial workers. Radiation doses that high, which appear likely, raise serious questions as to whether construction or maintenance workers could be permitted to work on satellites in GEO for as long as 90 days. Shorter work tours, however, would probably mean a substantial reduction in efficiency and would require a larger work force. Another alternative might be to construct shielded enclosures where the workers would both live and work by using highly sophisticated robots and teleoperators for outside activities.

Microwave Radiation

The Report often does not distinguish carefully between what is well known and what is not well known about the effects of microwave

radiation. Furthermore, the Report does not make it clear that the substantial current interest in revising the standards for exposure to microwaves involves making the standards more rather than less restrictive. Some experts believe that the ultimate U.S. standard may be as low as 0.1 watt per square meter (W/m^2) to $1 W/m^2$. Since the current standard is $100 W/m^2$, a new standard as low as $0.1 W/m^2$ to $1 W/m^2$ would influence the design and, hence, the cost of an SPS based on microwaves. Finally, the Report does not make it clear that a quantitative assessment of the effects of microwave exposure at these low levels is not likely to come from either direct experiments on animals or from epidemiological research, but only from theoretical understanding and extrapolation from dose-response relationships at higher power levels.

Future Electrical Energy Demand

The Report has little to say about future demand for electricity in relation to the capacity of the reference SPS, and points to a single source (Ridker and Watson 1980) for its demand projections. The base case demand projection for the United States in Ridker and Watson (171 quadrillion British thermal units, or quads, in the year 2025, of which 65 quads, or 38 percent, are for the generation of electricity) comfortably accommodates a 300-gigawatt (GW) system corresponding to about 20 quads of primary energy input per year for electric energy. But future energy demands are highly uncertain, both in demand for total energy and for electrical energy. For example, projections by the Electric Power Research Institute (1979) and the International Institute for Applied Systems Analysis (Häfele 1980) are higher; the lower projections of the Committee on Nuclear and Alternative Energy Systems, or CONAES (NRC 1979), are much lower.

It is therefore important to consider whether an SPS can be expanded to provide significant proportions of electrical energy in high-demand cases, or scaled down without substantial penalties of cost in low-demand cases. The ability to expand the SPS is particularly important if it is to be an international, hemispheric, or global electrical energy system. The Report does not address these questions.

Limits to SPS Growth

Although the reference system might be able to provide one-fifth or more of the United States' electrical energy needs in the year 2030 depending on demand, such a system might be at a disadvantage in comparison with coal or nuclear power, for example, because of the limited prospect for increasing the amount of power available from an SPS.

The Report does not point out that the power output from the reference SPS would be limited because of the finite number of suitable geosynchronous orbit positions for SPS satellites. Each SPS satellite would prevent other uses of the space around it. The 60 power

satellites in the reference system satellites might preempt 30° of arc, somewhat less than half of the 70° of arc at the longitudes of the United States currently suitable for communications, weather, defense and other satellites. Expansion of the system by occupying additional positions in GEO would greatly affect other users, but some estimate of the severity of this constraint is not found in the Report.

Power radiated from a single satellite antenna is limited by waste heat per unit area and the power density of the beam that the ionosphere can tolerate. Accordingly, the report qualitatively suggests that use of GEO could be reduced or that system capacity could be expanded by placing one structure with several antennas, each delivering on the order of 5 GW to earth, at one orbital position. Further exploration of the limits of this approach, and similar ones, would have been useful. For example, it might be found possible to replace each single satellite with perhaps six, arranged in a figure-eight pattern. This idea has been put forward in connection with communications satellites and it might warrant further analysis for an SPS.

ASSESSMENT

The DOE/NASA Concept Development and Evaluation Program was a well conceived and well managed project in which an exhaustive number of aspects of an SPS were examined in detail by experts. The many supporting documents developed during the 3-year program provide a tremendous amount of information useful for policy-making as well as other purposes.

The Report taken by itself, however, does not do justice to the imaginative work accomplished in the program. Consequently, the Report must be taken together with the materials in the separate technical, environmental, societal, and comparative assessment reports to provide an adequate basis for judgments on the future development of an SPS. The usefulness of the Report for this purpose would have been enhanced if its findings had been accompanied by conclusions and recommendations.

Finally, we believe that many of the contractors that contributed to the CDEP were substantially more optimistic in their estimates of costs and in their projected development and deployment schedules than is warranted. The Report adopted an optimistic rather than a pragmatic outlook.

EPILOGUE

In retrospect, several considerations stand out from our deliberations. A commitment to develop a system on the scale of an SPS would bring into being the largest technological enterprise in the history of the world. An SPS would surpass such previous programs as the Panama Canal, World War II shipbuilding, the Tennessee Valley Authority, the Manhattan Project, the Federal highway system, commercial nuclear power, and Apollo. Over a 30-year period investment in the reference SPS would add up to the equivalent of about the gross national product of 1980, requiring a huge technical work force and large quantities of natural resources. Such a program would strain the managerial, skilled labor, and capital resources of the country and require unprecedented technological and financial support structures. The global implications are so complex and far-reaching that a unilateral approach appears to be impractical.

Would a 50-year commitment to such a challenging development ever be possible? We do not know, but we can imagine future circumstances in which an SPS might become realistic. By then, a more advanced system concept might take advantage of expected technological progress over the next few decades in low-cost space transportation, in lightweight "gossamer" structures, in robotic space construction, in low-cost, high-performance photovoltaic cells, and in wireless power transmission. Even so, we believe that an SPS would have to meet the same general conditions that must be met by any large-scale technological system before a national commitment is made to its development and deployment. Such conditions include the following:

a. The scientific foundation of the system under consideration must be sound, and the technology must have been developed to the point where it will support projections of performance and cost. It is possible for scientific understanding to lead to demonstrable technical achievement, but at unacceptable cost. For the reference system, in its role as a tool for inquiry, there are unavoidably a number of features for which the science is available, but for which the technology and cost remain uncertain.

b. The research and development required to bring the system from a stage of conceptual design to demonstration of prototypes, where deployment decisions can be made, must be clearly defined. A major

research, development, test, and engineering program must be laid out and then consistently and adequately supported. A great deal of critical but undefined research and development underlying the SPS falls into this category.

c. There must be commanding evidence that a future need will exist and that it can be met by the time of deployment. The future need for an SPS is uncertain and will depend on the changing form of demand for electrical energy in the next century, on the economic competitiveness of an SPS with other advanced alternatives, and on the sociopolitical attitudes of new generations.

d. The system must be socially, politically, and economically acceptable. Unacceptability related to any of these considerations could block a technological project, no matter how sound the technology on which it is based. The development of nuclear power in this country is currently foundering on some of these very issues, and an SPS could encounter similar troubles.

e. There must be step-by-step demonstrations of success with each part of the system as it progresses. The Apollo program was an excellent example of a well-structured program with well-planned milestones. An entirely new system like the SPS, by its nature, makes sequential, partial demonstrations costly and difficult.

f. The Congress and the public must have continued confidence in the system and in the team developing it over the years from inception through deployment, during which inevitable setbacks and criticisms will occur.

The likelihood of a future national commitment to the development of an SPS can be examined taking these general conditions as a starting point. We sought to identify the issues critical to an SPS in light of these conditions and to highlight them in our report. As the reference system is now conceived, it is estimated to require at least 20 years of development and an expenditure on the order of \$100 billion before its performance and viability could be demonstrated. Even so, critical technologies may not be ready to support an SPS by then. We doubt that any administration or any Congress would commit the country to a program of such a speculative nature. Nor should they. The future holds too many uncertainties--and possibilities--in expected advances in SPS and competing technologies 20, 30, or 40 years from now; in future demands for electrical power; and in the global political environment of the twenty-first century.

We pondered a further question: Is it worthwhile to study in detail a specific "reference system" design of a large, complex, system in the way DOE and NASA assessed the SPS, far in advance of any possible deployment? If the necessary science and technology were all in place, we can imagine circumstances in which it would be productive to make such detailed analyses of a hypothetical design, as was done for the reference system, in competition with projected alternative systems to meet estimated future needs. This type of analysis could provide valuable guidance to those who must make major policy decisions. We cannot, however, endorse detailed mechanical and electrical design down to the component level, which characterizes the

DOE/NASA SPS study, so many decades ahead of a system's possible deployment.

We have a final concern. It is hard to project the course of technology 20 years into the future, and yet the future practicality of an SPS will depend upon advances in space technology, photocells, and power beams in coming decades. We can make reasonably sound predictions about development based on existing science and technology for the SPS and competing systems. We can see far enough to know that any practical future SPS concept will be substantially different from the reference system. We can see that oil and gas will become scarce, that the breeder reactor will be needed to extend uranium resources, and that the environmental consequences of coal combustion must be controlled. We can even make the roughest sort of cost estimates. But it is impossible for us to foretell those scientific developments like fusion, which in time could, perhaps radically, alter energy technology and costs. To take account of new science and technology we must reexamine today's projections periodically and make fresh assessments. In the meantime, it is important to assure the vigorous conduct of research in areas relevant to SPS technologies, where such areas are already being investigated in pursuit of the goals of other programs.

We enjoyed the challenge of grappling with a concept as immense as the SPS. We hope that our report will be useful to those who must make decisions on the direction and pace of U.S. research and who cannot defer their judgments until the last fact is known.

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GLOSSARY AND ABBREVIATIONS

ac: Alternating current.

Albedo: The fraction of the total visible radiation falling on a surface (e.g., of a satellite) that is reflected or scattered diffusely; a number that can only be estimated in the case of solar power satellites.

Ambient: The prevalent condition of an environmental factor, e.g., power density of electromagnetic radiation.

Amorphous silicon: Silicon having no real or apparent crystalline structure; some preparations of amorphous silicon contain hydrogen bonded to some of the silicon.

Annealing: Freeing from internal stress by heating and gradual cooling.

ANSI: American National Standards Institute.

Array: A grouping or arrangement of units; e.g., a solar cell array is a group of solar cells complete with supporting structure and wire interconnections.

Atmosphere: The mass of air surrounding the earth: The lower atmosphere includes the troposphere, extending outward about 10 km to 13 km from the earth's surface; the stratosphere, beyond the troposphere, extending to about 50 km above the earth's surface; the mesosphere, beyond the stratosphere, extending to about 80 km above the earth's surface. The upper atmosphere is composed of the thermosphere (80 km to 500 km) and the magnetosphere (110 km or 150 km to many thousand kilometers) which is dominated by the earth's magnetic field so that charged particles are trapped in it. The plasmasphere extends from about 1000 km (or somewhat lower) well into the upper magnetosphere and is highly ionized. See also Ionosphere.

- Band:** (1) A continuous sequence of frequencies within given limits; e.g., the band 2400 MHz to 2500 MHz is designated for industrial, scientific, and medical (ISM) applications.
(2) A range of energy levels, in a semiconducting solid.
- Bandgap:** The gap between the valence band and the conduction band in a semiconductor. In the valence band, electrons are more or less bound in position relative to the crystalline structure. In the conduction band, electrons are free to move under the action of an electric field.
- Bandwidth:** The range within a band of frequencies, wavelengths, or energies.
- Baseload electricity:** The minimum load of an electric utility company over a given period of time. Thus a baseload plant is one designed for continuous operation to satisfy the system's constant demand.
- BEIR-III:** The 1980 report by the Committee on Biological Effects of Ionizing Radiation [BEIR], Assembly of Life Sciences of the National Academy of Sciences, entitled The Effects on Populations of Exposure to Low Levels of Ionizing Radiation.
- Blanket:** A sheet of photovoltaic cells on a solar power satellite.
- BMEWS:** Ballistic Missile Early Warning System.
- BOL:** Beginning of life.
- Bremsstrahlung:** Refers to the secondary electromagnetic radiation produced by the sudden deceleration or deflection of a charged particle in an intense electric field.
- Btu:** British thermal unit; a unit of energy defined as the heat required to raise the temperature of one pound of water one degree Fahrenheit; it is equal to approximately 1055.056 joules.
- Carrier:** An electrical oscillation (for example, a radiowave) that may be modulated at lower frequencies for the purpose of conveying information.
- Cathode:** The electron-emitting electrode of an electron tube, such as a klystron.
- CCIR:** The International Radio Consultative Committee of the International Telecommunication Union, which studies and issues recommendations concerning technical and operating questions relating to radiocommunications.

- CDEP:** (Satellite Power System) Concept Development and Evaluation Program; the name of a study conducted by DOE and NASA from 1977 to 1980 culminating in a final report, Program Assessment Report: Statement of Findings.
- cm:** Centimeter(s); a unit of length equal to 10^{-2} (one-hundredth) meter.
- CO₂:** Carbon dioxide.
- CONAES:** Committee on Nuclear and Alternative Energy Systems of the National Academy of Sciences. The acronym, as used in the text, refers to that Committee's 1979 report, Energy in Transition 1985-2000.
- Continuous-wave radiation:** Single-frequency, uniform-amplitude electromagnetic radiation.
- Cosmic radiation:** High energy particle and photon radiation resulting from cosmic rays, which are streams of atomic nuclei of heterogeneous, extremely penetrating character that enter the earth's atmosphere from outer space at a speed approaching that of light.
- Coupling:** The mechanism by which electromagnetic energy is delivered to a system or device.
- cw:** Continuous wave(s); see continuous-wave radiation.
- dB:** Decibel; a logarithmic measure of a ratio, equal to 10 times the logarithm (base 10) of the ratio.
- dB(W):** Decibels with respect to a reference level of 1 W.
- dc:** Direct current.
- Dipole:** An electrical antenna consisting of two colinear rods with their adjacent ends slightly separated.
- Directivity:** The property of being directional, that is, suitable for sending radio signals in limited directions or receiving them from limited directions.
- DNA:** Deoxyribonucleic acid; the genetic material in cell nuclei.
- DOE:** U.S. Department of Energy.
- Dosimetry:** The accurate measurement of doses, e.g., of energy deposited by radioactivity or ionizing radiation. See Rad.

Electromagnetic compatibility: The condition of shared use of the electromagnetic spectrum without unacceptable interference.

Electromagnetic spectrum: The entire range of wavelengths or frequencies of electromagnetic radiation extending from gamma rays to the longest radiowaves and including visible light.

Electromagnetic wave: One of the waves that are propagated by simultaneous periodic variations of electric- and magnetic-field intensity, including radiowaves, infrared, visible light, and others.

Electron: A subatomic particle having a negative electrical charge.

EOL: End of life.

EOTV: Electric orbital transfer vehicle.

EPRI: Electric Power Research Institute.

FCC: Federal Communications Commission.

FET: Field-effect transistor; it has various features that make it superior to conventional transistors for certain uses.

Field: A region of space within which magnetic or electrical lines of force exist.

Field strength: The magnitude of an electric or magnetic field.

Flux: The rate of transfer of particles or energy across a given surface.

Frequency: The number of complete oscillations per unit of time of an electromagnetic wave, measured in hertz (Hz).

Gallium arsenide cell: A solar cell made from gallium arsenide, GaAs, or gallium aluminum arsenide, $Ga_xAl_{1-x}As$.

g/cm²: Gram(s) per square centimeter.

GEO: Geosynchronous earth orbit. See Geosynchronous orbit.

Geosynchronous orbit: Denotes an orbit in which it takes an object 24 hours to circle the earth. Approximately 36,000 km (22,300 miles) above the earth's surface. A satellite at this point appears not to move when viewed from earth. See also GEO.

GHz: Gigahertz; a unit of frequency equal to 10^9 (one billion) hertz.

- Grating lobes:** In the reference SPS, microwave power-density patterns which appear as isolated spots arranged in a grid surrounding the receiving antenna; spacing ≈ 400 km, power density ≈ 0.1 W/m².
- GW:** Gigawatt(s); a unit of power equal to 10^9 (one billion) watts.
- Harmonic:** A component frequency of an electromagnetic wave that is an integral multiple of the fundamental frequency.
- Heterojunction cell:** A photovoltaic cell in which the major components of the semiconductor on either side of the active photovoltaic region are different.
- HLLV:** Heavy-lift launch vehicle; used to transport SPS materials from earth to low earth orbit.
- High Z:** High atomic number energetic particles ($Z > 2$); the most significant biological characteristic of a high-Z particle is its ability to inactivate many cells along its path.
- Hz:** Hertz; a unit of frequency equal to 1 cycle per second.
- Interference:** Unwanted electromagnetic signals preventing good reception.
- International Telecommunication Convention:** The primary treaty governing the use of the radio spectrum, to which the United States is a party.
- 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:** Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, by adding electrons to, or removing electrons from, an electrically neutral atom, group of atoms, or molecule. The SPS would be built and operated in an ionizing radiation environment.
- Ionosphere:** The part of the earth's atmosphere (extending from about 50 km to 1000 km above the surface of the earth) containing free electrically charged particles of sufficient concentration to affect radiowave propagation over a broad frequency range. The ionosphere is coincident with the mesosphere and the thermosphere and reaches into the magnetosphere. The ionosphere consists of several ionized layers or regions, each having chemical and electrical characteristics different from those of the other regions; the D and E regions make up the lower ionosphere; the F region, the upper. See also Atmosphere.

- Ionospheric heating:** A conceivable increase in the energy (and corresponding temperature) of the electrons in the ionosphere resulting from SPS microwave power transmission through the ionosphere, so that radiocommunications might be affected.
- Ionospheric hole:** A neutral hole in the ionized ionospheric medium caused when rocket effluents of heavy-lift launch vehicles result in recombination of ions and electrons.
- ISM:** Industrial, scientific, and medical; an International Telecommunication Union category for devices that convey no signs, signals, writing, images, sounds, or intelligence of any nature.
- ISM band:** Industrial, scientific, and medical band; one such band occurs from 2400 MHz to 2500 MHz, including the radiofrequency of 2450 MHz proposed for an SPS.
- ITC:** International Telecommunication Convention.
- ITU:** International Telecommunication Union; a specialized agency of the United Nations, established by the ITC, to which the United States is a party. The ITU, which has no police powers, achieves its mission by gaining accommodation among users.
- J:** Joule; a unit of work or energy equivalent to that expended by one watt in one second.
- Klystron:** A vacuum tube with several ultrahigh-frequency applications; one of three alternatives studied by DOE and NASA for converting direct current power to microwaves in a solar power satellite, klystrons are assumed in the reference system studied in this report.
- km:** Kilometer(s); a unit of length equal to 1000 meters. One kilometer is about 0.6 mile.
- kV:** Kilovolt(s); a unit of electrical potential difference equal to 1000 volts.
- kW:** Kilowatt(s); a unit of power equal to 1000 watts.
- kWh:** Kilowatt hour(s); a unit of work or energy equivalent to that expended by 1 kilowatt in 1 hour.
- LEO:** Low earth orbit, altitude approximately 500 km.
- LET:** Linear energy transfer; average amount of energy lost per unit of particle track length.

Linear hypothesis (L): The hypothesis that excess risk is proportional to cumulative dose; it is usually assumed that excess risk is independent of the degree of protraction and fractionation of dose. It assumes that a dose-response curve derived from data in the high dose ranges may be extrapolated linearly through the low dose range. See also Linear-quadratic hypothesis.

Linear-quadratic hypothesis (LQ): The hypothesis that excess risk is given by a polynomial of the second degree in dose, that is, the dose-response curve is linear in the low-dose range and as dose increases becomes an upward curving quadratic function of dose (until cell killing occurs); it assumes that excess risk from an instantaneous exposure is the sum of components proportional to dose and to dose squared. It is usually the case that the dose-squared component is less important if dose is spread out over a period of time. For this report it was assumed that the dose-squared term was of negligible importance for exposures on the order of less than 1 rad per day over a 90-day period. See also Linear hypothesis.

LMFBR: Liquid-metal fast-breeder reactor(s).

Lower atmosphere: See Atmosphere.

LWR: Light water (nuclear) reactor(s).

m: Meter(s); a unit of distance. One meter is about 3.28 feet.

Macromolecule: A large molecule (as of a protein) built up from smaller chemical structures.

Magnetosphere: See Atmosphere.

Magnetron: A two-element vacuum tube used to generate extremely short radiowaves; an alternative to the klystron for converting direct-current power to microwaves in an SPS.

Metric ton: A unit of mass equal to 1000 kilograms. One metric ton is approximately 1.1 U.S. ton.

MHz: Megahertz; a unit of frequency equal to 10^6 (one million) hertz.

μm : Micrometer(s); a unit of length equal to 10^{-6} (one-millionth) of a meter.

μW : Microwatt(s); a unit of power equal to 10^{-6} (one-millionth) watt.

$\mu\text{W}/\text{cm}^2$: Microwatt(s) per square centimeter.

mW: Milliwatt(s); a unit of power equal to 10^{-3} (one-thousandth) watt.

mW/cm²: Milliwatt(s) per square centimeter.

Microwave: An electromagnetic wave between approximately 1 mm and 1 m in wavelength, or, equivalently, between 0.3 GHz and 300 GHz in frequency. Microwaves are a form of energy potentially suitable for beamed power transmission, e.g., for beaming energy from a solar power satellite to its ground receiving antenna.

Microwave beam: A beam that transmits energy from a solar power satellite to its receiving antenna on earth.

Microwave radiation: Electromagnetic radiation at microwave frequencies. Unlike ionizing radiation, microwave radiation does not have sufficient energy to ionize biological molecules, but at relatively high intensity it can cause agitation in molecules that produces internal heating of tissue.

Mills/kWh: Mills per kilowatt-hour.

Modulation: The process of varying the amplitude, frequency, or phase of a carrier wave; the resultant variation.

Molecule: The smallest particle of an element or compound that can exist in the free state and still retain the characteristics of the element or compound.

MW: Megawatt(s); a unit of power equal to 10^6 (one million) watts.

NASA: National Aeronautics and Space Administration.

Noctilucent cloud: A luminous, thin cloud occurring at a height of about 80 km.

Noise: Electrical or electromagnetic oscillations (as radiowaves) that are composed of several frequencies and that involve random changes in frequency or amplitude.

Nonlinear: Of or pertaining to a system such as an electric circuit whose response or output is not strictly proportional to stimulus or input. In particular, outputs proportional to higher powers and cross products of the inputs may occur.

NSF: National Science Foundation.

OSHA: Occupational Safety and Health Administration.

Out-of-band interference: Interference caused by a radiofrequency device to systems operating outside the frequency band allocated to the device.

Parametric instability: An instability that may occur in an oscillating system characterized by more than one natural frequency, when a driving force at a different frequency is applied.

Phase: The measure of the progression of a periodic wave in time or space from a chosen instant or position.

Photon: A quantum of electromagnetic energy.

Photoionization: Ionization (as in the ionosphere) resulting from interaction of a photon with a molecule or atom.

Photovoltaic: The power conversion process in which sunlight is directly transformed into electricity.

Photovoltaic cell: A cell that generates electrical energy when light falls on it.

Pilot beam: See Pilot signal.

Pilot signal: A signal sent from the ground (at the receiving antenna site) to the transmitting antenna of the solar power satellite, used in forming and directing the microwave beam from the satellite to its receiving antenna. Also called a pilot beam.

Plasma: A collection of charged particles exhibiting some properties of a gas but differing from a gas in being a good conductor of electricity and in being affected by a magnetic field.

PLV: Personnel launch vehicle(s), used to transport SPS workers to low earth orbit.

POTV: Personnel orbital transfer vehicle(s), used to transport SPS workers between low earth orbit and geosynchronous earth orbit.

Power density: The quantity of electromagnetic energy that flows through unit area per unit of time.

Primary beam: Main microwave power transmission beam as distinguished from the pilot beam.

Proton: An elementary particle identical with the nucleus of the hydrogen atom; along with neutrons it is a constituent of all other atomic nuclei, and it carries a positive charge numerically equal to the charge of an electron.

Pulse: A momentary, sudden fluctuation in an electrical quantity, as in voltage.

Quad: 10^{15} (one quadrillion) British thermal units (Btu).

Quantum: An elemental amount of energy.

Radiofrequency heating: Heating of a medium, such as biological tissue or the ionosphere, by the absorption of radiowaves.

Radio Regulations: Annexed to the International Telecommunication Convention, Radio Regulations set forth the services which use the radio spectrum and allocate certain portions of the spectrum to each service.

Radio spectrum: The range of frequency or wavelength appropriate to radiowaves.

Rad: A unit of energy absorbed from ionizing radiation, equal to 100 ergs per gram or 0.01 joules per kilogram.

R&D: Research and development.

Rectenna: Coined term for a receiving antenna on the ground to which microwaves are radiated from a solar power satellite and there converted into conventional electric power, which is injected into utility grids.

Reference system: The theoretical satellite power system studied in the DOE/NASA Concept Development and Evaluation Program. The reference system consists of 60 satellites in geosynchronous orbit above the conterminous 48 states. Each satellite would collect energy from solar radiation and convert it into microwaves radiated to its own receiving antenna on earth. The receiving antenna would collect the transmitted energy and convert it into electricity, which could then be fed into the utility grid.

Rem: (roentgen equivalent in man): a unit of dose equivalent equal to absorbed dose (in rads) times quality factor times any other necessary modifying factors. It represents a quantity of ionizing radiation that will cause the same biological damage (of a specified sort) as one rad of 250 kV (peak) x-rays.

RF: Radiofrequency; an electromagnetic wave frequency intermediate between audio frequencies and infrared frequencies, used in radio transmission.

Satellite power system: See Reference system.

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 the power radiated from an antenna in a direction other than the desired direction of transmission.

Signal: Electrical impulses, sounds, etc., received or transmitted.

Solar cell: A photovoltaic cell that is able to convert sunlight into electrical energy and is used as a power source.

Solar (cell) array: A group of solar cells with supporting structure and wire interconnections; the array converts sunlight into electricity and is the single most important element of the SPS.

Solar flare: A sudden temporary outburst of energy from a small area of the sun's surface.

Solar maximum: A period of maximum solar activity in the solar cycle of approximately 11 years duration, characterized by variations in sunspot number. See also Solar minimum.

Solar minimum: A period of minimum solar activity in the solar cycle. See also Solar maximum.

Solid-state (microwave) amplifier: A device that could be used in a solar power satellite to convert direct-current power to microwaves. See also Klystron.

Specular reflection: A bright, directed reflection, like that produced by a mirror or mirror-like surfaces.

SPS: Satellite Power System(s). See Reference system.

Spurious power: Electromagnetic energy produced at frequencies that are not easily related to a specified operating frequency.

STS: Reuseable Space Transportation System, popularly known as the "space shuttle."

Terrestrial photovoltaic systems: Technologies involving photovoltaic cell arrays on earth for converting solar energy to electricity.

Terrestrial solar systems: Technologies, in various stages of development, amenable to small-scale use on earth, for converting solar energy to electricity; they involve solar-thermal, photovoltaics, wind, ocean-thermal energy, and biomass.

Thermionic emitter: A conducting material that when heated to high temperatures emits electrically charged particles.

TPS: Thermal protection system.

Transmitting antenna: The antenna, about 1 km in diameter, attached to the solar power satellite that beams microwaves to a receiving antenna on earth.

TVA: Tennessee Valley Authority.

U: Uranium.

UHF: Ultrahigh frequency.

Ultraviolet: Electromagnetic waves lying just beyond the violet end of the visible spectrum.

Upper atmosphere: See Atmosphere.

Van Allen belts: A region comprising two broad zones of intense, natural ionizing radiation encircling the earth at varying levels in the upper atmosphere.

VHF: Very high frequency.

W: Watt(s).

WARC: World Administrative Radio Conference. One of various conferences of the ITU that deals with international issues concerning use of the electromagnetic spectrum.

W/kg: Watt(s) per kilogram.

W/m²: Watts(s) per square meter.

APPENDIXES

NOTICE: The Appendixes contain supporting papers relevant to the report of the Committee on Satellite Power Systems which appears as the main body of this volume. The appendix material was prepared for the information and use of the Committee during its work and does not necessarily represent the views of the Committee or the National Research Council.

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APPENDIX A

THE TASK*

BACKGROUND

The U.S. Department of Energy (DOE), with the assistance of the National Aeronautics and Space Administration (NASA), conducted a three-year, \$18 million study of the concept of solar power satellites. The National Science Foundation (NSF) was authorized to consider the feasibility of such systems with satellites constructed from lunar and asteroidal materials. The objective of the DOE assessment was to prepare a report summarizing and analyzing the state of knowledge pertinent to the concept and recommending future actions, including implementation of more comprehensive programs of research. The DOE report was issued in December 1980.

In early 1979, the NSF, with the concurrence of DOE, asked the National Academy of Sciences (NAS) to provide assistance in identifying critical issues and potential gaps in the DOE assessment, including such matters as environmental impact, socio-economic acceptability, international implications, comparisons with competitive potential energy sources, and the possible use of orbital structures manufactured from lunar and asteroidal material.

SCOPE OF NAS STUDY

Accordingly, the NAS, through its National Research Council (NRC), undertook a study of the environmental, technical, socio-economic and international aspects of the concept of satellite power systems and of the comparison of such systems with other new energy sources. The objectives of this study were:

- (1) to identify critical scientific and technical issues in the evaluation of the concept,
- (2) to identify gaps that may exist in the DOE assessment, and
- (3) to provide an independent, authoritative critique of the results of the DOE program.

It was expected that the study would address issues similar to the following:

*Excerpted largely from the NAS proposal, as incorporated into the study contract.

(a) Environmental: What are the environmental impacts of launch, flight, and recovery of space vehicles? What are the effects of microwave radiation on the ionosphere and atmosphere? What are the effects of a number of large, highly-charged structures in geosynchronous orbit? What are the effects of occupational exposure to microwave radiation? How might safe levels of exposure for the general population be determined? What are the effects of working prolonged periods in geosynchronous orbit? What are the land use impacts associated with resource use, launch and recovery operations, and receiving stations? What is the likelihood that microwave radiation from power satellites will interfere with other uses of the electromagnetic spectrum and how might that interference be mitigated?

(b) Technological: What aspects of the reference design system bear most heavily on the assessment of the environmental and other aspects of the concept? What is the feasibility of using lunar and asteroidal materials in the construction of orbiting structures?

(c) Socio-economic: What are the land-based resources needed to develop and construct a satellite power system? What institutional arrangements will be used or need to be developed to implement the concept? How will the resulting electric power be integrated into the national electric power grid? What issues in the development of such systems are likely to affect public acceptance?

(d) International: What are the international implications of the construction of solar satellite power stations? Do such structures have military uses and are they vulnerable to military attack? What international treaties or organizations will be affected by such a system? What levels of international cooperation are desired or necessary to develop a system and how might that cooperation be instituted?

(e) Comparisons: What methods are available for comparing the technical feasibility, economic and social acceptability, environmental impacts, and international consequences of alternative potential energy sources?

PROCEDURES

Under the auspices of the Environmental Studies Board, the National Research Council established a Committee on Satellite Power Systems. This Committee, in cooperation with other units of the NRC with expertise in specific technical areas pertinent to the topic, conducted the study. The period of performance for the study was two years. The final result of the study is this report.

PURPOSE

The Committee's purpose was to develop an integrated overview of the concept in order to elucidate those scientific and technical issues which are most critical to future decisions about developing a system.

APPENDIX B
COMPOSITION OF WORKING GROUPS;
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APPENDIX C
REPORT OF THE WORKING GROUP ON SPACE SYSTEMS*

FOREWORD

The Working Group on Space Systems of the NRC Committee on Satellite Power Systems (SPS) was organized to examine those aspects of an SPS that are concerned with space technology. The scope of our assignment included:

- Transportation between earth and low earth orbit (LEO);
- Transportation between LEO and geosynchronous earth orbit (GEO);
- Construction and logistic bases in LEO and GEO;
- Design and orbital construction of power satellites;
- Operation and maintenance of vehicles and satellites; and
- Cost estimates for the development, production, deployment, operation, and maintenance of the space systems of an SPS.

Except for operations and maintenance, our charge did not include the power system, from solar cells to rectenna, which was the purview of other working groups.

Within this broad scope, we undertook to assess the feasibility of achieving the technical and economic performance proposed for the reference system SPS and also for future SPS options which might differ substantially from the reference system. To accomplish our task, we reviewed DOE/NASA study documents and received extensive briefings by representatives of DOE, NASA, and industry. Members of the group met separately with knowledgeable persons in government and the technical community to explore or clarify relevant matters. We received support from the Aerospace Corporation, which performed a technical review and cost analysis of SPS space transportation systems under a subcontract (see Appendix D) and also made available to us the results of an internal study of construction in space (Mosich 1981). In addition, the American Institute of Aeronautics and Astronautics provided a valuable projection of the probable state of the art of space technologies in the early decades of the next century (AIAA 1981).

*See Appendix B for composition of the Working Group.

Our report is organized into five parts. First, we present the results of our consideration of the projected levels of space technology in the early decades of the next century, outlining the probable level of space activities in that period independent of a decision to pursue an SPS.

Second, we give our assessment of the future technical feasibility of the space systems that must be developed, deployed, and operated for an SPS like that of the reference system.

Third, we present our assessment of the cost estimates for the space systems required for an SPS program based on the reference system, with emphasis on the evaluation of space transportation costs performed by the Aerospace Corporation (Appendix D).

Fourth, we comment on the potential for using extraterrestrial resources in the construction of SPS facilities in GEO.

Finally, we summarize our conclusions with respect to the technical and operational feasibility of the space systems required for the reference system, comment on their probable cost, and submit recommendations with respect to appropriate research and development required to provide a sound basis for a future decision on an SPS system.

Overall, we believe the SPS space system concept is promising, but ahead of its time. The required technologies are not yet sufficiently demonstrated to justify major investments now. The reference system itself has technical and cost weaknesses that make it unacceptable for implementation and unsuited for further use as an evaluation baseline on which long-term decisions can be based.

The technology weaknesses of the reference system SPS are not generic to potential future SPS systems. In fact, experience indicates that evolutionary advances in science and technology can eventually overcome the formidable technical challenges of the reference SPS identified in our review. As so often happens in assessing future technical feasibility, we found it difficult to keep in mind that we stand today on a lower rung of the science and technology ladder from which others will climb steadily upward and out of our sight in a few decades. Fortunately, the required technology climb is not so steep: we know more in 1981 about deploying an SPS in 2021 than we knew in 1949 about landing on the moon in 1969. In addition, the R&D to support a future SPS decision is consistent with a well balanced space program leading to GEO operations.

Our technical confidence in future SPS systems is not entirely matched by our confidence in their competitive costs. Deploying an SPS involves major activities in space, and the projected costs of transport to orbit and construction and maintenance activities in orbit make it unlikely that an SPS could become competitive with other sources of electric power before 2020. Continued work on lower cost designs and on reducing the cost of space operations will be necessary before an SPS is competitive with terrestrial options.

PROJECTIONS OF SPACE TECHNOLOGY

The Relevant Time Period

Making judgments about the nature of technological enterprises far in advance of their existence is extremely challenging. In 1945 few people could envision the technical and economic practicability of today's multibillion dollar global communication satellite industry, but Arthur C. Clarke then foresaw today's geosynchronous communications satellite system. Lacking Arthur Clarke's prescience, we draw on the foresight of distinguished professional organizations (the American Institute of Aeronautics and Astronautics and the Aerospace Corporation), and applied our own judgements and experience to envision the state of the art of space technology 20 to 40 years in the future.

We recognize the pitfalls of making such projections in a period when both technology and society are changing so rapidly, but believe it is even less satisfactory to ignore the future environment. We cannot foresee revolutionary external occurrences, such as a major war, future OPEC crises, another "Sputnik", or revolutionary scientific advances equivalent to past breakthroughs in nuclear fission, solid state physics, lasers, recombinant DNA, and their resulting technologies. It is clear, however, that the nation that won World War II from a standing start in 5 years, and landed men on the moon in 8 years, could deploy an operational SPS by 2000. It is equally clear that such a crash program would not produce economically competitive electric power. A consideration of future technology suggests, however, that continuing progress in space technology based upon well-planned NASA progress in coming decades could make advanced SPS options attractive about 2020.

The reference system SPS essentially envisions a program based on 1990 technology, with construction and deployment of the system scheduled from 2000 to 2030, and operation scheduled through 2060. This hypothetical schedule, spanning the next eighty years, as with other assumptions of the reference system, was selected for analysis, not for implementation. The basic issue before us and the NRC Committee, however, is more general: the technical and economic feasibility on any useful schedule of a space-based solar power system, exemplified by, but not constrained to, the reference system and its schedule. We therefore went beyond 1990 technology and into the next century in projecting America's space capabilities as a baseline against which SPS feasibility should be assessed.

Probable Level of Space Activities Independent of an SPS Program

U.S. Government Programs

Civilian. NASA's long-range planning identifies programs regarded as candidates for new starts in the next five years or so, and some possible programs up to twenty years ahead, to guide advanced development. Most current plans involve extensions of types of space

activities now under way, such as unmanned orbital observatories, planetary probes, improved earth observation and communications satellites, shuttle improvements and derivatives (like the 25kw solar Power Extension Package), and chemical orbital transfer vehicles. Plans have not been approved for reusable transportation to GEO or cislunar space, for orbital operations bases, for manned or unmanned lunar operations, extraterrestrial resource exploration and development, advanced robotics (although NASA's planetary probes are contributing to robotics technology), genetic engineering of closed-cycle biological systems, large orbital structures, or other challenging new space enterprises. The budget restrictions of the last three administrations have not encouraged bold new R&D. NASA's plans do include continued advanced solar cell development, shuttle operations to LEO, test applications of electric ion propulsion, a modest program for experimenting with the construction of structural components in orbit, and studies of an operations center in LEO, all of which constitute first steps toward the major technological and operational challenges an advanced SPS system would present. Current NASA planning, however, will not raise U.S. space activities to a level that would support a rational future decision on a major undertaking like the SPS, and we recommend R&D emphasizing GEO operations to accomplish this.

Military. Long-range planning for future U.S. military activities in space also focuses principally on extensions of existing programs, but requirements for more advanced space systems are recognized as critical to U.S. national security. Needs for steadily increasing the payload and flight duration of the space shuttle and for better transport from LEO to GEO have already been identified, and some planners foresee future military needs for large structures and manned operations in both equatorial and polar low earth orbits and in GEO. Today's DoD mainstream space planning, however, does not include requirements for a heavy lift launch vehicle, high launch frequencies, major space bases, large space structures, advanced robotics, high electric power levels, or extensive man-tended operations in GEO. This will probably change as more experience is gained with shuttle operations and as new activities such as high energy lasers are pursued further.

Commercial

The only extensive commercial investments in space today are in communications and related services. Current planning centers on evolutionary extensions of existing systems, like direct TV broadcast from GEO. The usefulness of weather satellites is firmly established, and commercialization of remote sensing by satellite is promising as soon as the government develops a policy framework that provides a profitable opportunity for private investment. Space-based navigation systems might be a potential commercial opportunity, and shuttle transportation could be carried out by private enterprise. Beyond

these potential space business activities lie farther out opportunities in weightless materials processing and specialized manufacturing in space if future shuttle-based experiments show promise. A space operations center with laboratory facilities will have to be deployed in orbit to prove the practicality of weightless materials processing. Except for continuing advances in electronic components, commercial space activities appear unlikely to contribute significantly to the development of the future space capabilities needed for an SPS program.

Foreign and International

Among nations other than the U.S. and the Soviet Union, the outlook for future space activities is for growing competition with the U.S. in commercial and other application programs (including communication satellites, remote sensing and materials processing R&D in space) and a continuing modest but productive level of scientific activities. New conventional launch vehicles are appearing in Europe and Japan to provide freedom from U.S. control and to compete on a subsidized basis with the space shuttle, but manned space activities will continue to be limited to cooperative users of American and Soviet man-rated systems.

The Soviet Union is clearly committed to a long-range expansion of its space capabilities, with emphasis on manned space operations lasting many months. Continuing improvements in the Salyut space station, automated replenishment, and extended orbital missions by Soviet cosmonauts confirm the systematic long-range plan that Moscow has consistently described over the years: the development of large permanent space bases in earth orbit for terrestrial applications as a prelude to long duration manned voyages to the planets. Recent informed speculation suggests the forthcoming testing of a small manned shuttle and a new launch vehicle larger than the Saturn V for transporting heavy payloads to LEO. These developments would support announced Soviet long range plans. A continuing commitment to substantial military operations in space by the U.S.S.R. is also apparent, going beyond the U.S. in antisatellite systems and in manned military activities in orbit. Without postulating a major increase in the Soviet space program, their quantitative level of operations will probably exceed U.S. activities for the foreseeable future, unless NASA's success with the shuttle opens the way to a revitalized American space program.

Potential New Factors in Technological Forecasting

It is evident that all official and most unofficial long-range thinking on future U.S. space activities is constrained to relatively near time horizons and reflects today's generally pessimistic national outlook. History suggests that forecasters usually underestimate future technological progress and this tendency has been aggravated lately by the negative attitudes now prevalent in the United States toward major new technical undertakings. A more balanced long-term

view should take into account factors that suggest the possibility of a more vigorous U.S. space program in the first part of the twenty-first century than is now generally foreseen.

A principal new development that may impact the space program in the 1980s and 1990s is the number of new civilian and military users of space that will develop from experience with the space shuttle. The resumption of U.S. manned space flight after a six-year hiatus and the expansion of Soviet space station activities could create increasing public support for NASA and DoD space research during the 1980s. Continuing successes in robotic planetary exploration, new discoveries in astrophysics from the space telescope and other orbiting observatories, newsworthy international shuttle missions, and growing commercial returns from space systems could further stimulate bolder U.S. investments in space. An evolutionary long-range program to advance U.S. space capabilities might then develop along the lines of the post-Apollo Space Task Group report (1969), which recommended a balanced long-term NASA program, including space shuttles and space stations, planetary exploration, manned lunar exploration, a permanent lunar research base and the future development of extraterrestrial resources.

Such a program with long-range national goals could best be approached in a series of steps, each including an affordable financial commitment for a specific objective. These would include shuttle transportation to orbit (now initiated), the construction and operation of major space operations bases in LEO, reusable interorbit transport to GEO eventually extended to lunar transportation and surface bases. We are not forecasting this scenario, but it is a plausible alternative. It would permit America's space capabilities to evolve continuously within defined budgets for the rest of this century while creating a sound base for future advanced space undertakings such as an SPS, as they become economically practical.

Such a planned evolutionary NASA program may be encouraged by competition and cooperation among the U.S., other countries, and the U.S.S.R. Soviet perseverance and achievements in their long-range space program could stimulate closer U.S. collaboration with European nations and Japan. Given the potential economic progress of industrial nations, it is not unreasonable to anticipate increased availability of resources for space exploration and investment for the rest of the century. Barring a major conflict or economic depression, the international social, technical, and economic environment of 2000 could favor major space exploration and development projects, leading to advances beyond those envisioned today. Conversely, global political and economic disasters could turn western nations inward and away from the space frontier.

Probable Technical State of the Art in the First Decades of the Next Century

The state of space technology after the year 2000 is difficult to project. An increased national commitment to space programs would

produce advances in technology comparable to those of the 1960's. In such circumstances, the shuttle would become, by the turn of the century, the DC-3 of space transportation, and more economical space vehicles, akin to the wide-body jets, could be flying between earth, operating bases in LEO, and new man-tended facilities in GEO and on the moon. Conversely, a national neglect of space exploration in coming decades could prolong NASA's current lagging pace of development.

From these possible scenarios, we believe the most likely is that the next 40 years will see a progressive NASA program, outpacing the 1970s, but advancing at a more moderate pace than the 1960s. The cumulative result over this period would still produce very significant advances in U.S. space capabilities by 2020. We recall that manned space operations advanced in exactly two decades (April 12, 1961 to April 12, 1981) from the primitive rocket which launched Yuri Gagarin into orbit to NASA's reusable space shuttle, able to transport up to seven people and more than thirty tons of cargo routinely between earth and LEO.

The American Institute of Aeronautics and Astronautics (AIAA) recently conducted a review of space technologies likely to be available in the early decades of the twenty-first century in the absence of an SPS program (AIAA 1981). The AIAA report notes that the first requirement for space operations is reliable and economical transportation. Improvements to the current shuttle systems will probably peak in the 1990s. A next-generation launch vehicle deployed thereafter could increase performance and reduce costs by using new materials and fuels, higher engine pressures and temperatures, advanced thermal protection systems, and more economical turnaround procedures. Propulsion is the critical technology in space transportation, and new earth-to-orbit capabilities based on reusable, high performance booster engines burning cheap hydrocarbon fuels promise new economies. Bipropellant and tripropellant fuels and advanced dual-expander engines appear likely, and a single-stage-to-orbit (SSTO) vehicle capable of flying from earth directly to LEO is in prospect. Economical launch capabilities for payloads up to 100 metric tons appear to be within reach in the 1980s, based on the growth capability of the shuttle and increasing experience with reusability and low-cost refurbishment. For earth-to-LEO transportation, these developments appear to lie on a natural technology evolution path, and uncertainties concerning their realization lie more in mission requirements and economic justification than in technical barriers to performance and cost goals.

Interim transportation for limited payloads from LEO to GEO is under development with the Inertial Upper Stage and the Spinning Solid Upper Stage for launch from the shuttle orbiter. These initial systems, however, are likely to be replaced in this decade by a higher performance LEO to GEO stage using a new version of the reliable, high-specific-impulse RL-10 liquid oxygen-liquid hydrogen rocket engine. In a parallel program, economical propulsion based on low-thrust electric ion engines for possible planetary exploration or LEO to GEO cargoes will be developed further. NASA's solar electric propulsion system (SEPS) provides a good technological foundation for electric ion propulsion. This system appears to have good growth

potential, using either solar cells or nuclear electric power. By the early twenty-first century, the size of electric ion thrusters is expected to have increased from today's 30 cm to 120 cm, with enough thrust to support interorbit transfer of heavy payloads. The AIAA projection also suggests that nuclear power can probably become the workhorse energy source for ion propulsion exploration of the solar system by 2020. Magnetoplasmadynamic engines may be operationally available, and solar sailing may be developed for specific applications, but from today's perspective laser propulsion and mass drivers are considered somewhat less likely candidates for operational systems in the first quarter of the next century.

A significant increase in orbital operational capabilities and a decrease in costs would support the extension of manned facilities from LEO on out to GEO, and eventually to a lunar base. Based on NASA's successful Skylab and shuttle missions, the technology is already available to deploy and support permanent LEO bases. It is likely that continuously occupied operations centers will be deployed in both equatorial and polar low earth orbits by the end of the 1980s, with man-tended facilities in GEO possible by the middle of the 1990s. Pressure vessels designed for advanced regenerative life support systems and adequate radiation protection will be the continuing standard for occupied space structures. Large open frames, which can be deployed, assembled, or fabricated in space for antennas, interferometers, platforms, and other purposes are projected for continuing development throughout coming decades. Our lack of space construction experience is widely recognized, but shuttle experiments and the construction opportunities offered by a future LEO operations center are expected to lead to 300 meter diameter structures for antennas and other applications in the 1990s. Robotics are expected to play an increasingly important role in economical space fabrication and repetitive assembly.

Major orbiting facilities and high levels of space activity will require significant maintenance and support capabilities. A LEO operational center can provide experience with on-orbit service, transfer of fluid and solid cargoes, assembly of structures, vehicle docking, checkout and relaunching, and maintenance and repair of satellites and space vehicles. Wolfe (Appendix D) points out NASA's lack of experience in such orbital operations as fluid transfer. Current Soviet programs include liquid transfer in orbit, so it seems probable that U.S. experience in LEO over the next few decades will make possible routine orbital servicing well before 2020.

Improved materials are essential to future space technology, from engine components to structural beams. We can anticipate the steady introduction of new high-temperature alloys of molybdenum, tungsten, and other metals, of new ceramics, and new composites developed for space applications. In addition to ground-based research, materials processing research in orbit may lead to additional new materials and techniques for space applications, like gossamer structures, foamed metals, and evaporated metal and semiconductor films.

Other technologies relevant to space activities are expected to advance rapidly in coming decades (AIAA 1981). For example, the AIAA

report projects substantial improvements in photovoltaic cell life, conversion efficiency, weight, cost, and resistance to radiation (see also Appendix E). Improved solar cells for space applications are important to NASA, the Department of Defense, and commercial programs, so this technology is likely to continue to receive adequate emphasis. Communications and data management system requirements will stimulate continuing major advances in microelectronics, and lasers will be increasingly employed for direct communications between satellites. Similarly, demands on navigation, guidance, and control systems should lead to robotic systems that sense requirements, recognize patterns, make decisions, and take actions with minimal human intervention.

The role and scale of man in space in the first quarter of the next century is difficult to project, but manned missions in LEO should become more frequent and productive. Providing life support system--environment, food, hygiene, safety, and physical and emotional health--will continue to be expensive. Human effectiveness in external operations at GEO is uncertain, owing to the cost of transportation, life support, and radiation protection. In the next century, people operating in LEO can carry out research and can control and direct robots or automated equipment in the fabrication, erection, maintenance, and operation of platforms and facilities in space. The major uncertainty is the degree to which man's physical presence is required in GEO and the degree to which robots and remote teleoperators can be developed to perform effectively there with minimum on-site manpower.

Overall, the advancing technological environment of the early twenty-first century should be increasingly hospitable to new space programs such as an SPS. The difficult question to answer now is whether the costs of orbital operations about 2020 will allow commercial space developments to be competitive with advancing terrestrial systems. The development of space robotics is an important new factor here, but this has not yet been sufficiently programmed by NASA for projections to be made. Other shortfalls, not yet identified, may also be discovered, but the major problems of economic transport to LEO, interorbit transfer, LEO and GEO space stations, construction of large structures in orbit, and availability of new materials and components appear susceptible to resolution well before 2020 with a well-planned NASA R&D program.

ASSESSMENT OF TECHNICAL FEASIBILITY

Technical feasibility will be discussed in terms of four specific areas: Transportation Between Earth and LEO, Transportation Between LEO and GEO, SPS structural Design and Construction, and SPS Operations and Maintenance.

Transportation Between Earth and LEO

The requirements of the reference SPS for earth-to-LEO transportation are unprecedented in comparison with those of any

other proposed space system. Earth-to-LEO transport accounts for about 80 percent of all transportation costs and roughly 20 percent of the total cost of the reference system. Development of a transportation system to do the job reliably and economically would clearly merit high priority.

Among the key elements of the reference system SPS, the heavy lift launch vehicle (HLLV) has the broadest technical foundation and requires the fewest technology advances. Unlike massive space construction, economical interorbit transport, and efficient energy collection and transmission, the HLLV builds upon Apollo and the space shuttle. It represents an extension of demonstrated technology rather than new technology, and its proposed performance can probably be achieved. Nevertheless, alternative concepts employing more advanced technologies should be considered in the search for higher performance at lower costs than those offered by the HLLV. Such alternatives may go beyond the space shuttle to such new approaches as the single-stage-to-orbit vehicle (SSTO) which would fly directly from earth to LEO, perhaps using airbreathing engines for initial acceleration. SSTO would require a major development effort, but substantial operational savings might be achieved. New types of fuels and engines, smaller vehicles and payloads and particularly new ground support organizations and facilities should be examined to develop the optimum earth-to-LEO transportation system.

The massive (250t-400t) payloads and high thrust requirements of the reference system HLLV suggest a high-density fuel in lieu of hydrogen for the booster stage. Methane is proposed, leading to the requirement for a new high pressure, high temperature hydrocarbon booster engine. Although not required by NASA's on-going programs, a reliable hydrocarbon-fueled engine which can be reused more than 50 times appears technically achievable.

A new thermal protective system (TPS) for reentry is another challenging technology advance. TPS alternatives were extensively explored in the space shuttle program and the current tile TPS was selected, but it appears inadequate for the HLLV. NASA is already pursuing alternative systems, including metallic approaches, and it appears likely that a solution will be found. In addition to the TPS, reusable insulation is needed for cryogenic fuel tanks. Reusable tank insulation has not previously been called for in space operations, and will require some development effort.

An HLLV equal to, or even superior to, the reference system performance can probably be developed by the next century. The most critical HLLV components are those associated with low-cost refurbishment and turnaround. Space shuttle operating experience will provide data on spacecraft reuse; Columbia's tile TPS showed little degradation after its initial flight. The Aerospace report (Wolfe 1981) points out that recurring costs are the major HLLV cost drivers, and that spares, overhaul, and refurbishment required after each flight are the principal components. (See section on Assessment of Costs Estimates.) From a technology standpoint, this emphasizes the necessity of developing highly reliable, durable, and easily repaired HLLV systems and subsystems. R&D efforts to achieve low-cost

refurbishment and turnaround of the HLLV can produce large returns through operating economies. Aerospace (Wolfe 1981) points out that the fastest turnaround is not necessarily the lowest cost turnaround; the amount of effort required to accomplish the repairs, replacement, and refurbishment is more cost critical than the duration of the turnaround period.

A separate personnel launch vehicle (PLV) was proposed for the transport of personnel from earth to LEO in the reference system. The PLV was essentially based on an upgraded shuttle with a cabin pod adaptable for use in a similar vehicle to carry personnel from LEO to GEO. The safety requirements for such man-rated vehicles are stringent, but there appear to be no technical obstacles to their development. There is, however, a question whether a special PLV is required for earth-to-LEO transport, or whether selected HLLV fleet units could be man-rated to accommodate personnel pods. This economical alternative is under consideration by DOE/NASA.

The earth-to-LEO transportation element of the reference system SPS appears achievable but expensive in this century. New HLLV concepts promising lower costs after 2000 should be explored as part of NASA's on-going programs. Improving the economics of earth-to-LEO transportation for all applications warrants a major R&D effort in coming decades.

Transportation Between LEO and GEO

Most SPS concepts require the economical movement of large quantities of material and personnel between LEO and GEO; this is well beyond today's experience, and can only be accomplished through the development of entirely new interorbit transportation systems. Personnel transport in the reference system relies on chemical rockets to achieve rapid transit of the personnel orbit transfer vehicle (POTV) through the Van Allen radiation belts. The POTV would differ greatly from the solid-fueled Inertial Upper Stage (IUS) and the Spinning Solid Upper Stage (SSUS) now being developed for interorbit transfer in the 1980s. POTV propulsion would probably be based on extensions of NASA's advanced hydrogen-oxygen rocket engines, and the passenger compartment would probably be a modification of the personnel module proposed for the PLV.

Low cost transport of heavy cargo from LEO to GEO in the reference system utilizes an electric orbit transfer vehicle (EOTV) to provide slow but very efficient transfer. The EOTV propulsion concept is based on NASA's Solar Electric Propulsion System (SEPS), which is now in the demonstration phase. The EOTV structural concept is like that of an SPS power satellite: a 1 km square truss, 1/2 km deep, covered with solar cells and incorporating a cargo platform to hold 4,000 tons (10 HLLV payloads).

A successful EOTV would represent a breakthrough in the low cost transport of cargo from LEO to GEO. Chemical rockets appear prohibitively expensive, but the costs of LEO-to-GEO cargo transport using an EOTV would not be a major factor in the total costs of an SPS,

although interest costs during the six month trip from LEO to GEO must be considered. The successful development of some form of low cost LEO to GEO transport is essential to both the technical and economic feasibility of an SPS. Resolving the technical uncertainties of the EOTV deserves high priority, and can lead to many applications for transfer between orbits and for high energy missions beyond earth orbit.

EOTV Power Sources

The reference system EOTV employs solar cells to provide the power for its efficient thrusters, and both silicon and gallium arsenide cells were under consideration by DOE/NASA for this purpose. As detailed in the report of the Working Group on Photovoltaics (Appendix E), serious questions exist not only about the projected costs of photovoltaic cells, but also about the feasibility of annealing them (particularly the silicon cells) to remove radiation damage. Solar cells used to power EOTVs will be exposed to more severe radiation than SPS cells in GEO during the EOTV's long exposure in the Van Allen belts on each passage between LEO and GEO. Potential solutions to the problem of photocell radiation damage include the use of materials other than silicon, with gallium arsenide a primary candidate. Materials exist that promise to be both more radiation resistant and more easily annealed than silicon, although it is not yet clear how they will resist severe temperature cycling during earth eclipse periods. The utility of a solar-powered EOTV depends in part on resolving these questions, and future research on photovoltaic cells for space applications should include consideration of their ability to power interorbit transportation.

Dynamic Control of an EOTV

The photocell-powered EOTV of the reference system is a large vehicle whose location, thrust vector, and orientation with respect to the sun must be carefully controlled at all time. The vehicle must be under continuous control during LEO construction and launch, during its six month flights through eclipses and Van Allen belts, and during loading, off-loading, and servicing after each flight. A separate hydrogen-oxygen power source is required for the vehicle's control system and for periods when the EOTV is in the earth's shadow.

Electric Thrusters

Successful development of the 120 cm ion thrusters proposed to power the reference system EOTV will require a major scaling up from the current 30 cm thrusters of the SEPS. If today's smaller engines had to be used, however, a relatively small amount would be added to the estimated cost of each SPS satellite in the reference system, roughly 2.5 percent if 60 cm engines were used, and 5 percent if 30 cm

engines were used. Although these percentage increases are relatively small, their absolute values reach several hundred million dollars per satellite, more than enough to pay for developing the 120 cm engines. Additional design trade-off studies appear warranted here, including low maintenance and turnaround costs in space.

EOTV Integration

The breakthrough in economical transport to GEO represented by the EOTV rests on an array of new technologies--more than for any other element of the reference system. In addition to the major ones cited above, there are complex electric power systems, mechanical operating systems, and separate and extensive fuel systems for the main thruster propellant (argon, in the reference system) and for the hydrogen-oxygen control system thrusters. The integration of these new technologies and systems into a kilometer-sized vehicle that must operate unattended and navigate stably for 6 months is a difficult challenge. We believe that EOTV can only be achieved by a major development program. It is such a potentially valuable capability for future space programs of many types that we recommend that NASA explore EOTV and alternative low cost LEO-to-GEO possibilities. We believe that alternative electric power sources, such as nuclear or possibly solar-thermal, should be studied for use as backups if solar cell problems appear intractable for EOTV purposes. Nuclear electricity would also be useful for high energy orbital changes and missions to the outer solar system beyond the range of solar collectors.

Structural Design and Construction

Each of the 60 power satellites of the reference system SPS is a huge open frame structure in the form of a rectangular prism, roughly 10 km x 5 km x 0.5 km, to provide a 50 square km planar area for solar arrays. Internally, this 50,000 ton structure is composed of triangular lattice-work sections fabricated from lightweight materials. Before building the 60 power satellites, major orbital bases must be built in both LEO and GEO. Although these orbital construction and support bases appear more complex and difficult to build and operate than the power satellites themselves, the power satellites were better defined, more numerous, and more expensive, so we confined our structural assessment to them.

The reference system power satellite is orders-of-magnitude larger than any existing spacecraft, and requires structural fabrication and assembly, which have never been attempted in orbit. Some key technical factors in considering the feasibility of rapidly building these huge satellites in GEO are the SPS structural design (including construction materials), the control system to be employed, and the automated construction process.

Structural Design

The reference system structural design employs a traditional truss structure similar to those regularly built on earth. The 10 km length, 5 km width, and half km depth reflect the area required for solar arrays and the depth required for structural stiffness. Design loads include those from gravity, thermal transients, solar wind, control system thrusters, and transients incurred during construction and maintenance. Selection of construction materials is complicated by considerations of weight, cost, strength, ease of joining, resistance to cosmic and solar radiation, reaction to extensive thermal transients, the proposed fabrication process (rolling structural shapes on site in orbit), and the projected mix of men and robotic devices.

Independent observers who have reviewed the structural design have emphasized the existence of significant unresolved design questions, but have generally not faulted the structural analysis work to date. They have, however, called for study of more innovative structural concepts which take better advantage of the unique space environment. These new structural concepts would rely more on tension members, membranes, mirrors, "gossamer construction" techniques, gravity gradients, centrifugal forces, evaporated films, and other techniques (Naugle and Bekey 1980; NASA 1980a, 1980b). We concur with the thrust of these comments and recommend that lighter weight, lower costs, simpler alternatives be explored. The massive structure of the reference system is more reminiscent of 19th century railroad bridges than of creative design for the next century. Success here would significantly reduce the total costs of a future SPS.

Control System

A large satellite without an active control system is unstable. The control system must keep the satellite stable at all times, and maintain it on location with the proper three-dimensional orientation.

Each power satellite, from the outset of its construction to its operational mode in orbit, is a dynamic structure, subject to multiple loadings. As the structural configuration changes during construction, new transient loadings are applied--the solar blanket, the control thrusters, and the antenna. Translation loadings and accelerations are applied as the growing structure is cantilevered outward from its construction base. Once separated from the base, the orbiting body must rely entirely on its own control system, with the transition carefully managed.

On station, the huge solar array must be maintained perpendicular to the sun while the antenna is kept aimed at the rectenna on the earth below. This requires a continual change in the relative attitudes of those two main elements as the antenna rotates once a day. The satellite must be precisely maintained in its orbital slot to avoid collision or interference with adjacent satellites despite changing thermal, solar wind, and gravity loadings. Additional control system requirements for the EOTV include navigation from LEO, with periodic

eclipses, and a slow passage through the Van Allen radiation belts on the six-month voyage to rendezvous with a construction base in GEO.

A reliable control system capable of coping with these changing conditions (particularly those during construction) represents a major extension of current art, requiring new analytical approaches and techniques. Because ground-based testing cannot reproduce all of the forces encountered by these large structures in GEO, control system development will require a high degree of modeling and extended dynamic analysis.

At NASA's request, independent observers have reviewed the scope of the control system requirements and progress in resolving the open questions. They felt that the demanding requirements of the control system may not have been fully appreciated, and suggested that the limited work on this problem to date does not justify full confidence in ultimate success (NASA 1980a). We believe the development of reliable and effective control systems for the SPS structures and vehicles is a task of first order difficulty and criticality. We believe it can best be accomplished through a combination of ground based analysis and space flight operations.

Automated Construction

Orbital construction is a technology about which little is known, negligible experience exists, and ground-based testing is generally ineffective. Constructing one 50,000-ton reference SPS in GEO every six months would require new space construction techniques and a high degree of automation. It can be thought of as erecting the framework of a floating office building 6 miles long, 3 miles wide, and 150 stories high. The tools, special fixtures, major items of equipment and construction bases have not been developed for fabricating and handling materials and for making joints and built-up structural members in space. A small prototype beam machine has demonstrated the automatic fabrication of structural shapes from rolls of thin metal and their subsequent automatic joining into a beam. With that exception, the materials, hardware and techniques of space construction are still in the preliminary stage. DOE/NASA studies reflect this current lack of knowledge and experience, but NASA representatives reported plans for experimental space construction as part of the on-going space program in the 1980s.

Reference system plans include extensive reliance on robotics, with which we concur. We question the concept of hordes of skilled mechanics in GEO operating enormous fast-moving equipment in this high and highly repetitive construction project. We are unable to define the scope and level of sophistication of robotics that may be required and feasible, but we lean toward bold application. We were also unable to identify specific NASA programs or commitments to develop the appropriate degree of robotics capability for precision space construction and we recommend that a modest start be made by a project such as constructing in orbit a 300 meter diameter steerable antenna. This, or an equivalent project, would demonstrate the space

construction capability required in coming decades, regardless of future decisions on an SPS.

An independent review of reference SPS orbital construction concepts (Mosich 1981) identified a number of unresolved questions, particularly in joints, fittings, alignments, and structural oscillations. In some cases, the time estimated by the reviewer to complete construction tasks was many times longer than called for in DOE/NASA studies. In other cases it was not clear what techniques and hardware could be developed to carry out the proposed rapid, continuous construction of the reference SPS. We believe that the automated handling of 600 meter beams with 225 meter cranes, and the precise installation of 15 meter long end-fittings on 12 meter deep beams with a work force in GEO, lie outside the realm of reliable scheduling and cost estimating today.

In spite of these substantial uncertainties, we believe that a space construction capability can and should be developed at an early date and demonstrated on a small scale as recommended above. This requires new techniques and hardware rather than discovering new principles. The increasing capability of robotics, now advancing rapidly in private industry, will be the key to rapid construction of large space structures in the 1990s.

Even if automated space construction technology is developed, other important questions remain for the reference SPS. One concerns the six-month construction schedule assumed for each reference SPS satellite. Based on the limited information available, we believe this time is too short. We also believe that there is inadequate information on which to base a realistic construction schedule, given the unprecedented size, design complexity, and unproven construction techniques of the reference SPS.

Another important issue in reference SPS space systems planning is the allowable degree of worker exposure to cosmic and solar radiation in GEO, including solar flares. (This problem is discussed further in Chapter 4 and Appendix G.) Nearly all construction work in the reference SPS is proposed to be done in GEO rather than LEO, but workers exposed to solar electron flux while living and working in GEO will require protective systems beyond those proposed in the reference system. NASA is aware of the need for additional effort to resolve this issue, including consideration of additional shielding to reduce exposure levels by a factor of 10 (R. A. Frosch, NASA, personal communication, October 7, 1980). The Aerospace Corporation concluded that the added weight of the additional radiation shielding required by current standards would probably not pose serious cost problems (Wolfe 1981). The effectiveness and impact on worker productivity and costs of whatever protective measures are used must be assessed. These considerations will significantly affect the trade-offs between construction in LEO and GEO, and between human workers and robots.

Information is still incomplete on the GEO radiation environment, the level of protection required, and the design, effectiveness, and cost of feasible protection systems. This area requires further work. Establishing a small man-tended base in GEO would provide operating experience in this critically important region. This program should

establish the feasibility and cost of manned construction, operations, and maintenance and repair in GEO, which will be important to many space operations as well as a possible SPS.

Operations and Maintenance (O & M)

Economically operating and maintaining SPS equipment and facilities in GEO over their thirty-year lifetime presents technical challenges that go well beyond the experience obtained in Apollo, Skylab, and other space systems. Some relevant facts will be gained from the shuttle program, but an SPS requires unique O & M activities. For example, the reference system envisions permanent manned facilities at GEO, with 60 power satellites spaced along a 48,000 km orbital arc over the Western Hemisphere, all requiring visits for continuing O & M. Another challenge is the fleet of orbital transfer vehicles based in space which require on-site refueling, refurbishing, and maintenance of engines, structural members, controls, and other subsystems. The EOTV in particular would require new O & M techniques for orbital rendezvous, docking, mooring, and transfer. As previously discussed, a potentially serious operational issue is the long-duration exposure to radiation in GEO of O & M personnel who are required to work away from the shielded GEO base to maintain and repair operational satellites. Whether remote systems can be designed to provide the necessary protection for manned servicing in GEO remains to be seen.

This consideration points again to the critical importance of minimizing the use of people in GEO by maximizing the potential of robotics and teleoperators. For example, the reference system envisions the removal and replacement of about a dozen klystrons per satellite per day, even assuming an average klystron life of 25 years. In the reference SPS most of the people stationed at GEO to perform maintenance functions would be engaged in repairing and replacing these klystrons. If a 25-year klystron lifetime cannot be achieved, the cost increment would be significant--almost \$3 billion additional cost per year for tubes with a 12.5-year life--and clearly enough to warrant a substantial development effort to extend tube life.

Among the O & M challenges of the reference SPS are the transfer and storage of large quantities of cryogenic fuels and other fluids, and the refurbishment of ion engines in orbit. Although orbital fluid transfer is recognized as essential for future space activities, NASA has not yet developed experience in this field. An LEO operations base would provide this. Ion engines require precise alignment and positioning of electrodes, the larger the engine the harder this may be. Refurbishing these engines would probably be performed by skilled technicians at the LEO base.

The total spectrum of on-orbit servicing, maintenance, and repair activities entails a number of technical and cost uncertainties. Some of the problems are not well understood, others have probably not yet been identified. The known problems have generally been addressed with idealized concepts. Although none of these tasks appears beyond achievement with reasonable effort, practical experience will be

required before realistic O & M cost estimates will be available. An evolutionary NASA R&D program would provide the required valuable GEO experience whether an SPS program is initiated or not.

ASSESSMENT OF COST ESTIMATES

No official cost estimates were available for the reference system SPS, but unofficial cost data prepared by DOE/NASA contractors were generously made available to the Working Group (Boeing 1980, Handley 1980). In addition, a contract with the Aerospace Corporation provided an independent assessment of space transportation costs (see Appendix D).

DOE/NASA estimates indicated that space transportation would represent about 25 percent of total reference SPS program costs, and that 80 percent of these transportation costs are attributable to earth-to-LEO transport via the HLLV. Because of this cost sensitivity, both the Working Group and the Aerospace Corporation concentrated their attention on HLLV costs.

The Aerospace Corporation cost analysis (Wolfe 1981) employed cost estimating relationships (CERs), empirical factors which relate costs to specific parameters of a vehicle or structure, such as mass, volume, or surface area. Initial Aerospace estimates of the total costs of the HLLV as designed by the contractors (including R&D, fleet acquisition, and operation and maintenance) ranged from 1.4 to 2.2 times the contractors' cost estimates. Aerospace then modified the HLLV designs to use more conservative weight estimates (and other factors) and reestimated the earth-to-LEO costs. This resulted in the initial cost factor of 1.4 increasing to 1.7 and the initial factor of 2.2 increasing to 3.0, although Aerospace estimate of HLLV weights exceeded those of the contractors by only 15 percent. Both the contractors and Aerospace noted the criticality of the recurring costs of HLLV operation, especially spares, overhaul, and refurbishment. Cost of operations are almost 2/3 of total HLLV system costs.

The Aerospace estimate of total EOTV weight exceeded the contractors' estimates by about 50 percent. A separate cost estimate of the EOTV was not prepared by Aerospace, but since weights are so critical in cost estimates, contractor estimates of EOTV costs are probably also low. Closely related to this is the Aerospace judgement that the EOTV is a high risk development from both the technical and cost standpoint.

Cost sensitivity analyses were also prepared by Aerospace for other selected space systems whose performance would significantly affect reference SPS total costs. These analyses indicated that total reference SPS costs are particularly sensitive to the mass of the power satellites (which directly influences the number of HLLV flights), and to the turnaround maintenance and refurbishment requirements of the HLLV between flights. For example, doubling satellite mass increases total system cost 40 percent; replacement of an additional 1 percent of the HLLV thermal protection system (TPS) increases total system cost by 1 percent; and replacement of an additional 4 percent of the HLLV

avionics increases total system cost by 10 percent. Reductions in these parameters would produce comparable cost savings.

The sensitivity of total SPS system cost to HLLV turnaround effort points out the importance of utilizing space shuttle experience in the next decade to develop more efficient and economical turnaround procedures. The cost sensitivity to total satellite mass is important because the reference SPS mass may have been underestimated. The principal contributors to satellite mass are the solar array and structural elements. We recommend that NASA restudy the design concept of each of these key elements. Future design alternatives should emphasize major weight reduction as well as improvements in cost and performance.

We were unable to assess the costs of space construction or of orbital operations and maintenance--neither experience nor adequate descriptions of the efforts required are now available for reliable estimates. A forward looking NASA program would help rectify this. An extremely important assumption in reference SPS cost estimates is the six months construction schedule. We believe that this period is too short, but were unable to judge by how much or to assess the cost implications of longer construction periods. An Aerospace Corporation internal study (Mosich 1981) indicated that reference SPS construction operations would require more time than previously contemplated. We concur with Mosich's judgement that adequate information is not currently available to make meaningful schedule and cost assessments.

Based on all of the information available to us, the Aerospace Corporation estimates and analyses appear reasonable. The significant discrepancies in HLLV transportation costs estimates (factors of 1.7 to 3.0) are particularly troubling because they are in the area of launch vehicles, where the best experience and data exist.

Overall, it appears to us that the total transportation costs of the reference SPS may be 2 to 3 times the estimates of the DOE/NASA contractors. Future progress in space transportation should reduce this. It also appears that growth in reference SPS satellite weight and extension of the construction schedule would generate additional substantial costs increases. Refinement of these assessments would not be productive since it is clear that a future SPS will employ more advanced technologies and more economical designs than those of the reference SPS. Based on experience with cost trends of space transportation and communications, the costs of an advanced SPS could become competitive around 2020. Better data for future schedule and cost estimates of advanced SPS systems and other projects would be obtained in a forward-looking program to gain initial experience with space construction in LEO and man tended operations in GEO.

POTENTIAL USE OF EXTRATERRESTRIAL RESOURCES

It has been suggested that construction of an SPS could be enhanced and costs reduced by the use of lunar or other extraterrestrial resources (see, for example, Criswell and Waldron 1978). The long-range possibilities are intriguing and deserve some consideration.

The Apollo missions of the 1960s proved the technical feasibility of travel to the moon. From 1968 to 1972 NASA astronauts dramatically demonstrated the effectiveness of manned lunar exploration, but American's bold voyages to the moon ended with Apollo 17 in December, 1972. During the rest of the 1970s NASA concentrated its diminishing budgets on the reusable shuttle to initiate reliable, low-cost transportation between earth and LEO. The shuttle was envisioned as the critical first step in an economical space transportation system (STS). The STS would then be extended out to GEO in the 1980s, via a LEO base and an orbit transfer vehicle, and in the 1990s outward to the moon.

Today, however, NASA has no approved program to create a LEO operations base (although there are preliminary plans for a modest space operations center), and no program to extend the STS to GEO, and beyond to the lunar surface. NASA has no program to establish a lunar research station, to explore the moon's resources, to develop advanced robotics for automated processing of lunar materials, or to experiment with an electric mass driver for future low cost transport of cargo from the moon. Until NASA initiates such programs, the use of lunar resources must realistically be considered to lie in the indefinite future. With current extraterrestrial resource activity confined to modest paper studies, it is difficult today to judge the potential significance of lunar or asteroidal resources for future SPS systems.

Only one-twentieth the energy is needed to deliver a payload from the surface of the moon to geosynchronous earth orbit as is required to deliver the same payload from earth (Criswell and Waldron 1978). The potential savings in energy and costs associated with this difference are the primary reasons for proposals to use extraterrestrial materials to build an SPS in GEO. Bock (1979) and Miller and Smith (1979) claimed that if 95 percent of the mass of a future SPS were obtained from the moon, the potential savings could approach 30 percent of the total project cost, although this result depends on estimates of costs of other activities required to build an SPS.

These estimates of potential cost savings appear to us to be premature. Not all the elements required for an SPS may be found on the lunar surface. Aluminum, magnesium, and silicon are certainly available, but not necessarily in concentrated deposits; zinc, molybdenum, and other metals important for making alloys, may be deficient on the moon (Ayres et al. 1979). Although oxygen is plentiful in lunar soils, hydrogen is scarce (Arnold 1976), so it may be necessary to import hydrogen or water from earth at high cost for lunar industrial activities (Williams 1976). Mining and beneficiating extraterrestrial materials to produce raw stock and then fabricating finished products on the moon for transport to GEO introduces many costly complications compared with simply launching finished components from earth. Despite the energy savings, it is not clear that extraterrestrial materials can be processed in space and components fabricated there at net costs lower than launch from earth as proposed in the reference SPS.

Nonetheless, lunar resources may become progressively competitive in the next century, starting with oxygen extracted from lunar rocks

for refueling lunar spacecraft. Six steps will be required to achieve lunar resource development. They are, with estimated potential times of initiation:

- (1) establishment of a LEO orbital base (1980s)
- (2) extension of the reusable STS to GEO and the moon (1990s);
- (3) establishment of a lunar research base (2000);
- (4) development of advanced space robotics technology (continuing);
- (5) development of automated lunar resource mining, processing, and fabrication, starting with oxygen from lunar rocks (2010); and
- (6) operation of an electric mass-driver for economical transport from the moon (2020).

NASA programs in these fields on this approximate timetable could be combined in the next century to initiate the utilization of selected extraterrestrial resources. These six development steps appear technically possible, with potential major spin-offs, but would require a vigorous and future-oriented U.S. space program based upon an accepted long-range plan. Such a phased NASA plan appears economically practicable in concert with other long-range national goals, but it remains to be developed, accepted and initiated. Lunar resources development would proceed naturally within the framework of the multi-decade national space program proposed last year by Senator Schmitt (Defense Daily 1980).

We conclude that any future decision to proceed with an SPS program should not rely on a concurrent decision to utilize lunar or other extraterrestrial resources. Foreseeable SPS programs should be based upon the use of earth-based resources if the path of least complexity is to be followed. Once space-based construction is demonstrated, it may become practical and desirable to fabricate materials in space from resources recovered on the moon or asteroids. In the initial stages, however, it appears more realistic to base cost estimates on the use of earth-based resources, thus minimizing the number of new technologies that must be developed successfully to achieve an SPS.

CONCLUSIONS AND RECOMMENDATIONS

In this section we summarize our principal conclusions on the technical feasibility and cost of the space system of a future SPS program and recommend specific actions.

Technical Feasibility

The technical feasibility of future SPS systems depends upon evolutionary technological advances and operational experience in many areas, most of which are also required for other advanced space systems, but on a much smaller scale. We have identified no major problems not covered in the NASA/DOE assessment, although we differ in the relative importance of some issues. Our review indicated that the

greatest technological challenges for a future SPS lie in two areas: low cost transport to LEO and GEO, including the EOTV, and automated space construction. For these and other critical technological areas, special attention should be given to monitoring and evaluating progress in the next two decades, looking toward the day when an advanced SPS may become feasible.

The Electric Orbit Transfer Vehicle

EOTV success depends on the development and integration of many new technologies and techniques; each of these appears possible, but in aggregate they constitute a major technological challenge. The electric ion engines for propulsion, and the complex control system for stability, navigation, and orientation are demanding, but probably achievable. The huge EOTV structure and solar array are formidable, but most of the required technology can be expected to flow from the development of the SPS satellites. Repeated passages through Van Allen radiation belts and eclipses in the earth's shadow, however, are peculiar to the EOTV, and present special problems for solar cells and perhaps other EOTV elements. Nuclear generation of the electric power required for ion propulsion is suggested as a back-up that would also be useful for outer planet missions. The on-board EOTV electrical, fuel, and mechanical systems are extensive and complex; their integration would be a demanding task.

We recommend special NASA attention to low cost interorbit transfer in the next decade. The recognized significance of low-cost interorbit transportation for future space operations should make this a sound investment whether or not an SPS program is ever initiated. We recommend that the EOTV be further studied to establish whether it can be developed as a highly desirable breakthrough in low cost space transportation.

Automated Space Construction

Rapidly building the huge reference SPS truss structures in GEO would require the development and demonstration of large-scale automated space construction technology using novel engineering concepts and unique equipment. This would probably involve major advances in robotics for space construction. Radiation protection for space workers in GEO will impose limitations on their performance and productivity which must be resolved. Research and development on economical space construction techniques should be an essential part of NASA's programs. We believe that NASA can develop practical systems for the economical construction of large structures in space. For example, a smaller structure, such as a steerable 300 meter diameter antenna, built in LEO would be a logical first step to develop and demonstrate space construction techniques. For the reference SPS truss design we see at least three major problems: the strong possibility that the six-month construction schedule is unachievable (with major

cost consequences), the possibility that the construction bases in LEO and GEO cannot achieve the assumed productivity, and the possibility that radiation exposure protection for workers in GEO may greatly inhibit manned construction activities there.

Heavy Lift Launch Vehicle

Transporting large quantities of material and personnel from earth to LEO appears to be technically possible using a vehicle like the reusable HLLV of the reference system. The primary technical challenge is very low-cost turnaround through the development of reliable hardware that minimizes recurring launch costs. Many HLLV technology requirements are likely to be met by future NASA development programs in the continuing effort to improve the shuttle and upgrade the nation's space transportation system. We believe that NASA should also consider entirely new concepts, vehicles, engines, fuels, and procedures beyond today's space shuttle, with turnaround economy and systems reliability the primary goals.

Alternative SPS Systems

We believe that the current reference SPS system has outlived its usefulness. Future SPS efforts should explore new concepts and consider improved systems that take into account recent DOE, NASA, NRC, and other studies. Major reductions are required in mass and manpower in orbit to achieve substantially lower costs. The search for radical alternatives should include approaches which offer flexibility in the amount of electrical power delivered and are adaptable to incremental robotic construction and demonstration programs.

Potential Use of Extraterrestrial Resources

We believe that a vigorous NASA program in coming decades including the extension of the space transportation system to the moon and the establishment of a lunar base about 2000 could make extraterrestrial resources promising after 2020. Extending manned operations to GEO is a major first step toward a return to the moon. Without a long-range plan for the rest of this century it is premature to consider the use of lunar or asteroidal resources for the construction of an SPS or any other purpose. The availability of extraterrestrial resources in the next century depends upon the timing of NASA's return to the moon, lunar surface exploration, robotic resource development, automated materials processing and fabrications, mass driver programs, and asteroid missions; none of these programs exists today. Until lunar plans and programs are initiated, no realistic estimates can be made of the future availability and costs of extraterrestrial resources.

Space System Costs

Our best estimates of the costs of transporting the mass required by the reference SPS from earth to LEO are 2 to 3 times the estimates of NASA's contractors. Space technology advances will reduce these costs in future decades. Given the uncertainties in the technologies of electric interorbit transfer and automated space construction, we cannot reliably assess the costs of these significant elements of the reference SPS, but suspect that these have also been underestimated. We conclude that these space system costs preclude the reference SPS from becoming competitive with terrestrial sources of electric power, but that more advanced SPS designs taking better advantage of the space environment coupled with future technological advances could make an SPS competitive sometime after 2020.

RECOMMENDED ACTIONS

Based on our assessment of the uncertainties in the space systems of the DOE/NASA reference SPS, and the gap between today's space technology and that required for a cost competitive SPS, we conclude that a specific SPS program should not be established now, and probably not for the next decade. We believe, however, that a more advanced SPS may become an important national option in the next century, and that space technology could be developed to support it by that time. Therefore, we conclude that a future SPS option should not be foreclosed.

While we believe that the reference SPS should now be abandoned, we recommend that NASA continue conceptual studies on promising new SPS concepts. We recognize, however, that a meaningful SPS option will in fact be foreclosed unless sufficient research, development, and testing are conducted on the main elements of a future SPS to provide a basis for sound assessments of feasibility and cost.

We believe that the basic elements of foreseeable future SPS systems would include:

- Economical shuttle operations between earth and LEO, as a prelude to a next generation reusable vehicle designed to achieve much lower launch cost per pound of cargo,
- Deployment of a LEO operations center, including robotic construction capability to build, large structures in orbit (e.g., a 300 meter steerable antenna),
- Economical LEO-to-GEO transportation systems for men and cargo, including low-cost electric orbit transfer or alternative systems,
- Space-qualified, efficient, very low-cost, lightweight photocells, or equivalent solar collectors, and
- Construction in LEO, and later transport to GEO, of a man-tended base designed for the GEO radiation environment.

We do not believe that research and development directed at these objectives should be part of an SPS project or be primarily justified by its relation to SPS. These technological objectives are not unique to SPS, however, and represent logical steps in the future development of space technology independent of an SPS project. We conclude, therefore, that preserving a meaningful future SPS option requires a forward looking U.S. space program that includes R&D directed at the above objectives.

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APPENDIX D*

REPORT BY
THE AEROSPACE CORPORATION:

SATELLITE POWER SYSTEM (SPS) TRANSPORTATION
COST ASSESSMENT STUDY

January 1981

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Prepared for

NATIONAL RESEARCH COUNCIL
ENVIRONMENTAL STUDIES BOARD

NATIONAL ACADEMY OF SCIENCES
Washington, D.C.

Subcontract No. CNR 20-80-358 of
Prime Contract No. PRM-7919687
Aerospace Report No. ATR-81(7898)-1

*This appendix is a reproduction of the report prepared by The Aerospace Corporation. It has not been edited to conform in style to the rest of this volume.

FOREWORD

This report documents the results of a study for the National Research Council (NRC) Environmental Studies Board of the National Academy of Sciences. It is concerned with the transportation segment of the Satellite Power System program, and will serve as part of the technical input to an assessment of the total program that is being conducted by the NRC Committee on Satellite Power Systems. A Committee final report is planned to be published June 1981.

The study was performed under Subcontract No. CNR 20-80-358 of Prime Contract No. PRM-7919687 entered into by and between the Academy and the National Science Foundation. The Aerospace effort was managed by Dr. Malcolm G. Wolfe, Space Launch Vehicle Division. Technical monitoring was provided by Dr. Myron F. Uman, Senior Staff Officer, Environmental Studies Board.

ACKNOWLEDGMENTS

The weight analyses reported in this document were performed by J. E. Kimble, Vehicle Design Subdivision, Vehicle Engineering Division. The cost analyses were performed by H. G. Campbell, Resource Analysis Directorate, Advanced Orbital Systems Division. The invaluable contributions of the following Members of the Technical Staff at Aerospace to the technology assessment are also gratefully acknowledged:

M. Aswani	R. B. Laube
F. X. Appell	R. A. Meyer
D. G. Bienhoff	A. F. Robertson
D. R. Croley, Jr.	D. D. Thomas
W. F. Davenport	K. A. Turner
B. C. Edgar	E. K. Weinberg
R. H. Holzworth II	K. L. Wilson
F. L. Knight	E. G. Wolff

Miss B. Madison and Mrs. M. L. Smith of Aerospace Space Launch Vehicle Division provided dedicated support in the form of copy preparation and manuscript typing.

Thanks are also due to the two SPS contractors, Boeing Aerospace Company and Rockwell International, for their cooperation in supplying additional documents and information necessary to conduct this study.

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1. SUMMARY

This study assesses the transportation costs associated with the development and operation, over a period of about 60 years, of a Satellite Power System (SPS) capable of supplying 300 GW of usable power to the ground. This was accomplished by:

- a. Assessing the reliability of cost estimates made by two industrial contractors, Boeing Aerospace Company and Rockwell International.
- b. Identifying areas of large uncertainty in technology and cost goals that need to be narrowed by further study.

The space system consists of 60 solar power satellites, in geosynchronous orbit (GEO), each providing 5 GW of usable power; a low earth orbit (LEO) construction base; and a geosynchronous orbit construction base. The transportation system consists of a Heavy Lift Launch Vehicle (HLLV), an Electric Orbit Transfer Vehicle (EOTV), a Personnel Launch Vehicle (PLV), a Personnel Orbit Transfer Vehicle (POTV), a Personnel Module (PM), and an Inter-Orbit Transfer Vehicle (IOTV). The two SPS contractors studied different solar power satellite designs: the Boeing design weighed 51,000 MT, and the Rockwell design weighed 32,000 MT. Consequently, the two contractor transportation system cost estimates cannot be compared directly with one another.

Review of the contractor data disclosed that the HLLV comprised about 90 percent of the transportation system cost. HLLV operations account for about 58 percent and fleet investment for about 28 percent of total transportation cost. The cost analyses therefore focused on the HLLV.

Costs (in 1980 dollars) were estimated for each contractor's baseline HLLV design and for a modified version of each design. These modified versions were established following review of, and subsequent increase in, the vehicle weight estimates. Both contractors HLLV weight estimates were assessed as being about 15 percent optimistic. Compensation for this factor decreased the HLLV payload capability, thus requiring both additional flights at an increased operational cost and an increased fleet size with an accompanying increase in investment cost. When all such factors were taken into account, the contractors' cost estimates were judged to be low--Boeing by a factor of about 3.0 and Rockwell by a factor of about 1.7. Ostensibly, both contractors used Shuttle cost data as a basis for their estimates; however, those used by Boeing resulted in overly optimistic estimates. It is pertinent to note that all transportation cost estimates, both contractor and Aerospace, assumed a successful achievement of the required technology goals.

The depth and emphasis of the Department of Energy/National Aeronautics and Space Administration (DOE/NASA) studies apparently precluded a detailed contractor consideration of transportation system technology and cost goals. However, the major uncertainties affecting the transportation cost estimates were determined to be:

- a. Satellite Weight
- b. HLLV Thermal Protection System
- c. EOTV System Design, Development, and Operation.

A successful EOTV design is considered perhaps the most critical technology challenge. If the EOTV is only capable of a single flight instead of the intended 20 flights, total system cost would increase about 15 percent. Should the EOTV prove infeasible, and should the use of a chemical OTV be required, the HLLV flight requirements could increase by over a factor of 2, resulting in a significant transportation cost increase. At this time, the EOTV design has not reached an adequate level of maturity to permit identification of all the relevant cost and technology issues.

As a result of the technology assessment it was concluded that:

- a. In general, the transportation vehicle technology goals established by the contractors (with the possible exception of some of those associated with the EOTV) are achievable if dedicated effort and adequate funding are provided.
- b. If it is intended to proceed with a full-scale SPS development, the potential for SPS transportation cost savings achievable through technology advancement should be exploited by allocating dedicated SPS funding support.
- c. Advancement of many of the critical SPS transportation vehicle technologies has wide application independent of SPS needs.

2. INTRODUCTION

2.1 BACKGROUND

The National Research Council Environmental Studies Board appointed a Committee on Satellite Power Systems to review SPS studies being conducted by the Department of Energy with the help of NASA. These studies include environmental, technical, socio-economic, and international aspects of the SPS concept and will compare such systems with other new energy sources. The Committee has been tasked to identify critical scientific and technical issues in the evaluation of the SPS concept, point out any gaps that may exist in the DOE assessment, and provide an independent, authoritative critique of the results of the DOE program.

As part of the effort, an independent assessment of the cost estimates and the uncertainties in cost estimation for the SPS transportation system was deemed necessary. The Aerospace Corporation was selected, and this report summarizes the Aerospace assessment study results.

The fundamental elements of the total SPS program are illustrated in Figure 2-1. However, program elements other than those constituting the transportation system are considered in this study only insofar as they affect transportation costs. When fully operational, the space system will consist of 60 solar power satellites, each contributing 5 GW of usable power. These will be deployed over a period of about 30 years and each will operate for an additional 30 years.

2.2 OBJECTIVES

The objective of this study was to provide to the National Research Council Committee on Satellite Power Systems an assessment of the transportation costs associated with the development and operation, over a period of about 60 years, of a satellite power system capable of supplying 300 GW of usable power to the ground. This assessment was accomplished by:

- a. Evaluating the reliability of present cost estimates.
- b. Identifying areas of large uncertainty in technology and cost goals that need to be narrowed by further study.

2.3 SCOPE

A typical Solar Power Satellite Program Work Breakdown Structure (WBS) is illustrated in Figure 2-2. However, this study was confined to WBS items 1.3.1 through 1.3.7, which include consideration of the HLLV, EOTV, PLV, POTV, PM, IOTV, and the Ground Support Facilities (GSF).

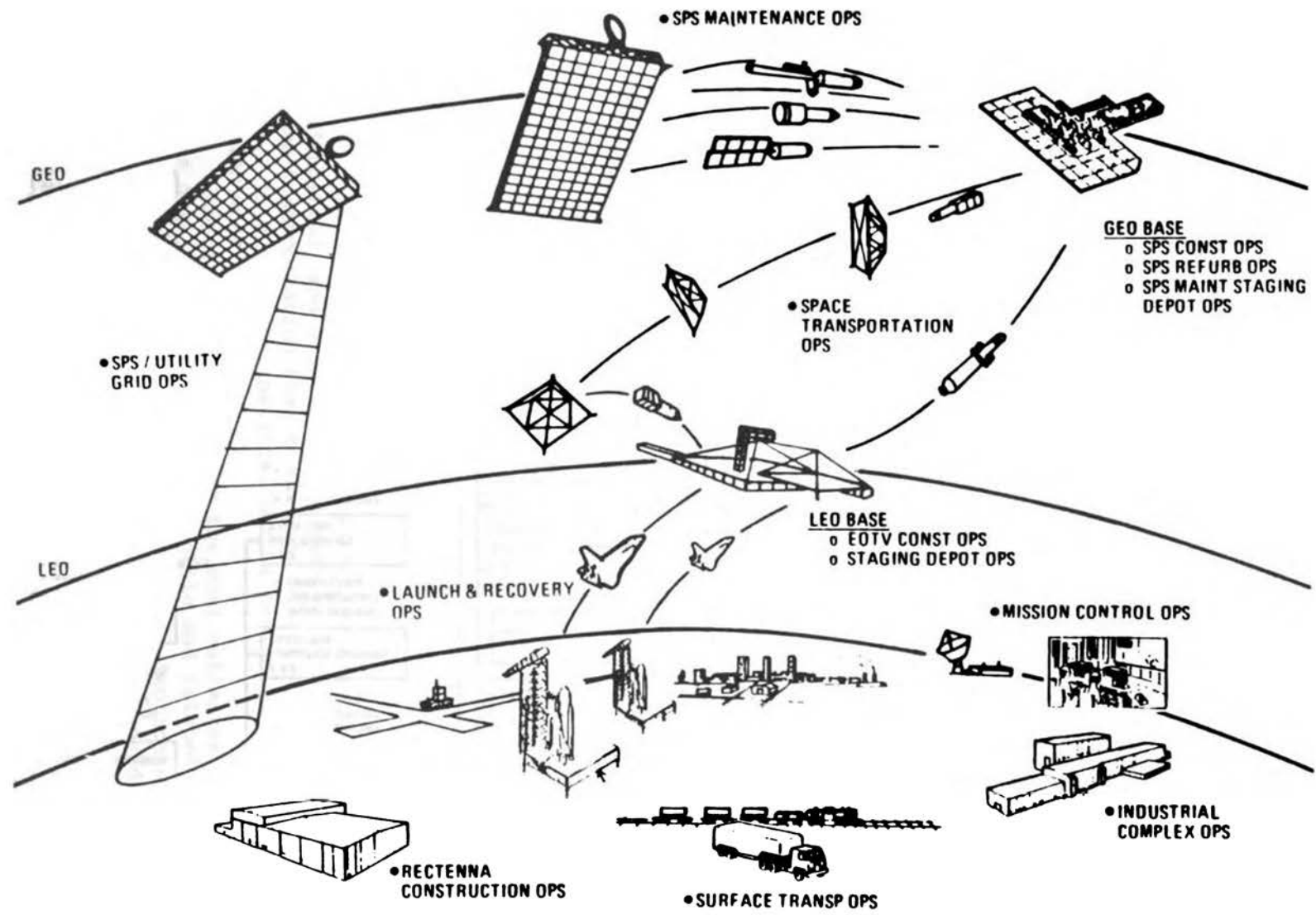


FIGURE 2-1. INTEGRATED SPS PROGRAM OPERATIONS

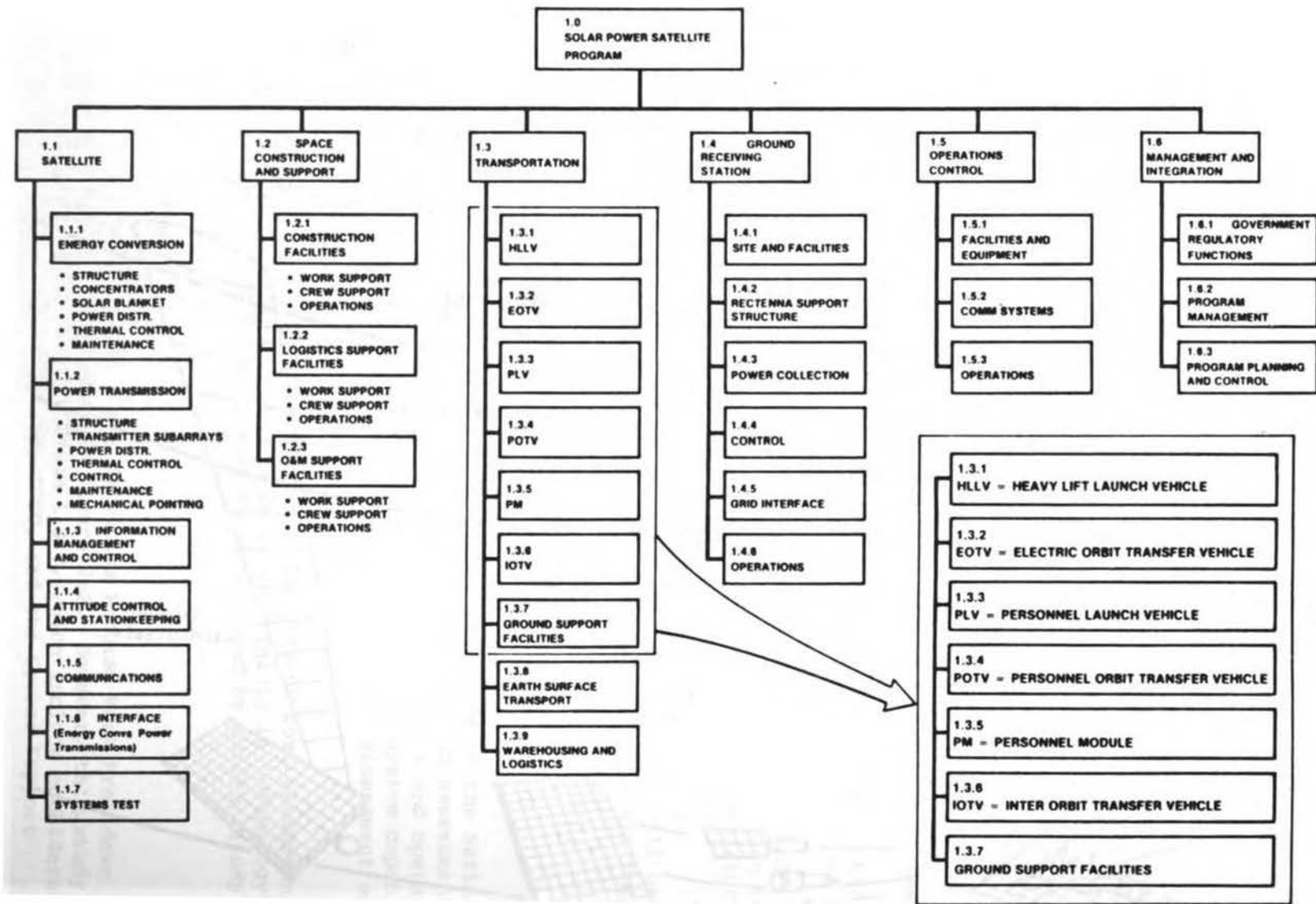


FIGURE 2-2. TYPICAL SPS WORK BREAKDOWN STRUCTURE

Many companies and individuals have conducted studies of the SPS concept. This assessment, however, was confined to the concepts studied in recent years by Boeing and Rockwell under contract to NASA. The contractor documents that were examined are listed in Section 6 of this report.

Although a reference system, generally known as the "DOE October 1978 Reference System" was established by DOE, the document describing it (Report No. DOE/ER-0023) contains no cost information; in fact, no cost data were made available by DOE to the Committee for assessment in this study. Instead, the Aerospace assessment was made of data that the two contractors considered to be representative of their most up-to-date design concepts and costs. The contractor concepts differed from each other in a number of fundamental ways and were, therefore, assessed separately.

2.4 GENERAL APPROACH

The general approach that was used in this study can be summarized as follows:

- a. Collect the contractor data and organize it in a form that could be analyzed by The Aerospace Corporation cost-estimating procedures.
- b. Identify and re-estimate the high-cost items using the contractor design assumptions.
- c. Identify and critique those contractor data and assumptions that were likely to significantly affect costs.
- d. Assess the critical SPS technologies and capabilities.
- e. Modify the contractor data where it was deemed necessary and re-estimate the cost of selected transportation elements.
- f. Perform sensitivity analyses of those technology items that may have a potential for influencing total system cost.

In addition, space transportation requirements unique to SPS were identified, and an attempt was made to identify potential advances in space transportation that could come about independent of the SPS program. In the latter instance, both a nominal and an optimistic projection were assumed.

Major justification for the cost estimates was based on the Aerospace data base which includes Shuttle and related cost information. Because the documents listed in Section 6 proved inadequate to conduct a satisfactory assessment, many discussions were held with each of the contractors and with representatives of the NASA Johnson Space Center (JSC), and the NASA Marshall Space Flight Center (MSFC).

Sensitivity analyses discussed in Section 4 were performed using cost estimates generated for the Rockwell system.

A reference set of cost data in 1979 dollars, received via telecon from Rockwell on 22 September 1980, reflects 13,849 HLLV flights. Those data can be summarized as follows:

<u>CATEGORY</u>	<u>BASIC ESTIMATE (\$M)</u>	<u>QUANTITY FACTOR</u>	<u>CONTRACTOR TOTAL COST (\$M)</u>
RDT&E	33,590.0	1	33,590.0
Investment/Sat	12,743.0	60	764,580.0
Replacement Capital Inv/ Sat/Yr	145.8	1,800	262,440.0
O&M/Sat/Yr	77.2	1,800	<u>138,960.0</u>
Rockwell Total			1,199,570.0
Total-Adjusted by Aerospace (Fee and 1980 dollars)			1,411,894.0

For cost sensitivity purposes, Aerospace used the \$1,412B Rockwell number plus the difference between the Aerospace and the Rockwell HLLV cost estimates developed in Section 4 (i.e., \$117B as shown in Table 4-8), for a total of \$1,529B in 1980 dollars.

In their March 1979 Report No. SSD 79-0010-2-2, Rockwell presented the costs shown in Figure 2-3. One of the items represents investment per satellite which amounted to \$13.9B investment for a total of \$834B for the complete 60-satellite system. However, this included investment only and excluded RDT&E and operations, which amount to an additional \$1,203B. It is important to note that the resultant total cost of over \$2,000B refers to a 22,811-HLLV flight program and is in 1977 dollars. (Rockwell attributes the reduction in HLLV flight requirements from 22,811 to 13,849 to improvements in klystron maintenance procedures. Verification of this claim is outside the scope of this study.)

According to the interpretation of the Boeing cost data for 1977 by NASA/JSC, the Boeing numbers total \$775B in 1977 dollars for the total system through the 33rd year.

The documents listed in Section 6 were used as sources of information. In some cases, conflicting data were found to exist, and, in such situations, resolution was achieved by verbal consultation with the contractors.

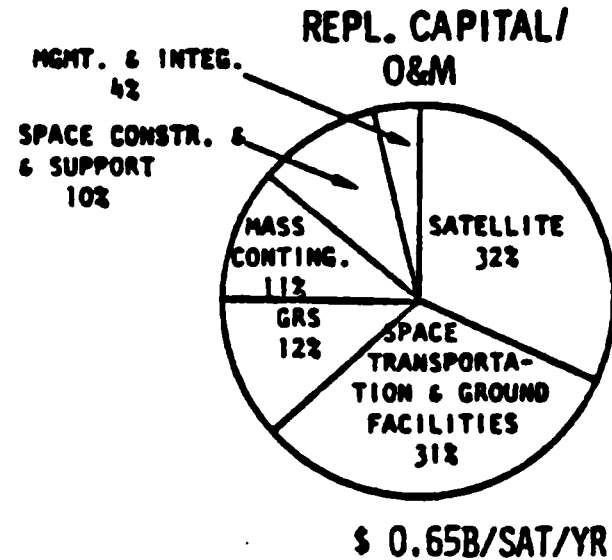
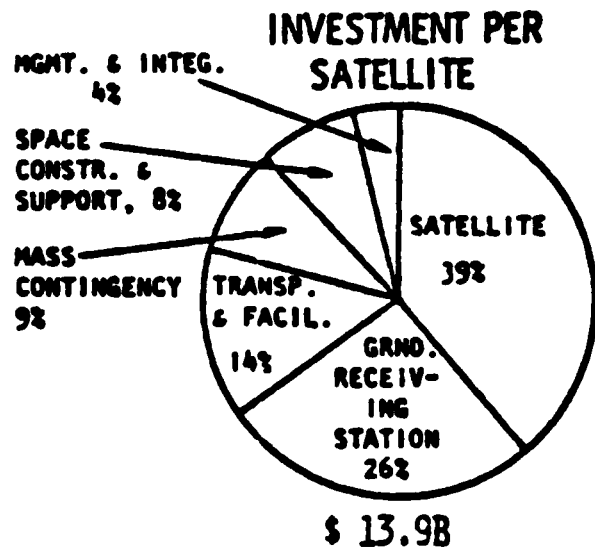
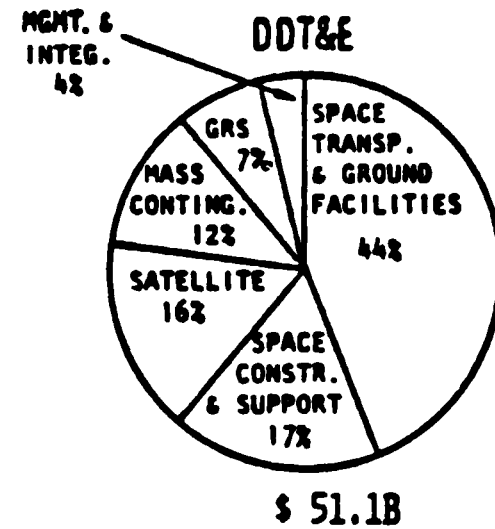
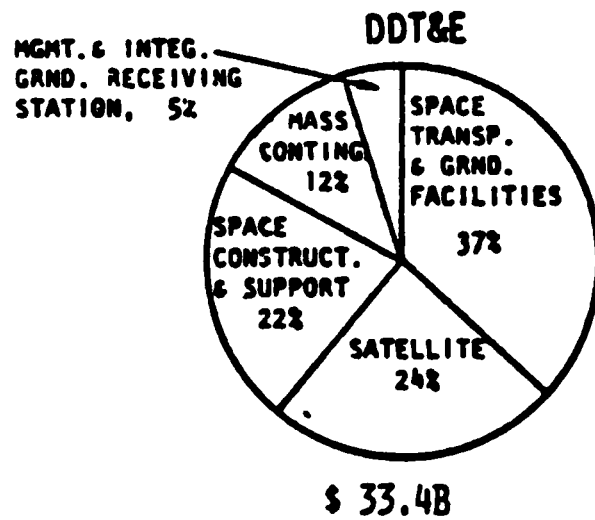


FIGURE 2-3. ROCKWELL MARCH 1979 PROGRAM COST DISTRIBUTION

3. SYSTEM DESCRIPTIONS

3.1 MODIFIED REFERENCE SPACE SYSTEM

The space system consists of 60 GEO satellites each providing 5 GW of usable power to the ground, a LEO construction base, and a GEO construction base. The basic characteristics of the Boeing and Rockwell space systems which the transportation systems under assessment are called upon to support are listed in Table 3-1. The fundamental difference between the two concepts is that Boeing studied a satellite system which utilizes silicon solar cells, whereas Rockwell studied a system utilizing gallium arsenide cells. The resulting nominal weights were 51,000 MT for the Boeing satellite and 32,000 MT for the Rockwell satellite. The solar power satellites differ only slightly from those defined in the DOE October 1978 reference system; the characteristics of the LEO and GEO bases, however, have been redefined by the contractors since the October 1978 reference system was established.

3.2 BOEING TRANSPORTATION VEHICLE CHARACTERISTICS

The fundamental characteristics of the Boeing transportation system are listed in Table 3-2. The basic transportation elements consist of the PLV, HLLV, POTV, EOTV, and the IOTV. A further item, the PM, which is identified separately in Table 3-2, is considered to be part of the POTV in some of both of the contractors' analyses.

The vehicle characteristics differ somewhat from those described in the DOE October 1978 reference system. For instance, the POTV complement is reduced from 160 people to 60 to 90 people, and the twin-stage POTV is replaced by a single stage vehicle.

3.3 ROCKWELL TRANSPORTATION VEHICLE CHARACTERISTICS

The fundamental characteristics of the Rockwell transportation system are listed in Table 3-3, and the basic transportation elements are defined in the same way as those for the Boeing system.

The prime differences between the Boeing and Rockwell concepts are that Boeing utilizes a very large HLLV with a gross payload capability of 424 MT, whereas Rockwell utilizes a smaller HLLV having a gross payload capability of 231 MT. Contrary to the conditions assumed in the October 1978 reference system where separate vehicles were defined, the Rockwell HLLV is also used as a PLV for transporting passengers from ground to LEO. Boeing retained a separately configured PLV.

TABLE 3-1. MODIFIED REFERENCE SPACE SYSTEMS

<u>CHARACTERISTIC</u>	<u>BOEING</u>	<u>ROCKWELL</u>
SATELLITE		
USEFUL POWER OUTPUT	5 GW	5 GW
TYPE CELLS	SILICON	GALLIUM ARSENIDE
CONC. RATIO	1.0	1.83
TYPE DC/RF CONVERTERS	KLYSTRON	KLYSTRON
ARRAY DIMENSIONS	10.7x5.3x0.47 KM	16.0x4.2x0.61 KM
ANTENNA DIA	1 KM	1 KM
WEIGHT	50,984 MT	31,600 MT
LEO BASE		
CREW SIZE	200 ⁽¹⁾	30
SUPPLY REQUIREMENTS	400 MT/YR	TBD
WEIGHT	1832 MT	225 MT
GEO BASE		
CREW SIZE	444	600
SUPPLY REQUIREMENTS	1251 MT/YR	1500 MT/YR
WEIGHT	6657 MT	5300 MT
MAINTENANCE		
CREW SIZE	385	30
SUPPLY REQUIREMENTS	206 MT/YR	130 MT/YR

NOTE: (1) PLUS 35 DURING EOTV CONSTRUCTION

TABLE 3-2. BOEING TRANSPORTATION VEHICLE CHARACTERISTICS

CHARACTERISTIC	HLLV	EOTV	PLV	POTV	10TV
GROSS PAYLOAD (MT)	424	4000	89	23 ⁽⁵⁾	400
NET PAYLOAD (MT)	360	3600	80 PEOPLE	80 PEOPLE & 16 MT CARGO	-
DESIGN LIFE (FLIGHTS)	300	10	300	50	-
TURNAROUND TIME ⁽¹⁾ (DAYS)					
BOOSTER	4.0	-	4.0	-	-
ORBITER	5.3	-	10.0	-	-
STAGE	-	235	-	-	-
FLIGHTS/REFUELING	1	2 ⁽²⁾	1	1	24 ⁽³⁾
TOTAL DRY WT (MT)	1170	1462	334	81	-
USABLE PROPELLANT (MT)					
LO ₂	7102	39.4	1748	171	15.6
LH ₂	329	6.6	78	29	2.6
LCH ₄	1709	-	424	-	-
ARGON	-	470	-	-	-
RP-1	85	-	26	-	-
RESIDUALS, RESERVE, ETC	159	7	16	3	-
TOTAL (P/L INCL) WT (MT)	10978	5985	2715	307 ⁽⁴⁾	-

NOTES: (1) FLIGHT & REFURBISHMENT
(2) ONE ROUND TRIP
(3) 12 ROUND TRIPS
(4) INCL POTV, PM, 2CSM

(5) INCL PERSONNEL AND CARGO ONLY (NOT PM)
(6) PM WT (LESS PERSONNEL = 46.3 MT)

TABLE 3-3. ROCKWELL TRANSPORTATION VEHICLE CHARACTERISTICS

CHARACTERISTIC	HLLV	EOTV	PLV ⁽¹⁾	POTV	10TV
GROSS PAYLOAD (MT)	231	6814	231	5 ⁽⁶⁾	TBD
NET PAYLOAD (MT)	227	-	227	60 PEOPLE	-
DESIGN LIFE (FLIGHTS)	300	20	300	100	200
TURNAROUND TIME ⁽²⁾ (DAYS)					
BOOSTER	-	-	-	-	-
ORBITER	7.0	-	7.0	-	-
STAGE	-	-	-	-	-
FLIGHTS/REFUELING	1	2 ⁽³⁾	1	1	TBD
TOTAL DRY WT (MT)	804	1129	804	17	578
USABLE PROPELLANT (MT)					
LO ₂	4708	-	4708	28	257
LH ₂	380	-	380	5	43
LCH ₄	-	-	-	-	-
ARGON	-	798	-	-	-
RP-1	926	-	926	-	-
RESIDUALS, RESERVE, ETC	120	66	120	-	-
TOTAL (P/L INCL) WT (MT)	7169	8807	7169	55.0 ⁽⁴⁾	878 ⁽⁵⁾

NOTES: (1) SAME AS HLLV
(2) FLIGHT & REFURBISHMENT
(3) ONE ROUND TRIP
(4) INCL POTV, PM

(5) P/L EXCLUDED
(6) INCL PERSONNEL ONLY
(7) PM WT (LESS PERSONNEL) = 13.3 MT

In the case of both contractors, some of the characteristics were not clearly defined in the documentation identified in Section 6, and numerous discussions were held with the contractors to resolve these uncertainties. In this manner, the basic characteristics of all system elements representing significant costs were adequately defined for study purposes.

3.4 PROGRAMMATICS

It is important to recognize that the two system concepts developed by the contractors, Boeing and Rockwell, are not directly comparable for a number of reasons. Boeing considered a 33-year program, in which they deploy 60 satellites and fly 13,200 HLLV flights; Rockwell assumed a 60-year program, in which they deploy and maintain 60 satellites and fly 13,849 HLLV flights. The maintenance policies at LEO and GEO (and, of course, the satellite weights) are also different.

4. ANALYSIS

4.1 WEIGHT AND PERFORMANCE ANALYSES

Component weights are important ingredients in any cost estimating exercise; consequently, Aerospace weight estimating relationships (WERS) were used to estimate subsystem weights for each of the transportation elements identified by each of the contractors. In general, Aerospace estimates were found to be 12 to 15 percent higher than those derived by the contractors. In the case of the EOTV, however, Aerospace estimates of dry weights were about 50 percent greater than the contractor estimates. The larger discrepancy is believed to be a result of the higher ignorance factors that Aerospace used to account for the lack of maturity in the EOTV design. Boeing used a factor of about 20 percent; Rockwell a factor of about 25 percent. Experience on past missile and space systems has indicated that factors of 60 to 70 percent are more realistic.

The HLLV technology advancement goals related to weight reduction that were assumed by Rockwell are listed in Table 4-1 and appear achievable. Comparative summaries of contractor and Aerospace HLLV weights are given in Table 4-2 for the Boeing design and Table 4-3 for the Rockwell design.

The vehicle performances were also examined and found to be reasonably accurate. Engine performance goals set by the contractors are considered achievable.

4.2 COST ANALYSIS

Transportation cost estimates and cost-influencing factors were extracted from the available contractor reference material, which consisted of published data, unpublished contractor working notes, and inputs from verbal discussions. These data were then processed by Aerospace, and the important cost parameters which were extracted are highlighted in Table 4-4 for Boeing and in Table 4-5 for Rockwell. (It was not possible to obtain IOTV cost estimates from the Boeing data; however, as can be seen from Table 4-5, an estimate of IOTV costs can be deemed to be inconsequential to total system cost.) A summary of contractor total transportation cost estimates is given in Table 4-6 for each contractor.

Early in the study, it became clear that the HLLV was by far the single largest item of transportation cost and, thus, a major contributor to total system cost. Evidence of this is depicted in Figure 4-1 which shows Rockwell's estimate of the breakdown of total system cost. In addition, Figure 4-1 shows the distribution of HLLV cost. This can be compared with the Space Shuttle Program cost distribution shown in Figure 4-2. Accordingly, it was agreed that the HLLV should receive major attention in the subsequent cost and technology assessment effort.

TABLE 4-1. HLLV TECHNOLOGY ADVANCEMENT GOALS

	ANTICIPATED WEIGHT REDUCTION (%)
• BODY STRUCTURE	• 17
• WING STRUCTURE	• 15
• VERTICAL TAIL	• 18
• CANARD	• 12
• THERMAL PROTECTION SYSTEM	• 20
• AVIONICS	• 15
• ENVIRONMENTAL CONTROL	• 15
• REACTION CONTROL SYSTEM	• 15

TABLE 4-2. WEIGHT SUMMARY - BAC HLLV

ITEM	BOEING		AEROSPACE	
	lb	kg	lb	kg
BOOSTER				
STRUCTURE AND THERMAL MECHANICAL SYSTEMS	1,037,127	470,352	1,143,400	518,549
ELECTRICAL POWER	77,309	35,061	112,800	51,156
ENV CONTROL	16,449	7,460	18,800	8,526
AVIONICS	534	242	600	272
PROPULSION	3,759	1,705	4,300	1,950
	621,988	282,081	715,100	324,308
BOOSTER DRY WEIGHT	(1,757,166)	(796,901)	(1,995,000)	(904,761)
ORBITER				
STRUCTURE AND THERMAL MECHANICAL SYSTEMS	588,939	267,092	689,600	312,744
ELECTRICAL POWER	33,070	14,998	49,200	22,313
CREW ENV AND LSS	16,277	7,382	16,800	7,619
AVIONICS	7,409	3,360	7,700	3,492
PROPULSION	6,559	2,975	6,900	3,129
EQUIPMENT	164,091	74,418	176,600	80,091
	6,560	2,975	6,800	3,084
ORBITER DRY WEIGHT	(822,905)	(373,200)	(953,600)	(432,472)
TOTAL DRY WEIGHT	2,580,071	1,170,101	2,948,600	1,337,233
BOOSTER - PROPELLANT	15,282,000	6,930,612	15,282,000	6,930,612
- FLY-BACK FUEL	190,100	86,213	190,100	86,213
ORBITER - PROPELLANT	5,211,300	2,363,401	5,211,300	2,363,401
- PERSONNEL AND P/L ACCOM	9,040	4,100	9,040	4,100
TOTAL EXPENDABLES	(20,692,440)	(9,384,326)	(20,692,440)	(9,384,326)
TOTAL LOADED WEIGHT	23,272,540	10,554,427	23,641,040	10,721,559
ASCENT PAYLOAD WEIGHT	934,920	424,000	748,000	339,230
GROSS LIFT-OFF WEIGHT	24,207,460	10,978,430	24,389,040	11,060,790

TABLE 4-3. WEIGHT SUMMARY - RI HLLV

ITEM	ROCKWELL		AEROSPACE	
	lb	kg	lb	kg
BOOSTER				
STRUCTURE AND THERMAL MECHANICAL SYSTEMS	558,518	253,296	681,300	308,980
ELECTRICAL POWER	55,638	25,233	60,700	27,528
ENV CONTROL	14,300	6,485	15,600	7,075
AVIONICS	500	227	500	227
PROPULSION	8,625	3,911	5,000	2,268
PERSONNEL PROV	407,075	184,615	447,100	202,766
	820	372	900	408
BOOSTER DRY WEIGHT	(1,045,476)	(474,139)	(1,211,100)	(549,252)
ORBITER				
STRUCTURE AND THERMAL MECHANICAL SYSTEMS	515,866	233,590	588,200	266,798
ELECTRICAL POWER	56,361	25,561	39,000	17,687
ENV CONTROL	13,800	6,258	15,200	6,899
AVIONICS	6,555	2,973	7,000	3,175
PROPULSION	9,775	4,433	6,900	3,129
PERSONNEL PROV	122,610	55,605	140,100	63,537
	3,450	1,565	4,000	1,814
ORBITER DRY WEIGHT	(727,617)	330,660	(800,400)	(362,993)
TOTAL DRY WEIGHT	1,773,093	804,799	2,011,500	912,245
BOOSTER - PROPELLANT	9,702,000	4,400,000	9,702,000	4,400,000
- FLY-BACK FUEL	187,000	84,807	187,000	84,807
ORBITER - PROPELLANT	3,648,000	1,654,422	3,648,000	3,648,000
TOTAL EXPENDABLES	(13,537,000)	6,139,230	(13,537,000)	6,139,230
TOTAL LOADED WEIGHT	15,310,093	6,943,350	15,548,500	7,051,470
ASCENT PAYLOAD WEIGHT	507,150	230,000	403,000	182,000
GROSS LIFT-OFF WEIGHT	15,817,250	7,173,350	15,951,500	7,234,240

TABLE 4-4. BAC TRANSPORTATION SYSTEM - CONTRACTOR COST ESTIMATES (1980 DOLLARS)

VEHICLE	HLLV	EOTV	PLV	POTV	PM	IOTV
DRY WEIGHT (000 LB)	2580	3220	736	30	97	↑ NOT AVAILABLE ↓
PAYLOAD WT (000 LB)	794	7938	195		15	
TOTAL FLIGHTS	13200	~900	1913	1500	-	
FLIGHTS/VEHICLE	300	10	300	50	-	
FLEET QUANTITY	44	116	8	32	4	
COST PER FLIGHT (\$M)	10.7	10.9	11.6	.6	-	
- OPS. & MAINT.	1.9	1.0	-	.1	-	
- SPARES & OVERHAUL	8.8	9.9	-	.5	-	
FLEET UNIT COST (\$B)	1.2	.4	1.0	.7	.2	
DDT&E (\$B)	17	3	4	1.3	1.3	
FLEET (\$B)	53	47	9	2.1	.8	
OPERATIONS (\$B)	141	10	22	.9	~	
TOTAL (\$B)	211	60	35	4.3	2.1	

TABLE 4-5. RI TRANSPORTATION SYSTEM - CONTRACTOR COST ESTIMATES (1980 DOLLARS)

<u>VEHICLE</u>	<u>HLLV</u>	<u>EOTV</u>	<u>PLV</u>	<u>POTV</u>	<u>PM</u>	<u>IOTV</u>
DRY WEIGHT (000 LB)	1773	2490	556	8	29	-
PAYLOAD WT (000 LB)	500	15025	100	-	10	-
TOTAL FLIGHTS	13849	392	135	1544	1738	27662
*FLIGHTS/VEHICLE	300	20		100		200
FLEET QUANTITY	47	20	2	15	5	139
COST PER FLIGHT (\$M)	14.8	22.0	22.1	.4	.6	.015
- OPS. & MAINT.	3.6	1.2	-	.1	.1	-
- SPARES & OVERHAUL	11.2	20.8	-	.3	.5	-
FLEET UNIT COST (\$B)	2.2	1.0	.4	.02	.06	.0015
DDT&E (\$B)	12	-	.4	.5	.2	.1
FLEET (\$B)	103	19	.7	.3	.3	.2
OPERATIONS (\$B)	205	9	3.0	.6	1.0	.4
TOTAL (\$B)	320	28	4.1	1.4	1.5	.7

TABLE 4-6. TRANSPORTATION SYSTEM SUMMARIES - CONTRACTOR COST ESTIMATES
(BILLIONS OF 1980 DOLLARS)

<u>ELEMENTS</u>	<u>BOEING</u>	<u>ROCKWELL</u>
HLLV	211	320
EOTV	60	28
PLV	35	4
POTV	4	1
PM	2	2
IOTV	N/A	1
GSF	<u>7</u>	<u>21</u>
TOTAL	319	377

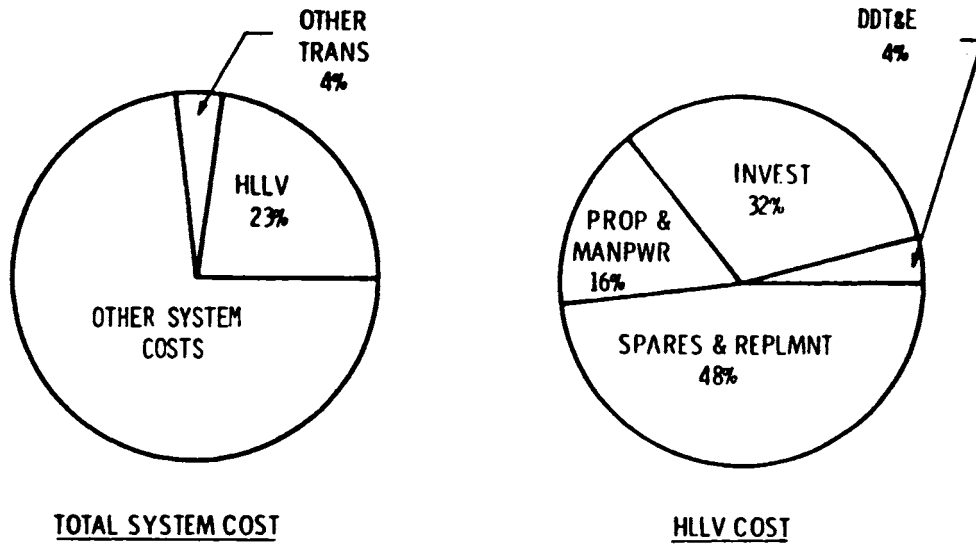
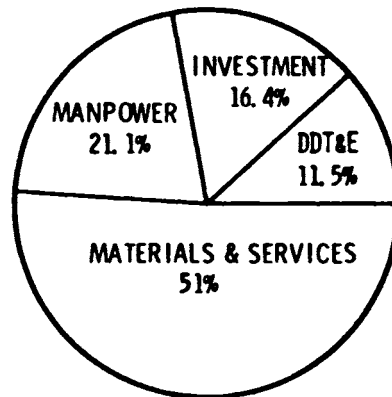


FIGURE 4-1. ROCKWELL PROGRAM COST DISTRIBUTION - CONTRACTOR ESTIMATE

- 30 YEAR PROGRAM PROJECTION*
- 1161 LAUNCHES



* BASED ON 487 FLIGHT NATIONAL MISSION MODEL

FIGURE 4-2. SPACE SHUTTLE PROGRAM COST DISTRIBUTION

Weight estimates to a next level of detail to those that were listed in Tables 4-2 and 4-3, together with other relevant design information, were used as input to the Aerospace cost-estimating procedures.

The unchanged contractor designs were re-examined using Aerospace procedures, which are based on Shuttle cost data and related cost-estimating relationships (CERs). The results are compared with original contractor estimates in Tables 4-7 and 4-8 where Aerospace numbers for the Boeing HLLV design are more than twice those of Boeing and a little more than a third greater than those of Rockwell, respectively.

The independent weight estimates made by Aerospace, that were summarized in Tables 4-2 and 4-3, resulted in an increase in dry weight that translated into a decrease in payload weight. The vehicles were re-examined again, using Aerospace cost-estimating procedures, and the results are listed in the third column of Tables 4-7 and 4-8. These results, compared with the original contractor estimates, show an increase in cost for the Boeing vehicle of almost 200 percent and approximately 70 percent for the Rockwell vehicle.

4.3 CRITICAL TECHNOLOGIES

4.3.1 Critical Technology Selection

It was decided that those technologies and capabilities that exert a strong influence on system performance, system reusability, and turnaround time and effort could potentially be strong cost drivers. For this reason, the technologies and capabilities listed in Table 4-9 were selected for detailed investigation. The crosses indicate which of the three parameters identified above are influenced by each of the selected technologies.

Also listed in Table 4-9 is a subjective assessment (H = high, M = medium, L = low) of the technical risk and cost sensitivity of each of the technologies.

4.3.2 Technology Assessment

4.3.2.1 Improved Thermal Protection System (TPS)

It is unlikely that the existing Space Shuttle Orbiter TPS technology will provide the "airline" (that is, fast turnaround and low maintenance) operations capability demanded of the SPS launch vehicles. The Shuttle TPS consists of a number of generic types of materials whose functions are dependent on temperatures ranging from room temperature to over 2700° F. Carbon composite material coated with silicon carbide is used for the nose cap and the leading edges of the aerosurfaces. The TPS body section consists of over 30,000 alumina tiles which are bonded to the structure by means of strain isolation pads of felted nomex fibers. The tiles are very fragile, must be

TABLE 4-7. BOEING HLLV SYSTEM COST COMPARISONS (1980 DOLLARS)

ITEM	BAC DESIGN		AEROSPACE DESIGN MODIFICATION
	BAC COST	AEROSPACE	
DRY WEIGHT (000 LB)	2580	2580	2949
PAYLOAD WT (000 LB)	794	794	635
TOTAL FLIGHTS	13200	13200	16500
FLIGHTS/VEHICLE	300	300	300
FLEET QUANTITY	44	44	55
COST PER FLIGHT (\$M)	10.7	22.3	23.0
- PROPELLANT	1.9	1.9	1.9
- MANPOWER	4.2	3.6	3.4
- SPARES & OVERHAUL	4.6	16.8	17.7
FLEET UNIT COST (\$B)	1.2	3.4	3.6
DDT&E (\$B)	17	31	34
FLEET (\$B)	53	149	196
OPERATIONS (\$B)	141	294	380
TOTAL (\$B)	211	474	610
\$/LB TO LEO	20	45	58

TABLE 4-8. ROCKWELL HLLV SYSTEM COST COMPARISONS (1980 DOLLARS)

ITEM	RI DESIGN		AEROSPACE DESIGN MODIFICATION
	RI COST	AEROSPACE	
DRY WEIGHT (000 LB)	1773	1773	2012
PAYLOAD WT (000 LB)	500	500	396
TOTAL FLIGHTS	13849	13849	17486
FLIGHTS/VEHICLE	300	300	300
FLEET QUANTITY	47	47	59
COST PER FLIGHT (\$M)	14.8	20.1	20.1
- PROPELLANT	3.6	2.4	2.4
- MANPOWER		3.6	3.4
- SPARES & OVERHAUL	11.2	14.1	14.3
FLEET UNIT COST (\$B)	2.2	2.8	2.9
DDT&E (\$B)	12	27	29
FLEET (\$B)	103	132	169
OPERATIONS (\$B)	205	278	352
TOTAL (\$B)	320	437	550
\$/LB TO LEO	46	63	79

TABLE 4-9. CRITICAL TECHNOLOGY ASSESSMENT

	<u>PERFORMANCE</u>	<u>REUSABILITY</u>	<u>TURNAROUND</u>	<u>TECHNICAL RISK</u>	<u>COST SENSITIVITY</u>
STRUCTURE / MATERIALS					
- IMPROVED TPS	X	X	X	H	H
- REUSABLE INSULATION		X	X	M	M
- ADVANCED COMPOSITES	X	X		L	L
- TITANIUM HONEYCOMB	X	X		L	L
PROPULSION					
- ADVANCED SSME (2-POS. NOZZLE)	X	X	X	L	L
- CH ₄ BOOSTER ENGINE	X			L	L
- ADVANCED SPACE ENGINE (ASE1)	X			L	L
- ELECTRIC PROPULSION STAGE	X			H	H
GROUND SYSTEMS					
- BUILT-IN TEST			X	L	M
- IMPROVED LOGISTICS			X	M	M
ON-ORBIT SERVICING & MAINTENANCE		X	X	H	H

NOTE: H = HIGH, M = MEDIUM, L = LOW

carefully installed to control the gaps between them, and have to be tested individually to verify that successful adhesion has occurred. Tile alignment is critical because height misalignment causes turbulent heating, oversized gaps induce local heating, and undersized gaps cause chipping of the tiles. If the adhesion stress-strain characteristics do not meet specification, the tiles must be removed and replaced, which is a very time-consuming process. Also, there are complementary materials such as gap fillers, insulation blankets, etc., which assist in forming an integral thermal insulative shell around the Orbiter.

Two alternatives to the present Space Shuttle Orbiter TPS are under consideration:

- a. Improved Resuable Surface Insulation (RSI)
- b. Metallic TPS.

NASA/Ames is developing a new generation of RSI which uses high-temperature organic material fibers for the strain isolation pads and lighter weight and more rugged tiles of advanced carbon composites with very high modulus carbon fibers. However, some of the installation and servicing problems associated with the present Orbiter TPS design may still be present. Rockwell is under contract to design a metallic TPS for the Shuttle Orbiter; a typical example is illustrated in Figure 4-3. This particular system is reminiscent of the type of metallic heat protection systems in vogue in the early 1960's and examined for such programs as X-15, X-20 (Dynasoar), ASSET, and early fully reusable Shuttle concepts. It is proposed that such a system be test-flown on the Shuttle. The metallic TPS is probably the most promising, and possibly the only approach that could satisfy the SPS transportation requirements.

Improved TPS is considered a high technical risk item because it appears that a Shuttle-type TPS would provide very little basis for a system design capable of meeting the SPS HLLV requirements and cost objectives and that a completely new technology development (albeit based on the discontinued work of the early 1960's) would have to be undertaken. Although the level of maturity in metallic TPS design precludes development of reliable weight estimates at this time, the weight of a metallic system is expected to exceed that of the present Shuttle system.

Improved TPS is considered a cost-sensitivity item because HLLV recurring costs are very sensitive to changes in TPS maintenance and replacement requirements and policy. This conclusion is graphically illustrated later, in Figure 4-9, which accompanies the discussion on cost sensitivity.

4.3.2.2 Reusable Insulation

There is a need to be able to use cryogenic tank insulation indefinitely for reusable orbit transfer vehicles and space storage tanks as well as for launch vehicles. There is no on-going program to develop reusable insulation since no requirement for it has been

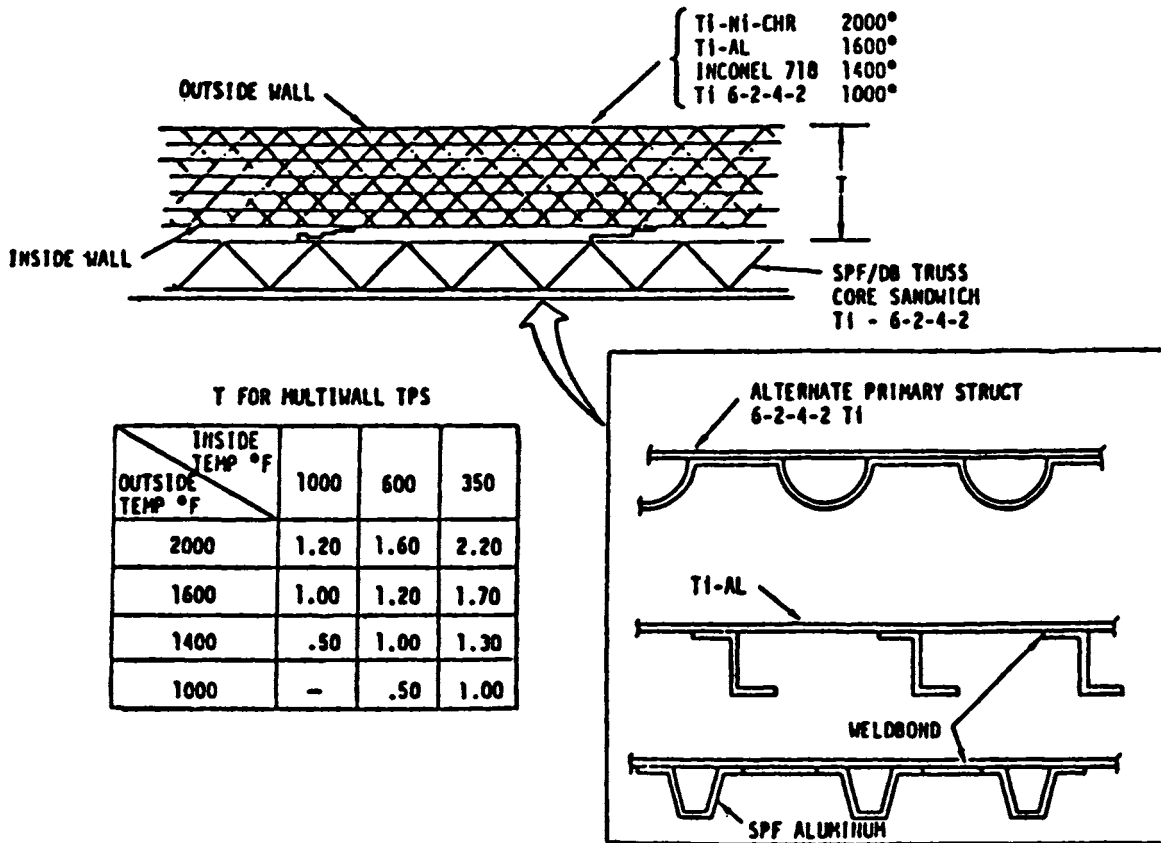


FIGURE 4-3. TYPICAL METALLIC MULTI-WALL TPS CONCEPT

established. Foam-type insulation has been used internally on the Saturn SIV-B stage and is used externally on the Shuttle External Tank (ET); multi-layer insulation is used externally on the expendable Centaur upper stage. None of these systems are reusable. Propellant tank common bulkheads of honeycomb, which utilize cryo-pumping to reduce heat transfer, have been used on Saturn SIV-B, and honeycomb has also been proposed for side-wall tank construction.

A comprehensive program for the design, development, and test of reusable insulation, taking into account the range of applications that might be relevant, is required prior to, or concurrent with, SPS development.

4.3.2.3 Advanced Composites

In the case of SPS, transportation costs represent more than 25 percent of total system costs. It is, therefore, very important to reduce the structural weight of the launch vehicles, the orbit transfer vehicles, and the space systems.

The substitution of composite structure for conventional aluminum can result in weight reduction over 20 percent for some subsystems and it has been projected that all structural and some thermal/electrical components could ultimately be made of composites.

Because of its wide application in the aircraft industry, composite technology is progressing in a relatively satisfactory manner. The Shuttle Orbiter uses composites; the largest item is the payload bay doors, which are 15 ft wide x 60 ft long. The SPS subsystem weight goals listed in Table 4-1 appear to be reasonable if the advanced composites technology effort continues its current progress. In addition to the widely-used graphite epoxies, other advancements, such as the metal matrix concepts, could be considered.

4.3.2.4 Titanium Honeycomb

The present Space Shuttle carries its main propellants in an expendable external tank; however, future fully recoverable launch vehicles will have to carry the maximum amount of fuel integrally if they are to be economically viable. In the early stages of the Shuttle program, considerable attention was given to the problem of integral propellant tanks, but the need for a solution was delayed by the decision to use expendable tanks. Titanium honeycomb is a possible solution to the design of structurally efficient integral tanks.

The development of titanium honeycomb structure technology was delayed by cancellation of the B-70 bomber but was continued by Boeing in the mid-1960's for application on the Supersonic Transport (SST). The cancellation of the SST delayed the technology progress, but Boeing has found applications on their most recent commercial transport aircraft and is pursuing the development with this application in mind.

Titanium is subject to hydrogen embrittlement. In addition to titanium, Rene' 41 and possibly other materials should be investigated for application to honeycomb structure for advanced launch and orbit transfer vehicles. Some fabrication studies currently underway are being sponsored by the Air Force Manufacturing Technology Program and by NASA, in addition to those privately funded to further the commercial interests of the airframe manufacturers. Nevertheless, a much more aggressive program aimed at the specific needs of advanced space transportation is probably needed if the technical goals of the SPS contractors are to be realized.

4.3.2.5 Advanced Space Shuttle Main Engine (SSME)

Improvements in the performance of the SSME contribute to satisfying the cost and technology goals postulated by the SPS contractors for their HLLV system concepts. However, the performance can be further improved by:

- a. Incorporating a two-position nozzle
- b. Reducing weight by the use of improved materials (such as composites)
- c. Uprating engine thrust
- d. Increasing engine lifetime.

Trade studies are being conducted on the two-position nozzle, and the other items mentioned above are recognized in NASA planning. There is no practical application (and therefore no requirement) for the two-position nozzle on the Shuttle Orbiter because of lack of geometrical clearance. Nevertheless, the activities above probably need to be continued and expanded if the goals of the SPS contractors are to be met. The results will have useful application for increasing future space transportation capability even if the SPS program is not implemented.

4.3.2.6 Methane (CH₄) Booster Engine

The larger size of the two-stage HLLVs proposed by the SPS contractors makes the use of hydrogen fuel in both stages impractical. Therefore, a high pressure hydrocarbon booster engine is needed which will be efficient at low altitude and will provide a high reusability factor.

High pressure LO₂/CH₄ engine technology needs to be developed. Only parametric studies and small-scale correlation tests have been conducted by Aerojet and Rocketdyne under NASA sponsorship. In order to meet the SPS contractor technology goals, considerable funding would have to be allocated and engine development begun 10 years ahead of any postulated initial operational capability (IOC) date.

4.3.2.7 Advanced Space Engine (ASE)

An advanced space engine has been the subject of a number of studies under contract to NASA/MSFC, NASA/Lewis Research Center (LeRC), and AF/Rocket Propulsion Laboratory (RPL). Full-scale components have been fabricated to verify performance, and all three domestic engine manufacturers (Aerojet Liquid Rocket, Pratt & Whitney, and Rocketdyne) have participated. Both advanced expander and staged combustion cycles have been proposed. The existing Pratt & Whitney RL-10 engine (or a relatively low-cost modification thereof), which has had a spectacularly successful career, could provide a very adequate interim capability for an early cryogenic OTV.

The development of an advanced cryogenic OTV utilizing ASE technology is fundamental to expanded future space transportation, independent of whether the SPS is deployed or not. It is required for personnel transfer and to transfer heavy time-dependent cargo. Neither solid nor storable orbital transfer vehicles will meet the expanded requirements envisioned for the late 1980's and 1990's.

A cryogenic OTV may be developed whether the SPS is deployed or not. This OTV will probably be planned to utilize a modified RL-10 engine in the mid to late 1980's, with an advanced LO_2/LH_2 engine replacing the RL-10 in the 1990's.

4.3.2.8 Electric Propulsion Stage

Because of the very high payload mass that must be transferred from low earth orbit to geosynchronous orbit, an electric OTV is fundamental to SPS economic viability. The utilization of an electric OTV provides very large payload capability. In addition, the EOTV permits efficient use of the POTV since it can carry to GEO the propellant required by the POTV for its return trip, allowing the POTV to operate essentially with the efficiency of an expendable OTV. The EOTV is, however, a source of technical risk since it is unlikely that any kind of electric stage comparable in size to this vehicle will be developed during this century for any use other than SPS. Therefore, experience with a smaller scale precursor will not be available.

Potential development problems do not appear to lie in the ion thruster technology, since the goal to develop a 120-cm diameter ion thruster extrapolated from the current 30-cm diameter, although ambitious, appears achievable if adequate funding is provided. The problems are likely to arise in the design and integration of some of the major subsystems, and in the EOTV's operational characteristics. Some of the areas that require detailed investigation are discussed in the following paragraphs.

4.3.2.8.1 Design of the Power Supply

The Boeing power supply consists of a 1510 x 1044 m silicon solar cell planar array; the Rockwell power supply consists of a

1400 x 1500 x 605 m structure of gallium arsenide solar cells and solar concentrators to produce a concentration ratio of 2. The major part of the development costs are assumed to be absorbed by the solar power satellite development.

It is conjectured that the design of the EOTV solar cell power supply must meet a different set of criteria than the solar cell blankets on the satellite and, therefore, should be considered a separate design that precedes and is space-proven well ahead of deployment of the satellite. Some of the factors that could generate problems are the docking loads, the loads occurring during transfer, the effect of the radiation environment, the spacecraft charging effects (both natural and artificial), and the incorporation of satisfactory annealing equipment and procedures.

4.3.2.8.2 Broad Application of Composite Structures

The ambitious weight goals for the EOTV assume the extensive use of composite structures. The use of composites on such a large scale and the effect on composites of long-term exposure to the space environment are not well understood.

4.3.2.8.3 Power Conditioning

The Boeing EOTV concept assumes power conditioning; the Rockwell concept does not. Power conditioning imposes extra complexity, weight, and cost, and the need for and the design of the power conditioning system require detailed investigation.

4.3.2.8.4 Cryogenic Propellant Storage

Both contractors have selected argon as a propellant, presumably because it is inert and readily available. Although mercury would provide better performance, it is toxic and could cause contamination; therefore, argon is a preferred choice. Because the boiling point of argon is -302° F, the problems of long-term liquid storage at cryogenic temperatures are similar to those of oxygen (boiling point = -297° F).

There is insufficient information in the contractors reports to verify that the effects of boiloff and the need for thermal insulation have been adequately considered. Light weight, cryogenic liquid storage tanks must be developed. A gas venting system that prevents liquid entrainment, provides thrust verification, prevents gas impingement, etc., must be developed. Thermal protection concepts for insulation or Dewar double-wall construction and sun shielding must be defined and system weight allowances assigned. Provisions for separating liquid from gas for fluid transmission in a near-zero gravity environment must also be developed and included in the weight estimates.

4.3.2.8.5 Propellant Transfer

The contractor's reports do not discuss the design of the propellant transfer system. The transfer of cryogenic fluids over distances exceeding half a mile in space is not a trivial task. Some of the factors that need detailed investigation are: pressure variations in the system, whether the fluid is pumped or pressure fed, and whether the feed lines are sized for liquid or gas flow. (Gas flow will require large line diameters approaching sewer pipe dimensions; liquid flow will require extensive line insulation and double-wall construction that will impose severe weight penalties.)

4.3.2.8.6 Attitude Control

The contractors have assumed LO_2/LH_2 propellants for the attitude control system. Boeing assumes 46 MT for the propellant weight, although no analysis is provided. Such factors as tankage design, number and location of thrusters, thrust level, and validity of the LO_2/LH_2 assumption must be investigated.

4.3.2.8.7 Spacecraft Charging

Spacecraft charging results from the natural effects of kilovolt charging of the kapton backing on the solar cells during the injection of keV (1 keV) plasma during magnetic storms and local charge buildup in the dielectrics due to energetic particle bombardment. Pinpoint failure of the dielectric surfaces could induce arcing, and a conductive coating over the dielectric backing electrically tied to the solar cell conductive coating may be necessary.

The Air Force SCATHA (P78-2) satellite has demonstrated that materials at different locations on a satellite charge to different levels at different rates, that portions of a vehicle in shadow can charge to kilovolts even though the vehicle is in sunlight, and that material properties change in the space environment. Artificial charging can occur if a high potential exists which interacts with the magnetospheric plasma environment. The local plasma will try to neutralize the high potential with a sheath and with the acceleration of local thermal particles. SCATHA has demonstrated particle acceleration whenever metal surfaces are charged to a high potential in reference to the plasma. The acceleration of ions gives rise to sputtering effects; the acceleration of electrons produces soft X-rays. A possible cure is the provision of a Faraday (conductive) shield around the solar array.

Natural and artificial charging effects must be investigated for both the EOTV and the solar power satellite.

4.3.2.8.8 Solar Array Annealing

The Boeing EOTV design assumes silicon solar cells and the Rockwell design gallium arsenide cells. The gallium arsenide cells are assumed to be self-annealing although this should be space-demonstrated; the silicon cells need to be annealed in space. The annealing system design and development is not a trivial task and requires detailed investigation.

4.3.2.8.9 Probability of Space Collision

There is concern that the increasing population of objects orbiting the earth represents a very real potential for collision, and, hence, a hazard of increasing severity for operational satellites. It is predicted that, in the year 2000, the EOTV could be struck by a piece of debris every few days. Every collision will produce more debris, some of which will re-collide with the EOTV on the next revolution and produce more debris. A detailed investigation of this problem is necessary.

4.3.2.8.10 Assessment

In summary, the EOTV is considered a high technical risk item because virtually no detailed design data are available on the concept proposed by the contractors, no design precedence is likely to be established independent of SPS requirements, and many complex subsystem design problems will have to be solved. It should be stated, however, that both contractors are examining the EOTV in more detail under activities separately funded from SPS. Also, the Solar Electric Propulsion Stage (SEPS) Program is receiving some NASA Funding in FY 1981.

In addition, the EOTV is considered a high-cost-sensitivity item because its use is crucial to the viability of the SPS. Substitution of a chemical OTV would increase costs significantly.

4.3.2.9 Built-in Test

In order to limit the quantity of ancillary ground equipment and to provide fast, efficient turnaround, a built-in test design policy must be used for all transportation vehicles. This policy was intended to be implemented in the Shuttle program but was shelved early in the program in the interests of reducing non-recurring costs.

Analogous systems are currently employed on operational aircraft, such as the C5-A transport. The goals established by the contractors appear to be a natural progression of existing technology and achievable in the time frame of interest. This conclusion is reinforced by the electronics industry's capacity for rapid progress in technology that is not paralleled by propulsion and structures

technology. The Shuttle could probably be used as a test bed in the development of the necessary technology base.

4.3.2.10 Improved Logistics

The SPS transportation system is called upon to move very large quantities of personnel and freight efficiently and safely in a limited period of time. This introduces a new concept in space transportation, very different from past experience with expendable launch vehicles and representing at least an order of magnitude advance over the Shuttle program. Limited experience will be developed in ground logistics and some in space logistics as the Shuttle program matures; however, virtually no other applicable experience is likely to be acquired in the near future.

The proposed techniques for improving logistics operations are discussed only very briefly in the contractors reports, and the level of detail is inadequate to serve as a basis for assessment. In concept, an order of magnitude improvement in such key factors as fuel loading rate and turnaround time over the corresponding Shuttle goals is necessary. It is evident that Shuttle experience will have to provide a basis for determining whether the contractor goals can be achieved. HLLV operations are a major cost driver, and improved logistics is keyed to such technology goals as:

- a. Repeated use of thermal protection and insulation
- b. Extended-life liquid rocket engines
- c. On-board, self-monitoring checkout systems
- d. Airline-type ground operations.

Because of the relatively large fleet size and high flight rates over a long period of time, turnaround time per se is not a cost driver. Turnaround effort, that is, the recurring manpower cost per launch, could be a factor. However, if improved logistics goals can be achieved, contractor estimates of manning requirements appear to be conservative compared with aircraft experience. The Aerospace estimate of the HLLV turnaround man-years per flight compared with current Shuttle estimates is given in Table 4-10.

Improved logistics appear to be an open question at this time and detailed study is required to examine this issue. One approach might be to perturb the planned Shuttle system operations, assuming a very high flight rate. Experience has shown that ocean freighters that used to take three weeks to unload and load can now be cycled in two days. Similar achievements must be accomplished in space transportation.

4.3.2.11 On-Orbit Servicing and Maintenance

The SPS transportation on-orbit servicing and maintenance requirements are exceedingly more complex than existing technology can

TABLE 4-10. HLLV TURNAROUND MAN-YEARS/FLIGHT⁽¹⁾

<u>VEHICLE SEGMENT</u>	<u>CURRENT STS⁽²⁾</u>	<u>HLLV⁽³⁾</u>	
		<u>STS TECHNOLOGY</u>	<u>ADVANCED TECHNOLOGY</u>
BOOSTER	-	45	37
SRM	29	-	-
ET	21	-	-
ORBITER	<u>122</u>	<u>71</u>	<u>52</u>
TOTAL (MAN-YRS/FLT)	172	116	89

NOTES: (1) ESTIMATES BASED ON STS TURNAROUND DATA
 (2) 40 FLIGHTS PER YEAR
 (3) 400 FLIGHTS PER YEAR

satisfy. Valuable experience has been gained on the Apollo, Soyuz, Soyuz-Apollo, and Skylab Programs, and further experience will be gained on Spacelab and on the Cryogenic Fluid Management Experiment (CFME) and the Cryogenic Fluid Management Facility (CFMF) Programs being planned by NASA. However, such concepts as spacebased orbit transfer vehicles, permanent manned habitats at GEO, and the assembly of large structures on orbit, which would serve as a technology departure point for SPS, may not materialize early enough to support SPS goals. For instance, the need for developing the capability to transfer fluids, and specifically cryogenic propellants, was identified 20 years ago, but little effort has been made (in the USA) to design, develop, and space-test the critical subsystems necessary to satisfy this need.

The SPS program studies did not reach a level of maturity that included the detailed delineation of the numerous subsystem developments associated with on-orbit servicing and maintenance of the transportation system elements. However, some of these can be easily identified:

- a. Transfer of large quantities of fluids (particularly cryogenes)
- b. Rendezvous, docking, and grappling
- c. Shirt-sleeve transfer of large numbers of personnel
- d. Advanced manipulator devices
- e. Component and subsystem replacement on orbit
- f. Engine replacement and maintenance on orbit
- g. Solar cell annealing on orbit
- h. Advanced space suits for sophisticated extra-vehicular operations in high radiation environments
- i. Radiation protection devices (routine and emergency)
- j. Personnel rescue systems
 - 1) Space lifeboats
 - 2) Individual reentry capsules
- k. Fast turnaround subsystems and procedures.

On-orbit servicing and maintenance is identified as a high technical risk item because there are so many individual elements involved which are not well understood and many other elements that have not even been identified. For instance, even though many space rescue studies have been conducted, the required technology base has not been defined. It is anticipated that it would take many years to achieve international agreement on space rescue policy without even facing the technical problems of designing, developing, and testing satisfactory hardware.

On-orbit servicing and maintenance is identified as a cost-sensitive factor because preliminary weight and cost estimates are being made against idealized conceptual designs. Many idealized concepts will require design compromises that must be identified in the future. Experience has shown that unanticipated design compromises can produce a cascaded effect on the total system that may result in severe cost and schedule overruns.

4.4 COST SENSITIVITY

4.4.1 Objective

The primary objective of examining cost sensitivities of selected system characteristics is to isolate those items that are most critical to system success and to measure the effect on total cost of any short-fall in performance. The baseline used in these cost sensitivity analyses consisted of the Rockwell satellite and transportation system, including the Rockwell HLLV vehicle design; cost estimates were based on Aerospace procedures. The parameters selected for individual examination were:

- a. Satellite Weight
- b. HLLV Size
- c. HLLV Lifetime
- d. HLLV Turnaround Time
- e. HLLV Turnaround Effort
- f. HLLV Spares and Overhaul
- g. HLLV TPS
- h. HLLV Engine Lifetime
- i. HLLV Avionics
- j. EOTV Dry Weight
- k. EOTV Lifetime
- l. Radiation Shielding

4.4.2 Principal Factors

The factors that contribute to total system cost sensitivity and that are accounted for in the analysis of each of the parameters under examination are briefly discussed below.

4.4.2.1 Satellite Weight

If satellite weight increases or decreases, three contributors to total system cost are affected in a major way. First, both the EOTV flights and the EOTV fleet size are altered. Second, the number of HLLV flights changes and, consequently, the number of HLLV vehicles required also changes. (They change because of differences in satellite weight plus changed EOTV flight requirements.) Finally, the cost of the satellite changes appreciably with large changes in weight. (There could also be increases or decreases in PLV or space construction requirements; however, such considerations exert second-order effects on costs and would not materially change the results of the sensitivity analysis.)

4.4.2.2 HLLV Size

If the size of the HLLV increases or decreases substantially, the payload capability changes, which has a direct effect on the number of HLLV launches and the HLLV fleet size. DDT&E and ground support facilities are also affected, but in a minor way.

4.4.2.3 HLLV Lifetime

Three cost components will change if the HLLV lifetime is altered: (1) the fleet size, (2) the ground support facilities, and (3) operations (spares and overhaul). The final item would tend to vary inversely with the first; that is, if the fleet size increases, because fewer flights are demanded from each HLLV, then fewer sets of replacement components are needed because more components would be available as part of the larger fleet.

4.4.2.4 HLLV Turnaround Time

Because the fleet size is so much greater than any extra units needed as a result of an increase in turnaround elapsed time and because all vehicles are eventually used to satisfy the total flight requirements, total system cost in terms of constant 1980 dollars is virtually unaffected over a wide range of possible turnaround times. If the cost of money is considered, however, then the requirement to buy vehicles earlier than otherwise planned (because of increased turnaround) would have an effect (but a relatively small effect) on total cost.

4.4.2.5 HLLV Turnaround Effort

Turnaround effort deals only with the personnel complement at the launch site required to sustain the ground facilities and related activities needed to launch the HLLV. The Aerospace estimate of approximately 90 man-years per HLLV flight (which is based on projected Shuttle estimates) can be varied over a wide range with little effect on total system cost.

4.4.2.6 HLLV Spares and Overhaul

The principal cost associated with flight operations is the provision for spares and overhaul. The major components of this cost element, in estimated order of importance to cost, are: (1) TPS, (2) rocket engines, (3) avionics, (4) mechanical and structure (less TPS), and (5) air-breathing engines. The sensitivity of total system cost to spares and overhaul (as well as its major constituent elements -- TPS, engine life, and avionics) is primarily a function of those items with little or no cascading effects on other transportation elements.

4.4.2.7 EOTV Dry Weight

A change in EOTV dry weight is reflected directly in a change in the EOTV payload capability, thus altering the number of EOTV flights and the related EOTV fleet size. In addition, this will result in slight changes in the number of HLLV flights and the size of the HLLV fleet.

4.4.2.8 EOTV Lifetime

Changes in EOTV lifetime have an effect on the EOTV fleet size and cost of operations. The cost of operations tends to decrease as flights per EOTV are decreased because fewer spares and overhaul provisions would be needed as reuse diminished. Changes in HLLV flights and in fleet size would also result.

4.4.2.9 Radiation Shielding

Because of the complexity of the shielding problem, no design analysis was attempted in support of this issue. However, if it is assumed that varying weight penalties are used to provide adequate shielding, then cost would be a function of the additional shielding itself, plus the additional HLLV flights required to transfer the increased payload.

4.4.3 Results

The sensitivity of total system cost to Items (a) through (c) and (e) through (k) in Section 4.4.1 is shown in Figures 4-4 through 4-13. Items (d) and (l) represent special situations that are not amenable to graphical display and neither, in fact, exhibit much measurable effect on total system cost. The effect of HLLV turnaround time is delineated in Table 4-11 (the requirements for turnaround effort were given in Table 4-10). The effect of requirements for radiation shielding is provided in Tables 4-12 and 4-13.

Only five of the parameters examined showed a possibility of affecting total cost in a material way -- that is, in excess of 10 percent of total cost -- over a range of reasonable values. Foremost among these items would be TPS replacement and satellite weight. Any major excursion beyond planned designs would result in unacceptably high cost changes. EOTV lifetime, if reduced to one flight per vehicle, would affect total cost by slightly more than 15 percent, and that percentage could probably be reduced if the EOTV were specifically designed to be expendable. Engine reuse appears only to be a design and test problem so that 40 to 50 flights per engine should be an achievable goal. Experience on the Shuttle will play an important part in gauging actual engine lifetimes. Similarly, Shuttle experience

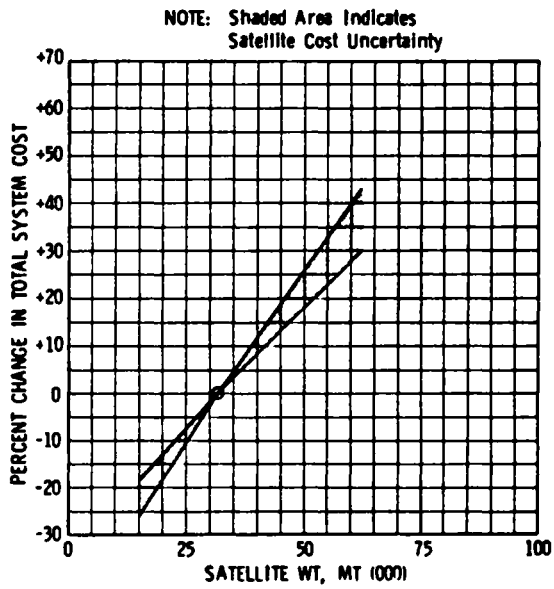


FIGURE 4-4. TOTAL SYSTEM COST VS SATELLITE WEIGHT

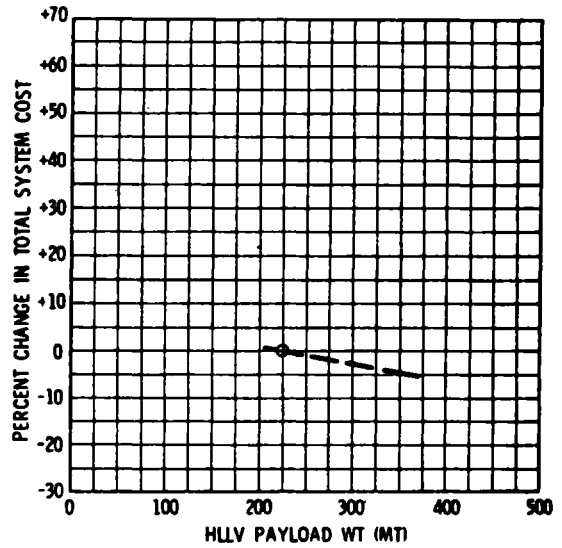


FIGURE 4-5. TOTAL SYSTEM COST VS HLLV SIZE

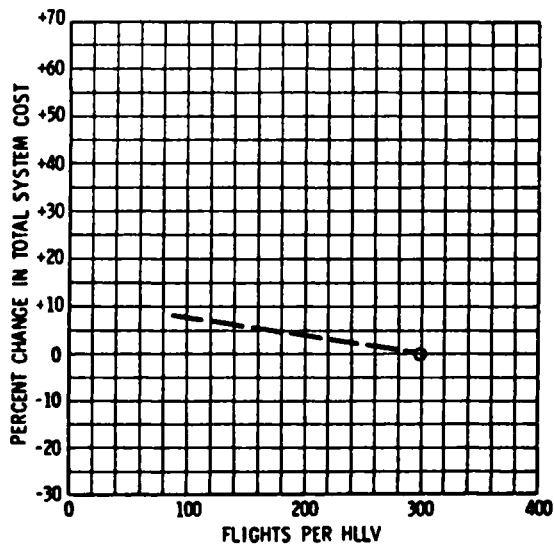


FIGURE 4-6. TOTAL SYSTEM COST VS HLLV LIFETIME

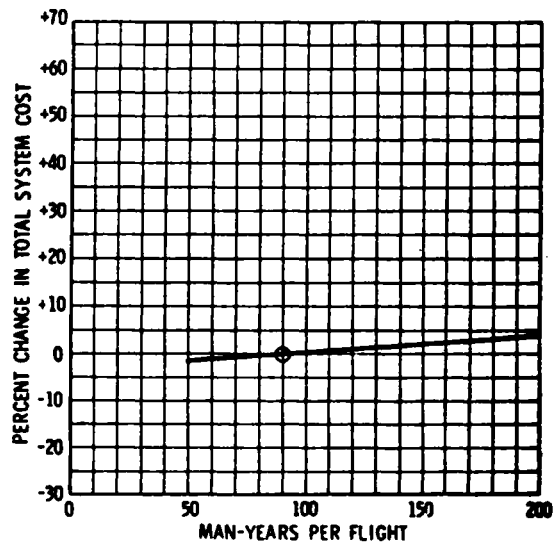


FIGURE 4-7. TOTAL SYSTEM COST VS TURNAROUND EFFORT

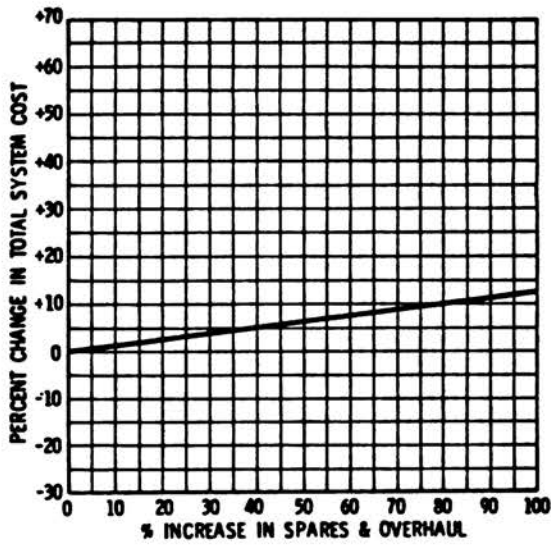


FIGURE 4-8. TOTAL SYSTEM COST VS PERCENTAGE HLLV SPARES AND OVERHAUL

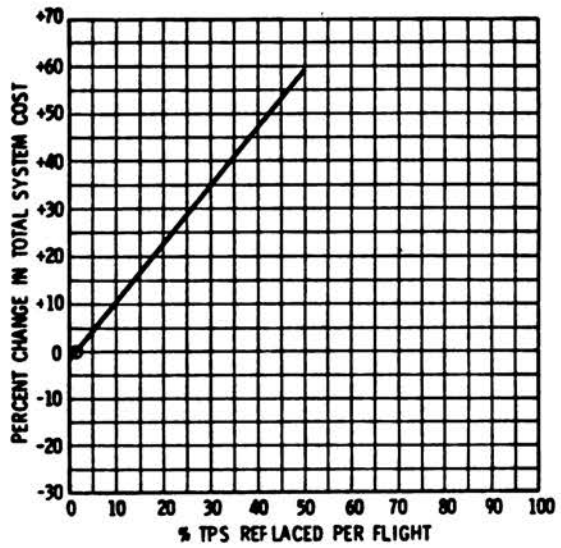


FIGURE 4-9. TOTAL SYSTEM COST VS PERCENTAGE HLLV TPS REPLACED

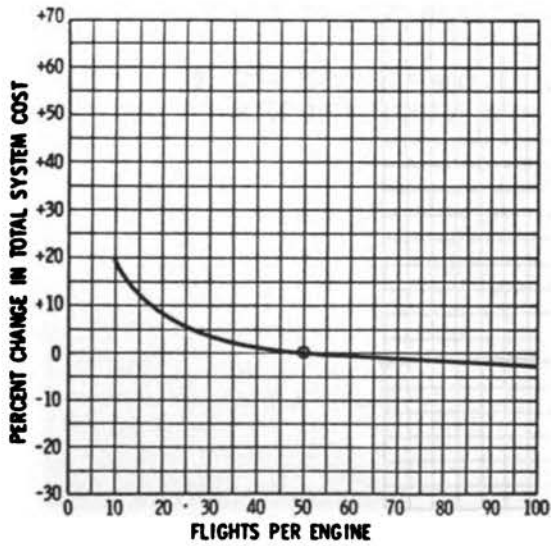


FIGURE 4-10. TOTAL SYSTEM COST VS HLLV ENGINE LIFETIME

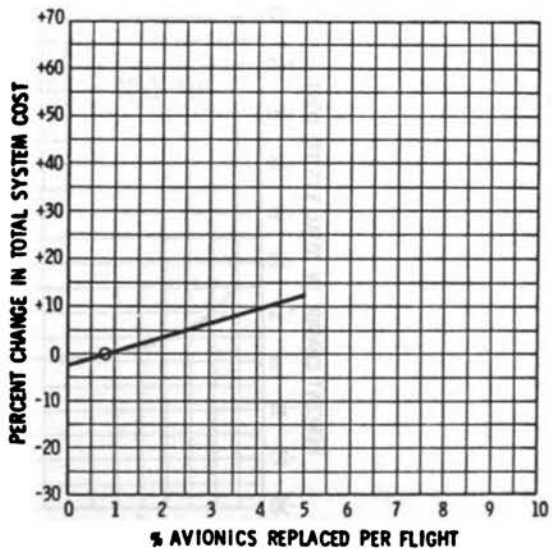


FIGURE 4-11. TOTAL SYSTEM COST VS PERCENTAGE HLLV AVIONICS REPLACED

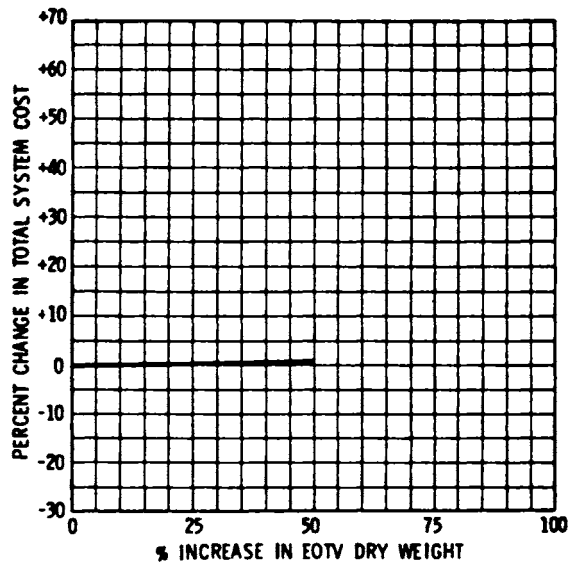


FIGURE 4-12. TOTAL SYSTEM COST VS PERCENTAGE INCREASE IN EOTV DRY WEIGHT

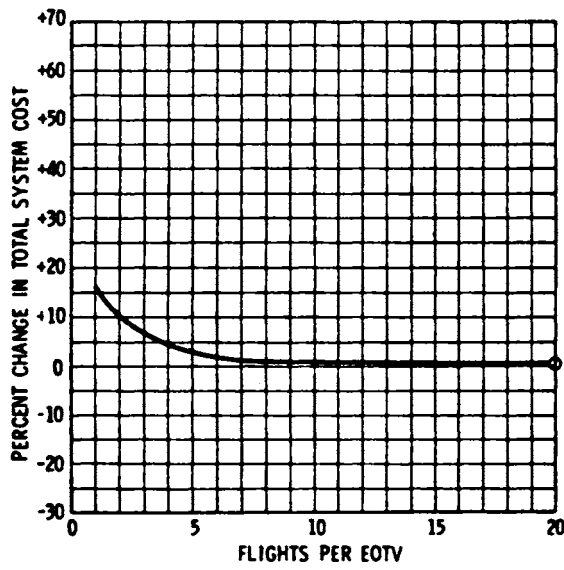


FIGURE 4-13. TOTAL SYSTEM COST VS EOTV LIFETIME

TABLE 4-11. HLLV TURNAROUND TIME

- ASSUMPTIONS
 - / BASELINE TURNAROUND TIME = 7 DAYS
 - / 50 FLIGHTS PER YEAR PER VEHICLE
 - / 8 VEHICLES REQUIRED FOR TURNAROUND
 - / 47 VEHICLES REQUIRED FOR 13,849 FLIGHTS

- ALTERNATIVE TURNAROUND PERIODS AND VEHICLES REQUIRED
 - / 7 DAY TURNAROUND; 8 VEHICLES
 - / 14 DAY TURNAROUND; 16 VEHICLES
 - / 21 DAY TURNAROUND; 24 VEHICLES

- IMPACTS VEHICLE ACQUISITION SCHEDULE - DOES NOT ALTER TOTAL VEHICLE BUY

TABLE 4-12. RADIATION SHIELDING REQUIREMENTS AT GEO

SITUATION ⁽¹⁾	THICKNESS ALUMINUM (CM)	DOSE (RAD/DAY)
NATURAL RADIATION (SEA LEVEL)	30.7 ⁽²⁾	6×10^{-5}
INDUSTRIAL WORKER ⁽³⁾	14.4	1.5×10^{-2}
CHEST X-RAY	8.7	1×10^{-2}
ASTRONAUT (LEO)	6.6	2×10^{-1}
50% FATALITY ⁽⁴⁾	0.23	3×10^2
100% FATALITY ⁽⁴⁾	0.2	6×10^2

NOTES: (1) REDUCE GEO RADIATION TO EQUIVALENT CONDITIONS
 (2) EQUIVALENT WT = 168 LB/FT²
 (3) OSHA STANDARDS
 (4) STATISTICAL ESTIMATE FROM WEAPON EXPERIENCE

TABLE 4-13. SENSITIVITY OF RADIATION SHIELDING REQUIREMENTS

● ASSUMPTIONS

- / NO DESIGN ANALYSIS ATTEMPTED
- / A RANGE OF ADDITIONAL WEIGHTS FOR SHIELDING HYPOTHESIZED
- / 1800 PERSONS AT PEAK

● CHANGES IN TOTAL SYSTEM COST FOR EACH WEIGHT ASSUMPTION

- / 1 MT SHIELDING/PERSON = 0.1% INCREASE IN TOTAL SYSTEM COST
- / 5 MT SHIELDING/PERSON = 0.6% INCREASE IN TOTAL SYSTEM COST

NOTE: 1 MT = 13 FT² OF 30.7 CM THICK SHIELDING

should provide a sound basis for establishing spares and overhaul factors.

4.5 SPACE TRANSPORTATION REQUIREMENTS UNIQUE TO SPS

The space transportation requirements unique to SPS are related, in general, to the very large payload masses that have to be transferred on a very tight schedule and the very large number of personnel that are in orbit, particularly at GEO. Any major disruption in the smooth flow of personnel and materiel could have a significant effect on program cost. The requirements unique to SPS are summarized in the following paragraphs.

4.5.1 Very Large HLLV (Payload Capacity Over 400 MT)

Without any specific program requirement being established for a large HLLV, any advances over Shuttle capability are most likely to be provided by some kind of Shuttle-derivative vehicle. The largest Shuttle-derivative vehicle that appears in anyway practical is one which dispenses with the Orbiter, utilizes four liquid rocket boosters in place of the standard two solids, and has a payload capability of about 140 MT.

4.5.2 Very High Launch Vehicle Flight Rates (Up to 400 Flights/Year)

Even using optimistic mission model projections, if SPS is not included in future space operations, the Shuttle will be called on to provide only a tenth of this flight rate.

4.5.3 Very Large EOTV (GEO Payload Capacity Close to 7,000 MT)

Any other proposed missions that are considered practical within the constraints of the present social, political, and economic environment demand payload capabilities to GEO of about two orders of magnitude lower than 7,000 MT.

4.5.4 Very Large Number of Personnel on Orbit at One Time (Particularly Contractor's Requirement for Peak Personnel Complement of about 1800)

Such large numbers are not contemplated for any other program, even at LEO. Some investigators believe that the problems likely to be encountered in counteracting the radiation environment will mandate remotely controlled operations to reduce man's presence at GEO to an absolute minimum.

4.6 POTENTIAL INDEPENDENT ADVANCES IN TRANSPORTATION

4.6.1 Nominal Projection

If the nation is to maintain a viable and expanding space program, it is evident that space transportation improvements will come about independently of whether the SPS program is implemented or not. Indeed, it is projected that many of the individual technologies identified for SPS will be needed to support other, possibly less ambitious, space transportation goals.

A nominal projection of specific vehicles, and of proposed space capabilities which have been studied extensively and which, if developed, could provide some technology base for SPS, are summarized in succeeding paragraphs.

4.6.1.1 Unmanned Space Shuttle Derivative with Capability to Transfer Commercial/Military Payloads of about 140,000 lb (63.5 MT) from Earth to LEO

It is becoming evident that it may be appropriate to have two versions of the Space Shuttle: one which includes the Orbiter and is used for manned missions and one in which the Orbiter is replaced by an unmanned payload capsule and a separately recovered engine module. The latter version would have more than twice the payload capability of the standard Shuttle and utilize any of the Shuttle augmentation concepts that have been proposed.

4.6.1.2 Single-Stage, Unmanned Cryogenic OTV, Possibly Retrievable, with One-Way Payload Capability up to 15,000 lb (6,800 kg) from LEO to GEO (OTV Expended) or 6,000 lb (2,700 kg) (OTV Recovered)

It begins to appear that the Inertial Upper Stage (IUS) will not provide the high energy payload capability needed in the late 1980's and early 1990's and that a cryogenic engine technology base exists that could contribute to a low-technical-risk cryogenic OTV development. An interim version of this vehicle could utilize an existing space-proven engine system (the Pratt & Whitney RL-10) or a proposed modification (the RL-10 Derivative IIB). A later version could use an advanced, high-pressure engine that is being studied under NASA sponsorship by Aerojet Liquid Rocket, Pratt & Whitney, and Rocketdyne.

4.6.1.3 Man-Rated Cryogenic OTV Vehicle with Aerobraking Recovery to provide Round-Trip GEO Payload Capability of Approximately 11,000 lb (5,000 kg)

If a requirement is established to deploy man to GEO, possibly on a short-term pioneering sortie flight, this could be

achieved with a single launch vehicle flight by combining a single-stage, aerobrake-recovered OTV with a man-rated version of the vehicle described in 4.6.1.1. The aerobrake increases the stage structural weight but dispenses with the propellant normally required for the return trip of a two-way transfer.

4.6.1.4 LEO Space Base (Similar to NASA Space Operations Center)

NASA (and DOD) have performed and sponsored space-station studies for many years. In recent years, interest has been generated in building large structures in space for such applications as spacebased radar and multi-beam communication systems. The NASA designation of Space Operations Center conveys a mission-oriented role of construction, assembly, and servicing of space systems and spacecraft and not just the traditional space-station role of conducting experiments and gathering scientific and applications data.

4.6.2 Optimistic Projection

If a very aggressive and well-funded national space program is initiated, other more advanced transportation goals could be achieved in the time period of interest. In addition to (or possibly substituting for) the vehicles described under 4.6.1, the following vehicles and capabilities could constitute part of an optimistic projection.

4.6.2.1 Fully Reusable HLLV for Commercial/Military Use with Earth-to-LEO Payload Capability Up to 250,000 lb (113 MT)

Even without an SPS development program, if the nation decides to aggressively exploit space, there will be pressure to develop a fully reusable launch vehicle. To justify consideration of such a vehicle, it will have to show a considerable advance over Shuttle or Shuttle-derivative payload capability, whatever economic claims are made for it.

4.6.2.2 Single-Stage, Manned, Resuable Launch Vehicle (Horizontal or Vertical Takeoff/Sled- or Air-Launched) with an Earth-to-LEO Payload Capability of at Least 5,000 lb (2,300 kg)

For many years, the concept of a rapid-response, single-stage-to-orbit (SSTO), manned vehicle has appealed to certain sectors of the military because of its operational flexibility and survivability potential. In recent years, NASA and DOD have described SSTO concepts with payload capabilities up to 65,000 lb (29,000 kg). A

large-payload SSTO has the potential to be used in the SPS program to transport personnel from earth to LEO.

4.6.2.3 Advanced, Two-Stage, Space-Based, Man-Rated, Cryogenic OTV, Requiring Multiple Shuttle Flights with Various Payload Capabilities from Earth to LEO

<u>OPERATIONAL MODE</u>	<u>PAYLOAD TO GEO</u>
Payload Returned/OTV Retrieved	15,000 lb (6,900 kg)
Payload Expended/OTV Retrieved	28,000 lb (12,700 kg)
Payload Expended/OTV Expended	38,000 lb (17,200 kg)

Some investigators consider a manned GEO sortie mission to be the next major manned space flight goal. One approach is to utilize multiple Shuttle flights and assemble and fuel a two-stage OTV in LEO orbit. If such a system were developed, it could provide a technology base for a POTV for the SPS program.

4.6.2.4 Electric OTV (possibly Nuclear Powered) with LEO-to-GEO Payload Capability Up to 2000 MT

An aggressive expansion in planetary exploration could develop a need for advanced transfer capability that might be satisfied by an advanced electric stage. It is unlikely, however, that the payload requirements would in any way be comparable to those associated with the SPS EOTV.

4.6.2.5 LEO On-Orbit Propellant (Oxygen and Hydrogen) Production Facility

It has been proposed that surplus payload capability from earth to LEO could be assigned to carrying water to LEO. A facility at LEO could then use electrolysis to turn the water into oxygen and hydrogen for use as propellants. Such a facility might be part of the NASA Space Operations Center concept.

4.6.2.6 GEO (or Some Other High-Altitude Orbit) Manned Space Base

There is no specific requirement for a GEO space base, either to satisfy commercial or military needs, but the concept still retains its proponents and opponents and from time to time appears in both commercial and military proposed planning documents. If a requirement develops and the system is implemented, it will provide a useful technology base for the SPS program.

5. CONCLUSIONS

The principal conclusions of the study may be summarized as follows:

- The HLLV constitutes the dominant element in transportation cost. Recurring cost is the prime driver with spares and maintenance the largest component. HLLV fleet investment is the second largest component.
- The major transportation cost drivers are those that influence the number of HLLV flights and, consequently, HLLV recurring cost. Satellite weight is therefore a major transportation cost driver.
- When high flight rates are involved, there is a large payoff in providing sufficient non-recurring (DDT&E) expenditures needed to develop technologies that reduce weight and increase reliability for both the satellite and the launch vehicle.
- The EOTV is fundamental to SPS system viability. The EOTV provides very large orbit-to-orbit payload capability and permits efficient use of the POTV by transferring the propellant it needs to return from GEO to LEO.
- For both contractors, the weights of most of the SPS transportation elements are reasonable; on the average estimates were low by about 12 to 15 percent. However, the contractors estimated weights for the EOTV are considered to be about 50 percent low.
- Boeing cost estimates for the unmodified system are judged to be low by more than a factor of two. If the modified design is assumed, Boeing cost estimates are low by a factor of three.
- Rockwell cost estimates for the unmodified system are considered to be 35 percent low. If the modified design is assumed, the Rockwell estimated cost should be increased by 70 percent.
- Within the technological goal assumptions made for the SPS program, both contractors have provided adequate manning on the ground and in space. However, if the complexity of the space base and satellite construction activity has been underestimated, the orbital manning requirements and

the time for construction could increase dramatically and could adversely affect transportation costs. (Investigation of this issue is outside the scope of this study.)

- The lack of maturity in subsystem design has resulted in inadequate system data. In many instances, the contractors were compelled to assume technology and cost goals without identifying specific methods for their achievement.
- Certain technologies and capabilities that are associated with high technical risk also have a strong influence on total system cost. They include:
 - a. Improved TPS
 - b. Electric Propulsion Stage
 - c. On-Orbit Servicing and Maintenance
- The SPS program as outlined by the contractors is a success-oriented program; the number of interdependent elements is astronomical. Any reduction in reliability in a few important system elements could result in a snowballing effect that could radically change total system cost.
- Many of the transportation technology goals that must be achieved to support the SPS program are goals that will have to be achieved to support other projected space plans, whether the SPS program is implemented or not. However, the potential for SPS transportation system cost savings achievable through technology advancement justifies dedicated SPS funding support.

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7. GLOSSARY

ASE	advanced space engine
BAC	Boeing Aerospace Company
CER	cost estimating relationship
CFME	cryogenic fluid management experiment
CFMF	cryogenic fluid management facility
CSM	crew supply module
DDT&E	design, development, test, and engineering
DOD	Department of Defense
DOE	Department of Energy
EOTV	electric orbit transfer vehicle
ET	external tank
GEO	geosynchronous orbit
GSF	ground support facilities
HLLV	heavy lift launch vehicle
IOC	initial operational capability
IOTV	inter-orbit transfer vehicle
JSC	Johnson Space Center (NASA)
LEO	low earth orbit
LeRC	Lewis Research Center (NASA)
LSS	life support system
MSFC	Marshall Space Flight Center (NASA)
NASA	National Aeronautics and Space Administration
O&M	operation and maintenance
OTV	orbit transfer vehicle
P/L	payload
PLV	personnel launch vehicle
POTV	personnel orbit transfer vehicle
PM	personnel module
PROP	propellant
RDT&E	research, development, test, and engineering
RI	Rockwell International
RPL	Rocket Propulsion Laboratory (USAF)
RSI	reusable surface insulation
SEPS	solar electric propulsion stage
SOC	Space Operations Center
SPS	satellite power system
SRM	solid rocket motor
SSME	Space Shuttle main engine
SST	supersonic transport
SSTO	single-stage-to-orbit
TPS	thermal protection system
WBS	work breakdown structure
WER	weight estimating relationship

APPENDIX E
REPORT OF THE WORKING GROUP ON SOLAR CELLS*

Conversion of solar radiation into electricity is a crucial step in the operation of the Satellite Power System (SPS). For the purposes of the present discussions, especially as it relates to the SPS, we will consider only the photovoltaic conversion technology and leave out other possible technologies such as photothermal. Several parameters, not necessarily independent, of the solar photovoltaic cells need to be examined for their ability to meet the operating, life cycle, and cost efficiency requirements of the SPS.¹ These parameters include:

1. Beginning of Life (BOL) efficiency.
2. Radiation and particle damage to solar cells in geosynchronous earth orbit (GEO) and its impact on solar cell efficiency.
3. Methods of annealing solar cells in space--centers of damage, repeatability of annealing cycles, and finally permanent unannealable damage left in the cell which will accumulate over the life cycle.
4. End of Life (EOL) efficiency.
5. Weight of the solar cell: semiconductors, encapsulant, array structure, bus bar configuration, and diode by-pass for protection.
6. Cost: the same five items as under weight.
7. Time frame.

In a sense, the first six parameters derive easily from the necessity for the SPS generated electrical power costs to be competitive with that generated terrestrially by a variety of sources. To be sure, the above six are not completely unconnected insofar as their impact on SPS feasibility since, for example, it should be possible to trade increased efficiency for increased weight and vice-versa or increased weight with immunity to particle damage. It is this interplay of the above parameters that makes the task of addressing the issue of solar cells for SPS challenging (and difficult). That the seventh item above is important and forms an important caveat of the present report is easily seen from the fact that the issues which we are able to deal with in any certainty are those involving technology and exploitation of known science. Thus,

* See Appendix B for composition of the Working Group.

from a historical standpoint, we are forced not to speculate and comment about feasibility questions beyond 2000. It is clear that new scientific insights will play a major role in the photovoltaics of the next century, but it is patently impossible to predict the nature and timing of these basic science advances which will shape the technology of photovoltaics in the years beyond 2000. We must, then, restrict ourselves to the known science, and the technology that has been and can be derived from it. The ability to look ahead twenty years requires reasonable extrapolation of technology and that we have done. Here again, the crystal ball begins to get cloudy as one goes from the ability to construct a pilot plant to full-scale manufacturing facilities which need to roll out acres and acres of space-qualified solar cells. We can, at best, assign only probabilities to achieving various goals by the year 2000.

In order to assess the technology and its evolution in the next twenty years and to arrive at conclusions which are based on the most current technological details, the Working Group on Solar Cells of the SPS Committee met in Washington, D.C. on August 28-29, 1980. The group heard briefings from individuals in industry, government laboratories, and from academic institutions which are intimately connected with various aspects of solar photovoltaic technology primarily directed towards space applications but also included were experts who provided information regarding advanced photovoltaic research and terrestrial photovoltaic technologies. (See Attachment for details of the program.) Further, two members of the study group (Harris and Patel) visited TRW, Incorporated on September 22, 1980, and discussed the problems associated with solar cell array fabrication with Dr. Paul Goldsmith and Mr. Robert Yasui. In what follows, we summarize our conclusions, based on what we heard and what we knew and arrived at through discussions among the members of the study group.

BEGINNING OF LIFE EFFICIENCY

From the consideration of BOL efficiency, at this time only the single crystal photovoltaic technologies are viable. Polycrystalline and amorphous approaches are well below the SPS efficiency requirements and these technologies are not sufficiently well-advanced for us to make an optimistic prognosis about their usefulness in the 2000 time frame for SPS applications. Both single crystal silicon and gallium arsenide are candidates which satisfy the efficiency requirements. But whether these efficiencies can be met within the framework of other requirements--namely radiation resistance, weight, and cost--is at best unclear at the present and at worst it appears not possible in the 1990-2000 time frame. From the point of view of BOL efficiency then there is no significant reason to choose between silicon and gallium arsenide, since BOL efficiencies for both will meet the necessary 16 to 18 percent air mass zero (AM0) requirement set down for SPS applications. To be sure, if cost is not a consideration we believe both the efficiency and weight requirements can be simultaneously met.

Advanced photovoltaic concepts such as multigap cells, i.e., AlGaAs-GaAs, will not be sufficiently well-developed by the time decisions regarding manufacturing have to be made for a year 2000 implementation of the SPS. The technical and economic viability of the SPS will have to be based on silicon or gallium arsenide single crystal approaches. Because gallium arsenide is a direct bandgap material, only one-tenth the amount of material as compared with an indirect bandgap material such as silicon is required. The gallium arsenide cells are more efficient; their efficiency decreases less rapidly with increasing temperature and the cells are more resistant to radiation damage. However, it is still not a material that has been as extensively studied as silicon. The economic leverage of higher efficiency, particularly under moderate solar concentration, afforded by gallium arsenide if strong enough might influence the initial cell choice between silicon and gallium arsenide because of the long-term options. If a gallium arsenide approach is followed, then the multiband gap cells could be introduced as a long term replacement because such a change is a perturbation in the manufacturing technology. However, considering the present BOL efficiencies and the differential in the current technology for making silicon vs. gallium arsenide solar cells, it appears prudent that for the present purposes we address ourselves only to the silicon cells. There is only one caveat here, namely, that if the silicon approach is followed it seems very unlikely that the necessary capital investment and manufacturing changes would be made at some later date to replace the silicon cells with multiband gap gallium arsenide cells.

RADIATION DAMAGE AND METHODS FOR ANNEALING THE SOLAR CELLS IN SPACE

The solar cells will be damaged due to energetic particle bombardment in GEO. The primary components of the energetic particles are electrons and protons. There are fairly reliable data available on long-term energetic electron and proton damage to solar cells in orbit. Two types of situations have been observed. The first is long term continuous degradation from particles trapped by earth's magnetic field; the second is due to solar flare proton events. Both types of degradations are slowed significantly by the use of cover glass over the solar cells. It is also seen that thicker cover glass affords greater protection against radiation damage. Data on these two types of damage were obtained from a paper by Goldhammer and Gelb (1976) of Hughes for silicon solar cells protected by 300 μm thick cover glass. Continuous degradation results in 0.1 to 0.14 percent damage per month. Solar proton flare events result in 4 to 5 percent damage per event. The 30 year cumulative extrapolation then would be $[1 - (0.999)^{360} \text{ to } 1 - (0.9986)^{360} + n(4 \text{ to } 5)]$, i.e., $[(30 \text{ to } 40) + n(4 \text{ to } 5)]$ percent, where n is the number of significant solar flares. In addition, there is a 2 to 4 percent degradation in the solar cell output during the first two months of operation.

A further damage mechanism not included in the above estimates is the damage that the solar arrays would be subjected to while being

transported from low earth orbit (LEO) to GEO using slow orbit transfer vehicles. Such a transfer is expected to take about 3 to 6 months and the solar arrays will spend extended time going through the van Allen belts and the associated trapped high density energetic charged particles. No obvious means of preventing the damage other than shielding are seen to be plausible. Shielding would tend to increase the weight of the orbit transfer vehicle and associated increased costs would be incurred.

Nature of Damage and Preventive Possibilities

Energetic particle damage results primarily from point defects that are created in the effective collection depth of 50-100 μm for silicon solar cells. (For gallium arsenide or other direct bandgap solar cells, the effective collection depth is 1-2 μm and thus the cumulative degradation from point defects created by energetic particles is a factor of 5 to 7 lower than in silicon.)

Electron damage as well as low energy proton damage, is easily minimized by incorporating a thin cover glass slide over the solar cell. It is also known that the damage problem is considerably reduced when solar cells are made thin. For example, a 50 μm thick silicon solar cell is much less susceptible to particle and radiation damage compared to the thick ones on the order of 200 μm that are currently being made. Gallium arsenide cells are considerably more resistant to radiation damage because the direct band gap nature of gallium arsenide allows us to use much thinner semiconductor films for making the cells.

Damage results in reduction in solar cell efficiency as seen by reduced power output from the cells. The presently known data (Goldhammer and Gelb 1976) indicate that there is a 2 percent reduction in power output from solar cells when they are first injected into GEO due to ultraviolet radiation, probably arising from color center formation in the cover glass. In addition, particle radiation effects produce a slow decay in output power as a function of time which at times is hastened by solar flares that inject large doses of energetic particles into GEO (see above). Because it is necessary that the solar power satellite produce the required power output at the end of its thirty year life, radiation and particle damage is an important consideration.

Brandhorst (Briefing given to the Working Group at the August 28-29, 1980 meeting, see Attachment) has suggested that silicon solar cells can be improved in terms of their radiation hardness by reducing the carbon and oxygen content from the present value of $10^{16}/\text{cm}^3$ to less than $10^{14}/\text{cm}^3$. The Working Group does not believe such a reduction in carbon or oxygen content is technologically feasible for the large quantities of silicon that would be required and, further, even if quality control and technology were to be improved it certainly will add to the cost of silicon. Thus, the scientific findings about increased radiation hardness of silicon solar cells by reduced oxygen and carbon content appear not to contribute to improvements in this area for low cost SPS solar cells in the period of the next twenty

years. To be sure, a considerable amount of increased understanding of radiation-induced deep defect states (deep levels) is being obtained by the use of a powerful tool called Deep Level Transient Spectroscopy. Studies have shown that the nature of the deep levels created by radiation is not unique and a variety of deep levels are produced, each one of them requiring different annealing temperatures because of their different activation energies. There are suggestions regarding incorporation of lithium as a compensating dopant to reduce radiation effects or incorporation during the crystal growth of normally benign impurities that would form harmless complexes with vacancies and interstitial defects created by radiation damage. There is some remote possibility of growing radiation-hard silicon crystals. However, neither the science nor technology is sufficiently well developed to make concrete predictions in this regard. Thus, at present, extensive detailed study is required to look at an economic and a simple solution. However, solutions such as lithium doping are not totally problem-free in the sense that problems associated with lithium drift will first have to be overcome. Failing all of these preventive solutions, it is clear that some form of periodic annealing must be designed as a part of the SPS to keep the solar cells operating near their optimum efficiency throughout the thirty year life necessary for economical utilization of SPS.

In Situ Annealing of Solar Cells

The proponents of the SPS have recognized that periodic annealing will have to be carried out in space to meet the EOL efficiency requirements for the solar cells. Two of the proposed schemes involve pulsed heating by either a laser beam or an electron beam. The proposed schemes envision a laser or an electron gun mounted on a gantry that travels back and forth periodically above the solar cells and anneals them at some regular intervals. It is well established that the deep level impurities and dislocations created by radiation and particle damage in silicon can be removed or inactivated by annealing at temperatures approaching 400 °C to 500 °C. Brandhorst (Briefing given to the Working Group at the August 28-29, 1980 meeting, see Attachment) has indicated that not all damage centers created by radiation induced deep levels are alike. Some of the damage can in fact be annealed at a much lower annealing temperature approaching about 200 °C. However, the material in which these studies were carried out was low carbon, low oxygen material, which as mentioned above, is unlikely to be available in the quantities at a price that might make silicon solar cells for SPS economical.

The annealing that has been done so far and studied extensively involves annealing in ovens which is clearly not feasible in the space environment. Detailed studies of either laser or electron beam annealing, do not exist. Further, whatever studies do exist for laser annealing have been carried out on bare silicon cells (i.e., silicon cells without a cover glass for radiation protection). The cover glasses are usually bonded to the silicon with some type of encapsulant

adhesive which is not expected to withstand annealing temperatures of 400 °C. In fact, there is a very good likelihood that pulsed annealing either with a laser or with an electron beam will blow off the cover glass and, perhaps by providing local temperature gradients within the solar cell, may even result in peeling of the metallic film (metallization) applied to the solar cell to collect the current. Further, for a thirty year life, annealing will have to be carried out at regular intervals shorter than once every five or ten years. As seen from some of the deep level transient spectroscopy data, annealing at shorter intervals may require lower temperatures since the deeper level complexes are produced especially when several of the defects coalesce together to form a more stable complex defect. This might require that each of the photovoltaic panels be annealed once every ten to a hundred days which implies that over a period of thirty years each solar cell will have been annealed a hundred to a thousand times. There are no laboratory data about whether a solar cell regains its original output on repeated annealing or if mechanical and electrical integrity of the cell is maintained after these many annealing cycles. Without a concentrated and directed effort, it is unlikely that within the next twenty years there will be sufficient scientific and technological data gathered to allow us to determine the proper choice of annealing process for solar cells and to implement these processes for large scale deployment.

To the best of our knowledge no one has looked into the energy requirements for in situ annealing of solar cells using either lasers or electron beams. In what follows, we carry out an analysis of the energy considerations in the two presently used modes of laser annealing schemes. (1) Pulsed laser annealing: Typical energy densities necessary for laser annealing using the pulsed mode of operation with ~ 100 ns pulses are ~ 1 J/cm². These pulsed lasers operate at efficiencies of ~ 0.01 - 0.05 percent (optical power output divided by the electrical energy needed for its operation). Thus to produce 1 J/cm² of annealing energy, we need ~ 2 - 10×10^3 J/cm² of electrical energy. Let us now evaluate the time necessary for a 1 cm² silicon solar cell to generate 2 - 10×10^3 J of electrical energy.

$$T = 8.3 \times 10^4 \text{ s to } 4.2 \times 10^5 \text{ s, i.e., } T = 23 \text{ h to } 116 \text{ h.}$$

Thus to assure that no more than 5 percent of the electrically generated energy of the solar cell is used up in annealing, the annealing cycle cannot be repeated at intervals shorter than 20 to 100 days. This minimum time may be too long to prevent complex defect formation, particularly during periods of intense solar flare activity.

(2) Continuous wave (cw) laser annealing: For this mode of annealing typical power densities of ~ 5 W/cm² are needed when scan speeds of ~ 1 cm/s are used. These numbers translate to a needed energy of ~ 5 J/cm². The cw argon ion laser efficiencies are typically in the region of 0.01 percent, and thus we need 5×10^4 J/cm² of electrical energy. Following the arguments as in (1) above, for a 17 percent silicon solar cell, the annealing cycle can not be repeated more often than once every 580 days.

Use of high efficiency CO₂ lasers is attractive but here the laser energy will be absorbed by the cover glass since it is opaque at CO₂ laser wavelengths. Silicon solar cells will then be heated to the necessary annealing temperature of 500°C by conduction. To prevent undue thermal gradients, it would be necessary to anneal the glass-silicon-glass assembly from both sides simultaneously which requires that the kapton substrate schemes currently practiced be abandoned and use the scheme proposed in the reference system which utilizes for substrate a large sheet of glass with appropriate connecting grids formed directly on it. Heating small sections at a time for annealing is a dangerous proposition with respect to the effect of local heating on electrostatically bonded interfaces. No data exist today that allow us, or anyone, to claim that this scheme is viable.

In any case, let us calculate the power necessary to anneal solar cells using CO₂ lasers. The power necessary for an annealing period of ~10 seconds is determined by radiative heat loss, the heat capacity of the solar cell assembly, and so forth. The radiative heat loss per unit area per unit time is given by

$$P_r = \sigma T^4,$$

where P_r = heat lost by radiation per unit area per unit time

and σ = Stefan-Boltzmann constant
 $= 5.67 \times 10^{-12} \text{ W/cm}^2 \cdot \text{K}^4.$

It is reasonable to assume glass to be a good blackbody radiator when heated to ~500° C (800 K). We get

$$P_r = 2.32 \text{ W/cm}^2.$$

Due to the heat loss from radiation from both sides of the solar cells, the total heat loss per unit area per unit time is $2 \times P_r$. Thus to keep the solar cell assembly at 500 °C for ten seconds the energy needed is $W = 46 \text{ J/cm}^2$. Taking into account the reflectivity, R , of glass at 10.6 μm , $W(\text{CO}_2) = W/(1-R)$, where $R \approx 0.12$. Therefore $W(\text{CO}_2) = 52 \text{ J/cm}^2$. (Note that for the present we neglect contributions from the heat capacity of the solar cell assembly, heat conduction, and so forth, since we estimate these to be small compared to the radiative loss contributions.) With a CO₂ laser efficiency of approximately 10 percent, the electrical energy input into the CO₂ laser, $E(\text{CO}_2)$, is 520 J/cm^2 . As seen from the above, we can calculate the time, T , necessary for accumulating this amount of energy as $T \approx 6.7 \text{ h}$. If 5 percent of the solar cell energy is to be used up in annealing, the frequency of annealing can not exceed once every three days, and thus from the energy considerations above, CO₂ laser annealing appears reasonable.

While the above discussion addresses the suitability of a variety of lasers for annealing the defects created by radiation damage in silicon solar cells, no discussion is given so far for the intrinsic feasibility of such annealing in the space environment. From present

experimental studies, we are led to conclude that the above calculation does not contribute to the problem of annealing at present since heretofore all the tests carried out to anneal silicon solar cells with cover glasses have failed.² Thus annealing in space remains a major problem and optimistic solutions are just not believable. Further it should also be noticed that whatever few experiments that have been done for laser annealing of bare 50 μm silicon solar cells subsequent to radiation damage have failed to show a return to their original output.² As much as 16 percent loss of output is seen after only two radiation damage and annealing cycles.

We have been informed recently by Scott-Monck (1980b) that the Boeing tests were carried out "not under controlled conditions" and the "samples used were not space flight type solar cells, but rather rejects". We, however, do not see any reason to reject Boeing data (however preliminary) since even the "reject" cells had 16+ percent AM0 efficiency, and further may approximate the real situation in space annealing more accurately than one might conclude. This specifically points to the lack of scientific data to back up the feasibility of repeated laser annealing of encapsulated silicon solar cells. It is impossible to rely on a technology (for annealing solar cells in space) when even the science is not in hand.

There are further considerations which make in situ annealing with lasers or electron beams infeasible. These have to do with the thickness of the proposed silicon solar cells. With pulsed lasers the annealing is accompanied by regrowth of high quality, defect free crystalline material only when the substrate is a good single crystal. A 50 μm solar cell which has been damaged in the bulk by radiation and particle damage in space can hardly be considered to have a good crystalline substrate from which regrowth can occur. Clearly more research and development is warranted to explore specific advantages and limitations of pulsed laser annealing of thin silicon cells. Use of electron beams for annealing solar cells encapsulated with a cover glass is likely to be impossible. This is because the lower energy electron beams (~ 10 -20 keV) will deposit all their energy in the cover glass rather than in the cell. It is impossible to predict if one can ever anneal solar cells in this fashion until laboratory studies are carried out. Further, the electron beam which is stopped in the cover glass is likely to create color centers in the glass, making it less transparent to the solar radiation thus further reducing the efficiency of the solar cells. With repeated annealings, questions regarding the viability of the metallization and intercell connections need to be answered. (In-plane metallization will reduce thermal cycling stresses on the metallizations but will not eliminate them.) A further consideration during laser annealing is absorption of laser radiation by the metallization. A corrugated cover glass scheme can help some, but it has myriads of other problems such as making electrostatic bonding of the cover glass to the solar cell difficult if not impossible, thus having to use adhesives for bonding. Further, the metallization and the interconnection problems are crucial because of the large temperature fluctuations caused during in situ annealing cycles. Differential thermal expansion will surely play havoc.

At this point we may suggest that another annealing system such as using a Fresnel lens to focus the solar radiation rather than a laser be examined for inexpensive annealing process. However, this is clearly beyond the scope of the present study.

END OF LIFE EFFICIENCY

SPS requirements for a specified EOL efficiency requires a detailed understanding of semiconductor particle and radiation damage and its removal by repeated annealing cycles. A thirty-year expected life without prolonged life tests is unrealistic. The longest any solar cell has remained in GEO is about ten years and there is not enough statistical information regarding operation for thirty years.

(Whatever data are available have been obtained with solar cells fabricated using earlier designs. The conclusions derived from these data may have little applicability to solar cells being contemplated now for the long life operation in a GEO application.) The repeated annealing necessary to prevent formation of stable damage clusters which cannot be annealed needs to be studied in the laboratory to see if other problems arise from such a process. To maintain EOL efficiency, it is likely that entire subsections of the array may have to be replaced periodically when some fraction of the photovoltaic cells exhibit less than optimum operability due to problems other than radiation damage. These problems include metallization and interconnections which will go through some 3000 temperature cycles during the thirty year period. There are significant laboratory test data which indicate that metallization and interconnection failure rates go up drastically as the temperature change during a cycle goes to approximately 200 °C (P. Goldsmith, TRW, Inc., personal communication, September 22, 1980).

WEIGHT OF THE PHOTOVOLTAIC ARRAY (BLANKET)

For reasons of the high cost of transportation to GEO, the weight of the photovoltaic blanket is an important parameter. The SPS concept considers a specific power-to-weight ratio of about 500-700 W/kg for the blanket. The weight of the blanket has to include the weight of the substrate, semiconductor, encapsulant, contacts, interconnections, diode by-pass for protection, and so on. We make a lower limit estimate for these as follows:

1. Substrate about 50 μm kapton	60 g/m^2
2. Semiconductor about 50 μm silicon	120 g/m^2
3. Bottom radiation shield glass 75 μ	165 g/m^2
4. Top radiation shield glass 75 μ	165 g/m^2
5. Contact and interconnection	~ 10 g/m^2

Total mass (mimumum)	520 g/m^2
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BOL cell output is approximately equal to 230 W/m^2 (17 percent AM0 efficiency solar cell). Therefore, blanket weight is equal to 2.26 g/W, or specific power equals 440 W/kg. The Boeing reference system³ arrives at a specific power of $\sim 422 \text{ W/kg}$ using a somewhat different scheme where the substrate (kapton) is replaced by a glass sheet. Differences in details are not important for present discussions since the final result is nearly the same.

This number falls slightly short of the requirement for SPS³. It is possible to increase the W/kg number arrived at above by reducing the thicknesses of the protective cover glasses on the top and bottom of the silicon solar cells. However, this would increase the radiation dosage leading to faster damage and a corresponding increased need for more frequent annealing cycles. The present weight of arrays being deployed for space applications is 80 W/kg. Considering the progress in improving specific power of solar arrays over the last twenty years, it seems extremely unlikely that the 500 W/kg requirement for the SPS can be reached in the next twenty years. Finally, the weight of the annealing apparatus has been estimated at 621 metric tons by the Boeing Aerospace Corporation and has been included as a part of the maintenance systems of the SPS.

COST OF THE PHOTOVOLTAIC ARRAY

It is in this area that we find the greatest amount of uncertainty, disagreement, and unsupported optimism.* It is also in this area that it is difficult to obtain firm information from those with an interest in the manufacture of solar cell arrays. The cost of the photovoltaic arrays can be broken up essentially along the lines that the weight consideration is broken down. However, there are some differences. For that reason we will consider the cost of the solar cell array by breaking it down into the cost of starting silicon material, silicon single crystal wafer, cell fabrication, module fabrication, and inspection and certification. Table E.1 shows a summary of the present cost status (in 1980 dollars) for space and for flat plate terrestrial arrays. These numbers are obtained from the Jet Propulsion Laboratory (JPL) and are reasonably accurate, and are based upon current manufacturing technology. Further, the flat plate array cost figures are in reasonable agreement with those supplied by the Solar Energy Research Institute (SERI). The goal for terrestrial silicon solar cell costs is 70¢/W (peak) by 1986. The solar power satellite has a cost requirement* of about 30¢/W (peak) by the year 2000. Let us examine what is involved.

Silicon Cells

Present silicon solar cells are fabricated out of polysilicon whose costs have gone up from about \$60/kg to \$100/kg in the last couple of years. In order to reach the expected cost goal of 70¢/W (peak) for terrestrial solar cell applications, the polysilicon costs

TABLE E.1. Comparison of current costs for space and terrestrial silicon solar cell arrays (in 1980-year dollars per peak watt).

Item	Space	Flat-plate Terrestrial
Polysilicon	2.5	1.5
Single-crystal Wafer	20.0	1.8
Cell Fabrication	57.5	4.5
Module Fabrication and Inspection/Certification	500.0	3.2
Total Cost	\$580.0	\$11.0

have to come down to about \$15/kg. A number of possible techniques are believed to be possible solutions for reaching this goal. However, the carbon and oxygen content of the semiconductor grade polysilicon is inadequate (too high) for radiation hard solar cells. The current DOE efforts to produce solar grade silicon (i.e., less pure than semiconductor grade silicon) with the attendant cost reduction to \$15/kg falls short of the SPS requirements. Without significant research in the area of producing high purity silicon it is unlikely that the goal of reaching \$15/kg for low carbon, low oxygen semiconductor polysilicon can be reached. The 1986 extrapolation to 70¢/W (peak) for terrestrial flat panel photovoltaics is based on solar grade silicon which has a larger impurity concentration than that currently used for space-qualified solar cells. As mentioned earlier in this report, the price that is paid for this cost reduction is a 2 to 4 percent reduction in the conversion efficiency. The increased impurity concentration is undesirable in connection with increased susceptibility of solar cells to high energy electron and proton damage in space. Thus from both the efficiency and radiation damage points of view, anticipated terrestrial photovoltaic array cost reductions may contribute very little to reducing the cost of polysilicon for space applications.

High efficiency single crystal silicon solar cells of about 17 percent AM0 efficiency can be produced today in the laboratory. However, any production technology based on obtaining cells from single crystal ingots is unacceptable from the point of view of availability of silicon as well as cost goals for SPS. This is because an SPS array requiring 50 μm thick silicon cells will waste about a factor of 10 more single crystal silicon in kerf, thinning, and polishing losses. For a 10 GW SPS consisting of 50 μm thick silicon cells, about 10^4 tons of silicon are required. With ingot technology the needed starting single crystal silicon grown by the Czochralski technique would be approximately 10^5 tons. It is unlikely if not impossible to foresee a production of this quantity of low carbon, low oxygen, single crystal silicon of the quality necessary for solar cell production for SPS. The only alternative is the use of ribbon growth technology which would allow us to grow a 50 μm thick silicon that can be directly used for junction formation without any kerf, thinning, and polishing losses. Further, the web growth technique has the advantages of continuous growth and no cell area loss because the wafers are rectangular and the crystals contain fewer defects than those produced by economically competitive edge-defined film growth technique that is being practiced by Mobil-Tyco. So far, the cells fabricated from the dendritic web-grown material give indications of being as efficient as those made from the more traditional single crystal wafers. Web grown crystal films, to date, still are approximately a factor of four thicker than the 50 μm required for SPS applications. It is only very recently that 50 μm dendritic web single crystal silicon has been produced, but no data on efficiency and so on of solar cells made from this material are yet available. It is essential to be able to not only grow crystals 50 μm thick directly but also grow crystals of a width

greater than that currently demonstrated and to achieve the SPS cost goals for the silicon material. However, even under these conditions the present capacity of semiconductor grade silicon has to be quadrupled. This may be possible in the next few years. However, because of only a factor of four increased silicon production, there is very little room for significant cost reduction along a learning curve. The major single crystal wafering cost of \$20/W (peak) for space applications is unlikely to come down significantly until a considerable amount of additional work is done on the dendritic web growth technique which is just becoming practical. The time frame of year 2000, then, leaves very little time either to experiment or to take care of unforeseen problems arising from continuous processing of single crystal wafers for solar cell applications.

As mentioned above, the only ribbon growth technology capable of producing 50 μm thick single crystal material with high cell efficiency potential is the dendritic web silicon growth scheme. In this process the ribbon is grown from a melt of silicon without constraining dies, resulting in an oriented single crystal having excellent surface features. A recent announcement from Arthur D. Little, Inc. (1980) promises yet another technique for thin film silicon growth for possible solar cell applications. Without access to the details of what is involved here, the most optimistic guess is that the technique is comparable to the dendritic web growth scheme in the quality of the silicon single crystal film that is produced. It is clear, however, that demonstration of a new growth technique is still very far from completed silicon solar cells which need careful evaluation in terms of overall reliability in the space environment. Research in the area of efficiency improvement on ingot grown silicon is receiving some attention. Similar research on dendritic web silicon is not yet being done.

Metallization

Much of the metallization at present uses a titanium-palladium-silver (Ti-Pd-Ag) scheme in which the metals are evaporated onto the silicon p-n junctions. The use of a Ti-Pd-Ag system is neither the best nor cost effective. These metals are literally fast diffusers and form very effective recombination centers. From the point of view of the manufacturers of space qualified solar cells metallization is a major problem. It is necessary to find a technique that allows us to get away from vacuum deposition since it is costly and has many problems. The most severe problem of peeling is thought to be due to moisture getting under the metallization during steps between processing or during storage before qualification and deployment. Temperature cycling⁵ is another cause of lifting of the metallization for the semiconductor. The probability of finding a "cheapie" process such as, for example, screen printing, for metallization that is suitable for space applications is seen to be very small. Further, the problem of metallization (for SPS) is going to be considerably more serious from the point of view of quality control of the very large number of photovoltaic cells.

One aspect of cell fabrication involves the question of interconnections, and soldering vs. welding. There are laboratory data which indicate the failure rate for interconnections as a function of temperature cycles and extent of temperature fluctuation. In general, for larger temperature variations fewer temperature cycles are necessary before failures are observed. For a thirty year GEO mission there will be approximately 3,000 temperature cycles, which is where present laboratory data indicate a sizeable fraction of failures of interconnections for a 200 °C temperature cycling. The interconnection wire, because of temperature cycling, has to take a considerable amount of strain. To minimize the strain, at present 0.5 to 1 mil diameter invar or kovar wire is used together with stress relief loops. These are either soldered or welded; however, the welding technology is not well enough in hand to make real estimates regarding its long term usefulness. Solder joints being cycled in the presence of radiation and energetic particles turn out to be problem areas because of the lack of long-term integrity. Apart from the life problem of the metallization and interconnections, the real concern here is the relative cost of materials and processing in this aspect of fabrication. The skyrocketing costs of scarce materials (titanium, palladium, and silver) lead us to believe that cell fabrication cost cannot be reduced significantly without going to a different scheme and a different technique for putting down of the contacts.

Other items in the area of cell fabrication are module fabrication, junction diffusion, etc. These are areas where maximum cost reduction is possible through automation. But these areas contribute a relatively small fraction of the total cost of either space or terrestrial solar cells. Much of the cost reduction in diffusion, i.e., the p-n junction formation, is expected to come from large scale use of ion implantation technique followed by an electron or a laser beam annealing process. Laser annealing of free standing 50 μm silicon solar cells has not yet been demonstrated and is thought to be difficult if not impossible. Thus, these cells may have to be annealed using conventional heating in ovens after they have been damaged during ion implantation for junction formation. The large scale effectiveness of these techniques is being tested but there are not hard data at the present time which allow us to make reasonable estimates of the longevity of cells produced by this technique.

Inspection and Certification

As seen from Table E.1, the largest present cost contributor for space qualified cells (at \$580 for peak watt) is the area of inspection and certification. This is one area which is very amenable to automation and reduction in costs. However, reduction in cost here is likely to be connected with an overall reduction in the reliability requirement for modules fabricated for space deployment. It is difficult to estimate what the reductions might be, but reducing that cost by more than a factor of 100 through the use of automation and

with only minor sacrifice of reliability is seen to be unlikely as indicated by individuals close to the manufacturing of solar cells for space deployment.

As mentioned earlier, automation will contribute towards reduction in cost. If we look at the various items on the cost status, polysilicon costs will come down a little; the single crystal wafering costs may come down to a number smaller than \$20/W (peak), perhaps to \$1-2/W (peak) by the use of dendritic web growth technique. But at present that appears to be more hope than a guarantee. Cell fabrication and module fabrication costs will come down by use of automation but at present automation is already being implemented by manufacturers of space qualified solar cells with a capacity in the region of 100 kW/yr and these costs may not come down by more than a factor of ten. Finally, the inspection costs as mentioned earlier, are a serious problem and even if they were to come down by a factor of 100, still the goal of reaching less than \$1/W (peak) is unlikely by the year 2000. What is needed here is an entirely new technique of fabrication which makes inspection and certification unnecessary and makes cell fabrication and module fabrication even easier than what it is currently. The best industry estimate for the cost projection in 2000 based on presently known science and 1985 technology is approximately \$20-50/W (peak). These numbers come from individuals who are closely involved in the manufacture of solar cell arrays for space deployment (R. Yasui, TRW, Inc., personal communication, September 22, 1980) and are not too different from the Working Group extrapolation of \sim \$20/W (peak).

It is, at this point, worth commenting on a recent new cost estimate from JPL for space qualified silicon solar cells for SPS deployment in 2000 (Scott-Monck 1980a). This new estimate points out that the present cost of silicon solar panels are \sim \$580/W (peak). With very high annual demand extrapolations through automation and significant improvement in yield, the year 2000 cost is estimated to be \$16.1/W (peak). It is instructive to compare this number with the low end estimate of \$20 arrived at in the above discussions by the members of this Working Group. The assumptions appear to be the same, namely, extrapolation based on the science in hand today, technological improvements through the coming years, and no unpleasant surprises either in converting current science into technology or in going from laboratory scale technology to large scale production. We have no difficulty in accepting the \$16.1/W (peak) estimate since it is a reasonably optimistic but realistic estimate. Going one step further, the JPL document arrives at a lower figure of \$2.1/W (peak). In doing so, the estimate utilizes "new approaches towards processing" and unknown "second generation automation" together with spin-on anti-reflection coatings, and so forth, whose ability to withstand the severe environment in GEO is as yet untested. One would not go ahead with a full scale implementation of SPS without such tests in the real environment. Tests on satellites on GEO require no less than five years before one has enough data for evaluation. This puts a severe or unacceptable strain on freezing the technology of 1990 for a very large scale production of solar cells for SPS deployment in 2000.

With these considerations and looking at the aspects of the overall costs that are energy intensive, capital intensive, and labor intensive, the Working Group concludes that the probability of reaching the \$2.1/W (peak) figure for SPS in 2000 is less than 1 percent, and is not a realistic estimate. (The \$2.1/W (peak) estimate requires all the necessary parts of the programs arriving at their final results with no problems of any kind.) In any case, it is well to remember that the reference SPS system, for its economically viable operation, calls for solar array costs of \$0.30/W (peak). The two JPL costs \$16.1/W (peak) (realistic) and \$2.1/W (peak) (unrealistic) are respectively roughly 50 times and 7 times too high for economic viability of the SPS.

TIME FRAME

As mentioned above, we are discussing the feasibility of photovoltaic array availability in the year 2000 for deployment on a SPS for power generation. It is very likely that in the next few years there will be improvements in the understanding of solar cell materials as well as improved technology. However, it is difficult, if not impossible, to forecast new science and new materials. Thus, the statements made above apply to the year 2000 and not beyond. If we are required to assign probabilities to various processes leading to cost reductions in solar cell technology, we can assign the following. The probability that the cost of polysilicon will come down by a factor of ten is about 50 percent. The probability that we will be able to get away from cutting the large silicon single crystal boules into 50 μm wafers by using a web growth technique capable of producing silicon of the high quality that is necessary for solar cells is approximately 75 percent. The probability of reduction of cell fabrication and module fabrication costs by a factor of ten to one-hundred is another 50 percent, and the probability of inspection costs coming down by a factor of 100 is 90 percent. Thus when we multiply all the probabilities we see that the probability that the cost of photovoltaic arrays for solar power satellite application will be reduced to less than \$20/W (peak) is less than 15 percent. It is against this kind of probability in the year 2000 that we have to evaluate the feasibility of the entire solar power satellite. In our view, the present science and technology of photovoltaics puts an unacceptable barrier for extrapolations to the cost requirements for an economic SPS. The technical problems are considered solvable. These include the fabrication of large quantities of solar cells and even the technical possibility of annealing the solar cells in space. But the cost goals are unrealistic.

GALLIUM ARSENIDE

We have briefly discussed gallium arsenide. Gallium arsenide is a potential photovoltaic material for SPS because of its high

efficiency, lower damage probability, and lower temperatures at which the damage can be annealed. It is also possible that by slightly higher temperature operation, the material can be annealed continuously. However, the cost of making gallium arsenide cells by current technology is much higher than that of making silicon solar cells. Further, gallium arsenide cells become viable from the point of view of materials availability when the single crystal 5 μm thick films can be grown on substrates other than single crystal gallium arsenide substrates, or on reusable single crystal gallium arsenide substrates as has been demonstrated for the first time in the last few months (McClelland et al. 1980). As can be seen from the "Summary of Rockwell GaAs Solar Cell Position,"⁶ the higher efficiencies and higher possible temperatures of operation can be used economically only in conjunction with a concentration ratio of >2 . While a very strong case can be made for the suitability of gallium arsenide solar cells for SPS applications, the key requirement of economically fabricating a 5 μm to 10 μm thick gallium arsenide solar cell on a substrate other than single crystal gallium arsenide remains to be demonstrated. In addition, the cost estimates for gallium arsenide solar cell technology show no logical bases for extrapolating to a cost figure of $\sim \$68/\text{m}^2$. A realistic analysis similar to that carried out for the silicon solar arrays need to be carried out but the essential scientific and technical feasibility of continuous gallium arsenide growth on Al_2O_3 ribbons is far from being demonstrated even under laboratory conditions. Pulsed electron beam or laser annealing of imperfect gallium arsenide growth and junction formation have not been tried extensively to evaluate their positive and negative aspects (Davies et al. 1980). The Rockwell report correctly spells out the necessary successes and advances needed for a technological assessment of gallium arsenide solar arrays for SPS deployment in 2000. However, there is nothing that is said in the report which makes this group optimistic about gallium arsenide, in view of the existing differential in the technology in hand with respect to silicon solar cells (for the year 2000 deployment of an SPS). Further research and development in gallium arsenide solar cells clearly need to be continued but a commitment with respect to SPS is seen to be at least premature and perhaps unwise.

OTHER MATERIALS FOR SOLAR CELLS

The $\text{CdZnS}/\text{Cu}_2\text{S}$ cell has the advantage of being light because the absorption coefficient of Cu_2S is large, and it is cheap because of the thin polycrystalline films that can be used. However, the highest efficiency yet achieved is 10.2 percent air mass one (AM1) (i.e., \approx 8 percent AM0 efficiency) and that has been achieved only once in the laboratory and is still too low. The cell has serious open circuit voltage instability problems and cadmium availability is not at all consistent with applications to SPS. The $\text{CuInSe}_2/\text{CdS}$ cell is also thin and cheap, and CuInSe_2 is more stable than Cu_2S . However, the highest efficiency yet achieved in the laboratory is 9.2

percent AM1 (i.e., = 7.2 percent AM0 efficiency) and these solar cells are untested. There is even less indium than there is cadmium. These cells are considered high risk possibilities with very low probability that efficiencies much higher than the present 10 percent of AM1 can be achieved. However, radiation damage may not be a great factor in their operation and so whatever efficiency that can be obtained at beginning of life would also be the end of life efficiency. Before these thin film cells can be considered candidates for SPS, higher efficiencies have to be reached. A considerably increased amount of science and technological development has to be carried out and again it is unlikely that by the year 2000 we will have a manufacturing capability consistent with SPS needs.

CONCLUSIONS

The background manufacturing technology for recommending specific processes for a large scale-up to fulfill the photovoltaic requirements of a SPS system is either very weak or nonexistent. A considerable amount of research and development remains to be done to identify manufacturing and assembly processes which could even produce the volume and the quality of photovoltaic cells required for a SPS at a cost of more than ten to twenty times the SPS goals. Much of the extrapolations of anticipated manufacturing technology improvements and cost reductions are based on terrestrial photovoltaic program goals. However, the photovoltaics requirements for the SPS are so much more exacting compared to those for terrestrial applications that the extrapolation is at best meaningless and at worst invalid. It is our consensus that SPS photovoltaics will not benefit appreciably from the "fall-out" from the terrestrial photovoltaic program that has much less demanding goals. The space-qualified photovoltaic manufacturing technology will have to evolve independently of the corresponding program for terrestrial applications.

It is also our consensus that the probability of achieving the solar cell array costs for an economically viable SPS system is extremely low based on currently known science and practical technology. Photovoltaic cost projections for the SPS appear to be totally based on the DOE low cost silicon array goal of 70¢/W (peak) in 1986 disregarding the fact that the technologies for space-qualified solar cells and for terrestrial photovoltaics are significantly different. Much of the cost reduction for terrestrial silicon arrays over the last six years--from >\$100/W (peak) to ~\$10/W (peak)--have resulted from some compromises in performance of the cells which, from the consideration of the stringent operating limitations, will be unacceptable for SPS applications. There are questions as to whether terrestrial photovoltaics can achieve the anticipated cost goals without any further performance compromises. There will, of course, be some benefit that will flow from the terrestrial solar cell program to the solar cell program for SPS applications in the form of increased understanding of semiconductor physics leading to higher conversion efficiencies. There is, however,

no evidence which leads one to believe that the ultra-high performance (requiring mass-production of the 17+ percent efficiency silicon solar cells which are only now beginning to be fabricated one at a time in laboratories), radiation hard, space qualified solar cells can be made at anything approaching the DOE cost goal for terrestrial solar cells. The increased complication of device designs, radiation shielding, higher purity starting materials (compared to those for terrestrial applications), tight fabrication tolerances, infrared reflective coatings, etc., which are required to reach the SPS performance requirements are going to contribute towards a substantial (not marginal) cost differential with respect to the terrestrial cells.

Individuals very close to manufacturing the photovoltaic arrays for space deployments are skeptical of the cost projections associated with SPS solar cells. Automation has already made inroads in the array fabrication technology with a resultant reduction in labor cost contribution to overall cost. Over the last ten years the ratio of the labor-to-materials cost of space qualified solar cells has declined from 60:40 to 40:60. But considerably faster-than-inflation increases in the cost of materials, brought about primarily by escalating energy costs, have prevented any substantial reduction in the total array costs. An array manufacturer with a presently installed fabricating capacity of 100 kW/yr silicon solar cell arrays makes projections for cost in 2000 based on 1985 (new) technology of \$20-50/W (peak). These projections are based on the assumptions of some beneficial fall-out from the DOE terrestrial photovoltaics program and of no significant problems associated with a further scale-up of the manufacturing and fabrication technology. Both assumptions in the above are, however, optimistic. The generally held belief by SPS proponents is that many of the cost reductions will accrue from the learning curve when manufacturing and fabricating facilities are scaled up. The above low estimate of \$20/W (peak) in fact takes into account the learning curve effect, and it is known that all learning curves based on a given science and technology eventually "bottom out" and that at \$20/W (peak) much of this bottoming has already occurred. Thus, further cost reduction necessary for the economic exploitation of the SPS concept must accrue from science not yet known and technology not yet contemplated. Considering the average time lag of at least 10-15 years between new science and large scale technological exploitation that incorporates new science, it is very unlikely that needed quality photovoltaic arrays can be produced by 2000 at the cost that is necessary for SPS. Summarizing our conclusions then,

- Technology in fact exists and will be further developed to make solar cell arrays compatible with the requirements of SPS. If cost of the solar arrays is not a consideration, all the needed technical requirements for SPS application can probably be met. However, for silicon solar cells there is virtually no likelihood that the cost projections and the technical requirements can be simultaneously met. It is our opinion that the best estimate for a low cost silicon

photovoltaic array is at least a factor of ten higher than that necessary for efficient and economical deployment of SPS.

- The technology for large scale production of gallium arsenide cells is virtually non-existent, and hence for the year 2000 time frame SPS requirements there exists no basis for predicting that cost and technical requirements can be met concurrently.
- A considerable amount of additional research and development should be supported in order to evaluate and solve technical problems which make the photovoltaics (at the time of the present deliberations) a potential show-stopper for SPS deployment in the year 2000.
- In view of rapidly developing solar cell technology using materials such as gallium arsenide, a reevaluation of the SPS concept would appear desirable in about ten years for a possible 2010 year implementation of the SPS.

NOTES

1. The working group has made certain assumptions regarding the numerical values for discussion of the solar cells. These assumptions may be somewhat different from those in the reference SPS system. However, our conclusions are based on what we feel is the best possible information available to us at the present time. We hold out the possibility that parts of our conclusions may have to be changed in light of new information that may become available.

2. Boeing Reference System handout at SPS Energy Conversion/Power Management Workshop, Huntsville, February 5-7, 1980.

3. Note that the Boeing Reference System arrives at a specific power of 422 W/kg using slightly different assumptions. (We thank Jim Lazar of the DOE SPS Project Office for bringing to our attention the material on the Boeing Reference System that was distributed at the SPS Energy Conversion/Power Management Workshop, Huntsville, February 5-7, 1980.)

4. Reference SPS, e.g. the Boeing Concept, calls for the solar array costs to be \$0.223/W (peak) for overall economical exploitation of the SPS. It is not clear if this figure is in 1977 or 1980 dollars (even though the numbers are derived from the handout material distributed at the Huntsville meeting mentioned earlier). If the \$0.223/W (peak) requirement is quoted in 1977 dollars, the extrapolated figure (through inflation) in 1980 dollars would be approximately \$0.30/W (peak).

5. Temperature cycling in space involves much larger temperature variations than those encountered for terrestrial applications. Temperature changes as large as 200 °C are not unreasonable.

6. "Summary of Rockwell GaAs Solar Cell Position" received on November 11, 1980, from Dr. G. M. Hanley of Rockwell International. This report briefly describes Rockwell SPS Reference Concept and an Advanced Concept. However, the proposal is based on existence of GaAs solar cells of efficiency and at cost necessary for economical operation of an SPS. The report is candid, nonetheless, in pointing out numerous areas where significant advances or breakthroughs both in science as well as technology need to occur for the availability of appropriate GaAs solar cells.

7. Recall the solar cell array cost requirement for SPS mentioned in note 4.

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COMMITTEE ON SATELLITE POWER SYSTEMS

Working Group on Solar Cells

Meeting: August 28-29, 1980

National Academy of Sciences, Washington, D.C.

Thursday, August 28, 1980

9:00 a.m. - 10:00 a.m.	Executive Session - committee members only
10:00 a.m. - 12:00 noon	Dr. John Scott-Monck - silicon solar cells
12:00 noon - 1:00 p.m.	Lunch
1:00 p.m. - 2:00 p.m.	Dr. Peter Iles - silicon solar cells and their performance under space conditions
2:00 p.m. - 3:00 p.m.	Dr. K. V. Ravi - silicon solar cells with special emphasis on new technology leading to cost reduction
3:00 p.m. - 4:00 p.m.	Dr. Henry Brandhorst - silicon solar cell technology, lifetesting of solar cells and arrays
4:00 p.m. - 5:00 p.m.	Dr. Muehlenberg - radiation and particle damage to solar cells
6:00 p.m.	Dinner

Friday, August 29, 1980

8:30 a.m. - 9:00 a.m.	Executive Session - committee members only
9:00 a.m. - 10:00 a.m.	Dr. Larry Kazmerski - overall subject of silicon solar cell technologies
10:00 a.m. - 11:00 a.m.	Dr. G. S. Kamath - III-V solar cells
11:00 a.m. - 12:00 noon	Dr. John Meakin - CdS-Cu ₂ S solar cells
12:00 noon - 1:00 p.m.	Lunch
1:00 p.m. - 2:00 p.m.	Executive Session - committee members only

SPEAKERS

Andrew Muehlenberg, Jr., Comsat Corporation
 Larry Kazmerski, Solar Energy Research Institute
 C.S. Kamath, Hughes Research Labs
 John D. Meakin, Institute for Energy Conversion, University of Delaware
 John Scott-Monck, Jet Propulsion Laboratory, California Institute of
 Technology
 Peter A. Iles, Applied Solar Energy Corp.
 K.V. Ravi, Mobil Tyco Solar Energy
 Henry W. Brandhorst, NASA Lewis Research Center

APPENDIX F
MICROWAVE ENERGY TRANSMISSION

Marvin Chodorow*

DIRECT CURRENT TO MICROWAVE POWER CONVERSION FOR THE SPS:
KLYSTRONS AND MAGNETRONS

A more detailed comparison of the technical characteristics of two major alternative SPS microwave sources is given here to justify the somewhat abbreviated judgements made in Chapter 2.

Klystron Performance and Operating Conditions

In DOE's contractors' recommendations for microwave power sources for the reference SPS, the klystron was rated as, by far, the most suitable choice for the application. This was based on the fact that the klystron has been, for a long time, the most electronically rugged, most predictable and consequently, by far the most commonly used amplifier for very high pulsed or continuous wave power.

Specific examples of high continuous wave power include the JPL Goldstone planetary radar transmitter with a single klystron producing 400 kW continuous wave at 2450 MHz; the MIT, Lincoln Lab Haystack planetary radar transmitter with four klystrons operated in parallel, producing 1 MW continuous wave at about 8000 MHz; and a large number of individual continuous wave klystrons used in electron storage rings at several hundreds of kW, including a number of (recently developed) 500 kW tubes at 350 MHz used at the Stanford Linear Accelerator Center (SLAC), with over 65 percent efficiency.

In these examples, as in most other applications, gain is typically 40 dB or greater. With high gain (> 40 dB) the drive power per klystron in the SPS would be quite small (< 10 W) and phase control can be provided by electronic control of the phase of a (likely) semiconductor driver. Changes in either amplitude or phase of the driver have no effect on the dc voltage or current of the output tube or conversely and, therefore, control of the output phase can easily be maintained under conditions of even large changes in dc voltage, current, or temperature of the driven tube. The output (rf) conversion efficiency is estimated to be over 75 percent, only a

*See Appendix B for acknowledgments.

slight extrapolation over the best (74 percent) that has been achieved, and the design changes needed are well understood. To get the overall efficiency quoted for the reference system (Boeing Aerospace Company 1977, LaRue 1980, Nalos 1980), 85 percent, requires the use of a depressed voltage electron collector beyond the output cavity. Such collectors have been commonly used with traveling wave tubes to improve their efficiency (e.g., all such tubes used in communication satellites), and the design theory for these is also well known. The only concern then is whether one can get from an rf output efficiency of 75 percent to an overall efficiency of 85 percent, but there can only be a few percent of uncertainty. One could design a suitable klystron immediately with performance characteristics very close to those stated in the various SPS proposals.

There are other characteristics of klystron performance that are relevant. First, at peak output power there is extreme gain saturation so that ± 1 dB or more variation in input signal has negligible effect on the output (of the order of 1-2 percent). This is an advantage and this gain compression also implies that if one sets the input signal for optimum power, any effects (such as temperature detuning of the intermediate cavities) which would reduce the small signal gain by 1 dB or even more, would not affect output power appreciably.

A similar statement applies to the external loading of the output cavity (coupling to the antenna). Excessive loading lowers the resonance quality factor, Q , but even a 20 percent change in Q may affect the maximum output power again only by a few percent. The advantages of such excessive loading (and lower Q) is that the output would be much less sensitive to detuning of the output cavity for whatever cause, such as temperature. For typical operating parameters, this implies, for example, that detuning (of the output cavity) by something of the order of 1 percent will only reduce the output power to 70 percent of its peak. It is also likely that one can design the cavities with a suitable combination of metals so that the differential expansions due to temperature change can still keep the cavity at more or less constant frequency. Changes in beam current or voltage would not affect these temperatures greatly since under most circumstances, there is almost no interception of electron beam on the circuit. For example, in the 250 kW Haystack klystrons about 600 kW in the beam pass through drift tubes of the order of 1 cm diameter with much less than 1 kW interception.

Some of these matters have been stressed to point out a major difference between a locked magnetron oscillator and a klystron. In the latter, the electron beam-controlling electrodes are completely isolated from the microwave portions of the device. There is no effect on the electron beam at the cathode due to changes in microwave parameters of the cavities. Similarly, since all of the cavities beyond the first are essentially passive circuits driven by an electron beam their responses to temperature change and loading change, for example, is that of a passive circuit and there is no effect back on the driving signal. Also, after interaction with the circuit (cavities), the electron beam enters a beam collector whose

sole function is to dissipate the residual power. This isolation of beam formation, beam collection, input and output cavities, and mechanical changes in the klystron due to temperature are not characteristic of a locked magnetron oscillator. In the latter, everything--cathode temperature, input-output signals, rf circuit--is all very closely coupled. For example, and of particular importance, any residual electron beam energy that has not been transformed into rf power is dissipated by impact on the cathode or anode (the microwave circuit) determining their temperatures. This also controls the anode circuit resonant frequency and phase shift, and this frequency determines the performance in a very critical manner. Many of the problems of the magnetron arise in trying to counteract this intimate coupling between input-output signal, cathode, rf circuit, electron beam, and so on.

Klystron Operation at Reduced Voltage

There were some statements made in a NASA (1980) document, that if for some system reason, one could not use 40 kV on the satellite, the klystron option would be out. The reasons for this statement are not clear. A klystron can operate quite well with about the same efficiency at lower voltages. Of course, the power per tube would be lower. For example, if one were restricted to something like 25 kV, with a correspondingly lower current, assuming the same perveance (ratio $I_0/v_0^{3/2}$) as for the higher voltage tube so as to maintain the same efficiency, one should get something like 17 kW per tube and presumably this would require 4 times as many tubes. One could operate at a higher perveance--i.e., higher current at the same voltage (25 kV)--say, 25 kW per tube. The price in efficiency would be small, if any. The quoted efficiency in the Boeing (1977), Nalos (1980) and LaRue (1980) proposals assumes a very low perveance. At a higher perveance, say by a factor of 2 (which corresponds to twice the electric current for the same voltage), the price in efficiency, very likely, would be only 2 or 3 percent.

The important thing, however, is that klystrons would function quite well at lower voltages, and everything that has been said about gain, stability, current densities, etc. would still be applicable to the lower voltage tubes and the only question is whether one could actually get the ultimate in efficiency.

Magnetron Performance

In the locked magnetron oscillator alternative, a locking signal is injected into port one of a three-port ferrite circulator; this enters the magnetron through port two and for a certain limited range of operating conditions, the oscillation frequency and phase of the magnetron will be locked, the power from the magnetron going to the antenna through port three. Measurements made on one or two devices indicated that locking would occur (Brown 1980 a,b). The efficiency

was about 60 percent with gain ranging from somewhere over 20 dB down to about 10 dB. The locking range (maximum difference between resonant frequency and operating frequency) will be reduced for the higher gain. It is to be noted that in a locked magnetron, there is an interaction between any change in resonant frequency (e.g., due to temperature change or other mechanical distortion), the phase shift of the locking signal through the device, and the operating current and voltage. Therefore, any such mechanical change will produce a non-trivial change in the amplitude of the signal, and it was found necessary in the research described (Brown 1980 a,b) to provide an auxiliary variable magnetic field coil controlled by a suitable signal amplitude sensor so as to vary the applied magnetic field to compensate for this kind of change. An equivalent control on each magnetron would be required in an SPS application.

The most serious deficiency in the magnetron alternative, however (as mentioned in Brown 1980 a,b), is that the system tested for locking a magnetron, using a non-reciprocal device (a ferrite circulator), can almost certainly not be used in a space environment. It is, therefore, irrelevant for the SPS application. The reason, not stated in the reports, is undoubtedly the characteristic power absorption in the circulator, approximately 5 percent of oscillator output power, according to some quoted experience at lower power levels. Such dissipation and heating of a circulator existing in a vacuum would require the device to operate at a high and probably intolerable temperature so as to be able to radiate this absorbed energy. To eliminate the circulator, Brown suggests using a completely different and almost completely untested approach, locking pairs of (identical) magnetrons driven through a symmetrical circuit known as a magic Tee. This presents many unsolved problems. There were some attempts to use this approach at MIT about 30 years ago as a means of driving a linear accelerator. A theory was developed and some tests made, with only partial success. The system was abandoned because of the difficulties which were encountered, complicated possibly by the fact that the application was to pulsed devices, and also because of the success of the alternate approach, namely, klystron amplifiers which were used at Stanford. The system used at MIT required feeding pairs of magnetrons symmetrically through a magic Tee, a four-port device (two symmetrical arms connected in series to a third arm and in shunt to the fourth arm). One feeds a signal into one of the central (shunt, series) arms of the magic Tee. This divides at the junction of the four arms and feeds the two parallel arms terminated by the magnetrons (in phase, antiphase). One magnetron has to be exactly a quarter of a wavelength further from the junction than the other and the two have to have identical resonant frequency, coupling, etc. (unless some as yet unidentified means are devised to make them appear identical). The signal enters each magnetron, performs its locking function as described in the circulator approach, and the power from each of the magnetrons comes back through the same arm through which the locking signal was injected. The signals reach the common junction of the four arms and because of the extra quarter wavelength in one arm, the signals arrive with an additional π phase shift

relative to each other, as compared to the injected signal. This causes the combined power to go out through the fourth arm (series, shunt) to the antenna. The detuning of either magnetron or changes in its characteristics in some way will result in a relative phase shift (or amplitude difference) between the two produced signals which then do not add up in the correct way at the common junction of the four arms. For not too great detuning, most of the power presumably would go to the antenna but the unbalanced portion of the two signals goes back through the input arm to the driver source. Even if the magnetrons could be chosen to be mechanically identical, it would be necessary to maintain this identity in the face of various effects, e.g., changes in temperature, voltage, or current of the two devices.

It is also true, and possibly may not have been considered, that any reflections from the antenna coming back through the output arm and reaching the junction would divide at the junction and go to the two magnetrons, adding an additional (antiphase, in phase) component to the (in phase, antiphase) signal from the locking driver, the alternative depending on which arm goes to the antenna and which to the driver. Therefore, any reflection would cause the two magnetrons to be driven by signals of different amplitude and phase. This comment is not intended as a detailed analysis, but to point out the kind of problems which will have to be solved in any use of locked magnetrons in a reciprocal system (no ferrite devices).

Magnetron Life

There were some predictions made about life (50 years), based on temperature measurement of the thoriated tungsten cathode in a single magnetron plus extrapolation of some data (taken in 1953 on cathode performance in industrial triodes). It is very hard to conclude anything about this projection based on the rather meager measurements quoted on filament temperatures and life of thoriated tungsten cathodes. It is known that triodes using thoriated tungsten have an anticipated life of the order of 6,000 hours and oven magnetrons which use thoriated tungsten also have life somewhat less than 10,000 hours. It is important to point out that, in operation in the SPS the filaments would have to be turned on for each start-up of a magnetron (after an eclipse), and then turned off by some kind of a monitoring device after a certain amount of warm-up time. The cathode is then maintained at the proper temperature by electron back bombardment. Presumably this bombardment would be a function of the rf level in the magnetron, possibly a function of the difference between the operating frequency and resonant frequency, and a function of operating current and voltage, which, as has been stated, would have to be controlled (via a variable magnetic field coil) in order to keep magnetron performance at the right amplitude while the phase of the driver was being changed. In summary, then the cathode cannot be considered as a merely passive element whose behavior depends only on the heat that is supplied or not supplied (as in a klystron). It is very strongly coupled to the whole rf structure and presumably will be affected in

some way by changes in all the various operating parameters of the rf structure.

Magnetron Construction Costs and Constraints

It should be pointed out that because of (1) demands on magnetron symmetry for use in the magic Tee, (2) requirements on control of the resonant frequency so that locking will work well, (3) requirements on optimum and uniform coupling to obtain the greatest efficiency and optimum and uniform sensitivity to the locking signal, and (4) other considerations required by the SPS application, one cannot simply extrapolate the low cost of microwave oven magnetrons for which the specifications are quite loose and quite different. The manufacturing and inspection process would have to be a much more precise operation than in a low-grade application like microwave ovens. Also, in the SPS the objective of optimum efficiency may be in conflict with other design restrictions made on the magnetron, in terms of frequency stability, external control of the signal by means of a locking signal (which puts very stringent requirements on the coupling mechanism), and so on.

Electrical Noise

One cannot make any simple statements about the noise measurements quoted in the magnetron reports (Brown 1980 a,b), which compared measurements made on one klystron and one locked magnetron. These data seem to be in disagreement with most previous experience. Magnetrons have normally been considered very noisy. A number of years ago, Raytheon, the principal manufacturer of doppler radar systems (for which the noise near the carrier is all important), attempted to use continuous wave magnetrons in such systems. As far as is known these attempts were discontinued, and all such radar systems running at power levels of several kilowatts use klystron amplifiers because of superior noise performance.

It is plausible, but by no means proven, that a magnetron operated as a locked oscillator may be quieter than the standard magnetron, but Brown's comparison between the locked magnetron and the klystron and the reasons for the comparative data is not at all clear and would certainly require more careful examination. It is known that whatever measurements have been made on klystrons which are very often used in communications application, such as satellite ground stations, indicate that a well-processed klystron shows noise outside of the operating frequency that agrees quite well with what one would calculate (assuming shot noise in a temperature-limited beam interacting with a series of cavities which behave in all ways like resonant circuits with corresponding Q's, in which their response and amplification fall off as one would expect for circuits of this kind). The data quoted by LaRue (1980), for example, was taken from this kind of calculated (and measured) performance, and it is

characteristic of most klystrons assuming they are processed carefully (pumped carefully to avoid ion noise, etc.). There is not a great deal of other comparative measurements. One can only say that all historic experience indicates that klystrons have been much quieter than magnetrons and if one is trying to compare specific devices, one would have to make very careful measurements in very carefully controlled circumstances.

Harmonic Output

As to radiation at harmonics, there is a common statement that one can make about both magnetrons and klystrons (and probably solid-state devices). In all cases, the rf current in the device, which is responsible for producing the power output is a highly non-sinusoidal one, and the amplitudes of the fundamental, second, third, etc., harmonics are comparable to the dc current, e.g., tens of amperes (A) for the klystron or magnetron. Therefore, the question of harmonic output really depends on the rf impedance of the output circuits at these higher harmonics. The impedances at the harmonics have to be reduced to extremely small values in order for the output at the harmonics to be sufficiently small. In a semi-quantitative sense, this means that the harmonic power can be roughly calculated by merely using a formula I^2R , where I is the rf current amplitude at the harmonic, which will be of the order of tens of amperes, and R represents the interaction (load) impedance as seen by the beam, including effects of all mismatches and waveguide reflections, etc. Given the complexity of the geometry that is connected to the output of the microwave device, it is not possible to design that geometry to reach some pre-assigned small value of this value of impedance (i.e., a small fraction of an ohm).

Almost certainly in any kind of device, it will be necessary to use in the output wave guide system filters which absorb second and third harmonics to a very large degree, without interfering appreciably with the main power output. Even if one tried to design the device with sufficiently low harmonic impedance, filters will still be required because among separate devices small changes in dimensions which may not show up at all in performance at the desired frequency, could have drastic effects on the impedance at the harmonics. What is really necessary is to have filters which absorb all harmonic power. It is anticipated that the dissipation in the filter would be very small, even though the same amount of power radiated could be troublesome.

Cathode Materials for Klystrons

As to the use of the matrix cathodes in the klystron, the present alternatives include: (a) the so-called B-type, the first and simplest, consisting of a porous tungsten matrix impregnated with barium and calcium aluminates, (b) the M-type which has in addition,

an osmium or iridium surface coating, and (c) the mixed matrix which is an osmium-tungsten or iridium-tungsten matrix material also impregnated with barium and calcium aluminates. The B-type simple matrix is currently used in many applications, and life experience with it has been very good. It should be stressed here that the klystron tubes used in the Ballistic Missile Early Warning System (BMEWS) radar (400 MHz, 75 kW average, 1 MW peak), which have seen up to 14 years of life, did not use a matrix-type cathode.

There currently seems to be a great deal of evidence from a number of laboratories (Green et al. 1980, Paulluel and Shroff 1980), both in this country and abroad, that indicate that the M-type are better than the B-type, and the mixed matrix is better than either, in terms of work function and operating temperature for a given current density (and consequently in terms of operating life).

Most of the long-life data has been obtained entirely on the oldest of these cathodes, the B-type. For example, data by at least 4 companies show life of various of these B-type cathodes to be somewhere between 6×10^4 h and 10^5 h at current densities of the order of 1 A. The SPS klystron will require about 0.2 A/cm^2 and cathode temperatures can be reduced by 50° to 60° for each factor of 2 in required current. This would correspond to perhaps 100° to 150° reduced temperature, and consequent improvement of life. The temperature and work function characteristics of the other kinds of cathodes would indicate that one should get much better performance in life, emission, and other desirable characteristics at these reduced temperatures. Without question, they would all run at something of the order of 50° to 100° lower than the B-type, and this would have major implications for life. Much of this will be much more completely investigated over the next several years since there are a large number of programs testing these performance characteristics. These programs will certainly contribute in a most valuable way to our general knowledge of cathodes and to an SPS program in particular.

CONTROLLING A MICROWAVE BEAM

Of the three beam control systems for an SPS that have been investigated by various NASA contractors, the first, retrodirectivity, has been analyzed in greater detail than the others. Some comments on these various systems are included here and, in addition, we have quoted at some length detailed remarks from the final report of the NASA (1980) workshop that epitomize some of our reactions.¹

The Retrodirective Array

The retrodirective array is a system for automatically phasing the separate elements in a radiating system, so that each element radiates a signal component with a carrier phase which is the negative of the phase of the pilot received at that element. This assures that the total signal then arrives in phase at the rectenna (the source of the

pilot beam). In the case of the reference SPS the pilot is sent from the center of the ground area and is received at various points on the satellite.

The arrangement proposed for the reference SPS uses signal mixing with a local phase reference to produce the required phase reversal for transmission (of power) from the satellite elements to ground. If a signal (received) at a frequency f_1 with phase ϕ is mixed with a locally supplied local oscillator signal at frequency f_2 with phase ϕ (phase reference), a component at the different frequency $f_2 - f_1$ is produced. If f_2 is twice f_1 , the modulation component is at a difference frequency back at f_1 with a phase $-\phi$.

Such mixing and generation of a signal for transmission is done for each element or module of the array. All parts of the array are thus co-phased at a reference surface parallel to the incoming wave front, and a beam is produced in line with the direction of the received pilot beam. Any phase change due to the displacement of any part of the array or due to phase shifts along the path (caused by ionospheric effects, for example) is reversed in the mixing process so that a receiver at the originating location of the pilot senses no net phase difference between signal components received from any of the many transmitting elements in the satellite. Even distortions in the transmission path are compensated. Many such elements, using a common reference (mixing signal) f_2 with an identical phase at the mixer and a common pilot signal, will thus cooperate in producing a beam directed toward the pilot transmitter. Note that there is no restrictive requirement on the relative location of the respective elements in the satellite and only limited restrictions on the orientation and rigidity of the satellite depending on the width of the main lobe of individual elements. Mechanical precision, then, has been exchanged for precision in control of the phase of the mixing signal.

Obviously, the relative phase of the mixing signal at each individual element of the array is critical. Each mixing circuit in the system must be excited from a common source, and with precisely the same phase. In principle, to register precisely the right phase variation between the ground transmitter and satellite, the pilot signal transmitted from the ground should somehow contain the identical frequency as the transmitted signal to provide the right phase information. To do it in precisely this way would put requirements on shielding and balancing that would be prohibitive, so various modulation schemes involving sidebands of the carrier are normally used. One such procedure is given in great detail in the LinCom (Lindsey 1978) reports. They describe a retrodirective array scheme (conjugate phase) which involves a secure modulation system to prevent interference and a more erudite spread spectrum modulation to provide the "phantom" carrier, instead of simple carrier suppression modulation using just a pair of sidebands. The LinCom scheme also uses the same transmitter receiver combination for a command circuit. None of this changes the practicality of the system, though it would probably be preferable not to have all the information transferred between ground and transmitter through one channel. It would probably

be preferable if command and control of the satellite involved channels that were separate from the phase control of the power array. We assume that command and control with redundancy and security is someone else's problem.

In any case, providing proper phase information at each transmitter element location with required precision, is an important matter. We would suggest that optical fibers with equal and co-located return paths, and equal length of fiber to each transmitter element, would appear to be a sound way of proceeding. There was some indication in some of the LinCom reports of using a 490 MHz carrier for the common phase reference distribution on the satellite, because of lower rf attenuation. It would probably be better to use a higher frequency signal, modulated on an optical carrier, with the signal distribution by means of an optical fiber. In general, it also would be important to give more consideration to phase errors in the distribution system which might be caused by physical effects, such as thermal changes. For example, any spatially periodic error in phasing would put energy into undesired minor lobes.

Inverse Radio Interferometry

An alternative phase control scheme which has been proposed can be broadly described under the heading of inverse radio interferometry. This involves measuring the phase of signals received at a single ground location from several separated elements on the satellite, all operating at the same frequency. Distinguishing signals from the many elements transmitting on a common carrier can be accomplished by transmitting different pairs of sidebands, produced by carrier-suppressed modulation with a slightly different modulation frequency at each radiator, and by demodulation at the several ground receivers to recover the original carrier phase. This system also requires a phase reference at each of the points on the satellite, with the same kind of distribution problem as in the case of the retrodirective array, and has built in 180° ambiguities. To use inverse interferometry to control the orientation of the satellite would still lead to a formidable mechanical problem. However, it would appear that replication of the system on the ground could be used to control the shape (position and orientation of subarray modules within the structure). It would seem that a good division of the whole problem would be to have rough mechanical control based on interferometry, with precise phasing based on retrodirectivity.

Coherent Multitone Ground-Based Phase Control

A third scheme which has been proposed, called coherent multitone ground-based phase control, is really also a kind of inverse radio interferometry. If an array of radiators or subarray are separated laterally by a distance large compared to their effective diameters, a number of grating lobes are produced. By probing the field one can

mathematically transform the field structure to deduce the relative position of the source elements. In the satellite system, one cannot afford to probe the field on the ground in detail, but by shifting the relative phase of elements continuously, one can cause a grating lobe to sweep through the beam envelope of the radiators and then by measuring the modulation at each receiver caused by the passing of the grating lobe, a modest number of receivers on the ground, measuring the phase of the modulation against a telemetered reference, can be used to deduce the pattern of radiation at the source and the mechanical distribution and orientation. Continuous sweeping of the phase is the same as using a small constant frequency offset between radiators, and the passage of the grating lobe results in a modulation whose phase relative to the telemetered reference from the center contains the information necessary to deduce the relative positions. With many receiving stations and many satellite radiators with different but correlated frequency offsets, accurate and redundant information can be obtained and ambiguities reduced or eliminated.

Comments

One of the schemes described above proposed measuring orientation and position of the various elements on the transmitter by sequential phase measurements on the ground, with a one second scan period proposed. This may be too low a sampling rate since structural distortion of the satellite as well as excessive satellite motion might occur during a one second interval. A 5° phase error in one second, at a wavelength of 12 cm allows only 2 millimeters per second of relative motion. In general, it would probably be better if one applied such a system to groups of subarrays as units, rather than making separate measurements on units determined by the partitioning of the power unit.

In general, it appears to be most useful to use a ground-based system (inverse radio interferometry) to control the physical orientation and shape of the array on the average, and to rely on the retrodirective feature to maintain electric phase. Phase control and satellite orientation and shape are not independent problems.

The following quotations from the final report of the NASA (1980) workshop represent some further related points that we endorse.

The panel believes the microwave power transmission system for the SPS is probably technically feasible, given sufficient resources....It is likely, however, that the final system will bear little resemblance to the present reference system. The panel feels that it is imperative that NASA not become locked onto the reference system as a basis for all future design. (Page 2)

There should be more emphasis on system engineering in the SPS and its microwave power transmission system design. Sensitivity trades should be employed more frequently to reveal optimum design parameters and directions. Design decisions made early in the program do not appear to have

been subject to continued scrutiny and review. Updating the design approaches and major reviews of the overall concept should be done on a frequent basis....Detailed design work has gotten ahead of systems level planning in some areas. (Page 3).

It would be useful to attempt to feed innovative or novel ideas into the design concept from time to time, rather than trying always to refine the original reference design. The panel feels that some of the major electronics and communications companies should become involved in the microwave power transmission system design, since some of the design concepts do not appear to be up to contemporary standards for equivalent military systems. (Page 4)

NOTE

1. The evaluation of the NASA-DOE-SPS beam control proposals and investigations was largely the effort of Professors C.C. Cutler and R.N. Bracewell of Stanford University.

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APPENDIX G

WORKING PAPER:

ASSESSMENT OF THE CURRENT STATUS OF THE DOSIMETRY OF IONIZING RADIATION IN THE SPS ENVIRONMENT

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INTRODUCTION

The construction of the reference satellite power system (SPS) would necessitate the placement of a substantial number of individuals into regions of space that extend out to about 7 earth radii. The concomitant exposure to various radiations must be an important, and perhaps critical, consideration.

Direct dosimetric measurements in this domain have been episodic and estimates of the doses likely to be received must at present be based on calculations. This in turn requires:

1. A knowledge of the major primary radiations encountered including nature, fluence rate, direction and energy.
2. A knowledge of the modifications of the primary radiations by exposure arrangements, especially as a result of shielding by interposed material or by body tissues. This will not only reduce the primary radiation, but generally also results in the production of secondary radiations.
3. The conversion of the charged particle fluence in critical organs to absorbed dose and dose equivalent. This, in essence, requires a knowledge of stopping powers.

The principal source used in this assessment is a DOE document entitled Workshop on the Radiation Environment of the Satellite Power System (SPS) (Schimmerling and Curtis 1979).¹ The calculations referred to are usually the ones by Dr. E.G. Stassinopoulos as reported in the DOE document. In addition, I am much indebted to Dr. Stassinopoulos and Dr. Madey, who also contributed to the DOE workshop, for additional information obtained in discussions. Further information is based on personal knowledge and in particular, on experiences gained as Chairman of the Federal Aviation Administration Committee on the Super Sonic Transport.

RADIATIONS

The relative importance of the various space radiations varies among the regions that are to be occupied in SPS activities. These regions are the low earth orbit (LEO) in which materials will be stored and perhaps also partially (or completely) assembled and the transfer ellipse (TE) which is the trajectory to the third region, the synchronous geostationary orbit (GEO) where the stations are to be located. There are three major types of radiations to be considered.

Galactic Cosmic Radiation

This originates outside the solar system and while it is somewhat modulated (decreased) by solar activity (by roughly a factor of 2 or so) it is relatively constant. The contribution of these particles to the dose equivalent is generally small compared to that from other sources. Energetic heavy nuclei (Z larger than about 10) may represent an especial hazard because of possible effects on cells in interphase. However, this subject will not be dealt with here (as requested).

Solar Cosmic Radiation

The sun emits protons and other nuclei and this sporadic radiation is more intense during the periods of increased sun spot frequency which follows the well-known 11 year cycle. However, particularly strong emissions are associated with solar flares that occur infrequently with highly variable intensity. It is important to note that the optical appearance of a flare is an unreliable index of the intensity of the radiation to be expected subsequently near the earth (usually arriving after a period of the order of an hour). The reason is that the charged particle trajectories are controlled by the interplanetary magnetic field which, in turn, is determined by the interplanetary plasma (the "solar wind"). Frequently, the field has a configuration so that storms in certain areas of the sun (e.g., the eastern limb) are more likely to be a source of significant radiation in the vicinity of the earth. However, the magnetic field is highly variable and predictions as to the radiation hazard that might result from the brightening of a given region of the sun are uncertain. Because of the changeable path length it is also not possible to unambiguously anticipate the magnitude of the total particle fluence from the initial rate of rise of the fluence rate. It appears that efforts to predict the timing and magnitude of doses from solar flares have been increasingly successful. Nevertheless, errors in the assessment of intensity alone are admitted to commonly amount to an order of magnitude.

It is apparent that protection against major solar particle emissions will require massively shielded enclosures ("storm cellars") which must be reached not much later than about an hour following the arrival of the first solar flare particles. Since false alarms are

likely, they may cause interference with construction activity although they would perhaps occur only about once a month.

A further serious question is concern over the maximum intensity of flare-initiated terrestrial irradiation. On three occasions (1956, 1961, and 1972) events were observed that substantially exceeded those previously experienced and it was surmised that they might represent at least approximately the largest possible magnitude. On each of the later two dates a further increase, by roughly a factor of three, was measured in the low energy proton fluence. The mean proton energy was inversely related to the magnitude of these events and under a shield of more than 20 g/cm^2 the 1956 event would have produced a dose equivalent index² that was higher than for the 1972 flare. However, there is no a priori reason for the inverse relations between fluence and mean energy observed in these three instances and there can be little assurance that still more hazardous events may not occur in the future. Our reasonably detailed experience on the subject covers less than three decades which makes it improbable that any such events could occur within a given decade.

Finally, there is incomplete information on flare particles other than protons. The dose calculations reviewed (Schimmerling and Curtis 1979) do not include contributions by these other particles although it has been stated that the number of helium ions can be comparable to that of protons. Since the protons and helium ions are believed to have essentially the same velocity distributions, helium ions would then produce an absorbed dose index that is more than four times larger than that of protons. This is so because the charge of the helium nucleus is twice that of the proton, causing the linear energy transfer (LET) at a given velocity to be four times as large. In addition, the quality factor (Q) also increases (in general) with LET. This calculation still does not include a substantially higher production of spallation products (nuclear fragments produced by the collision of an incident particle of sufficiently high energy with an atomic nucleus). It seems thus possible that the dose equivalent index in free space could be substantially larger for these other flare particles (compared to protons). They are more readily stopped by shielding, but in this process they again produce more secondaries. The net result of these complicated interactions is not easy to judge, but it must at any rate depend on spectral distributions. There is little information on the subject and there is also some disagreement (e.g., Dr. Stassinopoulos believes that nuclei other than protons add no more than 10-15 percent to the dose equivalent index).

Because LEO is planned to be an orbit with an inclination of 30° or less, the earth's magnetic field is a effective shield for protons having energies of less than 150-200 MeV. Since these constitute a very large fraction of the spectrum, the geomagnetic cut-off has been assumed to eliminate solar flare protons as a serious hazard in LEO. However, the massive shielding of "storm cellars" would, in fact, remove most of the low energy protons in any case and the earth's magnetic field would cause a lower energy cut-off for helium nuclei. No calculations seem to be available that estimate the dose equivalent

produced by all nuclei in major solar flares under heavy shielding in LEO (or, for that matter, in any other locations).

Since transit in TE is relatively brief and can be scheduled, it would appear that solar storms can be largely avoided.

In GEO and beyond, the earth's magnetic field is so weak that only those protons are eliminated that represent a negligible hazard even in the absence of shielding (energy less than about 10 MeV). Thus, the flare hazard in GEO is essentially as high as in interplanetary space.

Trapped Particle Radiations

These are primarily protons and electrons in the Van Allen belts. The fluence rate of these particles has been (and is being) measured by a number of satellites which have yielded extensive and relatively consistent data. However, it was found necessary a few years ago to revise the estimates for the electrons in the GEO region sharply upwards.

Because of fluctuations in the solar wind and diurnal variations, these fluence rates can vary by one or even two orders of magnitude in a matter of hours.

The main contribution to the dose equivalent index in LEO is made by protons having substantial energies (of the order of 100 MeV). These are primarily encountered in the South Atlantic anomaly when the orbit is higher than about 300 km and as a result the (most convenient) 30° inclination results in the highest intensities. The distribution of protons in height and in latitude is such that at lower elevations intensities decrease with decreasing angle at all inclinations.

Since TE involves a traversal of the heart of the radiation belts, it involves very substantial irradiation and despite the relative brevity TE may require substantial personnel shielding.

In GEO the proton contribution is negligible because energies are again very low. However, the electron fluence rate is still quite substantial. Also, the electron fluence rate depends on latitude which may introduce a ten-fold variation--especially at high electron energies.

DOSE CALCULATIONS

Since many, if not most, of the SPS activities will have to be carried out under shielding that exceeds that afforded by a space suit, the dose equivalent received by various organs must depend on the degree of shielding, including the geometrical arrangement as well as thickness (in g/cm²) and the atomic composition of the shield. Since most of this information is as yet unspecified, the available calculations (Schimmerling and Curtis 1979) must be considered to be only rough guides and their authors have characterized them as such.

RELIABILITY OF RESULTS

An important consideration is the detail in which secondary radiations are allowed for. Since the most important radiations are charged particles, it is relatively easy to multiply their fluence by their stopping power to derive the "absorbed dose". However, secondary and higher order radiations are produced in the shield and the calculations become more difficult if these are considered as well. Calculations are particularly difficult for high energy protons which initiate complex spallations and hadron cascades. The latter process is important indeed since it can increase the dose equivalent index under substantial shielding by a factor of 3 or more when the proton energy exceeds ~ 500 MeV. In the most detailed calculations reviewed (Stassinopoulos 1979), this effect has been neglected.

In the Workshop's electron calculations (Schimmerling and Curtis 1979), in which electrons are the primaries, account has also been taken of the very important bremsstrahlung. However, the calculations were for the rather unrealistic geometry of a semi-infinite aluminum slab. Under conditions of isotropic incidence over a solid angle of 2π , the dose at some depth in the slab is only about one-quarter of the dose in an aluminum sphere having a radius equal to the depth of the slab. In addition, the results are given in terms of the aluminum dose which is roughly 30 percent lower than the corresponding absorbed dose in tissue.

If the currently accepted NASA dose limits are to be applied in SPS operations, the margin for error must be narrow. Even a four- or five-fold error might result in acute radiation sickness. If the allowable radiation dose limits are to be reduced the relative error might be somewhat larger, but the absolute error must be less.

The majority of the existing assessments are not sufficiently accurate to meet these requirements either because of uncertain input (magnitude of solar flares and variability of intensity in the trapped radiation zone) or because of omission of or inadequate allowance for secondary radiations. It would appear that the uncertainties could collectively quite possibly amount to an order of magnitude and it is especially significant that virtually all of them seem to be such as to suggest that the current assessments are substantial underestimates of the true radiation doses.

These problems seem to be less serious in LEO where radiation levels are so low that extra vehicular activity may be possible except perhaps for the relatively short passes through the South Atlantic anomaly. Most of the doses to superficial unshielded body tissues in LEO are due to electrons of low energy (< 3 MeV). Beyond 1 cm of unit density material, protons are dominant. The dose component produced by protons may have been underestimated, but probably by a factor of less than four which would make the average daily dose equivalent index less than 1 rem (10 mSv). However, a further reduction of dose requires maximum shielding (because of the high proton energy).

Realistic dose calculations for TE must assume substantial shielding. Proton doses are somewhat less and the energy is generally lower in TE than in LEO. However, the electron intensities and energies are maximal with the result that uncertainties in bremsstrahlung production become very significant. It should, however, be noted that the dose equivalent index rate behind a shield of given mass depends critically on atomic composition of the shield. The available calculations for aluminum slabs yield values that are higher than those for compound shields and in this respect the dose calculations may tend to result in overestimates because shields constructed of suitable layers of materials of high and low Z could result in more effective protection for equal weight. However, as already mentioned, the available bremsstrahlung calculations yield results that are generally too low by a substantial factor.

In GEO, electrons normally contribute the bulk of the doses and although their mean energy is somewhat less, much the same considerations apply as in TE. Although the dose rates are less, they must be integrated over far longer periods than the few hours required for TE. The employment of compound shields would appear to be mandatory if dose equivalent index rates of more than one rad per day are to be avoided. In GEO, the effects of solar storms will be maximal and very substantial shielding or perhaps even the capability for rapid descent must be available. This consideration may well be of crucial importance. It must be realized that a cylindrical shield that has a thickness of 40 g/cm² aluminum (which might be a suitable choice) and a diameter of 2 m weighs more than 2 tons per meter. Each circular end plate would weigh more than one ton.

CONCLUSIONS AND RECOMMENDATIONS

It appears that the radiation doses received in SPS activities are potentially quite high and that existing calculations are not only merely rough approximations, but also likely to underestimate the hazards substantially.

More detailed and more accurate calculations need to be made before radiation protection can be planned realistically. This is an urgent task if SPS is to be seriously considered because the radiation exposure of personnel appears to be a serious and possibly a decisive consideration. The data for such calculations are available to some extent. Further measurements and analysis of the trapped radiation zone environment are highly desirable. Solar flare projections will, however, always be uncertain. The knowledge of cross-sections for attenuations of primary radiations and the production and attenuation of secondary and higher order radiations is largely available, but much of it has not been utilized. It is essential that a major program be initiated in which both the acquisition of input data and their processing in dose calculations be intensively pursued. This would be in sharp contrast to the present status; there has been little activity in this field in recent years because of financial constraints. The Radiobiology Advisory Committee of NASA (of which I am a member) has made recommendations along the same lines.

Although the design of shielding must be based on a knowledge of ambient radiations and their energies, absorbed doses--or even dose equivalents--can be measured directly and more easily. Such measurements as telemetered from satellites would not only yield numerical values of the quantities desired in any given geometry, but these values would also provide an important check on the accuracy of calculations.

NOTES

1. Since this appendix was written, new DOE reports (U.S. DOE 1980a, b) have appeared with dose estimates from the Workshop report having been modified according to Seltzer (1979). Seltzer's calculations have not been reviewed here, but are noted in Chapter 4.

2. The dose equivalent index (ICRU) is the maximum dose equivalent in a 30 cm sphere of tissue-equivalent material centered at the point of interest. The absorbed dose index is the maximum absorbed dose in such a sphere. Numerical values of dose equivalent or absorbed dose are meaningless (especially at high energies) unless the irradiation geometry is specified. These and a number of other vague characterizations of radiation quantities in space radiation dosimetry should be eliminated for reasons that are more than pedantic. It appears that inaccurate terminology has caused confusion on a number of occasions.

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APPENDIX H
WORKSHOP ON MECHANISMS UNDERLYING EFFECTS OF
LONG-TERM, LOW-LEVEL, 2450 MHz RADIATION ON PEOPLE*

July 15-17, 1980

WORKSHOP SUMMARY

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*The workshop was organized by the Committee on Satellite Power Systems of the Environmental Studies Board, Commission on Natural Resources, National Research Council. The Workshop Summary was used as a resource document by the Committee in preparing its final report.

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INTRODUCTION

The Issue

The Department of Energy (DOE), with the help of the National Aeronautics and Space Administration (NASA), is conducting a three-year comprehensive assessment of a satellite power system (SPS) concept. The system being studied for reference purposes would use 60 satellites to collect sunlight and convert it into microwave radiation, which would be transformed into electricity by a receiving antenna (rectenna) on earth. The technological design for such a system exists, but many questions remain.

A National Research Council Committee on Satellite Power Systems was appointed in the fall of 1979 to review DOE's SPS Concept Development and Evaluation Program to be sure the critical issues have been addressed. A brief statement of the Committees' objectives is contained in Appendix A. One issue that the Committee decided to study in some detail is the possible health effects of the constant transmission of low-level microwave radiation. According to NASA calculations, the SPS microwave transmission system would increase U.S. background levels up to 1 W/m^2 (0.1 mW/cm^2). Accordingly, potential health effects must be analyzed.

A limited data base exists on the health effects of the microwaves of the particular type that would be generated by the SPS. Existing data tend to be incomplete, often contradictory, and not entirely pertinent to SPS microwave radiation parameters. Present information consists mainly of limited observations of the effects on animals of short-term exposures to microwaves of relatively high power density. While these data are useful, there is an essential need for data either on or to permit one to predict the effects on human health of continuous or chronic exposure to the low level of microwave radiation that would be associated with a SPS.

Missions of the Workshop

The Planning Group on Microwave Health Effects (Appendix B) of the NRC Committee convened a workshop on July 15-17, 1980 to identify what is known about biological effects and mechanisms underlying the effects of microwave radiation at power densities below 1 W/m^2 and at the proposed SPS frequency of 2450 MHz. The current SPS reference system is designed so that the center of the rectenna on Earth receives 230 W/m^2 (23 mW/cm^2) and at its exclusion boundary 1 W/m^2 . Therefore, the power densities of concern in terms of public health impact are less than 1 W/m^2 . The major objective of the workshop was to suggest research aimed at reducing the uncertainties concerning public health effects associated with exposure to SPS microwave power densities and frequency. The following topics were addressed as the most critical areas where experiments have demonstrated or suggested biological effects at power densities of 1 W/m^2 or lower:

1. Local or general thermal effects.
2. Interaction with drugs or other chemicals (evidence of additive or synergistic effects).
3. Immunological effects.
4. Effects on calcium efflux in brain tissue.
5. Effects on organized structures (e.g., effects on central nervous system or other system components as related to motor function, short- and long-term memory, and general behavior).

The SPS Concept

Briefly, the SPS is a concept that transforms solar energy into electrical energy that could be used on Earth. As an initial basis for studies, a reference system has been defined comprising up to 60 large (35-50 x 10⁶ kg) satellites in geosynchronous orbit at various locations around the Earth. Each satellite would be equipped with a solar cell subsystem to convert solar energy into electrical, a subsystem for generating microwave frequency energy, and an antenna to beam the microwave energy to Earth. An elliptical rectenna subsystem on Earth with approximate dimensions of 13 x 10 km and surrounded by a 0.7 km wide exclusion area to preclude public access to power density levels greater than 1 W/m² would receive and process the microwave energy for insertion into electrical utility systems. The total area of a rectenna site would be approximately 14 x 11 km. The DOE/NASA Reference System Report of 1978 contains further technical details, including diagrams of the microwave power density as a function of distance from the center of the beam.

It is estimated by NASA that the postulated system of 60 satellites and their receiving rectennas would cost a total of \$830 billion in 1978 dollars. It would deliver 300,000 megawatts to the nation's electrical utility systems. The system would be constructed and deployed over a forty year period commencing in 1990.

Current Federal Emphasis on Microwave Bioeffects Research

Federal efforts to conduct microwave bioeffects research is dispersed throughout a number of Federal agencies and their subcontractors including the Department of Energy, the Environmental Protection Agency, the Department of Defense, the Department of Commerce (National Telecommunications Information Administration), the Department of Health and Human Resources (FDA-Bureau of Radiological Health; Occupational Safety and Health Administration; National Institute of Environmental Health Sciences; National Institute for Occupational Safety and Health), and the Veteran's Administration. Bioeffects research relevant to SPS is funded by DOE and administered

by EPA. In its Preliminary Environmental Assessment for the SPS of January 1980, DOE summarized present knowledge of the potential effects of SPS microwave energy on biological systems in space, at rectenna sites, and outside rectenna sites as follows:

- Immunology and Hematology
 - Effects in space largely unknown
 - Effects at rectenna sites possible
 - Effects beyond rectenna sites unlikely
- Mutation
 - Effects unlikely in space or terrestrial environments
- Cancer
 - No effects expected
- Reproduction
 - Potential effects unknown in space and on rectenna sites
 - Small risk of effects elsewhere
- Growth
 - Effects unlikely
- Behavior
 - Effects on SPS workers and other species endemic to rectenna sites possible
 - Effects beyond rectenna sites uncertain
- Physiology and Integrative Processes
 - Effects in space and at rectenna sites possible
 - Effects beyond rectenna sites unlikely
- Interactive Situations: Medications and Special Populations
 - Possible adverse but largely unpredictable implications

Currently, there are three active studies of relevance to SPS being investigated for DOE by EPA under contract. These include:

1. Studies of the behavior of bees as influenced by 2450 MHz fields of 30, 60, 90, 250, and 500 W/m². Thus far, no significant effects on behavior, development, or navigation have been detected. Future work will entail chronic exposure of whole hives of bees to low-level 2450 MHz fields.

2. Studies of the effects of acute exposure to ~200 W/m² 2450 MHz fields on the immunology and hematology of small mammals. Thus far, no effects have been reported.

3. Studies of the effects of acute and chronic exposure to 2450 MHz fields on the behavioral and navigational capability of birds. Thus far, no major effects on behavior from 10-1000 W/m² fields have been detected. Acute exposure designed to establish lethality thresholds and involving exposure of birds to strongly thermal fields

of 1300-1600 W/m² has resulted in some mortality and have suggested that tolerance of such strong fields may be species dependent as a function of body geometry. The intensity of these fields far exceeds the maximum intensity of 230 W/m² anticipated to occur at the center of an SPS rectenna during operation. Some birds exposed chronically to 250 W/m² fields have exhibited some increase in aggressive behavior probably associated with hot spots in various portions of the body, but the results of these studies need to be verified. In general, exposure to fields of 1-250 W/m² has not resulted in any major statistically significant changes in animal behavior.

WORKSHOP TOPICS OF DISCUSSION

Each of the major topics addressed by the workshop was subject to three fundamental questions:

1. What human and animal cellular and molecular data exist? Is there any indication that such observed changes might be beneficial, deleterious, or indifferent to humans?
2. What theories or potential theories exist that could enable extrapolation to low power levels (1 W/m² and below)?
3. What kinds of data are needed to reduce the uncertainties in questions (1) and (2)? What research recommendations can be made? Is it possible to design appropriate epidemiological surveys to establish a useful upper limit on any effects determined to be deleterious?

Local or General Thermal Effects

The discussion of this topic was largely theoretical in nature rather than a review of the existing, well-known data. It is unanimously acknowledged that at sufficiently high field intensities (greater than 100 W/m²) heating will occur in humans and animals as a function of frequency relative to body or organ size and power density. Controversy continues to exist, although far less so than in the recent past, about effects below 10 W/m². The sentiment of the workshop was that the thermal/non-thermal mechanism argument has been belabored for too long and should be supplanted by a cogent effort to understand the underlying mechanisms of low-level microwave effects (or better stated, phenomena).

It was noted that approximately 10 percent of the literature used as supportive information in the American National Standards Institute (ANSI) standard was below 1 W/m²; it is not known, however, what fraction of this percentage is scientifically significant and reproducible. At such a low field level, it is difficult to implicate thermal mechanisms in observed phenomena. The majority of phenomena reported at 1 W/m² and below are of Soviet, Polish, and Czechoslovakian origin, although an increasing number are being found in France and other Western countries. Some reported responses to microwave fields around 10 W/m² but well below 2450 MHz, such as

calcium efflux from brain tissue and behavioral and neural changes, can be replicated in repeated experiments (see also below). At the same time, many can not. That such phenomena are generally acknowledged to be real, however, was considered significant enough to justify further experimentation, particularly long-term experiments, at the whole-body, organ, and organelle level. A considerable body of experimental data already exists from measurements of the microwave properties of aqueous dielectrics and extensive work on phantom models simulating the human body. Accurate determinations of the attenuation function of biological tissue up to a frequency of approximately 10,000 MHz exist in the literature.

Of fundamental value are studies of the basic physical interactions of electromagnetic fields with the molecular components of living tissue. An understanding of these interactions can lead to the construction of useful models of biological effects of phenomena. The electronic structure, charge localization, and mobility of large molecules, particularly in biological systems, suggest the remote possibility of sensitivity (which may involve cooperative or collective response phenomena) to electromagnetic fields of 1 W/m^2 and below. Resonant interactions with continuous wave fields have been demonstrated at frequencies above 10,000-100,000 MHz. The question of interactions at the SPS design frequency (2450 MHz) and power densities has yet to be explored experimentally. Biophysical experiments are therefore required to determine the role of microwaves at SPS frequencies and intensities at the molecular level, their action on ionic conductivity in the vicinity of supramolecular structures, and modulation effects. 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 conformational changes.

Dosimetry, the calculation or measurement of energy absorbed during irradiation, is an extremely important element in the assessment of microwave bioeffects, particularly so because most effects or phenomena studied in animals are extrapolated to expected responses in humans. The concept of specific absorption rate (SAR), which defines the rate of energy deposition in a unit mass of tissue, or the intensity of the electric field at any location, provides a powerful tool for quantifying interactions of biological tissues with microwaves. Nonetheless, in order to interpret and extrapolate data involving exposure to microwave levels of 1 W/m^2 or below it is likely that better dosimetry techniques than are now available will be needed for calculating and measuring internal field patterns. Conventional numerical dosimetric techniques have been used to calculate whole body SARs at 2450 MHz, however, when localized SARs are calculated and the body broken down into many small compartments, the requirements for computer memory exceed the capacity of present computers. Accordingly, special and quite expensive techniques may have to be devised to resolve this important problem. Additionally, a design is needed for a probe that can measure in a nonperturbing way the field at a point in living, moving biological organisms.

Interactions With Drugs

Exposure to microwaves has been found in some experiments to affect the reactions of animals to a small number of drugs by mechanisms not yet determined. Studies of this nature have come to the attention of the public which is becoming increasingly more concerned about combined effects of microwaves and other physical and chemical factors in the environment. The data base on this subject is scant. Microwaves of about 10 W/m^2 intensity have been shown to affect the action of both stimulatory and depressive drugs, in some cases enhancing reactions, in other cases suppressing them. Some observers theorize that the microwave/drug interaction phenomenon may be associated with nonlinear, possibly synergistic effects with other physiological stresses. As a result, the modeling of effects or phenomena in this category presents a serious challenge. The involvement of the dopamine systems of the brain has been suggested.

In order to reduce uncertainties about microwave/drug interactions, it might be appropriate to repeat selected experiments that have demonstrated these effects and to conduct long-term, dose-response studies at power densities around 1 W/m^2 . Such studies are feasible but require careful design so that good statistical analysis can be done. It is important that approaches be made toward testing hypotheses which address such effects, since the potential magnitude of the problem in terms of the total number of people consuming drugs is quite large.

Immunological Effects

This category is now receiving considerable attention and a number of experiments at the SPS-relevant frequency and field intensities of a few tens of W/m^2 or below are underway in the United States, France, and the Soviet Union. As with the previous topic, experimental findings have tended to be complex: Low-level microwaves (10 W/m^2 and below) have been found to both stimulate and suppress immune factors. However, there have been relatively few low-level, long-term studies and a number of studies have yielded no-effect data. Some research groups from France have observed a fluctuation of lymphocyte activity in rats and mice exposed to 2450 MHz, fields of 10 W/m^2 or higher. These effects are not evident at lower power densities. At the same time, some Russian scientists have observed fluctuations in immunological activity at field intensities above and below 0.5 W/m^2 . There appears to be a trend toward a biphasic (stimulation/suppression) response to low-level microwaves, the magnitude of which seems to be a function of increasing power levels below 100 W/m^2 . Thus, the results of experiments conducted thus far remain indeterminate, and accordingly, the mechanisms underlying immune responses to microwaves remain obscure (though at high power levels the thermally-induced endocrine basis of the reported responses remains secure). Therefore, it cannot be predicted whether the observed responses are potentially beneficial, deleterious, or

indifferent in humans. Mechanistic and molecular biological experimentation in this field is clearly needed and some work is already underway. Long-term studies are imperative as is replication of some of the Russian research, particularly that involving autoimmune responses to microwave radiation below 1 W/m^2 .

Effects on Calcium Ion Efflux in Brain Tissue

One of the more provocative neurologic phenomena evidently evoked by low-level microwaves (around $1\text{-}10 \text{ W/m}^2$) is the enhancement of calcium ion efflux from brain tissue exposed in-vitro and in-vivo. a number of studies have reported that fields at certain power densities and modulation frequencies can enhance this process. Experiments using continuous wave fields are negative. Effective power densities have been demonstrated, for example, between 5.5 and 13.8 W/m^2 for a 147 MHz carrier wave amplitude modulated between 9 and 16 Hz . In similar experiments using a 450 MHz carrier wave modulated at 16 Hz , enhanced calcium ion efflux occurred at 1.0 and 10 W/m^2 . However, the phenomenon is still quite elusive since even the same laboratory does not get a positive result every time, and some investigators remain openly skeptical about the phenomenon. If, as has been postulated, this response is based on cooperative interactions in the CNS, a considerable reevaluation of current concepts of brain function is required. It is interesting that considerable effort has been expended in replicating this effect, but apparently little effort has been expended, save by the original author, in deriving and testing an adequate model system.

The carrier frequencies that have been studied thus far are well below the SPS frequency of 2450 MHz , so that it remains to be determined whether similar efflux enhancement will occur at low power densities for that carrier frequency. Indeed, it remains to be determined whether and to what degree the SPS beam which is a continuous wave might become unintentionally modulated. In fact, the presence of modulation in the SPS beam would cover a wide range of modulation frequencies ($0\text{-}100 \text{ Hz}$) but is predicted to be infrequent in time and space and to be at average power levels $< 0.01 \text{ W/m}^2$.

Future experimentation will address the fundamental questions: Does the range of effective power densities exhibit a carrier-frequency dependence? Will the type of modulation expected from an SPS--infrequent, shallow, possibly produced by a beat frequency, subject to drift--have an effect?

The significance of the efflux phenomenon relative to neurologic/behavioral function remains to be determined. Does the phenomenon correlate with may Russian and East European findings of neurologic/behavioral decrements in people and animals exposed to low-level microwaves? At present, there is no evidence of such a correlation. Are other ions such as sodium, potassium, and magnesium similarly affected? Since calcium rarely occurs uncomplexed, what other structures are affected? These and other questions concerning the carrier-frequency/modulation-frequency/power-density dependence of

the phenomenon remain to be answered. Indeed, the effect opens up several questions as to how the brain functions.

Effects on Organized Structures
(e.g., Behavioral, CNS, and Genetic Effects)

There was considerable discussion about studies of the effects of microwaves on the central nervous system and possible behavioral changes associated with those effects. A fairly large number of studies conducted in the United States, Poland, Czechoslovakia, and the Soviet Union have consistently reported a variety of behavioral responses to low-level microwaves (10 W/m^2 or below) or fields that produce slight heating. In the United States a sizeable number of studies on the effects of electric fields on behavior have been conducted over the past 10-15 years. Although these studies differ widely in electric field parameters (strength, duration, frequency) and in sophistication of behavioral measures, certain principles of behavioral testing as well as behavioral responses recur which will be useful in designing behavioral studies related to anticipated SPS fields.

In general, behavioral responses to weak microwave fields tend to be consistent in nature as a function of behavioral measure. Time-based schedules of reinforcement are suggested as both sensitive and reliable measures of such effects. Recent studies on rats have demonstrated behavioral responses to pulsed microwaves (2450 MHz carrier modulated at 500 Hz) at average power densities as low as 10 W/m^2 . A study of mallard ducklings exposed to 3 and 16 Hz modulated fields (450 MHz carrier) demonstrated effects at 10 W/m^2 . Indications are from a number of studies that the significant thing is not carrier frequency but rather the presence of modulation and the frequency of that modulation. The neurological and physiological significance of such findings remain to be determined. The sophistication of U.S. research in this field is advanced enough, so that a realistic evaluation of the behavioral effects of simulated SPS fields is possible.

Thus far, most U.S. experiments have been of a duration of 3-9 months. Some experiments have reported behavioral decrements at low levels of exposure (5 W/m^2) while other experiments have reported no effects. A usual criticism of U.S. experiments is that they do not follow an appreciable portion of the experimental animal's life span and only rarely examine progeny. Nonetheless, since behavioral responses to low-level microwave and electric fields appears to be a function of carrier frequency modulation rather than a function of the carrier frequency itself, the existing body of U.S. behavioral data is relevant to the establishment of SPS guidelines. Studies using time-based schedules of reinforcement need to be repeated at SPS intensity levels and relevant modulation frequencies.

A large number of Soviet, Polish, and Czechoslovakian epidemiological studies of people exposed to microwave fields below 1 W/m^2 have reported a whole plethora of neurological and behavioral

changes primarily of a reversible nature. These studies are not complemented by similar surveys in the United States and other Western countries so that it is difficult to evaluate that data. One large epidemiological study of the State Department personnel assigned to the U.S. Embassy in Moscow provided no convincing evidence that microwaves caused detectable changes in morbidity or mortality. A questionnaire technique was used to attempt to find behavioral changes. The controls indicated many times more effects than the exposed individuals. Limitations of the study, however, preclude conclusions about possible microwave-related health effects. For example, small effects, such as behavioral effects, may have been masked by confounding variables. The radiation intensity at the strongest point in the Embassy was only a few tens of W/m^2 . Average exposure was even lower. This particular study suggests that such an epidemiological approach to the study of low-level microwaves is extremely expensive and may not prove to be useful in terms of yielding positive results. The epidemiological approach could provide confirmation of mechanisms and theories and offer metrics meaningful to public health concerns, such as life length and disease incidence as functions of exposure. However, when dealing with such low exposure levels, the probability of obtaining positive results seems negligible.

Considerable work has been done to assess the effects of microwaves on central nervous and other tissues at the cellular, cell membrane, and molecular levels. One phenomenon frequently reported in the U.S. literature is a change in the permeability of the blood/brain barrier. Reports on this phenomenon are inconsistent in their findings, however, it should be noted that some studies reporting no-effect data may be statistically suspect. In small mammals, changes in blood-brain barrier permeability are often accompanied by lesions and structural changes at the cellular and cell membrane level such as nerve cell swelling, vacuolization, and dendritic damage in response to microwave fields of 10 to 250 W/m^2 . Effects have been reported at levels of microwave radiation as low as 0.3 W/m^2 at 1300 MHz under certain pulse characteristics. Thus, evidence exists that something is happening in the brain in response to low-level microwave exposure. These findings along with those related to calcium efflux are of interest in terms of reported behavioral indices and deserve continuing evaluation in that light. Research should be directed at confirming the power density levels at which effects occur and determining the underlying variables in the brain that are being influenced and the mechanisms of interaction.

A number of Russian studies have reported changes in neural function in-vitro in response to microwave and magnetic fields of low intensity. Further confirmation and evaluation of such findings is appropriate in terms of SPS radiation parameters and relative to previously reported changes in behavior, blood/brain barrier, and calcium efflux. Longer-term, well controlled and coordinated experimentation is needed. Long-term, low-intensity radiation experiments on organized structures should be considered not only from a mechanistic point of view but to evaluate whether there is any trend

toward life-shortening in animals. Life-shortening experiments might be too difficult to do, however, because of the large numbers needed to detect any small effect above random variability.

Finally, some genetic studies have been performed by both U.S. and French researchers using sensitive microbial systems. Yeast and bacteria were acutely exposed to 2450 MHz continuous wave or 8500-9600 MHz pulsed radiation at various power densities from 10 to 450 W/m². No evidence of mutation was found. These findings suggest, if the results can be extrapolated to SPS power levels, that no direct initiating carcinogenic effects would be expected in humans.

Microwave Standards

Standards for human exposure to microwaves vary widely around the world. In the United States, there is no mandatory standard. Rather, ANSI recommended in 1974, and OSHA subsequently adopted as a guideline, an occupational level of no higher than 100 W/m² (10 mW/cm²) for a working day. In contrast, the Russian standard is the most stringent in the world with a formal occupational level of 0.1 W/m² (10 µW/cm²). For the general public in the Soviet Union, the standard is even lower (0.05 W/m²). The contrast in these levels reflects the differing scientific and occupational health philosophies of the two nations. On the one hand, there is no evidence that the U.S. guideline has resulted in any deleterious health effects. However, there simply have not been studies carried out to look for health effects that are currently being suggested by animal and in-vitro experiments. On the other hand, there is little evidence that the Soviet standard is enforced, is enforceable, or if enforced, is any more effective in terms of public health than the U.S. limit.

In terms of the SPS, the issue of a microwave standard is an important one. For example, the Planning Group on Microwave Health Effects (of the NRC SPS Committee) which met in April, 1980 conjectured that the future U.S. public exposure guideline might be as low as 0.1 W/m² or the equivalent of the present Soviet occupational standard. A decision to establish formally such a limit would have a profound effect on the present SPS concept. Therefore, it is imperative to examine on a worldwide basis the various philosophies and criteria that have been employed to establish microwave exposure standards.

CONCLUSIONS

A. There are relatively little microwave health and bioeffects data available of direct relevance to the radiation parameters of the proposed SPS. What data are available are difficult to evaluate in terms of a potential public health impact of the SPS.

B. There is no presumptive evidence in the data available that exposure of the general public to 1 W/m² or lower at the frequency

of 2450 MHz generated by the SPS will result in any health decrements. However, because a number of functional phenomena of known significance have been reported in response to exposure to microwave radiation at levels $\leq 1 \text{ W/m}^2$, further research and evaluation--as described in the preceding paragraphs, and summarized in Table H.1--is necessary in order to decrease present uncertainties about potential low-level microwave health effects.

TABLE H.1. Research needed 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 animal experiments at power densities $\leq 1.0 \text{ W/m}^2$ at whole body, organ, and organelle levels, testing for biological endpoints such as alteration of enzyme reaction rates and cell membrane conformational 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 conformational 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

- Repetition of selected animal experiments showing effects (including the potential of microwaves as a cocarcinogen), using carefully controlled dosimetry and statistical analysis.
- Development and testing of hypotheses to explain effects.
- Long-term dose-response animal experiments at power densities around 1.0 W/m^2 and with a larger number of drugs at whole body, organ, and organelle levels.

Immunological Effects

- Repetition of selected Russian research at levels of 0.01 W/m^2 to 5.0 W/m^2 ; repetition of selected U.S. work to validate it.
- Mechanistic and molecular biological experimentation.
- Long-term animal studies, particularly autoimmune response.

Effects on Calcium Ion Efflux 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 extremely low frequency 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 levels of microwaves below 1.0 W/m^2 .
- 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 SPS power levels.
 - Determination of the neurological and physiological significance of behavioral responses.
 - Molecular-level studies of biological relaxation times.
 - Consideration of long-term animal experiments at 2450 MHz to evaluate, if possible, whether there is any trend toward life-shortening in animals.
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APPENDIX I
REPORT OF THE WORKING GROUP ON
ELECTROMAGNETIC COMPATIBILITY*

INTRODUCTION

A Working Group on Electromagnetic Compatibility was set up in May 1980 to review the work that had been done on the electromagnetic compatibility of a satellite power system (SPS) with radio-communications and other electronic systems, and to determine the existence of any problems of allocation of spectrum and orbit resources to SPS.

The electromagnetic compatibility problems of SPS are large and complex. The International Telecommunication Convention, signed by nearly 150 nations, is paramount in harmonizing and coordinating the use of the radio spectrum world wide. National radio regulations concerning the operation of terrestrial stations can, and frequently do, depart from the Radio Regulations (ITU 1968 as amended) annexed to the Convention. This is because a country may do what it pleases in regard to the use of the spectrum, as long as such action does not cause harmful interference to the stations of other nations operating in accord with the Convention. This freedom of action is often used by territorially large nations such as the United States. Hence, when it comes to the question of electromagnetic compatibility issues affecting the main receiving antennas (rectennas) of the SPS, the principal radio regulations are likely to be the national ones, i.e., within the USA, the radio regulations of the Federal Government and of the Federal Communications Commission (FCC).

On the other hand, for space stations, the national radio regulations of member nations closely follow the structure and detail of the Radio Regulations annexed to the Convention. Therefore, the International Telecommunication Convention provides the relevant regulations for the satellite elements of SPS.

Potentially, SPS could cause harmful radio interference to both space and terrestrial electronic systems. In both cases, in-band, adjacent band, and out-of-band interference effects need to be considered. Although terrestrial interference effects would tend to be limited to the conterminous 48 states, low earth orbit (LEO) and geosynchronous orbit (GEO) satellites of all nations would be exposed

*See Appendix B for composition of the Working Group.

to SPS radiations, and any satellite interference problems would therefore tend to be international in scope. Space systems operating in LEO would be subjected to very large power densities should they transit the link from an SPS satellite to its rectenna. Satellites in high earth orbit would find their communication paths blanked momentarily by the interposition of an SPS satellite between them and a desired earth station. Possibilities that SPS could cause multi-path effects on satellite communications, as well as the potential for actual collision, also need to be considered.

The Working Group considered its principal task to be the identification of possible electromagnetic compatibility problems sufficiently large and complex in scope to present insurmountable problems to the SPS. Following a preliminary review of available studies, the Group came to the conclusion that the electromagnetic compatibility problems would be most severe, both technologically and politically, for neighboring geosynchronous communication satellites. Consequently, the attention of the Working Group became focused primarily upon the question of the compatibility issues surrounding the SPS satellites.

While potential interference to terrestrial telecommunications systems and other electronic devices may not constitute an insurmountable problem, it is a matter of serious concern, and the Working Group also reviewed that problem at length. In performing our task we have attempted (1) to review the Radio Regulations relevant to geosynchronous spectrum and orbit utilization, (2) to gather and review evidence concerning the anticipated use of GEO in the year 2000, (3) to review available Department of Energy SPS electromagnetic assessment documents (U.S. DOE, in press, together with various unpublished working papers prepared by the Institute for Telecommunication Sciences of the National Telecommunications and Information Administration under contract to DOE that served as input to the basic reference), and (4) to prepare conclusions and recommendations relating to the above for consideration by the Committee on Satellites Power Systems.

SPECTRUM AND ORBIT UTILIZATION

The Reference SPS as a User of the Geosynchronous Orbit/Spectrum Resource

The reference SPS consists of 60 satellites in GEO at longitudes corresponding to the conterminous 48 States. Each satellite radiates approximately 6.7×10^9 W at a frequency in the industrial, scientific, and medical (ISM) band at about 2450 MHz to its own large rectenna on the ground, using a 1 km diameter radiating antenna at the satellite.

At least five factors make the reference SPS a uniquely large user of the spectrum/orbit resource, and one which therefore may produce unusually severe electromagnetic compatibility problems. These factors are:

(1) The number (60) of geosynchronous SPS satellites proposed for U.S. use is considerably more than for any other single service; it would at least double the number of geosynchronous satellites of all types currently active or planned for the longitude sector appropriate to the USA.

(2) The power radiated per SPS satellite is some 10^7 times larger than that of any other geosynchronous satellite.

(3) The SPS transmitting antenna directivity is some 10^4 times larger than that of any other geosynchronous satellite operating at frequencies of 1000-5000 MHz. The combination of large radiated power and large antenna directivity, means that the effective on-frequency radiated power (and hence the power level produced in the main beam) is about 10^{11} times greater for a single SPS than for any other geosynchronous satellite operating in the vicinity of this ISM band.

(4) Each SPS is some 10^5 times larger in cross-sectional area than any other geosynchronous satellite. It therefore represents a much greater potential source of scattered electromagnetic radiation (including sunlight), and is a much larger radiator of thermal energy.

(5) Because of the large powers involved, the great variety of materials used, and the huge size of the SPS space structures and rectennas, each SPS system is potentially a major source of out-of-band energy produced by the nonlinear mixing of the SPS carrier frequency with other electromagnetic signals.

Uniqueness and Value of the Geosynchronous Orbit

The geosynchronous orbit is an exceedingly valuable resource in the use of the radio spectrum. It is the only orbit wherein satellites remain fixed with respect to points on the earth. It permits the use of fixed earth station antennas with high gains and avoids the enormously expensive cost of continuously tracking antenna systems. Most importantly it minimizes the number of satellites required to establish both domestic and international telecommunications systems. A telecommunications system using orbiting satellites would require at least two antenna systems at each earth station, so that one satellite about to go out of view could be tracked while another satellite coming into view could be acquired in order to maintain a continuous stream of communication traffic. Without the use of GEO, a system such as Intelsat would be much more expensive and the cost of communications would probably be raised to prohibitive levels.

International Radio Regulations Relevant to SPS

Use of the radio spectrum would result in utter chaos unless users coordinated their operations to avoid harmful electromagnetic interference. This fact was realized at the turn of the century when several administrations began working together to establish institutions and procedures to guarantee that all those who have need

to use the spectrum could do so harmoniously. The primary treaty governing the use of the radio spectrum, to which the United States is a party, is the International Telecommunication Convention. This convention established the International Telecommunication Union (ITU), the oldest intergovernmental organization involved in coordinating the use of the spectrum, and now one of the specialized agencies of the United Nations. The Radio Regulations annexed to the International Telecommunication Convention establish services to be supported by use of the radio spectrum and allocate certain portions of the spectrum to each one. The Radio Regulations also stipulate the procedures to be followed by all member nations in notifying each other of their intent to establish new radio services. The ITU has no police powers and achieves its mission by gaining accommodation among users in the interest of all parties.

Although the SPS is not planned for deployment until the year 2000, one must consider the possible impact on it of radio regulations adopted by the 1979 World Administrative Radio Conference (WARC), even though the purpose of that conference was to establish radio regulations that would apply only until the year 2000. Radio regulations pertaining to frequencies in-band and adjacent to the SPS power signal at 2450 MHz are shown in Tables I.1 and I.2. A pictorial relationship between the SPS and frequency bands allocated to the various radio services is provided in Figure I.1. Since the SPS conveys no signs, signals, writing, images or sounds, or intelligence of any nature, it is perhaps appropriate to consider it (in ITU terminology) as an industrial, scientific, and medical (ISM) device. Such devices are recognized by the ITU, and a number of scientific frequency bands have been designated in the sense that radio services operating within them must accept harmful interference from ISM devices. One of these bands is the 2400-2500 MHz band where the SPS is proposed to operate. In-band radiation from ISM equipment is to be minimal; outside the designated bands, ISM radiation is to be at a level that does not cause harmful interference.

The primary services which the SPS must cope with in the lower adjacent band are ground-based fixed, mobile, and radiolocation services. Amateur radio enthusiasts operate both in-band and in the lower adjacent band on a secondary basis. Although they may not claim protection from harmful interference caused by other services to which the band is allocated, it may be possible for them to claim protection from harmful interference caused by an ISM device as unusual as the SPS.

As indicated in the Introduction, the Working Group concluded that the most severe electromagnetic compatibility problems would most likely arise in the coordination of SPS satellites and space stations operating in fixed-satellite, broadcasting-satellite, space-research, and earth-exploration satellite services. Although the space-research and earth-exploration satellite services operate on a secondary basis, operators of stations in such services may not willingly accept interference from a non-telecommunications device. Within the continental United States current national radio regulations permit the use of the fixed-satellite service for common carrier and

TABLE I.1. Frequency allocations, 2300 MHz to 2500 MHz: ITU Radio Regulations pertaining to Region 2 (Western Hemisphere) according to Final Acts of the 1979 World Administrative Radio Conference.

Allocated Radio Services:	Description of Service
Primary Services (2300 MHz to 2500 MHz)	
Fixed	A (terrestrial) service of radiocommunication between specified fixed points.
Mobile	A (terrestrial) service of radiocommunication between mobile and land stations, or between mobile stations.
Radiolocation	A radiodetermination service involving the use of radiolocation.
Secondary Services^a (2300 MHz to 2450 MHz)	
Amateur	A service of self-training, intercommunication and technical investigations carried on by amateurs, that is, by duly authorized persons interested in radio technique solely with a personal aim and without pecuniary interest.
Amateur-Satellite	A radiocommunication service using space stations on earth satellites for the same purposes as those of the amateur service.

NOTES:

1. The Amateur-Satellite Service may operate in the 2400 MHz to 2450 MHz band subject to not causing harmful interference to other services operating in accordance with the Table of Allocations (MOD 3644 320A).
2. The Amateur-Satellite Service cannot claim protection from harmful interference caused by other services to which the band is allocated (NOC 3442 148).
3. The band 2400 MHz to 2500 MHz (centre frequency 2450 MHz) is designated for industrial, scientific and medical (ISM) applications.^b Radio services operating within this band must accept harmful interference which may be caused by these applications (MOD 3709 357). Administrations shall take all practical and necessary steps to ensure that radiation from industrial, scientific and medical equipment is minimal and that, outside the bands designated for use by this equipment, radiation from such equipment is at a level that does not cause harmful interference to radiocommunication services and, in particular, to a radionavigation or any other safety service (any radiocommunication service used permanently or temporarily for the safeguarding of human life and property) operating in accordance with the provisions of the Radio Regulations (5002A).

^aSecondary Service--Stations of a secondary service: a) shall not cause harmful interference to stations of a primary or permitted service to which frequencies are already assigned or to which frequencies may be assigned at a later date; (b) cannot claim protection from harmful interference from stations of a primary or permitted service to which frequencies are already assigned or may be assigned at a later date.

^bIndustrial, Scientific and Medical (ISM) Applications--Operation of equipment or appliances designed to generate or use locally generated radio-frequency energy for industrial, scientific, medical, domestic or similar purposes, excluding applications in the field of telecommunications (any transmission, emission or reception of signs, signals, writing, images and sounds or intelligence of any nature by wire, radio, optical or other electromagnetic systems).

TABLE I.2. Frequency allocations, 2500 MHz to 2690 MHz: ITU Radio Regulations pertaining to Region 2 (Western Hemisphere) according to the Final Acts of the 1979 World Administrative Radio Conference.

Allocated Radio Services:	Description of Service
Primary Services (2500 MHz to 2690 MHz)	
Fixed	A (terrestrial) service of radiocommunication between specified fixed points.
Mobile (except aeronautical mobile)	A (terrestrial) service of radiocommunication between mobile and land stations, or between mobile stations.
Fixed-Satellite (space to earth)	A radiocommunication service between earth specified fixed points when one or more satellites are used; in some cases this service includes satellite-to-satellite links, which may be also effected by the intersatellite service; the Fixed-Satellite Service may also include feeder links (a radio link between an earth station at a specified fixed point to a space station) for other space radiocommunication services.
Broadcasting-Satellite	A radiocommunication service in which signals transmitted or retransmitted by space stations are intended for direct reception by the general public.
Secondary Services (2655 MHz to 2690 MHz)	
Space Research (passive)	A radiocommunication service in which spacecraft or other objects in space are used for scientific or technological research purposes.
Earth Exploration-Satellite (passive)	A radiocommunication service between earth stations and one or more space stations in which: information relating to the characteristics of the Earth and its natural phenomena is obtained from instruments on earth satellites; similar information is collected from airborne or earth-based platforms; such information may be distributed to earth stations within the system concerned; platform interrogation may be included.

NOTES:

1. The Broadcasting-Satellite Service is limited to national and regional systems for community reception and such use shall be subject to agreement obtained under the procedure set forth in Article N13A.
2. The power flux density at the earth's surface, assuming free space propagation condition, shall not exceed:
 - 152 dB(W/m²) in any 4 kHz band for angles of arrival between 0 and 5 degrees above the horizontal plane;
 - 152 + 0.75 (δ - 5) dB(W/m²) in any 4 kHz band for angles of arrival δ (in degrees) between 5 and 25 degrees above the horizontal plane;
 - 137 dB(W/m²) in any 4 kHz band for angles of arrival between 25 and 90 degrees above the horizontal plane.
3. In Canada, the band 2500 MHz to 2550 MHz is also allocated on a primary basis to the radiolocation service.

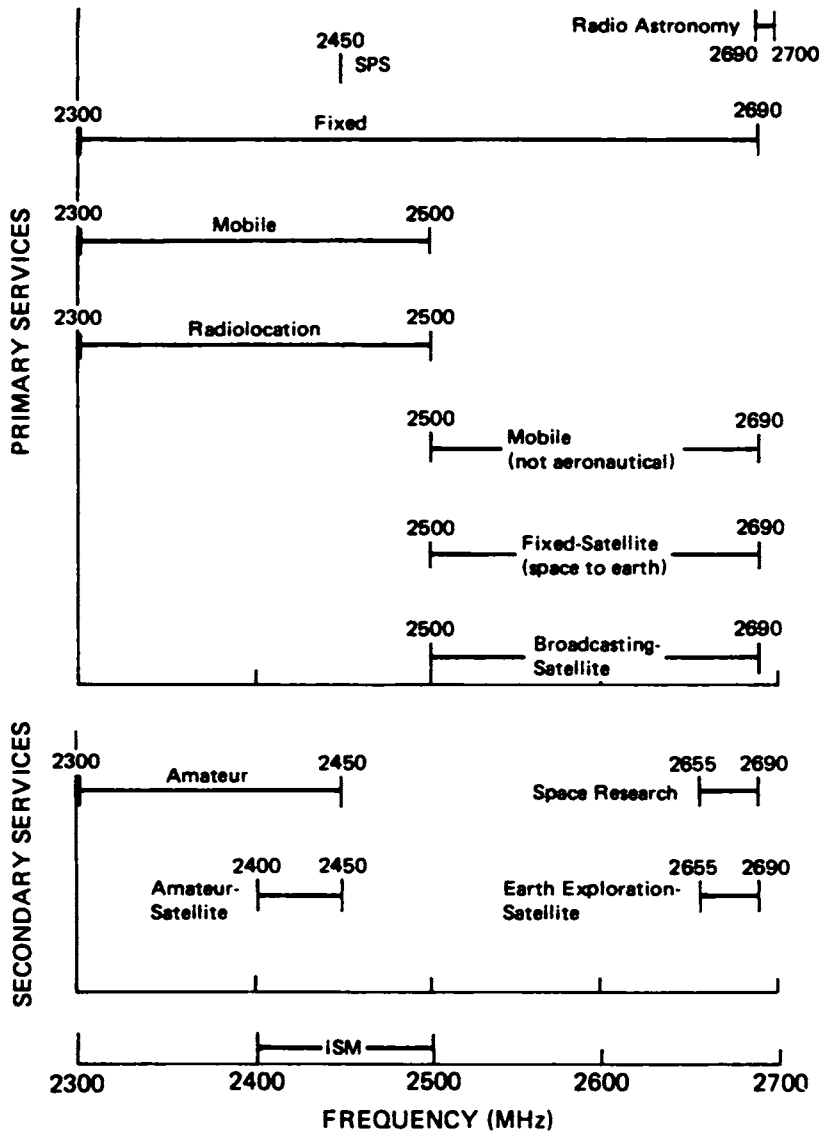


FIGURE I.1. The reference SPS transmitting frequency and nearby International Telecommunication Union radio services pertaining to Region 2 (Western Hemisphere). (See Tables I.1 and I.2 for definitions of the various services.)

government uses. The broadcasting-satellite service is proposed for use in the individual reception of television programs.

The SPS could also be a potential source of harmful interference to systems operating beyond adjacent frequency bands, normally termed "out-of-band." The potential sources of out-of-band interference are harmonics and other spurious emissions of the solar power transmitter, and the noise generated by the solar power station.

The limitations on the level of power flux density that a satellite may create at the earth's surface as specified in the Radio Regulations and repeated in Table I.2 are a safeguard against interference but are not directly applicable to an SPS at 2450 MHz, except for the general prohibition against harmful interference which applies to all users of the spectrum. The regulations do contain very precise limitations on power flux density at the earth's surface from space stations of the fixed satellite service and certain other space services but those values are only appropriate for the named services when they operate in bands allocated for coequal sharing by the specific space and terrestrial services; the bands in which they are applicable are enumerated in the regulations.

It is important to recognize that the power flux density limits given for cochannel operation are not applicable to spurious emissions from space stations operating in other bands. The International Radio Consultative Committee (CCIR) is studying that point and its current Report 713 states that spurious emissions would need to be 10 to 20 dB below the cochannel limits. In the case of SPS, where 60 similar satellites are proposed rather than satellites of random characteristics as assumed by CCIR, it seems likely that the power flux density of the spurious emissions from a single SPS may be required to be 30 to 40 dB below those for cochannel operation.

Projected Geosynchronous Satellite Station-Keeping Capabilities in the Year 2000

The huge size and large radiated power of a solar power satellite will undoubtedly require that some separation from other geosynchronous satellites be maintained to prevent collision and avoid harmful interference. Upon coordination with other countries through the mechanism of the ITU, each space station is assigned a nominal longitudinal position. The extent to which the position of a space station may deviate from its nominal position is defined in the Radio Regulations. When taken in conjunction with the probable station-keeping capabilities of a solar power satellite and the minimum separation that must be maintained to avoid harmful interference, the deviation permitted becomes a significant factor in determining the minimal allowable separation between the nominal position of a solar power satellite and other kinds of satellites. Therefore, it becomes important to consider the probable station-keeping capabilities of geosynchronous satellites in the year 2000. The Final Acts of the 1979 WARC established new station-keeping capabilities for space stations onboard geosynchronous satellites

entering service after 1 January 1987. Since the useful life expectancy of space stations is probably less than 10 years, all space stations, with the possible rare exception of those that live far beyond their expected lives, will be capable of meeting the new station-keeping requirements in the year 2000. A summary of those requirements taken from the Final Acts is shown in Table I.3.

The station-keeping capabilities and requirements of space stations depend upon the type of space station and the frequency band in which it operates. As shown in Table I.3 a satellite, for the purpose of specifying station-keeping limits, is classified as either a broadcast-satellite station operating in the 11.7-12.7 GHz band, as an experimental station, or as "any other" station. The ITU radio regulations recognize two groups of frequency bands in setting station-keeping characteristics and requirements, namely, bands allocated to the fixed-satellite and the broadcast-satellite service and all other frequency bands allocated to space stations. While station-keeping requirements for broadcast-satellite stations operating in the 11.7-12.7 GHz band have been established for other regions of the world, they have not been established for the western hemisphere. Supposedly this is to be done at the 1983 ITU Region 2 Broadcasting Satellite Conference. If that conference chooses to adopt the station keeping requirements as stated in the Final Acts of the 1977 conference then space stations in the broadcast-satellite service in the 11.7-12.7 GHz band will have to stay coincident with, or within 1° to the east of, nominal orbital positions specified in the plan. The 1977 conference established specific longitudinal positions separated by 6 degrees in the orbital arc between 37° W and 146° E longitude.

The potential for physical collision or harmful out-of-band interference effects has not been a driving force in establishing station-keeping capabilities and requirements by the ITU. If the Radio Regulations of the ITU are read very carefully, it is seen that only cochannel interference is expected. The ITU Radio Regulations only require coordination among administrations having space stations operating in the same band. Satellite networks sharing the same frequency band, consequently, maintain separation because of potential in-band harmful interference effects and for no other reason. The potential for collision or for the occurrence of harmful out-of-band interference effects has been considered to be so negligible that separation requirements between the space stations of networks operating in one band and space stations of a network operating in another band are not necessary. The huge size and large radiated powers of the SPS satellites will make collision and out-of-band interference aspects significant factors in coordinating orbit space allocations between SPS and non-SPS satellites.

From the foregoing discussion it is clear that the chances of successfully coordinating the inserting of a satellite into GEO are enhanced by filing the earliest possible notification of intent to do so with the International Frequency Registration Board of the ITU. While it might not be possible to provide advance notification for SPS satellites from the standpoint of the use of the spectrum to transmit

TABLE I.3. Geosynchronous station-keeping requirements according to Final Acts of 1979 World Administrative Radio Conference.

Type of Space Station	Requirement for Stations Operating in Bands Allocated to Fixed-Satellite and Broadcasting-Satellite Services	Requirement for Stations Not Operating in Bands Allocated to Fixed-Satellite or Broadcasting-Satellite Services
Broadcasting-Satellite Station Operating in 11.7-GHz to 12.7-GHz Band	To be determined at 1983 ITU Region 2 Broadcasting-Satellite Conference	Not applicable
Experimental Station	± 0.5 degrees	± 0.5 degrees
Space Stations Other Than Broadcasting-Satellite or Experimental	± 0.1 degrees	± 0.1 degrees

NOTE: Space stations need not comply with requirements of the Final Acts as long as the satellite network to which they belong does not cause unacceptable interference to any other satellite network whose space stations comply with these requirements.

power, advance notification could be filed in regard to other systems required onboard. Each SPS satellite will require some form of telemetry, tracking, and control (TT&C). Consequently, each SPS satellite will have onboard a TT&C radio telecommunications space station subject to ITU regulations. Currently, advance notification cannot be filed with the IFRB more than five years prior to the date of bringing each satellite into service. There is a possibility, of course, of placing a portion of each SPS satellite into orbit at an early date containing a suitable TT&C space station. If this were planned for 1990 it would be possible to file advance notification as early as 1985; thus, by reserving space in the orbit for a TT&C station for each satellite, space could be reserved for the solar collecting and power transmission elements to be built later.

Projected Use of the Geosynchronous Orbit in the Year 2000

Satellites using the geosynchronous orbit between 135° and 65° W longitude are shown in Table I.4 (Morgan 1980). Also shown in the table are satellites that are expected to be launched in the near future. Of the 56 satellites listed, 30 have been launched and are on station.

In his article, "Geosynchronous Satellite Log for 1980," Morgan (1980) has plotted the number of geosynchronous satellites in orbit versus time from approximately 1963 to the present (Figure I.2). Approximately 80 percent of the world's space stations in geosynchronous orbit are intended for communications purposes.

Although interest in the potential use of GEO is becoming increasingly intense as both administrations and entrepreneurs begin to realize the potential economic rewards involved, it can be argued (for example) that the number of active geosynchronous meteorological satellites required internationally for weather monitoring and prediction purposes is small, and certainly not ten times the present number. Similarly, as the need for satellite communications increases, there is a tendency to achieve this by increasing the capability of each individual satellite (for example, by the use of larger antennas, orthogonal modulation schemes, and broader bandwidths) rather than by launching more geosynchronous satellites of the same capability. The high cost of geosynchronous satellites also makes a continued exponential growth of their number unlikely.

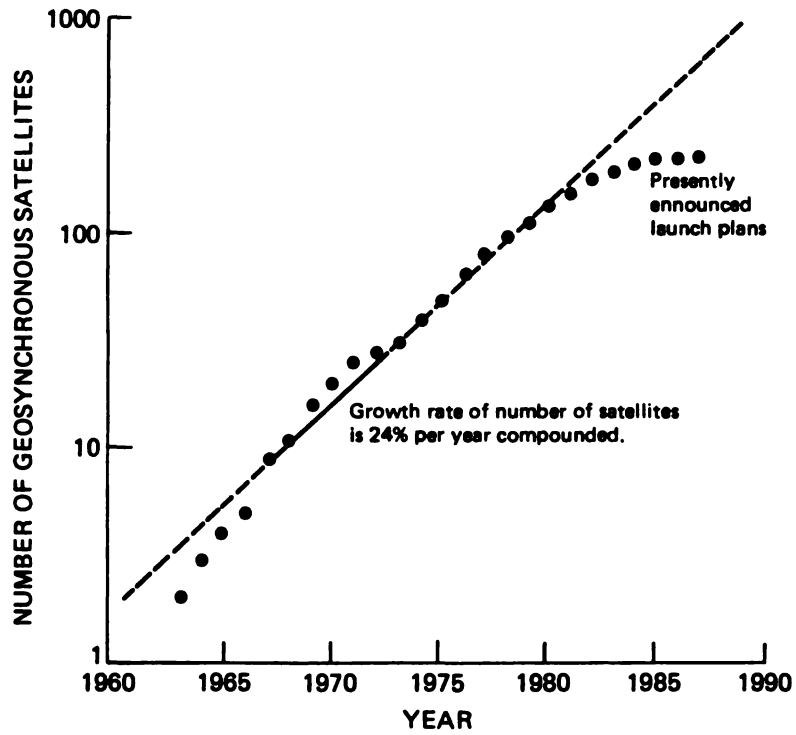
Nevertheless, there can be no doubt that use of GEO will continue to grow, though probably at a doubling rate slower than in the past. Much of this growth is expected to take place in positions co-longitudinal with developed nations such as the United States. Consequently, the future portends an ever increasing congestion in the use of GEO, particularly that part co-longitudinal with the conterminous United States, the site of the proposed deployment of 60 SPS platforms. This congestion will become even more severe as other countries (such as Canada, Mexico, and Peru) that share this longitude band with the United States begin to make increased use of GEO.

TABLE I.4. Geosynchronous satellite data.

Longitude	Launch Date	Life (yr)	Satellite Name	Sponsor ^a
135° W	NA	--	E Pac DSCS Net	DOD (USA)
135° W	1978	5	DSCS-2 F11	DOD (USA)
135° W	1979	5	DSCS-2 F14	DOD (USA)
135° W	1983	10	DSCS-III	DOD (USA)
135° W	1977	5	NATO-3B (F-2)	NATO
135° W	1975	8	Satcom 1	RCA Am (USA)
135° W	NA	--	W US Met Net	NOAA (USA)
135° W	1978	--	GOES-3	NOAA (USA)
132° W	1981	8	Satcom III Rep.	RCA Am (USA)
130° W	1978	5	DSCS-2 F9	DOD (USA)
128° W	1976	7	Comstar D-1	COMSAT Gen (USA)
125° W	NA	10	SBS-C (spare)	Sat Bus Sys
123.5° W	1974	7	Westar II	Western Union
122° W	1980	10	SPS-A	Sat Bus Sys
119° W	1981	10	SBS-B	Sat Bus Sys
119° W	1976	8	Satcom II	RCA Am (USA)
116° W	1981	8	Anik-C2	Telesat Canada
114° W	1975	7	Anik-A3	Telesat Canada
113° W	1974	--	SMS 1	NASA (USA)
112.5° W	1981	10	Anik-C1	Telesat Canada
110° W	1976	5	LES-8	DOD & MIT (USA)
109° W	1978	7	Anik-B1	Telesat Canada
109° W	1982	10	Anik-D	Telesat Canada
109° W	1982	8	Anik-C3	Telesat Canada
106.5° W	1973	7	Anik-A2	Telesat Canada
105.2° W	1967	--	ATS-3 ^c	NASA (USA)
105° W	1977	--	GOES 2	NOAA (USA)
104° W	1975	10	Anik-D	Telesat Canada
104° W	1972	7	Anik-A1	Telesat Canada
104° W	1982	10	Anik-D	Telesat Canada
103° W	1983	10	Adv Westar	Western Union
100° W	1976	5	LES-9	DOD & MIT (USA)
100° W	1978	5	Fltsatcom-1	DOD (USA)
100° W	1984	10	Leasat	DOD (USA)
99° W	1974	7	Westar I	Western Union
99° W	1982	10	Adv Westar/TDRS	Western Union
95° W	1976&95	7	Comstar D-2	COMSAT Gen (USA)
92° W	NA	--	CBSS	Canada
91° W	1979	7	Westar III	Western Union
90° W	1975	--	GOES 1 Sat.	NOAA (USA)
90° W	1988	5	Severe Storms	NASA (USA)
87° W	1978	7	Comstar D-3	COMSAT Gen (USA)
85° W	1968	2	LES-6	DOD & MIT
83° W	1980	10	Satcom-IV	RCA Am (USA)
79° W	1982	7	Hughes 2	Hughes, Inc (USA)
75.4° W	NA	--	Satcol-2 (spare)	Columbia
75° W	NA	--	Satcol-1	Columbia
75° W	NA	--	Brasilsat (SBTS)	Brazil
75° W	NA	--	Met Sat	NOAA (USA)
75° W	1975	--	SMS Met Sat	NASA (USA)
75° W	1981	7	Hughes 1	Hughes, Inc (USA)
72.5° W	NA	--	Satcol	Columbia
71° W	1978	--	Ultrav. Expl.	NASA (USA)
70° W	1969	--	ATS-5	NASA (USA)
70° W	NA	--	Brasilsat (SBTS)	Brazil
67.5° W	NA	--	Brasilsat (SBTS)	Brazil

^aKey to acronyms: DOD = Department of Defense; NATO = North Atlantic Treaty Organization; RCA = RCA Corporation; NASA = National Aeronautics and Space Administration; NOAA = National Oceanic and Atmospheric Administration; MIT = Massachusetts Institute of Technology.

SOURCE: Adapted from Morgan (1980).



SOURCE: Morgan (1980).

FIGURE 1.2. Number of satellites in geosynchronous earth orbit, by year.

Projecting the number of satellites that will be on station in GEO between 65° and 135° W longitude in the year 2000 is at best a difficult conjecture. A straight-line projection on Morgan's logarithmic scale suggests that there will be nearly 70 times as many as are now in use. This seems unrealistically high in view of the considerations mentioned above. From a conservative point of view, it is possible to speculate that the number of satellites in GEO will be 10 times as many as are now in existence. Given the present count now on station, this means at least 300 satellites will be on station between 65° and 135° W longitude in the year 2000. If the current mix of satellite types continues into the year 2000, then approximately 240 will be employed in the fixed-satellite service. These satellites should be capable of maintaining their positions within $\pm 0.1^\circ$ in the year 2000. The remaining 60 satellites, with the possible exception of broadcasting-satellites, should be capable of maintaining position within $\pm 0.5^\circ$ of their nominal positions.

A way of examining the potential impact of deploying a 60 satellite SPS is to consider the effect that it would have upon reducing the space available in GEO for other satellites. The 300 satellites conservatively projected in the year 2000 in GEO have access to 70 degrees of arc between 65° and 135° W longitude. If, either because of sheer physical size or because of harmful interference potential, it is necessary that other satellites avoid the proximity of an SPS satellite, then the amount of room left in GEO to distribute the 300 satellites becomes smaller. If satellites, for example, must avoid coming within 0.3° longitude of an SPS satellite, 36° of longitude would be used up by 60 SPS satellites, and only 34° of geosynchronous arc space would be available to other satellites. Space available in GEO to other satellites for other SPS avoidance criteria are shown in Figure I.3.

Thus, increased congestion has two effects: It increases the potential for harmful interference between satellites and it increases the danger of collision. In order to reduce the danger of collision, it may be necessary for satellites to carry more propellant to maintain precise station position and execute collision avoidance maneuvers. It is also possible that the total number of separate satellite structures in GEO could be reduced by construction of multisatellite platforms.

TECHNICAL ISSUES

Compatibility of SPS with Other Satellite Systems

The analysis in this section is based in part on hearing the views of some representative organizations knowledgeable in satellite and frequency management. Representatives of INTELSAT, the National Aeronautics and Space Administration, the National Telecommunications and Information Administration, and the Electromagnetic Compatibility Analysis Center of the Department of Defense (DOD) met with the Working Group. However, classified DOD matters were not considered.

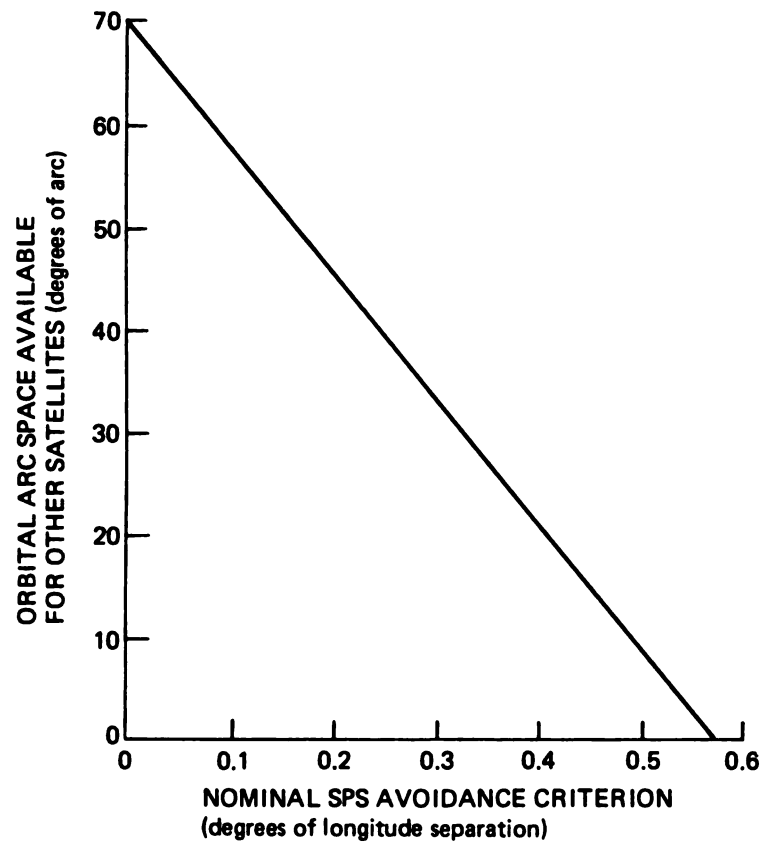


FIGURE I.3. Orbital arc space available between 65° and 135° West longitude for other satellites assuming a 60-satellite SPS.

Sharing the Spectrum with Other Satellites

The 2450 MHz frequency proposed for SPS is in an ISM band used for non-information bearing electromagnetic radiation in applications such as radiofrequency heating. The status of the SPS within the ITU radio regulations is an open question. Nevertheless, to proceed here, this discussion will treat SPS as operating within the ISM band and, in the traditional sense, will consider all SPS radiation outside the 2400-2500 MHz ISM band as out-of-band radiated signal energy. As noted earlier, CCIR requirements for the sharing of bands apply only to agreed-upon ITU services. Strictly speaking, ISM operations are not ITU services. Unless special provisions were made in the case of SPS, the current CCIR upper limits for sharing of bands therefore cannot be used as an SPS guideline. The total SPS system out-of-band radiation would therefore probably have to be some 10 dB to 20 dB below the current limits for sharing of bands by ITU-approved services. It will not be possible to comment on the feasibility of achieving this probable requirement, however, until considerably more technical detail about the SPS reference concept has been established. Specific limits for SPS need to be developed at future CCIR and ITU conferences.

Sharing the Geosynchronous Orbit with Other Satellites

Orbit sharing is the other aspect of sharing; it is unique among satellite systems. In GEO, orbit sharing reduces to the question of spacing the satellites along the geosynchronous arc and keeping them there. Satellites operating in different frequency allocations are now spaced as close as 0.2° or less in longitude of the arc. If the same frequency allocation is used, but the geographical service areas on the earth's surface are different and widely separated to avoid interference, spacings between separate satellites as close as 1° are now in use, and these spacings are considered in sharing studies. When satellites use the same frequency allocation and serve the same area on the earth's surface, such as with communications satellites, current practice requires 4° spacing with projections suggesting spacings as close as 3° in the future as technology advances and the need for geosynchronous satellites increases.

For the reference SPS, each of 60 satellites would have to be kept on station. Present NASA studies project that the physically large SPS would have a 24-hour elliptical satellite motion of $\pm 0.11^\circ$ in longitude about a stationary satellite position. With such a large structure in orbit, some guard space around this $\pm 0.11^\circ$ longitudinal arc and associated elliptical area will be prudent in anticipation of random drifts and unforeseen control anomalies. This guard space has not been considered in the reference system concept, so an additional 0.04° margin in longitude is assumed here for illustration. Spacing of all other satellites from an SPS, including other SPS vehicles, must then be considered relative to the outer boundary of this area of SPS controlled motion. In this discussion, 60 orbital windows of $\pm 0.15^\circ$ longitude each must be allocated. With these numbers, the

SPS concept of 60 separate satellites would foreclose a minimum of 18° longitude orbit arc from any other use simply because of the motion of the physically large SPS. (If two or more SPS satellites could be combined into a single platform, some reduction in GEO space allotted to SPS should be feasible.)

The question of mutually controlled synchronized orbit operation of two or more SPS satellites within a single $\pm 0.15^\circ$ longitude arc sector has apparently not been treated in detail, but may deserve consideration to increase the "parking density" of the SPS system. The maximum parking density would apparently be limited by the preference to locate each SPS satellite at the same longitude as its rectenna.

These numbers for the orbital arc may not be final or precise. However, the numbers emphasize that this is an important matter for which technically reliable numbers need to be developed.

SPS operations and performance will depend greatly on the mutual separation of the SPS vehicles, as well as on the rectenna locations and the related siting and operational criteria. For the continental United States, the GEO arc most useful for SPS runs from about 65° to about 135° W longitude, or about 70° of arc. Even with uniform spacings of 60 solar power satellites among themselves, spacings as close as about one degree must be considered for service to the continental United States. DOE studies presently suggest that some orbit clustering would be needed for the eastern sector of the United States, so that spacings among some SPS vehicles could be expected to be less than 1°.

Compatibility of the SPS Energy Beam with Other Geosynchronous Satellite Systems

Two basic issues have arisen concerning the energy beam in the reference system concept. The first addresses the manner in which SPS vehicle and power beam phase control is to be achieved. The second involves possible effects of the SPS fundamental frequency (2450 MHz) radiated energy on the multiple users of the geosynchronous orbital arc. These issues are basic in that successful operation of SPS requires high efficiency fundamental frequency power transfer to the earth. Precise on-station satellite vehicle position control and power beam phase control are necessary to achieve that objective.

In the first issue, control of SPS motion to within the nominal $\pm 0.15^\circ$ longitude about the satellite stationary position will require a command/control/telemetry two-way communication capability. In addition, the reference system includes an uplink transmission of a phase control pilot signal to the SPS for the retrodirective antenna array power beam control. The SPS antenna aperture for the power beam would have field strengths on the order of 3000 V/m on the side facing the earth. Field strengths are as yet not projected for other parts of the antenna and satellite. It is in this electromagnetic environment, however, that the command/control/telemetry receivers for position and power beam control must operate.

Receiver design for operation in high ambient electromagnetic fields is difficult because of signal distortion and associated error rates. Without proof, the question of SPS vehicle and power beam control feasibility must be treated as unresolved. In essence, given full freedom of design for the command/control/telemetry channels on or near the SPS, there is not yet a consensus that a design can be implemented to perform these two control functions successfully or that the technical parameters for the uplink are feasible.

The second basic issue concerns the +98 dB(W) energy delivered to the SPS antenna at 2450 MHz. The main power beam gain along boresight has been defined in the reference SPS as 86.8 dB(i) (decibels relative to isotropic). Sharing GEO with satellites other than SPS involves angles off SPS boresight on the order of 90° for closely spaced neighbors decreasing to the order of 7° off SPS boresight in the extreme case for cross-orbital interference situations.

The approximate SPS antenna models for the main power beam exploratory studies do not apply to the angles off boresight which are central to the orbit spacing issue. The physical size of the SPS array and the large number of elements prevents the use of simple models for antenna gains at 2450 MHz beyond 10° from the boresight. Very little supportable information is available for the SPS space antenna pattern at angles from 10° to 90° off boresight. To resolve issues related to spectrum and orbit sharing, information of this type must be obtained with sufficient accuracy to enable technical resolution of sharing issues.

To proceed with a discussion of the second basic issue and to illustrate the nature of the problem more exactly, some numbers are assumed here. Antenna gain of the SPS space antenna at 2450 MHz in the vicinity of 90° from SPS boresight may be -10 dB(i) on the average. There is a considerable range of uncertainty, perhaps ±20 dB, around the -10 dB(i). Lacking for other information, the -10 dB(i) value seems to be a reasonable choice.

Ideal far field free space propagation loss ($4\pi r^2$) implies that the power density at a point r meters along the orbit from the SPS antenna array is $p_t g_t / 4\pi r^2$, where the SPS transmitter power and array gain are p_t and g_t , respectively. The parameter $r > r_0$ applies only for distances from the SPS antenna array which are within the far field, with $r_0 = 2D^2/\lambda$, where D is the effective antenna diameter at the wavelength λ when seen at 90° to the SPS array boresight. The distance r is more conveniently expressed in degrees of longitude separation along the arc (ϕ) through $\phi = 57.3 r/d$ or $\phi = 1.36 \times 10^{-6} r$ with $d = 4.22 \times 10^7$ meters distance to the earth's center and 57.3 as the constant for converting radian into degrees. The 2450 MHz spatial power density at a point ϕ degrees separation in longitude from the SPS would then be on the order of

$$-(40 \text{ dB(W/m}^2) + 20 \log_{10} \phi) \pm 20 \text{ dB}$$

with $g_t = -10 \text{ dB(i)} \pm 20 \text{ dB}$, based upon the aforementioned numbers for illustration. The point of reference for this power density is the interfered-with satellite antenna aperture.

At 1° longitudinal spacing, the SPS spatial power density level at 2450 MHz is thus estimated as $-40 \text{ dB(W/m}^2) \pm 20 \text{ dB}$ for purposes of this discussion. Closer spacings increase this power density level; for example, at 0.5° spacing, the power density level is estimated at 6 dB greater or $-34 \text{ dB(W/m}^2) \pm 20 \text{ dB}$. At $\phi = 2^\circ$, the power density level is 6 dB less or $-46 \text{ dB(W/m}^2) \pm 20 \text{ dB}$. At $\phi = 10^\circ$, the power density level reduces only to $-60 \text{ dB(W/m}^2) \pm 20 \text{ dB}$. While uncertainty exists about these numbers (viz., largely because of the uncertainty about the SPS space antenna gain at 90° relative to boresight), it must be acknowledged that the rate of change of this interference power with orbit separation, ϕ , changes at the rate of $20 \log_{10} \phi$. Orbital arc separation alone may therefore not be an effective means to reduce adequately the interference effects of the 2450 MHz fundamental energy, if large values of ϕ are required.

At this point, it is necessary to introduce the question of interference coupling mechanisms. Both SPS and other geosynchronous satellites which attempt to operate in the vicinity of an SPS would be exposed to the power density of the SPS fundamental. Two general coupling mechanisms, referred to as direct and indirect, must be considered.

In the direct case, the SPS 2450 MHz signal would enter the other satellite receiver through the antenna, the rf network, and the front end. The level of interference with the other satellite's receiver mixer would be determined by the degree of attenuation encountered in the other satellite's antenna and the rf network preceding the mixer.

In the indirect case, the coupling would come about by 2450 MHz interference penetration into the receiver circuitry, bypassing the antenna and rf network. Determination of the attenuation of the SPS signal in this case is much more difficult without carefully controlled measurements with actual satellite vehicles.

We turn now to a brief discussion of the indirect coupling of SPS radiation into the communication satellite and its associated control and housekeeping functions. Here, the orbit spacing issue depends upon the sensitivity of the non-SPS satellite's entire system to the 2450 MHz SPS emission. Unfortunately, little is known as to the sensitivity of satellite subsystems to such radiation. To estimate the magnitude of this issue, we make use of 1.0 V/m as the level considered by many engineers to be a design objective for equipment immunity. Translating the previous relation into the field level in dB(V/m) by the relation

$$E^2 = 120 \pi P$$

we have $E[\text{dB(V/m)}] = 26 + P [\text{dB(W/m}^2)]$

or $= -14 \pm 20 - 20 \log_{10} \phi$.

Hence for a maximum field strength of 1.0 V/m one would require a 2° spacing in the worst case; a 0.1° spacing would require an ability to operate in fields up to 20 V/m.

Next, we turn to a brief discussion of the direct coupling of SPS radiation via the communication satellite antenna into the satellite receiver. In order to calculate the SPS signal available to the communication satellite receiver input, the effective collecting area of the antenna at 2450 MHz in the appropriate direction needs to be known. This antenna usually will be designed to operate at frequencies above 2450 MHz; its gain in the SPS direction is therefore likely to be at the isotropic level or lower. To continue the illustration introduced above, we now assume an effective aperture of $1 \times 10^{-3} \text{ m}^2$ in the direction of the SPS satellite, at 2450 MHz. (This corresponds to an antenna gain of -1 dB(i) , as may be shown using the relationship $A_e = G\lambda^2/4\pi$ relating the effective aperture A_e , the wavelength λ , and the antenna gain, G .)

If the reference point is taken as the input to the antenna feed on the interfered-with satellite, the interfering power level available at 2450 MHz for a separation of ϕ degrees along the geosynchronous arc will be: $-(70 + 20 \log_{10} \phi \pm 20) \text{ dB(W)}$. This is to be compared with in-band noise levels for typical communication satellite receivers of about -160 dB(W) for a 4-kHz reference bandwidth. While out-of-band interfering signals often can be tolerated at levels considerably higher than the in-band noise level, under some circumstances nonlinear frequency-mixing processes in the receiver can translate strong out-of-band interference into in-band interference of sufficient intensity to degrade communication capability.

For a spacing, ϕ , of 1° , the above SPS signal level is of the same order as the intentional saturation flux density levels of typical satellite communications transponders. With no further information about the design or shielding of the interfered-with receiver, it is not possible to judge the effect of such levels of out-of-band interference. However, preliminary data presented on tests of one satellite receiver suggest that in-band interference was caused by high order mixing products falling back within the communication band, but the detailed interference mechanism was not identified. Therefore, until the detailed interference mechanisms are understood, SPS interference levels that are of the same order as the intentional saturation flux density must be regarded as potentially harmful.

In view of the above, the Working Group concludes that a significant unresolved electromagnetic compatibility problem exists between SPS and communication satellites. It is clear that some minimum spacing (as yet not specified) will be required for successful operation of a communication satellite in the vicinity of an SPS satellite. Because a large number of SPS satellites are contemplated (60 in the reference system), this spacing must be reduced to a minimum. The spacing is dependent upon the design of the communication satellite. In the case of future satellites, it could presumably be reduced by incorporating appropriate design features, e.g., additional filters and shielding. However, since satellites from many nations would be involved, international cooperation would be required.

The willingness of non-U.S. owners of other geosynchronous satellite systems to accept the burden of making their complete satellites--including all housekeeping, telemetry, and control systems--invulnerable to SPS fields of (say) 20 V/m in order to permit operation within 0.1° of an SPS satellite is not discussed in this report. Obviously, their attitude could be a very significant factor in determining the ITU response to the SPS concept. Particularly if the additional shielding, filtering, and testing required to meet any such standard involve significant extra expense, countries not receiving benefits from SPS may oppose its use by the United States.

Compatibility of the SPS Harmonic Emissions with Other Geosynchronous Satellite Systems

The previous analysis should be applied to the SPS harmonic emissions at all multiples of 2450 MHz. Even greater uncertainties exist in this situation about the harmonic emission level and the SPS space antenna gain in the direction 90° from boresight. Harmonic levels in the range of 40 dB to 90 dB below the fundamental have been suggested in other studies. Antenna pattern and gain information is either not available or not conclusive. References have been made to the CCIR recommended level of $-154 \text{ dB(W/m}^2\text{)}$ in any 4 kHz band without recognition that this recommended level applies only to specific agreed-upon sharing situations as noted previously.

In order to consider possible harmonic levels along GEO the previous numerical illustration can be continued by reducing the emission level by 40 dB and assuming the SPS space antenna gain 90° from boresight to be 0 dB(i). The harmonic emissions bandwidth will be assumed to be 4 kHz. For a communication satellite effective aperture of $1 \times 10^{-3} \text{ m}^2$, the SPS harmonic level at the output of the interfered-with satellite antenna would be postulated to be: $-(100 + 20 \log_{10} \phi) \pm 20 \text{ dB(W)}$. Similar revisions for lower harmonic levels can be easily calculated.

These SPS harmonic levels require attenuations on the order of 70 dB at each harmonic frequency if the harmonics are to be reduced to 10 dB below the noise level. However, it is difficult to draw conclusions other than that the issue is not resolved and is potentially serious. If the SPS fundamental and harmonics are not adequately attenuated, they may combine in non-SPS receiver mixers with signals normally present to produce intermodulation products. In certain cases such intermodulations may fall somewhere in the interfered-with receiver's operating frequency band. Some preliminary tests of two satellite receivers exposed to the SPS fundamental and harmonics indicated serious intermodulation effects, and led at least one group to infer that a 0.5° separation distance from an SPS satellite would be required. These tests, however, are not available for detailed analysis, and in particular the precise mechanism of interference is not known.

Multipath

The SPS provides a large reflecting (or diffracting) object for radiowaves. Under proper positioning of a transmitter and its intended receiver, the SPS may cause a multipath condition (direct ray and ray reflected from SPS). The seriousness of the multipath will depend upon the relative attenuation of the two paths (including antenna directivity effects), the type of modulation in use and the actual magnitudes of the time delay. The magnitude of the scattered wave can be comparable to the direct signal, and can therefore cause deep fades and loss of communication capability.

Only limited investigations of this phenomenon have been made. The number of possible configurations that have been considered appears to be limited. Accordingly, it is considered that this problem deserves further attention with respect to both satellite-to-earth and satellite-to-satellite communications circuits.

Some Secondary SPS/non-SPS Satellite Issues

In view of the above substantive issues, other time- and frequency-sharing questions involving satellites in orbit have been considered as secondary in importance. These secondary questions concern:

- Sharing with non-SPS satellites operating at altitudes lower than GEO;
- Sharing with non-SPS satellites which are at GEO and must be moved past the SPS vehicles; and
- Sharing with non-SPS satellites at altitudes greater than GEO.

It must be stressed, however, that the SPS reference concept exploratory studies have not resolved these secondary sharing questions.

At altitudes lower than GEO, the satellites have an orbit motion relative to the earth's surface. If a LEO satellite passed over the continental United States with any or all of 60 SPS power beams in operation, the likelihood that the LEO satellite would traverse one or more power beams or their grating lobes needs to be established. Without extensive orbit control of all LEO satellites, it would appear that such incidents would occur and, unless other corrective actions were available, it could cause serious problems to the LEO missions.

DOE studies estimate that SPS main power beam illumination of a LEO satellite at orbit altitudes of 700 km would result in 2450 MHz power density exposures of about +3 dB(W/m²) (about 30 V/m) for about 1 second duration and -37 dB(W/m²) (about 0.3 V/m) for up to 13 seconds duration. Previous conclusions about possible interference effects for non-SPS geosynchronous satellites apply in this case with appropriate modifications.

Compatibility of SPS with Terrestrial Communication and Electronic Systems

General Equipment Susceptibility

Design standards for the susceptibility of general electronic equipment to radio-frequency fields have recently been studied under the auspices of the American National Standards Institute (ANSI), in response to an FCC inquiry. These studies have recommended a minimum design objective of 1 V/m, which would correspond to a separation of about 200 km from the center of an SPS rectenna, plus the exclusion of areas surrounding the four primary grating lobes.

Independent studies of the potential effects of SPS on general electronic equipment indicate that the principal area of concern is within 50 km of a rectenna, and propose that mitigation procedures could permit operation up to the exclusion area (about 7 km from the rectenna center). Between 50 km and 7 km the SPS field intensities are predicted to be 2 to 20 V/m.

The range and numbers of electronic devices that would require mitigation in order to be able to operate successfully in SPS fields of 1, 2, and 20 V/m (corresponding to distances of about 200, 50, and 7 km from the center of the rectenna) are not well known, nor is the optimum method of mitigation known for each device. Such mitigation requirements must be carefully evaluated with regard to cost. The fact that undesired effects may be mitigated in a given type of equipment probably will imply to an unsophisticated reader that the problem can be dismissed from further concern. In practice, some mitigative measures which might seem innocuous to one party might seem very expensive and/or inconvenient to the victim. Hence, one must go well beyond the determination that mitigation is conceivable. The public interest determination must take into account many subjective and practical considerations. For example, such cost estimates as have been presented reflect only the costs at the manufacturing level. In the field, the total costs at the retail level plus installation (which may involve special trips to isolated locations, provision of alternate facilities during conversion, etc.) would be expected to be much greater.

Terrestrial Communications Systems

The effects on terrestrial radiocommunications systems are generally similar to those on electronic equipment, but require even closer controls. Communications systems often consist of a number of elements in tandem as, for example, a 2500 km radio-relay system with 50 intermediate stations. The noise and distortion are cumulative and so the amount which can be tolerated in a single exposure must be held to a value far below that which would interfere with a single station. Any proposed SPS design must include a fundamental requirement that there be no out-of-band emissions at a level which could cause interference to terrestrial communications systems.

Earth Terminals of Earth-Space Communications Circuits

Among the most sensitive telecommunications receiving systems used at the earth's surface are the earth terminals of satellite communications systems. Since their antennas are directed toward GEO, they are particularly vulnerable to SPS emission, especially any out-of-band SPS radiation that falls in the reception band of the terrestrial station. Such radiation might originate as a harmonic of the SPS power beam (the 3rd harmonic of the 2450 MHz SPS signal lies in the 7300-7450 MHz band assigned to government, fixed-satellite, space-to-earth communication); as adjacent channel noise from SPS on satellite broadcast bands at 2500-2690 MHz; or as spurious radiations resulting from the nonlinear mixing of SPS signals with other radiations incident upon the SPS. Here it is appropriate to note that as little as 10 mW of spurious SPS emission, radiated isotropically from the geosynchronous orbit in some satellite communication band, could double the noise level in a 4 kHz band of an earth-based satellite receiver whose main antenna beam includes the SPS satellite as well as its own communications satellite. Unfortunately, estimates of the intensity of such radiations from an SPS satellite (or the system of 60 satellites) are extremely uncertain, being highly dependent on details of the SPS not currently available. Detailed information on the generation and radiation of adjacent channel noise, harmonics, and other radiations from SPS will be required before their effect on earth-space communications can be estimated.

Radio and Radar Astronomy

The electromagnetic compatibilities of the reference SPS with radio and radar astronomy systems (traditionally, among the most sensitive and demanding of radio receiving systems) are discussed in a paper by Thompson (1981). Of primary concern are out-of-band SPS radiations (which include thermal radiation, as well as transmitter-generated noise and harmonics) that fall within the radio astronomy receiver passband. Such radiations are most likely to occur in the 2380 MHz radar astronomy frequency and the 2690-2700 MHz radio astronomy band (near the SPS fundamental at 2450 MHz), and in the 4990-5000 MHz radio astronomy band (near the 4900 MHz SPS second harmonic).

The principal effect on radio astronomy would be to produce, for each radio telescope, a zone centered on the SPS satellites in which observations are precluded. The width of this zone will depend upon a number of factors, especially the type of observation, the observing frequency, and the side-lobe pattern of the radio astronomy antenna system. Typically, the precluded zone would be a few degrees to perhaps as much as 30° in declination, and would extend in hour angles somewhat beyond the length of the geosynchronous orbital arc occupied by the SPS.

In addition, unless protected by adequate filters, the sensitive receiver input stages of radio astronomy receivers could be damaged by

the reception of strong SPS signals, even if these lay outside the receiver passband. Such filters would have to be cryogenically cooled to prevent excessive degradation of receiver noise figures.

Radiation of noise, harmonics, and intermodulation products by SPS rectennas, as well as the higher SPS fields that exist in their vicinity, would make it desirable to separate them by at least 50 km from radio astronomy observatories.

Rectenna Siting

Preliminary studies of the feasibility of finding 60 rectenna sites in conterminous United States have not included consideration of effects on civil communications systems. Radio communications systems located within a proposed rectenna area would have to be displaced, and possibly those within 200 km would need to be displaced or substantially altered. This could seriously affect the availability and cost of essential communications services. Consequently, before any studies of siting feasibility are considered to be conclusive they should be refined to include a more thorough examination of the effects on civil communications systems and other civil facilities.

Non-linear Effects at the Rectenna

An area of considerable concern is nonlinear effects that could occur both at the solar cell blanket (and the satellite antenna) in orbit and at the rectenna on the ground. Investigators generally admit that much additional work must be done to evaluate the magnitudes of the effects that may occur. Although field strengths at the operating frequency are much larger at the satellite than at the rectenna, it is likely that the latter will be more significant in producing intermodulation products than the former because of the strength of emissions from local (earth surface based) transmitters. Large levels of harmonics are likely to appear at the antenna and solar blanket in orbit. Their importance as a source of interference is unknown, but, admittedly, their power could be weak when received at the earth's surface because of the large amount of space loss occurring in the transmission path. In most cases, present reports tend to indicate that significant effects could be handled by mitigation techniques, but quantitative evaluations of these effects have not yet been carried out. The Working Group believes these effects require much additional attention.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

(1) As discussed earlier, the SPS represents a major use of the electromagnetic spectrum in geosynchronous orbit, and therefore must

be very carefully analyzed from the point of view of its compatibility with other communications or electronic systems.

(2) The authors of the DOE electromagnetic compatibility assessment studies (U.S. DOE in press) are to be congratulated on their identification and discussion of the significant potential sources of non-compatibility. The Working Group found these studies to provide a valuable background for its discussions.

(3) One critical electromagnetic compatibility question relates to the internal compatibility of the SPS system itself. The SPS Reference System Report (U.S. DOE 1979) and the DOE electromagnetic compatibility assessment studies (U.S. DOE in press) leave some uncertainty as to the feasibility of receiving at the SPS the information required to control the steering and focusing of the SPS transmitting beam. They fail to make clear that the transmission of the 6.7 GW power beam is in fact compatible with the reception of antenna control information essential to successful operation of SPS satellites.

(4) With reference to orbit use and SPS impact on other satellite systems, the main concern is the unknown length of the orbital arc around each nominal SPS orbital position that is rendered unsuitable for communications or other non-SPS satellites. The minimum length of this arc would appear to be the diameter of the major axis of the ellipse traced out diurnally by the SPS in response to solar and lunar gravitational effects and solar radiation pressure. To this collisional-type protection zone must be added an electromagnetic compatibility protection zone. The magnitude of this latter zone cannot be specified at this time, primarily because of major uncertainties as to power flux densities produced by an SPS along the geosynchronous orbital arc (as a function of electromagnetic frequency) and the sensitivity of communications satellites to those flux densities. With today's knowledge of the reference SPS, the collisional plus electromagnetic compatibility protection zone around a single SPS satellite is significant, and may be of the order $\pm 0.5^\circ$ of orbital arc. For 60 SPS satellites, a significant international issue could arise if steps were not taken to reduce this zone.

(5) The creation of additional propagation paths on satellite-relayed communications circuits through scatter by an SPS satellite could under some circumstances be a significant problem. This multipath problem would be likely to be particularly severe on any future geosynchronous satellite-to-satellite radiocommunications relay paths.

(6) The large size of the SPS space structures, plus the high powers involved, make the generation and radiation of harmonics and unwanted intermodulation products at the spacecraft a matter of some concern. Because of the lack of information on the design of SPS, and specifically, the properties that control the generation and radiation of additional electromagnetic frequencies, it has not been possible to estimate the magnitude of interference that might be caused by such effects.

(7) Similarly, it is not possible at this time to identify quantitatively the effects of spurious electromagnetic radiations that

would exist in the vicinity of each rectenna due to generation of harmonics, and nonlinear mixing with other frequencies at the rectenna site.

(8) The reference SPS of 60 satellites would produce field strengths over significant areas of the United States in excess of the 1 V/m field strength limit recommended by ANSI for general electronics. Although many electronic devices can withstand considerably larger field strengths without degradation of performance due to intermodulation or overload phenomena, this suggests that the costs of improving the capabilities of all other electronic devices to (say) 10 V/m could be very large.

(9) All LEO satellites would traverse SPS power beams from time to time, and could therefore be exposed to field strengths in excess of 60 V/m, reaching a maximum of about 3000 V/m for a satellite passing through the main beam about 2000 km below the SPS satellite. This may ultimately impose operational constraints on SPS and/or the LEO.

(10) In view of the above, we conclude that obtaining spectrum and orbit resources for SPS through ITU will require a rigorous technical showing of compatibility that would be very hard to provide at our present level of knowledge about SPS.

(11) We also conclude that competition for the spectrum and orbit resources required for SPS from present and future telecommunications uses will be very severe, and that the procurement of such resources will therefore be administratively difficult.

Recommendations

(1) Additional work should be undertaken to reach quantitative conclusions concerning the magnitude of the electromagnetic compatibility problems SPS would produce, and the costs of accepting them, or finding and implementing strategies to avoid them. Such conclusions will require a detailed assessment of electromagnetic compatibility based on knowledge of the scattered and radiated fields produced by the SPS, and of the sensitivity of all possible interfered-with systems to those fields. At this time, despite the best efforts of DOE contractors, much of the detailed information required is missing. The following identifies the information required.

Ideally, the electromagnetic fields resulting from the operation of an SPS satellite should be fully determined as a function of distance, direction, and frequency.

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| Distance | - in the near, transitional, and far fields. |
| Direction | - in all directions, including angles near 90°, and in the rear hemisphere. |
| Frequency | - at the SPS power beam frequency; in adjacent noise bands; at harmonics of these frequencies; and at any additional frequencies produced by nonlinear mixing of SPS and non-SPS signals. Also included must be any incident fields scattered by SPS. |

In practice, it will not be possible to acquire all this information in one step. Instead, progress toward this ambitious goal should be made in a series of successively more detailed approximations, as the configuration of any eventual satellite power system is more fully defined.

(2) Further studies should be made of the internal compatibility of SPS with itself, and specifically of the feasibility of receiving at the satellite the necessary antenna control information. The possibility of multipath distortions resulting from the interaction of the pilot beam with the solar panel should be considered. Experimental tests will be required.

(3) Since the reference SPS involves 60 satellites, the resultant field distribution and electromagnetic compatibility of the total system, and not just of a single SPS, must be identified.

(4) The susceptibility of all relevant classes of terrestrial and satellite electronic devices to the above SPS radiation fields must be determined quantitatively. In many cases this will involve carefully documented tests involving pickup of SPS radiation via the antenna (if any) of the interfered-with system, as well as the coupling of SPS radiation into the device by other routes.

(5) In cases where some adverse effects would be caused and the use of mitigation measures is proposed, the total costs involved must be carefully determined. These will include component, installation, additional servicing, and lost revenue costs, as well as the initial cost of developing and testing the mitigation measures.

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