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

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.

CONTENTS

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; CONSULTANTS, CONTRACTORS, AND OTHER CONTRIBUTORS*

WORKING GROUP ON COMPARATIVE ASSESSMENT

Donald F. Hornig, Interdisciplinary Program in Health, Harvard School of Public Health, Chairman
Peter L. Auer, Department of Mechanical and Aerospace Engineering, Cornell University
Norman M. Bradburn, National Opinion Research Center, University of Chicago
Charles J. Hitch, Energy and Environment Division, Lawrence Berkeley Laboratory, University of California
Frank Kreith, Solar Energy Research Institute
Melvin K. Simmons, General Electric Corporate Research and Development
Morton C. Smith, Los Alamos Scientific Laboratory
Bernard I. Spinrad, Nuclear Engineering, Radiation Center, Oregon State University

WORKING GROUP ON ELECTROMAGNETIC COMPATIBILITY

C. Gordon Little, Wave Propagation Laboratory, Environmental Research Laboratories, National Oceanic and Atmospheric Administration, Chairman
Arnold L. Berman, Microwave Laboratory, COMSAT Laboratory
Peter McManamon, Institute for Telecommunication Sciences, National Telecommunications and Information Administration
Ralph Showers, Department of Electrical Engineering and Science, Moore School of Electrical Engineering, University of Pennsylvania
H. Edward Weppler, Technical Standards and Regulatory Planning, American Telephone and Telegraph Company
J. Arthur Zoellner, Electromagnetic Compatibility Analysis Center, Department of Defense

*Affiliations for purposes of identification only.

WORKING GROUP ON SOLAR CELLS

C.K.N. Patel, Physical Research Laboratory, Bell Telephone Laboratories, Inc., Chairman
David Carlson, RCA Laboratories
J.S. Harris, Rockwell Science Center
W. Dexter Johnston, Bell Telephone Laboratories, Inc.
Ken Jones, Department of Electrical Engineering, Colorado State University
Prosenjit Ray-Choudhury, Westinghouse Research and Development Center

WORKING GROUP ON SPACE SYSTEMS

Thomas O. Paine, Northrop Corporation, Chairman
Klaus P. Heiss, ECON, Inc.
J. Ross Macdonald, Department of Physics and Astronomy, University of North Carolina
Sidney Metzger, Assistant Vice President & Chief Scientist, Communications Satellite Corporation
George E. Mueller, Chairman and President, System Development Corporation
Willis H. Shapley, Washington, D.C., Consultant

PLANNING GROUP ON MICROWAVE HEALTH EFFECTS

Richard B. Setlow, Biology Department, Brookhaven National Laboratory, Chairman
Norman M. Bradburn, National Opinion Research Center, University of Chicago
Stephen F. Cleary, Department of Biophysics, Medical College of Virginia, Virginia Commonwealth University
James W. Frazer, Department of Diagnosis and Roentgenology, University of Texas Health Science Center
Sharon Nelson, Consumers Union
Maria A. Stuchly, Radiation Protection Bureau, Environmental Health Center, Health and Welfare Canada
Daniel F. Cahill, Experimental Biology Division, Environmental Protection Agency, Ex Officio

WORKSHOP ON MECHANISMS UNDERLYING EFFECTS OF LONG-TERM, LOW-LEVEL, 2450 MHz RADIATION ON PEOPLE

Participants

Richard B. Setlow, Brookhaven National Laboratory, Chairman
Richard Albanese, M.D., Air Force School of Aerospace Medicine
André J. Berteaud, Centre National de la Recherche Scientifique
Carl F. Blackman, Environmental Protection Agency

Daniel F. Cahill, <u>ex officio</u>, Environmental Protection Agency
Stephen F. Cleary, Medical College of Virginia, Virginia Commonwealth University
Carl H. Durney, University of Utah
James W. Frazer, University of Texas Health Science Center
Allan H. Frey, Randomline, Inc.
Karl H. Illinger, Tufts University
Donald McRee, National Institute of Environmental and Health Sciences
Rochelle Medici, Fairview State Hospital
Herbert Pollack, M.D., Washington, D.C.
Herman P. Schwan, University of Pennsylvania
Ralph J. Smialowicz, Environmental Protection Agency
Maria A. Stuchly, Radiation Protection Bureau, Canada
John Thomas, Naval Medical Research Institute
Christopher H. Dodge, Congressional Research Service, <u>Rapporteur</u>

CONSULTANTS, CONTRACTORS, AND OTHER CONTRIBUTORS

Aerospace Corporation
Ronald Bell, Solid State Labs, Varian Associates
R.N. Bracewell, Stanford University
Harry Cooke, Solid State Microwave Division, Varian Associates
Paul Crapuchettes, Consultant, Litton Corporation
C.C. Cutler, Stanford University
Lawrence Cwik, Graduate Student, University of Hawaii, Honolulu
Lewis M. Duncan, Los Alamos Scientific Laboratory
Clare Farley, Northrop Corporation
George Farney, Beverley Microwave Tube Division, Varian Associates
Joe G. Foreman, Consultant, Alexandria, Va.
Wilmot N. Hess, Director, National Center for Atmospheric Research
Erik Houts, Quality Reliability Engineer, Varian Associates
Joseph H. Johnson, Engineering, Communications Transistor Corporation
Gerhard T. Konrad, Klystron Division, Stanford Linear Accelerator Center (SLAC)
Charles E. Land, Environmental Epidemiology Branch, National Cancer Institute
Erling Lien, Palo Alto Microwave Tube Division, Varian Associates
Gerald Meltz, United Technologies Research Center, East Hartford, Connecticut
Ervin J. Nalos, Boeing Aerospace Corporation
James P. Naughton, Graduate Student, Energy Research Group, University of Illinois
Francis W. Perkins, Plasma Physics Laboratory, Princeton University
Donald Priest, Chief Advisory Engineer, Eimac Corporation
Harold H. Rossi, Radiological Research Laboratory, Columbia University College of Physicians and Surgeons
George W. Schreyer, TRW Semiconductor
Craig Snapp, Microwave Semiconductor Division, Hewlett-Packard
Paul Todd, Department of Microbiology, Cell Biology, Biochemistry and Biophysics, The Pennsylvania State University
John Zinn, Los Alamos Scientific Laboratory

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 contruction 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 <u>on any useful schedule</u> 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

<u>Civilian</u>. 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 psotulating 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 udertakings 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 reuseable 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 reuseable, 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 uncertanties 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 Intertial 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 strutures 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 Contruction, and SPS Operations and Maintenance.

Transportation Between Earth and LEO

The requirements of the reference SPS for earth-to-LEO transportation are unprecendented in comparision 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 state. 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 refect the area required for solar arrays and the depth required for strucutral 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 alteratives 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 condition (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 hugh 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 assesed. 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 seem.

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 kylstron 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 abut 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, <u>we conclude that a specific SPS program should not be established now, and probably not for the next decade</u>. 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, <u>we conclude that a future SPS option should not be foreclosed</u>.

While we believe that the reference SPS should now be abandoned, <u>we recommend that NASA continue conceptual studies on promising new SPS concepts</u>. 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.

REFERENCES

American Institute of Aeronautics and Astronautics (1981) Projected Space Technologies, Missions and Capabilities in the 2000-2020 Time Period. New York: American Institute of Aeronautics and Astronautics.

Arnold, J.R. (1976) Water on the Moon. In Lunar Utilization, D.R. Criswell, editor, pp. 61-65. Houston, Tx.: Lunar Science Institute.

Ayres, R.U., L.W. Ayres, and D.R. Criswell (1979) Economic Considerations in Space Industrialization. 79-1390. New York: American Institute of Aeronautics and Astronautics.

Bock, E. (1979) Lunar Resources Utilization for Space Construction. NAS-9-15560-DRL-T-1451. Houston, Tx.: National Aeronautics and Space Administration.

Boeing Aerospace Company (1980) Solar Power Satellite System Definition Study. D180-25969-1. Seattle, Wa.: Boeing Aerospace Company.

Caluori, V., et al. (1980) Technology for Future Earth-to-Geosynchronous Orbit Transportation Systems. NASA Contractor Report 3265, prepared for NASA Langley Research Center by Boeing Aerospace Co., April 1980.

Criswell, D.R., and R.D. Waldron (1978) Commercial Prospects for Extraterrestrial Materials. J. Contemporary Business 7:153-189.

Defense Daily (1980) Schmidt plans new space policy bill in next Congress. November 13, 1980, pages 57-58. Washington, D.C.: Defense Daily.

Eldred, C. (1980) Looking Toward Single Stage Launch Systems. XXXI International Astronautical Congress, Tokyo, Japan, prepared at NASA Langley Research Center, September 1980.

Handley, G. (1980) Satellite Power Systems (SPS) Concept Definition Study. Seal Beach, California: Rockwell International.

Henry, B.Z. and C. Eldred (1977) Advanced Technology and Future Earth-Orbit Transportation Systems. Proceedings of Third Princeton/AIAA Conference on Space Manufacturing prepared at NASA Langley Research Center, May 1977.

Miller, R. and D. Smith (1979) Extraterrestrial Processing and Manufacturing of Large Space Systems. CR161293. Huntsville, Ala.: National Aeronautics and Space Administration.

Mosich, J.T. (1981) Review of the Orbital Construction of the Solar Power Satellite. ATR-81(9545)-1. El Segundo, Calif.: The Aerospace Corporation.

National Aeronautics and Space Administration (1980a) Findings and Recommendations of the NASA Review Panel on the Structural Dynamics and Control of the SPS. Johnson Space Center, January, 1980.

National Aeronautics and Space Administration (1980b) Report of the SPS Construction and Materials Workshop. Johnson Space Center, January 1980.

National Research Council (1979) Energy in Transition 1985-2010. Washington, D.C.: National Academy of Sciences.

Naugle, J.F. and I. Bekey (1980) Just Over the Horizon, Astronautics and Aeronautics, May, 1980.

Rossi, H.H. (1980) Assessment of the Current Status of the Dosimetry of Ionizing Radiation in the SPS Environment, paper prepared for NRC-NAS. Reproduced as Appendix G of this report.

Space Task Group (1969) Space Task Group Report to the President. Washington, D.C.: National Aeronautics and Space Administration.

U.S. Department of Energy (1980) Program Assessment Report: Statement of Findings. Satellite Power System Concept Development and Evaluation Program. DOE/ER-0085. Springfield, Va.: National Technical Information Service.

Williams, R.J. (1976) Hydrogen Resources for the Moon. In Lunar Utilization, D.R. Criswell, editor, pp. 55-60. Houston, Tx.: Lunar Science Institute.

Wolfe, M.G. (1981) Satellite Power System (SPS) Transportation Cost Assessment Study. ATR-81 (78 98)-1 El Segundo, Calif.: The Aerospace Corporation. Reproduced as Appendix D of this report.

Wurster, K. (1980) Mass Reduction for Advanced Winged Entry Vehicles Through Integrated Thermostructural-Trajectory Design. AIAA Paper No. 80-0363, NASA Langley Research Center, January 1980.

APPENDIX D*

REPORT BY THE AEROSPACE CORPORATION:

SATELLITE POWER SYSTEM (SPS) TRANSPORTATION COST ASSESSMENT STUDY

January 1981

Prepared by

MALCOLM G. WOLFE

Space Launch Vehicle Division
Programs Group
The Aerospace Corporation
El Segundo, California 90245

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.

CONTENTS

TABLES

FIGURES

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).

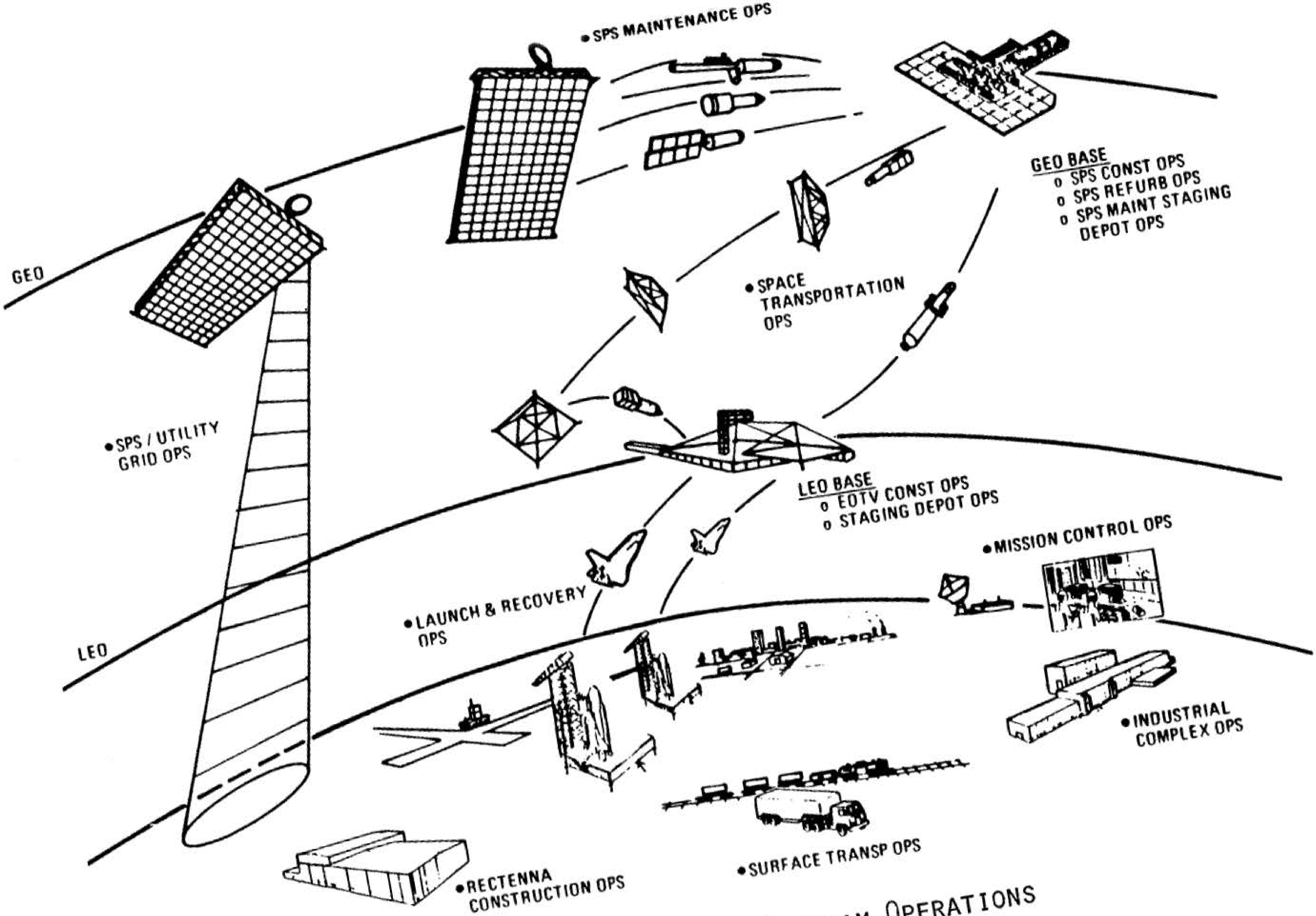


FIGURE 2-1. INTEGRATED SPS PROGRAM OPERATIONS

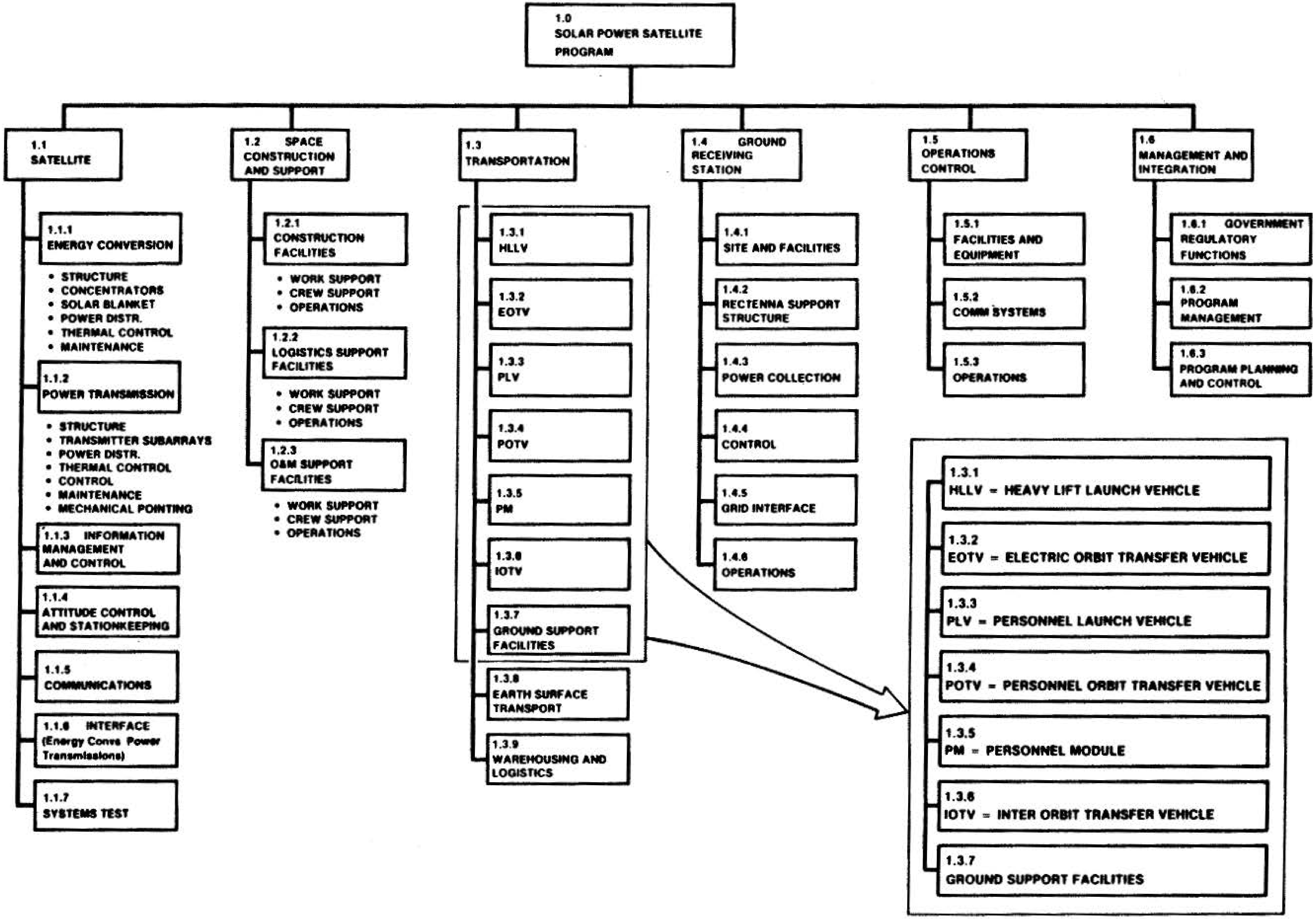


FIGURE 2-2. TYPICAL SPS WORK BREAKDOWN STRUCTURE

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:

CATEGORY	BASIC ESTIMATE ($M)	QUANTITY FACTOR	CONTRACTOR TOTAL COST ($M)
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	138,960.0
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.

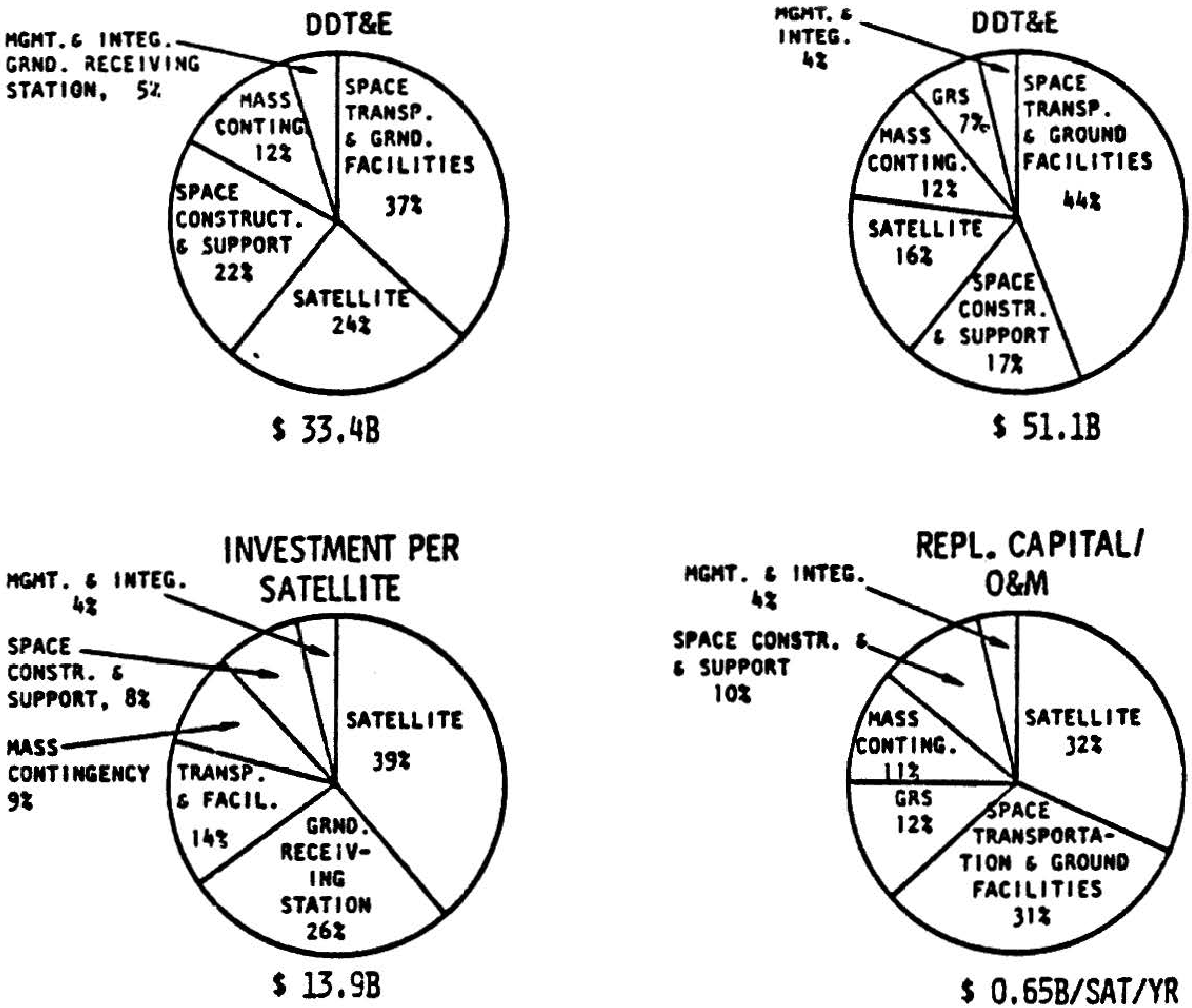


FIGURE 2-3. ROCKWELL MARCH 1979 PROGRAM COST DISTRIBUTION

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

CHARACTERISTIC	BOEING	ROCKWELL
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	IOTV
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	IOTV
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	1,037,127	470,352	1,143,400	518,549
MECHANICAL SYSTEMS	77,309	35,061	112,800	51,156
ELECTRICAL POWER	16,449	7,460	18,800	8,526
ENV CONTROL	534	242	600	272
AVIONICS	3,759	1,705	4,300	1,950
PROPULSION	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	588,939	267,092	689,600	312,744
MECHANICAL SYSTEMS	33,070	14,998	49,200	22,313
ELECTRICAL POWER	16,277	7,382	16,800	7,619
CREW ENV AND LSS	7,409	3,360	7,700	3,492
AVIONICS	6,559	2,975	6,900	3,129
PROPULSION	164,091	74,418	176,600	80,091
EQUIPMENT	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	558,518	253,296	681,300	308,980
MECHANICAL SYSTEMS	55,638	25,233	60,700	27,528
ELECTRICAL POWER	14,300	6,485	15,600	7,075
ENV CONTROL	500	227	500	227
AVIONICS	8,625	3,911	5,000	2,268
PROPULSION	407,075	184,615	447,100	202,766
PERSONNEL PROV	820	372	900	408
BOOSTER DRY WEIGHT	(1,045,476)	(474,139)	(1,211,100)	(549,252)
ORBITER				
STRUCTURE AND THERMAL	515,866	233,590	588,200	266,758
MECHANICAL SYSTEMS	56,361	25,561	39,000	17,687
ELECTRICAL POWER	13,800	6,258	15,200	6,893
ENV CONTROL	6,555	2,973	7,000	3,175
AVIONICS	9,775	4,433	6,900	3,129
PROPULSION	122,610	55,605	140,100	63,537
PERSONNEL PROV	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	182,800
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)

VEHICLE	HLLV	EOTV	PLV	POTV	PM	IOTV
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)

ELEMENTS	BOEING	ROCKWELL
HLLV	211	320
EOTV	60	28
PLV	35	4
POTV	4	1
PM	2	2
IOTV	N/A	1
GSF	7	21
TOTAL	319	377

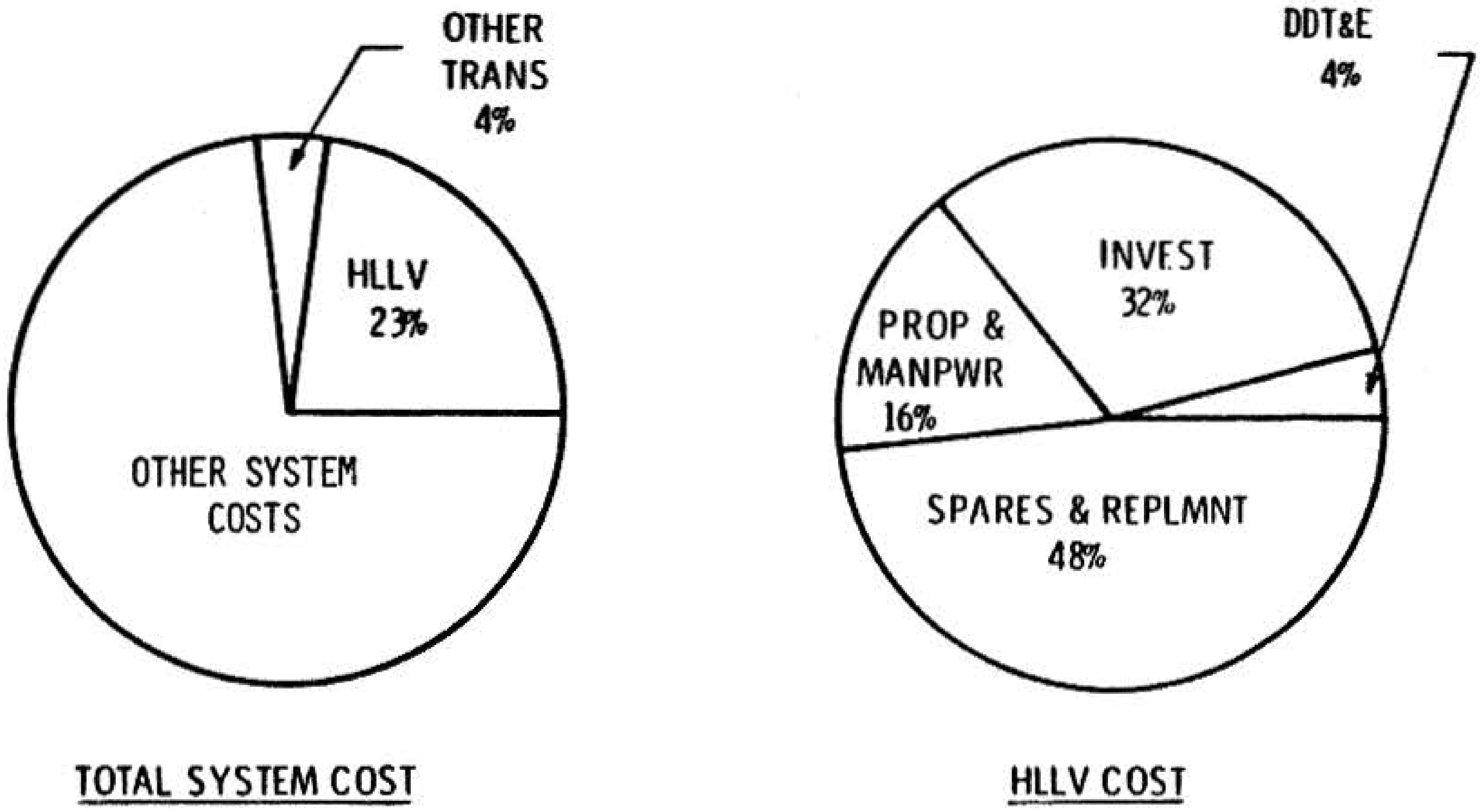


FIGURE 4-1. ROCKWELL PROGRAM COST DISTRIBUTION - CONTRACTOR ESTIMATE

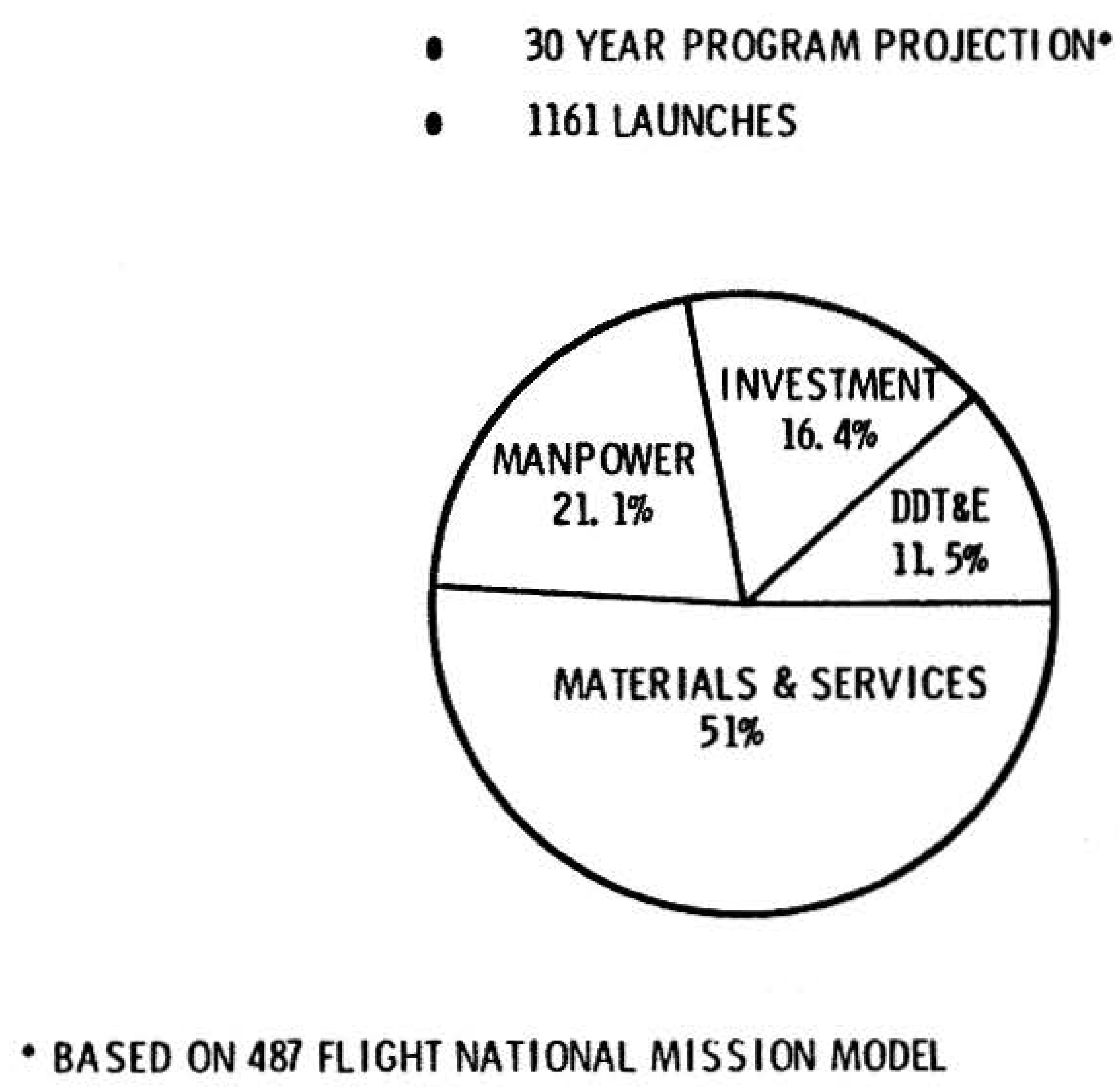


FIGURE 4-2. SPACE SHUTTLE PROGRAM COST DISTRIBUTION

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 BAC COST	BAC DESIGN AEROSPACE	AEROSPACE DESIGN MODIFICATION
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 RI COST	RI DESIGN AEROSPACE	AEROSPACE DESIGN MODIFICATION
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

	PERFORMANCE	REUSABILITY	TURNAROUND	TECHNICAL RISK	COST SENSITIVITY
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 (ASE)	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, oversize 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.

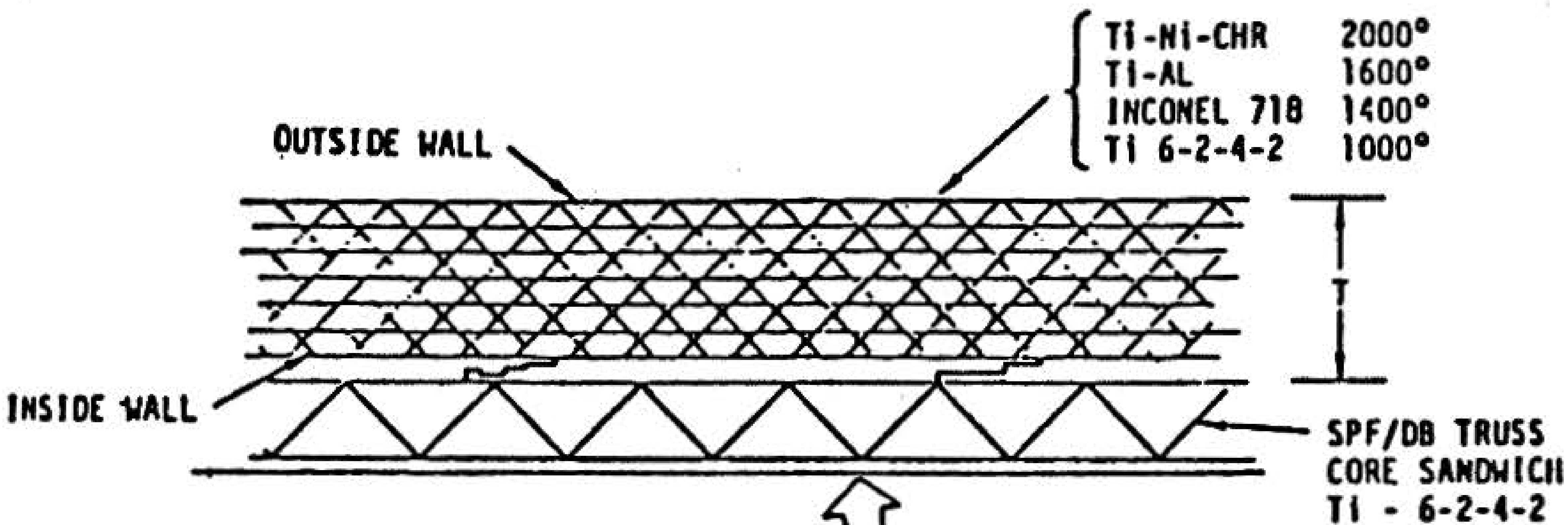
NASA/Ames is developing a new generation of RSI which uses high-temperature organic material fibers for the strain isolation pads and lighter weight and more rugged tiles of advanced carbon composites with very high modulus carbon fibers. However, some of the installation and servicing problems associated 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 resuable 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



T FOR MULTIWALL TPS

OUTSIDE TEMP °F \ INSIDE TEMP °F	1000	600	350
2000	1.20	1.60	2.20
1600	1.00	1.20	1.70
1400	.50	1.00	1.30
1000	–	.50	1.00

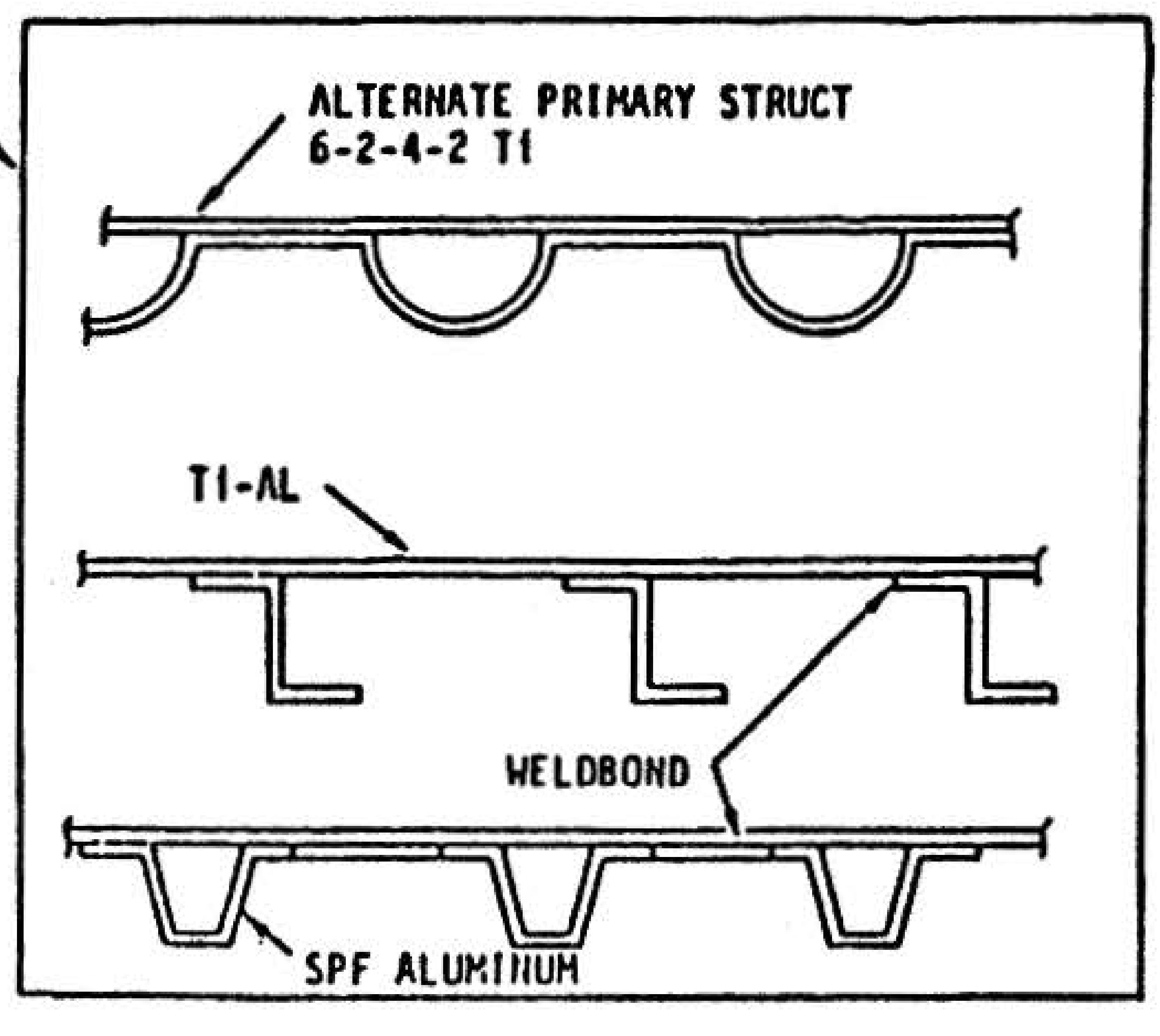


FIGURE 4-3. TYPICAL METALLIC MULTI-WALL TPS CONCEPT

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 (CH_4) 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 LO_2/CH_4 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 contractors 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 articifical 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]

VEHICLE SEGMENT	CURRENT STS[2]	HLLV[3]	
		STS TECHNOLOGY	ADVANCED TECHNOLOGY
BOOSTER	-	45	37
SRM	29	-	-
ET	21	-	-
ORBITER	122	71	52
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 spacebasing of 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 cryogens)
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

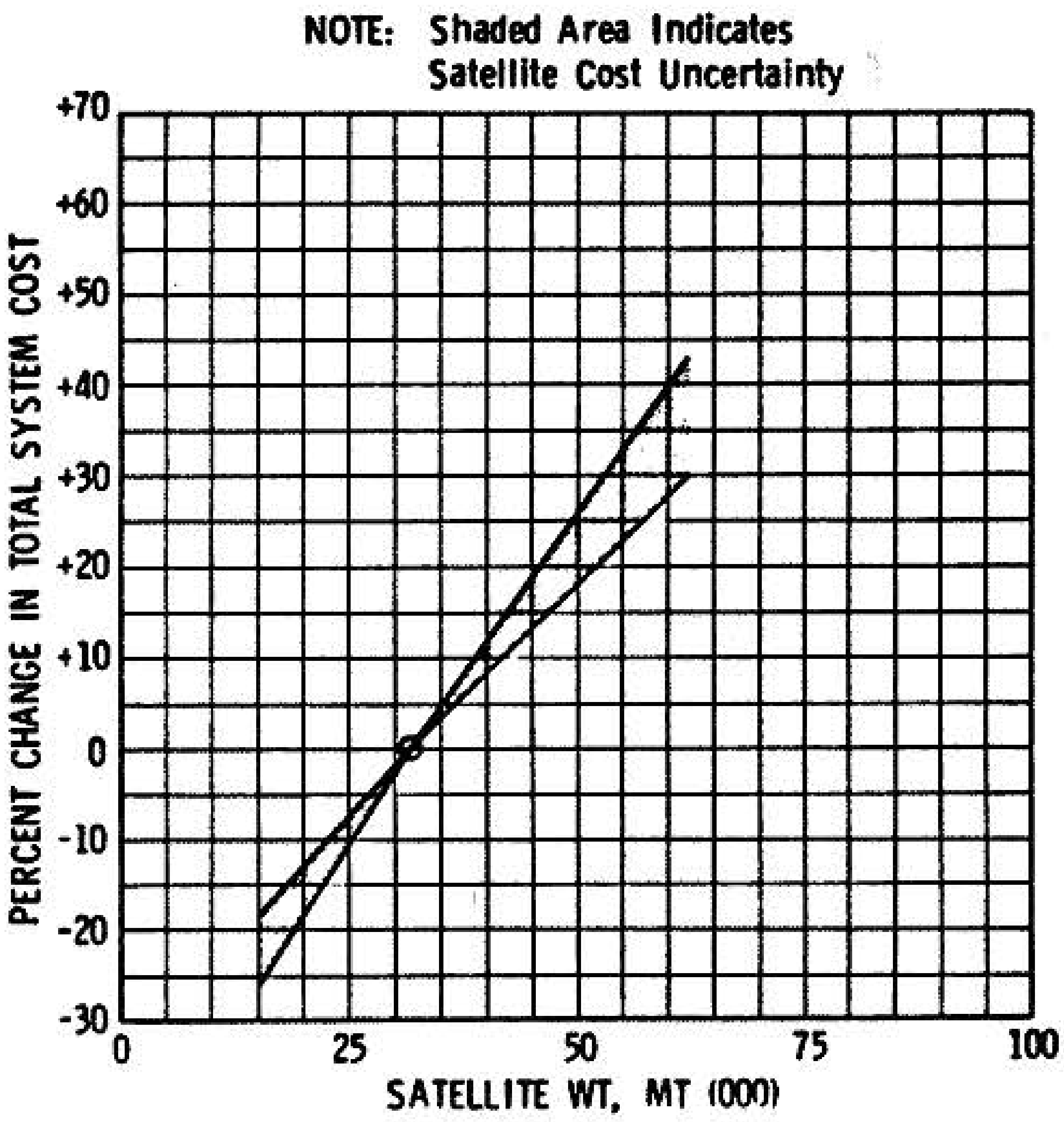


FIGURE 4-4. TOTAL SYSTEM COST VS SATELLITE WEIGHT

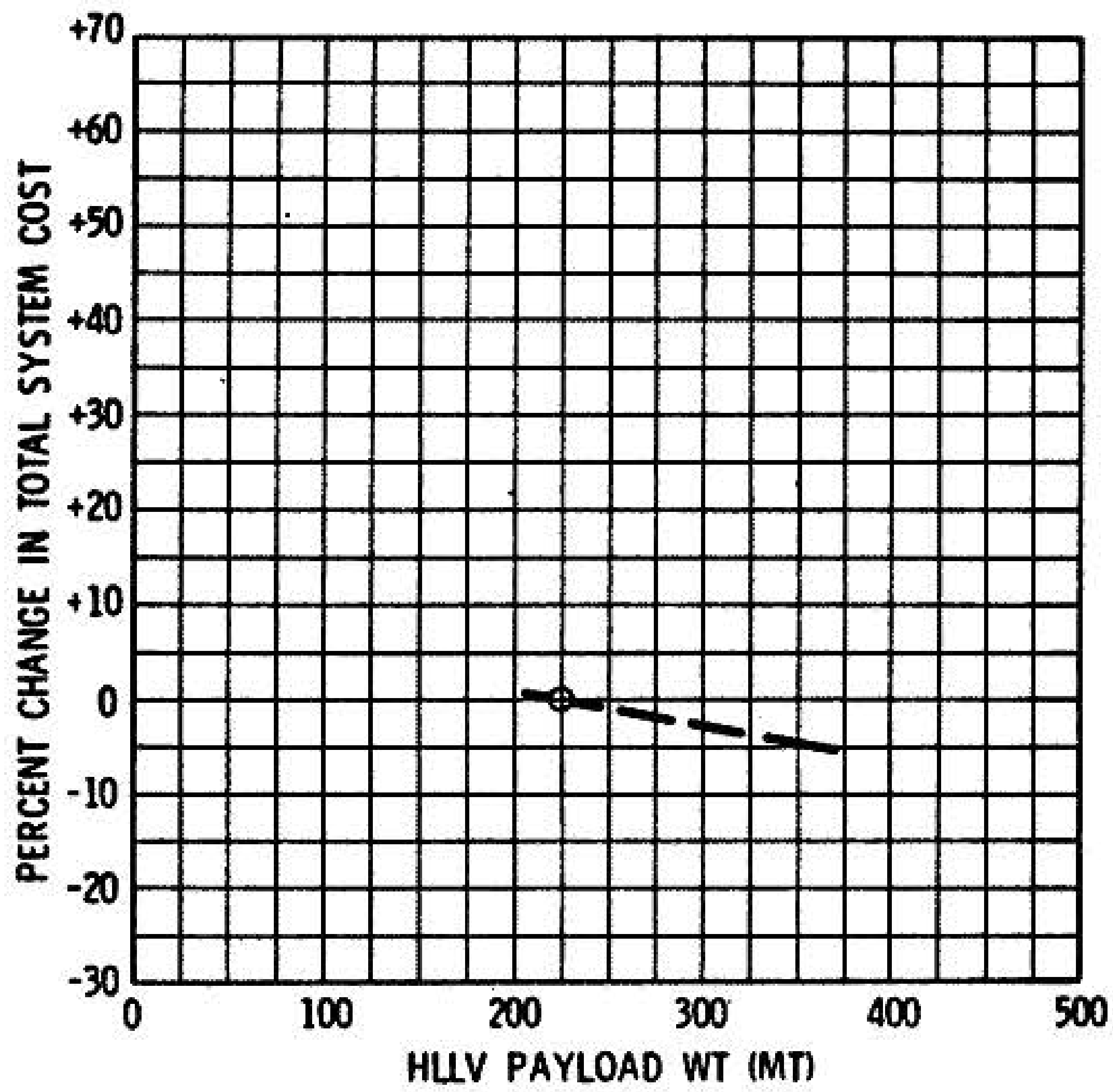


FIGURE 4-5. TOTAL SYSTEM COST VS HLLV SIZE

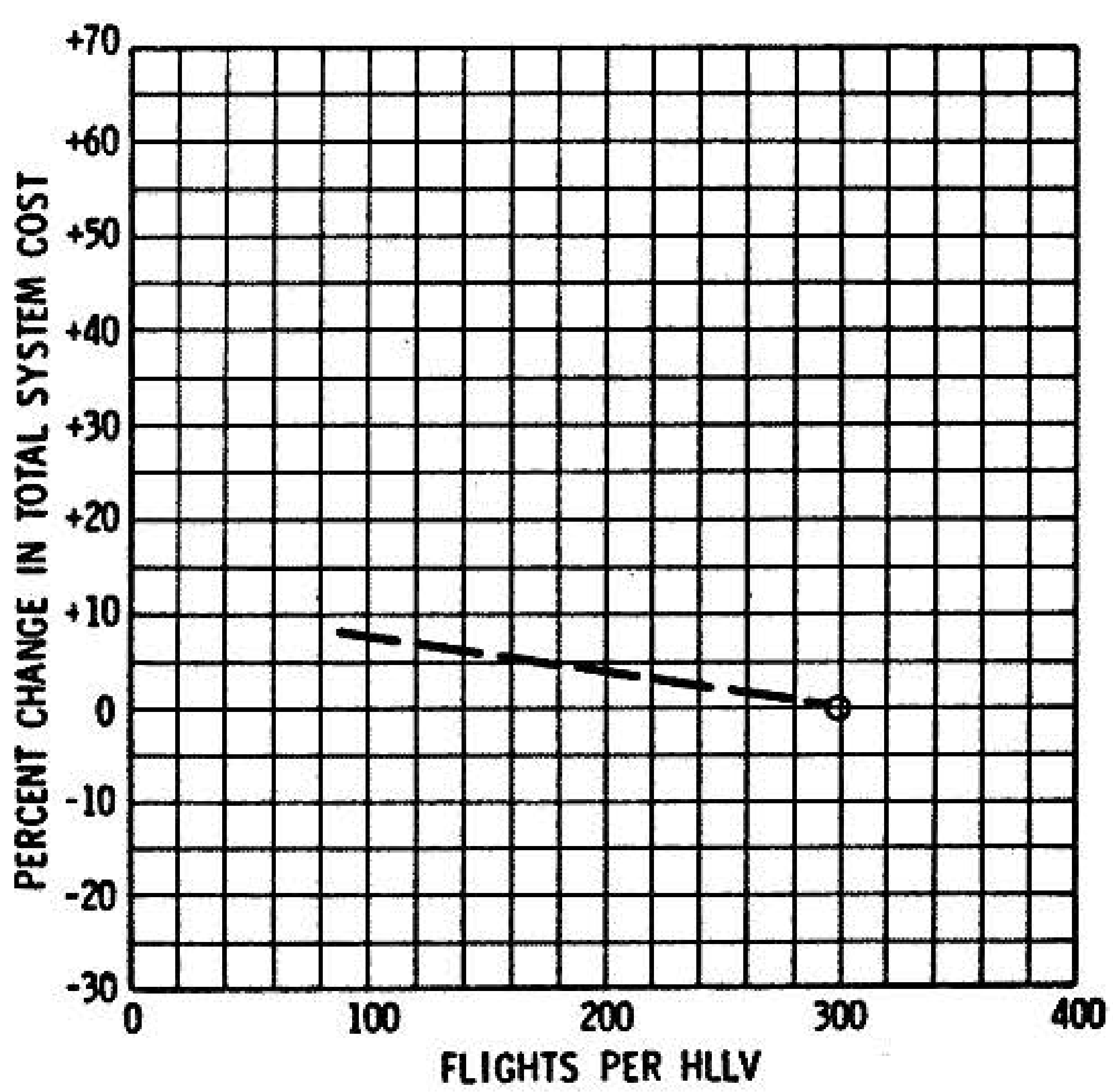


FIGURE 4-6. TOTAL SYSTEM COST VS HLLV LIFETIME

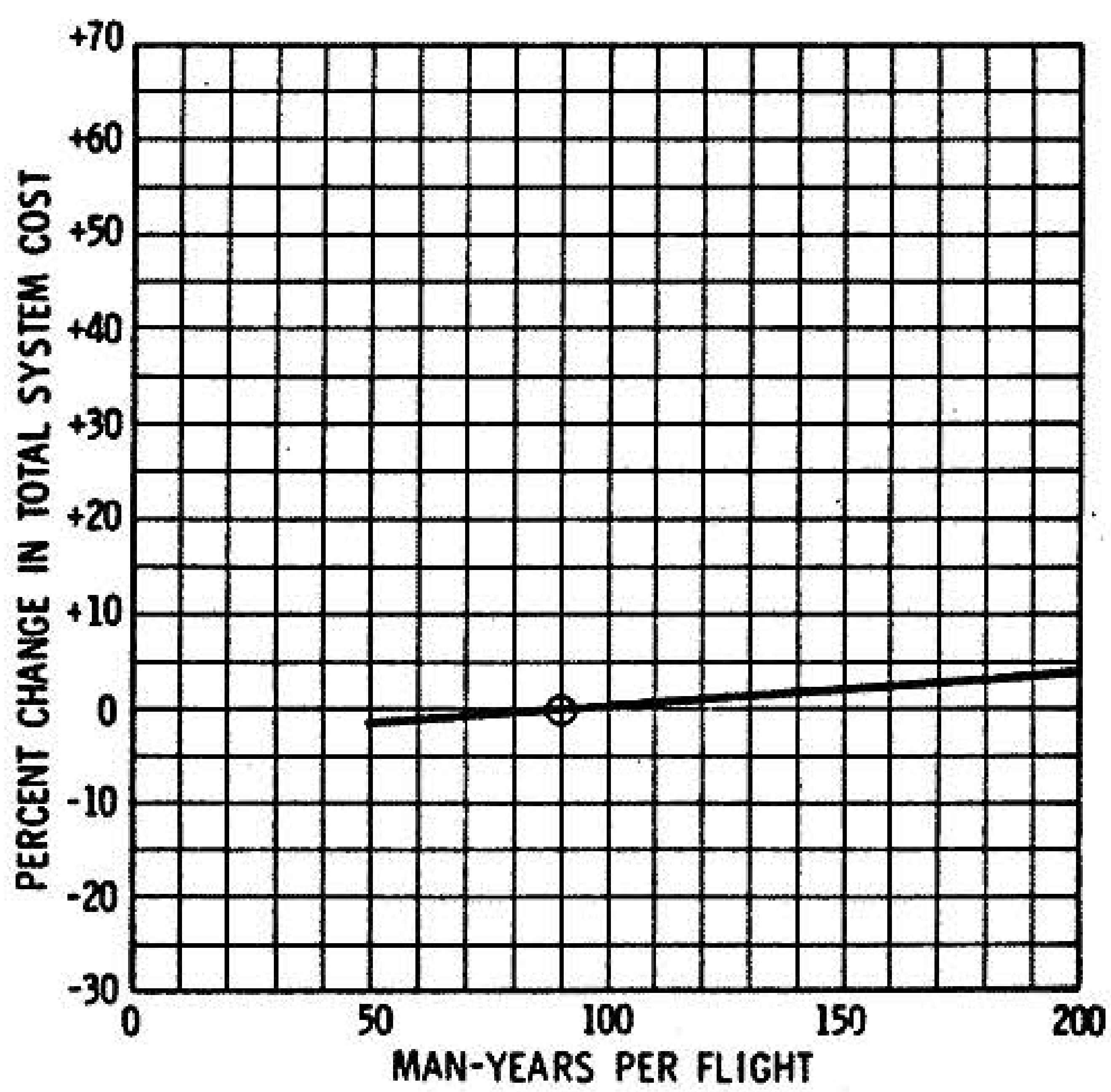


FIGURE 4-7. TOTAL SYSTEM COST VS TURNAROUND EFFORT

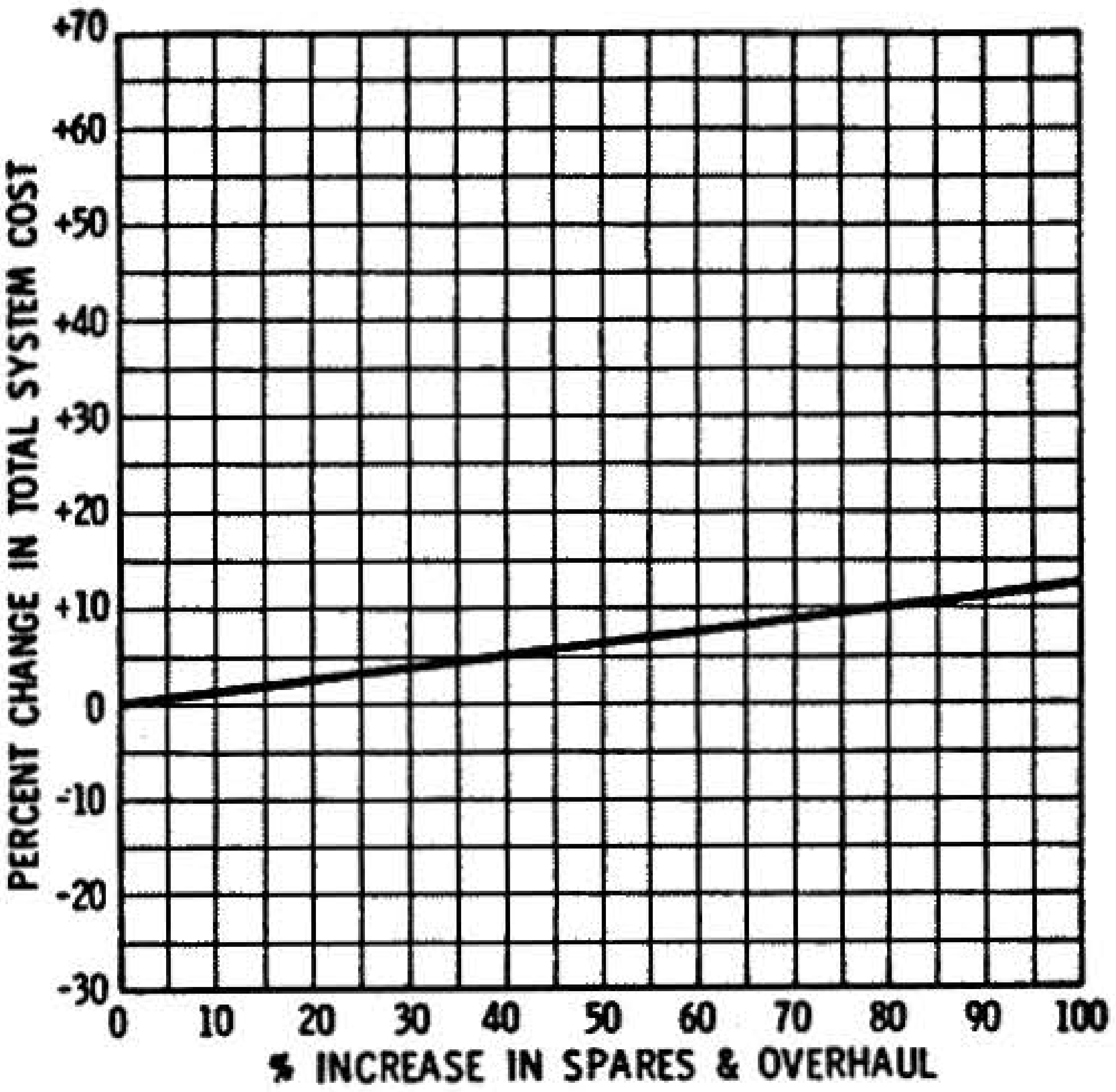


FIGURE 4-8. TOTAL SYSTEM COST VS PERCENTAGE HLLV SPARES AND OVERHAUL

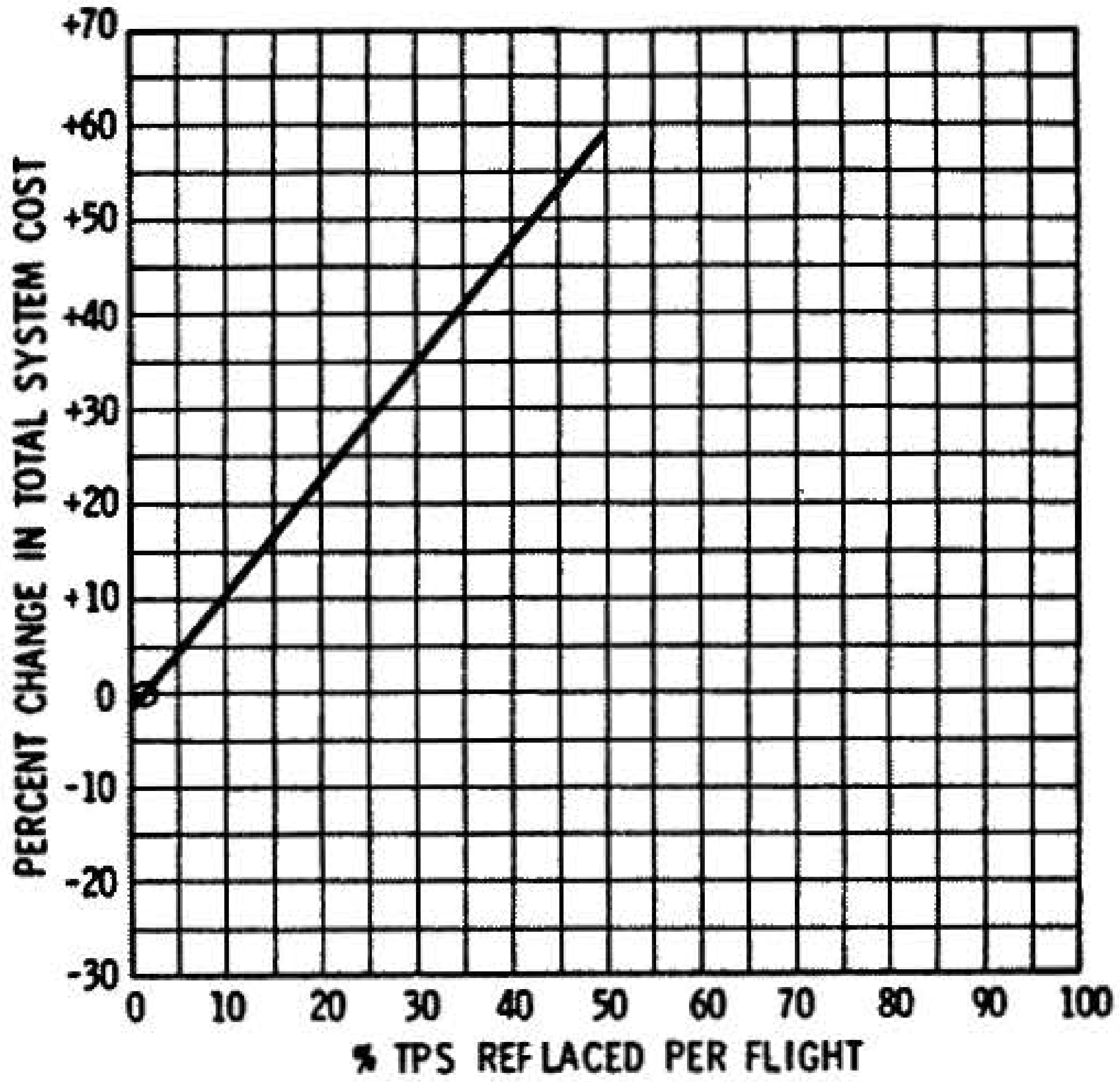


FIGURE 4-9. TOTAL SYSTEM COST VS PERCENTAGE HLLV TPS REPLACED

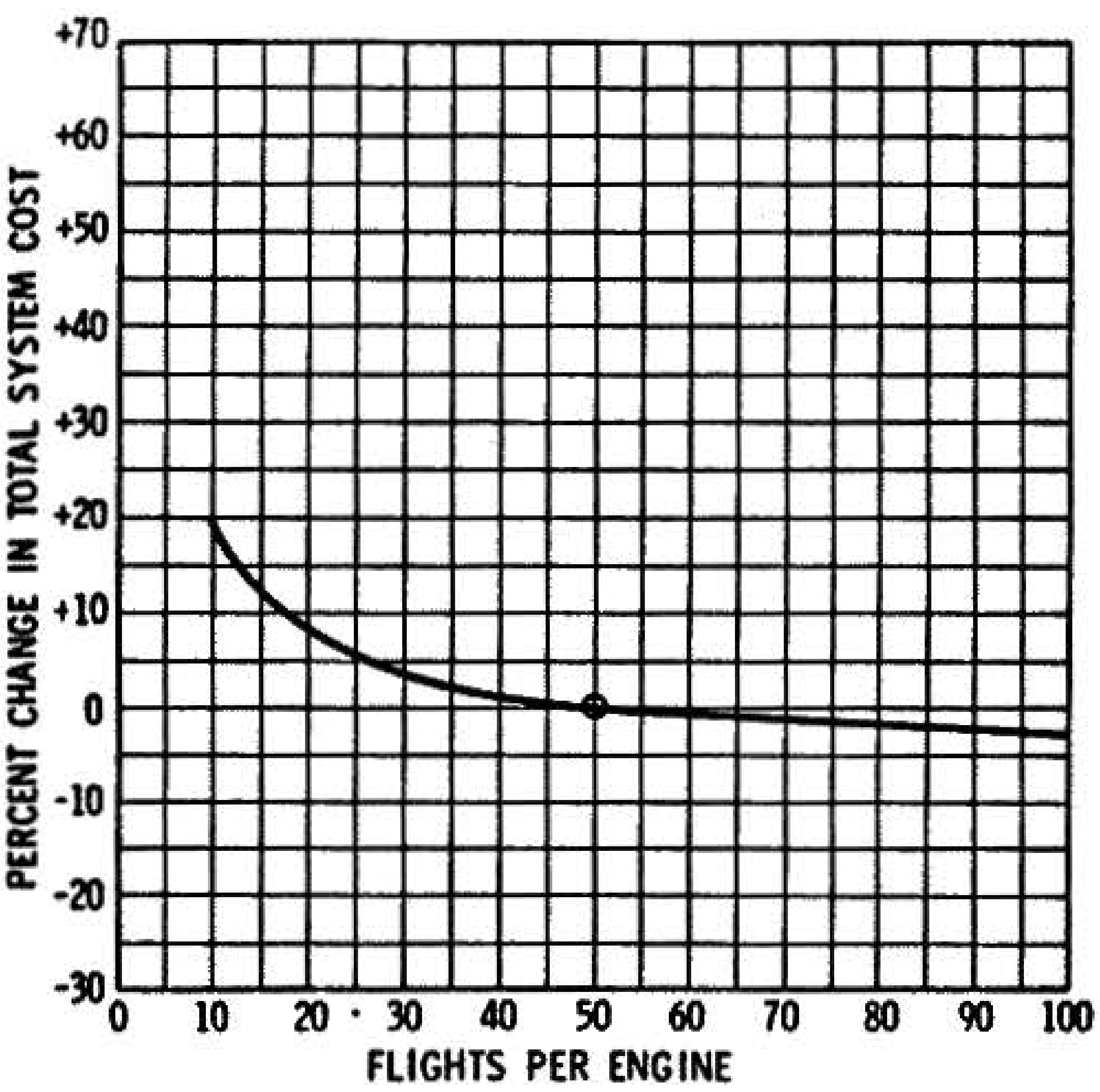


FIGURE 4-10. TOTAL SYSTEM COST VS HLLV ENGINE LIFETIME

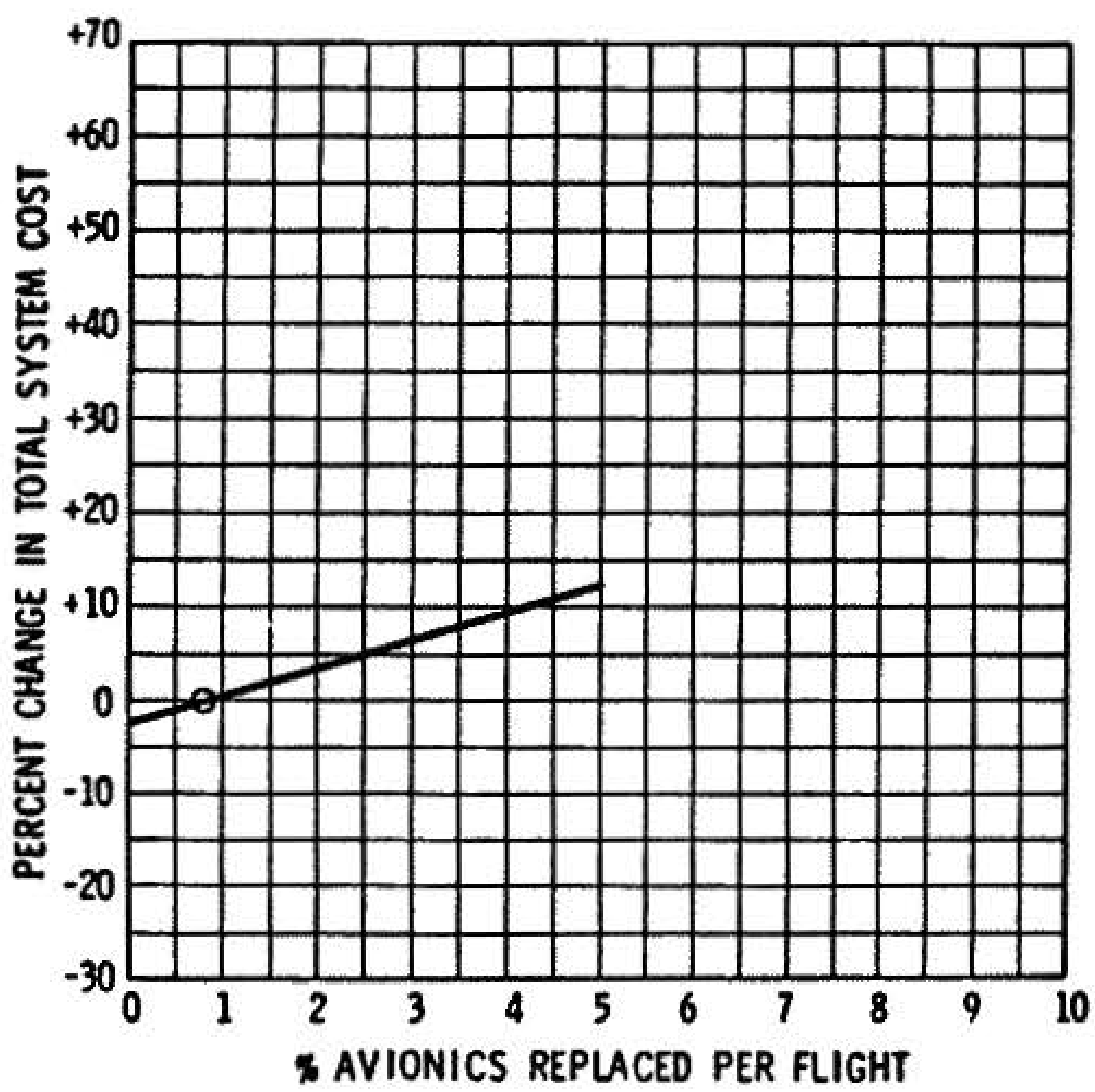


FIGURE 4-11. TOTAL SYSTEM COST VS PERCENTAGE HLLV AVIONICS REPLACED

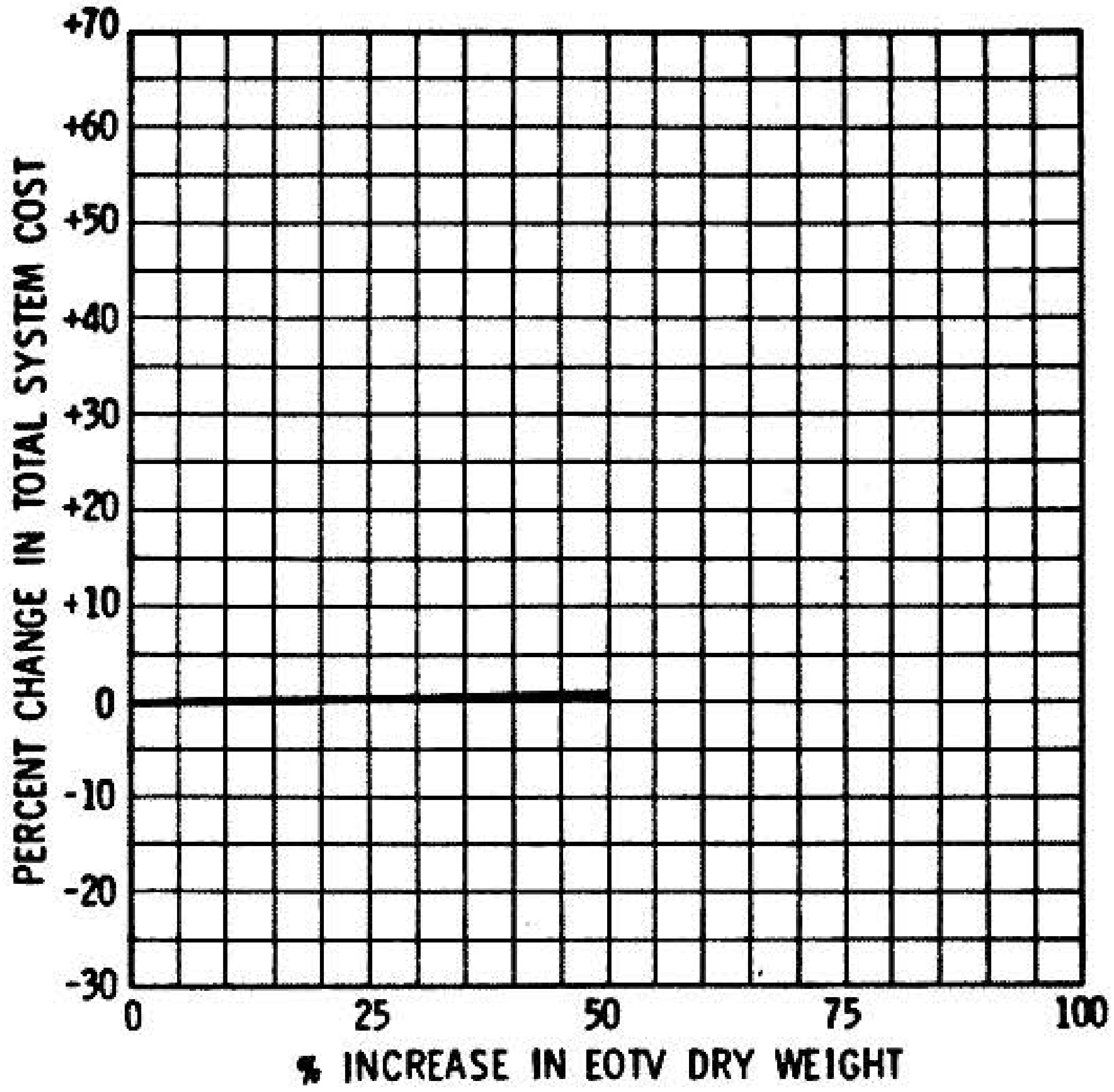


FIGURE 4-12. TOTAL SYSTEM COST VS PERCENTAGE INCREASE IN EOTV DRY WEIGHT

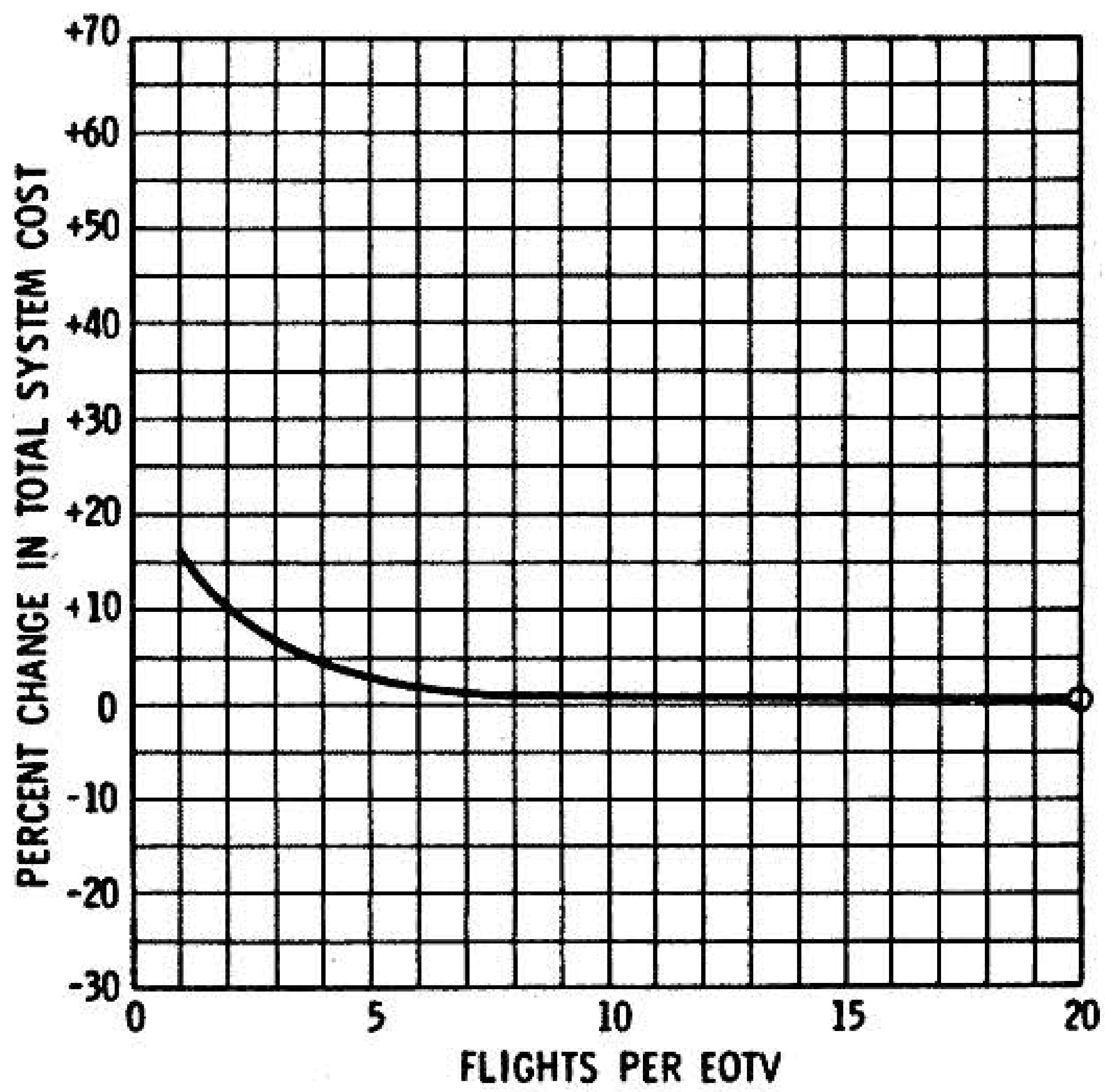


FIGURE 4-13. TOTAL SYSTEM COST VS EOTV LIFETIME

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/FT^2
(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 FT^2 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

OPERATIONAL MODE	PAYLOAD TO GEO
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.

6. BIBLIOGRAPHY

1. Battelle, Satellite Power Systems (SPS) Space Transportation Cost Analysis and Evaluation, Final Report (May 1980).

2. Boeing Aerospace, SPS System Definition Study, Part II, Midterm Briefing, D180-20748-1, (NAS9-15196) (August 24, 1977).

3. Boeing Aerospace, SPS System Definition Study, Vol. VI, Part II, Evaluation Data Book D180-22876-6, (NAS9-15196) (December 1977).

4. Boeing Aerospace, SPS System Definition Study, Part III, Preferred Concept System Definition D180-24071-1, (NAS15196) (March 1978).

5. Boeing Aerospace, SPS System Definition Study, Part III, Final Briefing, D180-24071-3, (NAS9-15196) (1978).

6. Boeing Aerospace, SPS System Definition Study, Vol. I, Phase 1, Final Report, Executive Summary, D180-25037-1, (NAS9-15636) (February 1979).

7. Boeing Aerospace, Solar Power Satellite System Definition Study, Vol. II, Phase 1, Final Report, Systems Analysis and Tradeoffs, D180-25037-2, (NAS9-15636) (March 1979).

8. Boeing Aerospace, SPS System Definition Study, Vol. II, Phase I, Final Report, Operations & Systems Synthesis, D180-25037-3, (NAS9-15636) (April 1979). (partial document)

9. Boeing Arospace, SPS System Definition Study, Vol. VI, Phase I, Final Briefing, Space Construction and Transportation, D180-25037-6, (NAS9-15636) (December 1978).

10. Boeing Aerospace, SPS System Definition Study, Vol. VII, Phase I, Final Briefing, SPS and Rectenna Systems Analyses, D180-25037-7, (NAS9-15636) (December 1978).

11. Boeing Aerospace, SPS System Definition Study, Vol. I, Phase II, Final Report, Executive Summary, (NAS9-15636) (November 1979).

12. Boeing Aerospace, SPS System Definition Study, Phase II, Vol. II, Reference System Description, D180-25461-2, (NAS9-15636) Revision A dated February 1980 (November 1979).

13. Boeing Aerospace, SPS System Definition Study, Vol. III. Phase II, Final Report, Operations and Systems Synthesis, D180-25461-3, (NAS9-15636) (No Date).

14. Boeing Aerospace, SPS Definition Study, Vol. III, Phase II, Operations and Systems Synthesis, D180-25461-3, (NAS9-15636) (No date).

15. Boeing Aerospace, SPS Definition Study, Vol. IV, Phase II, Technical Analysis Report, D180-25461-4, (NAS9-15636) (December 1979).

16. Boeing Aerospace, SPS System Definition Study, Space Transportation Analysis, Final Report for Phase III, December 1978-May 1980, Vol. 5, (NAS9-15636) (June 1980).

17. Boeing Aerospace, SPS System Definition Study, Space Transportation Analysis, Final Report for Phase III, December 1979-May 1980, D180-25969-5, (NAS9-15636) (June 1980).

18. Boeing Aerospace, SPS System Definition Study, Final Report for Phase III, D180-25969-1, (NAS9-15636) (June 1980).

19. Rockwell International, SPS Feasibility Study, Final Report, Executive Summary, SD 76-SA-0239-2, (NAS8-32161) (December 1976).

20. Rockwell International, SPS Concept Definition Study, Final Report, Vol. II, System Engineering, Part 2 (Cost and Programmatics), SSD 79-0010-2-2, (NAS8-32475) (March 1979).

21. Rockwell International, SPS Concept Definition Study, Final Report, Vol. III, Experimentation/Verification Element Definition, SSD 79-0010-3, (NAS8-32475) (March 1978).

22. Rockwell International, SPS Concept Definition Study, Final Report, Vol. IV, Transportation Analyses, SSD 79-0010-4, (NAS8-32475) (March 1978).

23. Rockwell International, SPS Concept Definition Study, Final Report (Exhibit C), Vol. VI, In-Depth Element Investigation, SSD 79-0010-6, (NAS8-32475) (March 1979).

24. Rockwell International, SPS Concept Definition Study, Final Report (Exhibit C), Vol. VII, System/Subsystem Requirements Data Book, SSD 79-0010-7, (NAS8-32475) (March 1979).

25. Rockwell International, SPS Concept Definition Study, Final Report, Vol. V, Transportation and Operations Analysis, SD 78-AP-0023-5, (NAS8-32475) (April 1978).

26. Rockwell International, SPS Concept Definition Study, Final Report, Vol. VII, SPS Program Plan and Economic Analysis, SD 78-AP-0023-7, (NAS8-32475) (April 1978).

27. Rockwell International, SPS Concept Definition Study, Final Report (Exhibit C), Vol. 1, Executive Summary, SSD 79-0010-1, (NAS8-32475) (March 1979).

28. Rockwell International, SPS Concept Definition Study, Final Report (Exhibit C), Vol. II, Systems Engineering, Part 1 (Systems Engineering Aspects), (NAS8-32475) (March 1979).

29. Rockwell International, SPS Concept Definition Study, Final Report (Exhibit D), Vol. I - Executive Summary, SSD 80-0108-1, (NAS8-32475) (October 1980).

30. Rockwell International, SPS Concept Definition Study, Final Report (Exhibit D, Vol. III - Transportation Analyses, SSD 80-0108-3, (NAS8-32475) (October 1980).

31. Rockwell International, SPS Concept Definition Study, (Exhibit D) Final Performance Review, SSD 80-0123, (NAS8-32475) (August 12, 1980).

32. Rockwell International, SPS Concept Definition Study, Final Report SSD 80-(TBS) (NAS8-32475) (October 1980). (unapproved draft)

33. Rockwell International, Boeing, NASA/MSFC & NASA/JSC Study, SPS Space Transportation (October 1980).

34. Rockwell International, Advanced Satellite Power System Concept, PD80-61 (September 1980).

35. Battelle Columbus Labs., Satellite Power Systems (SPS) Space Transportation Cost Analysis and Evaluation, Final Report Prepared for DOE, authors: R.W. Earhart, C. W. Hamilton, K. M. Maher, R. R. Teeter (May 1980).

36. Department of Energy, Satellite Power System Reference System Report, DOE/ER-0023 (October 1978).

37. NASA/MSFC, SPS Work Breakdown Structure Dictionary, TM 78155 (January 1978).

38. NASA, SPS Work Breakdown Structure Dictionary (November 1978).

39. NASA, Technology Requirements for Future Earth-to-Geosynchronous Orbit Transportation Systems, Vol. I - Executive Summary, authors: Vincent A. Calouri, Robert T. Conrad, and James C. Jenkins, NASA Contractor Report 3265, (Contract NAS1-15301) (June 1980).

40. NASA, Technology Requirements for Future Earth-to-Geosynchronous Orbit Transportation Systems, Vol. II-Technical Results, authors: Vincent A. Calouri, Robert T. Conrad, and James C. Jenkins, NASA Contractor Report 3266, (Contract NAS1-15301) (June 1980).

41. DOE/NASA, SPS Concept Development and Evaluation, The Final Proceedings of the SPS Program Review (July 1980).

42. University of California, Biology and Medicine Division - Lawrence Berkeley Laboratory, "Workshop on the Radiation Environment of the Satellite Power System," Doc. No's.: LBL-8581, UC-41, CONF-7809164; DOE Contract: W-7405-ENG-48; Editors: Walter Schimmerling and Stanley B. Curtis (September 15, 1978).

43. Harron, R. J. and R. C. Wadle, SPS Cost Estimate Draft (February 1980).

44. Hoffmayer, K. J., et al., Estimating USAF Aircraft Recoverable Spares Investment, Rand Corporation Report R-2552. PA&E (August 1980).

45. Woodcock, Gordon R., Boeing Aerospace Company, Solar Power Satellites and The Evolution of Space Technology, (No Date).

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 photvoltaic 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 (AMO) requirement set down for SPS applications. To be sure, <u>if cost is not a consideration we believe both the efficiency and weight requirements can be simultaneously met.</u>

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 efficencies 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 $\{1-(0.999)^{360}$ to $1-(0.9986)^{360} + n\ (4$ to $5)\}$, i.e., [(30 to 40) + n(4 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 $10^{16}/cm^3$ to less than $10^{14}/cm^3$. 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 $\sim$100 ns pulses are $\sim$1 J/cm^2. These pulsed lasers operate at efficiencies of $\sim$0.01-0.05 percent (optical power output divided by the electrical energy needed for its operation). Thus to produce 1 J/cm^2 of annealing energy, we need $\sim$2-10 x 10^3 J/cm^2 of electrical energy. Let us now evaluate the time necessary for a 1 cm^2 silicon solar cell to generate 2-10 x 10^3 J of electrical energy.

$$T \simeq 8.3 \times 10^4 \text{ s to } 4.2 \times 10^5 \text{ s, i.e., } T \simeq 23 \text{ h to } 116 \text{ h.}$$

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 $\sim$5 W/cm^2 are needed when scan speeds of $\sim$1 cm/s are used. These numbers translate to a needed energy of $\sim$5 J/cm^2. The cw argon ion laser efficiencies are typically in the region of 0.01 percent, and thus we need 5 x 10^4 J/cm^2 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 CO_2 lasers is attractive but here the laser energy will be absorbed by the cover glass since it is opaque at CO_2 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 CO_2 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 $= 5.67 \times 10^{-12}\ \mathrm{W/cm^2 \cdot K^4}$.

It is reasonable to assume glass to be a good blackbody radiator when heated to ∿500° C (800 K). We get

$$P_r = 2.32\ \mathrm{W/cm^2}.$$

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 $W \simeq 46\ \mathrm{J/cm^2}$. Taking into account the reflectivity, R, of glass at 10.6 μm, $W(CO_2) = W/(1-R)$, where $R \simeq 0.12$. Therefore $W(CO_2) = 52\ \mathrm{J/cm^2}$. (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 CO_2 laser efficiency of approximately 10 percent, the electrical energy input into the CO_2 laser, $E(CO_2)$, is 520 $\mathrm{J/cm^2}$. As seen from the above, we can calculate the time, T, necessary for accumulating this amount of energy as $T \simeq 6.7$ 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, CO_2 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 <u>only when</u> 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 ($\sim$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 75μ	165 g/m^2
4.	Top radiation shield glass 75μ	165 g/m^2
5.	Contact and interconnection	∿10 g/m^2
	Total mass (mimimum)	520 g/m^2

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 system[3] arrives at a specific power of ~422 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 SPS[3]. 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.[4] 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[4] 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 50μm 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 dendrictic 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 dentritic 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 necesary 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 cycling[5] 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 inteconnection 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. <u>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</u>. 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 ∿\$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 ∿\$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 $\sim\$68/m^2$. 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 CdZnS/Cu_2S 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., ≈ 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 $CuInSe_2$/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 $\geq$\$100/W (peak) to $\sim$\$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,

- <u>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</u>

photovoltaic array is at least a factor of ten higher than that necessary for efficient and economical deployment of SPS.[7]

- 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 technlogy 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.

REFERENCES

Arthur D. Little, Inc. (1980) New Process for Making Silicon Ribbon Could Lead to Mass Production of Low-Cost Solar Cells. News release, October 13, 1980.

Davies, D.E., J.P. Lorenzo, and T.G. Ryan (1980) Pulse annealing deficiencies in GaAs. Applied Physics Letters 37:612.

Goldhammer, L.J. and S.W. Gelb (1976) Synchronous orbit performance of Hughes Aircraft Company solar arrays. Pages 1379-1386, Proceedings of the 11th Intersociety Energy Conversion Engineering Conference. New York: American Institute of Chemical Engineers.

McClelland, R.W., C.O. Bozler, and J.C.C. Fan (1980) A technique for producing epitaxial films on reusable substrates. Applied Physics Letters 37:560.

Scott-Monck, J. (1980a) Letter to Simon Manson, NASA, October 13, 1980. Refers to: #3413-JSM/dd.

Scott-Monck, J. (1980b) Letter to C.K.N. Patel, Bell Laboratories, December 17, 1980. Refers to: #3413-JS/dd.

Attachment

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_2S 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 communicaton 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 ouptut 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 klyston. 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 $I_o/V_o^{3/2}$) 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 measurments 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 that 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 optial 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 orignal 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 probaby 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 techically 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.

REFERENCES

Boeing Aerospace Company (1977) Solar Power Satellite System Definition Study (Boeing). Part II, vol. 4, D180-22876, NAS-9-15196. Seattle, Wash.: Boeing Aerospace Company.

Brown, W.C. (1980a) Microwave Beamed Power Technology Improvement. JPL Contract #995104, Waltham, Mass.: Raytheon Co.

Brown, W.C. (1980b) Solar Power Satellite (SPS) Magnetron Tube Assessment Study. Contract NAS 8-33157. Waltham, Mass: Raytheon Co.

Green, M.C., H.B. Skinner, and R.A. Tuck (1980) Osmium-tungsten alloys and their relevance to improved M-type cathodes. Presented at Tri-Service Cathode Workshop, February 1980. To be published in Applications of Surface Science.

LaRue, A.D. (1980) High efficiency klystron for the SPS application. In Workshop on Microwave Power Transmission and Reception, (4) Power Amplifiers. Houston, Tx.: Johnson Space Center.

Lindsey, W.C. (1978) A Solar Power Transmission System Incorporating Automatic Beam Forming, Steering, and Phase Control. LinCom TR-7806-0977. Pasadena, Ca.: LinCom.

Nalos, E.J. (1980) Role of power amplifiers in reference systems. In Workshop on Microwave Power Transmission and Reception, (4) Power Amplifiers. Houston, Tx.: Johnson Space Center.

National Aeronautics and Space Adminstration (1980) Workshop on Microwave Power Transmission System for the Solar Power Satellite: Review Panel Final Report. Houston, Tx.: Johnson Space Center.

Palluel, P. and A.M. Shroff (1980) Experimental study of impregnated-cathode behavior, emission, and life. Journal of Applied Physics 51(2):2894-2902.

APPENDIX G

WORKING PAPER:

ASSESSMENT OF THE CURRENT STATUS OF THE DOSIMETRY OF IONIZING RADIATION IN THE SPS ENVIRONMENT

Harold H. Rossi

Radiological Research Laboratory, Department of Radiology
Columbia University College of Physicians & Surgeons

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 index[2] 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/cm^2) 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 $\sim$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 isotopic 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/cm^2 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.

REFERENCES

Schimmerling, W. and S. B. Curtis, eds. (1979) Workshop on the Radiation Environment of the Satellite Power System (SPS). Lawrence Berkeley Laboratory, September 15, 1978, Berkeley, Calif. Sponsored by the U.S. Department of Energy. CONF-7809164. Springfield, Va.: National Technical Information Service.

Seltzer, S.M. (1979) Electron, electron-bremsstrahlung and proton depth dose data for space-shielding applications. IEEE Transactions on Nuclear Science NS-26(6):4896-4904.

Stassinopoulos, E.G. (1979) A preliminary study of the charged particle radiation for the Satellite Power System. Pages 184-215, Workshop on the Radiation Environment of the Satellite Power System (SPS), edited by W. Schimmerling and S. B. Curtis. CONF-7809164 (U.S. DOE). Springfield, Va.: National Technical Information Service.

U.S. Department of Energy (1980a) Ionizing Radiation Risks to Satellite Power Systems (SPS) Workers in Space. DOE/ER-0094. Prepared by the Lawrence Berkeley Laboratory under contract no. W-7405-ENG-48. Springfield, Va.: National Technical Information Service.

U.S. Department of Energy (1980b) Program Assessment Report: Statement of Findings. DOE/ER-0085. Springfield, Va.: National Technical Information Service.

APPENDIX H

WORKSHOP ON MECHANISMS UNDERLYING EFFECTS OF LONG-TERM, LOW-LEVEL, 2450 MHz RADIATION ON PEOPLE*

July 15-17, 1980

WORKSHOP SUMMARY

Prepared by:

Christopher H. Dodge
Science Policy Research Division
Congressional Research Service

*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.

Participants

Richard B. Setlow, Chairman, Brookhaven National Laboratory
Richard Albanese, M.D., Air Force School of Aerospace Medicine
André J. Berteaud, Centre National de la Recherche Scientifique
Carl F. Blackman, Environmental Protection Agency
Daniel F. Cahill, ex officio, Environmental Protection Agency
Stephen F. Cleary, Medical College of Virginia, Virginia Commonwealth University
Carl H. Durney, University of Utah
James W. Frazer, University of Texas Health Science Center
Allan H. Frey, Randomline, Inc.
Karl H. Illinger, Tufts University
Donald McRee, National Institute of Environmental and Health Sciences
Rochelle Medici, Fairview State Hospital
Herbert Pollack, M.D., Washington, D.C.
Herman P. Schwan, University of Pennsylvania
Ralph J. Smialowicz, Environmental Protection Agency
Maria A.Stuchly, Radiation Protection Bureau, Canada
John Thomas, Naval Medical Research Institute

Staff: Adele King Malone
Connie Reges
Environmental Studies Board

Rapporteur

Christopher Dodge, Congressional Research Service

Guest Speakers

Daniel F. Cahill, Environmental Protection Agency
C. William Hamilton, Battelle Memorial Institute
Douglas S. Lilly, National Aeronautics and Space Administration
George A. Sacher, University of Chicago
Charles Susskind, University of California, Berkeley, (unable to attend; submitted paper)
Nicholas H. Steneck, University of Michigan

Observers

Martin M. Abromavage, Argonne National Laboratory
Ernie N. Albert, School of Medicine, George Washington University
Leonard David, PRC/Energy Analysis Company
Fred Koomanoff, Department of Energy
Richard L. Olson, Boeing Aerospace Company
Elizabeth Peterson, Department of Energy
Anthony Valentino, Argonne National Laboratory

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 10^6 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/m^2 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/m^2. Thus far, no significant effects on behavior, development, or navigation have been detected. Future work will entail chronic expsoure of whole hives of bees to low-level 2450 MHz fields.

2. Studies of the effects of acute exposure to $\sim 200\ W/m^2$ 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/m^2 fields have been detected. Acute exposure designed to establish lethality thresholds and involving exposure of birds to strongly thermal fields

of 1300-1600 W/m^2 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/m^2 anticipated to occur at the center of an SPS rectenna during operation. Some birds exposed chronically to 250 W/m^2 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/m^2 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/m^2 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/m^2) 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/m^2. 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/m^2; 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/m^2 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/m^2 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 1-10 W/m^2) is the enhancement of calcium ion efflux from brain tissue exposed <u>in-vitro</u> and <u>in-vivo</u>. 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 (0-100 Hz) but is predicted to be infrequent in time and space and to be at average power levels < 0.01 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, Czechosloviakia, 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 may 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 way 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 whch 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 <u>in-vitro</u> 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/m^2. 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/m^2 (10 mW/cm^2) 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/m^2 (10 $\mu W/cm^2$). For the general public in the Soviet Union, the standard is even lower (0.05 W/m^2). 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/m^2 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/m^2 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 ≤ 1 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 ≤ 1.0 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.

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 radiocommunications 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).

[a]Secondary 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.
[b]Industrial, Scientific and Medical (ISM) Applcations--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/m^2) 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/m^2) in any 4 kHz band for angles of arrival δ (in degrees) between 5 and 25 degrees above the horizontal plane;
   - -- 137 dB(W/m^2) 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.

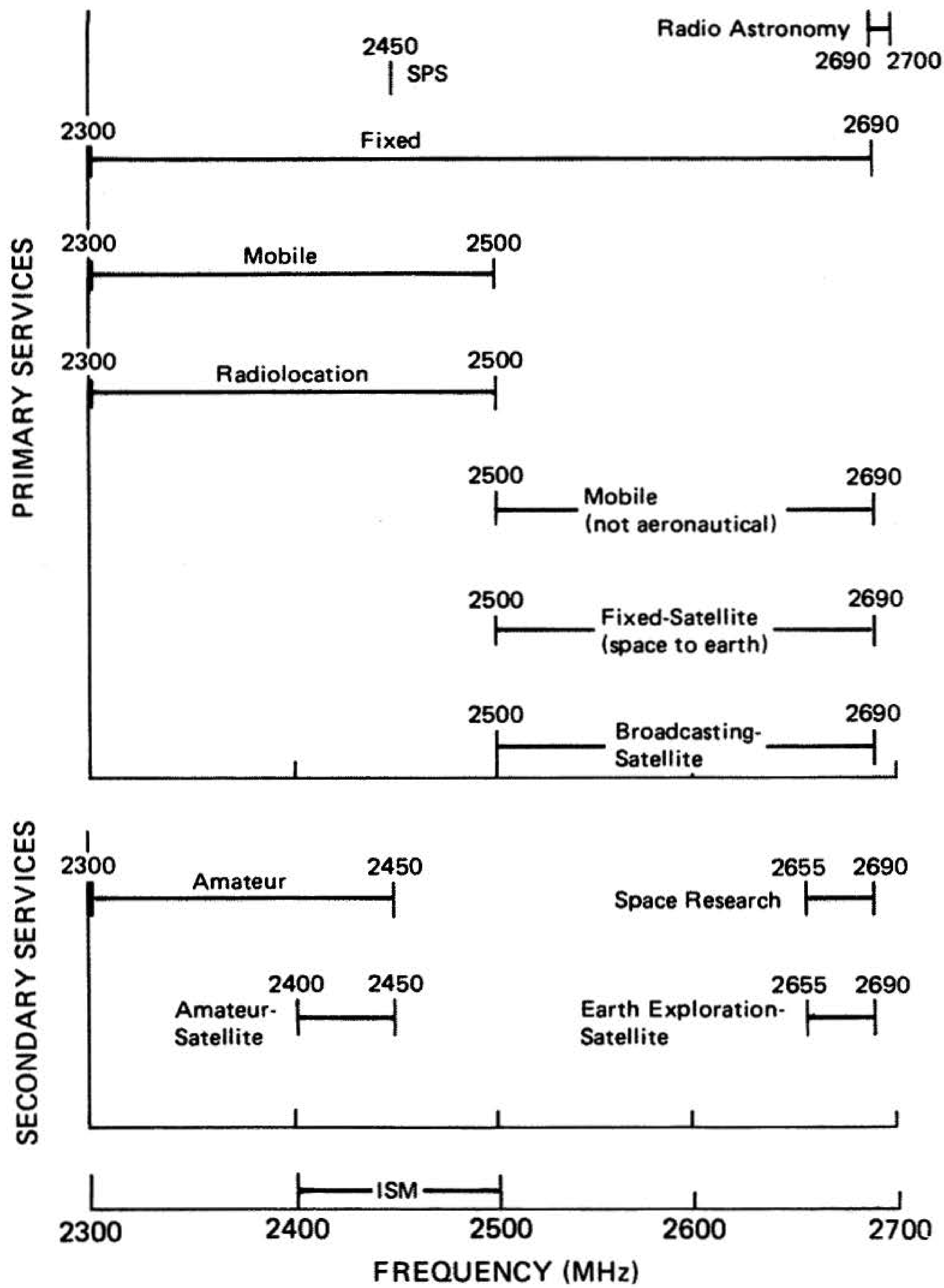


FIGURE I.1. The reference SPS transmitting frequency and nearby International Telecommunication Union radio services pertaining to Region 2 (Western Hemisphere). (See Tables I.1 and I.2 for definitions of the various services.)

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	$\pm$ 0.5 degrees	$\pm$ 0.5 degrees
Space Stations Other Than Broadcasting-Satellite or Experimental	$\pm$ 0.1 degrees	$\pm$ 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 geosychronous 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.

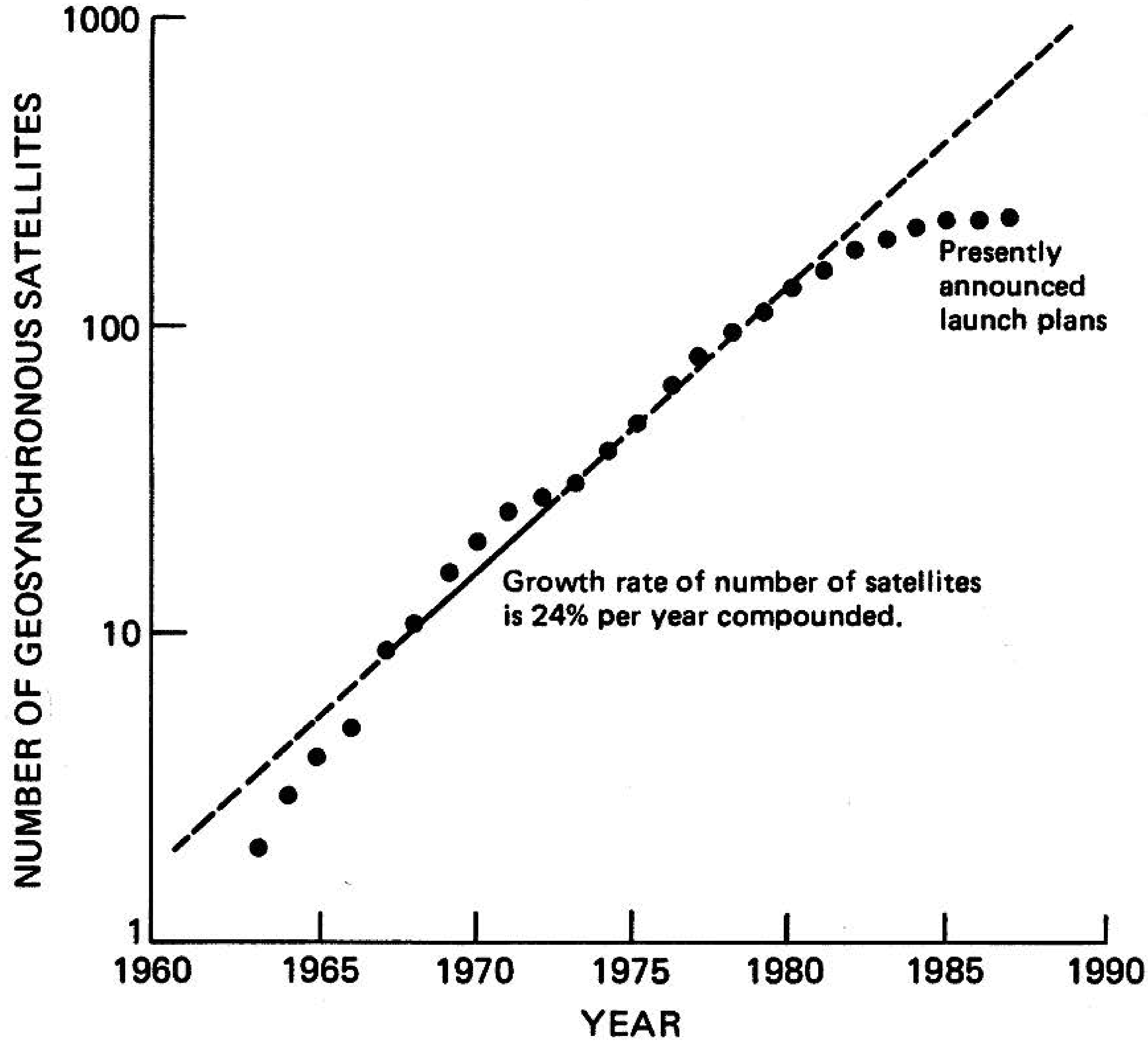
Nevertheless, there can be no doubt that use of GEO will continue to grow, though probably at a doubling rate slower than in the past. Much of this growth is expected to take place in positions co-longitudinal with developed nations such as the United States. Consequently, the future portends an ever 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

[a]Key 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 I.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 ±0.1° in the year 2000. The remaining 60 satellites, with the possible exception of broadcasting-satellites, should be capable of maintaining position within ±0.5° 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 Adminstration, 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.

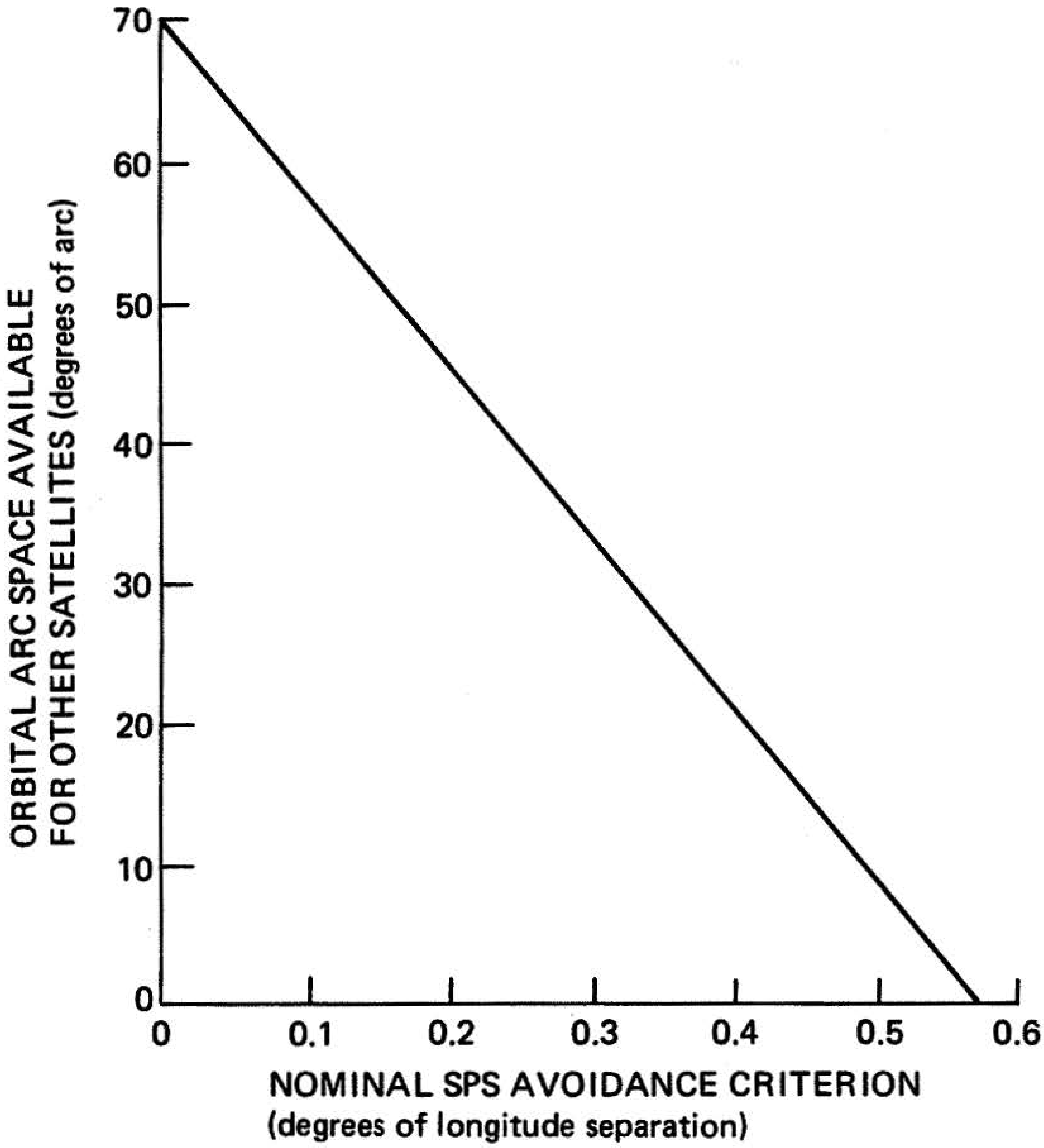


FIGURE I.3. Orbital arc space available between 65° and 135° West longitude for other satellites assuming a 60-satellite SPS.

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 ±0.11° in longitude about a stationary satellite position. With such a large structure in orbit, some guard space around this ±0.11° 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 ±0.15° 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 ±0.15° 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 ±0.15° 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 $r > r_o$ applies only for distances from the SPS antenna array which are within the far field, with $r_o = 2D^2/\lambda$, 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 $\phi \simeq 57.3\ r/d$ or $\phi \simeq 1.36 \times 10^{-6}\ r$ 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

$$-(40\ \mathrm{dB(W/m^2)} + 20\ \log_{10}\phi) \pm 20\ \mathrm{dB}$$

with $g_t = -10$ dB(i) ± 20 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 dB(W/m^2) $\pm$ 20 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 dB(W/m^2) $\pm$ 20 dB. At ϕ = 2°, the power density level is 6 dB less or -46 dB(W/m^2) $\pm$ 20 dB. At ϕ = 10°, the power density level reduces only to -60 dB(W/m^2) $\pm$ 20 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 $$E[\mathrm{dB(V/m)}] = 26 + P\ [\mathrm{dB(W/m^2)}]$$

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 1×10^{-3} 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: $-(70 + 20 \log_{10} \phi \pm 20)$ 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 dB(W/m^2) 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 1×10^{-3} m^2, the SPS harmonic level at the output of the interfered-with satellite antenna would be postulated to be: $-(100 + 20 \log_{10}\phi) \pm 20$ 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 altitdues of 700 km would result in 2450 MHz power density exposures of about +3 dB(W/m^2) (about 30 V/m) for about 1 second duration and -37 dB(W/m^2) (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 compatability protection zone around a single SPS satellite is significant, and may be of the order $\pm 0.5°$ 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 compabitility 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.

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.

REFERENCES

International Telecommunication Union (1968) Radio Regulations (as amended). Geneva: General Secretariat of the International Telecommunication Union.

Morgan, W.L. (1980) Geosynchronous Satellite Log for 1980. COMSAT Technical Review 10 (1).

Thompson, A. R. (1981) Effects of a satellite power system on ground-based radio and radar astronomy. Radio Science 16(1):35-46.

U.S. Department of Energy (1979) Satellite Power System Concept Development and Evaluation Program Reference System Report. DOE/ER-0023. Springfield, Va.: National Technical Information Service.

U.S. Department of Energy (in press) Environmental Assessment for the Satellite Power System Concept Development and Evaluation Program--Electromagnetic Systems Compatibility. DOE/NASA Report, in press.