

Environmental Assessment for the Satellite Power System (SPS) Concept Development and Evaluation Program (CDEP)

August 1980

MASTER

Prepared for:
U.S. Department of Energy
Office of Energy Research
Satellite Power System Project Division

Under Contract No. 31-109-ENG-38

DOE/NASA
Satellite Power System
Concept Development
and
Evaluation Program

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Available from:

National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

Price: Printed Copy: \$10.00
Microfiche: \$4.00

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Prepared for:
U.S. Department of Energy
Office of Energy Research
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FOREWORD

The 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 and transfer this energy to earth. A reference system has been described that would use photovoltaic cells to collect the solar energy, convert it to microwaves, and transmit the microwave energy via directive antennas to large receiving/rectifying antennas (rectennas) on earth. At the rectennas, the microwave energy would be converted into electricity. The potential environmental impacts of constructing and operating the satellite power system have been assessed as a part of the Department of Energy's SPS Concept Development and Evaluation Program.

This report is the last environmental assessment for the SPS Concept Development and Evaluation Program. It has been preceded by the Preliminary Environmental Assessment for the Satellite Power System, first published in October 1978. A revision was issued in January 1980. This report is a summary of more-detailed information published in five volumes that refine and extend the earlier assessments and provide guidance for DOE recommendations regarding future SPS research and assessment.

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GLOSSARY

- ablate - to remove by cutting, erosion, melting, evaporation, or vaporization.
- aerodynamics - a branch of dynamics that deals with the motion of air and other gaseous fluids and with forces acting on bodies in motion relative to such fluids.
- albedo - the fraction of incident light or electromagnetic radiation that is reflected by a surface or body.
- ambient - the natural condition of an environmental factor.
- amplitude - the maximum departure of the value of an alternating wave from the average value.
- artifact - a product of artificial character due to an extraneous agent.
- attenuation - a reduction in amplitude of electromagnetic energy.
- beam width - the angular width of a beam of radiation, measured between the directions in which the power intensity is a specified fraction, usually one-half, of the maximum.
- bias current - the electric current applied to a device (e.g., a transistor) to establish a reference level for operation.
- biota - the plants and animals of a region.
- COTV - cargo orbit-transfer vehicle, used to take cargo between LEO and GEO.
- circadian - pertaining to events that occur at approximately 24-hr intervals, such as certain biological rhythms.
- cloud condensation nuclei (CCN) - particles upon which water vapor condenses to form water droplets, which in turn form clouds and fogs.
- cm - centimeter.
- continuous-wave radiation - single-frequency, uniform-amplitude electromagnetic radiation.
- convection - circulatory motion that occurs in the atmosphere due to non-uniformity in temperature and density, and the action of gravity.
- cortical tissues - tissue from the outer layer of gray matter of the brain.
- cosmic ray - a stream of atomic nuclei of heterogeneous, extremely penetrating character that enters the earth's atmosphere from outer space at a speed approaching that of light.
- coupling - the mechanism by which electromagnetic energy is delivered to a system or device.
- cytogenetics - a branch of biology that studies heredity and variation by the methods of both cytology and genetics.
- cytology - a branch of biology dealing with the structure, function, multiplication, pathology, and life history of cells.
- dB - decibel; a unit for expressing the ratio of two amounts of electric or acoustic signal power equal to 10 times the common logarithm of this ratio. A ratio of 10 is 10 dB, a ratio of 100 is 20 dB, a ratio of 1000 is 30 dB, etc.

dB(A) - "A-weighted" noise in decibels. The weighted average sound level over the frequency spectrum in accordance with the performance of the human ear.

dosimeter - a device for measuring doses of radioactivity.

ecology - a branch of science concerned with the interrelationship of organisms and their environment.

ecosystem - the complex of a community, and its environment functioning as an ecological unit in nature.

electromagnetic energy - energy in the entire range of wavelengths or frequencies of electromagnetic radiation extending from gamma rays to the longest radio waves and including visible light.

electron - a subatomic particle with a negative electrical charge.

endocrinology - a science dealing with the endocrine glands, which produce secretions that are distributed in the body by way of the bloodstream.

epidemiology - a branch of medical science that deals with the incidence, distribution, and control of disease in a population.

exosphere - the outer fringe region of the earth's atmosphere.

field intensity - the magnitude of the electric field in volts per meter or the magnitude of the magnetic field in amperes per meter.

flux - the rate of transfer of particles or energy across a given surface.

frequency - the number of complete oscillations per second of an electromagnetic wave, measured in hertz (Hz). One hertz equals one cycle per second.

geostationary - geosynchronous.

geosynchronous earth orbit (GEO) - the orbit at which it takes a satellite 24 hr to circle the earth so that it is stationary as viewed from the earth; altitude approximately 36,000 km.

GHz - gigahertz: one billion (1,000,000,000) hertz.

GW - gigawatt: one billion (1,000,000,000) watts; a measure of electric power.

harmonic frequency - a component frequency of an electromagnetic wave that is an integral multiple of the fundamental frequency.

hematology - a branch of biology that deals with the blood and blood-forming organs.

Hz - hertz: a unit of frequency equal to one cycle per second.

heavy-lift launch vehicle (HLLV) - used to transport SPS materials from earth to low earth orbit.

HZE - cosmic-ray particles with high charge and high energy.

immunology - a science that deals with the phenomena and causes of disease resistance.

intermodulation - the mixing of the components of a complex wave with each other in a nonlinear circuit. The result is that waves are produced at frequencies related to the sums and differences of the frequencies of the components of the original waves.

ion - an atom or group of atoms that carries a positive or negative electrical charge as a result of having lost or gained one or more electrons.

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

ionosphere - the part of the earth's atmosphere beginning at an altitude of about 5 km and extending outward 500 km or more, containing free electrically charged particles by means of which radio waves are transmitted great distances around the earth.

kg - kilogram: metric measure of mass. One kilogram is about 2.2 pounds.

klystron - an electron tube used to generate and amplify microwave current.

km - kilometer: a metric measure of distance. One kilometer is about 0.6 mile.

low earth orbit (LEO) - altitude approximately 500 km.

m - meter: a metric measure of distance. One meter is about 39.8 inches.

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.

mesoscale - of or relating to a meteorological phenomenon approximately 1-100 km in horizontal extent.

mesosphere - a layer of the atmosphere extending from the top of the stratosphere to an altitude of about 80 km.

μ Pa - micropascals: see Pa.

μ W - microwatt: 1/100,000 watt, a unit of energy or power.

microwave - a comparatively short electromagnetic wave, especially one between 100 cm and 1 cm in wavelength or, equivalently, between 0.3 and 30 GHz in frequency.

mW/cm² - milliwatts per square centimeter: unit of energy flow or power density. A milliwatt is 1/1,000 watt.

morphology - a branch of biology that deals with the form and structure of animals and plants.

multibiotic - having or consisting of many plants and animals.

neuroendocrine - of, relating to, or being a hormonal substance that influences the activity of nerves.

neutral particles - molecules, atoms, or subatomic particles that are not electrically charged.

neutron - an uncharged elementary particle that has a mass nearly equal to that of the proton and is present in all known atomic nuclei except the hydrogen nucleus.

noctilucent cloud - a luminous thin cloud seen at night at a height of about 80 km.

occultation - the state of being hidden from view or lost to notice: eclipse.

ohmic heating - a heating mechanism in a plasma or other conducting medium. The free electrons in the medium are accelerated by an applied electric field and give up kinetic energy by collision with other particles.

ppm - parts per million: used to measure proportion.

Pa - pascal: a unit of pressure equal to one newton per square meter. Twenty micropascals ($20 \mu\text{Pa}$) is about the threshold of hearing at 1000 Hz.

phase - the measure of the progression of a periodic wave in time or space from a chosen instant or position.

photoionization - ionization (as in the ionosphere) resulting from collision of a molecule or atom with a photon.

photon - a quantum of radiant energy.

plasma - a collection of charged particles exhibiting some properties of a gas but differing from a gas in being a good conductor of electricity and in being affected by a magnetic field.

PLV - personnel launch vehicle, used to transport SPS workers to low earth orbit.

POTV - personnel orbit-transfer vehicle, used to transport SPS workers between low earth orbit and geosynchronous earth orbit.

power density - the quantity of electromagnetic energy that flows through a given area per unit of time. Formally, power density is specified in watts per square meter (W/m^2), but by tradition in biological effects studies it is usually expressed in milliwatts per square centimeter (mW/cm^2).

propagation - the transmission of electromagnetic wave energy from one point to another.

proton - an elementary particle that is identical with the nucleus of the hydrogen atom, that along with neutrons is a constituent of all other atomic nuclei, that carries a positive charge numerically equal to the charge of an electron.

rectenna - a coined term for the SPS reference system receiving antenna that also converts the microwave power to direct-current electricity.

rectification - the conversion of an alternating current to direct current.

refraction - deflection from a straight path undergone by a light ray or energy wave in passing obliquely from one medium into another in which its velocity is different.

root-mean-square - for an alternating voltage, current, or field quantity: the square root of the mean of the square of the quantity during a complete cycle.

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

s - second: the 60th part of a minute of time.

side lobe - refers to power radiated from an antenna in a direction other than the desired direction of transmission.

spurious power or frequency - electromagnetic energy produced at frequencies that are not easily related to a specified operating frequency.

stratosphere - an upper portion of the atmosphere above approximately 10 km (depending on latitude, season, and weather) and in which temperature changes little with changing attitude and clouds of water are rare.

susceptibility - the sensitivity of an electromagnetic receiver to undesired electromagnetic waves that may result in interference.

symptomatology - a branch of medical science concerned with symptoms of diseases.

t - metric ton: 1000 kilograms.

teratology - the study of malformation or serious deviations from the normal development of fetuses.

thermosphere - the part of the earth's atmosphere that begins about 80 km above the earth's surface, extends to outer space, and is characterized by steadily increasing temperature with height.

troposphere - the portion of the atmosphere below the stratosphere, which extends outward about 15 km from the earth's surface, and in which temperature generally decreases rapidly with altitude.

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

SUMMARY

In the satellite power system (SPS), satellites in geosynchronous earth orbit would collect solar energy in space, convert it to microwaves, and transmit the microwaves to receiving antennas (rectennas) on earth. At the rectennas, the microwave energy would be converted to electricity. This SPS environmental assessment considers the microwave and nonmicrowave effects on the terrestrial environment and human health, atmospheric effects, and effects on electromagnetic systems. No environmental problem has been identified that would preclude the continued study of SPS technology. To increase the certainty of the assessment, some research has been initiated and long-term research is being planned.

Microwave Effects on Health and Ecosystems

SPS workers in space or on earth, the general public, and plants and animals would be exposed to microwaves from the power transmission system. Nonionizing microwave radiation cannot cause biological effects by the types of mechanisms effective in ionizing radiation. Most of the reported microwave effects on humans, animals, and plants are ascribed to the heating produced by the microwave energy. The current assessment is that at high levels microwaves have the potential to affect immune systems, reproductive processes, physiology, and behavior.

Maintenance space workers near the SPS transmitting antenna and terrestrial workers beneath the rectenna panels or just above them could be exposed to microwaves. The intensity and duration of the exposures could be controlled, and protective clothing might prove valuable. If international standards for microwave exposure are developed in the future, the microwave power transmission system would have to be designed to comply with such standards. Considering the small number of persons that would be involved and the options in design and environment control that are available, occupational exposure to microwaves is not considered to be a critical issue in the development of SPS technology.

Based on current knowledge, there would appear to be little risk of public health problems. However, the low level of microwave power density off the rectenna site would increase the median population exposure to background radio-frequency power density by more than an order of magnitude. A quantitative assessment of the risks associated with chronic exposure of the general population must be developed.

The potential for effects on the ecosystem as a whole due to the very low SPS microwave power densities is unknown, and research is needed. Initial studies of honey bee behavior and survival show no effect of exposure to SPS-level microwaves. Considering the very low microwave power density outside the rectenna site and the adaptability of the ecosystem, significant effects would not be likely.

Nonmicrowave Effects on Health and Ecosystems

Development of the satellite power system would entail conventional mining, manufacturing, and transportation activities. Their environmental consequences also may be regarded as conventional and would occur even if the SPS were not developed, as a result of the development of other new power sources. However, the space activities associated with the satellite power system must be given special consideration.

SPS depletion of resources and generation of conventional air and water pollutants and waste products could be locally significant and noticeable to the public near industrial centers and SPS rectenna and launch sites. None of these potential impacts would be peculiar to the satellite power system, and all could be controlled to some degree by conventional strategies. However, noise due to rocket launches and landings would present a special problem, and sites and trajectories would need to be carefully chosen. Also, sunlight would be reflected to earth by the solar satellites and other SPS structures. Initial studies of the effects of the reflected light on the eye are in progress and mitigation strategies may be required.

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. Available industrial safety measures appear to be adequate to maintain SPS-related risks at generally accepted levels.

One of the principal issues regarding the SPS is the ability of humans to work efficiently in space for extended periods of times without undue risk of life shortening or persistent disability. Available data provide no substantial evidence of unpreventable or noncorrectable adverse effects on the health of SPS space workers. Preliminary calculations of predictable exposure to ionizing radiation for SPS space workers indicate that radiation doses might exceed current limits recommended by national and international commissions on radiation protection. Unpredictable radiation, from solar storms for example, is also of concern. 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 as well as through special monitoring systems and personnel dosimeters.

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. Some of the impacts would be site specific and could be mitigated or eliminated by judicious site selection. Other principal ecological effects, yet to be quantitatively assessed, might stem from light reflected from power satellites and noise near launch and landing sites. Both of these, however, could be expected to be either minor perturbations or subject to mitigation by appropriate engineering changes.

Atmospheric Effects

The waste heat generated by rectenna operation and the effect of the structure on air flow and heat transfer would have a small impact on regional

weather and climate. The impact would be comparable to that of other non-industrial land-use changes covering the same area and would be of little consequence. The absorption of microwave power in the troposphere would be greatest during rainstorms, but even then would have a negligible effect on the weather.

Air quality impacts of SPS rocket launches should not be significant or involve violations of current standards. Nitrogen oxides could be expected in the ground cloud at concentrations comparable to those observed in power plant plumes. Promulgation of an air quality standard for nitrogen dioxide is anticipated, and although SPS heavy-lift-launch-vehicle launches by themselves would not be expected to violate the standard, launch emissions combined with existing levels could cause a problem. Nitrogen dioxide production could also lead to slight increases in acid rain locally and intermittently, but it is unlikely that the enhancement would be great enough to cause any environmental effect. Rocket effluents from heavy-lift launch vehicles might temporarily modify local weather under certain meteorological conditions; cumulative effects might be produced by multiple launches. Some mitigation would be possible through launch scheduling.

Carbon dioxide and nitrogen oxide emissions during the rocket launches would not have any detectable effect on the stratosphere and mesosphere. The average change in the total ozone column due to water vapor emissions from rockets, and its effect on ultraviolet radiation, would be undetectable. Significant corridor (local concentration) effects would not be expected. Theoretical calculations indicate that while some noctilucent clouds might form at the mesopause due to water vapor emissions, a permanent global-scale cloud would not be created. On this basis, no significant climatic effect would be expected.

The lower region of the ionosphere is important because of the effect of its ionization on the propagation of radio waves. Water vapor emitted by launch rockets might deplete the ionospheric plasma, while nitric oxide produced during reentry could enhance the ionization. Current capabilities do not allow a definitive assessment of the ultimate change in the plasma density and its effect on radio-wave propagation. SPS rocket effluents would reduce plasma density in the upper ionosphere, producing ionospheric holes that could interfere with telecommunications systems. Each injection burn of a personnel orbit-transfer vehicle would create an ionospheric hole the size of the continental United States. The circularization burns of the heavy-lift launch vehicles would produce holes one-tenth the size. While a confident prediction of cumulative effects is not yet possible, it has been estimated that a chronic, low-level ionospheric depletion would develop in a ring-shaped global region centered around the launch latitude. More-detailed modeling and an assessment of radio-wave propagation effects are required.

Because the chemical and argon-ion effluents deposited in the upper atmosphere by personnel and cargo orbit-transfer vehicles would be substantial compared to naturally existing quantities, these effluents could affect radiation levels in the Van Allen Belts, terrestrial weather, space-based optical sensors, magnetic storms, and space-based communication systems. The probability that any of these effects would occur is unknown, but the current assessment is that the consequences would not be so severe or the required mitigating strategies so difficult as to impede the SPS project.

Effects of Ionospheric Heating on Telecommunications

Changes in the ionosphere can alter the performance of telecommunication systems whose power is transmitted within and through the ionosphere. The microwave power density transmitted from solar power satellites to earth might be sufficient to heat the ionosphere, even though only a small fraction of the microwave power would be absorbed by the ionosphere.

Effects on the lower ionosphere would be due to enhanced heating through the ohmic heating mechanism. Telecommunications experiments have been performed using ground-based ionospheric heating facilities to observe the performance of representative systems whose radio waves are affected by the structure of the lower ionosphere. The results obtained indicate that the SPS, as currently configured with a peak power density of 23 mW/cm^2 , would not adversely impact the performance of very-low-frequency, low-frequency, and medium-frequency (3 kHz - 3 MHz) telecommunication systems. Continued theoretical and experimental work is required to establish the maximum microwave power density that would not adversely affect communications systems that use the lower ionosphere.

It is expected that heating effects in the F-region would be due to plasma irregularities caused by the thermal self-focusing phenomenon. Results obtained from experimental simulation of SPS operation to measure thermal self-focusing impacts have revealed potential heating effects on satellite signals propagated in the very-high-frequency band. The observations are preliminary, and further work is required before the SPS impact on telecommunication system performance can be assessed with confidence.

Electromagnetic Systems Compatibility

The satellite power system would be designed and operated in ways that would satisfy established national and international rules for using the electromagnetic spectrum. Nevertheless, there would be a substantial potential for producing interference. The amount of microwave energy transmitted from space to earth would be 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. The size of the microwave beam would also be very large at the earth's surface.

Conventional engineering practices and models of electromagnetic interference can be used to determine the electromagnetic susceptibility of electronic equipment to microwave energy produced by the satellite power system. The uniqueness of SPS interference relates more to the scope of the potential problem (the number of systems that might be affected) than to the kinds of interference that might result in the absence of ameliorative measures. The principal strategies for avoiding or minimizing SPS interference would be careful engineering design of the microwave transmitting and receiving antennas, judicious rectenna siting, and conventional methods such as shielding, filtering, and design of the affected systems. With the exception of sensitive military and research systems, equipment more than 100 km from a rectenna site should not require modification or special design to avoid degradation in performance.

Solar power satellites could interfere with the communications and electronic circuitry of other satellites. Satellites in low earth orbit that would pass through the SPS microwave beam would require special design modification, shielding, and filtering. Their operational procedures would probably also need to be adjusted to account for passage near or through the beam. Satellites in geosynchronous earth orbit, if sufficiently separated from a solar power satellite, should not be affected. The allowable spacing between a solar power satellite and other satellites in geosynchronous orbit would probably not be less than 1° , but this is based on approximate analyses that will require refinement as the SPS technology develops.

Military equipment used at major national defense installations for combat training and equipment evaluation usually is especially sensitive to extraneous electromagnetic fields. Although sensitive military systems could be modified and adapted to restore a predetermined level of performance, the low probability of error or the high safety margins designed into these systems could be compromised. It is likely that the only acceptable strategy for mitigating SPS interference with military systems would be rectenna siting.

Radio and optical astronomy involves study of the weakest measurable signals from the sky. The SPS would produce large additions to existing interference in the radio, infrared, and optical portions of the spectrum, thus hindering astronomical observations. Mitigation strategies that require modification of the astronomical equipment (e.g., filtering) would reduce the range of the observations. Rectenna siting and terrain shielding would not be effective because the interference source (i.e., the solar power satellite) would be high in the sky. As the SPS technology develops, the compatibility with astronomy will be a major consideration. The most likely mitigation strategies would involve the design of the satellite power system.

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 has been studied by the U.S. Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA). This joint program generated the information needed to make a rational decision regarding development of the satellite power system (SPS) program after 1980.* NASA defined the engineering and operating characteristics of the SPS. DOE evaluated the system's health, safety, and ecological impacts; examined economic, international, and institutional issues; and developed comparative assessments of the SPS and alternative future power sources.

An SPS "reference system" developed by NASA provided the technical and operational information DOE needed to conduct its environmental and socio-economic studies and comparative assessments.** The reference system was an interim working concept; NASA's current work has provided 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 km² built on a graphite-fiber-reinforced structure, as illustrated in Figure 1. A microwave transmitting antenna 1 km 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 100-km² rectenna for each satellite would be built at the same time. The reference system presumes 60 satellites would be constructed over a 30-yr 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 vehicles, personnel launch vehicles, cargo orbit-transfer vehicles, and personnel orbit-transfer vehicles.

The environmental assessment for the concept development and evaluation phase of the SPS program is designed to:

- Identify and describe the environmental issues associated with the SPS reference system;
- Prepare an assessment based on existing data;
- Suggest mitigating strategies and provide environmental data and guidance to other components of the program as required;

*See Satellite Power System Concept Development and Evaluation Program Plan (July 1977 - August 1980), Dept. of Energy Report DOE/ET-0034 (Feb. 1978).

**See SPS Concept Development and Evaluation Program Reference System Report, Dept. of Energy Report DOE/ER-0023 (Oct. 1978).

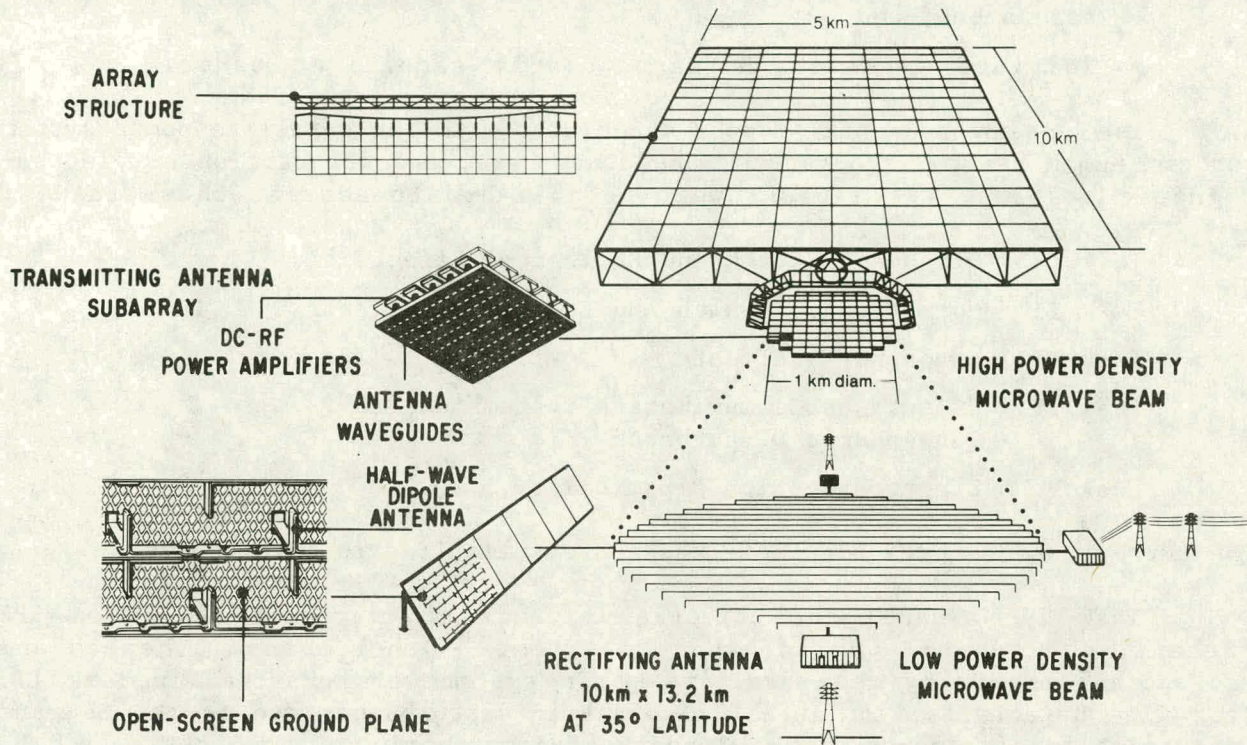


Fig. 1. Basic Satellite Power System Characteristics

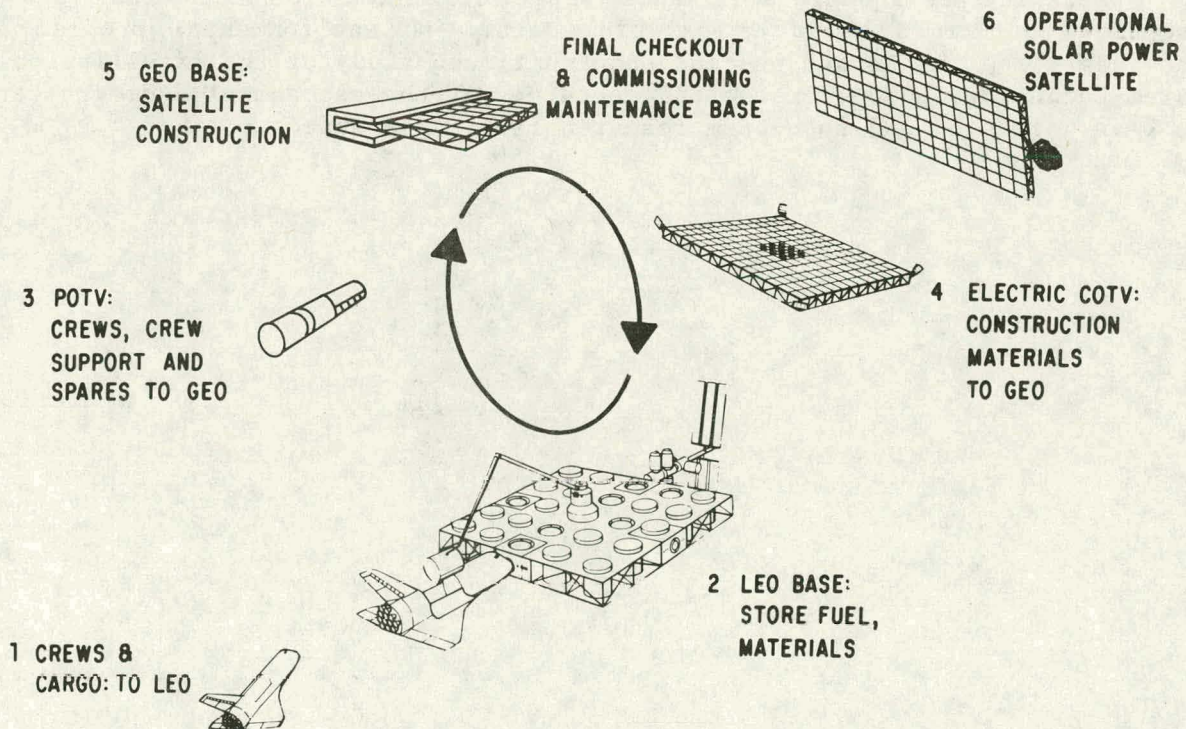


Fig. 2. Conceptual SPS Earth-to-Space Transportation Plan

- Plan long-range research to reduce the uncertainty in the assessment; and
- Initiate research on particularly sensitive issues.

The key environmental issues associated with the satellite power system concern human health, ecosystems, the atmosphere, and interaction of electromagnetic systems. Five tasks were 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 evaluated 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 were examined in Task II. Task III characterized potential atmospheric disturbances due to the SPS and assessed climatic impacts. The impacts of ionospheric disturbances caused by microwave heating on communication systems that use the ionosphere for radio-wave propagation were evaluated in Task IV and in part in Task III. Task V addressed the direct effects of the microwave power transmission system on communication and other electromagnetic systems.

Specific environmental issues were identified for each task and an assessment performed based on existing data. No environmental problem has been identified that would preclude the continued study of the satellite power system technology. To increase the certainty of the assessment, some research has been initiated and long-term research is being planned.

1 HEALTH AND ECOLOGICAL EFFECTS OF MICROWAVE RADIATION

1.1 INTRODUCTION

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. In light of these facts, the health and ecological effects of exposure to SPS microwave power must be analyzed.

The SPS microwave radiation assumed for this assessment is that presented in the SPS reference system report.^{1*} The reference system microwave frequency is 2.45 GHz; the power density profile at and near an example rectenna site is illustrated in Figure 3. If there were 60 rectennas in the continental United States spaced an average of 300 km apart, the tails of the power beam patterns would combine and the minimum power density at any point would be about 0.0001 mW/cm².

The power density beneath the rectenna panels would depend on design details and location under the panels and could be as high as 5 mW/cm² near the edge of a rectenna panel. However, for most of the area the power density would be less than 1 mW/cm². In space, near the satellite's transmitting

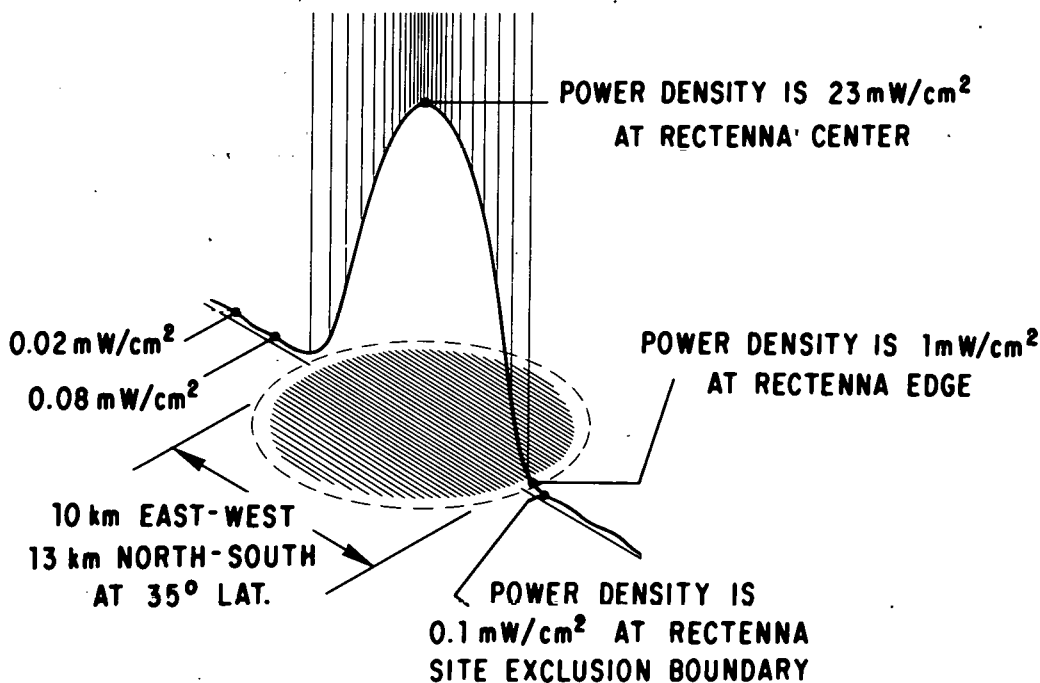


Fig. 3. SPS Microwave Power Density Characteristics at a Rectenna Site

*References for Section 1 are listed in Section 1.4.

antenna, the power density would be about 2200 mW/cm² near the center of the antenna and 240 mW/cm² near its edge.

The SPS energy beam would be under the control of a ground-based pilot beam. Each subarray of the transmitting antenna would have its own radio-frequency receiver and phasing electronics to process the pilot-beam instructions. If the phase-control system failed, the power beam would diverge and the peak power density would drop to about 0.003 mW/cm². If the main power beam began to drift from the center of the rectenna, sensors at the rectenna site would feed back signals to the transmitter and the power flow would be interrupted. Harmonics of 2.45 GHz would be generated at the transmitter and the rectenna, but the power densities associated with them would be orders of magnitude less than the power density at 2.45 GHz.

The basic exposure situations to be considered are:

- Space workers could be occupationally exposed to high power densities and their space suits would need to be designed for protection.
- Persons working at the rectenna site would be exposed for controlled periods of time to power densities up to 23 mW/cm², or perhaps higher if reflections and enhancements are considered. Suitable exposure standards must be developed.
- The general population would be continuously exposed to power densities of 0.1 mW/cm² or less.
- Airborne biota within the microwave beam would be exposed to power densities of up to 23 mW/cm² for durations that depend on whether the biota are transient or indigenous to the rectenna site.
- Transient and indigenous ground animals and plants within a rectenna site would likely be exposed to power densities less than 1 mW/cm² because the rectenna would absorb most of the incident radiation.
- Plants and animals outside the exclusion boundary would be continuously exposed to 0.1 mW/cm² or less.

1.2 ASSESSMENT

This assessment summarizes a more-detailed treatment of the subject,² and also makes use of preliminary assessment reports prepared for the satellite power system project^{3,4} and other general reviews.⁵⁻⁷ These documents represent a comprehensive review of the relevant literature.

1.2.1 Nonionizing versus Ionizing Radiation

The distinction between microwave radiation and ionizing radiation is often not made. Consequently, the known hazards of the latter are linked -- by implication -- with exposure to microwaves. In essence, ionizing radiation

(which includes ultraviolet light, x-rays, and the emissions from radioactive materials) has sufficient photon energy to expel an electron from a molecule, leaving the molecule positively charged (ionized) and thereby strongly affecting its interactions with neighboring molecules. Ionization can alter the functions of biological molecules fundamentally and often irreversibly. By contrast, the photon energies of microwaves are so much smaller that their primary effect is to agitate molecules rather than ionize them. Also, microwave-induced agitation ceases after exposure is halted. At low microwave intensities, the heat that such agitation represents is well accommodated by the normal thermoregulatory capabilities of the human, plant, or animal exposed, and therefore such effects are generally reversible. At high intensities, the thermoregulatory capabilities may be unable to compensate for such effects, thereby leading to thermal distress or even irreversible thermal damage. In summary, a single photon of ionizing radiation that is absorbed by a molecule alters the properties of that molecule and thereby may profoundly affect the function of the biological entity involved, whereas the concurrent absorption of many photons of microwave radiation is necessary to cause biologically significant effects.

It follows from the discussion above that even if a biological effect were produced by microwave radiation, that effect might not necessarily be deleterious. It should be stated that one of the reasons why the levels of allowable exposure of humans to microwaves are generally lower in Eastern European countries than in the rest of the world is the philosophically based Eastern European assumption that every effect produced by microwaves is potentially harmful. This view is not generally shared by scientists in Western countries.

1.2.2 Exposure Standards

The term "exposure standards" is generally applied to specifications or guidelines for permissible occupational and nonoccupational exposure of humans to electromagnetic fields. The standards are expressed as maximum power densities or field intensities in specific frequency ranges and for indicated exposure durations.

The present U.S. standard is based on average power densities and is essentially the same as the American National Standards Institute (ANSI) radiation protection guideline.⁸ Under this standard, which applies to the frequency range from 10 MHz to 100 GHz, a power density of 10 mW/cm² should not be exceeded when averaged over any exposure period of 0.1 hr. This maximum permissible level is appropriate for exposure under moderate temperature and humidity conditions; lower values should be used under environmental conditions that induce significant heat stress.

The 10-mW/cm² value originated from (1) the physiological consideration that whole-body exposure of a human to levels above 100 mW/cm² would produce a mild to severe increase in thermal load, depending on the level, and (2) the application of a safety factor of 10 to the lower limit of this power-density range.

The U.S. standard does not contain specific enforcement or punitive provisions for violations. It has been promulgated by the Occupational Safety

and Health Administration (OSHA) as a radiation protection guide for occupational exposure and has been adopted by a number of organizations, including the Department of Defense. The principle underlying this guideline was the belief, based on the then-available scientific evidence, that nearly all workers could be exposed to such a level of microwave radiation during the normal series of working days without adverse effects. The guideline thus recognized that electromagnetic fields might cause biological effects that have no medical consequences, or that the workers could readily adjust to the effects.

Based on recent experimental and theoretical results, the U.S. Environmental Protection Agency (EPA), National Institute for Occupational Safety and Health (NIOSH), and ANSI are considering possible revisions to the U.S. standard. A provisional frequency-dependent standard based on an average specific absorption rate (SAR) limit of 0.4 W/kg in exposed tissue is being discussed. Environmental levels of electromagnetic fields are very much lower than occupational levels, and the question of environmental standards for the general population is still under consideration by the EPA.

Present standards in the United Kingdom, France, and West Germany are essentially the same as the current ANSI guideline.² This was formerly true for Canada also. However, the Canadian government has recently revised its standard. The maximum permissible nonoccupational level for continuous exposure is 1 mW/cm², applicable to frequencies from 10 MHz to 300 GHz. For occupational exposure, the maximum levels are frequency- and duration-dependent. For example, for the frequency range of 1-300 GHz, the new standard permits exposure to 5 mW/cm² for a maximum of 8 hr/day, up to 10 mW/cm² for 6 min or less, and up to 25 mW/cm² for 2.4 min or less.

The Swedish standard, which formerly was essentially the same as the U.S. standard, was revised in 1976.² Again, the new maximum occupational exposure levels are about ten times lower than they were. The new standard is assumed to apply to the general population as well.

Presumably, the reductions of maximum permissible microwave exposure in the Canadian and Swedish standards were engendered in part by consideration of some of the relatively recent research results indicative of biological effects due to chronic exposure to power densities of 1-10 mW/cm². For similar reasons, it is likely that the exposure allowed by the U.S. standard may also be comparably reduced.

In the Soviet Union, the maximum level for 24-hr exposure of the general population is 5 μ W/cm², and the occupational standard specifies higher maximum levels.² For example, in the frequency range from 300 MHz to 300 GHz, it permits levels from 10 μ W/cm² for a full working day to 1 mW/cm² for 20 min of exposure. However, Soviet military personnel are specifically exempted from such standards. While the process by which the Soviet standard was set is unknown, we can surmise that the standard is based in part on the claimed existence of effects due to nonthermal mechanisms and on the philosophy that exposure to microwaves of any power density is potentially harmful, leading to the application of large safety factors in formulating maximum permissible exposure levels.

It is possible that international standards will be developed in the future. As the SPS technology develops, the microwave power transmission system would have to be designed to comply with such standards.

1.2.3 Ambient Electromagnetic Power Densities

SPS microwave power-density levels can be indirectly compared with background or ambient power densities of radio-frequency radiation. The EPA is measuring ambient electromagnetic field intensities at selected metropolitan locations to permit estimations of cumulative fractions of the total population being exposed to various power densities. A recent report presents the results for 15 cities, including a total of 486 sites.⁹ The report concludes that, for the population group studied -- representing 20% of the total U.S. population, the median exposure value is $0.005 \mu\text{W}/\text{cm}^2$ time-averaged power density. Less than 1% of the population is potentially exposed to levels above $1 \mu\text{W}/\text{cm}^2$. It was observed that FM radio broadcasts at 88-108 MHz are responsible for most of the continuous exposure of the general population. Direct comparison with SPS microwaves cannot be made because of the frequency difference. Nevertheless, these data provide a measure of the ambient non-ionizing radiation.

These ambient levels may be compared with the $0.1\text{-}\mu\text{W}/\text{cm}^2$ minimum level expected if 60 rectennas were constructed in the continental United States. The conclusion is that nearly all of the general population would be exposed to levels significantly greater than the current background levels. Before these rectennas are constructed, a quantitative assessment of the risk associated with this exposure must be developed.

1.2.4 Interpretation of Experimental Results

Most of the data available for this assessment results from experiments with laboratory animals. The difficulties in interpreting the literature for this type of assessment have been discussed in detail.^{2,3,5} The problems include:

- Proper treatment of experimental conditions such as methods of animal care, the role of seasonal and circadian rhythms, temperature, humidity, etc.
- Consideration of differences in size, metabolism, and physiology.
- Proper application and interpretation of statistical analyses.
- Proper dosimetry.

To illustrate the effect of frequency and body size on dosimetry, it has been estimated² that a man exposed to $1 \text{ mW}/\text{cm}^2$ of microwave radiation at a frequency of 70 MHz would absorb 0.2 W/kg, but at 2.45 GHz, only 0.03 W/kg would be absorbed. By contrast, exposure of a laboratory rat to $1 \text{ mW}/\text{cm}^2$ at 2.45 GHz would result in a specific absorption rate of 0.2 W/kg. The inherent difficulties in extrapolating from animals to humans and in interpreting data at other frequencies are apparent.

1.2.5 Biological Effects Research

The potential implications of human microwave exposure due to SPS operation have been assessed through a thorough review of the literature.^{2*} The following categories have been adopted to present the results of this review and assessment:

- Epidemiology
- Genetic and cytogenetic effects and cancer induction
- Teratogenesis and developmental abnormalities
- Ocular effects
- Nervous system
- Behavior
- Endocrinology
- Immunology

When appropriate, effects on animals are discussed under these categories as well; additional information on microwave effects on ecosystems and airborne biota is presented in Section 1.2.6.

Epidemiology

Several epidemiologic studies have been performed to determine if one or more health conditions can be associated statistically with chronic exposure to nonionizing electromagnetic radiation such as microwaves. Although none of these studies has clearly defined the exposure conditions, they do represent the recent information on possible effects of human exposure to radio-frequency radiation.** Studies done in the United States, Poland, and Czechoslovakia offer no evidence of detrimental effects associated with exposure of the general population to RFR. Soviet studies offer findings that occupational exposure to RFR at average power densities less than 10 mW/cm² does result in various symptoms, including symptoms associated with central nervous system disorders. Because the Soviet findings have never been duplicated in Western studies, and because there are marked differences between Soviet and Western publications in the procedures used for reporting data, any prediction of possible RFR hazards based on the Soviet epidemiological studies would require acceptance of these findings at face value. Thus, available epidemiological studies do not provide the data necessary to either make a quantitative assessment or qualitatively suggest or dismiss the possibility of effects from human exposure to microwaves.

*See the detailed assessment report (Ref. 2) for citations of the studies referred to in this summary.

**The term radio-frequency radiation (RFR), as used here, is intended to apply to frequencies from approximately 10 MHz to 18 GHz. RFR includes microwaves.

Genetic and Cytogenetic Effects and Cancer Induction

Mutations may occur in any plant or animal species due to 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.

Although a number of papers published over the last 30 years have claimed that microwave radiation at various frequencies can produce mutations, chromosome aberrations, and cancer, a careful review of these papers indicates that all of the reported effects are probably due to temperature rise, faulty experimental procedure, or other incidental causes. There is no reliable or systematic evidence that microwave radiation can induce any type of mutation in living systems other than -- possibly -- by heating the tissue under examination. The mechanism by which temperature rise could induce apparent mutagenic effects is not understood. Possibly an increase in temperature accelerates the rate of spontaneous mutagenic processes in the tissue. There is no evidence that microwave irradiation induces cancer, although it is possible that some cancer-promoting effect could result from action of microwaves on the endocrine system (see later discussion of endocrinological effects). On the whole, however, there is probably no possibility of mutations or cancer from microwave radiation.

The SPS microwave transmission system would not be expected to produce mutations or cancer in humans or animals. 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 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.

Teratogenesis and Developmental Abnormalities

In the narrowest sense of the word, teratogenesis refers to the production of anatomical aberrations in a developing fetus. The term is most often applied to development of mammalian fetuses, but studies of microwave effects on the development of bird eggs and the darkling beetle's pupae have also been performed. Teratologic studies also have included observations of fetal death or resorption and of physiological and cellular abnormalities observed in the offspring after birth.

Teratogenic effects of microwave radiation have been reported by a number of studies. At power densities greater than 10 mW/cm², fetuses of small rodents have exhibited delayed growth and increased teratologic changes, whereas representative avian species showed no evidence of teratologic effects. Also, squirrel monkeys exposed to power densities up to 10 mW/cm² daily during most of the gestation period showed no birth defects. Although

the mechanism for induction of teratologic effects is not known, it may be presumed that temperature rise or heat load in the irradiated subjects plays a significant role.

In summary, exposure to power densities greater than 10 mW/cm² may delay fetal growth in mammals, but not in birds. Some rodent fetuses could be harmed at the rectenna site. However, harm to human fetuses off the rectenna site would not be expected because of the lower power densities (0.1 mW/cm² or less) and the frequency/body-size relationship, which would further diminish the absorption of energy by humans.

Ocular Effects

During the past 30 years, various studies have examined RFR effects on the eyes of animals. Many of the results indicate that temperature increases within the eye of about 5 C° or more are necessary for eye damage. The eye damage most often takes the form of cataracts. Also, lens opacifications caused by RFR exposure alone have not been produced at the same power density when the eye was cooled.²

Many of the results of RFR exposure studies indicate that (1) there is an inverse relationship between average power density and exposure duration as causes of cataract formation and (2) a threshold average power density for cataract formation exists at about 100 mW/cm².^{2,5} For example, for average power densities decreasing from about 500 mW/cm² to 200 mW/cm², the exposure duration needed to damage rabbit eyes increases from 1-2 min to about 20 min. However, cataracts have not been produced at 100 mW/cm² for exposure durations of up to 100 min. Thus, it is not expected that humans or animals would suffer eye damage from chronic exposure to SPS microwaves, either at the rectenna site, in transit through the beam, or outside the rectenna site.

Several retrospective epidemiological studies were performed to ascertain whether or not chronic exposure to RFR could cause cataracts. As with other retrospective epidemiological studies, the exposure histories (frequencies and intensities of radiation, duration of exposure, etc.) in either the exposed or the control groups used in these studies were difficult to determine accurately. However, it is quite likely that the exposed groups did receive more RFR exposure than the control groups. The results support the conclusion from animal studies that chronic exposure to RFR at average power densities well below 150 mW/cm² is not likely to produce cataracts.

Nervous Systems

People near some types of pulsed radar systems have perceived individual pulses of RFR as audible clicks. This phenomenon has often been cited as evidence that microwave effects due to nonthermal mechanisms can occur. An initial hypothesis was that one of the possible mechanisms for perception was direct stimulation of the central nervous system by RFR. However, various theoretical and experimental studies, the latter with both human volunteers and laboratory animals, have been conducted to determine the conditions under which pulsed RFR can be heard and to investigate the mechanisms involved.

Many of the results support the hypothesis that a pulse of RFR having the requisite power density and duration can produce a transient thermal gradient large enough to generate an elastic shock wave at some boundary between regions of the head with dissimilar dielectric properties, and that this shock wave is transmitted to the middle ear, where it is perceived as a click. Furthermore, this auditory phenomenon is a pulsed-RFR effect and would not be of concern with regard to the proposed SPS continuous microwave transmission.

One series of studies^{2,3} indicates that the nervous system is selectively responsive to weak electromagnetic fields with frequencies below 30 Hz or to microwave fields that are modulated at these low frequencies. Electromagnetic radiation can alter the flux of calcium ions in cortical tissues of brains isolated in the laboratory, but only when the RFR is modulated by frequencies between 5 Hz and 25 Hz, which are near natural biological frequencies (e.g., near the 8- to 16-Hz range of the electroencephalogram [EEG] alpha rhythm). The effect may be related to subtle but reliable shifts of timing behavior that are seen in experiments using monkeys. Because the effect is modulation-frequency dependent, it may be considered irrelevant to SPS. However, a field that is not modulated by its source can nonetheless be modulated by an exposed animal as it moves in the field.³ A particularly relevant example is that of a bird's wings as it flies through a microwave beam.

The existence of a "blood-brain barrier" in most regions of the brain has been established experimentally, although its specific structure is still conjectural. This barrier normally provides high resistance to movements of large molecules, such as proteins or polypeptides, from the blood vessels into the surrounding brain tissue, presumably to protect the brain from invasion by various blood-borne pathogens and toxic substances. Several investigators have reported that low levels of RFR can increase the permeability of the blood-brain barrier to certain substances of large molecular weight. However, others have been unable to confirm such effects, thereby rendering the results controversial and inconclusive. •

There have been reports of microwave effects in animal tissue at energy levels presumed to be below those that would cause increased temperature. However, later studies, with a better understanding of localized power deposition, have shown that although the conditions varied widely, all effects reported were clearly due to thermal mechanisms.

Many studies have been conducted of the EEG of animals exposed to radio-frequency radiation. Some of these have been carried out with metal electrodes either implanted in the brain or attached to the scalp during exposure. The use of such metallic electrodes grossly perturbs the electromagnetic fields and greatly enhances energy absorption near the electrodes. Such enhancement produces artifacts in the experiment that can be minimized by use of electrodes appropriately designed from high-resistivity materials. Experiments in which such specially-constructed electrodes were used, or in which electrodes were applied after exposure, show no evidence of statistically significant differences in EEGs or evoked responses between control and RFR-exposed animals.

For humans and animals outside the SPS rectenna site, it would seem that effects on the nervous system are unlikely. Beneath the rectenna panels,

the power density is also probably too low to expect effects on the nervous system. For airborne biota, having access to the power beam and power densities up to 23 mW/cm², the question is whether effects might be induced by "biological modulation." However, there is nothing in the current literature that allows a definitive assessment. Studies of microwave effects on airborne biota have been initiated as part of DOE's evaluation of the SPS (see Section 1.2.6).

Behavior

Behavior is one of the most-explored aspects of microwave effects; a number of studies have examined several aspects of behavior that could be altered by nonionizing radiation exposures relevant to SPS microwaves. These include studies of microwave perception, the effects of microwaves on the learning and performance of trained tasks, and interactive effects of microwaves and drugs on behavior.

Many of the studies seem to have been prompted by Soviet reports claiming that RFR had direct effects on the central nervous system at low power densities. Evidence to support this claim from U.S. neurophysiological research is meager, and the behavioral evidence also does not support the claim.² The studies of microwave radiation as a noxious stimulus do not show that animals can perceive microwave radiation as such. The radiation avoidance observed in some experiments appears to be part of the thermoregulatory behavior of animals, and under circumstances where the environment is cold, animals will use microwave radiation as a source of warmth. Disruption of performance or learning appears to have power-density thresholds in the region of thermal load on the animal. The most sensitive behavioral responses to microwaves appear to arise when the microwaves interact with drugs affecting the central nervous system, but even studies that examine such interactive effects do not prove direct effects of microwaves on the central nervous system. Overall, the behavioral studies do not indicate a special effect of microwaves on the nervous system, and the mechanism of most of the results that have been reported remains unknown.

It has been shown that rodents react to the microwave power densities expected at rectenna sites with lowered activity, avoidance of the radiation field, and decreased discrimination. As a result, continued research is required to define the potential for behavioral response at the rectenna site. Although some of the effects have been reported at lower power densities in the East European literature, they have not been confirmed in U.S. studies. Behavioral effects outside the rectenna site are very unlikely, but this must be confirmed by further research.

Endocrinology

Endocrine glands secrete hormones into the bloodstream. Microwave irradiation of mammals has produced somewhat inconsistent effects on the endocrine system. In general, the effects appear to be related either to the heat load associated with the irradiation or to the stress induced in the animals by the irradiation and, possibly, by other experimental circumstances.

Some effects also appear to be related to alteration of the circadian rhythm by microwaves. There do not appear to be any effects arising from direct stimulation of the endocrine system or the associated parts of the central nervous system. Although most of the effects of microwaves on the endocrine system appear to be relatively straightforward and predictable from physiological considerations, there are still some details that require further study.

Immunology

Reports to date have shown that microwave radiation has effects on the immune system of mammals. Some of the reported effects were obtained at low power densities, but most of the studies were performed at relatively high power densities, and in some cases effects obtained at high power densities were not found at lower power densities, suggesting the possibility that power-density thresholds exist. Some of the results indicate immunosuppressive effects, some indicate immunostimulative effects, and some indicate that the state of the immune system depends on the duration of exposure or the time -- in relation to the time of irradiation -- when measurements were taken. The existing evidence indicates that the immune system effects are probably mediated through the effect of the radiation on the endocrine system, involving the general adaptation syndrome to stress. It appears doubtful at present that microwaves have any direct stimulatory effect on the cells of the immune system.

Two main points need to be elucidated in experimental studies. First, the relationship of the immunological responses to the duration, intensity level, and timing of the radiation needs to be clarified. In particular, it is desirable to determine if, and at what power densities, animals can accommodate to the radiation so that the immune system returns to its normal state. Second, the mechanism for induction of immunological effects needs further study. Present evidence suggests that the immune system effects are part of a general stress reaction, but clarification is needed as to the nature of the stress in relation to other environmental stresses. The Department of Energy has initiated research on the effects of microwave exposure on the immune system.

The current assessment is that no effect on the immune system could be expected for the general population off the SPS rectenna site. Within the rectenna site, only temporary alterations in these systems could be expected as a result of short-term exposures, and the effects of long-term occupational exposure are not yet known. For animals, no effect would be expected outside the rectenna site; on-site, effects would be anticipated from prolonged exposures and reversible effects from transient exposure also would be possible.

1.2.6 Ecosystems and Airborne Biota*

There is no indication in the literature that comprehensive studies of microwave exposure of complex ecological systems have been made. The

*Microwave effects on animals are also discussed in Section 1.2.5.

complexities inherent in multibiotic systems will pose a difficult and time-consuming challenge in the evaluation of SPS impact. As an ecosystem becomes more complex, there is an increased likelihood that data based on its elements as studied in isolation cannot be generalized to the whole system. A perturbation to a component of the ecosystem may be amplified or suppressed by the interrelationships of the system.

Although some data are available on the effects of acute exposures of man and some animals to microwaves, there is a dearth of information on chronic exposures of most of the animal kingdom. Likewise, there is little information concerning effects of microwaves on plants or soil. Particularly lacking is information on the effects of long-term exposure of large land areas and the ecosystems they contain.

Before any valid assessment of the ecological impact of SPS can be made, information must be obtained about the effects of exposure on plants, insects, microbes and fungi, heterotherms such as snakes and lizards, birds, and small and large mammals -- to name but a few.

Much of the scarce data available on plants is not applicable to predicting the impact of microwaves on plant communities. Early research was designed primarily to determine gross thermal effects, and most initial power densities were in excess of 100 mW/cm². Relationships between incident and absorbed microwave energy and associated changes in plant temperatures are virtually unknown. Rates of microwave energy absorption and morphophysiological characteristics that influence microwave heating have not been determined. No attempts have been made to determine plant response to continuous exposure to low-level microwave illumination over several generations. Thus, there is much to be learned about the impact of microwaves on specific plant species and plant communities.

Microbes and fungi play an important role in general ecological balance. They can instigate diseases in higher orders of plants and in animals. Also, fungi are responsible for the decomposition of dead cellulose matter. It is conceivable that microwave power transmission could alter the biological balance so that regulatory mechanisms that maintain order in fungal ecosystems would no longer be synchronous. The result could be interactions leading to plant disease. Alternatively, there might be negligible effects. Again, no data are available at present.

Heterotherms or heliotherms are animals that regulate body temperature by behavioral means. Within the vertebrates, these include reptiles, fish, and amphibians. These forms are often called "cold-blooded," suggesting that body temperature may be near the ambient soil-air interface temperature. This is true for fish and amphibians, but reptiles can regulate their temperature to a level considerably higher than that of the air. Orientation of the body is one reptilian mechanism for maximizing or minimizing interception of radiation. In addition, many reptiles seek out or avoid radiant energy in the environment by such behavior as seeking shade.

Lizards and snakes are two heterotherms that could be influenced by adding a source of energy such as the SPS power system to the environment. Studies with rattlesnakes, boas, and anacondas have shown that these snakes

detect microwave energy at very low levels, well below 10 mW/cm^2 , apparently by means of infrared receptors. Although diurnal snakes do not have specialized infrared detectors, they still may use the energy. The implications of these findings are unclear at present.

Effects on the human population around a rectenna system could be minimized by bordering that system with a large restricted area that would not be accessible to the general population. Such a conservative approach, however, would not prevent airborne biota from flying through the area. Specific studies of the impact on bees and birds are of the highest priority.

Birds in flight are close to their thermal limit, and passing through the microwave beam might impose an additional thermal burden. Furthermore, birds apparently use the earth's magnetic field as one of several inherent navigational aids, and the SPS electromagnetic beam might affect their use of inherent navigational capabilities. Bees are important because of their impact on the pollination process, which is important to humans' food supply. Fortunately, they are relatively easy to handle experimentally and have a short life cycle; therefore, they are attractive experimental subjects.

Two research studies have been initiated as part of DOE's study of the SPS. One will investigate microwave effects on birds. The other is examining (1) the behavioral elements of orientation, navigation, and memory of honey bees; (2) survival and development in immature stages of honey bees; and (3) survival and longevity of adult worker bees. The initial results of the first two studies show no effect of SPS microwave power densities. The third study is not yet completed.

The SPS would require large areas of natural and man-altered ecosystems for rectenna sites. The ecological effects of long-term, low-dose exposure cannot be accurately predicted at the present time. Even if the basic biological effects of such exposure were well known, prediction of ecological impact based on laboratory studies of individual species would be speculative. Site-specific ecological field research eventually will be necessary to answer critical questions for the SPS.

1.3 SUMMARY AND CONCLUSIONS

The distinctions between ionizing radiation (e.g., x-rays and emissions from radioactive materials) and nonionizing microwave radiation are often not made. However, microwaves do not have the photon energy needed to ionize biological molecules and cannot cause effects comparable to those due to ionizing radiation. Furthermore, almost all of the credible reported microwave exposure effects are ascribed to the heating produced by the microwave energy. Whether microwaves can cause biological effects by nonthermal mechanisms remains uncertain.

Microwave biological effects are a relatively immature scientific study area. An appreciation for certain important features of experimental protocol, especially with regard to dosimetric details, has only developed in recent years. Microwave power deposition in laboratory biological preparations, animals, and humans is nonuniform and depends on the microwave

frequency and polarization, the size and shape of the exposed object, the properties of the biological materials and their nonuniform distribution, the material surroundings of the test subject, etc. Extrapolation of laboratory data to man is complicated and has affected the interpretation of experimental results.

1.3.1 Occupational Exposure to Microwaves

The maintenance spaceworker near the transmitting antenna and the terrestrial worker beneath the rectenna panels or just above them would be exposed to SPS microwaves. The exposures could be controlled in intensity and duration. Protective clothing might also prove valuable and be developed.

Current occupational standards and guidelines vary from country to country because of differences in the interpretation of scientific data and basic philosophy. It is possible that international standards will be developed in the future. As SPS technology develops, the microwave power transmission system would have to be designed to comply with such standards.

Continued research is required to develop a quantitative risk assessment and an appropriate international standard for occupational microwave exposure. The small number of persons that would be involved would permit controlling exposure time and conditions. Options in system design and environment control would also be available, and therefore microwave occupational exposure is not considered to be a critical issue in the development of SPS technology.

1.3.2 Public Exposure to Microwaves

The general public would be exposed to SPS microwave power densities between 0.0001 and 0.1 mW/cm². Based on current knowledge, there seems to be little risk due to exposure at these levels. Certainly, no effects due to thermal mechanisms would be expected. However, these levels of microwave power density would increase the median population exposure to radio-frequency background power density by more than an order of magnitude.

Before a microwave power transmission system is deployed, a quantitative assessment of the risk of chronic exposure for the general population should be developed. A comprehensive understanding of the effects and their mechanisms is critical to such an assessment. A coordinated program that includes acute and chronic exposure experiments, as well as theoretical and experimental studies of effects mechanisms, will be necessary.

1.3.3 Ecosystems and Airborne Biota

The potential for effects on the ecosystem as a whole due to the very low SPS microwave power densities is unknown at this time. The data being developed in various laboratories for human health assessments will be useful but data on specific animal species, plants, and soils will be required for an ecosystem assessment. In addition, an understanding of the response of the ecosystem as a whole must be developed.

Studies of airborne biota that would have access to the power beam have taken priority. Research using honey bees and birds has been initiated. Initial experiments on honey bee behavior and survival show no effects of exposure to SPS-level microwaves.

Considering the very low level of microwave power density outside the rectenna site and the adaptability of the ecosystem, significant effects are not likely. However, the far-reaching implications of this issue require that a more definitive assessment be developed.

1.4 REFERENCES FOR SECTION 1

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2 NONMICROWAVE HEALTH AND ECOLOGICAL EFFECTS

2.1 INTRODUCTION

The assessment described here identifies and assesses the nonmicrowave-related health effects and ecological impacts arising from the development and operation of the SPS reference system.^{1*} The information presented here is a summary of a detailed assessment² that covers the health, safety, and ecological impacts of all nonmicrowave aspects of SPS, including:

- Mining raw materials
- Processing materials and fuels
- Manufacturing components
- Transporting materials on the earth and in space
- Packaging materials for transport into space
- Manufacturing space vehicles
- Launching space vehicles
- Traveling in space
- Living and working in space during construction and maintenance of satellites
- Returning to earth (both personnel and space vehicles)
- Siting, constructing, and operating the ground receiving station (rectenna).

Figure 4 shows the cause and effect relationships for terrestrial impacts of the satellite power system as currently understood.

SPS-related mining, construction, and manufacturing would result in impacts that are common to all such operations: air and water pollution, land disturbance, and the like. The importance of these impacts to the SPS assessment comes from the need to evaluate the incremental effects caused by the satellite power system. This assessment provides rough indications of the extent of the incremental impacts caused by SPS deployment. The only unconventional effect of these activities is the exposure to toxic materials that are unique to the SPS.

The transport of materials and equipment would involve the logistics of moving the SPS supplies between mining sites, construction locations, manufacturing facilities, launch and recovery areas, and ground stations. Again, most of the impacts would be conventional, and the issue of interest is the incremental effect. Two unconventional and SPS-specific impacts would, however, be significant: the exposure to toxic materials and the potential for catastrophic accidents while moving large quantities of highly flammable and potentially explosive materials (e.g., liquid hydrogen, propellants, etc.). Although materials of this type are currently being transported, the

*References for Section 2 are listed in Section 2.4.

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	Recovery
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	
Ozone Depletion	

Fig. 4. Cause and Effect Relationships for Terrestrial SPS Impacts

increase in quantity for SPS use and the concentration of movement along selected transport corridors must be carefully planned.

Ground station operation and maintenance is of concern because of the high-intensity, low-frequency electromagnetic fields associated with the power distribution system. However, low-frequency fields are common to all electrical power systems.

The launch and recovery operations would be similar to those undertaken in current space program activities; however, the satellite power system would require significantly larger launch vehicles and a considerable increase in launch and recovery activity. To transport the necessary materials into space, the SPS reference system uses vehicles approximately five times the size of the Saturn V, launched about twice per day for 30 yr.

All space operations would result in effects about which there is limited information. Figure 5 depicts the effects believed to be of concern. Both the type of individual exposed to the space conditions (i.e., construction or maintenance worker instead of astronaut) and the exposure pattern would be different from space program experience. This assessment is based on data from the Apollo and Skylab programs and identifies future research needs for the satellite power system.

2.2 ASSESSMENT

The nature of SPS effects dictates that they be assessed in two ways. First, a number of impacts result from conventional processes that would be used more extensively because of development of a satellite power system (e.g., manufacture of steel). In these cases, the assessment evaluates the incremental effects of an increased exposure to conventional hazards (e.g., increased public exposure to air pollution from steelmaking). Second, a number of impacts are unique to the SPS (e.g., effects of living and working in space). In these cases the assessment identifies the potential effects; evaluates the possibilities that they would create health, safety, and welfare problems; and reviews the research needed to establish the magnitude of the effects more conclusively. The assessment is divided into discussions of the nonmicrowave SPS effects on the public, terrestrial workers, space workers, and ecosystems.

2.2.1 Effects on the Public

Incremental Effects of Conventional Processes

To determine the incremental effects of SPS deployment on public health and safety, it is necessary to determine the increase in mining, construction, manufacturing, and transport activity that would be attributable to the satellite power system. Studies of SPS materials requirements can be used as a rough gauge of the increase in activity dictated by the SPS.^{1,3,4} Figure 6 shows the materials requirements of the two tentative SPS designs

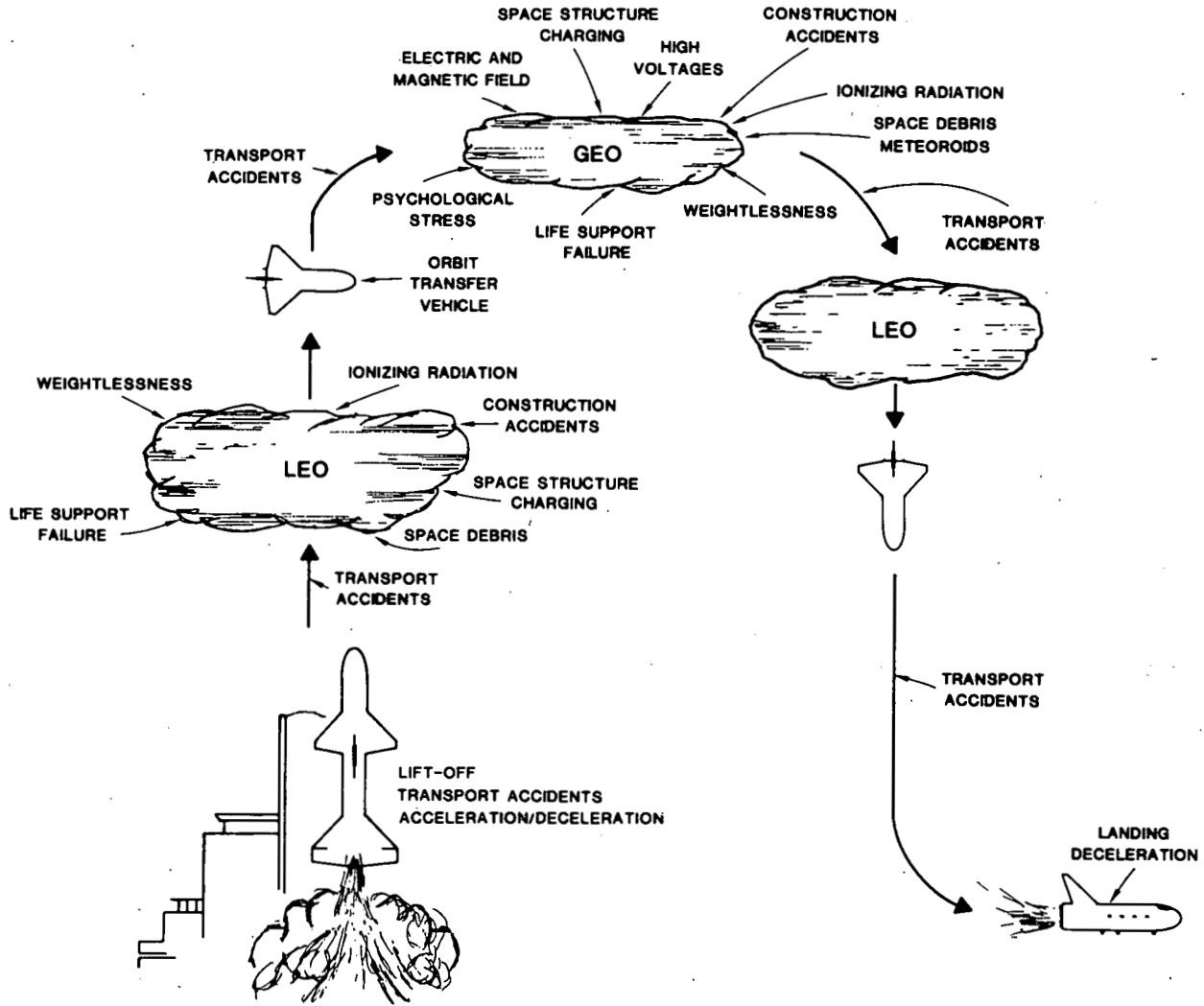


Fig. 5. SPS Environmental Effects on Space Workers

from Ref. 1 (silicon or gallium aluminum arsenide solar cells) compared to current U.S. production of these materials. Some of the SPS materials requirements represent substantial increments to current production rates (e.g., mercury, argon, hydrogen, oxygen); hence the effects associated with these processes would be significantly increased by deployment of the SPS reference system. For other materials the increment is small (less than 4%).

An attempt has been made to quantify the impacts of the reference system on air pollutant emissions, water effluents, water use, solid waste generation, and land requirements. These data, presented in Table 1, are from Ref. 4 and give an order-of-magnitude estimate of the impact. Emissions, effluents, and resource requirements can be compared either to U.S. totals or to the requirements of alternative electrical generating systems. For example, the particulate emissions of 110,000 t are about 0.8% of the U.S. total in 1973; the sulfur dioxide, carbon monoxide, and hydrocarbons are about 0.05%; and the nitrogen dioxide is about 0.005%. As another example, the

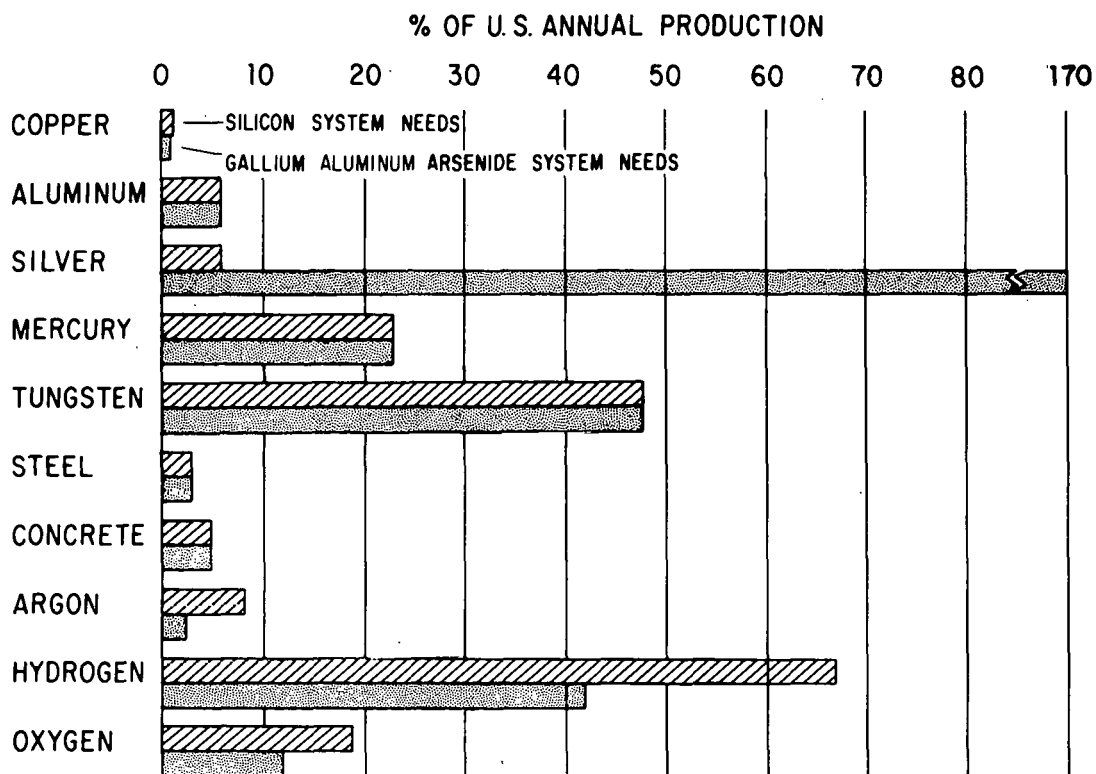


Fig. 6. Comparison of Annual SPS Materials Requirements with U.S. Production (assuming two satellites are built annually; "silicon system" and "gallium aluminum arsenide system" refer to the two types of solar cells being considered for use; materials requirements are from Ref. 1 and U.S. production figures are from Ref. 6).

water-pollutant burden of a coal-fired power plant is 8-600 t/MW-yr versus 2 t/MW-yr for the satellite power system⁵ (this normalized comparison is incomplete because it does not identify the potential for locally severe problems caused by heavy loading of streams and aquifers).

The data upon which to base an assessment of public health and safety effects are reasonably good, but the analyses done to date are incomplete. It can be stated tentatively that the available analyses indicate that the satellite power system would produce a measurable increase in air and water pollution, water scarcity, solid waste, and land requirements. Therefore, public health and safety effects associated with these increases must be quantified in detail as the SPS project develops.

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,⁷ and sizable quantities would be needed

Table 1. Annual Environmental Effects of the Satellite Power System

Type of Impact	SPS ^a	U.S. Total
Air pollutants ^b (10 ⁶ t) ^c		
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 ^d (10 ⁶ t)	3.4	1400
Solid waste generated ^e (10 ⁶ t)	1.6	230
Land requirements ^f (10 ³ km ²)	11	9400

^aAssumes two satellites and rectennas are built per year, Ref. 4.

^bSPS emissions from mining, processing, fabrication.

^ct = metric ton = 1000 kg.

^dSPS requirements for propellant manufacture, launch pad coating, construction.

^eSPS waste from aluminum and steel processes.

^fSPS requirements for rectenna sites. U.S. value is total U.S. land area.

for the satellite power system. Other materials might be highly toxic or possess unusual characteristics, such as the extremely low temperature of liquid oxygen. A spill of liquid oxygen 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 Effects

Launch and Recovery Effects on Air Quality. Air pollution would be caused by the exhaust products of the SPS launch vehicles and by the formation and dispersion of a launch "ground cloud" made up of exhaust gases, cooling water, and some sand and dust. Because of launch trajectory and vehicle speed, most exhaust products would be emitted in the troposphere (0-11 km altitude), although a sizable quantity would also be emitted in the stratosphere (11-50 km).⁴ The ground cloud, on the other hand, would rise to only 0.7-3 km, where its buoyancy would be neutralized by a cooling of the gases.

The ground cloud has been the subject of extensive research, particularly with regard to the space shuttle.⁷ The ground cloud could expose the public to air pollutants because of its low altitude. A mathematical model

has been developed to estimate the maximum concentrations of various pollutants in the ground cloud as a result of a space-shuttle launch. These results are not directly applicable to SPS operations because of the probable use of liquid-fueled rockets (versus solid-fueled for the shuttle) and the significantly larger launch vehicle. This is discussed further in Section 3.

As a result of previous work, ambient concentration limits can be identified for various launch-related air pollutants. The standards used for the space-shuttle program were based on the National Ambient Air Quality Standards promulgated by the U.S. Environmental Protection Agency (EPA) and exposure limits recommended by the Committee on Toxicology of the National Academy of Sciences/National Research Council. The latter limits include a short-term public limit designed to avoid irritation of the mucous membrane of the upper respiratory tract and a public emergency limit related to accident conditions that might result in some irritation but with reversible effects. The space-shuttle study indicates that concentrations of all pollutants in the SPS ground cloud would probably be below both limits.

Launch and Recovery Effects on Water Quality. Information available for the space shuttle⁷ has been used to identify the water-quality effects of the launch and recovery of SPS vehicles. Pollutants could enter the water through contamination of the launch-pad cooling water with engine exhaust products, removal of ablative insulation from reentry vehicles, and spillage of residual propellant if the launch vehicle were recovered from the ocean. The first two conditions could be controlled by on-site water-treatment facilities and would not normally present a public health problem.

Launch and Recovery Noise. A preliminary evaluation of the noise impact of SPS vehicles on communities and ecosystems near a hypothetical launch site has been performed, using the Kennedy Space Center (Cape Canaveral) as the prototype site.⁸ Since the heavy-lift launch vehicle (HLLV) would create more noise and be launched more often than the personnel launch vehicle (PLV), the study emphasized the HLLV launch impacts. Though other noise mechanisms may be present in a rocket engine, most of the noise produced is a result of turbulence in the exhaust, and in this study only the exhaust noise was considered. The evaluation also examined launch and re-entry sonic booms.

The sound level of HLLV launch noise has been estimated as a function of distance from the launch pad and is presented in Table 2. Table 3 lists familiar sound levels for comparison.

The Occupational Safety and Health Administration (OSHA) requirement for protection against hearing damage is a maximum exposure of 115 db(A). Thus, from the values given in Table 2, a potential hearing hazard would exist within 1500 m from the HLLV launch point if people were outdoors and exposed to the sound every day. Using a more-stringent technique employed by the U.S. EPA, which averages the sound over a 24-hr period, the range of the potential hearing hazard would extend to 3000 m.

Launch noise could interfere with speech for about two minutes at distances as great as 30,000 m. However, since the noise would occur only

Table 2. Estimated Sound Levels of HLLV Launch Noise^a

Sound Level and Duration	Distance from Launch Pad				
	300 m	1,500 m	3,000 m	9,000 m	30,000 m
OASPL ^b (dB)	149	136	130	120	109
A-Level ^c [db(A)]	130	114	105	89	72
Duration (s)	12	42	54	77	77

^aFrom Ref. 8

^bOASPL: Overall sound pressure level expressed in decibels (dB) above the level corresponding to a reference pressure of 20 μ Pa (Pa = pascal = 1 N/m²).

^cA-level: Weighted average sound level over the frequency spectrum in accordance with the performance of the human ear.

about twice a day and since its duration would be short, it should not interfere significantly with speech.

Sleep interference would be possible at distances as great as 30,000 m from the launch site. The percentage of people who would be annoyed by the noise also has been estimated, as a function of distance from the launch point, and is presented in Table 4. This rough estimate is based on a 24-hr averaging of the noise, the technique used by the U.S. EPA.

The potential effects of infrasound (frequencies below the auditory range of the human ear) from HLLV launches are difficult to assess because of the lack of data and criteria. The current estimate is that no physiological effects should exist, but annoyance would be likely at distances as great as 30,000 m from the point of launch, due to low-frequency vibration of buildings.

Sonic boom pressures on launch and reentry were also estimated and are summarized in Table 5. Booms with pressures of 1200 Pa (HLLV first-stage booster) and 700 Pa (PLV first-stage booster) would cause startle effects characterized by gross body movements but would not cause injury. Booms from reentry vehicles would not cause hearing damage (the threshold is at about 200 Pa). The trajectory for the launch vehicles would have to be designed to avoid populated areas.

Table 3. Representative Noise Levels Due to Various Sources^a

Source or Description of Noise	Noise Level (dB)
Threshold of pain	120
Riveter	95
Elevated train	90
Busy street traffic	70
Ordinary conversation	65
Quiet automobile	50
Quiet radio in home	40
Average whisper	20
Rustle of leaves	10
Threshold of hearing	0

^aFrom Ref. 9.

Since the sonic boom would last for only about half a second, it should not be a significant problem in terms of speech interference, but might interfere with sleep in the affected area. It is estimated that the sonic booms generated by the reentry vehicles would annoy 5% or more of the population over a distance of about 45 km from the landing site.

More information on noise levels, propagation phenomena, and human response is needed for a refined assessment. The forthcoming launches and returns of the space-shuttle orbiter can provide a valuable source of information. Nevertheless, based on the current state of knowledge, rocket launch and reentry noise is not considered to be an impediment to the continued study of SPS technology.

Launch and Recovery Accidents.

Injury to members of the general public due to SPS launch or recovery accidents would be unlikely but conceivable. Launch abort or landing accidents have been assessed for the space shuttle,⁷ and the conclusions are that these incidents would be analogous to conventional aircraft accidents and, in the case of launch abort, would occur over controlled range areas and thus present no unusual problems.

A preliminary analysis indicated the explosive potential of the HLLV to be about twice that of a Saturn V.³ 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 km 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 km to a launch pad.

Reflected Light. Sunlight would be reflected to the dark side of the earth by the solar satellites and other orbiting SPS structures. The magnitude of the reflections would depend on the size of the reflecting area, the smoothness of the reflecting surface, the reflecting angles, and the distance between the reflecting surface and the observer. For the general public, the issue is the tolerance of the human eye -- particularly if the reflected light were viewed through binoculars or telescopes.

Table 4. Community Reaction to HLLV Launch Noise

Distance from Launch Point (m)	% of People Highly Annoyed ^a
300	90
1,500	45
3,000	24
9,000	5
30,000	1

^aBased on a 24-hr average of the noise.

Table 5. Sonic Boom Summary (Pa)^a

Vehicle	Launch	Reentry
HLLV booster	1200	190
HLLV orbiter	--	140
PLV booster	770	140
PLV orbiter	--	70

^aData from Ref. 8.

There are two kinds of reflection to be considered: specular and diffuse. Specular reflection is the kind that occurs from very flat, mirror-like surfaces. In this case, nearly all of the light is reflected at an angle equal to the angle of incidence (both angles measured to a line perpendicular to the reflecting surface). Diffuse reflection occurs from relatively rough surfaces. Light is scattered throughout the half hemisphere above the surface, and the intensities in different directions depend on the surface characteristics.

If specular reflections occur from SPS structures, they would be visible from limited areas of the earth for short periods of time. These reflections would create the effect of a spotlight sweeping across the earth. Specular reflections could be kept below levels intolerable to the human eye by operational procedures to tilt the satellite surface so the reflected light would miss the earth or by design changes to make the surfaces nonspecular.

It has been estimated that the diffuse reflection from a solar power satellite in geosynchronous orbit (36,000 km above the earth) would be about as bright as Venus when it is most visible or 1/10 as bright as the starlight on a moonless night.¹⁰ The 60 satellites called for by the SPS reference system would provide as much light as the moon between its new and quarter phases across a band 70° long and 10° wide. Earth-based optical astronomy observations in the direction of such a band would be hindered (see Section 5).

Reflected light from smaller SPS structures in low earth orbit (LEO), 470 km above the earth, is also a concern because of the structures' nearness to earth. Special attention must be given to the design and development of these structures to reduce the reflected light to acceptable levels.

The reflected light for the SPS reference system is currently being characterized in some detail. Assessments of effects on the human eye also are being initiated.

Ozone Reduction - Skin Cancer. The ozone layer would probably be affected by SPS spacecraft activities. Preliminary calculations (see Section 3) indicate that emissions from the total HLLV activity for SPS would probably reduce the stratospheric ozone layer by only 0.02%, an undetectable change. Likewise, calculations of localized ozone concentration indicate there would be no significant corridor effect (see Section 3).

For each 1% decrease in ozone, there is approximately a 2% increase in the amount of biologically harmful ultraviolet light that reaches earth; this type of light is known to increase the incidence of skin cancer. It is believed that the small decreases in ozone caused by the HLLV emissions would be insignificant due to the variability of other factors influencing the ozone layer.²

Acid Rain. Acid rain may be of concern near the launch area. Acid rain occurs when raindrops form in or fall through a region of the atmosphere

containing a substance that, when dissolved in water, produces an acidic solution. Natural rainfall is only slightly acidic. In recent years, more-acidic rain has been observed in the Scandinavian countries as well as in Canada and the northeastern United States. Acid rain, which can have adverse effects on vegetation and soil and water quality, has been attributed to the emission of sulfur- and nitrogen-containing substances in the industrialized areas of Europe and the United States. When the estimated HLLV rocket exhaust emissions (see Section 3) are compared with the sulfur oxide and nitrogen oxide emissions from industrial and other sources in the southeastern United States, it is concluded that the contribution from SPS to regional- or continental-scale acid rain would be negligible.²

However, localized and temporary acid rainfall might occur in the vicinity of a launch area due to rain falling through the ground cloud. For the HLLV, since any acidity would be due to sulfur oxides and nitrogen oxides in the ground cloud, and not to a principal exhaust product, the effect would be similar to that of rain falling through the plume of a power plant, although on a much-reduced scale, since it would be due to a single cloud rather than to an extensive plume. It is expected that this effect could be minimized by monitoring weather conditions and launching at appropriate times.

Effects of Power-Transmission Electric and Magnetic Fields. People living and working in the vicinity of high-voltage transmission lines are exposed to electric and magnetic fields. While the exact voltage on transmission lines leaving an SPS rectenna has not been determined, these lines would not be expected to be different than conventional transmission lines. Also, there is some uncertainty about the biological effects of the fields. Research is presently being funded by the Department of Energy and the Electric Power Research Institute.¹¹

2.2.2 Effects on Terrestrial Workers

Incremental Effects of 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 would be 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.

Many activities in the production of SPS materials would be of a conventional type, and the level of activity can be compared with that of other industries, and thus the hazards can be quantified. Many activities required for construction of the rectenna and launch and landing pads would also be expected to be conventional.

Table 6 provides a rough estimate of the distribution of occupational illness and injury by various SPS functional activities. These data were

assembled using occupational illness and injury rates from the U.S. Department of Labor and SPS labor requirements.⁴ Occupational fatality information was not included. The information shows that the material acquisition activities (i.e., mining) would account for about half of the person-days lost for injury and illness and that the injury rate would be much higher than the illness rate. These rates are totals over the 30-yr life of the satellite power system and cannot be directly compared to published annual rates.

Unconventional Effects

The unconventional effects on the health and safety of terrestrial SPS workers would result from exposure to toxic materials, the transport of highly explosive materials, all of the launch and recovery activities, and exposure to electromagnetic fields (other than microwaves, which are discussed in Section 1) at the rectenna site. These are the same effects as were discussed in Section 2.2.1 with regard to public health and safety. The difference between public and terrestrial-worker impacts would be one of degree and intensity.

Some terrestrial workers would handle toxic materials that would be sent into space. They might also be exposed to fumes from fuels and to effluents from burned fuels as spacecraft were launched and landed. In transport accidents involving catastrophic explosions or fire, the workers involved (e.g., railroad crewmen, emergency personnel, etc.) would be more likely to be injured or killed than the general public would be.

Terrestrial workers in launch and landing areas could be injured or killed in accidents during launch and landing of space vehicles. They could conceivably be struck by a vehicle out of control. Fuels also could explode

Table 6. Distribution of Occupational Illness and Injury

Activity	10 ⁶ Person-Days Lost ^a	
	Occupational Injuries	Occupational Illnesses
Material acquisition	15	0.5
Ground construction	9	0.3
Ground operation and maintenance	<u>1.5</u>	<u>0.1</u>
Total	25.5	0.9

^aData are for conventional mining, construction, and manufacturing only and are totals over the 30-yr life of the satellite power system.

Source: Ref. 4.

or ignite. Since the amounts of fuels expected to be used in the HLLV are immense compared to those used in conventional aircraft, the explosion/ignition hazard would be greater. Terrestrial workers at these sites would be exposed to high levels of noise.

Workers at operating rectenna sites would be near equipment carrying very high voltages, and therefore there would be the possibility of electric shock causing injury or death. If the SPS used higher operating voltages than conventional power systems, the SPS worker at a rectenna site would be exposed to higher direct-current or low-frequency electric and magnetic fields than a conventional power-system worker.

None of the unconventional effects identified are considered to be an impediment to continuing SPS research and assessment. Any potential occupational risks could be ameliorated by education, training, environmental control, and safety procedures.

2.2.3 Effects on Space Workers

Space SPS workers would be more likely than anyone else to be exposed to unique health hazards as a result of SPS development. The SPS reference system¹ proposes 90-day tours in space, and a 5-yr career for space workers has been contemplated. This schedule could involve 90 days in space alternated with 90 days on earth. The longest flights for U.S. astronauts have been 84 days, and these have not been repeated. Thus far, experience for humans in space has been limited to American and Russian astronauts, who have been highly trained, highly motivated persons. Their tasks have been very different from those projected for most SPS space workers. It is imperative that all possible precautions be taken to avoid or minimize the health hazards for SPS space workers.

Health Effects of the Space Environment

The possible health consequences for SPS space workers have been assessed by NASA.¹² The study concludes that the SPS space worker would not suffer any long-term adverse health effects. This conclusion is based on the expectation that prior to SPS space flights, both ground-based and space experimentation and experience will assist in solving some of the problems that have been encountered by humans in space.

Acceleration/Deceleration. During acceleration or deceleration, physical forces act on the body to accelerate and displace all or part of the body. The body's response to force results in a range of physiological responses, from a level at which no effect can be perceived to a level resulting in massive tissue destruction. The duration of exposure to weightlessness is known to influence the extent to which linear and angular acceleration alter the body as well as the length of time required for the body to regain normal preflight response characteristics.

The magnitude of the force acting on a human body is determined by the body's mass and the magnitude of the acceleration. The duration of the

acceleration is a significant factor in human response, particularly at shorter-duration exposures approaching impact (duration < 0.2 s). Also significant are the direction of the force vector, the resultant direction of acceleration with respect to the body's orientation, and the specific body position. The restraint and support systems for the human body in an accelerating vehicle determine the manner in which forces are transmitted from the vehicle to the body, thereby strongly influencing the physiological response to the acceleration.

Maximum forces for the Apollo spacecraft reached approximately six times the force of gravity (6 g) on reentry, with lesser values for launch and orbital maneuvers. Mercury and Gemini spacecraft operated at slightly higher values. No acute operational problems, significant physiological deficits, or adverse health effects related to the cardiovascular and musculoskeletal systems are known to have resulted. The space shuttle (a prototype for the SPS personnel launch vehicle) will impose a quite different acceleration environment on the crew. The accelerations will be lower but will last longer. There is a compromise to be made between short-duration, high acceleration and longer-duration, lower acceleration.

Since the physiological effects of an acceleration force field are numerous, the potential for modifying these effects by a number of environmental factors would be considered. The primary limiting effect is a loss of oxygen in the blood due to effects on the cardiovascular and respiratory systems. Oxygen pressure is, therefore, a very important variable. Temperature can be expected to affect tolerance to acceleration when it results in dilation of blood vessels and decreased return of blood to the heart. Any other environmental factor that might affect the cardiovascular or respiratory system would be expected to influence acceleration tolerance. There is also a large individual variation in tolerance of acceleration.

Future work in this area will:

- Define the effects of various durations in a zero-gravity environment on subsequent tolerance to force fields in all directions.
- Define the ranges of acceleration forces resulting in physiological effects and of tolerance in the population that may fly in space.
- Optimize countermeasures that may be used under high-force-field conditions.

Weightlessness. A number of deviations from normal physical parameters have been noted in astronauts. Many of these effects have appeared to be adaptations to the lack of gravity, and the affected parameters have returned to normal either during the mission or very shortly after the return to earth, with no apparent adverse consequences to the astronauts. However, some of these deviations might be problems if flights were repeated at regular intervals. The effects can be summarized as follows:

Gross-Level Effects

- Muscles lose mass and there is a small, reversible loss of strength and ability to perform work at maximum levels.
- Skeletal integrity is compromised by slow losses of the protein matrix of bone mineral. Recovery is known to require a protracted period.
- There is a fluid shift, particularly from the legs to the head and upper torso, and some fluid is lost.
- The normal tolerance of the cardiovascular system to the stress of the earth's gravity is reduced. Symptoms such as dizziness, weakness, decreased heart rate, and decreased pulse pressure last for up to two weeks after a space flight.

Less-Important Effects

- There is a tendency to incur skin infections.
- Red blood cell mass is lost.
- Neuroendocrine activity, as measured in blood and urine specimens, changes.

Several organ systems have suffered minimal or no functional changes as a result of space flight. These include the reproductive, digestive, respiratory, lymphatic, nervous, sensory, and excretory systems.

Ionizing Radiation. The ionizing radiation environment in which the satellite power system would be built and operated is characterized by the presence of fluxes of electrons, protons, neutrons, and atomic nuclei.¹³ It is convenient to classify this radiation into three categories: (1) the electrons and protons trapped by the earth's magnetic field in the Van Allen belts, (2) the protons and atomic nuclei originating in the sun, and (3) the protons and atomic nuclei that make up galactic cosmic rays. The trapped radiation of the Van Allen belts is of greatest concern during operations in LEO and transfer to GEO. High-energy, heavy, charged particles (known as HZE) are a component of the galactic cosmic rays for which the biological effects are least adequately measured and perhaps least understood. The magnitude of solar radiation varies unpredictably (solar storms); such variations greatly alter the GEO radiation environment.

A critical question affecting SPS design is whether the current radiation exposure limits used in spacecraft design will be changed. It is clear that the radiation doses expected to be encountered by a space worker during a 90-day SPS mission might exceed the limits recommended for radiation workers by the National Council on Radiation Protection and the International Commission on Radiological Protection. Since many workers could receive a significant radiation exposure, the career limits established for astronauts by the National Academy of Sciences may not be appropriate. In any case, this question must be examined in detail as SPS technology and planning develops, including the allowable time in space and the possibility of using space robots.

The potential biological hazards of HZE particles are uncertain. The energy deposition of HZE particles is different from that of other types of radiation,¹⁴ and the tolerance level for exposure to HZE particles is not yet known. Research has been initiated to develop a data base on the biological effects of HZE particles.

The radiation-shielding requirements for each portion of the SPS mission must be based on consideration of the combined exposures for the total mission. For example, the allowable exposure within the vehicle at GEO would depend on the exposures in LEO, during orbital transfer, during scheduled and unscheduled extravehicular activity, and as anticipated from solar storms. Since there are uncertainties in the existing models of the space radiation environment, shielding requirements would be reviewed periodically as the models are improved. For example, an important improvement needed in the model of the electron environment for GEO is an accurate simulation of the dependence of electron concentrations on the solar cycle.

An important part of the radiation-protection design for the GEO base involves the health hazards of solar storms. A heavily shielded shelter would be necessary to protect workers from these storms. To minimize the design weight of the storm shelter, it is necessary to take into account self-shielding of critical organs by body tissues and to use personal protective clothing.

Dosimeters would be needed for monitoring radiation exposures. In addition to rugged, reliable, and simple dosimeters for each individual, real-time monitoring is needed of unpredictable radiation sources, solar storms, and short-term fluctuations of trapped electron fluxes in GEO. Space workers in GEO must be warned to move to areas affording greater protection whenever exposures to unpredictable radiation may exceed established limits. There is also a need to monitor exposure to HZE particles because of the unknown biological effects of these particles.

There is apparently no single instrument or integrated group of instruments that gives real-time readouts of flux and energy (which, in turn, are related to dose) of all the types of ionizing radiation that would be encountered by SPS space workers. Current dosimeter technology needs to be evaluated to determine whether instruments now being used can be integrated to make the measurements and provide readings on a real-time basis. Studies of personnel dosimeters are also needed. The radiation dose to individuals would vary considerably depending on work schedules and places of work. Personnel dosimeters now in use take excessively long times for readout and are probably not accurate enough to provide the information needed to protect SPS personnel.

The risks from ionizing radiation in space would be minimized through carefully designed shielding for space vehicles, working and living modules, and solar storm shelters. Monitoring systems should be developed to obtain comprehensive, immediate accounts of conditions in places occupied by space workers and to warn of radiation hazards.

Ionizing radiation in space is not considered a barrier to the continued research and assessment of SPS technology. Nevertheless, it will be necessary to quantitatively assess the hazard of this radiation to humans in space before long missions are carried out.

Electric and Magnetic Fields. The collection and transmission of large amounts of electric power across the solar cells would generate electric and magnetic fields that would surround the solar panels and antenna. Workers in the vicinity of the solar panels would be exposed to these fields.

The evidence that electric fields are harmful to humans is somewhat controversial at this stage. Russian studies of electrical workers appear to indicate some deleterious effects, but these have not as yet been substantiated by research in the United States. There has been some research with animals, and some abnormal effects have been reported. Well-controlled animal studies are currently underway; the larger studies are supported by the Department of Energy and the Electric Power Research Institute.¹¹

Research on the biological effects of magnetic fields is in the early stages. Because the space worker in geosynchronous earth orbit would be essentially out of the earth's magnetic field, the effects of no magnetic field should be examined. On the other hand, magnetic fields would be generated by the electric currents on the satellite. The effects of these fields, which some space workers would presumably move through, should be investigated.

Spacecraft Charging and Environmental Interactions with Space Structures. Electric charge would collect on SPS structures as they traveled through space. This might result in large discharges from the surfaces of spacecraft and from solar-collector panels. There appears to be a danger of electric shock large enough to injure or kill space workers. NASA and the Air Force are carrying out ground and satellite (SCATHA, in particular) experiments to gain a better understanding of these phenomena, which might endanger workers, spacecraft instrumentation, and the efficiency of solar-energy collection. Conclusions from these experiments may indicate ways of mitigating these effects. After mitigating strategies have been included in the SPS reference system, the residual dangers to space workers should be assessed.

Life Support, Medical-Dental Support, and System Emergencies

NASA has in progress research and design programs intended to make the space transportation and living and working modules as hazard-proof as possible for space workers and to provide all the necessities for life and health support. As the satellite power system develops, the support systems will be examined for their relevance to the project and new systems will need to be designed. The current assessment is that the necessary support systems can be designed, and their feasibility is not an impediment to the development of the SPS technology. Following are brief discussions of a number of possible life-support and safety hazards for SPS space workers.

Extravehicular Activity (EVA). In the case of the SPS, extravehicular activity would not be expected to be frequent, but must be planned for in case of emergencies. An example of an EVA requirement would be the case of machinery needing external repairs. Much construction work could be required outside the space module. This is expected to be done by machinery,

such as a beam builder, and would require a space worker in its "cab" working the controls. The hazards of EVA will need to be assessed as the system design is more fully developed.

Collisions with Meteoroids and Space Debris. Computer programs are available for examining this problem and have been used for previous space missions. The size of an SPS satellite would make it more vulnerable to collisions than vehicles and satellites that have been put in space to date. While it currently appears that the probability of collisions would be small, these collisions, if they occurred, could be catastrophic. The amount of space debris is also increasing at a fairly rapid rate. The problem of SPS collisions with meteoroids and space debris thus needs definitive study.

Other Health and Safety Hazards. Space workers may be more prone to conventional construction accidents than are terrestrial workers because of the possible awkwardness of working in the weightless state. Hazards may be associated with lift-off, landing, transfer between vehicles, or transport between satellites. Some space workers would work in the vicinity of equipment carrying high voltage, while others might be exposed to toxic materials. These hazards and others will require quantitative assessment as the SPS design develops.

Amelioration of Potentially Adverse Effects¹²

To ensure maximum productivity over a multiyear career, selection of space workers would be based on such considerations as good physical condition, resilience, adaptability to stress, dedication, and the intelligence to understand not only job requirements, but also the actions that must be taken to remain healthy in space. The exact criteria for selecting workers have yet to be developed.

Space workers for SPS would require extensive training and education prior to their initial space flight and on a continuing basis throughout their careers. Proper indoctrination of astronauts in the importance of food, exercise, hygiene, and other health-sustaining regimens minimized potentially adverse physiological effects of previous space missions. The space-shuttle and space-operations-center programs of the 1980s and 1990s will provide an opportunity to gain insight into the requirements for space worker training.

Motivation would be critical. A career as an SPS worker would place a severe physiological and psychological stress on the space worker and his or her family or associates. These stresses might result in a very high personnel turnover rate. Careful studies of the effects of repeated missions by the space-shuttle crews, and repeated, long (90-day) missions by the crews of the space operations center should identify means of motivating SPS workers to serve effective space careers.

The maintenance of good physical condition is a very significant factor in ameliorating the adverse effects of the space environment. Good programs of nutrition, exercise, rest, and hygiene -- coupled with a good

food system and enjoyable recreation -- would be required for SPS workers. These requirements would need to be met between missions as well as during space flight, and would have to be tailored to the needs of the individual. NASA has learned a great deal about these needs for astronauts and cosmonauts from previous space missions, but much is yet to be learned about the needs of the types of workers that would be expected to be employed in the SPS program.

Living and working conditions would be very important. The physical and psychological well being of the SPS space worker would be affected by environments that are controllable as well as those that are inherent to space flight. The living and working conditions of the space worker need careful consideration if the long and repeated missions are to be made palatable. Some of the more obvious of the controllable elements include:

- Lighting
- Temperature
- Toxic and noxious elements
- Architecture
- Humidity
- Breathing environment (pressures and constituent gases)
- Noise
- Clothing (protective and counterpressure suits)
- Social and management structure

With many hundreds of space workers involved, some would be likely to be adversely affected by the space environment. Some of the possible curative actions that might be needed are: task reassignment or schedule modification, variations in physical conditioning activities (possible supervision to prevent neglect of necessary exercise, nutrition, hygiene, etc.), medical treatment, and altered living conditions.

Currently, NASA is conducting only ground-based research, but it is anticipated that the space shuttle and space operations center will provide opportunities for research in space. This research can be designed to yield information needed to identify potential adverse effects of SPS-type space operations and suitable countermeasures.

2.2.4 Effects on Ecosystems

Satellite power system activities on and near the earth's surface probably would impact many ecosystem components. The most evident effects would likely be localized near the launch and landing sites and at the ground receiving stations. For the launch and landing sites, ecosystem disturbances could be limited by mitigating strategies. Ground receiving stations (rectenna sites) would alter local ecosystems.

Rectenna Siting

The impacts of rectenna siting have been assessed¹⁵ using a prototype site in the California high desert at the Coso Hot Springs geothermal lease area. While it is not expected that this specific site would be used for a rectenna, it was selected for study because it has many attributes preferred for SPS rectenna sites (little precipitation, flat terrain, low population density, etc.) and is the subject of a comprehensive environmental impact statement written for the Bureau of Land Management. The statement was prepared because the area is a prospective site for a geothermal facility. Thus, much of the information needed for a rectenna impact assessment has been obtained.

The study produced a comprehensive prototype environmental assessment of the SPS-reference-system rectenna facility in both the construction and operation phases. This effort also identified and calibrated, in terms of impacts on the natural environment, the critical engineering design and construction parameters that are most significant environmentally. Potential impacts and key design parameters were defined in the context of actual baseline data for a specific site. The study provided specific impact data relevant to siting a rectenna facility in proximity to California's urban centers and illuminated some potential impacts of rectenna siting elsewhere.

The impacts of rectenna construction and operation, along with suggested procedures for mitigation of impacts, are summarized in Table 7. Some of the impacts are site-specific and could be lessened or eliminated by judicious site selection. Criteria for site selection can be based on studies of this type.

This site-specific study points out possible detrimental environmental effects for areas with similar ecosystems. However, if 60 rectenna sites were developed, as called for by the reference system, they would need to be distributed in various areas of the country to supply populated areas with electricity. Thus, areas with many different types of ecosystems likely would be involved. Effects on these differing ecosystems will need to be studied when siting requirements are better known.

Production and Transport of SPS Components and Fuels

Most of the activities in the mining, processing, manufacturing, and transport of SPS components would be the same as those currently carried out in many industries. In these cases, SPS activities can be compared with those of conventional industries to determine if the satellite power system would add appreciably to present ecological impacts. SPS activities that would be unique or that would considerably multiply the ecological impacts of current industry will need to be carefully assessed.

While large amounts of fuels would be needed for the SPS, their properties would be those of conventional fuels, i.e., they would be toxic, flammable, and explosive. The same precautions would be needed as are now used with such fuels.

Table 7. Summary of Environmental Impacts of Rectenna Construction and Operation at a Specific Study Site^a

Technical Area	Rectenna Construction	Rectenna Operation	Mitigation
Air quality and climatology	<ul style="list-style-type: none"> ● Probable standards violation for nitrogen oxides, particulates, and hydrocarbons. ● No climatic impacts. 	<ul style="list-style-type: none"> ● No significant air quality impacts. ● Unknown, but possibly significant microclimatic effects at or near ground surface. 	<ul style="list-style-type: none"> ● Adequate dust suppression program during construction would mitigate particulates impacts. ● Extending construction schedule would reduce emission peaks for hydrocarbons and nitrogen oxides. ● Pending further research, project modifications might be needed for ground surface microclimate impacts.
Noise	<ul style="list-style-type: none"> ● Substantially elevated noise levels, but in areas with low population density. ● Possible impacts on noise-sensitive species. 	<ul style="list-style-type: none"> ● No significant impact. 	<ul style="list-style-type: none"> ● Improved noise control technology by construction time frame for vehicles, equipment, and processes would mitigate impacts. ● During construction, noise-sensitive habitats should be avoided to maximum extent possible during breeding and nesting seasons.
Geology and soils	<ul style="list-style-type: none"> ● Geologic impacts less important than geologic constraints. ● Study area very active seismically, but within normal range for southern California. ● Soils impacts significant: large disturbed area, compaction, wind/water erosion. ● Soils constraints: diversity of soils types implies variability in engineering properties (e.g., shrink/swell potential, corrosivity to metals/concrete). 	<ul style="list-style-type: none"> ● Seismicity has potential for facility destruction or loss of efficiency (alignment vs. satellite). ● Soil productivity impacted for project life: depends on extent and degree of construction-phase and ongoing operations disturbance. 	<ul style="list-style-type: none"> ● Thorough seismic and soils studies required as part of site-specific engineering. ● Careful soil-stabilization/drainage/erosion-control programs required.

Table 7. (Cont'd)

Technical Area	Rectenna Construction	Rectenna Operation	Mitigation
Hydrology and water quality	<ul style="list-style-type: none"> ● Project requirements: 2-14 x 10⁶ m³ (depends on dust suppression methods used). ● Meeting project needs from groundwater would lower water table 0.2-1.5 m/yr; would reduce underflow to adjoining valley, could lower water level in nearby lake; might contaminate usable water through hydraulic connection with unusable groundwater. 	<ul style="list-style-type: none"> ● Project requirements minor unless major revegetation program undertaken. Revegetation could require 27 x 10⁶ m³/yr for 3 yr, which could cause water table drawdown. 	<ul style="list-style-type: none"> ● Careful soil stabilization/drainage/erosion-control program required. ● Groundwater withdrawal impacts could be alleviated by importing water from outside study area. ● Proper sewage control program necessary during construction to prevent water quality degradation.
Flora	<ul style="list-style-type: none"> ● Land disturbance would completely modify site's floral communities. ● Possible indirect impacts on flora from hydrologic changes, air and water pollutants, and personnel activities. ● No endangered species present at Rose Valley/Coso; one rare species present. 	<ul style="list-style-type: none"> ● Impacts similar to construction phase. ● Microclimate changes at ground surface a key issue for severity and potential for mitigation of floral impacts. 	<ul style="list-style-type: none"> ● Reestablishment of preexisting flora problematic; major and difficult revegetation program required. ● Careful placement of ancillary facilities necessary to minimize impacts on sensitive habitats. ● Careful planning, design and construction/operations practices necessary to minimize indirect impacts (e.g., water quality degradation).

Table 7. (Cont'd)

Technical Area	Rectenna Construction	Rectenna Operation	Mitigation
Fauna	<ul style="list-style-type: none"> ● Land disturbance would completely modify site faunal communities. ● Possible indirect impacts on fauna from hydrologic changes, air and water pollutants, personnel activities, and loss of feeding areas for nearby fauna. ● Surface water sources for migratory water and land birds would be lost (playas) and jeopardized (Little Lake). ● One protected species (Mohave ground squirrel) found in Rose Valley. 	<ul style="list-style-type: none"> ● Impacts similar to construction phase. ● Impacts closely related to flora impacts. ● Microclimate changes at ground surface a key issue for severity and potential for mitigation of fauna impacts. 	<ul style="list-style-type: none"> ● Reestablishment of preexisting faunal problematic; closely linked to strategy and success of floral mitigation. ● Careful placement of ancillary facilities needed to minimize impacts on sensitive habitats. ● Careful planning, design, construction, O&M practices, and construction scheduling needed to avoid indirect impacts and to avoid sensitive habitats during breeding and nesting seasons.
Land use	<ul style="list-style-type: none"> ● Total displacement of existing site uses (e.g., farming, grazing, recreation). ● Minor loss of mineral resources (cinder, pumice). ● Minor indirect (growth-related) impacts. ● Potential land acquisition/use conflicts with Navy (China Lake NWC), energy (geothermal), wilderness, archaeological resources, native American use and access to cultural and religious sites. 	<ul style="list-style-type: none"> ● Same as construction phase. 	<ul style="list-style-type: none"> ● Major impacts could not be mitigated. It might be possible to achieve joint use of rectenna sites but this remains speculative.

^aFrom Ref. 15.

Launching and Landing of Space Vehicles

The noise created by launching and landing of space vehicles could affect nearby wildlife. There might be startle responses, disturbance of diurnal cycles and reproduction, etc. This could be especially damaging in areas where endangered species are located. Although the environmental impact statement for the space shuttle predicts that there will be no adverse effect from that activity,⁷ the possible effects of the SPS should be examined. Space-shuttle studies may clarify these effects.

Air pollution from space transportation could affect wildlife and vegetation. The possible impacts will need to be assessed as the system develops. Acid rain resulting from HLLV rocket launches would be expected to be minimal, as discussed in Sec. 2.2.1. Acid rain can have adverse effects on soil and water quality and vegetation.

The amount of ultraviolet radiation reaching the earth would be increased by the ozone depletion caused by fuel effluents from SPS space vehicles. In general, the biota of a given region are adapted to the ultraviolet light of that region. Appreciable changes in ultraviolet light might adversely impact an ecosystem. For each 1% of ozone lost from the atmosphere, the amount of biologically harmful ultraviolet radiation reaching the earth's surface is increased by approximately 2%. However, as pointed out in Section 3, the change in the total ozone layer and the resulting change in the intensity of ultraviolet radiation at the ground surface would be negligible.

Reflected Light

Sunlight would be reflected to the dark side of the earth by the solar satellites and other satellite power system structures, as described in Section 2.2.1. Since biota might be affected by this unusual light, for example by disruption of diurnal cycles in wildlife or growing cycles in plants, an assessment has been initiated. Mitigation strategies might be required.

High-Voltage Power Transmission

Ecosystems might be affected by the construction of SPS transmission lines. This impact would be comparable to that of conventional transmission line construction, and probably does not need to be investigated until specific sites and routes are proposed. Then these impacts should be investigated with respect to endangered or fragile species. The electromagnetic field intensities surrounding SPS transmission lines would depend on the operating voltage. The SPS project will make use of results from research on this subject currently sponsored by the Electric Power Research Institute and the Department of Energy.¹¹

2.3 SUMMARY AND CONCLUSIONS

Although there are questions to be resolved, quantitative assessments to be made, and plans to be developed, none of the issues discussed in Section 2.2 precludes the continued research and assessment of SPS technology. The nonmicrowave health, safety, and ecological effects of the SPS reference system are summarized below.

2.3.1 Terrestrial Effects

Air Pollution. The potential for air pollution would be increased by SPS-related mining, construction, manufacturing, and transport, as well as by the launch and recovery of space vehicles. A prototype rectenna site study indicates that construction activities would cause air pollution in excess of that allowed by existing standards if corrective measures were not taken. Most pollutants would be the same as those encountered in conventional activities and federal and state regulations would apply.

Air pollution can affect the human respiratory and cardiovascular systems and cause skin and eye irritation. The effects of air pollutants on wild and domestic animals are uncertain but some adverse effects of air pollution on plants are known. It is currently assumed that by using mitigating procedures, SPS activities could be carried out without unduly exposing the public or SPS workers to noxious air pollutants.

Water Pollution. Water pollution could be increased by a number of SPS activities, including construction, manufacturing, transport, launch, and recovery. A quantitative assessment of water quality impacts has not been made for the SPS reference system. If the SPS is developed, it will be necessary to plan the disposal of wastewater to comply with federal and state water quality standards. Nevertheless, this is not considered a critical issue and it is assumed that mitigating strategies could keep pollution at an acceptable level.

Solid Waste. Solid waste would be produced by SPS-related mining, manufacturing, and construction. The impacts would depend on the types of waste and methods of disposal. Land might be lost to the public and, if toxic materials were not disposed of carefully, there might be a danger to human health. Solid waste could disrupt the ecosystem in disposal areas. As the SPS design develops, quantitative assessments will be needed so that mitigation measures can be designed.

Land Use. In areas where land was cleared for SPS activities, the local ecosystems would be destroyed. Areas on perimeters of these cleared areas might be damaged by traffic, waste, and drainage changes. Depending on the type of ground cover and the type of continued use, some peripheral areas might repair and wildlife could return. An impact assessment would be needed for each site to avoid, where possible, irreparable damage to ecosystems, especially where rare and endangered species are involved.

Noise. Noise would be produced by SPS launch and recovery activities and by terrestrial construction. For the public and the SPS worker, hearing damage and psychological stress are the concerns. The sites and transportation corridors must be selected to minimize the effects on the public. Other conventional mitigation strategies would be needed and workers would require hearing protection. The noise might startle and otherwise disturb wildlife; animals might adapt to certain of the noises but this is not certain.

Safety. SPS workers would be subject to the hazards of conventional mining, manufacturing, construction, and launch and landing activities. The public as well as SPS workers might be subjected to the hazards of accidents in the transport of SPS materials. No quantitative assessment of these hazards has yet been made. As the SPS design develops, quantitative assessments will be required so that mitigation strategies can be designed.

Toxic Materials. The SPS worker and the public might be subjected to increased amounts of toxic materials during the manufacture and transport of SPS materials. Some unique materials might be involved, such as gallium aluminum arsenide, and, in these cases, procedures for protection would need to be developed. Some toxic materials from fuel burning, such as hydrocarbons, would be released during the launch and recovery of spacecraft. Quantitative assessments will be needed as SPS technology develops.

High-Voltage Shock and Electromagnetic Field Exposure. The high-voltage electric shock hazard at the rectenna sites should be no different than that at conventional power stations. The effect of exposure to electromagnetic fields at these sites and near the power transmission lines would be no different than that associated with conventional power stations and transmission lines. The current assessment is that these fields would not be harmful, but the need for additional data is recognized.

Reflected Light. Sunlight reflected to earth by the solar satellites and other SPS structures could exceed the tolerance of the human eye, especially if the light were viewed through binoculars or telescopes. This light also could affect ecological diurnal or growing cycles. Initial studies are in progress, and mitigation strategies might be required.

Ozone Reduction. Ozone reduction and the resulting increase in ultraviolet light reaching the earth due to SPS spacecraft activities are estimated to be very low compared with other activities that affect the ozone layer. If those estimates are approximately correct, the effect of SPS would be undetectable due to the variability of other factors affecting the ozone layer.

Acid Rain. Acid rain can affect vegetation and soil and water quality. Based on current studies, any acid rain caused by chemicals in SPS rocket effluents would be expected to be highly localized and small compared to that caused by other terrestrial activities.

2.3.2 Health and Safety of Space Workers

Weightlessness. In earlier space flights, astronauts have experienced changes in a variety of medical parameters from preflight baseline values. Some of the changes are probably due to the body's adaptation to a zero-gravity environment and are not expected to affect future health. Other variations from normal may affect work efficiency and future health. It is expected that, prior to SPS construction, the cause and effect relationships will be explained and methods of ameliorating the unwanted effects will be developed.

Acceleration. It is known that the length of time a person spends in the weightless state affects the body's tolerance of acceleration forces. It is expected that acceleration effects in SPS vehicles could be ameliorated by tradeoffs between acceleration loads and duration, by proper body positioning of personnel, and by counterpressure suits. Research and experience are needed to develop mitigating strategies.

Extended Confinement. Prolonged confinement in remote working situations has sometimes resulted in psychological stress and a high personnel turnover rate. A system of screening prospective SPS space workers for adaptability, resilience, dedication, etc., would be needed. Also, recreational facilities in space and the needs of the workers' families and friends on earth would need to be considered.

Life Support Systems and Environment. NASA has previous experience with life-support systems and is continuing to improve this equipment. The SPS module, living conditions, and working stations would differ greatly from those of previous space activities. Designs of modules and work stations are underway, and some aspects of these may be tested in the planned space shuttle and space operations center. Design of SPS life-support systems would take into account the need for emergency extravehicular activity, accidents during space transport, other occupational hazards enhanced by the space environment, emergency medical treatment, and the possibility of infectious disease outbreaks.

Meteoroid and Space Debris Collisions. The large size and long life of the solar satellite would make it more vulnerable to this hazard than other space vehicles. Relevant data exist but a quantitative assessment has not yet been made.

Spacecraft Charging and Environmental Interactions. The extent of this problem would depend on the types of materials used in the space structures. The effect could be mitigated by proper system design.

Electromagnetic Field Exposure. Space workers near the solar energy panels and microwave transmitting antenna would be working in electromagnetic

fields. The intensity of these fields has not been defined. Research programs are underway to assess the biological hazards of such fields, but results to date are limited. When the strength of the fields is defined, a study of potential effects will be needed.

Ionizing Radiation. There are many uncertainties about the dosage and character of radiation in space. Research is needed before a quantitative assessment of the hazard can be made and mitigating strategies developed. Nevertheless, this uncertainty is not considered a barrier to the continued planning and development of the SPS technology.

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3 SPS EFFECTS ON THE ATMOSPHERE

3.1 INTRODUCTION

3.1.1 Background

Every level of the earth's atmosphere would be affected to some extent by the construction and operation of a satellite power system. This section considers effects resulting from space transportation and satellite operations as well as effects of the rectenna's structure and operation.

Figure 7 illustrates the various levels of the atmosphere referred to in the following text. Atmospheric regions are most commonly classified with regard to the observed variations of temperature with altitude, although if one is mainly concerned with ionic processes, a different classification scheme is often used for altitudes above 60 km. Some terms, such as troposphere and exosphere, refer to the general atmosphere dominated by electrically neutral constituents. Coexisting with the neutral atmosphere, above an altitude of about 60 km, are ionized constituents that make up the various regions of the ionosphere and plasmasphere. The magnetosphere, which extends from about 150 km out to about 10 earth radii on the sunlit side of the earth and far beyond that on the dark side, is the region in which the motion of the ions is dominated by the earth's magnetic field (i.e., ion-ion and ion-neutral collisions are much less important). For a more detailed discussion of the natural atmosphere, see Ref. 1.*

A large variety of processes occur naturally in the atmosphere, and many of these processes could be influenced by various aspects of the SPS. Figure 8 illustrates some of the disturbances that might result from the deposition of rocket effluents and the operation of a rectenna system. As the altitude increases, the atmosphere becomes increasingly rarified, the possible degree of modification increases, and the amount of knowledge regarding possible modifications decreases.

Preliminary studies of SPS atmospheric effects have been completed, potentially important issues have been identified, research and assessment approaches and tasks have been defined, and further studies are in progress. Information has been acquired through analysis of existing data and theoretical calculations using existing computer models and by taking advantage of already planned experiments (such as rocket launches) that could yield useful information. The space-shuttle program may present many new opportunities for improving our understanding of the natural and perturbed atmosphere and for verifying current predictions of atmospheric effects.

This assessment is organized by atmospheric region, starting with the tropospheric and ending with the magnetospheric effects. The information presented here is a summary of a detailed assessment of the subject.²

*References for Section 3 appear in Section 3.4.

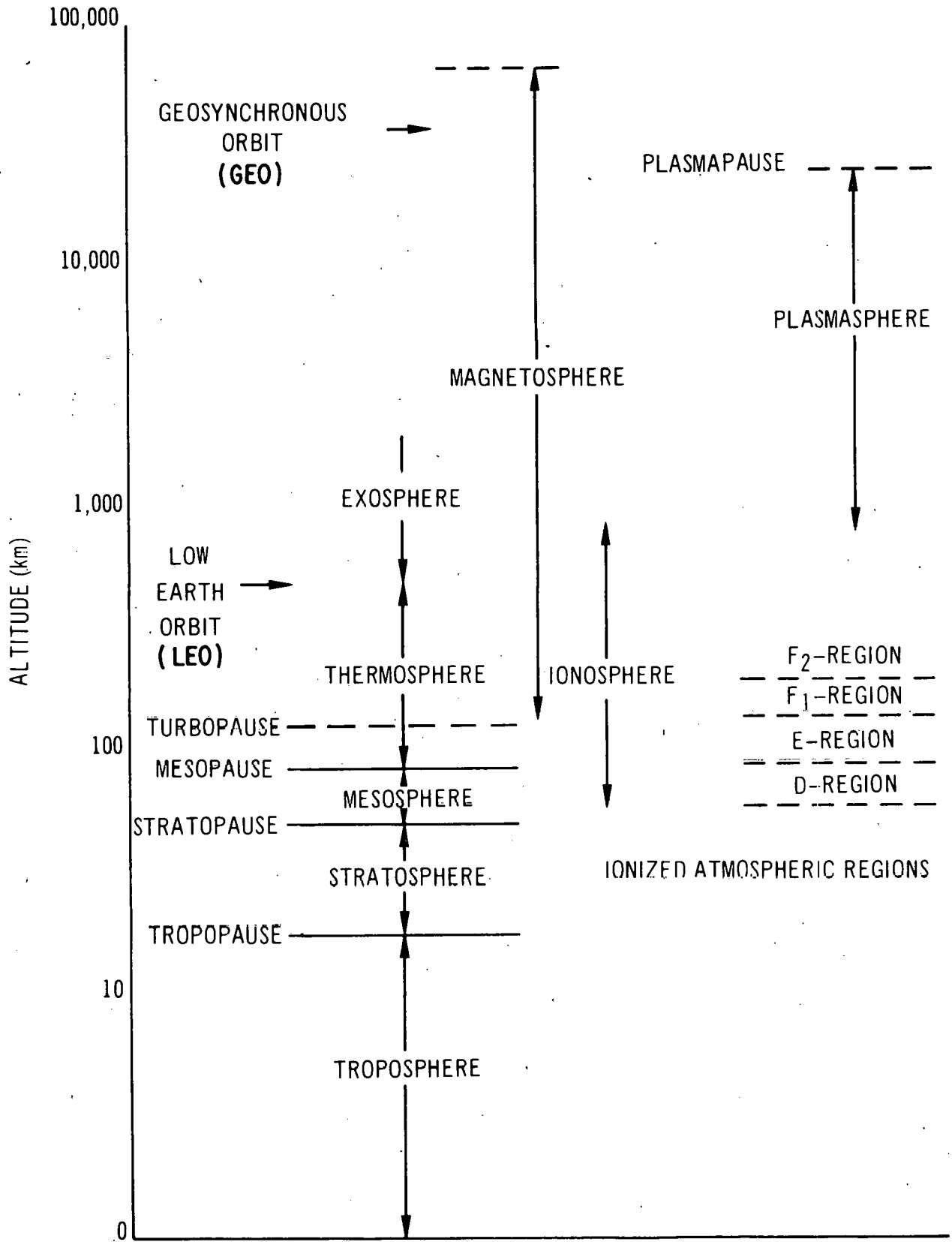


Fig. 7. Regions of the Atmosphere

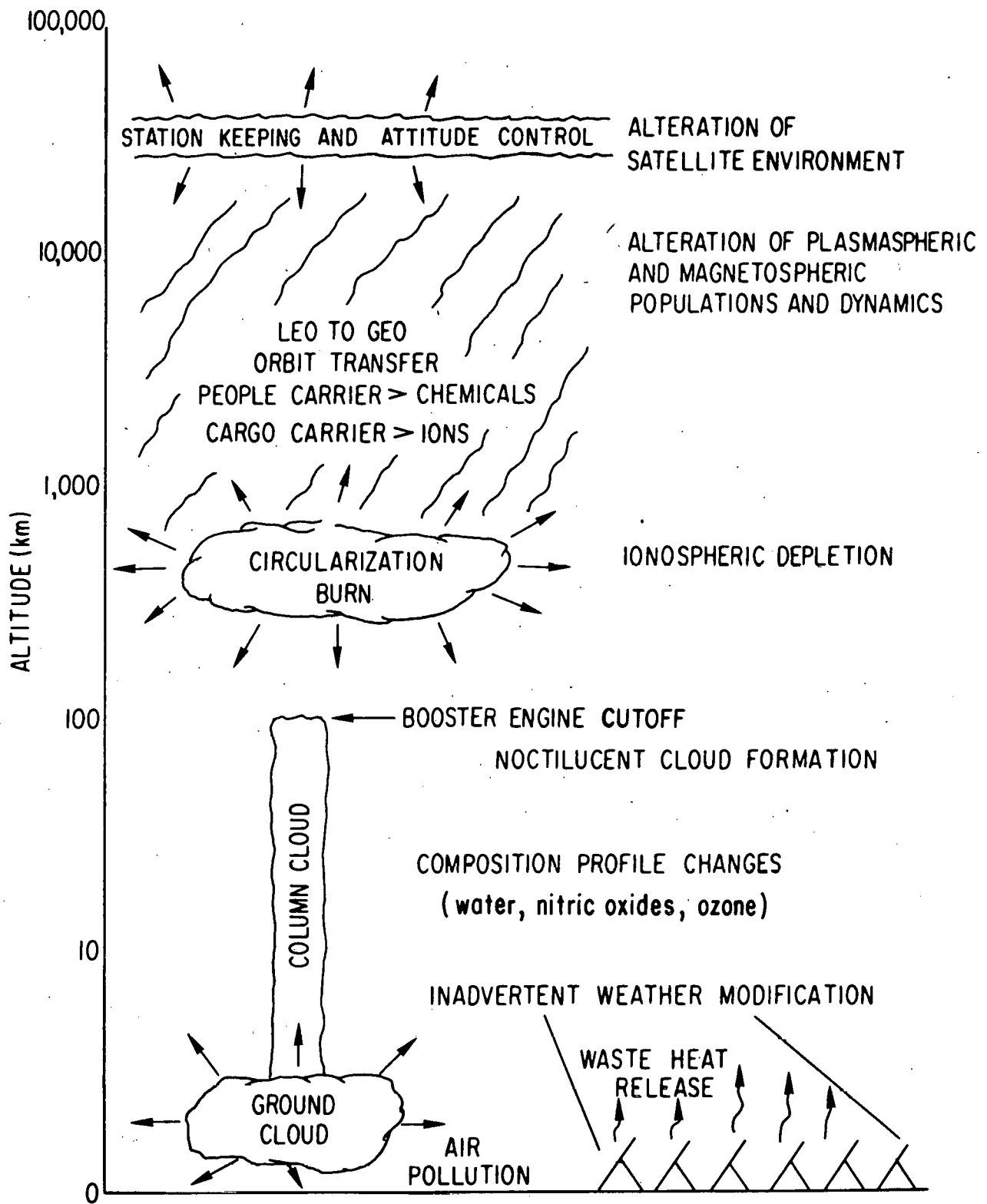


Fig. 8. Summary of SPS Atmospheric Effects

3.1.2 Space Transportation System

The construction and maintenance of the space components of the SPS reference system³ would require a space transportation system of unprecedented size and launch frequency, as outlined in Table 8. The 375 heavy-lift-launch-vehicle (HLLV) flights per year listed in the table are predicated on the construction of two 5-GW satellites per year. Additional flights would be required to maintain the satellites and supply stationkeeping propellants and other materials. Hence, toward the end of the 30-yr construction period, a maximum of about 500 HLLV flights annually might be required.

With a gross liftoff weight nearly five times that of the Saturn V launch vehicle, the HLLV would be by far the largest of the SPS space vehicles. The HLLV and personnel launch vehicle (PLV) would transport cargo and personnel, respectively, between earth and low earth orbit (LEO), while the personnel orbit-transfer vehicle (POTV) and the cargo orbit-transfer vehicle (COTV) would carry personnel and cargo between LEO and geosynchronous earth orbit (GEO). The basic concept involves the construction of a fleet of reusable, round-trip vehicles and their dedicated solar array in LEO. Table 9 lists the rocket propellant exhaust products for the SPS reference system space vehicles.

Table 8. SPS Space Transportation Vehicles

Name	Function	Propellants ^a	Launches ^b per year	Operating Altitude (km)	Main Exhaust Products ^c
Heavy-lift launch vehicle (HLLV)	Transport materials between earth and LEO	CH ₄ /O ₂ (stage 1)	375	0-57	CO ₂ , H ₂ O
		H ₂ /O ₂ (stage 2)	375	57-120	H ₂ O, H ₂
		H ₂ /O ₂ (circular- ization/deorbit)	375	450-500	H ₂ O, H ₂
Personnel launch vehicle (PLV)	Transport personnel between earth and LEO	Details not available (probably same as HLLV)	30	0-500	CO ₂ , H ₂ O, H ₂
Cargo orbit- transfer vehicle (COTV)	Transport materials between LEO and GEO	Argon H ₂ /O ₂	30	500-35,800	Ar ⁺ plasma H ₂ O, H ₂
Personnel orbit- transfer vehicle (POTV)	Transport personnel between LEO and GEO	H ₂ /O ₂	12	500-35,800	H ₂ O, H ₂

^aCH₄/O₂: liquid methane/liquid oxygen
H₂/O₂: liquid hydrogen/liquid oxygen

^bAssuming construction of two (silicon option) 5-GW satellites/year.

^cCO₂: carbon dioxide
H₂O: water
H₂: hydrogen
Ar⁺: argon ion

Table 9. Exhaust Products of SPS Space Transportation Vehicles^a

Atmospheric Region	Altitude Range (km)	Source ^b	Total Mass (t) ^c	Mass of Specific Emission Products (t)				
				CO ₂	CO	H ₂ O	H ₂	Ar ⁺
Troposphere	0-0.5	HLLV, PLV	650	260	117	260	13	-
	0.5-13	HLLV, PLV	2850	1140	513	1140	57	-
Stratosphere	13-50	HLLV, PLV	3027	1210	546	1210	61	-
Mesosphere	50-80	HLLV, PLV	758	199	90	450	19	-
Thermosphere	80-125	HLLV, PLV	2031	-	-	1960	71	-
	LEO ^d	HLLV, PLV	33	-	-	32	1	-
	LEO	POTV	460	-	-	443	11	-
Exosphere	GEO ^d	POTV	153	-	-	147	6	-
	477-GEO	COTV ^e	985	-	-	0	0	985 ^f

^aMass emissions per flight.

^bPLV emissions would be chemically similar to those of the HLLV, but are not otherwise determined at this time. The numbers shown are emissions of the HLLV only.

^ct = metric ton = 1000 kg.

^dLow earth orbit (LEO) is at 477 km; geosynchronous earth orbit (GEO) is at 35,800 km.

^eIn addition to mass emissions, the argon plasma engines of the COTV would inject a significant amount of energy into this altitude range. Also argon plasma engines would be used for satellite attitude control and stationkeeping control at GEO; these emissions are unknown at present and have not been included.

^fAr⁺ mass for the silicon photovoltaic cell option. For the gallium aluminum arsenide option, the Ar⁺ mass would be 212 t.

3.2 ASSESSMENT

3.2.1 Troposphere: Effects of Rocket Effluents

The direct effects of the satellite power system on the troposphere would result from manufacturing, transportation, rocket launches, and test firing of rocket engines. The effects of HLLV rocket launches on air quality and weather are emphasized here because of the HLLV's larger size and higher launch rate compared to the PLV. Figure 9 indicates the general tropospheric environmental effects of rocket launches. Estimates of acoustic noise and its impacts are discussed in Section 2. Estimates of possible acid rain are given here, and potential impacts are addressed in Section 2.

Air Quality Impacts

The air quality and meteorological effects of rocket launches are due primarily to the ground cloud formed during the first 20 s following ignition and lift-off. After a rocket begins to rise at an appreciable rate, the exhaust products are deposited in a thin column that quickly mixes with the ambient air and dissipates. No significant adverse environmental effects associated with the exhaust emissions in the middle and upper troposphere have

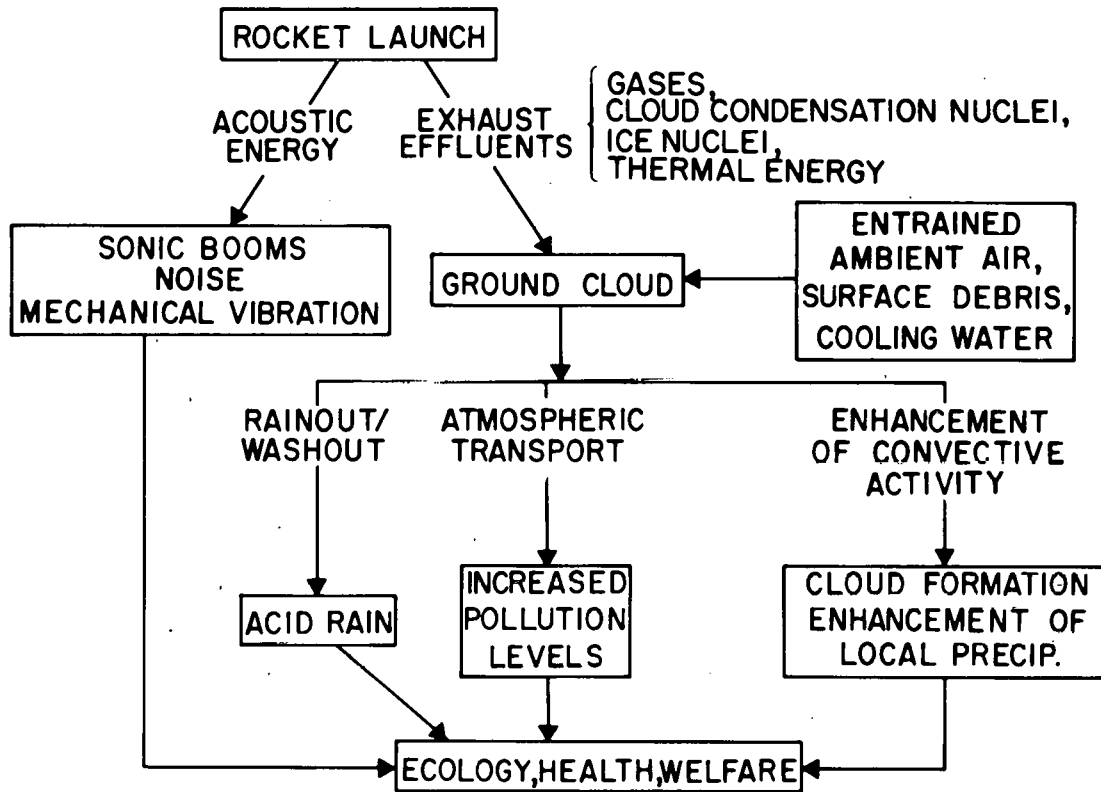


Fig. 9. Tropospheric Environmental Effects of Rocket Launches

been identified. The ground cloud, on the other hand, is a source of potential air pollution and weather modification.

Because of the high initial thermal energy content of the ground cloud, it rises to an altitude of 0.7 km to 3 km, depending on meteorological conditions and the size of the rocket. As the cloud rises, a substantial fraction of the heavy particles (entrained surface dust and debris) falls out of the cloud. The range over which this fallout continues depends on the turbulent mixing forces within the ground cloud, the particle size distribution, and ambient meteorological conditions. This range has not been evaluated for the HLLV, but could extend to a few (less than ten) kilometers, depending on wind speed.

The amounts of the principal exhaust constituents in a typical HLLV ground cloud after neutral buoyancy is attained are estimated to be: water = 400-650 t, carbon dioxide = 450-700 t, and submicron-size suspended particulate matter after early fallout = 0.01-1 t. In addition, measurements made on the ground cloud of an Atlas/Centaur launch (see discussion below) indicate that 20-30 t of nitrogen oxides would also be formed. The concentration of these species within a ground cloud is greatly modified by entrainment of the ambient air (the stabilized ground cloud is approximately 99% air) and steam from the flame trench and cooling water sprays.

After stabilization, the surface and airborne concentrations of some substances in the cloud can be estimated with air pollution dispersion models developed especially for this purpose.^{4,5} In the case of liquid-fueled rockets such as the HLLV, however, the only substances that can be handled by relatively standard dispersion models are water, carbon dioxide, and possibly sulfur dioxide if a sulfur impurity is present in the fuel; however, it is not expected that sulfur would be a significant fuel impurity if methane were used, as projected in the reference system design. Carbon monoxide would be present in HLLV exhaust, but would be converted to carbon dioxide. Water and carbon dioxide are of no interest from an air quality standpoint. The total annual carbon dioxide emissions amount to only 23% of those from a typical 1000-MW coal-fired electric power plant and are therefore insignificant. The substances of greatest concern are the nitrogen oxides, due to the possibility that a short-term national ambient air quality standard for nitrogen dioxide may be promulgated in the next year or so. Moreover, nitrogen oxides can contribute to the acid rain problem (see Section 2). Very specialized dispersion models must be used to assess the effects of nitrogen oxides, primarily because of their chemical reactivity. Limited calculations have been carried out to estimate the potential contribution of an HLLV ground cloud to ground-level nitrogen dioxide concentrations, and the results indicate that under adverse conditions the HLLV contribution might be significant. It seems unlikely that the cloud by itself would give rise to a violation of current air quality standards under normal conditions, but it could cause a violation if the ambient nitrogen dioxide concentration were already close to the standard.

A useful source of information about the nature of liquid-fueled rocket ground clouds is the results of measurements made during the launch of an Atlas/ Centaur rocket in November 1978. A number of cloud parameters were measured, such as the concentrations of several gaseous substances, the particle size distribution, the concentrations of cloud-condensation nuclei (CCN) and ice-forming nuclei (IN), and the physical dimensions of the cloud.* A number of aerosol samples also were returned to the laboratory for investigation of size distribution and trace-metal content and for CCN and IN studies.

A total of 52 aircraft passes through the ground cloud were made during approximately 2.5 hr after launch. After about 135 min the ground cloud became indistinguishable from an industrial plume in the area. The highest concentrations of the gaseous components were measured five minutes after lift-off during the first successful pass through the cloud. The observed concentrations of nitric oxide (NO), nitrogen dioxide (NO₂), and sulfur dioxide (SO₂) were 0.635, 0.500, and 0.023 ppm, respectively. The cloud subsequently drifted downwind and dispersed until at 110 min after launch the measured concentrations were 0.045, 0.065, and 0.007 ppm, respectively. Primarily, the cloud grew in size horizontally, vertical dispersion being strongly suppressed by a nocturnal inversion. As a result, although measurements are not available, the ground-level concentrations due to the ground cloud were undoubtedly below detection limits.

*The monitoring program was conducted, under contract to Argonne National Laboratory, by L.F. Radke and others, Department of Atmospheric Sciences, University of Washington, and E.E. Hindman and L.O. Grant, Department of Atmospheric Science, Colorado State University.⁶

In view of the presence of sulfur as an impurity in the Atlas/Centaur fuel (0.047% according to analysis), SO_2 was expected in the ground cloud and was indeed observed. Even the highest observed concentration of SO_2 was, however, considerably lower than concentrations observed in the plumes from fossil-fuel-fired power plants, which range from 1 ppm to 10 ppm at a distance of 1.6 km from the stack.⁷

The substantial quantities of nitrogen oxides observed in the ground cloud are thought to result from rocket exhaust afterburning. In this case, the concentrations observed are comparable in magnitude to those observed in power plant plumes, which range from 0.5 ppm to 5.0 ppm at a distance of about 1.6 km from the stack.⁸ In addition, a systematic conversion of NO to NO_2 was observed at greater elapsed times, due presumably to the entrainment of ambient air containing ozone and reaction of that ozone with NO to produce NO_2 . The ambient ozone concentration at the altitude of the cloud was measured to be about 0.060 ppm, but within the ground cloud the ozone concentration was below detection limits until the cloud had almost entirely dispersed, indicating that reaction with NO was undoubtedly occurring.

As mentioned above, emissions of nitrogen oxides can in principle contribute to excess acidity in precipitation. Consideration of several possible mechanisms and their rates, however, shows that precipitation taking place after an HLLV launch would not be significantly more acidic than before the launch, and that the slight possible increase in acidity would probably not be detectable. It is also expected that any change in the long-term, regional average rainfall acidity would be undetectable and completely negligible.

Inadvertent Weather Modification

The principal concerns about inadvertent weather modification by SPS rocket effluents are the possibilities that individual ground clouds might temporarily modify local weather and that one or two HLLV launches per day might lead to cumulative effects under certain meteorological conditions. Enhanced convective activity in response to heat and moisture from the rocket exhaust and the launch facility for a given meteorological condition would be one possible effect. Another would be the alteration of the microphysical processes of clouds in the general area, resulting from rocket effluents, entrained debris, and cooling water used during the launch.

Effluent from solid- or liquid-fueled rockets would be expected to produce both cloud-condensation nuclei and ice-forming nuclei in the ground cloud. The addition of these nuclei to the atmosphere can alter cloud microphysical processes that are significant for cloud and weather modification in Florida and tropical regions. In general, the addition of CCN may tend to slow down the formation of warm rain (in which ice plays no significant role) if there are more than 1000 CCN/cm³. However, if very large hygroscopic particles (giant nuclei with radii greater than 25 μm , such as are expected to come from launch pad debris) are present, rain formation may be accelerated. In Florida, some rainfalls are associated with condensation-freezing processes in a deep convection cloud system. In an IN -deficient, supercooled cloud, the addition of ice-forming nuclei can lead to precipitation, although the exact

effectiveness of cloud seeding is still controversial. The global concentration of IN is about one per liter at -20°C . In planned weather modification, approximately 10 effective IN per liter are added at a supercooling cloud temperature of -10°C to -15°C for precipitation enhancement, and one to several hundred IN per liter are added for thunderstorm modification.

The measurements of the November 1978 Atlas/Centaur ground cloud indicated that the IN concentrations generated by the rocket launch had limited potential for weather modification. However, because of uncertainties in measurement techniques and evidence for the creation of new IN as the ground cloud aged, the potential for weather modification due to IN production cannot be assessed with confidence at this time. The concentrations of CCN in the ground cloud were meteorologically significant. The initial emission was about 1.2×10^{17} CCN, approximately equivalent to a 10-s emission of similar nuclei by a large city. In addition, CCN were produced in the ground cloud at a rate of about 1 CCN/cm³ per second. This high a concentration of cloud-condensation nuclei in a rocket-exhaust ground cloud could alter the frequency and persistence of fogs and haziness on the surface. In addition, in a complementary study,⁹ field and laboratory investigations of a ground cloud from a Titan III (solid-fueled booster) launch concluded that both the IN and CCN concentrations were of meteorological significance.

In addition to these microphysical effects, the input of heat and moisture from an HLLV launch could, under certain conditions, enhance convective activity. General weather conditions that favor convective instabilities and active convective elements are conducive to inadvertent weather modification by SPS rocket launches. These general conditions were identified for the Kennedy Space Center area in a theoretical study of the space-shuttle exhaust cloud.¹⁰ The conditions include hurricanes; easterly waves of summer; stagnating frontal zones; cool-season squall lines; cool-season, low-latitude midtropospheric troughs; warm-season, weak midtropospheric troughs; and coastal sea-breeze convergence regimes. In the tropical regions, potentially unstable air in the boundary layer persists daily throughout the year.

In-cloud measurements have been made as long as 4 hr after a rocket launch. In view of the size of the HLLV, the potential for inadvertent weather modification from HLLV effluents could persist more than 24 hr after launch. The 500 launches proposed per year therefore might have some cumulative effects. Pending further study of the SPS and a better 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.

3.2.2 Troposphere: Effects of Rectenna Operation

A preliminary assessment of the possible meteorological effects of SPS rectenna operation has been conducted.¹¹ The study was based upon the maximum microwave-beam power density of about 23 mW/cm² and an average waste-heat release of 0.75 mW/cm² from a rectenna covering approximately 100 km². The preliminary findings were that the effects of an SPS rectenna on weather and climate would be small compared to the direct environmental consequences of construction. The rectenna's influence on weather and climate would be

similar to that of a typical suburban development. The intensity of the atmospheric perturbation due to SPS rectenna operation should be very small compared to that caused by other man-made installations. Microwave heating of the lower atmosphere through gaseous absorption would be negligible. Any actual effects of the microwave heating inside a cloud would not be detected in the presence of the natural variance of cloud and storm phenomena.¹¹

A workshop on the meteorological effects of rectenna operation and the related microwave transmission problems has assessed the state of knowledge and identified possible new issues.¹² The two most important topics discussed, the effects of waste-heat release at the rectenna site and microwave interactions with the atmosphere, are summarized below.

Waste-Heat Release

Construction of a rectenna would modify the thermal and radiative properties of the ground on which it was built; operations would introduce a heat source at the surface. Though the perturbations by the rectenna of the average surface heat exchange would be on the order of 10%, an increase in perturbation should be considered on the occasions of microwave-beam wandering and spreading due to atmospheric refraction effects.

Based on studies of the effects of land use changes, the following atmospheric effects could be expected from rectennas. Small temperature changes (on the order of 1 C°) could occur on occasions of light wind, and changes in cloud populations also would be possible. Somewhat larger man-made heat dissipation rates over comparable areas have been associated with apparent anomalies in the distribution of rainfall.

In hilly terrain, on scales smaller than the rectenna dimensions, there are diurnally varying changes in the surface energy budget that are larger than the projected rectenna waste heat. It is therefore expected that the meteorological effects of rectenna operation would vary from site to site, and the central maximum heat dissipation (about 1.6 mW/cm²) might become important in augmenting a naturally occurring topographical effect on the surface energy budget.

Assessment of possible weather and climate effects over areas larger than a regional scale should not be confined to the influence of the rectenna alone -- it is necessary to consider the whole satellite power system in the context of the energy demand it is designed to meet. The overriding feature of the system is that the major inefficiency, the rejection of waste heat, would be in space. Furthermore, there would be no significant emissions of material into the troposphere during operation. Of all major proposed power production systems, the SPS would be the least likely to have regional or global effects on weather and climate.

The above estimates have been confirmed by model simulations.^{13,14} These simulations have examined the effects of waste heat, surface roughness, and radiative properties. They indicate that surface roughness change due to the presence of the rectenna would perturb the heat flow more than waste heat would. Also, an approximate analysis indicates that reflected energy at the

rectenna and its diurnal variation would potentially be a source of larger perturbations of surface heat flow than waste heat would be. For potentially unstable moist conditions, only a surface roughness change would be conducive to the formation of cumulus clouds.

In summary, preliminary estimates of the local and regional effects of rectenna construction on weather and climate are that such effects would be generally small but detectable in some instances. The possibilities of avoiding weather and climate changes by construction manipulations not affecting system efficiency should be studied as the system design develops. Some atmospheric effects would likely be site specific; investigation of these effects by the best available methods should be part of the assessment of the environmental impact of rectenna construction at each site considered.

Microwave Propagation

The atmospheric absorption of microwave energy at the proposed SPS wavelength would be negligible in clear air for the projected tropospheric path lengths of about 20 km. However, some absorption by clouds and precipitation would occur when storms entered the beam path. Information is available regarding the amount of microwave absorption per unit path length as a function of rainfall rate.¹⁵ The total attenuation of this wavelength would be due predominantly to absorption. With the most extreme rainfall rate of 254 mm/hr as an example, the attenuation at the proposed 2.45-GHz frequency would be about 0.063 dB/km.¹⁵ At the proposed maximum power density of 23 mW/cm², the absorbed microwave power inside the storm would be approximately 3.2×10^{-3} W/m³, which is approximately two orders of magnitude smaller than the release rate of the buoyant energy of a cumulus cloud with an updraft of 10 m/s and a temperature excess of 2 C°. Therefore, it is reasonable to conclude that the absorption of SPS microwave power by a storm would have no significant influence on cloud dynamics and thermodynamics or the associated precipitation.

3.2.3 Stratospheric and Mesospheric Effects

Composition Perturbations

Since the early 1970s, there has been much concern about the possible alteration of the stratosphere's chemical composition by a wide variety of natural and man-made phenomena, including volcanic emissions, solar flares, supersonic aircraft, chlorofluoromethane emissions, nuclear weapons testing, and increased biological production of nitrous oxide (N₂O). Possible changes in the concentration of ozone have been the greatest concern, because of the role that upper-atmospheric ozone plays in shielding the earth's surface from solar ultraviolet radiation. In addition, the upper atmosphere's chemical composition is directly involved in its dynamics and circulation. For example, the increase in temperature in the stratosphere over that at the tropopause is due directly to the absorption of ultraviolet radiation by ozone, the absorbed energy being converted ultimately into thermal energy. In turn, the increase in temperature with altitude has a direct effect on the

rate of vertical transport. Also, between approximately 30 km and 70 km above the earth's surface, the absorption of solar energy provides the main driving force for the dynamics of the atmosphere. Thus, perturbations in upper atmospheric composition may affect meteorological variables, although in many respects such effects are less well understood than effects in the troposphere.

The most direct and obvious manner in which the satellite power system might affect the upper atmosphere would be through the direct injection of rocket exhaust. The estimated masses of various exhaust products emitted into different regions of the atmosphere during one flight of the HLLV were given in Table 9. The relatively large amounts of rocket exhaust could alter the natural chemical composition, particularly with regard to trace substances such as ozone and water vapor. In addition, the reentry of the upper stages of the launch vehicles would deposit ablation materials and produce NO in the mesosphere. The composition changes resulting from rocket effluents and reentry products would be the most important primary effects expected in the stratosphere and mesosphere.

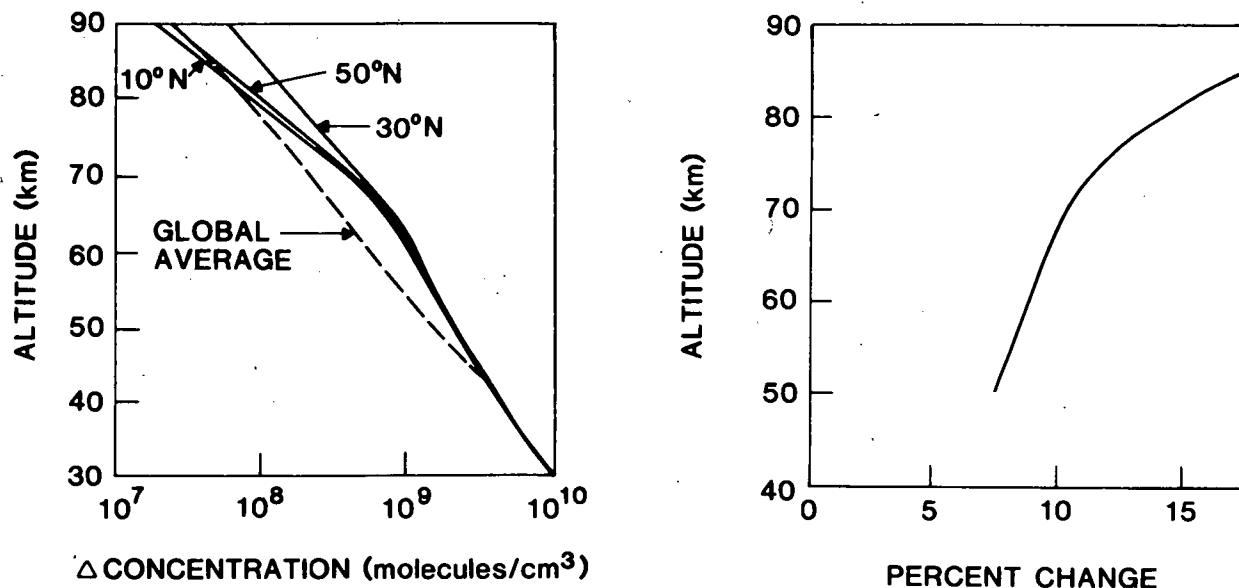
Quantitative estimates of the impacts expected from injections of rocket exhaust into the upper atmosphere, based on calculations of the global or hemispheric average concentrations, may be made relatively easily with available one-dimensional atmospheric models. However, because of the high expected launch rate, a significant "corridor effect" might exist. The corridor effect refers to a significant dependence of the composition perturbations on latitude, the perturbation being largest near the latitude at which rocket exhaust is injected. This effect would be expected whenever the exhaust injection occurred over a narrow latitude band at a rate that was significant compared to the rate of north-south atmospheric transport.

Initial calculations indicated that carbon dioxide emissions from SPS rocket launches would have no detectable effect on the upper atmosphere, taking into account the relatively large amount already present and using recent estimates of the rate of vertical diffusional transport.¹⁶ This assessment is still considered valid.

With respect to emissions of water vapor, the situation is different. Water is present in only trace amounts in the upper atmosphere; the mass-mixing ratio ranges between 3 ppm and 6 ppm. By comparison, the carbon dioxide mass-mixing ratio is about 500 ppm. Initial considerations indicated that water-vapor concentrations could be significantly affected by SPS rocket exhaust.¹⁷

More-recent calculations indicate that on a global basis, the increase in the water concentration could be approximately 0.4% at 30 km and 8% at 80 km altitude, based on an assumed 400 HLLV flights per year.¹⁸ Calculations made using a two-dimensional model indicate no corridor effect for water at altitudes below about 70 km, and only a slight effect above that altitude. For example, the predicted concentration increase at 80 km reaches a maximum at the assumed launch latitude (30°N) of approximately 15%, and decreases to near the global average value at 10°N and 50°N. Larger effects might occur at higher altitudes.

Figure 10 shows the estimated change in the water concentration as a function of altitude for an assumed 400 HLLV flights per year.¹⁸ The



(a) Change in water concentration at various latitudes compared to global average

(b) Percent increase of water at 30°N latitude

Fig. 10. Change in Water Concentration versus Altitude for 400 HLLV Flights per Year

figure illustrates that the most significant perturbations would be expected in the upper mesosphere and above and that the impact on the stratosphere would be minimal.

An estimated 60-70 t of NO would be generated by frictional heating during the reentry of a single HLLV second stage, the bulk of this production occurring at altitudes between 60 km and 90 km. Calculations made using a two-dimensional model indicate that at 75 km, the injection of NO at a rate corresponding to 400 reentries per year would increase the NO concentration by about 40% between 20°N and 30°N latitude, and by approximately 10% at 10°N and 40°N latitude.¹⁸ Thus the mesospheric NO concentration could be significantly affected, and a definite corridor effect would exist in the long-term NO distribution. In addition, a somewhat localized region of elevated NO concentration would be expected to persist in the mesosphere for 1-2 days following each reentry, although its position would change with time due to advection by the wind at those altitudes.¹⁸

Although reentry production of NO would occur in the mesosphere, a sufficient amount would be produced to affect stratospheric NO concentrations as well, due to downward diffusional transport. At 50 km, an increase of perhaps 5-15% would be expected, depending on latitude; at lower altitudes the effect would decrease substantially. Nitric oxide production due to rocket exhaust afterburning would essentially be confined to the lower stratosphere and would have a negligible effect.

Changes in the upper atmospheric ozone concentration and in the vertically integrated ozone "column" concentration would be expected due to the deposition of both water and NO.¹⁸ The expected effect of the deposition of water and NO from rocket exhaust afterburning would be to decrease the total globally averaged ozone column by about 0.01%, and no significant corridor effect would be expected. The effect of reentry-generated NO, as estimated from two-dimensional model calculations, would be to increase the total ozone column by about 0.1% on a global average basis, with variations about this value depending on season and latitude. This estimate is quite uncertain, however, because it corresponds to the difference between an increase at lower altitudes and a decrease at higher altitudes, and is undoubtedly model-dependent. Calculations using a one-dimensional model -- which cannot realistically simulate significant latitudinal effects or properly treat the localized nature of the NO production indicate a globally averaged value of 0.001-0.01% for the increase in the ozone column due to reentry-produced NO.

The change in the total ozone column due to SPS rocket reentry is therefore rather uncertain, but all model calculations made to date yield values that would be undetectable by currently available techniques. There are no indications at present that SPS-related rocket activity would affect the ozone column to an extent that would be observable.

In addition to the principal exhaust products, water and carbon dioxide, any impurities in the rocket fuel used would also be injected into the upper atmosphere. Present designs call for the use of liquid methane as the fuel for the HLLV and PLV first-stage rocket engines and liquid hydrogen for the second stages, with liquid oxygen as the oxidizer in both stages. It is expected that relatively pure methane would be used since it can be produced rather easily. Current liquid-fueled rockets use a hydrocarbon mixture with a higher molecular weight than methane, however. The 1975 mean sulfur content, for example, of RP-type hydrocarbon fuels was 0.05% total sulfur by weight. A rough calculation indicates that this level of sulfur in the hydrocarbon fuel used for the HLLV launches would result in the emission of about 300 t/yr of sulfur dioxide into the stratosphere. This injection rate may be compared with the estimated natural rate of sulfur dioxide production in the stratosphere of about 200,000 t/yr due to oxidation of carbonyl sulfide (COS)¹⁸ or with the estimated injection of 4,000,000 t from the 1963 volcanic eruption of Mt. Agung in Bali.¹⁷ Based on these comparisons, a 0.05% sulfur impurity in the HLLV booster fuel would have a totally negligible effect on the atmosphere, and a similar conclusion may be reached regarding any other known fuel impurity.

Climatic Effects

The effect on the tropospheric climate of changes in the upper atmosphere's natural composition is an active area of current research and is not well understood. However, information that allows estimation of some quantities of interest is available; one such quantity is the change in surface temperature resulting from changes in high-altitude atmospheric composition. Estimates of surface temperature changes indicate that the impact on the earth's surface temperature of the anticipated perturbations in

the upper atmosphere's composition would be completely negligible.^{17,18} The estimates are based on the composition-perturbation results described above and on results available in the scientific literature based on the use of one-dimensional radiative equilibrium models. Thus, only the direct effect of composition perturbations on the earth's radiation budget has been taken into account. With regard to more-general climatic or weather effects, current understanding of the coupling between the high-altitude environment and the tropospheric climate is such that reliable quantitative predictions of the general climatic effects of SPS-related perturbations probably cannot be made at this time.

It seems highly probable that transient noctilucent clouds (luminous, thin clouds occurring near the mesopause) would be induced in the vicinity of the burn trajectory following the launch of an HLLV or PLV. Several examples of such artificially induced noctilucent clouds have been reported in the scientific literature. For example, Benech and Dessens reported the formation of artificial noctilucent clouds on two occasions following the launching of rockets in southern France at a latitude of approximately 45°N.¹⁹ The persistence and growth of the clouds only near the mesopause indicated that the clouds were formed from water, and their extent and lifetime suggest that in view of the small amount of water injected (260 gm in the 80-90 km altitude band), the ambient water concentration must have been relatively near saturation. To put the emissions into perspective, a single HLLV launch would inject approximately 13 t of water into the same 10-km altitude range -- 50,000 times as much as emitted by the French rocket. In view of the large amount of water involved, it seems likely that very substantial artificial noctilucent clouds would be generated by HLLV and PLV launches.

The lifetimes of such artificial noctilucent clouds are uncertain, but preliminary theoretical estimates indicate lifetimes on the order of several hours for clouds produced during an HLLV launch. While clouds could persist on a local scale, the expected increase in water vapor near the mesopause from multiple launches would not be sufficient to form a permanent global-scale cloud. No significant climatic effect would be expected due to noctilucent-cloud formation.

Energy Injection

The construction and operation of the satellite power system would directly inject energy into the stratosphere and mesosphere in at least two ways: direct injection of thermal energy from HLLV and PLV rocket exhaust and direct absorption of energy from the microwave beam. It is not expected that either process would have any significant environmental impacts.

Taken individually, HLLV and PLV launches would have no thermal impact on the stratosphere and mesosphere beyond the transient heating in the exhaust wake, which is rapidly dispersed. The time-averaged energy flux into the upper atmosphere would also be extremely small compared to the energy naturally deposited via absorption by ozone of solar ultraviolet radiation. Averaged over the entire globe, energy injection into the stratosphere from SPS rocket exhaust would amount to approximately 0.00008 $\mu\text{W}/\text{cm}^2$ for an assumed 375 HLLV flights annually. This figure should be compared to

the average 4 mW/cm^2 ($4000 \text{ } \mu\text{W/cm}^2$) energy input due to absorption of ultraviolet light.

Estimates are available for the upper-atmospheric absorption of microwaves at the SPS frequency of 2.45 GHz. The fractional absorption, vertically incident on the atmosphere, has been reported to be approximately 0.01, of which only 0.001 occurs in the stratosphere and mesosphere.²⁰ The peak power in the microwave beam would be approximately 23 mW/cm^2 with an average power level of about 5 mW/cm^2 . Thus, a net continuous energy deposition in the stratosphere and mesosphere of approximately 0.005 mW/cm^2 would be expected per satellite. This figure is about 0.13% of the solar ultraviolet absorption input and may be considered negligible. When averaged over the globe, even assuming the presence of 60 5-GW rectennas, the average energy flux to the upper atmosphere would be only $0.06 \text{ } \mu\text{W/cm}^2$.

These values are small in an absolute as well as a relative sense. The effect of absorption is to heat the air. The total temperature change would depend on the length of time that an individual parcel of air spent in the microwave beam and therefore would depend on the beam diameter and wind speed. Assuming typical wind speeds and residence times and a beam diameter of 10 km, corresponding estimated temperature changes have been calculated and are completely negligible.

3.2.4 Ionospheric Effects

The ionosphere has traditionally been identified as that region in which the free-electron density is large enough to affect radio wave propagation over a broad frequency range. Because of associated physical phenomena, the ionosphere is usually thought of as a series of four not-too-distinct regions. The D-region extends from altitudes of about 60 km to 90 km and is roughly coincident with the mesosphere. The E-region extends from about 90 km to 150 km and coincides with the lower portion of the thermosphere. The F-region of the ionosphere begins at an altitude of about 150 km and extends upward into a highly ionized region called the plasmasphere. The F-region itself is subdivided into the F₁-region (140-200 km) and the F₂-region (200-1000 km).

Effects in the D-Region of the Ionosphere

The D-region is important because of the effect of its ionization on the propagation of radio waves extending from extremely low frequencies (ELF) to very high frequencies (VHF). The ions and electrons are produced primarily by photoionization of NO by solar radiation. Because of the high density of neutral gas in the D-region, electrons tend to become attached to molecules to form negative ions in the lower region. At night, many of the remaining free electrons form negative ions so that below 90 km free electrons essentially disappear. This has a significant influence on the reflection height, absorption, and polarization of radio waves.

Water vapor emitted by SPS launch-rocket engines might alter positive and negative ion composition in the lower ionosphere. In effect, added water

vapor could tend to increase the positive-ion cluster size, leading to faster effective electron-ion recombination with a subsequent reduction in plasma density. Hence, radio wave absorption in the daytime ionosphere could be reduced, leading to propagation anomalies. While the likelihood of altering the electron and ion composition seems to be fairly high, the impacts are judged not to be very significant at this time.

Nitric oxide, produced principally during rocket reentry, could allow additional ions to be formed in the D-region. Also, during reentry, sporadic E-layers (1- or 2-km thick layers of greatly enhanced electron concentration) might occur more frequently if the ion layers between 100 km and 110 km were augmented by ablation products. As mentioned in the previous section, preliminary calculations indicate that NO production during reentry would increase ambient NO concentrations by a factor of up to two in a 40°- to 50°-wide corridor centered on the reentry latitude. This might more than compensate for the plasma reduction discussed above. Current capabilities do not allow a definitive assessment of the ultimate change in the plasma density and its effect on radio propagation.

Recently, an attempt was made to detect rocket-launch-induced effects in the lower ionosphere on very-low-frequency (VLF) propagation (signals from the OMEGA navigation system).²¹ Evidence suggests, although not conclusively, that observed signal anomalies were caused by rocket-induced effects in the D- or lower E-region. The significance of such anomalies remains to be evaluated.

Effects in the E-Region of the Ionosphere

The E-region is formed by solar radiation. Oxygen (O_2^+ and O^+) and nitric oxide (NO^+) are the main positive ions. Even though the free-electron density drops by one to two orders of magnitude from daytime to nighttime, the density remains high enough during the night to reflect radio waves. This region of the ionosphere was the one discovered to be responsible for the first long-range transmissions of radio signals. This region also constitutes a transition zone between regions dominated by molecular and atomic ions. As altitude increases within the E-region, the O^+ -ion concentration becomes increasingly important and begins to dominate in the F-region (above 150 km). This is a key feature of this region of the ionosphere, because the electron-ion recombination rate is much greater in the presence of molecular ions. This point will be discussed again later.

Since the HLLV engines would be shut off above about 124 km, only the lower E-region would be subject to the direct rocket effluents. Since molecular diffusion is the main mechanism for vertical transport above 110 km, aside from gravitational settling, some effluents would diffuse upward into the higher E- and F-regions. In addition, effluents from the HLLVs, PLVs, and personnel orbit-transfer vehicles (POTVs) injected near LEO would enter this region by downward diffusion and gravitational settling of exhaust vapor molecules and ice crystals. The E-region conductivity is critical to plasma-sphere characteristics and magnetosphere-ionosphere coupling. This coupling involves a rather complex system of electric currents and fields as well as the precipitation of energetic particles into the lower atmosphere, with possible

implications for ozone levels and air conductivity at low altitudes. Climatic effects would therefore be possible but the probability is unknown.

Effects in the F-Region of the Ionosphere

The electron density profile in the F-region reaches a peak of about one million electrons per cubic centimeter during the daytime and drops by a factor of about 10 at night. Above the altitude of peak density, the electron density decreases. It undergoes a rather sharp tenfold reduction at the plasmopause (about four earth radii near the equatorial plane). The positive-ion population in the F₂-region is dominated by oxygen ions (O⁺) that recombine rather slowly with electrons. Solar radiation is the principal source of ionizing radiation in the F-region.

Charged-particle motion in the F-region is quite complicated because of collisions with the neutral particles of the much-denser, coexisting thermosphere and the presence of the earth's magnetic field. The extent to which the neutral and ionized components of the upper atmosphere are coupled may determine the degree to which changes in ionospheric structure caused by HLLV injections could influence upper-atmospheric or middle-atmospheric circulation. However, the extent of this coupling and its significance, if any, to climate and weather are essentially unknown. The major issues related to F-region effects and the current understanding of them are summarized below.

F-Region Plasma Depletions. Rocket effluents such as water, hydrogen, and carbon dioxide cause the dominant F₂-region oxygen ions to quickly form molecular ions (e.g., H₂O⁺), which very rapidly recombine with electrons. Hence a cloud of exhaust effluents would cause a depletion or "ionospheric hole" that could extend far beyond the local source of injected molecules and thus affect radio communication and navigation systems over a wide geographical area.

The deposition of rocket exhaust in the F₂-region has been established as a cause of ionospheric depletions. The 1973 launch of Skylab with a Saturn V rocket was the first time a substantial amount of rocket exhaust was injected into the F₂-region of the ionosphere.²² Based on observations of communication satellite signals from several ground-based observatories, it was reported that the ionospheric hole had a radius of about 1000 km and lasted for about four hours.²³ Subsequent analysis suggested that the hole may actually have lasted for 16 hr.²⁴

The first successful attempt to produce an ionospheric depletion under controlled experimental conditions occurred in September 1977.²⁵ Project "LAGOPEDO," as it was called, involved two rocket-borne experiments. Each rocket carried high explosives and an instrument package that was separated from the rocket prior to detonation of the explosives. The detonation products included water, carbon dioxide and nitrogen.²⁶ These experiments generally confirmed theoretical predictions. A major finding was the importance of suppressing the participation of the water molecules in the electron/ion removal process through initial formation of ice crystals followed by gravitational settling to lower altitudes, where the presence of the water is less significant (due to the natural abundance of molecular ions).

The launch of NASA's third High Energy Astrophysical Observatory (HEAO-C) in September 1979 by an Atlas/Centaur rocket produced an extraordinary opportunity to monitor a large-scale, artificially induced depletion of the ionosphere.²⁷ A merging of the results obtained from several diagnostic systems showed that the hole followed the rocket's ground track, extending at least 2000 km (and probably 3000 km) to the east of the launch site. Its north-south extent spanned 600-1000 km, and thus the overall disturbed region totaled one million to three million square kilometers. While the geographical location of the depletion centered on the rocket's trajectory for approximately three hours, evidence suggested a subsequent northward displacement. Approximately five hours after launch (and after sunrise) the effect of the launch on the ionosphere was no longer apparent.

The mechanisms involved in this hole-making process are well understood in general terms and have been modeled approximately. A variety of one-, two-, and three-dimensional models are now available that treat various physical, chemical, and electromagnetic processes that occur in both the natural and perturbed ionosphere. Specific details of the phenomenon and accurate prediction of the location, size, movement, and lifetime of the hole require further study. In addition, the cumulative effects of twice-a-day launches have not yet been studied.

Preliminary calculations indicate that each POTV injection burn would result in an ionospheric hole with an area the size of the continental United States that could last for 4-16 hr. According to the SPS reference system, the POTV burns would occur once or twice a month. It has also been estimated that the circularization burn of the HLLV would produce holes one-tenth that size, lasting for about 5 hr.²⁴ HLLV launches would occur once or twice a day. It is also possible that because of the multiple launches, a chronic low-level depletion would develop in a ring-shaped global region centered around the launch latitude. More-detailed modeling and assessment of radio propagation effects are required.

In addition to affecting radio communication and navigation systems, other possible effects of SPS rocket launches have been identified:^{22,28}

- Enhanced visible airglow would be associated with the plasma depletion but no adverse effects would be likely.
- The electron temperature would increase, but this would probably not affect anything else.
- The plasmasphere could be affected, which might increase the lifetime of particles in the Van Allen Belts. The probability of this event is unknown.
- Infrared emission density could be increased by chemical reaction. This could affect space systems and astronomical observatories, but the likelihood of this is unknown.
- 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.

Changes in the Hydrogen-Atom Cycle of the Exosphere. The hydrogen-atom cycle in the exosphere 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 in the upper thermosphere and exosphere.²⁴ A doubling of the hydrogen-atom density in this region would be plausible according to current estimates. Satellite drag could be increased, the Van Allen radiation belts could be altered, and radio communications could be affected by such an increase. The probability of these effects is unknown because the natural flux of water molecules from the lower to the upper atmosphere is not known.

3.2.5 Plasmaspheric and Magnetospheric Effects

The composition and dynamics of the outermost regions of the atmosphere are very complex. Figure 11 presents a simplified cross-sectional view of the plasmasphere and magnetosphere in a plane perpendicular to the earth's orbital plane. The sun is to the left of the picture and the orbital plane of the SPS satellite is perpendicular to the page. Inside the plasmasphere, a dipole-like (torus shaped) volume, the plasma density is several orders of magnitude higher than in the outer magnetosphere. In the magnetosphere, the earth's magnetic field dominates and traps the charged particles. The solar wind is a supersonic plasma flow away from the sun and is deflected by the earth's magnetic field.

The two SPS-related sources of disturbance of the natural plasmasphere and magnetosphere would be the rocket effluents used to propel the COTVs and

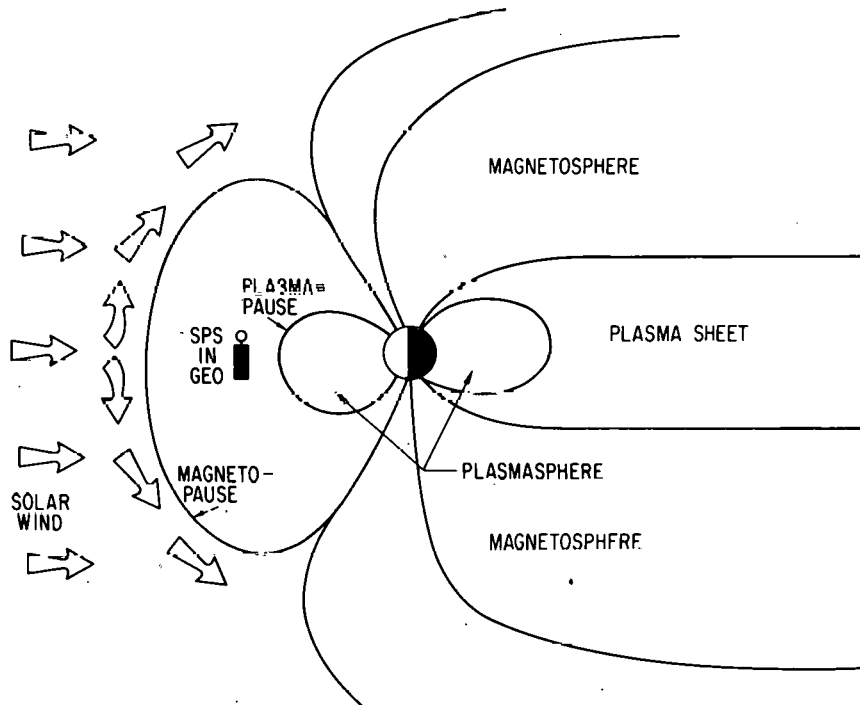


Fig. 11. Cross-Section of Magnetosphere and Plasmasphere

POTVs from LEO to GEO and the presence of the satellite structures themselves (including debris). Based upon the anticipated relative importance of these two sources of disturbance, most of the effort has been devoted to the rocket effluents.

The expected rocket effluents would be of two types: chemical exhaust products (principally hydrogen and water) from the POTV and argon ions (Ar^+) and electrons from the ion propulsion system of the COTV. Some additional chemical and Ar^+ propellants would also be used to control position and attitude during occultations of the satellites and COTVs. 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 in the plasmasphere or magnetosphere would depend on the effluent rates as compared to the natural residence times of particles.

Predictions concerning the effects of SPS activities beyond 500 km are very difficult and at this time are qualitative and tenuous.

The potential impacts of the COTV and POTV inputs on the composition, structure, and dynamics of the plasmasphere and magnetosphere have been addressed at two workshops.^{22,28} Investigations have been made using varied theories and information obtained from archived experimental data.²⁹⁻³¹ A number of these experiments have been reviewed³² and are recognized as having very limited applicability to the SPS case. One of the major issues is the manner in which the argon ions would interact with the ambient plasma and geomagnetic field and what the consequences of various interactions might be. According to the SPS reference system design, a large rectangular array of electric ion thrusters would be used to propel the COTV from LEO to GEO along a slowly unraveling spiral. The trip would require about 130 days. Approximately 80% of the argon ions would be deposited within the plasmasphere (within four earth radii) and the remainder in the outer magnetosphere, between 4.0 and 6.6 earth radii (GEO). The plasma ejected from the ion thruster array would be a dense beam of argon ions and electrons that would not be expected to recombine within the beam.²⁹

The main potential impacts of the COTV and POTV effluents are summarized below:

- The radiation levels in the Van Allen Belts could be affected by the additional heat energy associated with the argon ion exhaust, which might have a tendency to change the composition of the plasmasphere.²⁹
- Enhanced levels of ionizing radiation at GEO could shorten the lifetime of solar cells.³³
- The terrestrial weather could be affected by variations in the magnetosphere or solar wind caused by rocket exhaust gas or ion engine exhaust in GEO altering the interaction of the solar wind with the magnetosphere. Changes in particle distribution in the Van Allen Belts could affect the weather through changes in ozone and atmospheric electricity.^{22,28}

- The performance of space-based optical sensors used for military, scientific, weather, and earth resources sensing could be affected by air glow due to the chemical interaction between rocket effluents and the natural atmosphere.²⁹
- Public utilities (power, telephone, and pipelines) could be affected by earth current surges caused by changes in magnetospheric convection patterns or changes in ionospheric conductivity.^{29,34-36}
- Signals from space-based communications and navigation systems could be affected by the diffusion of the exhaust plasma cloud disrupting propagation paths.²⁹

The probability that any of these effects would occur is unknown; however, the consequences could be significant. These effects must be considered as the SPS technology develops and mitigation strategies, such as increased ion-electron recombination in the rocket exhaust and judicious timing of rocket firing, must be considered.

The issues associated with the satellite structure's presence in the magnetosphere are considered to be of lower priority. These are: obstruction to plasma flow, catastrophic accidents, surface weathering and production of dust clouds, electromagnetic disturbances, space debris, visible and infrared radiation source, and high-energy electron generation.

The current estimate is that the potential effects are not so severe and possible mitigating strategies are not so difficult as to impede the SPS project.^{22,28,29}

3.3 SUMMARY AND CONCLUSIONS

Although there are questions to be resolved, prediction models to be improved and validated, and mitigation strategies to be developed, none of the atmospheric effects identified precludes the planning and development of SPS technology.

3.3.1 Troposphere: Effects of Rocket Effluents

Air quality effects of SPS rocket launches would be due primarily to the ground cloud and would not be expected to involve violations of current standards. Carbon monoxide would be present in only small amounts. Sulfur dioxide would be emitted if sulfur were present as an impurity in the fuel but concentrations would be negligible compared to those observed in the plumes of fossil-fuel-fired power plants. Nitrogen oxides could be expected in the ground cloud due to afterburning, in concentrations three to four times those in power plant plumes. Promulgation of an air quality standard for nitrogen dioxide is anticipated, and although the HLLV launches by themselves would probably not violate the standard, HLLV emissions combined with existing levels could cause a problem.

Heavy-lift-launch-vehicle rocket effluents might temporarily modify local weather under certain meteorological conditions by producing cloud-condensation nuclei and ice-forming nuclei as well as by contributing heat and moisture that could enhance convective activity. Cumulative effects might be produced by multiple launches. Pending further study of the SPS and a better understanding of weather phenomena generally, it is judicious to assume that SPS rocket launches would have the potential to modify local weather conditions to some degree. Some mitigation would be possible through launch scheduling.

3.3.2 Troposphere: Effects of Rectenna Operation

The waste heat generated by rectenna operation and the effect of the structure on air flow and heat transfer would have a small impact on regional weather and climate. The effect would be comparable to that due to other nonindustrial land-use changes covering the same area and would be of little consequence. The absorption of microwave power in the troposphere would likely be highest during rain storms but even then would have a negligible effect on the weather.

3.3.3 Stratospheric and Mesospheric Effects

Carbon dioxide and nitrogen oxide emissions due to rocket launches would not be expected to have a detectable effect on the upper atmosphere. The presence of a 0.05% sulfur impurity in the fuel is not considered likely to have any impact, and a similar conclusion may be reached regarding other fuel impurities. However, water vapor concentrations could be significantly altered by SPS rocket exhaust. The change in the total ozone column due to SPS space flights would be expected to be undetectable and significant corridor (local concentration) effects would not be expected.

The effects on the climate (if any) of perturbing the stratosphere and mesosphere are not known. The most probable effect would be the local formation of optically thin noctilucent clouds at altitudes of about 80 km, which could affect the amount of solar radiation reaching the earth. Theoretical calculations indicate that a permanent, global-scale cloud would not form from multiple launches. On this basis, no significant climatic effect would be expected.

Injection of energy into the stratosphere and mesosphere due to thermal energy from rocket exhausts or absorption from the microwave beam would be negligible compared to natural heating and no adverse effects would be expected.

3.3.4 Ionospheric Effects

The D-region of the ionosphere is important because of the effect of its ionization on the propagation of radio waves. The two most likely D-region effects counteract each other. In the first case, water vapor emitted by launch-rocket engines might cause plasma depletion; while in the second

case, nitric oxide produced during reentry could increase the number of ions in the D-region. Current capabilities do not allow a definitive assessment of the ultimate change in the plasma density and its effects on radio propagation.

The E-region also reflects radio waves and the plasma density remains high enough to reflect radio waves at night. The HLLV rocket engines could be shut down soon after reaching E-region altitudes to minimize effluents in this region. However, effluents could reach the E-region by drifting from either lower or higher altitudes. The conductivity of the E-region plays a role in climate, but current knowledge does not allow a confident assessment of the probability of climate changes due to rocket effluents entering the E-region.

Rocket effluents have been observed to reduce the F-region plasma density, producing ionospheric holes. In addition to affecting radio-wave propagation, other possible effects have been identified. For example, visible airglow would be enhanced and electron temperature increased in association with the plasma depletion. Each POTV injection burn would create an ionospheric hole with an area the size of the continental United States. The HLLV circularization burn would produce a hole one-tenth that size. The POTV burns would occur once or twice a month and the HLLV burns once or twice a day. A confident prediction of cumulative effects is not yet possible; however, it has been estimated that a chronic low-level depletion would develop in a ring-shaped global region centered around the launch latitude. More-detailed modeling and an assessment of radio propagation effects are required.

SPS rocket effluents might introduce significant numbers of hydrogen atoms into the F-region. Current understanding of the F-region does not allow a confident assessment of any impacts.

3.3.5 Plasmaspheric and Magnetospheric Effects

Because the chemical and argon-ion effluents in the upper atmosphere from the POTV and COTV would be substantial compared with naturally existing quantities, a number of issues have been identified: changes in radiation levels in the Van Allen Belts, effects on terrestrial weather, effects on space-based optical sensors, changes in magnetic storms, and interference with space-based communication systems. The probability that any of these effects would occur as a result of SPS construction and operation is unknown, but the current assessment is that the consequences would not be so severe or the required mitigating strategies so difficult as to impede the SPS project.

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4 SPS EFFECTS ON COMMUNICATIONS SYSTEMS DUE TO IONOSPHERIC HEATING

4.1 INTRODUCTION

This section considers the potential effects on telecommunications systems of a disturbance of the ionosphere by the SPS microwave power beam.^{1*} The information presented here is a summary of a detailed assessment of the subject.²

The ionosphere is that region of the earth's atmosphere beginning at an altitude of about 50 km and extending outward 500 km or more. It contains free, electrically charged particles (ions and electrons). The electron density varies with altitude, time of day, season, and the solar cycle.

Because of the presence of free electrons, the ionosphere refracts and slows down electromagnetic (EM) energy that is sent into it. The amount of refraction depends directly on the ionospheric electron density and is also a function of the frequency of the electromagnetic wave sent into the ionosphere, the frequency of electron collisions, and the strength of the geomagnetic field. The electron density can be great enough to totally reflect the incident EM wave and return it to the earth's surface; this property permits the operation of long-distance, high-frequency, radio-wave propagation systems. The ionosphere therefore must be considered an integral part of such systems. At higher frequencies, radio waves travel directly through the ionosphere with speeds slightly below that of light.

Changes in the ionosphere can alter the performance of telecommunications systems whose energy is propagated within and through the ionosphere. In addition, small-scale (meters to kilometers) irregularities in the ionospheric electron density can cause fading and scintillation of signals that pass through the irregularity. This can result in loss of information associated with changes in amplitude and phase of the radio wave.

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 heating the ionosphere are shown in Figure 12.

To fully understand and predict the impact of SPS heating of the ionosphere, a coordinated program of theoretical and experimental work has been undertaken. The experimental work is concentrated around the ionospheric heating facilities at (1) the Arecibo Observatory of the National Astronomy and Ionosphere Center in Puerto Rico and (2) the Institute for Telecommunication Sciences Ionospheric Heater Facility in Platteville, Colorado. Both facilities use high-frequency (HF) transmissions to heat the ionosphere.

One area of experimental work is the simulation of SPS effects on telecommunications. These studies are conducted at Platteville, because of

*References for Section 4 are listed in Section 4.4.

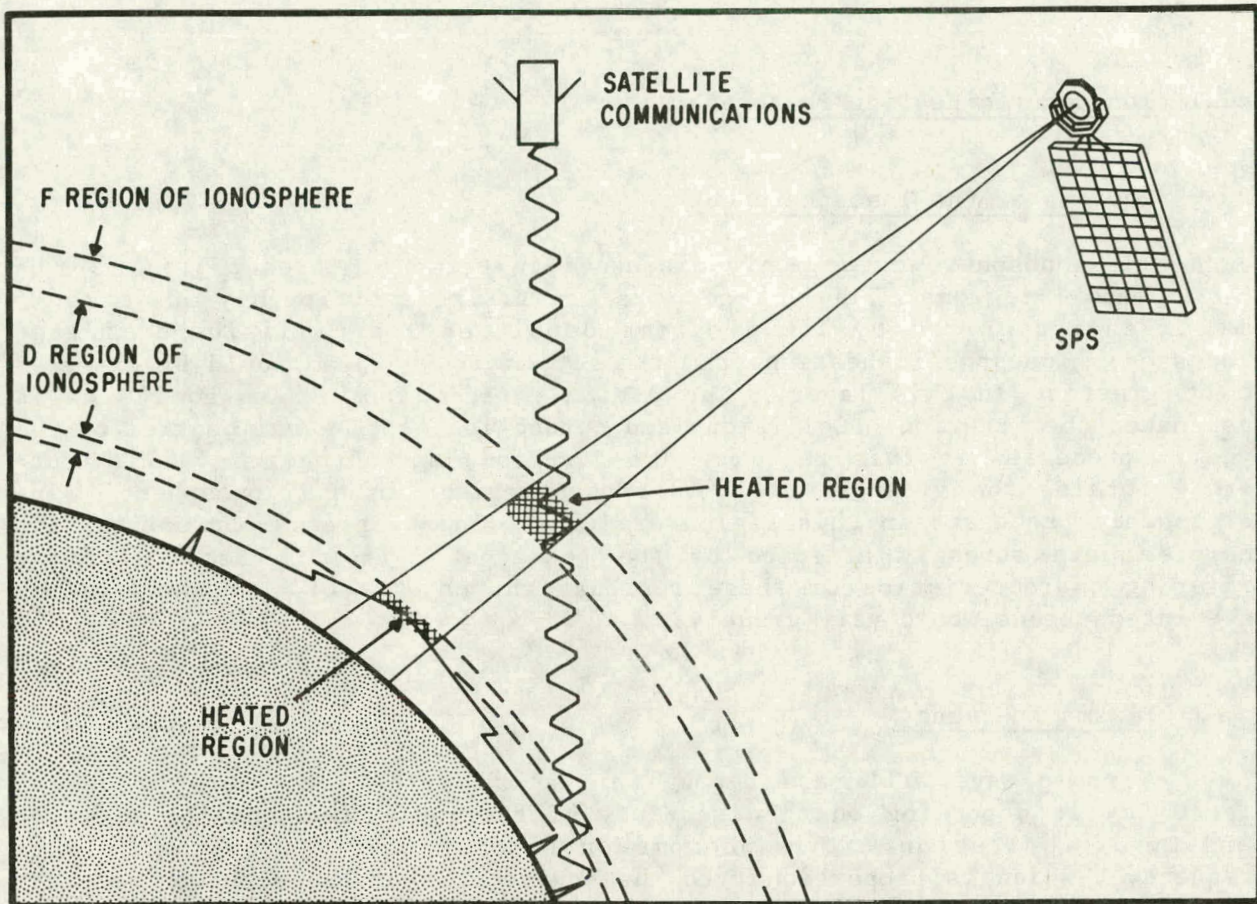


Fig. 12. Examples of SPS Microwave Transmission Effects on the Ionosphere and Telecommunication Systems

favorable logistics and because the communications environment there is believed to be representative of the environments in which an SPS would typically operate. The other experimental studies, devoted to understanding and analyzing the physical mechanisms that cause ionospheric heating, are carried out at Arecibo. The Arecibo facility has unique diagnostic capabilities, particularly in the "incoherent scatter radar," that enable direct measurement of electron density and temperature in the ionosphere.

Theoretical studies focus on the development of simulation models of the ionosphere that can both predict the effects observed in the experimental studies and provide the links between observed telecommunications effects, observed experimental physics effects, and predicted SPS operating conditions.

4.2 ASSESSMENT

4.2.1 Ionospheric Heating Phenomena

Regions of the Ionosphere

The ionosphere is commonly discussed in terms of three regions: the D-, E-, and F-regions. The D-region, at an altitude of roughly 50 km to 85 km, is characterized by low electron densities and collision-dominated processes. Ionospheric heating from the SPS microwave beam would be expected to be greatest in this layer. The altitude range from 85 km to 140 km is designated the E-region. Collisions and conduction exert equal control on the dynamic processes in this region. The F-region, extending from 140 km outward, contains the greatest electron concentrations in the ionosphere. The large-scale processes in this region are controlled by plasma conduction, and therefore are strongly affected by the geomagnetic field. Because of the differing characteristics of these regions, the physics of ionosphere/microwave interactions would vary greatly.

Plasma Frequency

A radio wave will pass through a region of the ionosphere or be reflected by it depending on the frequency of the radio wave and the electron density of the region. This phenomenon is characterized by the "plasma frequency," which is proportional to the square root of the electron density. When the radio-wave frequency is higher than the plasma frequency, the radio wave will pass through the plasma and the plasma is called "underdense." When the radio-wave frequency is lower than the plasma frequency, the radio wave will be reflected and the plasma is termed "overdense." The plasma frequency in the F-region of the ionosphere is much higher than it is in the D- and E-regions. The 2.45-GHz frequency of the SPS microwave power beam would be high enough to allow the beam to pass through all regions of the ionosphere.

Enhanced Heating and Thermal Self-Focusing

The power density associated with the passage of the SPS power beam through the ionosphere would be the same order of magnitude as the power density required to heat the lower ionosphere and create irregularities and striations in the ionospheric plasma at F-region altitudes of 250-400 km.³ The heating of the lower ionosphere associated with the passage of the SPS microwave power beam would result, it is believed, from ohmic-type interactions between the microwave beam and the ionospheric electrons. In the upper ionosphere (the F-region), the passage of the SPS beam would most probably give rise to the phenomenon of thermal self-focusing.

Solar photoionization in the ionosphere produces free electrons with an effective temperature usually exceeding that of the background neutral gas. As electrons gain energy through solar photoionization, they also lose energy by collisions with the much heavier atoms and molecules of this background

gas. The electron temperature therefore represents an energy balance between these heating and cooling processes. The collisional heating and cooling interactions of the ionospheric plasma all depend on the electron temperature. The microwave power beam might cause the rate of heating to temporarily dominate the normal cooling losses, initiating a rapid increase in electron temperature that would continue until compensating cooling processes develop, limiting the temperature rise. The compensating cooling processes would develop quickly enough to preclude unlimited increases in electron temperature, although significantly enhanced electron heating could occur. This enhanced electron heating could affect the electron-ion recombination rates, changing ionospheric densities, or could drive secondary, nonlinear ionospheric interactions, further disturbing the ambient plasma. These disturbances could produce potentially serious telecommunications impacts.

Thermal self-focusing⁴ can arise because small, natural fluctuations in ionospheric density cause a variation in the plasma's index of refraction. As a result, an electromagnetic wave propagating through the plasma is slightly focused and unfocused, with the local electric field intensity increased as the incident wave refracts into regions of comparatively less dense plasma. Differential ohmic heating of the plasma gives rise to a temperature gradient, driving plasma from the focused region and amplifying the initial density perturbation. This self-focusing instability continues until hydrodynamic equilibrium is reached, and it creates large-scale ionospheric irregularities. Thermal self-focusing caused by the SPS microwave beam could affect telecommunications systems using the F-region of the ionosphere.

Frequency Scaling and Ground-Based Simulation

At the 2.45-GHz frequency, the heating that the SPS power beam would provide to the lower ionosphere is believed to be that arising from ohmic interactions between the power beam and the electrons, ions, and neutral particles that make up the ambient ionosphere. Under conditions of ohmic heating, the resulting power flux at microwave frequencies can be related to the resulting power flux at another frequency through the relationship:²

$$\frac{P_{\text{SPS}}}{f_{\text{SPS}}^2} = \frac{P_{\text{HF}}}{f_{\text{HF}}^2} \quad (1)$$

where f_{SPS} and P_{SPS} are the SPS microwave frequency and power density and f_{HF} and P_{HF} are another frequency and the power density at that frequency. It follows from Eq. 1 that heating the ionosphere using radio waves at a lower frequency than that of the SPS requires a smaller power density to achieve an SPS-comparable effect. Provided the frequency is higher than the plasma frequency, the heating is accomplished by radio waves that pass through the ionosphere (the underdense case), and high-powered, high-frequency waves can be used to simulate SPS heating.

The threshold for the onset of thermal self-focusing is believed to be proportional to the cube of the wave frequency.² Thus, the rate at which energy is imparted into the self-focusing instability can be expressed as:

$$\frac{P_{\text{SPS}}}{f_{\text{SPS}}^3} = \frac{P_{\text{HF}}}{f_{\text{HF}}^3} \quad (2)$$

Equations 1 and 2 indicate that the amount of SPS microwave energy that would heat the ionosphere and generate thermal self-focusing instabilities can be realistically simulated using much lower frequencies and power densities, provided that the lower frequencies are higher than the plasma frequencies.

The validity of Eqs. 1 and 2 is crucial to the ground-based simulations of the SPS operation. The results obtained by heating the ionosphere with high-frequency waves must be extrapolated over a frequency range of nearly 1000 to arrive at the SPS operational frequency. It is possible that some instabilities in the ionosphere that would result from the passage of the SPS power beam cannot be simulated using the lower-frequency, ground-based ionospheric-heating facilities. However, the current understanding of the processes that are anticipated to occur in the SPS environment indicates that the ohmic heating ($1/f^2$) and thermal self-focusing instability ($1/f^3$) scaling laws are valid.²

The ionospheric heating facilities at Platteville and Arecibo can produce continuous SPS-equivalent ohmic heating in the lower ionosphere. At greater altitudes the delivered power flux density is significantly less than that of the frequency-scaled SPS microwave beam, following a $1/f^2$ scaling law. The energy density that scales to the SPS scenario for the onset of self-focusing ($1/f^3$) is greater than the SPS power density at all ionospheric heights up to 700 km, however. The ionospheric heating studies undertaken to assess the telecommunications impact of SPS operation have centered on simulating SPS operation using the two ground-based facilities.

4.2.2 D- and E-Region Effects

Platteville Experiments

Experiments were performed using the Platteville facility to determine the degree to which ionospheric changes induced by ohmic heating due to SPS operation would affect telecommunications systems. The Platteville facility can provide SPS-comparable ohmic heating to the lower ionosphere by exploiting the $1/f^2$ scaling law. Telecommunications systems whose signals are reflected and controlled by the lower ionosphere were investigated.

The current Platteville ionospheric heating facility is essentially the same as that described in Ref. 5. It provides SPS-comparable power density at 5 MHz to an area of the lower ionosphere that is 30 km in diameter at an altitude of 75 km and 40 km in diameter at 100 km. This area is three to four times larger than that anticipated for the SPS microwave beam as it passes through the ionosphere. The telecommunications systems chosen for investigation were representative of those operating in the very-low-frequency (VLF, 3 kHz - 30 kHz), low-frequency (LF, 30 kHz - 300 kHz), and medium-frequency (MF, 300 kHz - 3 MHz) portions of the electromagnetic spectrum.

VLF System Effects. The source of the VLF signals used in these studies was the OMEGA navigation station in Hawaii. OMEGA is a radio navigation system operating in the internationally allocated frequency band between 10 kHz and 14 kHz. It is designed to provide a precise position-location capability over the entire earth, with eight strategically located transmitters. The system is useful for general navigation by ships, aircraft, and land vehicles. OMEGA signals are relatively stable, and the system provides good accuracy.

The main receiving locations for the OMEGA-Hawaii signals were in the vicinity of Brush, Colorado. The field sites near Brush were chosen to locate the modified regions of the ionosphere above Platteville on or near the signal path between Hawaii and the field sites. The data were received using a standard VLF/LF tracking receiver. It was determined that the changes in the OMEGA-Hawaii signal, if they were to occur, should be discernable if the ionospheric structure was altered by the SPS-comparable power densities associated with the operation of the Platteville facility.²

Approximately 40 hr of recordings of amplitude and relative phase of the OMEGA signals from Hawaii were made while the Platteville facility was heating the ionosphere, and there were no observable changes in the OMEGA phase or amplitude that could be associated with operation of the facility.

Data were also recorded at locations south, north, and west of Brush. These locations were chosen in an attempt to determine if off-angle enhancements of signals propagated through the modified region might be detectable. All the OMEGA data were analyzed to determine if the amplitude and phase changed on average when the ionospheric heater was on compared to when it was off. The results clearly demonstrated that there was no significant change in the performance of the OMEGA system that could be related to the operation of the Platteville facility.

LF System Effects. The sources of LF telecommunication signals used in the investigation of ohmic heating effects were LORAN-C transmitters. Several LORAN-C chains are in operation as navigation systems. In the United States, LORAN-C navigation depends on the highly stable groundwave portion of its propagated signal for system accuracy. The LORAN-C signals were chosen as LF signal sources not because interference to LORAN-C navigation was anticipated from the heater-induced ionospheric modification, but because the LORAN-C stations provided a convenient, stable source of signals at 100 kHz. LORAN-C stations at Dana, Indiana, and Fallon, Nevada, were used as sources; signals were recorded, respectively, at Boulder, Colorado, and Brush, Colorado.

Although the effects on the LORAN-C signal of the disturbance induced by the Platteville facility were expected to be small, the sensitivity of the LORAN-C monitors is sufficient to detect significant changes in the performance of the LORAN-C system. Approximately 19 hr of relative phase data and 13 hr of relative phase and amplitude recordings were made of the LORAN-C signals from Nevada, during the operation of the Platteville facility. About 35 hr of amplitude and relative phase recordings were made of the LORAN-C signal from the Indiana station. A detailed study of the LORAN-C records

determined that ionospheric heating by the Platteville facility did not cause propagation effects of sufficient magnitude to be observed in the LORAN-C skywave phase and amplitude.

MF System Effects. Two receivers in Brush, Colorado, were used to monitor amplitude signals from stations in the AM broadcast band. Signals were recorded from 11 stations, 8 of which were local (less than 100 km from Platteville) and 3 of which were remote. The remote stations KREX (Grand Junction, Colorado), KNX (Los Angeles) and KSL (Salt Lake City) were the sources of the skywave signals received at Brush, Colorado. The groundwave signal from the local stations was so strong that skywave signals could not be discerned in the data. Since the operation of the Platteville facility does not impact groundwave radio propagation, only the effects on skywave signals need to be considered. The data show no effect on the received signals that can be attributed to ionospheric heating by the Platteville facility.

Auxiliary Diagnostics. During the time that the Platteville facility was simulating SPS ohmic heating of the lower ionosphere, a number of experiments were conducted to determine how the ionosphere responded to the high-power, high-frequency transmissions. These experiments were designed to provide information about ionospheric temperature and structure changes in a more direct manner than analysis of telecommunications data.

The experiments show that the electron temperature was changing in the D- and E-regions while the Platteville facility was operating. The electron temperature above Platteville can be raised from a background level of 200 K to between 300 K and 500 K using power densities such as those employed in the experiments.⁶ This change in electron temperature corresponds very closely to recent theoretical calculations of changes in D-region electron temperatures due to the passage of a 23-mW/cm² SPS power beam.² The same studies show, however, that increases in electron density of 10-15% should accompany the electron temperature increases. Both the diagnostic and telecommunications data seem to indicate that electron density in the lower ionosphere was not changed appreciably by the Platteville facility, or if it was, such changes did not have significant adverse impacts on telecommunication systems.

Natural Disturbances. During the Platteville experiments, changes in the amplitude and phase of the OMEGA, LORAN-C, and AM-station signals were observed that were associated with normal day-to-day changes in propagation conditions. These changes were much greater than any changes in system performance due to ionospheric heating, as the latter were undetectable. During the time periods for which VLF, LF, and MF data were collected, large-scale geophysical disturbances -- notably solar flares -- occurred. These disturbances produced changes in telecommunication systems performance that far exceeded any possible changes induced by intentional ionospheric heating.

Numerical Simulations. Attempts to simulate the performance of telecommunication systems operating when the ionosphere is modified by the passage of high-power radio waves are crucial to the overall SPS ionospheric heating

assessment. Such simulations provide a means to corroborate theory and experiment. The extent to which performance data pertaining to telecommunication systems operating in an SPS-simulated environment can be numerically calculated is directly related to the ability of theoretical models of the ionosphere to predict ionospheric heating effects. Numerical simulations of telecommunications systems also provide a means to study the behavior of a number of systems under varying situations without having to undertake all possible experimental scenarios.

Numerous calculations were made in an attempt to simulate the performance of VLF and LF telecommunication systems during ionospheric heating, using the method of Berry and Herman.⁷ For a given electron density (assumed constant over the entire propagation path), the method allows the calculation of the amplitude and phase of the groundwave and waves reflected from the ionosphere. The results indicate that little change in the performance of VLF or LF systems would result from ionospheric changes caused by the SPS.

Arecibo Experiments

An understanding of the physics of the specific interactions excited by the SPS microwave beam is an important part of the SPS environmental assessment. The experimental physics studies are designed to determine instability thresholds, growth rates and spatial extent of the resultant ionospheric disturbances, and frequency and power dependencies of the interactions. The objective is to determine how these interactions are affected by variations in the natural ionospheric conditions, how different instabilities occurring simultaneously may affect each other, and how multiple SPS microwave beams might interact.

The experimental studies of the physics of ionosphere/microwave-beam interactions have primarily been conducted using the ionospheric heating facility at the Arecibo Observatory. This high-power, high-frequency facility can produce continuous SPS-equivalent heating in the lower ionosphere, following a $1/f^2$ scaling. A full complement of ionospheric diagnostics is used to monitor the atmospheric response to the ionosphere/radio-wave interactions. The principal diagnostic is an incoherent backscatter radar that can measure electron densities, electron and ion temperatures, ionospheric winds, and currents and composition as functions of altitude and time.

Enhanced electron heating of the lower ionosphere was observed during a recent Arecibo ionospheric heating program. The facility radiated at 3.175 MHz and 5.1 MHz. This provided SPS-equivalent heating through an altitude of 100 km at 3.175 MHz, and somewhat less than SPS-equivalent heating at 5.1 MHz (frequency-scaled 10 mW/cm^2) at 75 km. Preliminary results of this study show that electron heating with radio waves at 5.1 MHz peaked at 75 km. Electron density increases were also observed during this heating. The preliminary results are in very good agreement with theoretical heating models at heights above 80 km. The measured electron temperatures are slightly higher than expected below this altitude.

4.2.3 F-Region Effects

Platteville Experiments

Experiments to determine whether thermal self-focusing effects could be produced in underdense plasma were undertaken using the Platteville facility. As described earlier, thermal self-focusing may create striations or irregularities in the ionospheric electron density. These irregularities, if they occur, could scatter radio waves in the high-frequency (HF), very-high-frequency (VHF), and ultra-high-frequency (UHF) portion of the spectrum. The performance of telecommunications systems operating in these bands could be degraded due to interference from scattered signals. The scattered signal could travel over great distances and interfere with systems operating far from the SPS power beam.

In earlier sections, the physical mechanisms involved in the generation of the self-focusing instability were described. It was pointed out that the threshold for the onset of the instability varied as $1/f^3$. The Platteville facility can provide more than 5 times SPS-equivalent power density to the ionosphere at 300 km for a 10-MHz scaling to the SPS operational scenario ($1/f^3$ scaling). At 5 MHz, the SPS equivalent power energy is more than 50 times the SPS operational power density of 23 mW/cm^2 . For this reason, measurements were made to determine if self-focusing instabilities could be generated using underdense radio waves and what effect these instabilities would have on specific telecommunication systems.

The effects of thermal self-focusing are anticipated to be most pronounced in the F-region. The instabilities could lead to striations in the electron density resulting from electrons aligning along the geomagnetic field lines. The experimental arrangement, therefore, emphasized use of telecommunications systems operating at frequencies that are sensitive to the electron distribution in the F-region. The systems utilized were satellite-to-ground and satellite-to-aircraft transmissions operating in the VHF (30-300 MHz) portion of the spectrum. Such transmissions are rather sensitive to irregularities in the electron density structure along the satellite-to-observer radio path. These irregularities give rise to fading and fluctuations in signal amplitude and phase similar to destructive interference resulting from diffraction of the signal about an object.⁸ The fading of the signal under these conditions is called "scintillation." Naturally occurring scintillation has been intensively studied in recent years.^{9,10} In addition to the satellite scintillation measurements, observations of HF (3-30 MHz) signals back-scattered from the ionospheric irregularities were obtained at Holloman Air Force Base, New Mexico.

The self-focusing experiments were conducted recently, and only preliminary results are available at this time.

Satellite-to-Aircraft Measurements. The satellite-to-aircraft transmission measurements were made using an Air Force Avionics Laboratory C135/662 aircraft. This plane is equipped to monitor signals transmitted from the LES-8 satellite (249.2 MHz) and the FLEETSATCOM satellite (244.0 MHz). Both amplitude and phase can be measured under test conditions.

The LES-8 signal was observed on the aircraft when the Platteville facility was operating in the underdense mode. Using the $1/f^3$ scaling law for thermal self-focusing, the power density in the F-region was calculated to be about 280 mW/cm² for this experiment.

The results indicated that ionospheric irregularities were created and that these irregularities induced scintillation in the LES-8 signal. Whether this result indicates that the SPS microwave beam would have an adverse effect on telecommunications is yet to be determined. This determination depends upon a validation of the $1/f^3$ scaling law and further experimentation similar to the preliminary experiment described above.

Satellite-to-Ground Observations. Satellite-to-ground telecommunications experiments conducted at Carpenter, Wyoming, monitored transmissions from the LES-8 satellite at 249.2 MHz. The observation methods were designed to detect underdense heating effects.

The LES-8 satellite can be viewed from Carpenter through the ionospheric volume heated by the Platteville facility in a direction parallel to the earth's magnetic field. Since theoretical studies of ionospheric heating predict irregularities in electron density that are aligned along magnetic field lines, this geometry provided a sensitive experiment to detect amplitude and phase fluctuations in response to ionospheric heating.

The results of these experiments clearly show effects of ionospheric irregularities on the LES-8 satellite signals. These preliminary results, however, cannot be interpreted at this time for the SPS reference system. The $1/f^3$ scaling law is yet to be validated, but if correct, indicates that about 90 mW/cm² of SPS comparable power density was delivered to the F-region for these experiments. Also, the experiments maximized the effect of the irregularities because the satellite signal was observed along the earth's magnetic field lines.

HF Observations. As part of the program to investigate the effects of the thermal self-focusing instability in the upper ionosphere, observations were made using a HF backscatter radar. The radar -- located at Hollaman Air Force Base, New Mexico -- could transmit signals in the range of 6-30 MHz. The radar signals were directed toward the volume of the ionosphere heated by the Platteville facility. If irregularities in the ionospheric structure were produced by the heating, part of the radar energy would be scattered back to the radar site. The amount of backscatter energy depends on the intensity of the radar energy, the direction the energy propagates with respect to the earth's magnetic field, and the radar frequency.

Backscatter of signals at HF, VHF, and UHF has been used to discern properties of ionospheric changes since the early days of heating experiments. For the SPS simulation experiments, the radar provided no evidence of backscatter from ionospheric irregularities. The reasons for these preliminary results are not yet understood.

Arecibo Experiments

No small-scale plasma striations have been detected at either E- or F-region altitudes in underdense ionospheric heating experiments conducted thus far at Arecibo. However, preliminary results indicate that large-scale (kilometer-size) irregularities did develop in the nighttime F-region for underdense heating. These irregularities disappeared abruptly near sunrise. Electron density variations as large as 2% were observed within the irregularities, with fading periods of several minutes. It is not known if the observed irregularities resulted directly from HF wave self-focusing or if they were a HF-triggered natural condition.

Theoretical Simulation

Theoretical studies have been undertaken to investigate the changes in the performance of HF systems operating in an SPS environment. Using the electron density profiles generated by Perkins and Roble¹¹ as indicative of the ionospheric structure resulting from the passage of an SPS power beam, the performance of a high-frequency circuit operating from Washington, D.C., to Albuquerque, New Mexico, has been simulated. Similar profiles generated for conditions when SPS operation is absent have also been used to assess SPS impact on such circuits. The results show that the changes in HF circuit performance (the maximum usable frequency) are small for SPS-related electron density changes.

SPS Pilot Beam

The SPS microwave power transmission system would employ a pilot beam, originating at the rectenna site, to control the focusing of the power beam. Irregularities in the ionospheric structure that arise from the passage of the power beam as well as natural causes would need to be considered in the design of the pilot beam system, so that the pilot beam's performance would not be affected.

4.3 SUMMARY AND CONCLUSIONS

Although there are questions to be resolved concerning the maximum allowable microwave power density in the ionosphere, the results of studies to date do not indicate that the interaction of a microwave power beam with the ionosphere would be an obstacle to the SPS reference system. A coordinated program of theoretical and experimental work is underway to better understand the impact of SPS heating of the ionosphere. Experimental studies are being 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; by exploiting frequency scaling laws, they can deposit energy in the lower ionosphere that is equivalent to the SPS energy for underdense ionospheric heating.

4.3.1 D- and E-Region Effects

SPS microwave effects on the lower ionosphere would be due to ohmic heating. Ohmic heating is inversely proportional to the square of the heater frequency, and this allows ground-based heaters to deliver SPS-equivalent power density to the lower ionosphere. Telecommunication experiments have been performed to observe the performance of systems whose radio waves are affected by the structure of the lower ionosphere. The telecommunication systems chosen for investigation were representative of those operating in the very-low-frequency, low-frequency, and medium-frequency portions of the electromagnetic spectrum. The results obtained indicate that the SPS, as currently configured with a peak power density of 23 mW/cm², would not adversely affect the performance of these telecommunication systems.

Continued theoretical work and additional experiments with more-powerful facilities are required to establish the maximum microwave power density that can be transmitted through the lower ionosphere without degrading the performance of telecommunications systems.

4.3.2 F-Region Effects

It is expected that SPS effects in the F-region would be due to plasma irregularities caused by thermal self-focusing. Current theory predicts the thermal self-focusing threshold to be proportional to the cube of the frequency of the electromagnetic wave passing through the ionosphere.

Results obtained from experimental simulation of the SPS ionospheric heating to measure thermal self-focusing have revealed potential underdense heating effects on satellite signals propagated in the VHF band. The observations are preliminary, and further work is required before a confident assessment can be made of performance impacts on telecommunications systems depending on the F-region. Studies using electromagnetic radiation with various input powers and frequencies are needed to establish the threshold for the onset of ionospheric irregularities generated by underdense thermal self-focusing instabilities and to validate the $1/f^3$ scaling law.

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5 ELECTROMAGNETIC SYSTEMS COMPATIBILITY

5.1 INTRODUCTION

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 are intended to permit the most effective use of limited radio spectrum resources by controlling interference between various users. 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" (EMC) is achieved when communications capabilities are maximized with a minimum of interference between systems.

Electromagnetic transmitters typically generate and radiate small amounts of power at unassigned frequencies. Emissions such as harmonics or noise sidebands outside the frequency band required for system operation, and perhaps outside the assigned band, are referred to as spurious emissions and are limited by regulation since they are potential sources of interference to other systems. Moreover, other rules are generally established that 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 to minimize interference to other users of the electromagnetic spectrum. Nevertheless, there would be a substantial potential for producing interference. The amount of microwave energy that 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 a relatively low potential for interfering with other systems. In addition, side lobes and scatter from the SPS power beams would produce significant microwave field intensities over wide geographic areas.

The SPS microwave power transmission system (MPTS) would produce EMC problems due to three major phenomena:

- High power levels of 2.45-GHz microwave radiation, especially near rectennas.
- Emissions of frequencies outside the band allocated for power transmission, i.e., harmonics (multiples) of the intended frequency, noise components, and thermal radiation.
- Ionospheric heating (discussed in Section 4).

Electromagnetic systems likely to experience interference from the MPTS would include satellite, military, communications, control, navigation, and radio astronomy systems. Sunlight scattered and reflected from the solar power

satellite might affect optical astronomy. The potential for electromagnetic compatibility problems due to the SPS is illustrated in Figure 13.

The SPS environmental assessment has addressed EMC problems for:

- Communication receivers
- Radar
- Optical sensors
- Medical electronics
- Computers
- Satellites and their earth terminals
- Radio and optical astronomy

The assessment has studied the electromagnetic environment that would be generated by the SPS, the mechanisms for interaction and coupling with other systems, and the methods of mitigating the interference. The assessment

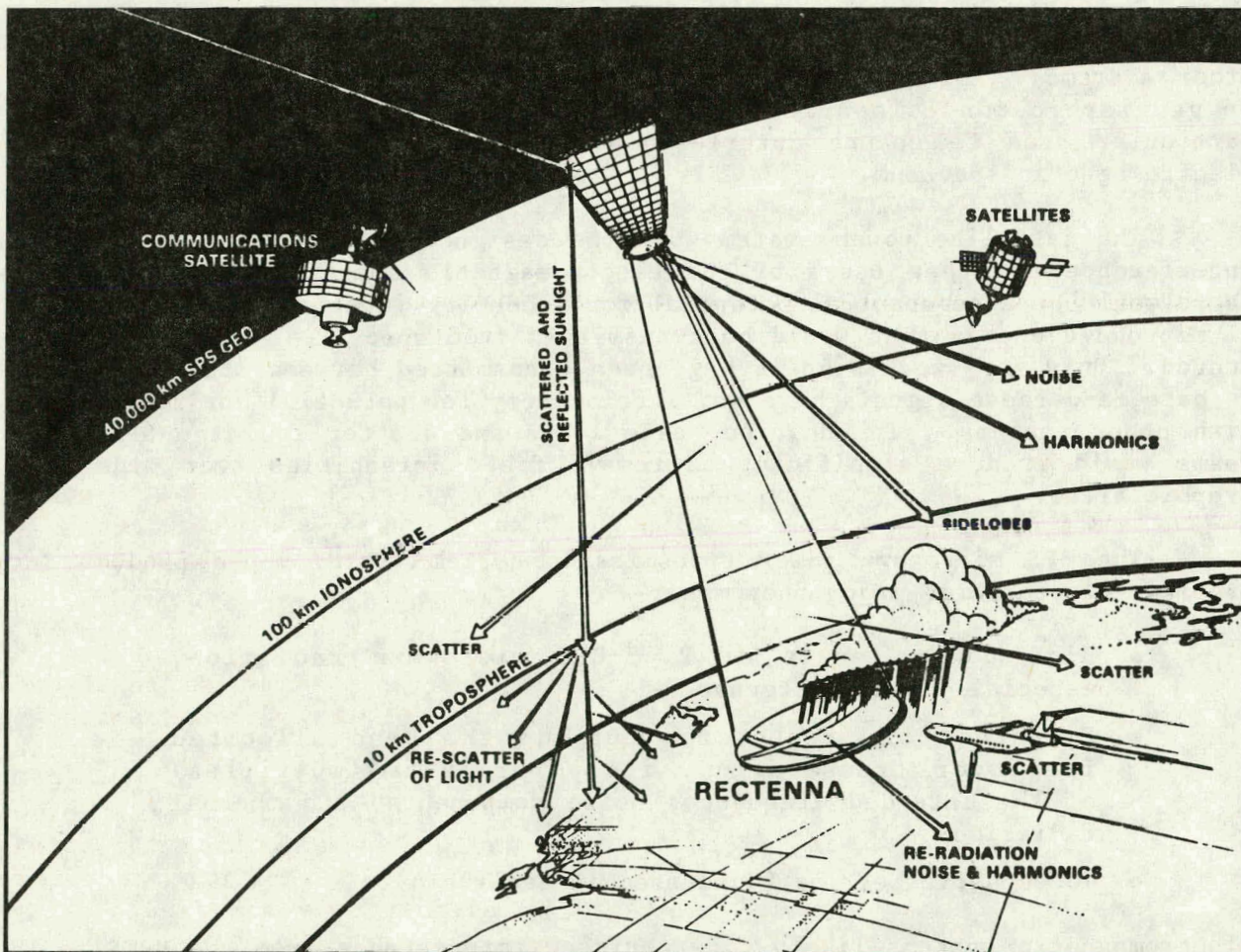


Fig. 13. Overview of Potential SPS Electromagnetic-Compatibility Impacts

presented here is based on the SPS reference system^{1*} and is a summary of a more-detailed analysis.²

5.2 ASSESSMENT

5.2.1 Electromagnetic Characteristics of the Satellite Power System

SPS Antenna Patterns

The SPS reference system uses a microwave beam with a frequency of 2.45 GHz and a power of about 6.85 GW. The beam emanates from a 1-km-diameter circular array in geosynchronous earth orbit (GEO).¹ The 6.85 GW of power would be generated using several hundred thousand microwave klystrons, each producing about 50-70 kW. The beam would be intercepted on the earth by a 10-km by 13-km elliptical receiving antenna (rectenna) to yield about 5 GW of electric power to a utility grid. The size of the rectenna and space antenna were selected so that approximately 90% of the transmitted energy would be intercepted by the rectenna (at 35° latitude) and flux densities in the ionosphere would be less than 23 mW/cm².

The radiation pattern of circular apertures is well understood. For the SPS reference system, the field distribution across the face of the transmitting antenna is Gaussian with a 10-dB taper.³ The analysis of the resulting radiation pattern is developed fully in Ref. 4. The results of this analysis are given in Figure 14.

The relationship between the power density, p (in mW/cm²), and the root-mean-square field intensity, E (in V/m), which is indicated in Figure 14, assumes propagation through free space and is described by:

$$E = \sqrt{3767 p}$$

The power density distribution as a function of distance from a rectenna site is illustrated in Figure 15. Here, contours of constant power density for a single rectenna are shown on a map of the United States.

Out-of-Band Emissions

Harmonics of the 2.45-GHz transmission frequency would be generated by the high-power klystrons and radiated by the SPS transmitting antenna. Using data from klystrons used in military radar, it has been estimated that the frequency of second, third, and fourth harmonic powers would be, respectively, 50 dB (10⁵ times), 90 dB (10⁹ times), and 100 dB (10¹⁰ times) below the power at the fundamental frequency of 2.45 GHz. The antenna radiation pattern for these frequencies would be substantially different than that for the fundamental frequency. It would not be as directive and predictable, although estimates of the pattern have been made.

*References for Section 5 are listed in Section 5.4.

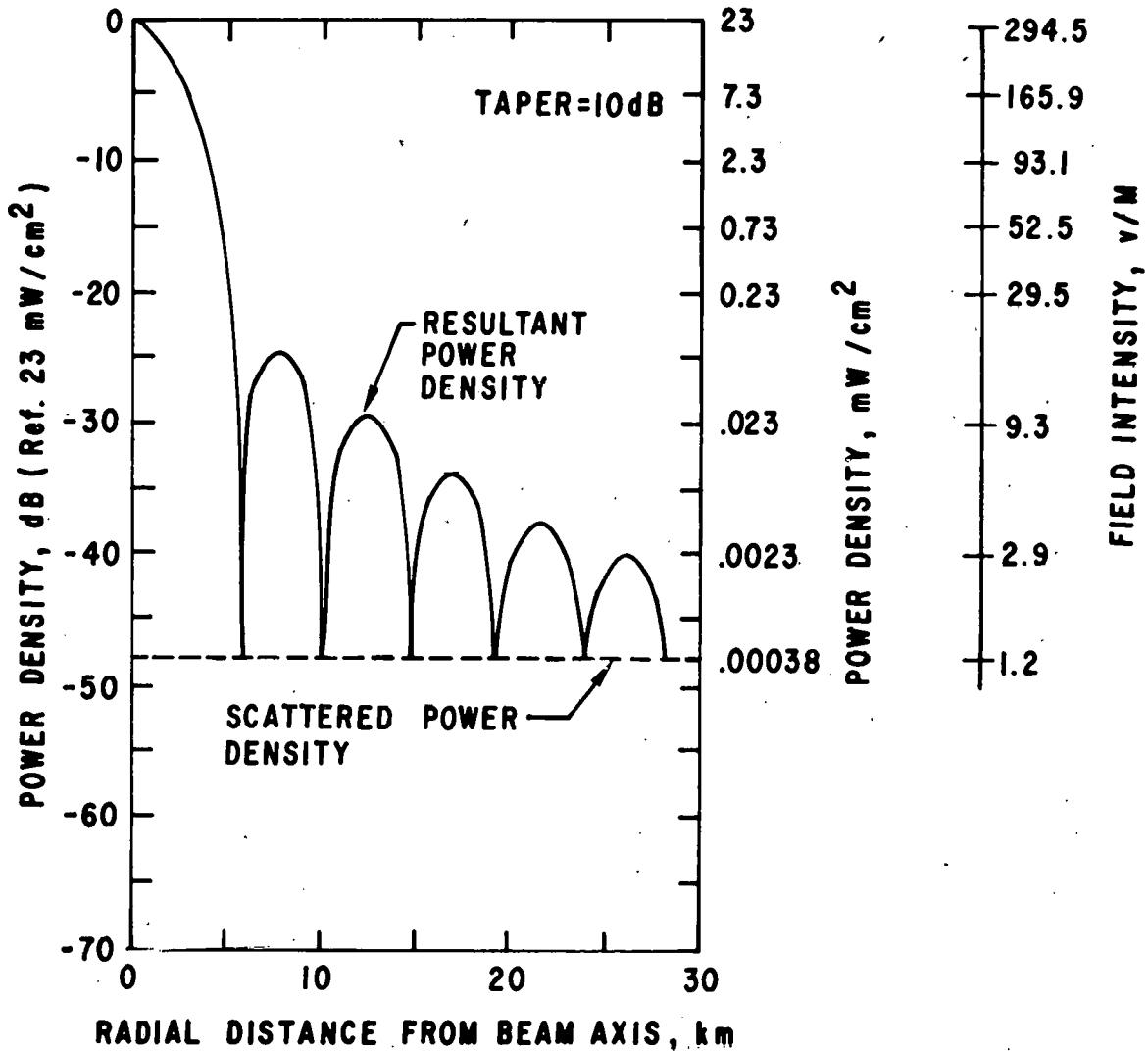


Fig. 14. SPS Transmitting Antenna Pattern

The spurious noise generated by the klystrons has been estimated.¹ It has been suggested that, by appropriate design and filtering, the noise power outside of the 2.45 + 0.05 GHz band could be reduced to levels that would not cause interference for most cases.

Interference power radiated from a rectenna would be generated by reflection of the 2.45-GHz power as well as reradiation of harmonics and other frequencies generated by nonlinear mechanisms in the rectenna structure. The power spectrum generated would vary with time and the aging of the rectenna structure. The radiation pattern for the 2.45-GHz power reflected from the rectenna has been estimated² and would be expected to be somewhat directive with a beam width of approximately 10°. The radiation pattern for the harmonics would be much broader than 10°.

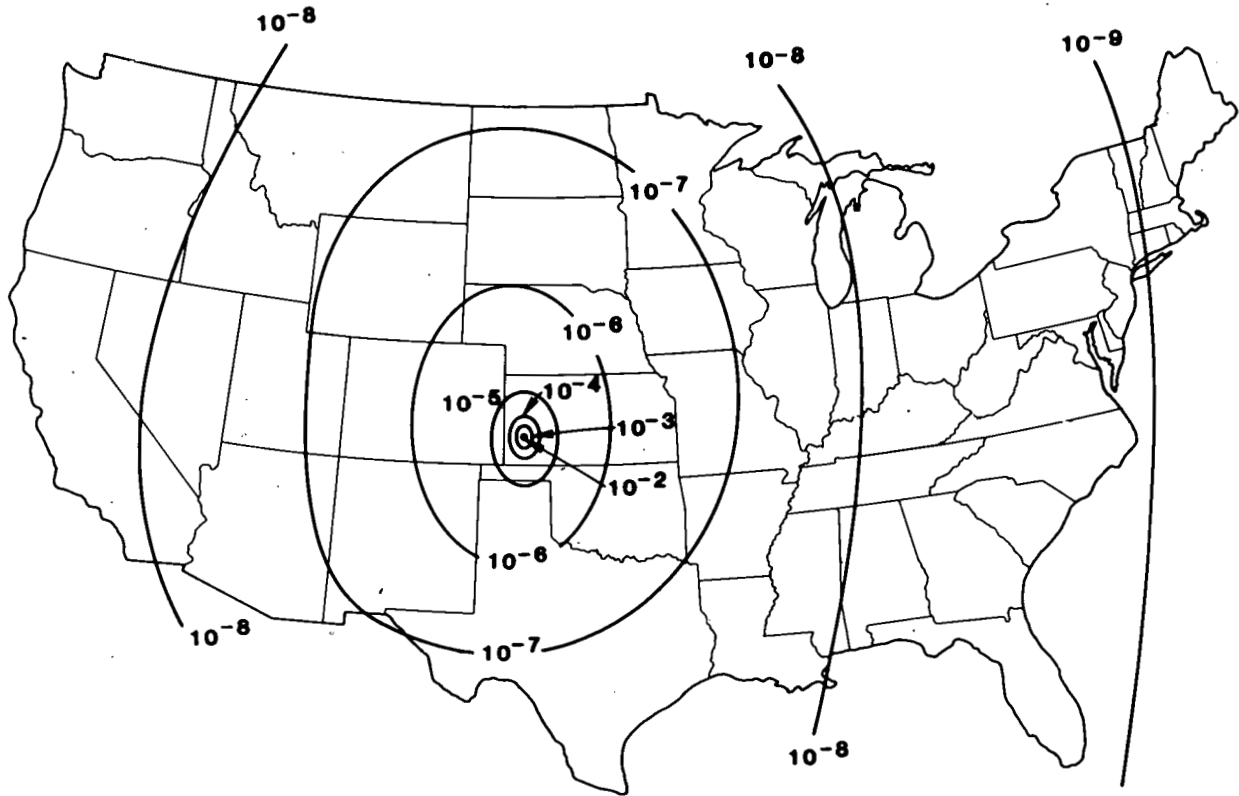


Fig. 15. Power Density Distribution (mW/cm^2) for a Single Hypothetical Rectenna Site

Propagation Effects

The propagation of the power beam in the ionosphere and the beam's effect on the ionosphere is treated in Section 4. Expected scattering of the beam in the troposphere could degrade performance of the SPS beam control system; this in turn could add to the power transmitted outside the rectenna area. Major natural phenomena of interest are:

- Variations in refractive index due to turbulence, stratification, and variations in temperature and humidity.
- Scatter due to particulates (e.g., dust and clouds).
- Scatter due to precipitation (e.g., hail, rain).

Attenuation and scattering due to precipitation would reduce the amount of power reaching the rectenna. This reduction would generally be proportional to the precipitation rate and the problem would vary with geographical location. Blowing dust or sand also might contribute to attenuation and scattering. These mechanisms would have small effects, as a percentage of main-beam power; however, because of the large power levels involved with the SPS, the absolute power fluctuations caused by these mechanisms could be large. Spacecraft and aircraft crossing the microwave power beam could also scatter appreciable amounts of energy.

The effect of the heat released from the rectenna has been studied and the results indicate that turbulence caused by this heat would not cause a problem. It would not reduce the power received by the rectenna and would not scatter power beyond the rectenna boundary.

Sandstorms would be minor contributors to rectenna power loss and increased power densities outside the rectenna area. For the larger sandstorms in the Southwest, the maximum power scatter would be expected to be in the range of 0.001-0.01% of the transmitted power. This assumes a storm centered on the rectenna, with a height of 1.5-3 km.

Variations in rain rates over the continental United States have been evaluated and scatter power determined for various regions. At maximum rain rates, a small percentage of the power would be lost due to absorption and scattering. A specific example is presented in Section 5.2.11 for a hypothetical rectenna site in the Mojave Desert.

5.2.2 Coupling Mechanisms

The principal mechanisms for the inadvertent coupling of SPS microwave power to other electromagnetic systems would be equipment case penetration, cable pickup, and interference voltages induced in antennas.

Case penetration would occur when microwave energy levels were high enough that some of the energy would pass through metal electrical cabinets or enter through door openings and seams and interfere with internal electrical circuits. Wood or plastic cabinets, such as those for home television receivers, would provide negligible shielding.

Cable pickup would occur if electrical cables illuminated by microwave energy inadvertently acted like receiving antennas. They generally would be inefficient receiving antennas, but they nevertheless could deliver substantial energy to receivers and transmitters if the microwave intensity were relatively high. The delivered energy could be sufficient to interfere with internal circuits.

Antenna-induced voltages can produce interference in the same way as cable pickup. A home television receiving antenna would not be efficient at microwave frequencies, but it could deliver enough energy to the television set to cause interference if the microwave energy were sufficiently high.

5.2.3 Microwave Fields inside Habitable Structures

To analyze electromagnetic compatibility, it is necessary in some cases to know the SPS microwave field strengths that would be expected inside various structures, particularly buildings and vehicles. Theoretically, such structures could concentrate incident microwave energy to produce fields more intense than would otherwise be expected. Very little work has been done explicitly on this problem, but a substantial body of theoretical and experimental information is available on the coupling of microwaves into enclosures and their behavior therein. An exact, detailed analysis of the microwave

properties of habitable structures is not practical due to the tremendous variety of materials and complex geometries involved.

The problem of estimating the fields inside habitable structures exposed to microwaves near an SPS rectenna has recently been analyzed, with particular attention to the possibility of increases in field strength.² This study analyzed the relevant physical processes and measured actual microwave field strength inside houses exposed to 2.6-GHz radiation from a satellite. Key elements of this analysis are summarized below.

To determine microwave field strengths inside a structure, the coupling of energy into the structure and its behavior inside, including reflections (possibly resonant), must be understood. Coupling to the interior could occur via relatively microwave-transparent openings (windows, for example) or through wall materials, which in general do not transmit microwaves as well. The following approximate microwave transmissions for representative structural elements have been measured:

<u>Structural Element</u>	<u>% Transmission</u>	
	<u>Dry</u>	<u>Wet</u>
Wooden wall	15	6
Frame wall	40	15
Window (wood sash)	70	40

Metal walls or screening, or even foil, transmit very little 2.45-GHz microwave energy (less than 1%) if openings or joints are substantially less than 3 cm long.

Average field strengths inside structures are thus expected to be less than those outside, due to coupling losses. The structure could, however, alter the spatial distribution of energy to produce localized areas of increased field intensity. Reflections within structures are the most likely causes of localized increases in field strength. Metallic surfaces are the only common elements of habitable structures likely to produce significant field increases. In the absence of any absorbing material, a single metallic reflection could increase power density at some locations by as much as a factor of four above the power incident on the surface. More complex geometries involving multiple reflections could, in principle, produce larger field increases. However, such large increases require special geometries and very little microwave absorption in the system. Neither of these criteria is likely to be satisfied by real habitable structures. In particular it should be noted that the presence and movements of people, who are significant microwave absorbers and reflectors, also modify reflection patterns.

Measurements have been reported giving the ratio of microwave field strength inside to that outside single family houses illuminated by 2.6-GHz microwaves from a satellite.^{5,6} Average fields inside were found to be about 25% of those outside, although interior fields varied substantially from point to point. For the case of the highest ratio of average inside fields to outside fields, the probability of encountering a microwave field inside that was larger than that outside was only 15%. If, in specific cases, interior microwave field strengths were found to be a problem, they could easily be reduced by conventional methods.

5.2.4 Communications Receivers

A communications receiver is designed to operate in the presence of internal system noise as well as undesired signals from outside the system. The performance of such receivers might, however, be degraded in the presence of the 2.45-GHz signal from the SPS. The SPS signal might be coupled into the receiver through the receiver antenna; apertures in the receiver cabinet such as cooling holes, louvers, and instrument openings; and the power supply.

Tests performed on a number of receiver systems have determined degradation thresholds and identified the basic interference mitigation techniques. The receivers tested included 2-, 4-, 6-GHz systems, and special units designed for operation at 12-14 GHz. The receivers were subjected to radiated interference power as well as interference power directly injected into the receiver terminals. The results of these tests indicated significant performance degradation could be expected for interfering power with a field intensity above 10 V/m, which corresponds to distances within about 5 km of an SPS rectenna boundary.

Interference to communications receivers can be mitigated by:

- Filtering at the receiver input.
- Modifying the receiver antenna to be nonresponsive in the direction of the interference source.
- Nulling the interfering signal by use of a separate nulling antenna.
- Improved shielding of equipment enclosures and cables.

5.2.5 Radar Systems

Radar systems exhibit interference-susceptibility characteristics similar to those of communications receivers, since many detection and processing functions are similar in design. Radar equipment evaluated for SPS interference susceptibility includes fixed-site, airborne, and future space-craft systems. Applications includes surface-, airborne-, and space-target detection and tracking; velocity control; and various military command/guidance functions. Radar configurations vary significantly for these applications. The criteria used to evaluate performance degradation depended on the application as follows:

- Surveillance and Search Systems
 - Target detection range, target identification time, false target probabilities.
- Tracking and Guidance Systems
 - Target lock-on time, track error distribution, loss-of-lock probability, control action delays (e.g., interference nulling).

- Mapping and Terrestrial-Target Detection Systems

Target detection range, spatial resolution, terrestrial feature resolution.

The effect of microwave interference on some military radar systems was tested as a function of the ratio of received power to interference. In general, the results showed significant performance degradation when the received power was less than 20 times the interference power. Approximate assessment of these results indicates that interference mitigation measures would need to be evaluated for radar systems within 50-100 km of an SPS rectenna site.

5.2.6 Computers and Microprocessors

Microwave power can affect a computer or microprocessor in various ways. The primary mechanism for interference is through rectification of the microwave power in the numerous semiconductor diode junctions found in all modern solid state circuits. The rectification process produces unwanted bias currents within the device that can affect the device in various ways. For example, erratic operation of switching circuits can be increased. The timing of clock circuits can also be changed, causing a loss of data during memory transfer or arithmetic operations within the computer. An interfering microwave field can also affect the operation of peripheral devices such as magnetic and cassette storage tapes.

Three different minicomputers and three different microprocessors were illuminated at various levels of microwave power from a 2.6-GHz source. Energy coupling modes and system degradation were studied. Once coupling modes were understood, mitigation techniques were designed and tested to determine how much performance could be restored. One test measured the percent increase in control pulse jitter (a measure of timing stability) present in the clock and control circuitry of the microprocessors' memory registers. The percent jitter under normal conditions is about 1%. The jitter increased to 12% in some equipment when illuminated by 2.6-GHz, 2-V/m microwaves (the intensity about 30 km from a rectenna center). When the field intensity of the interference signal was increased to 10 V/m (the intensity about 15 km from a rectenna center), the control pulse jitter increased by substantial amounts with the worst case reaching 33%. In many cases the 12% jitter would not be acceptable and in all cases 33% would be an unacceptable performance degradation.

Another test measured the increase in the noise in the microprocessor control circuitry as a function of increased field intensity. The increase exceeded the threshold for unacceptable performance at field intensities of about 15 V/m (the intensity about 10 km from a rectenna center). It was determined that the interference was coupled through the diode protector circuits on the power supply. A capacitor circuit was added to the power supply to filter the interference and the tests were repeated. The noise was reduced to an acceptable level for a 15-V/m field intensity.

A test of the increase in memory-transfer errors with increased exposure to 2.6-GHz, 15-V/m power showed that the addition of a complete wire

mesh shield inside the existing nonmetallic computer cabinet reduced the transfer errors by two orders of magnitude to a level near normal.

5.2.7 Optical Sensors

The effect of SPS microwave power on optical sensors would be important to the wide range of optical devices used for security monitors, target tracking, communications, resource monitors, and astronomy applications. Microwave power can penetrate such systems through the optical aperture; any other apertures, such as cooling louvers; plastic cases; control cables; and power-supply lines.

The performance criteria used in this evaluation included video noise, scan jitter, spatial resolution, and dynamic range effects. The sensors tested were illuminated with a 2.6-GHz signal directly into the optical aperture, at $\pm 30^\circ$ off the optical axis, and directly into nonmetallic and cable-entry areas of the outer casing.

Significant degradation was demonstrated for microwave field levels of 10 V/m. Increased video noise and reduced spatial resolution were the primary effects. No intermodulation was noted in the infrared detection systems tested.

Successful mitigation of interference at a field intensity of 15 V/m has been demonstrated using the following techniques:

- Use of an aluminum enclosure in place of a nonmetallic enclosure.
- Reducing the size of all access and cooling holes to less than 1 cm.
- Use of a wire mesh with a grid size of 1 cm x 1 cm in the optical path, out of focus so as not to affect imaging.
- Use of dual-shield coaxial cable in video and control cables.

Most television and infrared sensor systems would not experience interference if located more than 50 km from a rectenna site, depending on the required resolution accuracy. For certain very-sensitive military systems, a separation of 100 km might be necessary.

5.2.8 Medical Electronic Devices

The Bureau of Medical Devices at the Food and Drug Administration supported a study of electronic devices and the ambient electromagnetic environment in several major hospitals. The results establish guidelines for acceptable emissions from medical devices and safe susceptibility thresholds.⁷

The existing guideline for electric field susceptibility at 1 GHz would permit the manufacture of devices with thresholds of 7 V/m. The study did not evaluate frequencies above 1 GHz, but a higher susceptibility is expected.

Although the 7-V/m threshold is lower than the 19-V/m level at the rectenna exclusion boundary for the SPS reference system, it is clear that medical electronic devices could be designed to be immune to 2.45-GHz radiation at the 19-V/m level.

The electromagnetic compatibility of cardiac pacemakers has been under study for many years,⁸ and they are designed and manufactured to be resistant to electromagnetic interference. It is very unlikely that cardiac pacemakers would be affected by the SPS microwave field outside the rectenna site.

Although it is not likely that it would be required, the most cost-effective method for interference mitigation for hospitals, clinics, and emergency medical facilities would be to shield the sensitive area with a light-weight screening material.

5.2.9 Satellites

The electromagnetic compatibility of SPS with other satellite systems has been studied both analytically and experimentally. The detailed design of SPS and future satellite systems must take this problem into account. The ways SPS might interfere with future satellite systems include:

- Power at 2.45 GHz could interfere with satellites in low earth orbit (LEO) that pass through the SPS beam by penetrating to the internal electronics and adding to system noise or upsetting computer circuitry.
- Noise from SPS klystrons could interfere with assigned public service satellite broadcast frequency bands adjacent to 2.45 GHz, such as the 2.5-2.69 GHz band.
- Harmonics of 2.45 GHz might fall within satellite frequency bands. For example, the third harmonic, 7.35 GHz, falls within the 7.3-7.45 GHz space-to-earth band used by government satellites.

To define the magnitude of this problem and identify the useful mitigation techniques, a number of satellite systems and subsystems currently in use were analyzed and tested in various hypothetical situations. Some of these analyses are discussed here as examples. They include:

- Satellites in LEO passing through the SPS microwave power beam.
- Satellites in GEO positions adjacent (e.g., at separations of 0.1°, 1°, etc.) to a solar power satellite.
- Satellites in GEO positions "across from" a solar power satellite (i.e., 180° separation).

Satellites in Low Earth Orbit

The LANDSAT satellite is representative of satellites in LEO that could be affected by SPS interference. The LANDSAT satellite will provide global monitoring support for earth resources management; launch of LANDSAT-D is scheduled for late 1981. Subsequent launchings also are anticipated. The LANDSAT-D, illustrated in Figure 16, will provide imagery from a sun-synchronous, circular-orbit altitude of 705 km with a 98° inclination. Imagery is derived from a multispectral scanner and thermal mapper on the satellite. Scanner and mapper image data and system status are transmitted to control stations through TDRSS, a tracking and data relay satellite system in GEO.

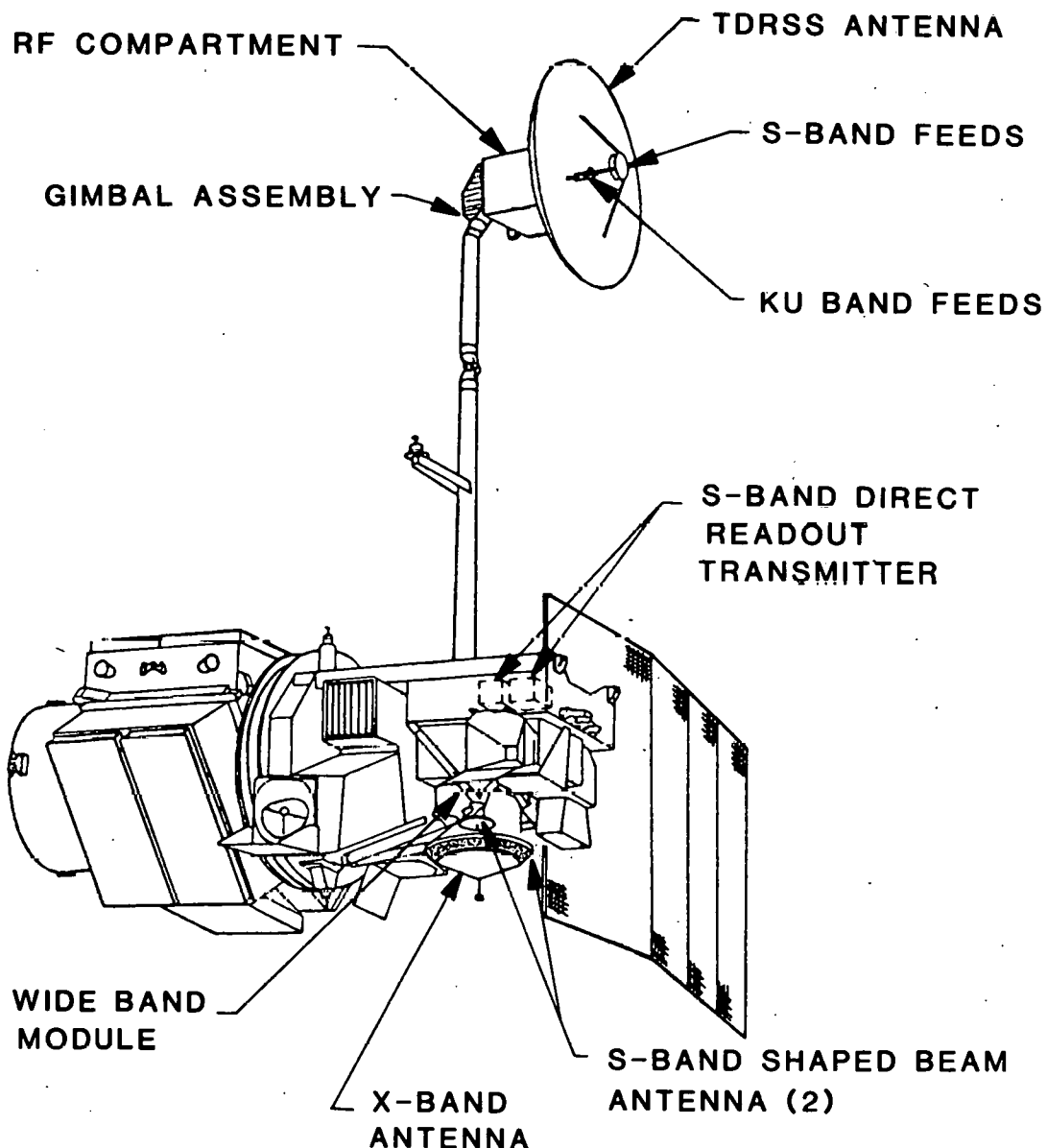


Fig. 16. The LANDSAT-D Satellite

If the LANDSAT were to pass through an SPS microwave beam, it would experience power density levels greater than 0.0002 mW/cm^2 for 13 s, 0.02 mW/cm^2 for 3 s, and 2 mW/cm^2 for 1 s. The power could enter the satellite through the communications antennas, attitude-sensor optical apertures, and the optical apertures and thermal louvers of the multispectral scanner and thermal mapper. Since the power units are filtered and regulated, energy would not be expected to enter through the solar panels.

The performance degradation of the multispectral scanner and thermal mapper subsystems in the SPS power beam might take the form of:

- Increased video noise, resulting in image degradation.
- Control signal jitter, causing image-line stagger.
- Reduced spatial frequency, affecting picture-edge sharpness.
- Reduced dynamic range, affecting picture sharpness.

Interference mitigation techniques for the multispectral scanner and thermal mapper could include circuit filters, special noise-extraction techniques in the data analysis process, and additional shielding for the detectors and video amplifiers. Additional shielding for the video channel and scan control circuitry could eliminate any jitter in the scan signal if interference power were to couple directly to these circuits. These techniques would have to be accounted for in initial satellite assembly.

The potential for SPS interference with the LANDSAT communications channels to TDRSS and the LANDSAT star tracking system also have been evaluated and mitigation techniques described.²

The GPS satellite, a global navigation and position fixing system in LEO at an altitude of 17,500 km, has also been analyzed. Since it is in a higher orbit than LANDSAT it would be exposed to more-intense SPS electromagnetic energy and consequently would experience more-severe interference. Nevertheless, similar interference mitigation techniques would apply.

Satellites in Geosynchronous Earth Orbit

Geosynchronous earth orbit is currently occupied by a number of satellites and will undoubtedly be occupied by more in the future. The solar power satellites would share this orbit altitude with these satellites, and an acceptable spacing between satellites in GEO must be determined. Electromagnetic compatibility is an important factor in this determination.

The interference caused by a solar power satellite at an adjacent satellite in GEO has been estimated. These estimates have been applied to some existing GEO satellites. To make the estimates, certain assumptions have been made, based on engineering judgment, regarding the following parameters: SPS noise and harmonic-frequency power, SPS off-axis antenna gain, off-axis antenna gain for the adjacent satellite, adjacent satellite filtering, and adjacent satellite system noise and interference susceptibility. This approximate analysis shows that GEO spacings of less than 1° would probably not be

acceptable. As the SPS technology and design develops and as the characteristics of future satellites become available, a more-accurate assessment of the required GEO spacings will be possible.

As an example of SPS interference with a GEO satellite separated from the solar power satellite by 180° , INTELSAT was analyzed. Figure 17, which shows the geometry used in these calculations, illustrates that the angle from the SPS antenna axis to the earth's optical horizon would be 8.65° , while the angle between the SPS antenna axis and INTELSAT would be 10.25° .

Using an estimate of the SPS antenna gain in the direction of INTELSAT, the 2.45-GHz power density at INTELSAT was calculated and compared with the INTELSAT transponder saturation levels. This comparison showed a wide margin of safety. Since other communication satellites have similar interference thresholds, the SPS would not interfere with GEO satellites near 180° separation.

5.2.10 Astronomy

Much of our knowledge about the universe outside of our solar system has been obtained by studying the electromagnetic emissions of celestial

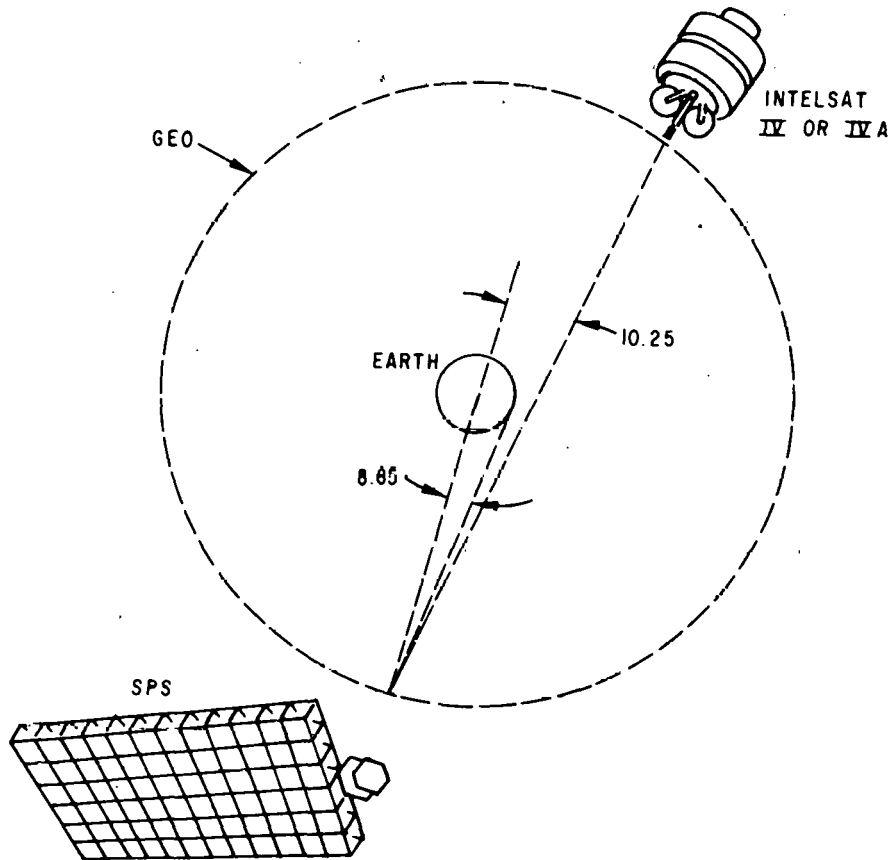


Fig. 17. Geometry Used in Calculations of Interference between SPS and INTELSAT Spacecraft

objects. Because the most distant objects also have the faintest emissions, astronomers have attempted to develop the most sensitive detectors possible. Because these detectors are so sensitive, they are limited by interference due to other sources of radiation. The effect of the SPS would be to substantially increase the amount of man-made interfering radiation. This would further limit astronomers' ability to observe faint objects. The primary SPS effect on optical astronomy would be a result of increased sky brightness.

The increase in sky brightness would come from sunlight reflected from the SPS solar cells. Using the lowest estimates of light scattering for the SPS reference system, each satellite would be as bright as the planet Venus at its brightest. This would make the satellites the third brightest objects in the sky; only the sun and the moon would be brighter. The magnitude of the effect is a function of SPS design.

Any increase in the brightness of the sky results in a proportional reduction in the effective aperture of a telescope when it is being used on faint sources. The predicted increases of sky brightness from 60 satellites suggest that, at a minimum, any observatory would be prevented from effectively observing faint sources in a 10° by 70° band defined by the line of satellites. There would also be a noticeable effect on observation over a region more than 60° by 90° (approximately half of the night sky).

For radio astronomy and deep space research, SPS would have three potential major effects. Microwave radiation leaking from a single satellite's power beam could temporarily overload or permanently damage sensitive receivers used for radio observation. This effect would prevent successful operation of centimeter-wave radio telescopes located too close to SPS rectennas or to regions of high leakage. Necessary avoidance distances could be hundreds of kilometers, and even at those distances some problems might remain. The effect would also prevent successful operation of such telescopes if they were pointed too near the line of power satellites. The magnitude of this effect could be influenced to a limited extent by the design of the radio telescope and by design of the SPS.

The second major effect would arise if power beam leakage from two or more satellites were received simultaneously by a single radio telescope. Depending upon SPS design, the result could be a slow, partly random variation in receiver properties. This could be extremely difficult to distinguish from natural astronomical processes. As a result, multisatellite power beam leakage could do markedly greater harm.

The third major effect would result from unintentional radio emissions associated with massive amounts of microwave power or with the presence of large, warm structures in orbit. These emissions from power satellites would make the satellites appear as individual stationary radio sources, unlike natural radio sources. Emissions originating at the rectennas could be much like other terrestrial sources of interference. Emissions in the allocated radio astronomy bands are subject to constraints under international treaty.⁹ Emissions at other frequencies can also harm a substantial number of important radio astronomy observations that occur at spectral lines and frequencies of opportunity outside the protected bands.

While the potential SPS effects on radio and optical astronomy are quite diverse, there are two important effects of common origin that would affect both areas of research. Because the satellites would be in geostationary orbit, they would occupy the same portion of the sky at all times. Therefore, a fixed region of the sky would not be usable for astronomical research. The size of the region would depend on the design of the satellites, the particular observation being made, and the kind of instrumentation being used. The second effect is that the source of electromagnetic interference and light pollution would be high in the sky. As a result, the general strategy of placing observatories in remote locations to avoid local interference and light pollution would be of very little help in mitigating SPS effects on astronomical observations.

Finally, increased sky brightness would affect not only optical astronomy, but aeronomy as well. Aeronomers study the physics and chemistry of the upper atmosphere by observing naturally occurring optical emissions such as airglow. This is difficult to distinguish from other increases in night sky brightness. It has been concluded that a substantial fraction of faint airglow studies are incompatible with the current SPS reference system.

As the SPS technology develops, the compatibility with astronomy will be a major consideration. Designs for solar power satellites should be based on careful consideration of reflectivity and its potential for change over the lifetime of the system. Baffling systems might be useful. Reflected light from LEO structures and its effects on sky brightness are now being analyzed for various meteorological conditions. The effect of optical and infrared emissions from ionospheric or atmospheric heating needs to be estimated.

Although a substantial basis already exists for quantitative evaluation of SPS radio interference, uncertainties remain concerning properties of SPS and radio astronomy equipment and in several cases preclude quantitative estimates of effects. Among the areas recommended for further study are:

- Noise Radiation. Uncertainties in the noise levels in the protected bands make it clear that noise measurements for any planned system will be required at an early stage.
- Effect on the National Astronomy Laboratory's Very Large Array facility in New Mexico and the Arecibo Observatory in Puerto Rico. Current engineering data are not adequate to determine the level of 4.9-GHz second-harmonic interference to these two unique facilities.
- Rectenna Siting. Rectennas would leak electromagnetic radiation. Its effect on existing facilities needs to be quantified.
- Reradiated Energy. Rectenna arrays would reradiate energy at various frequencies in the radio spectrum. Rectenna properties are not yet sufficiently defined to allow a meaningful assessment of the consequences of this radiation.

5.2.11 Mojave Rectenna Site Analysis

Representative rectenna sites have been identified by NASA.¹⁰ One of these sites, in the Mojave Desert in southern California, was selected for detailed study. The proposed rectenna would cover roughly 100 km². The evaluation of SPS electromagnetic compatibility for this site provided data for one possible site, helped establish future site selection and evaluation criteria, and allowed a limited exercise of the EMC data retrieval and analysis procedures that would be required for all candidate rectenna sites. A model was developed to predict field strengths at and near the surface of the earth from SPS microwave emissions. Equipment and systems near the rectenna site that would be susceptible to SPS radiation were categorized by function, coupling modes, location, and interconnections. Functional degradation due to SPS interference was then computed to determine to what extent normal or necessary operations would be compromised.

Figure 14 shows an SPS power beam profile for the assumed space antenna. Note that the field intensity beyond 30 km from the center of the rectenna site would be about 1 V/m at the 2.45-GHz frequency. This would represent a sizable interference input to communication systems operating within 100 km of the rectenna site. Field intensities measured at communication systems antennas are usually in the microvolts-per-meter ($\mu\text{V}/\text{m}$) range. For high-power television or AM and FM broadcasting stations, the field intensity beyond a kilometer, but within 30-50 km, may normally be in the millivolts-per-meter range. The level of a field intensity measured at a home TV antenna would most likely be in the microvolt-per-meter range. The amount of energy beyond the rectenna site, due to side-lobe structure, can be put into perspective by comparison with these values.

Added to the electromagnetic field due to diffraction would be the power scattered from the main beam by atmospheric effects. SPS energy could be dispersed through loss, beam scattering, and multipath mechanisms. Atmospheric scattering and multipath mechanisms include sandstorms, rain, melting hail, atmospheric layers (multipath), atmospheric aerosols, and turbulence. In addition, energy would scatter off the terrain and the rectenna surface.

To show the EMC effect of rain, even in a semi-arid location, statistics were gathered from Bakersfield, California, the nearest site to the study rectenna site where records are kept. Bakersfield receives rain at a rate of about 9 mm/hr on the average of about one hour per year, and at the extreme (one year out of 200) receives 17 mm/hr for one hour during a year. For about five minutes of an average year, Bakersfield receives 19 mm/hr of rain, and 47 mm/hr at the one-out-of-200-years extreme for five minutes. Scattered power densities can be predicted as a function of rain rate.¹¹ Results are shown in Table 10, based on Bakersfield data for average conditions, for five sites surrounding the Mojave rectenna site. These sites have relatively large deployments of military systems. The values listed in the table could be of considerable importance to systems operating in such an environment.

The amount of potential electromagnetic energy from all forms of scatter, including that from the rectenna itself (not calculated yet), added to the power from the side lobes, could be significant for systems out to 100 km from the rectenna site. To assess the impact on systems near the Mojave

Table 10. Scattered Power Densities - Average Rain Conditions

Site	Distance from Rectenna (km)	Power Density (10^{-7} mW/cm ²)		Field Intensity (mV/m)	
		1 hr/yr	5 min/yr	1 hr/yr	5 min/yr
China Lake Airstrip	64	5.3	21	45	88
Downtown Barstow	51	8.3	33	56	111
Edwards AFB Airstrip	43	1.2	46	21	131
Restricted Area R2524	53	7.7	30	54	107
George AFB Airstrip	61	5.8	23	47	93

site, an area 145 km by 145 km with the proposed rectenna site at the center was chosen as a data sample area. All electromagnetic systems operating within this geographic boundary between 75 MHz and 5 GHz were tabulated. The active files showed 813 government and 685 civilian systems in operation. The equipment/system categories identified were:

- Military Development and Operational Test and Evaluation

- Instrumentation radars - conical scan and monopulse modes

- Traffic monitor/control radars

- Radar transponders

- Radar signal and functional replicators

- Wideband monitor receivers with recognition/decision software-scan instantaneous-frequency modes

- Television cameras for target position track

- EM system operational monitors - multiple wideband receivers with processing software

- Range command/control communications networks

- Range telemetry communications networks

- Industrial Communications

- Utility network command/control and telemetry

- Pipeline network command/control and telemetry

- Water resource telemetry

- Multiplexed carrier networks - two major service systems

- Transportation Support Systems

- Railroad mobile equipments - yards and enroute complex

- Air traffic control network

- Emergency services - mobile, base station, and relay equipment - medical and general emergency applications

- Railroad "car condition" monitors

- Public Service Communications

- State of California backbone network
- Law enforcement systems - state, county, city - mobile, relay, and base station equipment
- Forest service units
- Fire and government emergency systems - county and city operations
- Common carrier networks - telephone, data, television services - remote-area voice links

- Specialized Services

- Space tracking and monitoring facilities (Goldstone area)
- Railroad hump radars

The character of functional degradation that would be induced by the SPS into major equipment categories deployed near the Mojave site is indicated in Table 11. The systems listed are high-priority operations that encompass relatively large geographic areas around the periphery of the rectenna site. The elements of performance degradation cited represent an average over all operating modes and geographic ranges for this particular site.

The performance degradation indicated in Table 11 would compromise the operation of the military instrumentation and systems employed in operational testing at the military sites listed in Table 10 and the command/control and other communications facilities associated with the resource management operations of utilities and municipal/county governments. This analysis provided the basis for current development of modification techniques for electromagnetic equipment and system operations to ensure an acceptable level of performance if illuminated by an SPS source.

For the Mojave rectenna site analyzed and other sites with a similar mix of military and civil systems, modification recommendations would emphasize the civilian area. Support equipment (e.g., radar telemetry, TV) could be modified for operation within a range of 40-50 km from a rectenna. Military electromagnetic systems could not be modified because of the unacceptable probability of operational compromise; system performance or procedures in "test and evaluation" exercises would have little or no relation to combat operations.

The preliminary assessment of the effect of SPS microwave emissions on electronic systems demonstrates the operational degradation that would occur within approximately 100 km of the rectenna site. The Mojave site evaluation shows a wide range of performance degradation, particularly in military systems. The basic functional and operational impacts of SPS would be of such magnitude that in many instances they would represent unacceptable or impossible compromises and biases for the test and evaluation exercises performed by the involved military facilities.

The Mojave site would allow a reasonable rectenna isolation from areas of even modest population density, but it would present serious interference impacts upon surface and aircraft electronic systems. Near this site,

Table 11. Induced Functional Degradation Summary for the Mojave Area

Function	Characteristic Effects
Instrumentation radar (military test ranges)	Cooperative target acquisition range: -(8-20%) Skin target acquisition range: -(13-28%) Cooperative target track error: +(15-40%) Skin target track error: +(22-65%) Loss of track loop lock (skin mode) probability increase: +(10-40%)
Command/control and telemetry communications (military test ranges)	Signal acquisition threshold: +(5-20%) Data error: +(5-28%) Sync loss probability: +(3-25%)
Tactical signal identifi- cation - analysis systems	False alarm probability outside mission zone: +(3-25%) False alarm probability within mission zone: +(18-60%) Receiver noise threshold: +(5-40%) Signal processing time: +(45-115%) Software overload probability increase: +(2-26%)
IR scanner (tactical system)	Video noise threshold: +(2-26%) Target detection/identification probability: -(5-33%)
Utility and pipeline command/control/telemetry communications	Signal acquisition threshold: -(5-15%) Data error: +(10-30%) Link noise: +(5-20%)
Image intensifiers	Video noise level: +(10-45%) Standard target detection/identification range: -(5-30%) Multiple target spatial resolution: -(2-60%)
Nonfederal government Communications	Channel noise: +(5-15%) Data error: +(8-35%)

military operations would suffer most of the interference problems; the systems that would be degraded are integral components of complex testing and evaluation programs. These military programs require the degree of isolation afforded by the Mojave region.

Based on the probable operational system degradation near the Mojave site and the inability to establish mitigating strategies without an unacceptable probability of operational compromise, a second site north and east of the original site was studied. A cursory look at the victim systems surrounding the new site indicates different functional classes that would lend themselves to mitigating strategies. Modifications to most of these could be accomplished to produce compatibility in the SPS rectenna environment.

The Mojave area lends itself well to resiting because of the large expanse of open, flat terrain. The development of new sites in most geographical areas would not be as simple, and might be impossible, due to population density, terrain features, electromagnetic-system density, etc. Generally the northern and eastern regions of the United States would include major transportation and commercial communications facilities. Because of the population and business densities, the total number of systems that would be affected by the SPS would be larger.

5.3 SUMMARY AND CONCLUSIONS

Although there are questions to be resolved, cooperative agreements to be made, and interference mitigation strategies to be developed, none of the electromagnetic compatibility issues assessed precludes the continued research and assessment of SPS technology.

5.3.1 Effect on Electronic Equipment in General

Conventional models of electromagnetic interference and engineering practices can be used to determine the electromagnetic susceptibility of electronic equipment to the microwave energy that would be 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) 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, filtering, and special design practices. With the exception of sensitive military and research systems, equipment more than 100 km from a rectenna site would not be expected to require modification or special design to avoid degradation in performance.

5.3.2 Satellites

Solar power satellites would have the potential to interfere with other satellites in space. Satellites in LEO that would pass through the SPS microwave beam would require special design modifications, shielding, and filtering. Adjustments in operational procedures to account for passage near or through the beam probably also would be required.

Satellites in GEO, if sufficiently separated from the solar power satellite, would not be expected to be affected. This would be true even for satellites in a GEO position opposite (separated by 180°) the power satellite. The allowable spacing between a solar power satellite and other satellites in GEO would probably not be less than 1°, but this is based on approximate analyses that will require refinement as the SPS technology develops.

5.3.3 Military Systems

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. Although sensitive military systems could be modified and adapted to perform at a predetermined level, the low probability of error or the high safety margins designed into these systems could be compromised. It is likely that the only acceptable strategy for mitigating SPS interference with military systems would be rectenna siting.

5.3.4 Astronomy

Astronomy, both radio and optical, involves study of the weakest measurable signals from the sky. The SPS would produce large additions to existing interference in the radio, infrared, and optical portions of the spectrum, hindering astronomical observations. Mitigation strategies that require modification of the astronomical equipment (e.g., filtering) would reduce the range of the observations. Rectenna siting and terrain shielding would not be sufficiently effective because the interference source, the solar power satellite, would be high in the sky. As the SPS technology develops, the compatibility with astronomy will be a major consideration. The most likely mitigation strategies would involve the design of the SPS.

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