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Preliminary Environmental Assessment for the Satellite Power System (SPS) Revision 1

Volume 1 - Executive Summary

January 1980

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U.S. Department of Energy
Office of Energy Research
Satellite Power System Project Office

DOE/NASA
SATELLITE POWER SYSTEM
Concept Development
and
Evaluation Program

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FOREWORD

The U.S. Department of Energy (DOE) is considering several options for generating electrical power to meet future energy needs. The satellite power system (SPS), one of these options, would collect solar energy through a system of satellites in space. A reference system has been described by NASA that would convert the solar energy to microwave energy and transmit the microwave energy from directive antennas to large receiving/rectifying antennas (rectennas) located on the earth. The microwave energy would be converted into conventional electricity at the rectennas. The potential environmental impacts associated with constructing and operating the satellite power system are being assessed as a part of the Department of Energy's SPS Concept Development and Evaluation Program.

This report summarizes the Preliminary Environmental Assessment for the Satellite Power System. Revision I. Vol. 2: Detailed Assessment. The revision refines and extends a 1978 assessment* and provides a basis for a 1980 revision that will guide and support DOE recommendations regarding future SPS development. This summary is Volume 1 of the revision.

This document has been prepared for the public, as part of the "participatory technology process" that guides the SPS Concept Development and Evaluation Program. The process allows members of appropriate scientific and engineering disciplines, as well as the general public, to contribute to the planning, analysis, and decisions involving the satellite power system.

While containing a minimum of technical detail, this summary uses technological terms and somewhat unfamiliar definitions and dimensions on occasion. Many of these terms are defined in the following glossary. Readers who desire to study the potential environmental impacts of the satellite power system in some detail are encouraged to read Volume 2 of this report and the references contained therein. A list of useful reports and ordering information appears at the end of this volume.

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*Preliminary Environmental Assessment for the Satellite Power System, Dept. of Energy Reports DOE/ER-0021/1 and DOE/ER-0021/2 (October 1978).

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GLOSSARY

Aerodynamics - the dynamics of gases, especially of atmospheric interactions with moving objects.

Ambient - the natural condition of an environmental factor; for example, an "ambient" outdoor temperature of 75°F.

Antenna Side Lobe - refers to radiated power that can be measured in some direction other than the desired direction of transmission, such as behind a radar antenna.

Continuous-wave radiation - single-frequency, uniform-amplitude electromagnetic radiation.

COTV - cargo orbit transfer vehicle, used to take cargo between LEO and GEO.

Decibel - a unit used to measure noise levels. A 3-decibel increase in noise denotes a doubling of sound intensity.

Dosimeter - a device that measures and indicates the amount of radiation absorbed.

Ecosystem - a community of living organisms and its physical environment.

Electromagnetic energy - a form of energy, both man-made and natural, with electrical and magnetic properties. Electromagnetic energy includes ionizing radiation, x-rays, ultraviolet and visible light, microwaves, radio waves, heat, and electricity.

Electron - a subatomic particle with a negative electrical charge.

Frequency - as used to describe electromagnetic energy, the frequency of an oscillating wave is the number of cycles that occur in one second, measured in hertz. One hertz equals one cycle per second.

GEO - geosynchronous earth orbit: the orbit at which a satellite is stationary relative to some point on earth; altitude approximately 36,000 km.

Gigahertz - or 1,000,000,000 hertz, a measure of radio wave frequency. Conventional electricity in the home has a frequency of 60 hertz. The proposed SPS operating frequency is 2.45 gigahertz, or 2,450,000,000 hertz. Microwave ovens also operate at gigahertz frequencies. Also see "frequency."

Gigawatt - or 1,000,000,000 watts, a measure of electric power.

Harmonic Frequency - a frequency that is 2, 3, 4, etc., times higher than the specified operating frequency of an electromagnetic system. The second harmonic of 2.45 gigahertz would be 2 x 2.45 or 4.90 gigahertz. Undesired emissions occur at harmonic frequencies.

Hematology - the science or study of blood.

HLLV - heavy-lift launch vehicle, used to lift SPS materials into space.

Immunology - the science or study of immunity, or resistance to disease.

Integrative Processes - biological processes resulting from and depending on the integrated sum of a number of biological functions.

Ion - an atom, group of atoms, or molecule that has a net positive or negative electrical charge.

Ionizing radiation - radiation capable of producing ions by adding electrons to, or removing electrons from, an electrically-neutral atom, group of atoms, or molecule.

Ionosphere - a layer of the earth's atmosphere which is important to radio communications. See illustration on page 26.

Kilogram - a metric measure of mass. One kilogram is approximately 2.2 pounds.

Kilometer - a metric measure of distance. One kilometer is approximately 0.6 miles.

LEO - low earth orbit; altitude approximately 500 km.

Magnetosphere - a region of the earth's outer atmosphere in which electrically-charged particles are trapped and their behavior dominated by the earth's magnetic field. See illustration on page 26.

Microwave - denotes the range of frequencies (0.3 to 30 gigahertz) used for radar and space communications.

Milliwatts per square centimeter - a commonly used measure of electromagnetic energy flow, called power density. It is most often used to measure energy transmitted by microwave systems and to identify microwave exposure levels for biological effects experiments.

Neutral particles - electrically-neutral subatomic particles, atoms, or molecules.

PLV - personnel launch vehicle, used to lift SPS workers into space.

POTV - personnel orbit transfer vehicle, used to take SPS workers between LEO and GEO.

Power Density - a measure of electromagnetic energy flow. See "milliwatts per square centimeter."

Propagation - the transmission of electromagnetic waves from one point to another.

Qualitative - pertaining to description of the qualities of a process or entity without the use of numerical measurement.

Quantitative - pertaining to number, quantity, measurement.

Scattered power - power which is reflected or dispersed as the result of an obstruction in the path of the primary power flow.

Spurious Power or Frequency - electromagnetic energy produced at frequencies that are not easily related to a specified operating frequency.

Stratosphere - a region of the earth's atmosphere where the temperature remains relatively constant. See illustration on page 26.

Susceptibility - the sensitivity of an electromagnetic receiver to undesired electromagnetic waves which may result in interference.

Van Allen Belt - a belt of intense ionizing radiation that surrounds the earth in the outer atmosphere.

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ABSTRACT

A preliminary assessment of the environmental impacts of the proposed satellite power system (SPS) is summarized here. In this system, satellites would collect solar energy in space, convert it to microwaves, and transmit the microwaves to receiving antennas (rectennas) on earth. At the rectennas, the microwaves would be converted to electricity. The assessment considers microwave and nonmicrowave effects on the terrestrial environment and human health, atmospheric effects, and disruption of communications and other electromagnetic systems.

Microwave Effects

The question of whether or not microwave energy produced in space and transmitted to earth might affect SPS workers in space or on earth, the general public, or plants and animals is being investigated. Public health effects appear unlikely; however, there is some small risk concerning human reproductive processes and an uncertainty about behavioral effects. Risks for persons in poor health, receiving medications, or under stress may be somewhat higher than for other members of the public, but this likelihood cannot be assessed with confidence at this time.

Workers at SPS rectenna sites would be exposed to higher levels of microwave energy than the public, with a proportionately higher risk of health effects. If health effects were to occur, they probably would affect the body's immune and blood systems, reproduction, general physiology, or behavior. The effects of relatively strong microwave energy on humans working in space (to construct and maintain the power satellites) are practically unknown as there is almost no experience to which the SPS situation can be related. Undesirable effects might be possible.

Microwave energy beams in the lower atmosphere and at rectenna sites have the potential to affect airborne and terrestrial animals that reside at or pass through rectenna sites. The greatest potential effects would be expected on immune or blood systems, reproduction processes, physiology, and behavior.

The current assessment of SPS microwave exposure effects is based principally upon what is known about biological effects that have been accompanied by heating produced by microwave energy. It is conceivable that levels of microwave energy too low to measurably increase body temperatures may nevertheless cause subtle, possibly important, changes in biological processes. The open question of non-heating effects thus increases the uncertainties in this assessment.

Nonmicrowave Effects

Conventional industrial activities common to the development of new electrical energy sources would be needed to develop the SPS. These activities produce air and water pollutants and waste products and deplete natural resources. These SPS-related effects would be measurable on a national

scale and might be significant at the local level. None are unique to the SPS, with the exception of noise at launch sites, and all could be controlled to at least some degree. Nonconventional environmental effects would stem from the light reflected from power satellites and the depletion of ozone in the atmosphere and the resulting increase in ultraviolet light reaching earth. These impacts require further study.

Workers in industries supporting the SPS would risk conventional occupational illnesses and injuries. Their exposure to environmental pollution would be greater than the public's. Available industrial worker protection devices and methods appear adequate to maintain risks at generally-accepted levels.

The principal risks to SPS space workers have been identified on the basis of what is known about the space environment, and needs to ensure that risks can be minimized have been defined. Many risks remain unpredictable at this time, however. Space workers could be injured or killed during space transportation accidents, by failure of life-support systems, and in other accidents in space. Weightlessness has adverse effects, as may the psychological stresses produced by unusual working and living conditions. Some workers would peform duties that are inherently hazardous and would be exposed to risks from ionizing radiation in space. Individuals could receive dose levels that are currently regarded as excessive. Much work remains in order to reduce uncertainties in the current assessment and to design adequate protection and monitoring systems and work procedures to minimize risks.

Atmospheric Effects

Limited present knowledge concerning atmospheric phenomena introduces significant uncertainties into the current assessment of SPS atmospheric effects. There is confidence, however, that the types of impacts which would be most significant to the earth's population and to space workers have been identified.

Few significant effects would be expected in the near-earth atmosphere from SPS space activities. Weather modification, temporary air pollution, and potential acid rains would be the possible impacts near launch sites. No significant atmospheric effects would be expected near rectenna sites. Rocket exhaust effluents could affect the stratosphere and mesosphere. Slight decreases might occur in ozone concentrations; at present these decreases seem insignificant.

Space vehicle exhaust effluents in the ionosphere might produce visible air glow and other interactions might produce satellite drag. The safety of space workers and travelers could be affected through changes in the radiation characteristics of the earth's Van Allen Belts.

Possible SPS impacts on the outer atmosphere are difficult to predict. It is currently expected that the principal impacts would be changes in the radiation characteristics of Van Allen Belts, interference to space-based communications and navigation, and the production of magnetospheric storms (which could affect terrestrial electric utilities).

Ionospheric Effects on Communications

The effects of heating the ionosphere with high-power, high-frequency radio waves have been demonstrated experimentally; however, results of these studies are not directly applicable to the type of heating that would be caused by the passage of the SPS microwave power transmission beam. Little is now known with certainty about the irregularities that would result from SPS-induced heating; however, any type of ionospheric heating is likely to have some impact on communications systems. Theoretical and experimental studies are underway to assess the SPS heating impact on the ionosphere and determine resulting telecommunication effects.

Space vehicle exhaust effluents in the ionosphere have been responsible for radio wave interference which has affected many types of telecommunications. SPS exhaust effluents would be likely to disrupt telecommunications for periods ranging from several minutes to several hours over large geographic areas.

Electromagnetic Compatiblity

The microwave transmissions of the satellite power system would be a source of potential electromagnetic interference with electronic and electrical equipment. The uniqueness of the SPS interference potential relates more to the scope of the potential problem (the number of systems that might be affected) rather than to the types of effects it would have on equipment users.

The principal strategy for preventing SPS interference would be careful engineering design of the power satellite and rectenna. Interference could be minimized by designing the SPS microwave system to stringent specifications. Judicious rectenna siting also is an important mitigation strategy. Conventional solutions, such as shielding and filtering, could be applied successfully to many problems that might be encountered. However, some innovative solutions might be necessary to eliminate problems such as interference involving electronic systems in aircraft and satellites.

Equipment used at national defense installations for combat training and equipment tests usually is especially sensitive to extraneous electromagnetic fields. Mitigation strategies are severely limited by the need to simulate combat-like environments at the installations, including electromagnetic emissions from foreign equipment. The only acceptable approach to preventing SPS interference would likely be rectenna siting. The strategy should not be difficult to apply, since most large military installations are remotely located in the southwestern United States, where alternative rectenna sites should be available.

While power satellites might interfere with the electronic systems of other satellites, there is substantial confidence that interference could be reduced or avoided through conventional engineering methods. Radio and optical astronomy could be significantly inhibited by microwave emissions from the SPS and by light reflected from satellite surfaces. The likelihood of this problem appears substantial; solutions may be especially difficult to develop.

INTRODUCTION

The possibility of collecting solar energy in space, converting it to microwave energy, transmitting a microwave beam to earth, and then converting the microwave power to electricity is being studied by the National Aeronautics and Space Administration (NASA) and the U.S. Department of Energy (DOE). This joint program will generate the information needed to make a rational decision regarding development of the satellite power system (SPS) program after 1980.* NASA is defining the engineering and operating characteristics of the SPS. DOE is evaluating the system's health, safety, and ecological impacts; examining economic, international, and institutional issues; and developing comparative assessments of the SPS and alternative future power sources.

An SPS "reference system" developed by NASA provides the technical and operational information DOE needs to conduct its environmental and socioeconomic studies and comparative assessments.** The present reference system is an interim working concept; NASA's current work is providing a more complete understanding of the satellite power system. Results of ongoing environmental studies will influence any future system designs.

An SPS satellite, as specified in the reference system, would be a flat solar-cell array of about 50 square kilometers built on a graphite-fiber-reinforced structure, as illustrated in Figure 1. A microwave transmitting antenna one kilometer in diameter would be mounted on one end of the satellite. Each satellite would be constructed in geosynchronous earth orbit, as shown in Figure 2; a ground receiving station (rectenna) for each satellite would be built at the same time (see Figure 1). The reference system presumes 60 satellites would be constructed over a 30-year period.

Construction bases in space, launch and mission control bases on earth, and fleets of space vehicles would be needed to build and maintain the satellites. The transportation vehicles would include heavy-lift launch

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*This program is described in the Satellite Power System Concept Development and Evaluation Program Plan (July 1977 - August 1980), Department of Energy Report DOE/ET-0034, February 1978.

**The reference system is described in SPS Concept Development and Evaluation Program Reference System Report, Department of Energy Report DOE/ER-0023, October 1978.

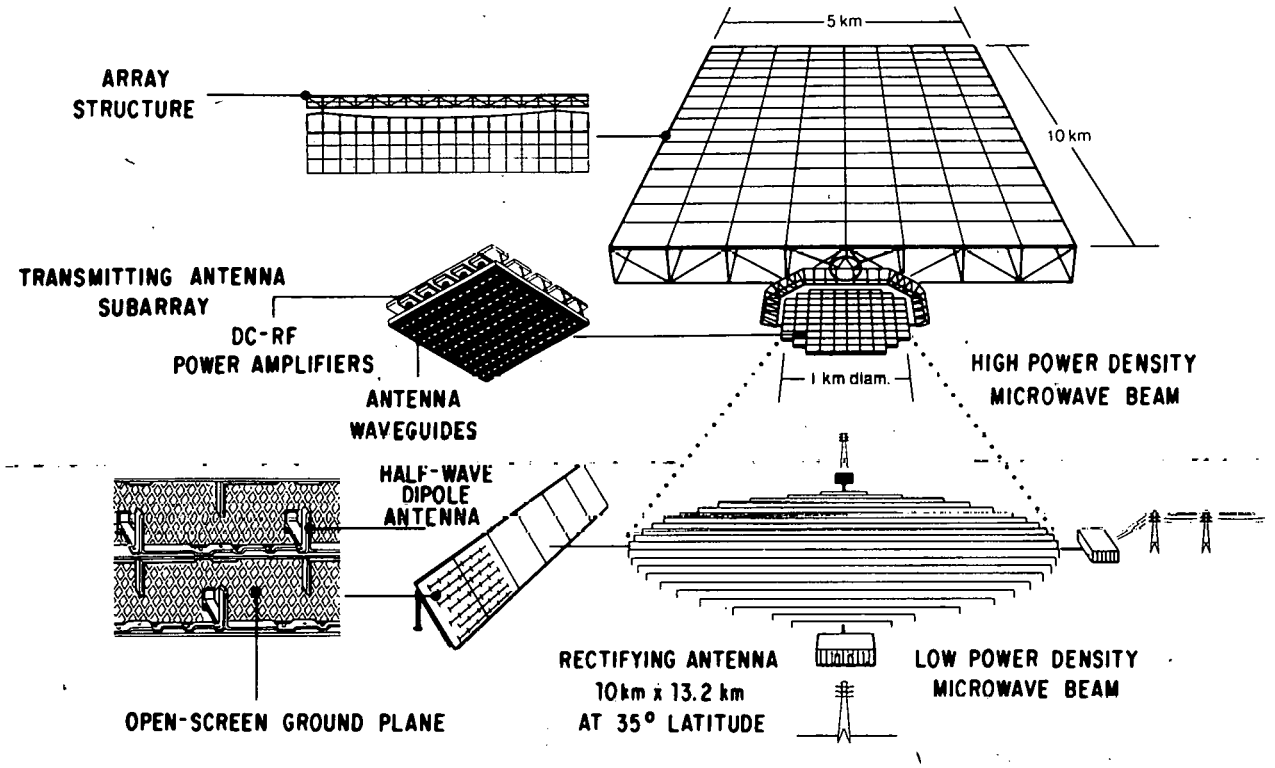

Fig. 1. Basic Satellite Power System Characteristics

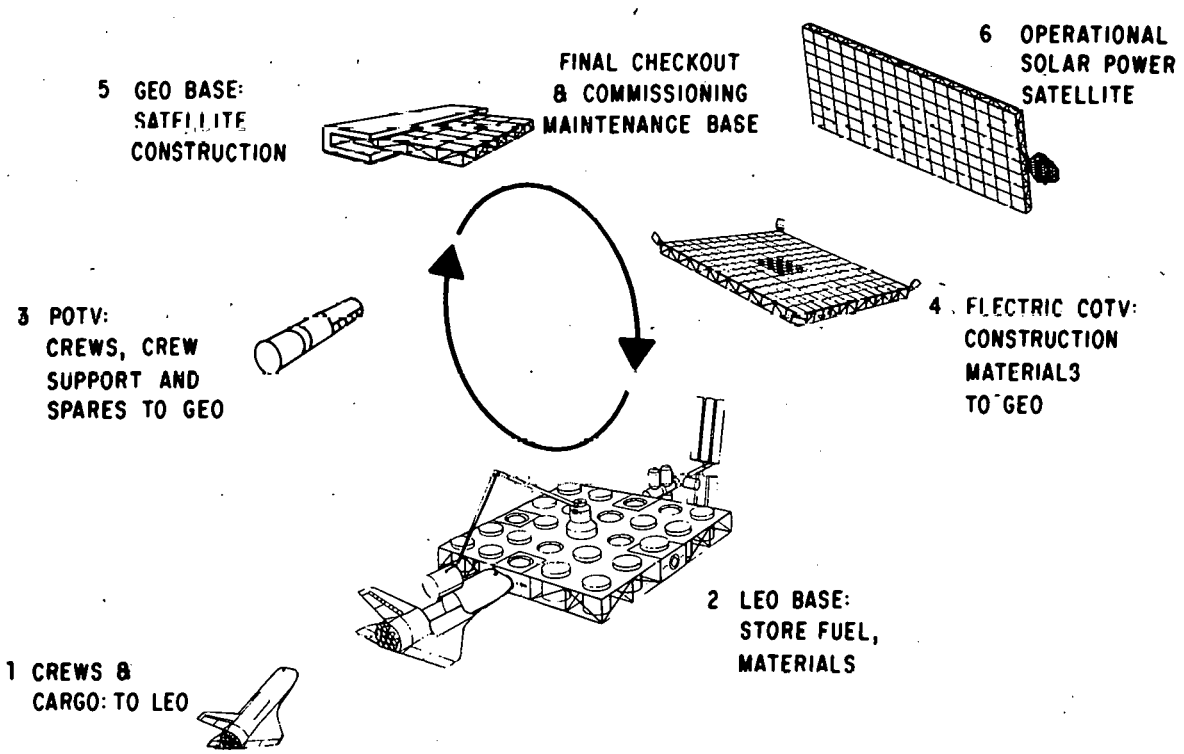

Fig. 2. Conceptual SPS Earth-to-Space Transportation Plan

vehicles, personnel launch vehicles, cargo orbit-transfer vehicles, and personnel orbit-transfer vehicles.

The key environmental issues associated with the satellite power system concern human health and safety, ecosystems, climate, and interaction of electromagnetic systems. Five tasks have been established to address these issues:

Task I	Microwave Health and Ecological Effects
Task II	Nonmicrowave Health and Ecological Effects
Task III	Atmospheric Effects
Task IV	Effects on Communication Systems due to Ionospheric Disturbance
Task V	Electromagnetic Compatibility

The current assessments for these tasks are summarized in this report.

Task I evaluates the potential effects of microwave energy on SPS workers, the general public, and ecosystems. Other possible health and ecological impacts of the satellite power system are examined in Task II, including the effects of the space transportation system, ionizing radiation in space, occupational risks due to manufacturing, and air and water pollution. Task III characterizes potential atmospheric disturbances due to the SPS and assesses climatic impacts, including the effects of rocket effluents on the atmosphere. The impacts of ionospheric disturbances (caused by microwave heating and space-vehicle effluents) on communication systems which use the ionosphere for radio wave propagation are evaluated in Task IV and in part in Task III. Task V addresses the direct eifects of the microwave power transmission system on communication and other electromagnetic systems. These include direct and scattered power effects, power at harmonic frequencies, and spurious power sources.

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1 MICROWAVE HEALTH AND ECOLOGICAL EFFECTS

The SPS microwave power transmission system would generally expose people and the natural environment to low levels of microwave radiation. In addition, higher exposure levels might be expected for SPS terrestrial and space workers as well as for vegetation, animals, and members of the general public near rectenna sites (the SPS microwave power density profile is illustrated in Figure 3). In light of these facts, the health and ecological effects of exposure to SPS microwave power must be analyzed.

Microwave energy would be transmitted to the rectenna as continuous waves with a frequency of 2.45 gigahertz. A limited data base on health and ecological effects exists for this type of electromagnetic radiation, but it is incomplete, often contradictory, and not entirely pertinent to the environmental conditions associated with the satellite power system. The present information consists mainly of limited observations of the effects on animal health of short-term exposures to high-level microwaves. These data are useful, but the essential need is for data on the effects on human health of continuous or chronic exposure to low-level microwaves.

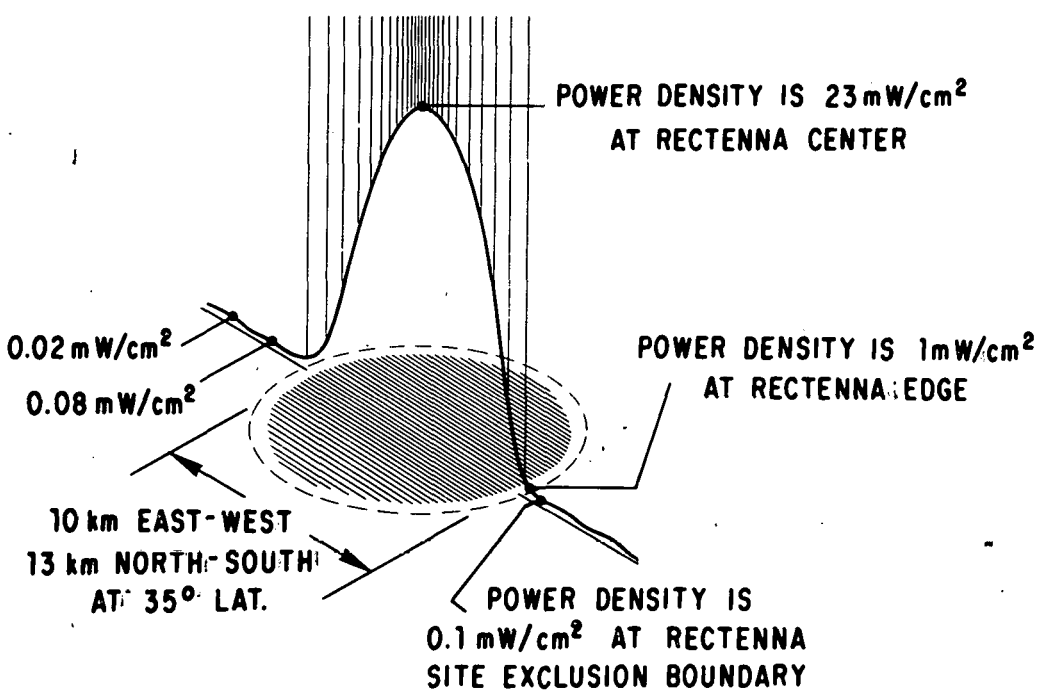

Fig. 3. SPS Microwave Power Density Characteristics at Rectenna Sites

Figure 4 lists the kinds of effects possible from exposure to microwave power of the type associated with the satellite power system. The probability of any particular effect occurring is rated in the figure, as is the severity of that effect. Neither the probability nor the severity rating has any quantitative basis at this time, because of the limited information available on microwave effects pertinent to the SPS. The notations do, however, represent the current scientific judgment regarding possible SPS impacts.

1.1 IMMUNOLOGY AND HEMATOLOGY

There is ample evidence that microwave radiation can affect the immune and blood systems of animals if the rate of heat absorbed by their bodies from the microwaves exceeds their basal metabolic rate. Even if the basal metabolic rate is not exceeded during exposure to microwaves with low power densities, responses similar to those elicited at high microwave power densities have been observed. These responses are somewhat similar to those exhibited by animals following stressful encounters. Microwave effects are most likely attributable to the heating properties of electromagnetic energy. There is no convincing evidence at this time that microwave energy interacts directly with blood cells.

The effects on the general population of exposure to the low microwave power densities that would exist outside SPS rectenna sites are not known. Microwave power densities might be sufficiently high within the rectenna sites to temporarily alter immune and blood systems with brief exposures. The implications for unprotected rectenna workers of long-term occupational exposure are not known.

Terrestrial and airborne animal species that normally inhabit areas near SPS rectenna sites would not be expected to be affected by the low microwave power levels which would be produced outside the site. Rectenna sites would be relatively large, however, and some native species probably would continue to populate each site. Others might occasionally traverse rectenna sites or periodically migrate through the areas. Animals passing through rectenna sites might therefore be briefly exposed to microwave power densities between 0.1 and 23 milliwatts per square centimeter, while species inhabiting the site would be exposed for longer periods. Microwave effects would be possible for these species. Any effects on nonresident animals might be temporary and reversible; effects on resident species might be permanent.

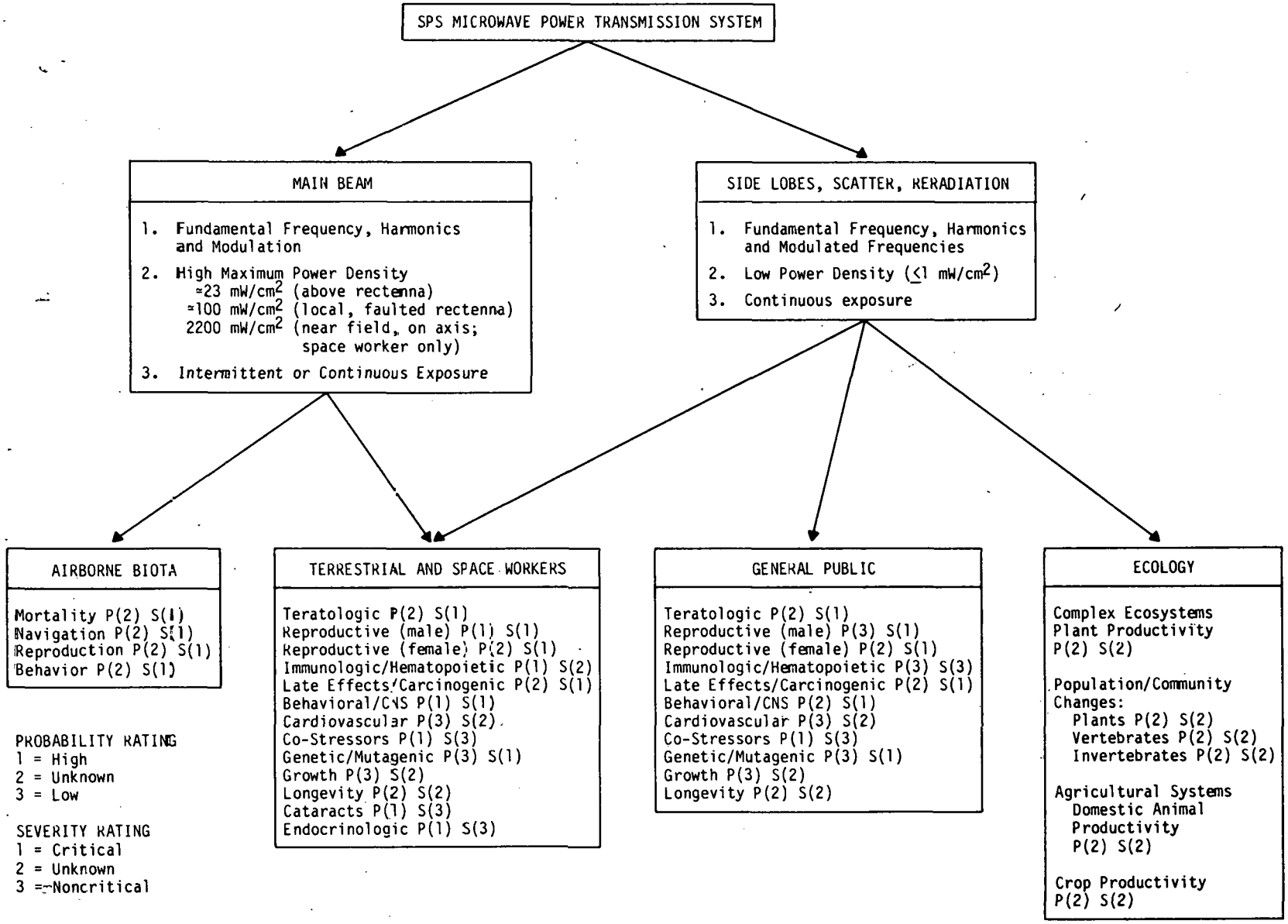

Fig. 4. Microwave Effects on Health and Ecosystems

1.2 MUTATION

Mutations may occur in any plant or animal species from a variety of causes. Microwave radiation can produce structural changes in genes if the intensity is so high that cells are substantially heated. This has been demonstrated with bacteria in tests employing intensities 100 times higher than those proposed for the SPS microwave transmission system. Microwaves of lower intensities have been shown to possess no mutagenic potential. Moreover, mutations have not been produced in more complex biological systems (whole-body animal tests) exposed to the proposed SPS microwave intensity and frequency.

The SPS microwave transmission system would not be expected to produce mutations in humans or other complex life forms. This expectation applies equally to terrestrial SPS workers, the general public, and ecosystems. Space workers conceivably could be exposed to relatively intense microwave energy for brief periods, but substantial body heating (a prerequisite for mutation) would be unlikely. Basic life forms, such as bacteria, probably would not be affected even if they were to exist in the immediate vicinity of an SPS microwave beam.

1.3 CANCER

Experimental data regarding the cancer-producing potential of microwaves are both meager and inconclusive. There are no experimental data or theories which suggest that microwave power with the characteristics proposed for the SPS is carcinogenic. Therefore, the SPS microwave transmission system is presently regarded as an unlikely source of cancer.

1.4 REPRODUCTION

Damage to the male reproductive system due to intense microwave radiation has been established experimentally in several species. The effects appear to be directly related to an internal heat rise generated by the microwave energy. The effects of intense microwave radiation on the female reproductive system are not known.

It cannot be stated with reasonable certainty at this time that SPS space workers -- and, to a lesser extent, SPS terrestrial workers -- would not risk reproductive damage because of occupational exposure to microwave energy.

The same uncertainty applies to animals and plants inhabiting SPS rectenna sites. Because the electromagnetic intensities beyond the rectenna site boundaries would be low, risks of reproductive system damage in males and females (in humans and other species) would be expected to be small.

1.5 DEVELOPMENT

Development has been used rather extensively as a biological indicator of microwave effects. Delayed growth in the fetuses of small laboratory rodents has been observed after exposure to SPS-level microwave intensities. Increased teratologic effects (abnormalities) may also be possible. Experiments with birds have not produced the types of effects observed in small rodents, and there are no pertinent data relating developmental effects in larger animals to microwave exposure.

Existing information is not sufficient to entirely dismiss the possibility that the microwave radiation at or near rectenna sites might affect normal development. In fact, there is evidence to indicate that the maximum power density at rectenna sites (23 milliwatts per square centimeter) might affect the development of small rodents.

1.6 GROWTH

Any undesirable effect of SPS microwave exposure on early development (if it were to occur) apparently would not be a lasting one. Microwave exposure effects observed at prenatal stages have not been evident after birth. Based on current knowledge, long-term growth effects would not be expected from the satellite power system for children of SPS workers or offspring of animals inhabiting rectenna sites, assuming that early developmental effects are not serious. The likelihood of growth effects on populations-at-large appears to be very small.

1.7 BEHAVIOR

Increased motor activity, changes in response to pain and other stimuli, and decreased ability to perform discrimination tasks are typical of the altered behavior observed in laboratory animals exposed to microwave energy at intensities comparable to that proposed for the SPS. The biological ramifications of altered behavior during exposure are complex and not well

understood. Inherent behavior is important to nearly all species, and alterations can have unpredictable consequences on ecosystems (for example, predator-prey relationships can be upset). Generalizations concerning species behavior are therefore inappropriate.

Eastern European scientists have reported a "neurasthenic syndrome" in humans exposed to microwaves. The syndrome is said to include mild behavioral changes which are for the most part reversible. The existence of microwave-induced neurasthenic changes in humans is not universally accepted for a variety of reasons, including differences in scientific philosophies. Attempts by Western scientists to duplicate reported observations in laboratory animals have produced inconsistent results.

Intermittent or continuous exposure to microwaves might cause behavioral changes in space or terrestrial SPS workers. Resident animal populations at rectenna sites also could be affected. The likelihood of behavioral effects from exposure to the lower microwave power densities beyond rectenna sites cannot be postulated with any degree of certainty. Moreover, consequences of altered behavior are largely unpredictable.

1.8 PHYSIOLOGY AND INTEGRATIVE PROCESSES

Demonstrated biological effects of microwave exposure often can be related totally to the resulting temperature rise in the body. Thermal physiology is useful in understanding such effects and often permits an interpretation of the biological consequences to individuals and populations. Environmental conditions such as temperature and humidity can influence the occurrence of microwave-induced changes in physiologic and integrative processes.

Microwave power density levels produced by the satellite power system in space and at rectenna sites might affect the physiologic and integrative biological processes of SPS workers and animals. Power density levels beyond rectenna sites would not be expected to produce discernible body-temperature increases in any species and therefore would not alter physiologic or integrative processes. Nonthermal effects of microwaves also would not be expected beyond rectenna sites.

1.9 INTERACTIVE SITUATIONS, MEDICATIONS, AND SPECIAL POPULATIONS

The microwave energy produced by the satellite power system might interact with other environmental and societal factors and thereby influence human health. Biological responses to such interactions are not predictable. Individuals taking medication may exhibit a very different response to microwave energy than healthy, young adults. Extreme heat or cold, weightlessness, and unusually high metabolic activity are other factors which may influence reactions to microwave exposure. Present knowledge, although limited and not thoroughly interpreted, suggests there may be some adverse implications, especially for SPS space and terrestrial workers.

1.10 ECOSYSTEMS

Microwave effects research amenable to direct ecological interpretation has seldom been performed. The impact of microwave radiation on an entire ecosystem has apparently never been examined in a systematic way. Nevertheless, available information implies that some plant species have increased susceptibility to drought and decreased productivity (yield) when exposed to very high microwave power densities. Similarly, some bird species have experienced decreased reproduction and altered behavior as a result of exposure to microwave power densities greater than one milliwatt per square centimeter. A full understanding of ecological exposure to continuous wave, low-power-density microwaves will ultimately require extensive experimentation with a cohesive ecological unit. Near-term SPS research is exploring the immunologic, teratologic, behavioral, and lethal effects on selected airborne and terrestrial species of electromagnetic energy with a frequency of 2.45 gigahertz.

1.11 CONCLUSIONS

Conclusions regarding the potential biological implications of the SPS microwave power transmission system remain tentative and qualitative at this time. This is due to the limited applicability of existing scientific data to the satellite power system. It is unlikely that sufficient scientific data can ever be obtained (and universally accepted) as proof of either the safety or the danger of SPS microwave transmission. Continuing research is important, however. Additional substantive, pertinent data are essential to future decisions regarding the SPS. The national interest would not be served

by either discontinuing the SPS program because of perceived high environmental risks from microwaves (presuming the satellite power system is an otherwise-viable energy option) or continuing the SPS program because of overriding concerns about energy supplies, regardless of microwave risks. The principal objective of SPS microwave-effects research is to reduce the uncertainty of the risk.

Based on conventional scientific interpretation of existing data, the following list summarizes present knowledge of the potential effects of SPS microwave energy on biological systems in space, at rectenna sites, and outside rectenna sites.

- 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

- Development

  Effects unlikely except for species inhabiting rectenna sites

- 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

2 NONMICROWAVE HEALTH AND ECOLOGICAL EFFECTS

Development of the satellite power system would require extracting certain natural resources, shipping those resources to factories for processing and manufacturing, transporting finished products to a launch site, and launching the products (and construction workers) into space for orbital assembly of the satellites. Relatively large areas of land also would need to be cleared so that SPS rectennas could be built; manufacturers would ship rectenna components to these sites. Space transportation vehicles would have to be built, either in manufacturing plants or at SPS launch sites. It is likely that existing launch sites would be expanded and new sites constructed.

Most of these activities would be conventional processes normally associated with mining, manufacturing, and transportation. Their environmental consequences also may be regarded as conventional, and potential SPS-related impacts can be assessed on the basis of experience with closely-related activities. The current evaluation of conventional SPS effects identifies the incremental increases in health and environmental impacts which would be expected from the satellite power system. In many cases, such increases may occur even if the SPS is not developed, as a result of the development of other new power sources.

However, the space activities associated with the satellite power system (transportation, assembly, operations, maintenance) can be considered unconventional, even though not all of them are unprecedented. The scope of SPS activities -- especially if a large number of satellites were placed in orbit -- would greatly exceed the extent of other space activities to date. Thus an analysis of environmental impacts resulting from SPS space activities is a formidable task and one which currently is largely qualitative due to the limitations of the existing data base. The analysis of unconventional SPS impacts is presently based principally on limited data and experience available from past and current U.S. space endeavors. Substantive differences between the SPS and other space programs are identified when it is important to recognize those distinctions.

2.1 THE PUBLIC

The principal environmental impacts of the satellite power system that could affect the general public are identified in Figure 5.

Conventional Processes

The public could be affected by the environmental impacts of extracting and processing the natural resources needed for the SPS, manufacturing, construction, and transportation. The principal impacts would be: land disturbance and use, air and water pollution, generation of solid and liquid wastes, and resource depletion.

As discussed above, incremental increases in conventional activities would occur to satisfy SPS needs. Figure 6 compares some mining and industrial process needs of SPS with U.S. production. SPS environmental impacts are compared with U.S. totals in Table 1. The SPS resource requirements and pollution burdens would be at least measurable relative to national levels and in some cases could represent substantial fractions of national totals. Localized impacts in areas where activities are concentrated might not be negligible because of the relatively high absolute levels associated with the project. (These two statements probably would also apply to other new electricity-supply systems.)

Certain toxic materials would be transported to manufacturing plants and SPS launch sites. Toxic materials transport is a contemporary hazard in industrialized societies, and federal and state regulations have been developed to minimize catastrophic risks. Rocket propellants such as liquid hydrogen are inherently explosive, and sizable quantities would be needed for the satellite power system. Other materials are highly toxic, hydrazine, for example, or possess unusual characteristics. Extreme cold is a characteristic of liquid oxygen; a spill could adversely affect components of an ecosystem. Some incremental increase in the risk of catastrophic transportation accidents would therefore be conceivable for the SPS.

Unconventional Processes

Air pollution at launch sites would result from SPS rocket exhaust products and from a ground cloud consisting of water vapor, gases, and dust.

EXTRACTION, PROCESSING, AND FABRICATION OF MATERIALS AND EQUIPMENT

Mining	Construction	Manufacturing
Land Disturbance (strip-mining, subsidence, spoil piles)	Land Disturbance	Air Pollution (stack emissions)
Air Pollution (fugitive dust)	Air Pollution (fugitive dust)	Water Pollution (process effluents)
Water Pollution (leaching, drainage modification)	Water Pollution	Solid Waste
Toxic Materials	Safety Hazards	Safety Hazards
Safety Hazards		Toxic Materials
Noise		Noise
Solid Waste		

MATERIALS AND EQUIPMENT TRANSPORT

- Air Pollution (vehicle exhausts)
- Water Pollution (spills)
- Accidents (conventional and catastrophic)
- Toxic Materials

RECTENNA OPERATION AND MAINTENANCE

- High Intensity Electromagnetic Fields

FLIGHT OPERATIONS

Launch	Landing
Air Pollution (vehicle exhaust, ground cloud)	Water Pollution (residual propellant spills, ablative material removal)
Water Pollution (launch pad cooling)	Noise (sonic boom)
Noise (acoustic, sonic boom)	Recovery Emergency
Launch Emergency (abort, off-trajectory failure)	Toxic Materials
Toxic Materials	
High Acceleration and Deceleration	
Ozone Depletion	

Fig. 5. Environmental Impacts of SPS Operation

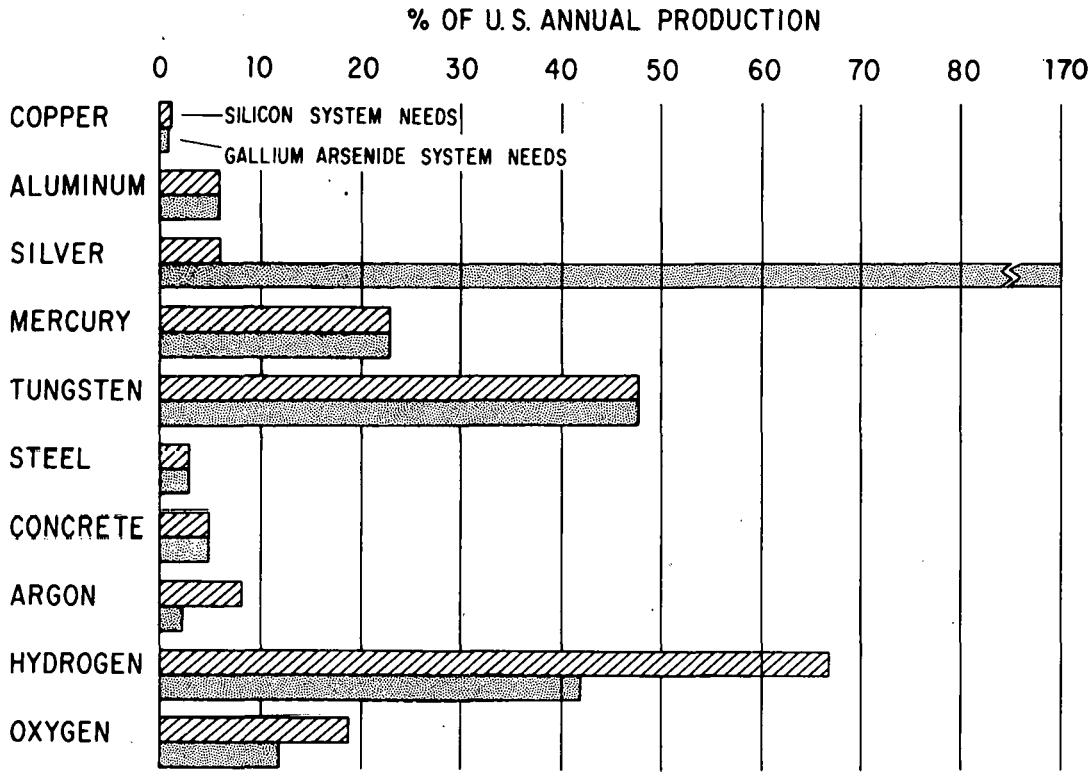

Fig. 6. Comparison of Annual SPS Materials Requirements with U.S. Production (assuming two satellites are built annually; "silicon system" and "gallium arsenide system" refer to the two types of solar cells being considered for use)

The ground cloud, which would disperse according to prevailing atmospheric conditions, would be the principal source of air pollution to which the public might be exposed. Maximum concentrations or specific pollutants cannot be estimated at this time. The liquid fuels which probably would be used for SPS rockets have not yet been characterized.

High noise levels would be another problem at SPS launch sites. High-intensity noise and sonic booms would be generated during lift-off and ascent. Reentry vehicles also would produce sonic booms. Sound pressure levels have been estimated for the proposed heavy-lift launch vehicle (HLLV): they would approximate the threshold of pain (130 decibels) for humans 5.2 kilometers from a launch pad and would be about as loud as "rock music" (120 decibels) at a distance of 14 kilometers from a launch pad. These noise levels probably would be considered excessive by most people within several kilometers of an SPS launch site. The "startle effect" from sonic booms also

Table 1. Annual Environmental Effects of the Satellite Power System

Type of Impact	SPS[a]	U.S. Total
	million metric tons	
Air Pollutants[b]		
Particulates	0.11	14
Sulfur dioxide	0.013	30
Carbon monoxide	0.042	88
Hydrocarbons	0.010	22
Nitrogen dioxide	0.0010	20
Nonrecoverable Water Use[c]	3.4	1400
Solid Waste Generated[d]	1.6	230
	thousand square kilometers	
Land Requirements[e]	11	9400

[a]Assumes two satellites are built per year.

[b]SPS emissions from mining, processing, fabrication.

[c]SPS requirements for propellant manufacture, launch pad coating, construction.

[d]SPS waste from aluminum and steel processes.

[e]SPS requirements for rectenna sites. U.S. value is total U.S. land area.

would be expected to be substantial; their intensity and frequency would likely be greater than that of other sonic booms experienced by the public to date. A more detailed assessment is being performed.

Injury to members of the general public due to SPS launch or recovery accidents is unlikely but conceivable. The effects of recovery accidents, if they were to occur, most likely would be contained within designated recovery areas. A catastrophic explosion of an HLLV could affect persons near launch sites. For example, the noise and shock waves from an HLLV explosion would blow out windows and doors in buildings as far as 15 kilometers from the launch pad. Structural failure would not be expected, however. Launch sites are typically surrounded by a buffer zone of land; it is not likely that any town would be closer than 15 kilometers from a launch pad.

2.2 TERRESTRIAL SPS WORKERS

Conventional Processes

Workers involved in conventional activities associated with SPS development would be exposed to the same types of environmental impacts as the public. The principal difference is one of degree, or intensity. Air and water pollution undoubtedly would be more severe at work places, for example, and the likelihood of personal injury from accidents would be higher for workers than for the public. On the other hand, practical safety measures are easier to apply and enforce at employment centers than for the public at large.

Unconventional Processes

Workers at operating SPS rectennas would be exposed to microwaves and waste heat to a greater degree than the public; microwave exposure was discussed previously. Most workers in the United States are not exposed to unusual amounts of heat or cold. Waste heat is recognized as a potential occupational stress at rectenna sites, but its effect cannot be characterized at this time.

Workers at SPS launch sites would be exposed to occupational hazards and stresses similar to those encountered by workers involved in current space endeavors. The impacts would be more intense than those associated with present space programs because of the scale of the SPS program (larger rockets, more frequent launches, etc.). The SPS work force would be large and, therefore, more individuals could be exposed to the types of effects previously identified as unconventional. Any potential occupational risks could be ameliorated, at least to some extent, by education, training, and safety procedures.

2.3 SPS WORKERS IN SPACE

The space environment is not well understood; some occupational hazards of working in space are self-evident, but others are not. Because of limited human experience in space, a comprehensive assessment of environmental effects on space workers is not currently possible. Figure 7 depicts the types of environmental effects that are believed to be of concern.

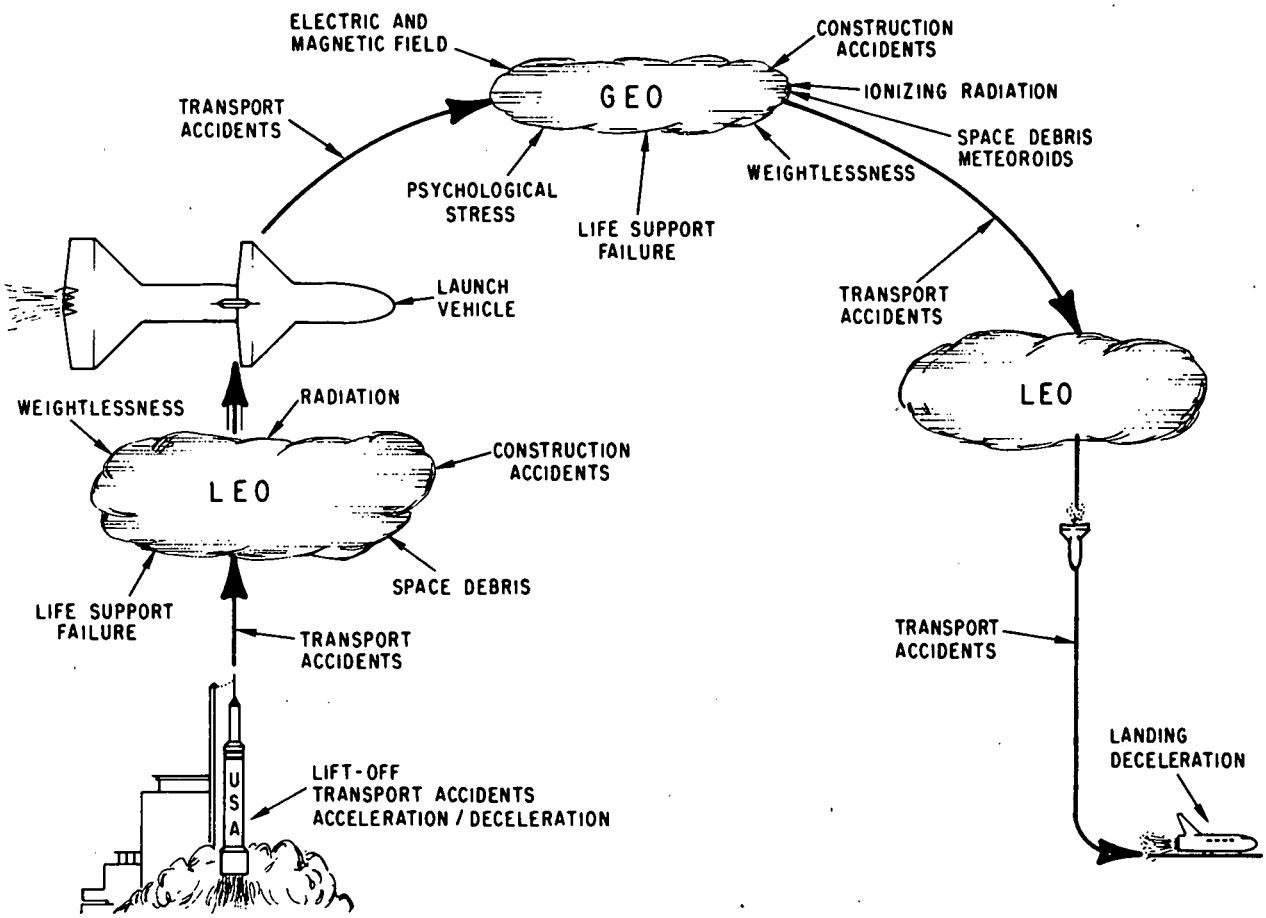

Fig. 7. SPS Environmental Effects on Space Workers

Space Travel

Space workers could be injured in SPS launch accidents and during journeys between earth and space construction stations in low earth orbit (LEO) and between LEO stations and satellite assembly points in geosynchronous earth orbit. While there is always the risk of catastrophic accidents during space travel, injuries may also occur due to rapid vehicle acceleration and deceleration. To date these risks have been faced by only a few people who have been intensively trained for space travel. In the case of the SPS, many more individuals would be exposed to these risks, and the level of training might be different than that possible for small groups of people.

Life Support

Appropriate life support systems would have to be developed for workers who would spend long periods of time in space and would be involved in

activities which have not yet been attempted in space. Such systems are essential to the development of the satellite power system.

Weightlessness

Physiological and biochemical alterations observed in astronauts during and after space flights have included:

- anemia
- immunological system changes
- blood plasma volume reduction
- bone calcium loss
- muscle tissue reduction
- blood chemistry changes
- body fat loss
- space motion sickness
- dizziness, spatial disorientation, sensation of rotation, etc.

Some of these changes may be adaptations to unique situations; there seem to be some cases in which a new equilibrium is approached as time in space is extended. Other effects, such as calcium loss, continue throughout space flight (up to 84 days in Skylab). Continuing research on these problems may produce ways of lessening their effects. This research and other information from manned space flights is being assessed to improve understanding of possible long-term and short-term effects on the health of SPS space workers.

Psychological Stress

A great deal of effort will be necessary to design and maintain working and living conditions that minimize psychological stress for SPS space workers. A screening process would be needed to select workers who could successfully cope with the stresses inherent in working for relatively long periods of time in space. Psychological stress must be considered a major concern at this time. Generalizations concerning its ramifications for individual health or interpersonal relationships are not possible at this time.

Ionizing Radiation

The predominant types of ionizing radiation which occur in space are known, but it cannot be assumed that all types of radiation in space have been identified or fully understood. Moreover, there is limited knowledge about the sources, intensity, and frequency of occurrence of some types of space radiation. While a reasonable assessment of the kinds of risks which would be faced by space workers is possible, a more complete understanding of radiation characteristics and radiation injury is needed for a thorough analysis.

The high-energy heavy ions (known as HZE particles) that would be encountered in space are of particular concern. Preliminary calculations made for HZE and other types of predictable ionizing radiation for SPS space workers indicate that radiation doses might exceed current limits recommended by national and international commissions on radiation protection. Individual doses would depend upon time spent in particular orbits, work schedules, shielding protection, and radiation contributions from unpredictable sources. The latter include releases of large numbers of solar particles and short-term fluctuations of electrons trapped by the earth's magnetic field.

The risks from ionizing radiation in space could be minimized through carefully-designed shielding for space vehicles, working and living modules, and solar storm shelters. A fail-safe warning system is being developed to protect workers from excessive, unpredictable space radiation. In addition, special monitoring systems would be necessary to obtain comprehensive, immediate accounts of radiation conditions in places occupied by space workers. Personnel dosimeters with quick readouts also would be required because of differences in exposure among individuals performing different tasks under varying conditions and work schedules.

2.4 ECOSYSTEMS

The environmental effects of SPS-related activities on and near the earth's surface probably would impact many components of ecosystems. The most evident effects would likely be localized near major SPS activity centers.

Vegetation and habitat would be lost where natural resources were mined. Air and water pollution could affect plants and animals near proces-

sing and manufacturing centers, rectenna and launch sites, and space-vehicle recovery areas. Noise is recognized as a potentially serious impact on terrestrial, aquatic, and airborne animals. Chemical pollution effects on terrestrial and airborne species are not entirely understood. Chemical pollution of waters probably is sufficiently understood as it effects animals and plants. The intensity of SPS impacts might be different from those produced by other activities and undoubtedly would be site-specific. Site-specific assessments are not possible at this time.

Some probable ecological impacts would not be site-specific. These include a potential depletion of ozone in the atmosphere due to rocket exhaust and the related increase in ultraviolet light reaching the earth's surface. The diurnal (day-night) cycles and other circadian rhythms of animals and the growing cycles of plants also could be affected by reflected light from solar power satellites. Studies of these impacts are beginning.

A hypothetical rectenna site has been selected in order to quantify representative site-specific ecological effects. The area is in the California high desert, a setting which would satisfy many rectenna siting criteria (relatively uninhabited, infrequent cloud cover, near centers of high demand for electricity). This analysis will be completed by summer of 1980 and will provide additional insight regarding site-specific impacts.

2.5 CONCLUSIONS

Environmental Impacts on the Public

Many industrial activities common to the development of new electrical energy sources would be needed to support the satellite power system. These activities deplete natural resources and produce conventional air and water pollutants and waste products. The magnitude of such effects from the SPS would be measurable relative to total U.S. generation of pollution and wastes Some effects could be locally significant and noticeable to the public near industrial centers and SPS rectenna and launch sites. None of these impacts are unique to the satellite power system, with the exception of noise generated by SPS rocket launches. All effects could be controlled to some degree by conventional strategies.

Environmental Impacts on Terrestrial SPS Workers

Workers in industries supporting SPS development would be exposed to the same kinds of environmental effects as the public but their level of exposure would often be greater. They also would risk conventional occupational illnesses and injuries. Available industrial safety measures appear to be adequate to maintain SPS-related risks at generally-accepted levels.

Effects on SPS Workers in Space

The principal risks to space workers have been identified on the basis of limited knowledge of the space environment, and needs to minimize risks have been defined. Workers could be injured or killed during space travel, by failure of life support systems, and by other accidents in space. Weightlessness has temporary adverse health effects, as may psychological stress produced by unusual working and living conditions. Some SPS workers would perform duties which are inherently hazardous (handling toxic materials or working near high-voltage sources, for example). It appears that individuals could receive dosages of ionizing radiation which are currently regarded as excessive. Some radiation would be produced by sources that are understood and predictable, while other types of radiation would be unpredictable. Much work remains in order to design adequate shielding and monitoring systems and work procedures to minimize health risks for space workers.

Effects on Ecosystems

Ecosystems might be affected by pollutants from industrial activities supporting SPS development; these effects would be the same as those from activities supporting other energy-supply endeavors. The effects of some pollutants on ecosystems are not entirely understood. Site-specific environmental impacts undoubtedly would have some effects on species that normally would inhabit SPS rectenna sites, such as changes in habitat and natural order of succession. A study of a hypothetical rectenna site in California will quantify representative site-specific impacts. Other principal ecological effects, yet to be studied, could stem from light reflected from power satellites and depletion of atmospheric ozone (and the resulting increase in ultraviolet light reaching the earth).

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3 SPS EFFECTS ON THE ATMOSPHERE

Every level of the earth's atmosphere would be affected to some extent by the construction and operation of a satellite power system. The principal conventional effects of construction (near-earth air pollution, water pollution, industrial by-products, etc.) were discussed previously. Atmospheric effects resulting chiefly from space transportation and satellite operations are considered here. Many different processes occur naturally in the atmosphere; a large number could be influenced by the SPS. Figure 8 illustrates the various levels of the atmosphere discussed here, while Figure 9 depicts some of the disturbances that might result from the satellite power system.

The current SPS reference system includes a schedule of space transportation operations (see Table 2). This schedule assumes that two 5-gigawatt satellites would be constructed each year for a number of years. The number of flights and the payloads of the various space vehicles required to construct two satellites are shown in Table 3 for the two photocell options currently being considered. The numbers do not include transportation requirements for satellite maintenance following construction.

The principal cause and effect relationships for SPS impacts on the atmosphere are outlined below:

- Rectenna waste heat and surface roughness → weather modification.
- Rocket effluents → air quality and weather modification.
- Rocket effluents in upper atmosphere → compositional changes in the neutral atmosphere, ionospheric depletion, and effects on the plasmasphere and magnetosphere, including telecommunications effects.
- SPS station-keeping → alteration of the satellite environment.

The most significant atmospheric effects from the SPS [illegible] to result from rocket exhaust effluents. The amounts of exhaust products possible can be appreciated by considering that the gross lift-off weight of the SPS heavy-lift launch vehicle (HLLV) would be nearly five times that of the Saturn rocket. Its thrust would be nearly four times greater, and its payload almost six times greater. In the absence of more appropriate data, the liquid fuel used for the Atlas/Centaur rocket has been assumed for the

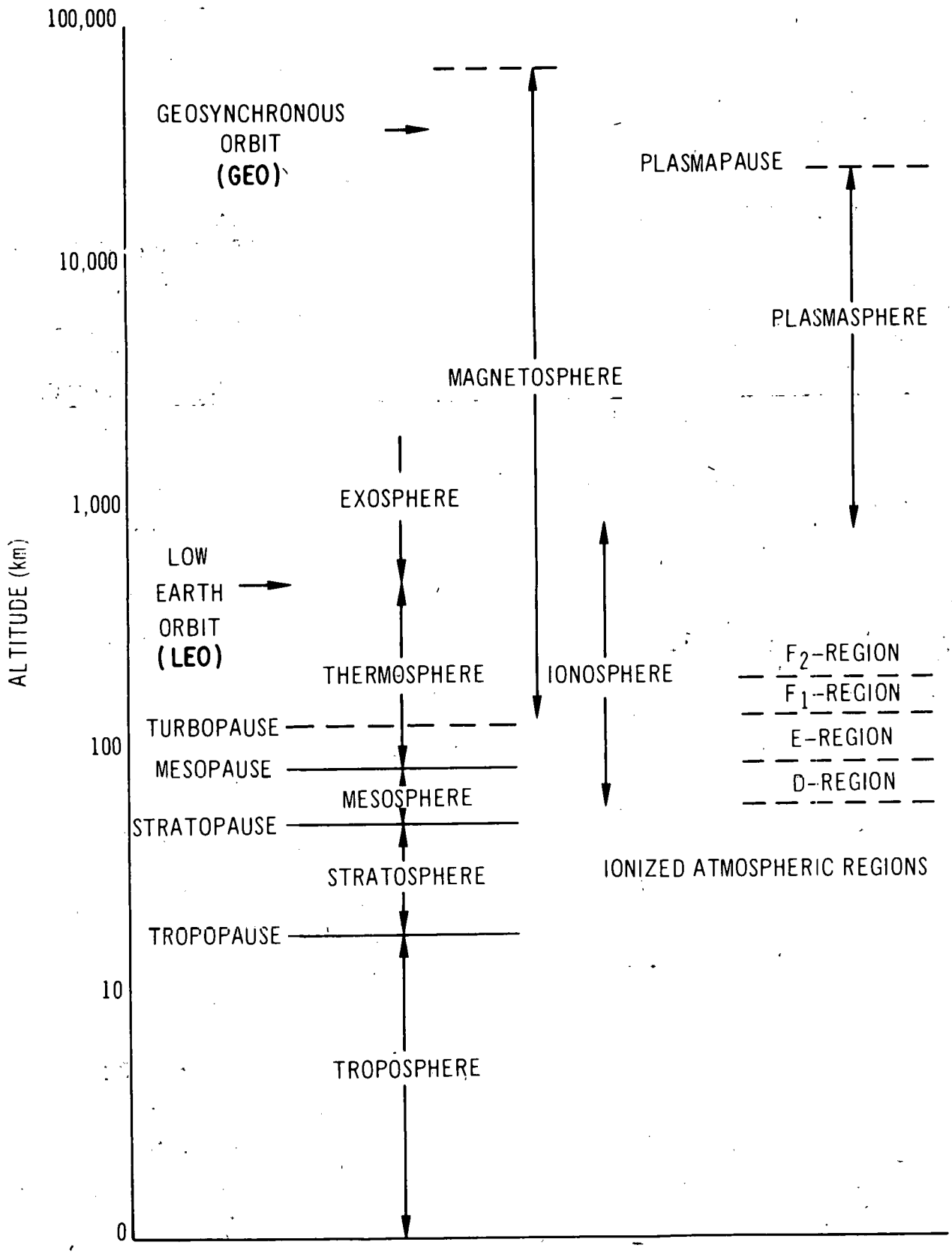

Fig. 8. Regions of the Earth's Atmosphere

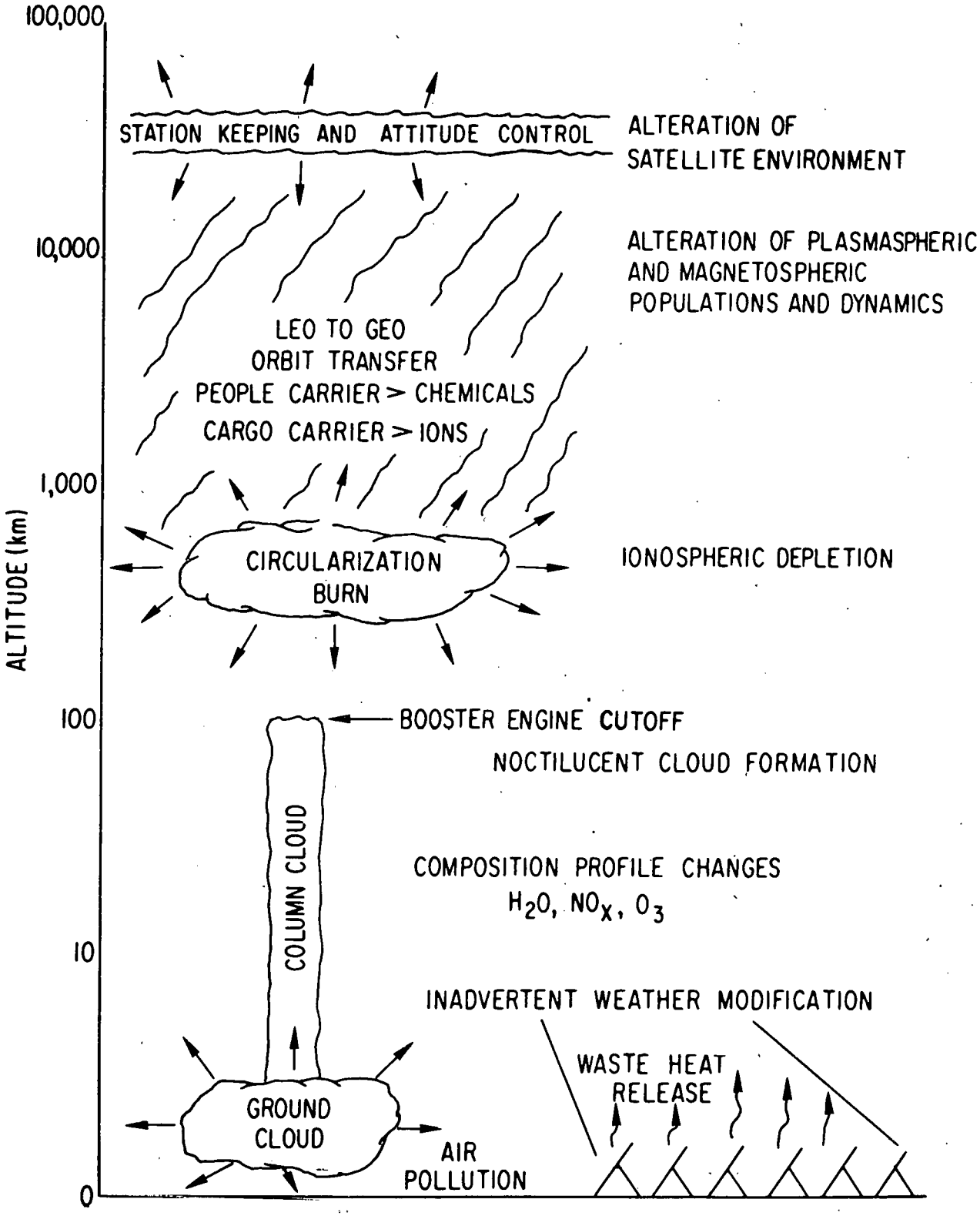

Fig. 9. Illustration of Potential SPS Atmospheric Effects

Table 2. Types of SPS Space Vehicles

Name	Abbreviation	Propellants	Operating Region (km)
Heavy-lift launch vehicle	HLLV	Liquid methane/liquid oxygen (first stage)	0-57
		Liquid hydrogen/liquid oxygen (second stage)	57-120
		Liquid hydrogen/liquid oxygen (circulation & deorbit)	450-500
Personnel launch vehicle	PLV	Details not available. Nominally, same as above.	0-500
Cargo orbit-transfer vehicle	COTV	Argon ions Liquid hydrogen/liquid oxygen	500-35,000
Personnel orbit-transfer vehicle	POTV	Liquid hydrogen/liquid oxygen	500-35,000

Table 3. SPS Yearly Launch Schedules and Loadings

Scenario Characteristics	Silicon[a] Satellite	Gallium[a] Satellite
Satellite mass (metric tons)	50,984	34,159
Payloads (metric tons)		
Heavy-lift launch vehicle	424	424
Personnel orbit-transfer vehicle	400	400
Cargo orbit-transfer vehicle	4,000	4,000
Payloads (number of persons)		
Personnel launch vehicle	75	75
Personnel orbit-transfer vehicle	160	160
Packing factors (%)		
Hardware	85	95
Propellants	95	95
No. of flights per year from earth to LEO staging base		
Heavy-lift launch vehicle	375	225
Personnel launch vehicle	30	38
No. of flights per year from LEO staging base to GEO		
Cargo orbit-transfer vehicle	30	22
Personnel orbit-transfer vehicle	12	17
No. of persons stationed in space		
LEO staging base	75	35
GEO	480	680

[a]These titles refer to the silicon and gallium options for the SPS photovoltaic cells.

heavy-lift launch vehicle. This is a conservative assumption and may overpredict some HLLV emissions. More than 100,000 kilograms of propellant exhaust would be emitted by an HLLV in the first 500 meters of altitude. An additional three million kilograms would be emitted at altitudes between 0.5 and 13 kilometers, and again between 13 and 50 kilometers. The principal constituents of this exhaust would be carbon dioxide and water, which are much less hazardous than the exhaust products from solid-fueled rockets; this would be one advantage of using liquid fuels for the heavy-lift launch vehicle.

3.1 TROPOSPHERE

Rocket Launches

The tropospheric effects of rocket exhaust are due primarily to the cloud of hot gases, steam, sand, and dust formed below a rocket immediately following ignition and lift-off. The exhaust products quickly mix with the air and dissipate. No adverse environmental effects of exhaust in the middle and upper troposphere have been identified, but the ground cloud from any rocket launch is a potential source of air pollution and weather modification. It rises to an altitude of 0.7 to 3 kilometers, depending on meteorological conditions and stabilizes as its gases cool. Heavy particles (surface dust and debris) fall out of the cloud over a distance that depends on turbulence, particle sizes, and ambient weather conditions. Ground-level concentrations of air pollution can be relatively high for several hours.

Air pollution concentrations produced by the Atlas/Centaur rocket have not exceeded legal limits (as established by current federal annual secondary standards). Assuming federal standards do not change significantly, HLLV launches also should not violate air pollution regulations.

Acid rain could be produced near SPS launch sites, depending on the amount of acidic pollutants in the troposphere from other sources near launch sites. Acid rain is becoming common in many regions of industrialized nations and can adversely affect vegetation, soils, and water quality. Contributions from HLLV launches would not be especially significant on a relative scale in probable launch regions.

Temporary local weather modifications would be conceivable from individual SPS rocket launches, and cumulative effects might be produced by multiple launches. Pending further study of the satellite power system and a better scientific understanding of weather phenomena generally, it is judicious to assume that SPS rocket launches would have the potential to modify weather conditions to at least some degree.

Rectenna Operation

Approximately 750 megawatts of waste heat would be released continuously by a rectenna with a surface area of 100 square kilometers. This is roughly equivalent to the heat released by a typical suburban development and represents about 10 percent of the average natural energy conversion at the earth's surface. Waste heat release near rectennas would not be expected to significantly affect the near-earth atmosphere. Aerodynamic alterations over rectennas likewise would not be expected to be substantial.

3.2 STRATOSPHERE AND MESOSPHERE

Composition Perturbations

Alterations in the chemical composition of the stratosphere and mesosphere are important because they can affect ozone concentrations. Ozone absorbs ultraviolet light and therefore shields the earth from some of this radiation, which has been implicated as a cause of skin cancer. Introducing chemical compounds into the stratosphere and mesosphere could decrease ozone concentration, allowing more ultraviolet light to reach the earth's surface. Moreover, chemical compounds could change the temperature of these regions of the atmosphere, possibly inducing weather modifications.

Heavy-lift launch vehicles and reentry vehicles would introduce rocket exhaust effluents into the stratosphere and mesosphere. Carbon dioxide and water vapor would be the principal HLLV exhaust products. Carbon dioxide is naturally abundant in the upper atmosphere, but water vapor is not. Insignificant amounts of other trace elements also would be produced by SPS vehicles.

The effect these changes in the stratosphere and mesosphere would have on the lower atmosphere is presently unknown. However, preliminary calcula-

tions indicate that the globally averaged change in total ozone and the resulting change in intensity of ultraviolet radiation at the ground surface would be negligible.

Climate

The effects on climate (if any) of perturbing the stratosphere and mesosphere are largely unknown, and the likelihood of climatic effects from SPS launches is relatively uncertain at this time. The most probable effect from the satellite power system would be the formation of optically-thin noctilucent clouds at altitudes of about 80 kilometers. Their size and lifetime cannot be predicted at this time. Noctilucent clouds are important because they affect the amount of solar radiation reaching the earth. Such clouds, if they were to occur, most likely would appear only in the regions of launch sites.

Energy Injection

Energy would be injected into the stratosphere and the mesosphere by SPS rocket exhaust effluents and by the microwave beam transmitted from satellite to rectenna. Both forms would have the potential to raise ambient temperatures in the stratosphere if sufficient energy was injected.

The stratosphere and mesosphere are heated by absorbed solar ultraviolet light; they absorb energy equivalent to an average of four milliwatts per square centimeter. All of the exhaust effluents produced in a year by SPS launches would inject energy of one ten-millionth (0.0000001) of a milliwatt per square centimeter on a global average -- a miniscule fraction of the natural heating. No adverse effects would be expected from this SPS-related heating.

About 0.1 percent of the energy in an SPS microwave beam would be absorbed in the stratosphere and mesosphere. The heat deposition would be about 0.005 milliwatt per square centimeter for each beam. This is about 0.13 percent of the solar ultraviolet absorption and should be negligible.

3.3 IONOSPHERE

The ionosphere contains a variety of chemical, physical, and electromagnetic phenomena involving solar and cosmic radiation, ions, neutral

particles, and the earth's magnetic and gravitational fields. The interactions of these phenomena produce periodic and random variations that are important to the earth's environment. The delicate balance of forces and the small numbers of particles contained in the ionosphere suggest that the possible effects of large quantities of rocket exhaust products (on a scale much larger than heretofore experienced) could be important.

E-Region

The E-region of the ionosphere reflects radio waves at night and permits long-range transmission of radio signals. The HLLV rocket engines would be shut down soon after reaching E-region altitudes, so few exhaust products would be emitted directly into this region. However, effluents might reach the E-region by drifting from either lower or higher altitudes. Its conductivity plays a prominent role in lower-atmosphere climate, but current knowledge does not permit a confident estimate of whether or not SPS rocket exhaust might produce significant climate changes.

F-Region

The F-region of the ionosphere is extremely complex and dynamic. Rapid changes occur in its characteristics, such as electron density, and the thermal, mechanical, and electromagnetic forces acting on the F-region vary with altitude. The earth's magnetic field interacts in important ways with the F-region. Changes which might be produced by HLLV effluents are poorly understood, and the extent to which such changes might affect climate and weather is essentially unknown.

Rocket effluents can reduce the electron density in the F-region, producing "ionospheric holes." Visible air glow, which can occur in the F-region for some period of time as exhaust effluents react with ions, is scientifically useful for studying ionospheric depletion. These holes can be quite large and affect radio communications and navigation over wide geographic areas. This phenomenon is well established; it has occurred during rocket launches (for example, during the 1973 Skylab launch) and has disrupted satellite communications for periods ranging from minutes to hours over areas several thousand kilometers wide. Ionospheric holes can be shifted or spread by upper atmospheric winds. Ionospheric holes would be expected to result from SPS rocket launches.

The hydrogen-atom production cycle in the F-region could be affected by HLLV launches. Based on current SPS launch schedules, over a five-day period rocket effluents would produce a quantity of hydrogen atoms equivalent to the total number naturally present. Satellite drag could be increased, the Van Allen radiation belts could be altered, and radio communications could be affected by an increase in the number of hydrogen atoms (see Section 4).

High-energy particles migrate to the F-region from higher regions of the atmosphere. The rate of this movement could be changed by HLLV exhaust products, possibly resulting in satellite drag and radio interference. The latter would not be expected to be significant, however.

The heat balance in the F-region also might be altered by the injection of water vapor into the ionosphere. The most likely effect would be an increase in the rate of cooling by radiation. The Van Allen belts could also be affected, possibly changing the amount of ionizing radiation in space.

3.4 PLASMASPHERE AND MAGNETOSPHERE

Satellite power system activities in the outermost regions of the atmosphere would include spacecraft flights between low earth orbit and geosynchronous earth orbit (GEO). Rocket effluents -- predominantly argon ions, hydrogen, and electrons -- would be introduced into the plasmasphere and the magnetosphere. The numbers of argon ions and hydrogen atoms that would be injected by rockets appear substantial when compared to the natural numbers of these particles at GEO altitudes. However, any effects on the plasmasphere and magnetosphere would also depend on the "residence time" of the particles, since the particles would not accumulate in a simple arithmetic way. Residence times would vary with altitude and other factors, ranging from one day to 100 days with increasing altitudes within the magnetosphere. Both the numbers of particles and their residence times could be reduced somewhat by careful timing of rocket-engine operation.

The natural processes which occur in the magnetosphere influence the amount of solar radiation which reaches the lower atmosphere. Rocket effluents added to the magnetosphere could alter natural conditions, with consequences such as the enhancement of radiation levels in the Van Allen belts. Materials and space travelers passing through or residing in the Van Allen belts could be adversely affected. Space-based communications and navigation

also could be impacted. Magnetospheric storms could be produced with effects on electric systems on earth similar to those experienced during naturally-occurring magnetic storms.

3.5 CONCLUSIONS

The present limitations of knowledge concerning atmospheric phenomena, whether natural or man-made, introduce significant uncertainties into the current assessment of SPS atmospheric effects. Many of the conclusions concerning atmospheric impacts, particularly those related to the highest altitudes, remain conjectural in terms of the magnitudes of effects that might be caused by the satellite power system. There is substantial confidence, however, that the types of impacts which would be most significant to the earth's population and to space workers have been identified.

Few significant effects would be expected in the near-earth atmosphere from SPS space activities. Temporary air pollution and potential enhancement of acid rains near rocket launch sites would be the most likely impacts. Rocket exhaust effluents could lead to slightly decreased ozone concentrations in the stratosphere and mesosphere, but these decreases would be expected to be insignificant.

Space-vehicle exhaust effluents in the ionosphere have been responsible for radio-wave interference which has affected telecommunications. Exhaust effluents produced by SPS vehicles would be likely to affect telecommunications for periods ranging from several minutes to several hours over large geographic areas. Other interactions between effluents and ionospheric constituents could produce satellite drag. The amount of ionizing radiation in space could be altered through changes in the radiation characteristics of the Van Allen belts.

Possible SPS impacts in the plasmasphere and magnetosphere are the most difficult to predict. It is currently expected that the principal impacts would be increased radiation levels in the Van Allen belts with adverse effects on space travelers; interference with space-based communications and navigation; and the production of magnetosphere storms which could interfere with terrestrial electrical systems.

4 EFFECTS OF IONOSPHERIC DISTURBANCE ON TELECOMMUNICATIONS

In the ionosphere, charged particles (electrons and ions) are sufficiently abundant to have profound impacts on the chemical and physical mechanisms responsible for forming and changing the atmospheric structure. The characteristics of the ionosphere vary daily, seasonally, and in response to sunspots.

The ionosphere refracts (deflects) and slows down electromagnetic energy (such as radio waves). The amount of deflection depends on ionospheric electron density, the wave frequency of the electromagnetic energy, the frequency of occurrence of electron collisions, and the strength of the geomagnetic field. The electron density can cause a radio wave to be totally reflected and returned to the earth's surface. This property is used for long-distance propagation of high-frequency radio waves. Radio waves at higher frequencies travel directly through the ionosphere.

Changes in the ionosphere can alter the performance of telecommunication systems whose energy is propagated within and through the ionosphere. Small-scale irregularities (meters to kilometers) in ionospheric electron density can produce radio signal fading and result in loss of information. Ionospheric changes due to the satellite power system could result either from interactions between the ionosphere and the SPS microwave beam (heating) or interactions with effluents from SPS space vehicles.

4.1 IONOSPHERIC HEATING

The amount of microwave energy transmitted from solar power satellites to earth might be sufficient to heat the ionosphere, even though only a small fraction of the microwave energy would be absorbed by the ionosphere. Some potential effects of ionosphere heating are shown in Figure 10. The heating mechanism is complex, resulting in phenomena such as increased electron temperatures, irregularities in electron density, and focusing of electromagnetic waves. The communications effects of such heating might include absorption or scattering of radio waves (which would disrupt communications systems depending upon the ionosphere as a signal propagation path) and scattering of both the SPS microwave power beam transmitted from space and the beam control signal sent from rectenna to power satellite.

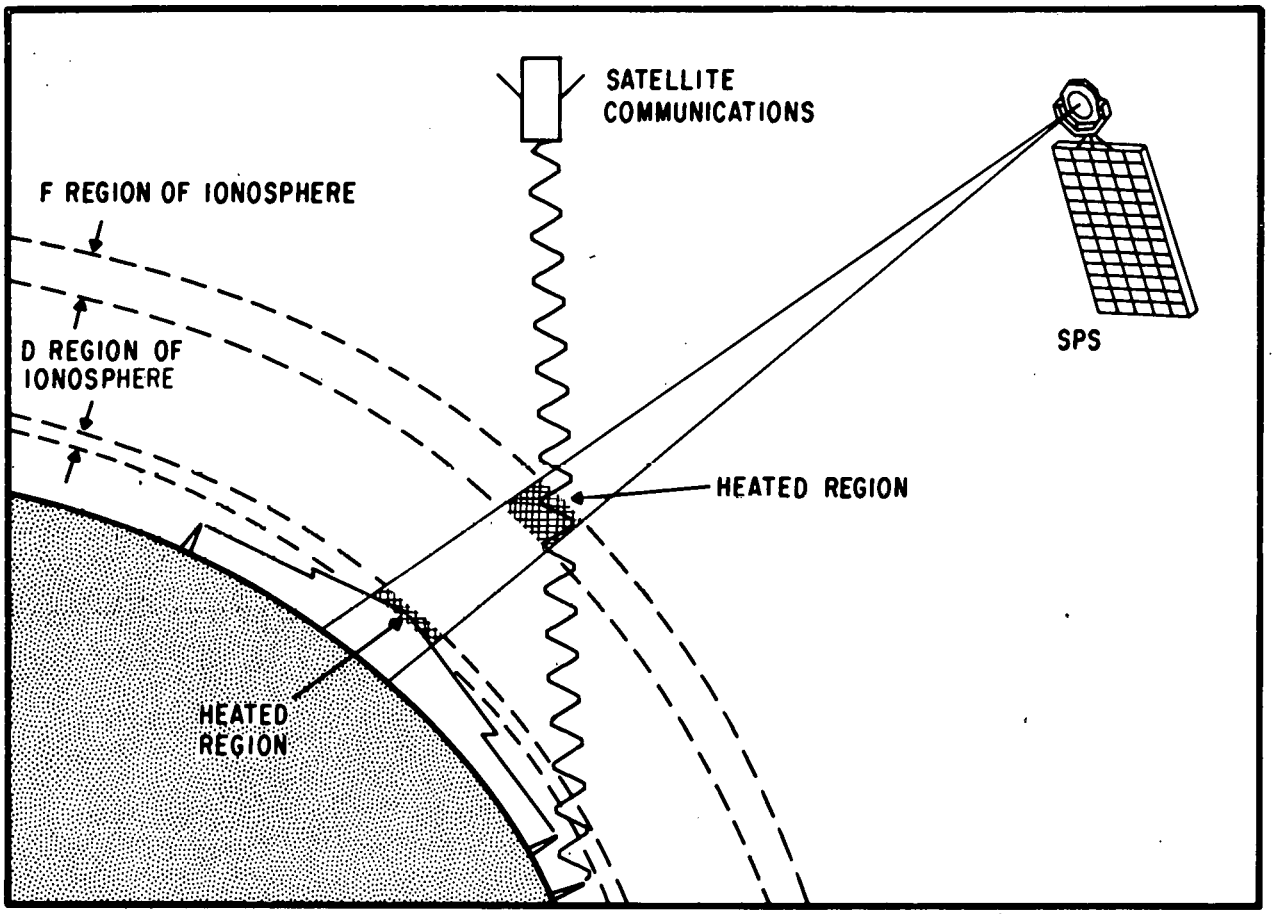

Fig. 10. Examples of SPS Microwave Transmission Effects on the Ionosphere and Telecommunication Systems

Considerable knowledge exists concerning the effects of some types of ionospheric heating. However, most of the theoretical and experimental work has focused on what is called the "overdense case"; that is, the case where the ionosphere reflects the electromagnetic wave that is causing the heating. If ionospheric heating were produced by the SPS microwave beam, it would be a case of "underdense" or "ohmic" heating, because the beam would pass through the ionosphere rather than be reflected by it. There is substantial reason to believe that ionospheric irregularities produced by underdense heating would differ significantly from those observed in overdense heating experiments. The effects of overdense heating on telecommunications systems performance cannot be extrapolated with confidence to those expected for underdense heating.

A coordinated program of theoretical and experimental work is underway to better understand the impact of SPS heating of the ionosphere. Experimen-

tal studies are performed at the Arecibo Observatory in Puerto Rico and the Ionospheric Heater Facility in Platteville, Colorado. Both facilities use high-frequency radio-wave transmissions to heat the ionosphere; they can deposit energy in the ionosphere, at an altitude of 80 to 100 kilometers, that is equivalent to the SPS energy for underdense ionospheric heating. Modified and expanded facilities are needed to deliver appropriate energy densities at higher altitudes.

Experiments related to SPS effects on telecommunications are conducted at Platteville, where the communications environment is representative of environments in which the SPS microwave-beam transmission would typically occur. Many different types of communications signals are monitored while the Platteville facility is heating the ionosphere. Data obtained from heating experiments in the early 1970s also are being analyzed to improve the assessment of potential SPS effects.

Potential SPS effects also have been studied through simulation exercises. The performance of a high-frequency communications circuit operating from Washington, D.C., to Albuquerque, New Mexico, has been analyzed with and without the influence of an SPS microwave beam. The results showed that the maximum usable frequency could be reduced by 15 percent and the overall reliability decreased by 20 percent if the circuit passed through a region of the ionosphere heated by the SPS.

A summary of potential heating effects which might be produced by SPS microwave beams passing through the ionosphere is presented in Table 4. The generic classes of telecommunications systems which depend upon ionospheric conditions for desired performance also are listed. Their dependence upon the ionosphere suggests that they conceivably could be affected by SPS underdense heating. The likely performance impacts on each class of equipment are also provided in the table.

4.2 ROCKET EFFLUENTS

The electron density of the ionosphere likely would be decreased by rocket effluents in the vicinity of the SPS launch sites creating "ionospheric holes," as discussed in Section 3.3 (see page 31). Theoretical predictions of electron depletion and data from Skylab and missile launches suggest that a wide range of communications services could experience blackouts and periods of marginal signal reception following SPS rocket launches.

Table 4. Potential Telecommunications Impacts of SPS Ionospheric Heating

Ionospheric Effect	Systems Affected	Potential Impact
Changed absorption characteristics	HF communications	Signal loss
Phase-path change	VLF navigation	Position errors
Electron depletion	HF communications	Reduced MUF
	SPS	Displaced beam
	HFDF, HF radar	Position errors, tilts
Irregularities	HF, VHF, UHF broadcast	Cochannel interference
	HF communications	MUF, coverage modifications
	VHF, UHF communications	Long-range propagation
	HF, VHF, UHF radar	Spread clutter
	Satellite communications	Signal scintillation
	Satellite navigation	Position errors
	HFDF	Position errors
Traveling waves	HF communications	MUF changes, fading
	HFDF	Position fluctuations
	HF radar	Fading
Intermodulation and harmonics	Radio astronomy	Radio frequency interference

Key: HF = high frequency
HFDF = high frequency direction finding
MUF = maximum usable frequencies
VLF = very low frequency
UHF = ultra high frequency

4.3 CONCLUSIONS

The effects of heating the ionosphere with high-power, high-frequency radio waves have been demonstrated experimentally, and theoretical studies provide a good understanding of the ionosphere's response to heating radio waves that are reflected by the ionosphere. However, little is now known with certainty about the ionospheric irregularities that would result from heating by the SPS microwave beam, which would pass through the ionosphere. This type of heating conceivably could produce communication effects similar to those observed with reflected radio signals. Theoretical and experimental studies are underway to assess the impact of SPS heating on the ionosphere and determine resulting impacts on telecommunication systems.

Studies of the effects of the ionosphere on the SPS microwave power beam and the pilot beam from earth that would guide it should be studied. Naturally-occurring irregularities in the ionosphere can cause significant fading of radio signals, known as scintillation, leading to the loss of the signals. Irregularities created by the transmission of the SPS power beam might magnify the effects of ionospheric scintillation on SPS pilot and power beams.

The HLLV launches needed to construct and operate the satellite power system might also impact communications services that depend upon the ionosphere. Blackouts or interference could be experienced for periods of hours after each launch for communications links using a 1000-to-1500 kilometer area around the launch trajectory.

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5 ELECTROMAGNETIC COMPATIBILITY

Radio, radar, and other wireless electronic systems can share the same air space and geographic area without interfering with each other, by operating at assigned frequencies and power levels. Operating assignments are made by national agencies (such as the U.S. Federal Communications Commission) according to international standards. The regulations and operating assignments take into account the potential for a wireless system to interfere with other electromagnetic systems and electronic devices. Examples of electronic devices subject to interference are telephone systems, monitor and control circuits used by pipeline transmission operators, and convenience products such as radio-controlled garage door openers. "Electromagnetic compatibility" is achieved when communications capabilities are maximized with a minimum of interference between systems.

An electromagnetic system also produces energy at unassigned frequencies called harmonics, sidebands, and spurious frequencies. There are general standards for controlling these undesirable emissions because they too can cause interference. In fact, they are more likely to be responsible for electromagnetic incompatibilities than is energy transmitted at assigned frequencies. Moreover, other rules are generally established which relate to geographic conditions and the number of electromagnetic systems in a particular area to ensure interference-free operations among users of the electromagnetic spectrum.

The satellite power system would be designed and operated in ways which would satisfy established national and international rules for using the electromagnetic spectrum. Nevertheless, there would be a substantial potential for producing interference for several reasons. First, the amount of microwave energy which would be transmitted from space to earth is unprecedented. Only very weak signals have been transmitted between space and earth to date, and these signals have had an inherently low potential for interfering with other systems. Second, the size of the microwave beam would be very large at the earth's surface. It would resemble an ellipse in shape (see Figure 1) with major and minor diameters of about 13 kilometers and 10 kilometers, respectively. The power density of the beam would be 23 milliwatts per square centimeter at its center and one milliwatt per square centimeter at its edge. The power density would decay rapidly at increasing

distances from the rectenna, but would remain substantial miles away, relative to conventional radio-signal strengths.

The SPS potential for producing interference through what is called "direct energy coupling" can be appreciated by comparing its microwave beam intensity with signal levels generally needed to receive information by radio waves. The SPS "field intensity" would be one volt per meter at a distance of 30 kilometers from the center of a rectenna site (field intensity is the measure used to define the strength of a radio signal). Communications systems generally operate with received-signal strengths of several microvolts per meter (one volt is equal to one million microvolts), so communications systems within about 100 kilometers of an SPS rectenna could receive sizable interference signals from the satellite power system. Commercial radio and television signals at distances of 1 to 50 kilometers from the transmitter range from several millivolts (one volt is equal to one thousand millivolts) to several microvolts. Thus the SPS could represent a nuisance interference on radio and television sets.

Electromagnetic systems likely to experience SPS interference would include military systems, public communications, radar, aircraft communications, public utility and transportation system communications, other satellites, and radio and optical astronomy. The interference potential of the SPS would not be especially unusual except in terms of geographic area. Many high-powered radar systems can produce interference of similar electromagnetic intensities, but the influence is generally limited to the immediate geographic area. Mitigating strategies such as cabinet shielding and radio receiver filters are commonly used to avoid interference near radar stations, and these strategies could be adapted, to at least some extent, if interference situations were encountered with the satellite power system. Equitable distribution of the costs of such strategies would require careful attention.

The principal mitigation strategy for preventing SPS interference by direct energy coupling to any class of equipment is the engineering design of the solar power satellite and the rectenna. Interference can be minimized by designing the SPS microwave system to stringent specifications, thereby reducing undesirable emissions at frequencies other than its operating frequency and constraining the size and shape of the transmitted microwave beam. Judicious rectenna siting -- including rational trade-offs between the desire to locate rectennas as near to energy load centers as practical and the need

to avoid interference with the maximum number of other users of the radio spectrum -- also is an important mitigation strategy.

Potential direct-coupling SPS interference situations are illustrated and summarized in Figures 11 and 12. The probability and severity ratings provided in Figure 12 are not quantitatively based. The probability ratings represent current engineering judgment based on experience. Severity denotes the seriousness of the likely effect on system users in the absence of mitigating strategies.

5.1 SPS INTERFERENCE AND NATIONAL DEFENSE

Military communications equipment is generally complex and uses especially low operating signal levels and therefore is particularly sensitive to

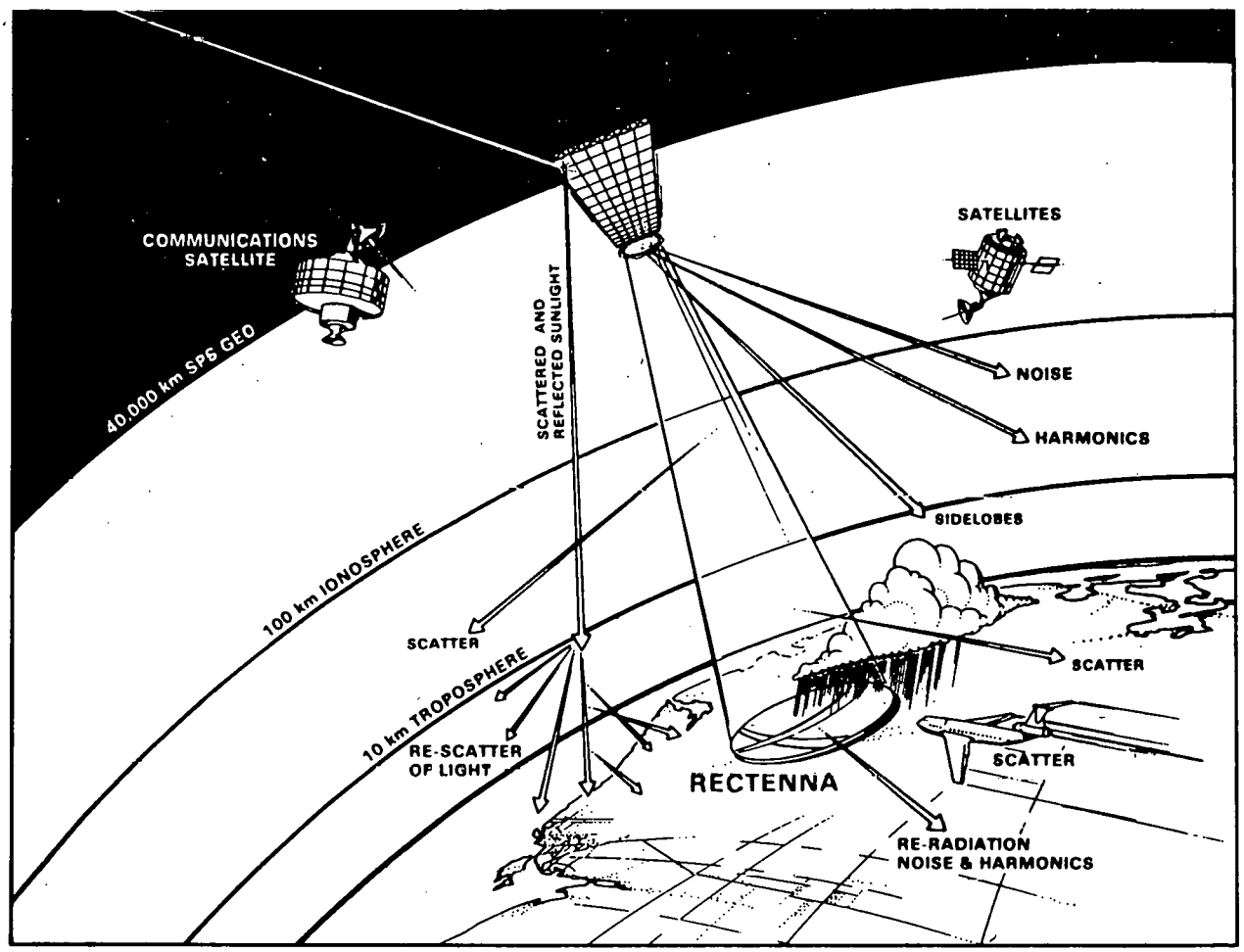

Fig. 11. SPS Electromagnetic Interference Mechanisms

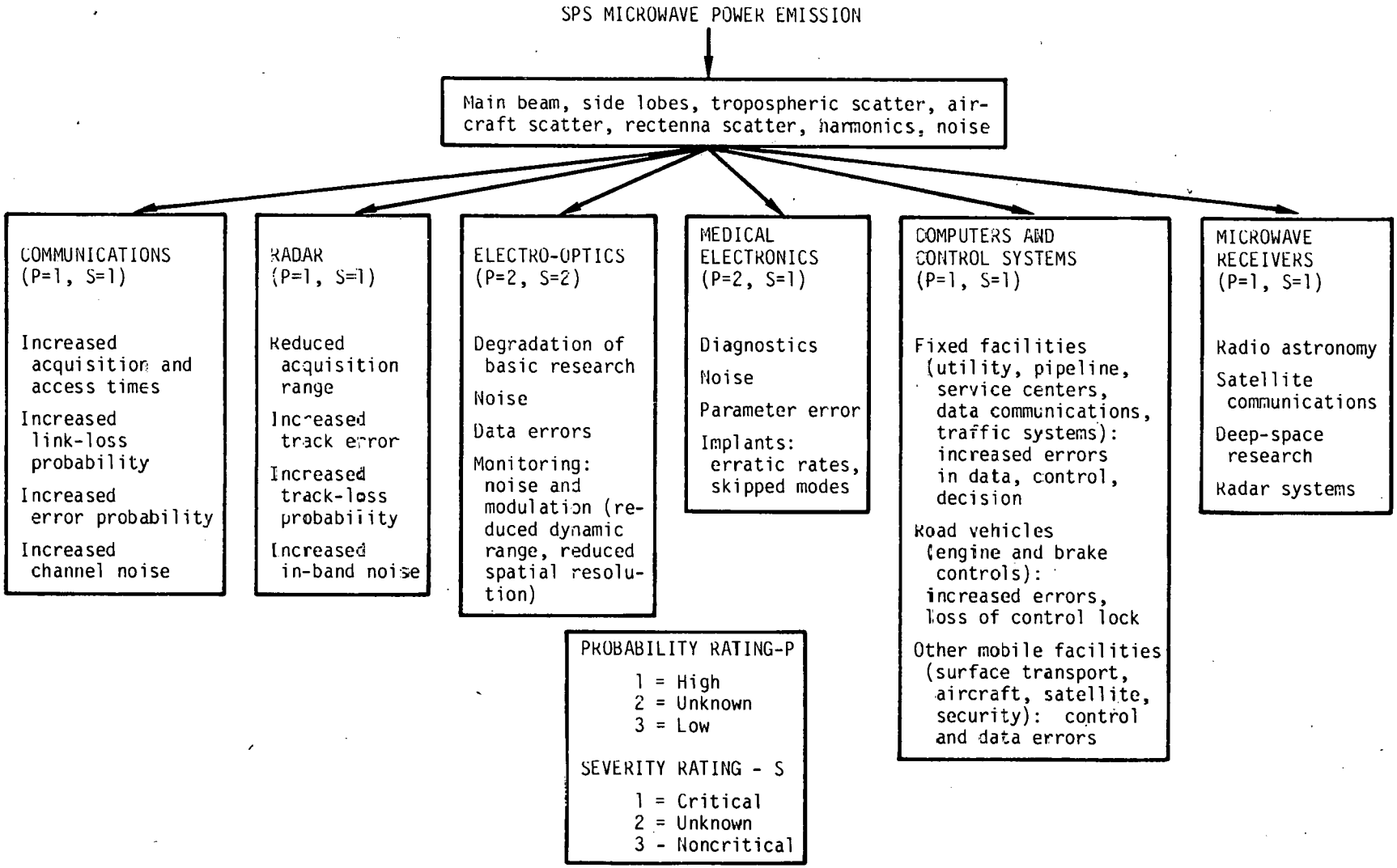

Fig. 12. SPS Electromagnetic Interference Cause-and-Effect Relationships

electromagnetic interference. Possibilities for modifying the equipment to reduce interference are extremely limited by the unique nature of its uses. A study has been completed that characterized the potential for SPS interference if a rectenna were located near a large military facility. The China Lake Naval Test Center and two Air Force bases in the Mojave Desert in Southern California were selected for the study. The site selected was especially useful because a wide range of civil telecommunications systems are located nearby and a major electric load center (Los Angeles) is some distance west of the Test Center. Thus the site may be regarded as potentially typical of an actual SPS rectenna site insofar as it conforms to several basic criteria (infrequent cloud cover, near a load center, low population density in the immediate vicinity, etc.). At least 813 government and 685 civil systems were on record as located in a 21,000-square-kilometer area surrounding the hypothetical rectenna and were analyzed.

The study showed there would be a significant potential for the satellite power system to interfere with national defense requirements as represented by large military operational, test, and evaluation facilities. The performance of radar instruments used at airstrips and on test ranges to acquire and track targets could fall by 10 to 65 percent. The reception and reliability of command and control communications could be reduced by 5 to 30 percent, and tactical systems performance could be reduced greatly.

Recognizing the constraints inherent in ameliorating interference involving military equipment, the sole mitigation strategy considered in the study was changing the location of the hypothetical SPS rectenna. A relatively minor change in location substantially reduced the impact on national defense facilities without increasing interference effects on civil systems. This scheme may be applicable in other places where large, essentially unoccupied land areas are potentially available as rectenna sites but may be of limited value because of nearby military and civil electromagnetic systems.

5.2 SPS INTERFERENCE WITH SATELLITES AND ASTRONOMY

Microwave energy transmission through space and the light that would be reflected from power satellite surfaces are two sources of potential interference to space-related endeavors. The latter is not an electromagnetic

effect, but is included here to provide a comprehensive assessment of potential effects on equipment involving space exploration and communications.

Geosynchronous earth orbit (GEO) is currently occupied by a number of space satellites, and undoubtedly will be occupied by others in the future. The SPS also would be located at GEO altitudes. The U.S. INTELSAT satellite has been analyzed as a "worst case" example of potential SPS interference with other GEO satellites. The microwave power which could be delivered to INTELSAT by a solar power satellite was computed and compared with the calculated interference threshold for INTELSAT. The comparison showed that, under maximum-interference conditions, the power delivered by the power satellite would be more than five times lower than that required for interference to occur. Interference thresholds for other commercial GEO satellites are similar to that for INTELSAT, so it can be inferred that the SPS would not be likely to interfere with commercial satellites in GEO. Military satellites are now being analyzed.

Low earth orbit also is occupied by satellites, such as LANDSAT, which is used to monitor earth resources management, and GPS, which is used as a global navigation and position-fixing system. LANDSAT traverses the continental United States six to eight times each day, so it conceivably could encounter an SPS microwave beam. The transit time through the beam would be approximately four seconds; sensor and communications interference could occur during transit. Modifications to the resource satellite to prevent interference appear to be feasible. The GPS satellite is in a higher orbit than LANDSAT and therefore would be exposed to more intense SPS electromagnetic energy and consequently would experience more severe interference. Mitigation strategies are currently being studied for GPS.

Both radio and optical aotronomy are used to study the weakest measurable sky signals. Since the satellite power system would contribute power to the radio, infrared, and optical spectrums, there would be significant potential for limiting capabilities for astronomical observations. Radio-astronomy could be affected by SPS microwave power beams at distances of hundreds of kilometers from rectenna sites.

Power satellites in space would be expected to reflect substantial amounts of light. As much as four percent of the sunlight illuminating a satellite could be reflected and scattered, according to conservative estimates. Each power satellite would appear to be brighter than all but the

brightest bodies in the sky (the sun and the moon) and would be about as bright as Venus when it is most visible. Multiple satellites would brighten the sky considerably. For example, 60 satellites would provide as much light as the moon between its new and quarter phases across a band 40° long and 10° wide. Earth-based optical observations would be severely hindered under these conditions.

5.3 CONCLUSIONS

Conventional models of electromagnetic interference and engineering practices can be used to determine the electromagnetic susceptibility of electronic equipment to microwave energy produced by the satellite power system. Microwave transmission by a power satellite would represent a source of potential interference to many types of electronic and electrical equipment under a wide range of rectenna siting situations. The uniqueness of SPS interference relates more to the scope of the potential problem (the number of systems that might be affected) rather than to the kinds of interference that might result in the absence of ameliorative measures. The principal strategies for avoiding or minimizing SPS interference are careful engineering design of the microwave transmitting and receiving antennas, judicious rectenna siting, and conventional methods such as shielding and filtering.

Military equipment used at major national defense installations for combat training and equipment evaluation usually is especially sensitive to extraneous electromagnetic fields. Mitigation strategies are severely limited by the need to simulate combat-like environments at the installations, including electromagnetic emissions from foreign equipment. The only acceptable mitigation strategy to prevent SPS interference is likely to be rectenna siting. Most military installations of this nature are remotely located in the southwestern United States, where alternative rectenna sites should be available.

Power satellites may interfere with other satellites in space. However, there is substantial confidence that mitigation measures could be applied successfully now and in the future to prevent incompatibilities. Radio and optical astronomy could be affected by SPS microwave emissions and light reflected from satellite surfaces. The potential for significantly inhibiting astronomical observations appears to be substantial; solutions to this problem may be especially difficult to develop.

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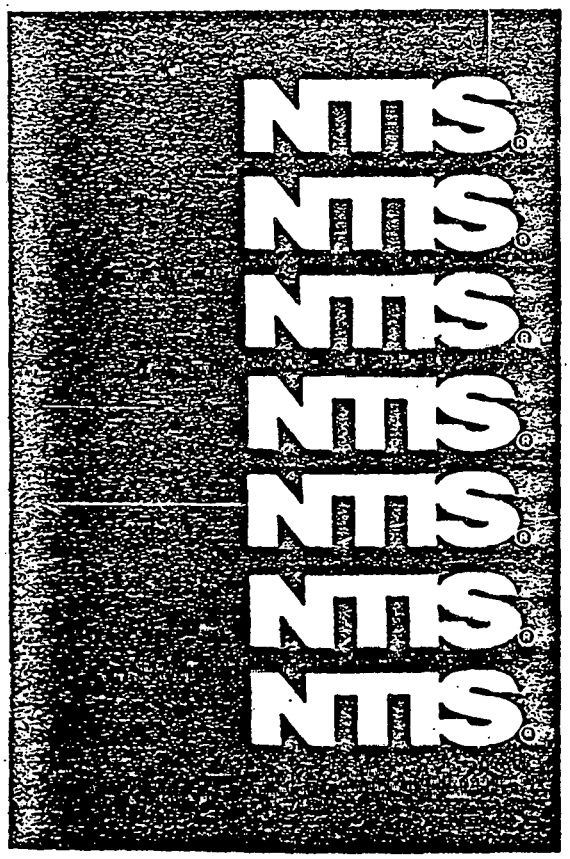

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