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

Volume 2 - Detailed Assessment

MASTER

January 1980

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

DOE/NASA
SATELLITE POWER SYSTEM
Concept Development
and
Evaluation Program

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FOREWORD

The 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 convert the energy to microwaves and transmit the microwave energy via directive antennas to large receiving/rectifying antennas (rectennas) located on the earth. At the rectennas, the microwave energy would be converted into electricity. The potential environmental impacts of constructing and operating the satellite power system are being assessed as a part of the Department of Energy's SPS Concept Development and Evaluation Program.

This report is Revision I of the Preliminary Environmental Assessment for the Satellite Power System published in October 1978. It refines and extends the 1978 assessment and provides a basis for a 1980 revision that will guide and support DOE recommendations regarding future SPS development. This is Volume 2 of two volumes. It contains the technical detail suitable for peer review and integrates information appearing in documents referenced herein. Volume 1 is an executive summary of Volume 2 and provides an informative abstract of the assessment.

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INTRODUCTION

The possibility of collecting large quantities of solar energy in space, converting it to microwaves, transmitting it to earth, and converting it to electricity is being studied by the National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE). This joint program, described in the SPS Concept Development and Evaluation Program Plan (July 1977 - August 1980) (Department of Energy Report DOE/ET-0034, Feb. 1978), will generate the information needed to make a rational decision regarding development of the SPS program after 1980. NASA is conducting systems definition studies of the SPS. DOE is evaluating health, safety, and ecological impacts; examining economic, international, and institutional issues; and making comparative assessments of the SPS relative to alternative power sources for the future.

An SPS "reference system" is described by NASA in the SPS Concept Development and Evaluation Program Reference System Report (Department of Energy Report DOE/ER-0023, Oct. 1978). This reference system provides the technical and operational information DOE needs to conduct the environmental, socioeconomic, and comparative assessment studies. The reference system is an interim working concept and NASA's systems definition work is developing a more complete understanding of the satellite power system. Environmental impact studies can also be expected to influence future system designs.

An SPS satellite, as specified in the reference system, would be a planar solar-cell array of about 55 km² built on a graphite-fiber-reinforced structure. A phased-array microwave transmitting antenna one kilometer in diameter would be mounted on one end of the satellite. The antenna would use klystrons as power amplifiers with slotted waveguides as radiating elements. The satellite would be constructed in geosynchronous orbit during a six-month period; a ground receiving station (rectenna) for each satellite would be completed at the same time. The reference system calls for 60 satellites to be constructed over a 30-year period.

Also required for the satellite power system would be construction bases in space, launch and mission control bases on earth, and fleets of space vehicles to support the construction and maintenance of the satellites. These transportation vehicles would include heavy-lift launch vehicles, personnel

launch vehicles, cargo orbit-transfer vehicles, and personnel orbit-transfer vehicles. The earth launch site would be the Kennedy Space Center, pending further study.

The key environmental issues associated with the SPS concern human health and safety, ecosystems, climate, and electromagnetic systems interactions. In order to address these issues in an organized manner, five tasks have been established:

- Task I Microwave-Radiation 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 from these tasks are presented in Sections 1-5 of this report.

Task I evaluates the potential effects of 2.45-GHz microwaves on SPS workers, the general public, and ecosystems. All other possible health and ecological impacts of the SPS are examined in Task II, including the effects of the space transportation system, ionizing radiation in space, occupational hazards due to manufacturing, and air and water pollution. Task III characterizes potential atmospheric disturbances due to the SPS and assesses climatic impacts. This task's topics include the effects of rocket effluents on the lower and upper atmosphere and the effects of rectenna waste heat and surface roughness. The impacts of ionospheric disturbance caused by microwave heating and space-vehicle effluents on communication systems, which use the ionosphere as a part of the propagation path, are evaluated in Task IV. Task V focuses on the direct effects of the microwave power transmission system on communication and other electromagnetic systems. These effects include those of direct and scattered power at 2.45 GHz, power at harmonic frequencies, and noise power.

1 HEALTH AND ECOLOGICAL EFFECTS OF MICROWAVE RADIATION

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1.1 SCOPE

Section 1 of this assessment considers the effects of microwave radiation emanating from the satellite power system on:

- The general public outside the exclusion zone for the rectifying antenna (rectenna) and in transit through the zone,
- Terrestrial workers who maintain or operate the rectenna,
- Space workers who maintain or operate the SPS, and
- Ecosystems inside and outside the exclusion zone for the rectenna.

The pertinent design data of the SPS reference system^{1*} are used in this assessment. The frequency of the microwaves transmitted from a satellite is expected to be 2.45 GHz. The approximate expected values of the relevant microwave power densities associated with the SPS are listed in Table 1.1.

Harmonics of 2.45 GHz would be generated within the half-wave rectifying diodes and reradiated. The power densities of these harmonics would be orders of magnitude less than the power density for the 2.45 GHz transmission.

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 (RF) receiver and phasing electronics to process the pilot-beam instructions. If a total failure of the phase-control system occurred, the power beam would diverge and the peak power density would drop correspondingly. 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.

Only the space worker, under accidental circumstances, could be exposed to the 240-2200 mW/cm² power densities near the transmitting antenna. Exposures above 23 mW/cm² would only be possible for the terrestrial worker under conditions of rectenna malfunction. Thus, the prime considerations for effects of microwaves on health and ecosystems derive from normal SPS opera-

*References for Section 1 are listed in Section 1.7.

Table 1.1. SPS Microwave Power Densities

Location	Power Density (mW/cm ²)
<u>Space Equipment</u>	
Center of transmitting antenna	2200
Edge of transmitting antenna	240
<u>Terrestrial Equipment</u>	
Center of rectenna	
Malfunction	100
Normal operation	23
Edge of rectenna (5 km from center)	1
At exclusion boundary around rectenna site (5.7 km from center)	0.1
Beyond exclusion boundary	
9.0 km (first side lobe) ^a	0.080
13.0 km (second side lobe)	0.030
17.0 km (third side lobe)	0.010
Grating lobe levels (at spacing of 440 km) ^b	<0.01

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

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

tion. For the purposes of this assessment, the following general estimates of typical exposure conditions and exposed populations are made:

- Intermittent short-term occupational exposures of much less than 240 mW/cm² for protectively-clothed space workers.
- Intermittent short-term occupational exposures of less than 23 mW/cm² for protectively-clothed terrestrial SPS workers.
- Brief, transient exposures of 0.1-23 mW/cm² for airborne biota.
- Continuous exposures of 0.0001-0.10 mW/cm² for the general population (composed of all age groups) near rectenna sites.
- Continuous exposures of 0.1-23 mW/cm² for ecosystems on rectenna sites and of 0.0001-0.10 mW/cm² for all other ecosystems near rectenna sites.

1.2 METHODOLOGY

1.2.1 Effects on Public and Workers

The published literature on the biological effects of microwave radiation has been reviewed for its relevance to the SPS, but no firm conclusions can yet be drawn concerning the effects of exposure to relatively low levels. Results obtained so far are difficult to interpret in terms of health risks, with many cases of conflicting results from similar experiments. The existing data base, however incomplete, must be used as a starting point for assessing the impact of the SPS microwave power transmission system (MPTS).

A combination of two types of studies must be used to assess impacts. One type will investigate research areas where no data exist and which might pose questions about the advisability of using a microwave beam to transmit energy from space. Principal among these questions is the effect of long-term human exposure to low levels of 2.45-GHz radiation. Long-term studies using experimental animals will be the primary determinants in answering this question, but much of this work cannot be completed before the 1980 assessment of SPS impacts.

The other type of study, which addresses effects already documented in the literature, is being made to validate published reports of potential adverse health effects of microwave radiation. The intent behind these studies is to determine the validity of reports that are germane to the SPS environmental assessment program. The information developed from this work will also be used to design the long-term experiments.

1.2.2 Effects on Ecosystems

Microwave-effects research with direct ecological implications has rarely been performed. Moreover, the impact of microwaves on an entire ecosystem has apparently never been examined in a systematic way. Nevertheless, available literature has identified several reports that may have a bearing on the SPS program.² These studies imply that, at least at very high levels of exposure to microwaves, some plants have increased susceptibility to drought and decreased productivity; avian species suffer increased lethality, decreased reproductive success, and alterations in behavior. Data concerning the ecological effects of continuous, low-level exposures generally are not found in the literature.

As a first step, a comprehensive review and critical interpretation of the literature on the ecological effects of microwaves will be conducted to identify ecological information gaps. Ecological research protocols that address these gaps and are specific to SPS needs will be formulated. Particular emphasis will be placed on the relationship between rectenna operation and ecosystems.

1.3 CAUSE AND EFFECT RELATIONSHIPS

The cause and effect relationships for the biological effects of microwaves are shown in Fig. 1.1. Each effect is given a probability (P) rating and an issue-severity (S) rating. Both ratings are principally subjective but are based on current scientific opinion. Moreover, they are SPS project-specific and should not be regarded as broadly applicable to the case of microwave biological effects generally. In effect, the ratings represent a priority system for planning and conducting research pertinent to the SPS program. Sections 1.4-1.6 discuss the basis for the assigned ratings.

1.4 STATE OF KNOWLEDGE

The presence of microwave radiation in the environment was negligible prior to World War II. Since then, electromagnetic emissions from microwave-frequency generators for communications, radio-navigation, military applications, diathermy, food ovens, and other industrial purposes have increased dramatically. In 1970, the First Task Force on Research Planning in Environmental Health Science conservatively estimated that nearly one-half of the U.S. population lived in a measurable microwave environment. Since 1970, the number of microwave sources has increased as new and broader domestic, medical, industrial, and military applications have been found. However, U.S. research programs to determine and evaluate biologic effects of nonionizing radiation have not yet generated a data base upon which quantitatively-sound and scientifically-valid population exposure standards for microwave radiation can be established.³

Research during the past five years has indicated that some biological systems exhibit responses to microwave radiation at intensities that were previously considered to be too low to produce detectable alterations (i.e., in the range of 1-10 mW/cm²). At frequencies of 2-3 GHz, the full extent to

Fig. 1.1. Cause and Effect Relationships for Microwave Effect on Health and Ecosystems

which microwaves impact living systems has not been determined nor are the conditions necessary to produce an observed alteration well defined.⁴⁻⁷

The major difficulties in reliably evaluating consequences of human exposure to microwaves are the paucity of human data, difficulty in establishing dose distribution within a body, insufficiency of replicated data on experimental animals, and the usual problems of extrapolating data from animals to humans. The current lack of understanding of basic mechanisms by which low-intensity fields interact with biological systems compounds the problem. Recent research has helped define the nature and scope of the problem and has provided directions for continuing research.⁸ Only experimental study of continuous-wave (CW) radiation at the proposed SPS frequency of 2.45 GHz can reveal whether the SPS concept can be implemented safely.²

A data base for making an ecological assessment is not available. A wide range of information is needed concerning the quantitative and qualitative responses of an ecosystem to microwave exposure. This information must be directly related to the type and level of exposure expected to be found at and beyond the rectenna site. Important areas for which information is currently lacking include effects on crop productivity and on the survival, behavior, and reproduction of airborne biota.

The full impact of the effects of microwave radiation on ecosystems and human health will not be known until the spatial distribution and field characteristics of the microwave beams from a multiplicity of SPS transmitters are known. Such parameters as the field distributions inside buildings or vehicles, the proximity to a rectenna site, and the total number of orbiting transmitters and how they interact must be determined. Much of this work is being undertaken as part of this environmental assessment.

1.5 ASSESSMENT

1.5.1 Introduction

The following assessment is meant to concisely answer the question: "What do we currently know and not know about the health and ecological implications of operating an SPS?" This assessment in no way is meant to be a detailed review of the body of knowledge concerned with the biological effects of microwaves; to that end, the reader is referred to a number of reviews

in the forms of scientific articles, books, and government documents.^{2, 9-11} Generally, this assessment is limited to the bounds of estimates of SPS-related exposure conditions and exposed populations defined previously (see Table 1.1). Further, the discussion includes only results which could be evaluated using specific criteria. These criteria include studies which are published in peer-reviewed journals and which contain adequate descriptions of techniques, materials, and results; and studies in which negative effects were not influenced by only small test populations or by the application of an inappropriate or inadequate test system. Also, the discussion does not treat repetitive chronicity of exposure, except in extreme cases.

Section 1.5 is organized into the general areas of toxicologic responses listed below.

- Immunology and hematology
- Mutagenesis
- Carcinogenesis
- Reproduction, development, and growth
- Behavior
- Physiologic and integrative processes and thermal aspects
- Interactive situations, drugs, and special populations

Much of the subsequent discussion centers on results and conclusions from experimental animal research; Table 1.2 presents the whole-body energy absorption rates for humans and various animal species. For a given power-density exposure, animals have much greater absorption rates than humans. The table shows, for instance, that at any given power density the specific absorption rate (SAR) for a mouse is approximately 30 times that of an adult man, and a rat's specific absorption rate is six times that of a man. However, it should be pointed out that the SAR of a man's head is similar to that of a guinea pig and the SAR of a man's testes is similar to that of a mouse.

1.5.2 Immunology and Hematology

There is ample evidence that microwaves affect the immunologic and hematologic systems of exposed animals,¹³⁻²² particularly if the rate of heat absorption from the microwaves exceeds the animal's basal metabolic rate. Increases in lymphocyte numbers and lymphocytic activity have been

Table 1.2. Estimates of Whole-Body Specific Absorption Rates for Various Species at 2.45 GHz of Continuous-Wave Radiation

Power Density (mW/cm ²)	Specific Absorption Rate by Species (W/kg)				
	Man (≈70 kg)	Dog (Medium)	Guinea Pig	Rat (Medium)	Mouse (Medium)
23.00	0.92	1.15	3.45	5.75	32.2
1.00	0.04	0.05	0.15	0.25	1.4
0.80	0.032	0.040	0.12	0.20	1.12
0.10	0.004	0.005	0.015	0.025	0.14
0.03	0.0012	0.0015	0.0045	0.0075	0.042
0.01	0.0004	0.0005	0.0015	0.0025	0.014

Source: Ref. 12.

reported, as have changes in the relative frequency of lymphocyte subpopulations and the immune responsiveness of microwave-exposed animals. Even when the basal metabolic rate is not exceeded, responses similar to those elicited at higher power densities are also observed.^{14,15,19-22}

High-intensity microwaves can induce thermal loads in animals which in turn can affect the immunologic and hematologic systems.¹³⁻¹⁵ More subtle microwave-induced heating, in the absence of core body-temperature increases, may also account for the observed effects on these systems.^{14,16-22} These responses are similar, if not identical, to responses elicited in animals following a stressful encounter or administration of corticosteroids.¹⁶ These effects are more likely attributable to the heating properties of microwaves because there is no convincing evidence at this time for a direct interaction of microwaves with hematopoietic cells in vitro or in vivo.

Summarizing, then, there is evidence of both increased and decreased responsiveness of the immune system in animals exposed to 2.45-GHz microwaves; there are also reports of the unresponsiveness of the immune system. There is evidence that a response, when seen, is reversible; there is no evidence that the response is permanent. The altered immune response is very similar to the response seen in stressed animals.

On the basis of present knowledge:

- No effect on the immune and hematologic systems would be expected from exposures of the general population to power densities anticipated outside the rectenna site.

- Within the rectenna site, only temporary alterations in these systems would be expected as a result of short-term exposures.
- The hazards of long-term occupational exposure are not yet known.
- For animal and avian members of the ecosystem, no hazard would be expected outside the rectenna site; on-site, hazard would be anticipated from prolonged exposures and reversible effects from transient exposure also would be possible.

1.5.3 Mutagenesis

The mutagenic potential of microwaves has been tested in many systems.²³⁻³² A battery of standard "first-tier" tests for mutagenic activity which employ bacterial test systems has been performed using microwaves. All the results indicate that microwaves possess no mutagenic activity without substantial heating. In addition, several "second-tier" tests for mutagenicity which employ whole-animal test systems have demonstrated under carefully controlled conditions that microwaves are not mutagenic.^{31,32}

Structural gene (cytogenetic) changes arise from exposure to extremely high-intensity microwave fields, as are present in microwave ovens. In these circumstances, the field intensities are two orders of magnitude above the intensities anticipated for exposures to SPS microwave radiation. No mutagenic activity has been found for 2.45-GHz radiation at power densities on the order of SPS levels in various biological systems used for first-tier screening of chemicals.²⁷⁻²⁹ Under conventional interpretations, microwaves would not even be listed as a weak stressor to be examined for mutagenic activity with second- and third-tier screens. No mutagenic activity was observed in a mammalian Dominant Lethal Assay.³¹

Summarizing, then, there is no evidence for a mutagenic effect except when the test system has been heated substantially. There is evidence for no mutagenic effect. Any mutagenic effect seen is observed at high power intensities not relevant to SPS. In screening tests meant to detect mutagenic agents, 2.45 GHz would be considered a less-than-weak mutagenic agent.

Based on present knowledge:

- There is no current expectation that SPS microwaves would cause mutagenic effects in any population, inside or out-

side the rectenna site, except as associated with substantial thermal insults.

- Tests using whole animals provide evidence of the absence of SPS microwave-induced mutagenic activity.

1.5.4 Carcinogenesis

A report by Prausnitz and Susskind³³ surfaces frequently in support of an oncogenic (leucosis and leukemia) relationship of microwaves in mice. Even though this work was conducted with pulsed 9.27-GHz radiation using very short daily exposures at 100 mW/cm², we have cited this report because of its frequent reference as an example of the carcinogenic potential of microwaves. The authors reported data of an increase in white-blood-cell cancers in one sacrificed group one month after irradiation. Fifteen months later, a second group had a similar or greater incidence of blood cancer; however, a group sacrificed four months later contained normal incidences. The inconsistency of the results (that is, the cancer incidence disappeared) and the lack of other reports of the occurrence of leukemia preclude confidence in these results and in the oncogenic theory of microwaves generally.

There is no theoretical basis for expecting microwave exposure to be oncogenic. Essentially, there are no data in the scientific or medical literature relating to carcinogenic effects of microwave exposure. The relevant literature has been extensively reviewed, with the conclusion there is little indication of any carcinogenic potential of microwaves.^{9,10}

On the basis of present knowledge:

- There is no confirmatory evidence that microwaves cause cancer.
- There is insufficient evidence to dismiss the possibility that microwaves may cause cancer.

1.5.5 Reproduction, Development, and Growth

Reproduction in the Male. Exposure to high power densities of microwaves can alter the male reproductive system. The effects (degeneration of the seminiferous tubules,³⁴ decreased normal sperm and sperm concentration,³⁵ and decreased prostatic activity³⁶) appear to be directly associated with heat input. However, these effects are reversible. At near-normal testes temperatures none of these effects are evident.

In summary then, there is no evidence that the male regenerative system is permanently impacted or impaired and it is expected that pathologic lesions are lost with time.³⁷ There is evidence that decreased sperm concentrations return to normal levels after exposure ceases.³⁵ There is no evidence for loss of functional fertility.^{31,36,38,39}

On the basis of present knowledge:

- Testicular damage, male germ-cell mutagenesis, or decreased male functional fertility would not be expected to occur in the general population as a result of SPS microwave transmission.
- Because of the importance of the subject, experiments valid to SPS occupational exposure conditions must be conducted.
- Effects of exposure levels within the rectenna site on pertinent members of the ecosystem are also unknown.

Reproduction in the Female. There is little evidence upon which to base a judgement of the effect SPS may have on the female reproductive system. Of the two relevant reports dealing with effects on this system, one used fruit flies and exposed them to high power densities (300-1000 mW/cm²).⁴⁰ The second lacks an adequate description of exposure and other data.⁴¹ Nevertheless, the latter study employed an adequate sample size of mice and chronic-exposure techniques. These scant results indicate that there is no expectation for a change in female reproductive capability in mice exposed to 0.3 mW/cm². Studies of the domestic chicken and its egg⁴² revealed decreased egg production and decreased egg-shell quality without a loss of hatchability at 1 mW/cm².

Summarizing, then, there is little confirmed evidence for alteration in female reproductive capability. There is no evidence to dismiss the possibility of microwave effects on the female reproductive system.

Based on present knowledge:

- No alteration in the female regenerative system in the general population would be expected at SPS microwave levels.
- There is insufficient data on which to make a reasonable judgement of the effects on occupationally-exposed females.
- Effects of chronic exposures of pertinent ecosystem populations are largely unknown.

- The effect on bird reproduction could be significant within the rectenna site.

Development. Development has been examined to a sufficient degree to begin evaluations of SPS as an influence. At power densities like those expected at the rectenna site, fetuses of small rodents have exhibited delayed growth and possibly increased teratologic changes,⁴ whereas representative avian species showed no evidence of teratologic effects.^{42,43} There are no useful data available for animals larger than laboratory rodents.

In summary then, rectenna-site power densities may cause delayed growth in the mammalian fetus, but not in avian species. There are no usable data for larger animals.

Present knowledge indicates that:

- Fetuses of some rodent species may be harmed by power densities predicted for the SPS rectenna site.
- Harm to human fetuses off the rectenna site would not be expected because of lower power-density levels and the frequency/size interaction which would further diminish the absorption of energy by humans.
- Studies are required in larger animals to help ensure these safety aspects.
- Continuous exposure to on-site power densities could at least affect egg-shell fragility and survivability in avian species.

Growth. Microwaves appear to have no influence on growth. Studies of rats exposed in early neonatal life and later have not shown any change in growth, as an integrated maturational response.⁴⁴ Based on present knowledge, growth alterations due to SPS would not be expected in the general population, rectenna-site workers, or animals.

1.5.6 Behavior

Behavior is one of the most-explored aspects of microwave effects; a number of studies have examined several aspects of behavior altered by exposures relevant to SPS microwaves.

Mice will avoid microwaves or make an escape response when exposed to power densities somewhat higher than the maximum SPS terrestrial level.⁴⁵ Exposures to power densities expected on the rectenna site cause rats to alter their patterns of operant response,⁴⁶ and repeated (22 weeks) exposures have caused increases in their motor activity and decreases in their discrimination performance.⁴⁷

Most of the reports of microwave-induced mild behavioral changes in humans are made by Eastern Europeans. This is often referred to as the "neurasthenic syndrome," a collection of reversible symptoms of behavioral disturbances. Because of disparities in scientific philosophies and, therefore, experimental design and interpretation, the neurasthenic syndrome as attributed to microwaves has not received credulity in American and Western European scientific circles. Recent attempts to duplicate Soviet research in the microwave field have produced inconsistent results. In one study, rats exposed to 10 mW/cm^2 of 2.45 GHz for 22 weeks would not alter their avoidance of shock.⁴⁷ In another study (included here for its importance, though not peer-reviewed or published), rats exposed to 0.5 mW/cm^2 demonstrated perception of electric shock and decreased locomotor activity after seven months of exposure; reversion to normal occurred within one month.⁴⁸

In summary 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. Some of these effects at power densities expected outside the rectenna site are also reported in East European literature.

Based on present knowledge:

- Motor activity, pain response, and discrimination are behavioral responses that present research has shown to be altered by SPS-level microwaves.
- Transient, intermittent, and continuous exposures to power densities expected on the rectenna site may cause these and other changes in man and animals.
- The effect of continuous exposures to off-site radiation levels is not clear. Past work is not sufficient to allow generalizations regarding the appearance of the neurasthenic syndrome.

1.5.7 Physiologic and Integrative Processes and Thermal Aspects

There is little, if any, firm evidence to suggest that microwaves have a biologic capability beyond that associated with the direct application of heat. Sufficiently high power densities can cause a gross input of energy to a system and the energy deposition is expressed as a rise of temperature. An animal's response to this heat application is what is currently believed to be assayed in biologic studies.

However, there are certain aspects of microwave-energy application which are unlike those of other heat energy sources. First, depending on the frequency, the energy may penetrate deeply into the absorber and be distributed unevenly. Second, the body responds both locally and generally with reactions which are not necessarily easy to quantify. The measurements of the uneven distribution and of local response are not completely adequate. Third, the application of medium-level and lower power densities causes responses which are very difficult to assess; these responses are transient, variable, often adaptive, and lie in a gray-zone of biological appreciation. A considerable amount of evidence points to 2.45-GHz microwave radiation as an influence on the physiologic processes of animals. This influence includes changes in serochemistry and thyroid hormone values.⁴⁷⁻⁵¹ A considerable body of research provides no evidence of change in other important physiologic tests. Fourth, the body switches in and out of physiologic systems as it responds to increasing power densities. Therefore, there is little hope of developing anything but poor estimates of the most important data....dose-response curves.

In summary, there is acceptable evidence for changes in some physiologic and integrative processes, and no evidence for change in many other processes. Those processes are very variable and very responsive to common environmental changes. If the effects of microwaves are through the pathway of increased thermal burden, then the ambient temperature and humidity play a role in the appearance and depth of the effect because ambient environmental conditions are an important factor in physiologic loss of heat. A number of studies have shown the synergistic behavior interaction of power-density levels and ambient conditions.⁵²⁻⁵⁴

On the basis of present knowledge:

- The effects of microwave exposure at SPS levels may be totally related to heat input. If this is so, then the entire body of thermal physiology may be used to further the understanding of these effects and determine their status as hazards.
- Physiologic and integrative processes are expected to be influenced by exposures to power-density levels anticipated for the rectenna site.
- Exposure consequences are not yet adequately understood and may not be readily demonstrable.

1.5.8 Interactions, Drugs, and Special Populations

There is little work available to help understand the interaction of microwaves with other factors in today's environment. This lack of information is probably insurmountable as a practical matter. One example of interaction is the potentiation of the effects of chlordiazepoxide, a common tranquilizer, on operant behavior in rats exposed to 1 mW/cm² at 2.45 GHz (though this work was done with pulsed rather than continuous-wave radiation, it is included here because of its importance).⁵⁵ If microwaves are a minor stress, their addition to the environment generally may have the potential to cause interactive effects.

There are special human and animal populations that deserve consideration. Animals with high metabolic activity (birds, very small mammals) may be more susceptible to SPS microwaves than the larger, common laboratory animals. Children and elderly people do not have the same physiologic capacity as young healthy adults. Almost all animal experiments are conducted on young healthy adults.

Present knowledge indicates that microwaves interact with other environmental and societal factors; however, the response to these combinations is unpredictable. There may be implications for occupationally-exposed workers using medications.

1.6 CONCLUSIONS

1.6.1 Public and Occupational Personnel

Public health and safety could be affected by chronic exposure to low levels of microwave radiation outside the rectenna exclusion zone and brief

exposures to higher levels (e.g., in transit through the main beam in aircraft). The effects that might occur, their assumed impacts based on existing knowledge, and their qualitative probability and severity ratings are summarized in Table 1.3.

Some workers at a rectenna site could be exposed to both high (≈ 23 mW/cm²) and low (≈ 1 mW/cm²) levels of microwave radiation during work periods (see Table 1.1). Exposures could be increased temporarily by a factor of four under the conditions of rectenna malfunction, e.g., loss of the terminal electrical load. Increases in power density levels to ≈ 100 mW/cm² could induce pronounced thermal effects in an unprotected worker located near the center of a rectenna. The effects which might occur at power densities of 23-100 mW/cm², their assumed impacts based on existing knowledge, and their probability and severity ratings are summarized in Table 1.4.

Space workers would be exposed to widely varying levels of microwave radiation during a tour of duty in space. Workers in close proximity to an operating transmitting array could be exposed to a power density near 2200 mW/cm². Diffraction of the fields at the edges of the transmitting array or the reflection of waves from local boundaries could also cause exposure of workers to high power densities. Certain modes of failure in the microwave transmission systems, e.g., leakage from cracked waveguides, could cause locally unacceptable increases in power density. The effects which might occur in space, their assumed impacts based on existing knowledge, and their probability and severity ratings are summarized in Table 1.4.

1.6.2 Ecosystems and Airborne Biota

The rectenna-site ecosystems could be affected by chronic exposure to maximum microwave radiation levels of approximately 23 mW/cm². Chronic levels of microwave radiation ≤ 0.1 mW/cm² would be experienced outside the exclusion zone. Either high or low levels of radiation may produce effects. The possible effects, their assumed impacts based on existing knowledge, and their probability and severity ratings are summarized in Table 1.5.

Table 1.3. Potential Effects of the SPS Microwave Power Transmission System on Public Health

Type of Effect	Probability Rating ^a	Severity Rating ^b	Existing Knowledge ^c
Immunologic/Hemopoietic	3	3	Several reports of temporary effects on white blood cells in both Western and East European literature (1.5.2).
Genetic/Mutagenic	3	1	Effects only noted at extremely high levels, with body temperature increase (1.5.3).
Late Effects/Carcinogenic	2	1	No pertinent data (1.5.4).
Reproductive (male)	3	1	No effects noted at low exposure levels (1.5.5).
Reproductive (female)	2	1	Little experimental evidence (1.5.5).
Teratologic	2	1	Birth defects in mice and infant mortality in monkeys reported. ^d
Growth	3	2	No effects noted (1.5.5).
Longevity	2	2	No data. ^d
Behavioral/CNS	2	1	Alterations in behavior and blood-brain barrier noted in rodents (1.5.6).
Co-Stressors	1	3	Effects demonstrated with temperature, humidity, and medication (1.5.8).
Cardiovascular	3	2	Change in heart rate noted <i>in vitro</i> . ^d

^a1 = high; 2 = unknown; 3 = low.

^b1 = critical; 2 = unknown; 3 = noncritical.

^cSee section cited for discussion.

^dThis effect is not discussed in the text because knowledge has not advanced since publication of the Preliminary Environmental Assessment for the Satellite Power System, DOE/ER-0021 (Oct. 1978). See Ref. 2 for additional information.

Table 1.4. Potential Effects of the SPS Microwave Power Transmission System on Occupational Health (Terrestrial and Space Workers)

Type of Effect	Probability Rating ^a	Severity Rating ^b	Existing Knowledge ^c
Immunologic/Hemopoietic	1	2	Various effects noted at moderate dose, short exposures (1.5.2).
Genetic/Mutagenic	3	1	Effects only noted at extremely high levels with body temperature increases (1.5.3).
Late Effects/Carcinogenic	2	1	No pertinent data (1.5.4).
Reproductive (male)	1	1	Effects noted at moderate and high doses on male reproductive system (1.5.5).
Reproductive (female)	2	1	Little experimental evidence (1.5.5).
Teratologic	2	1	Birth defects in mice and infant mortality in monkeys reported. ^d
Growth	3	2	No effects noted (1.5.5).
Longevity	2	2	No data. ^d
Behavioral/CNS	1	1	Alterations in behavior and blood-brain barrier noted after short exposures (1.5.6).
Co-Stressors	1	3	Effects demonstrated with temperature, humidity, and medication (1.5.8).
Cardiovascular	3	2	Change in heart rate noted <i>in vitro</i> . ^d
Cataracts	1	3	Cataractogenesis noted at high doses. ^d
Endocrinologic	1	3	Changes noted at high dose, short exposure. ^d

^a1 = high; 2 = unknown; 3 = low.

^b1 = critical; 2 = unknown; 3 = noncritical.

^cSee section cited for discussion.

^dThis effect is not discussed in the text because knowledge has not advanced since publication of the Preliminary Environmental Assessment for the Satellite Power System, DOE/ER-0021 (Oct. 1978). See Ref. 2 for additional information.

Table 1.5. Potential Effects of the SPS Microwave Power Transmission System on Ecosystems^a

Ecosystem Member or Feature Affected	Probability Rating ^b	Severity Rating ^c	Current Judgement
Plant productivity	2	2	Change in productivity could alter dynamics and composition of ecosystem. Change in productivity of crops could have economic impact.
Plant reproduction success	2	2	Change in reproduction could alter ecosystem composition and dynamics; also could affect crops.
Plant community structure (effects due to species-specific differences in sensitivity)	2	2	Impact as above.
Airborne biota	2	1	Potential exists for a variety of aesthetic and economic losses. General ecosystem change.
Invertebrates	2	2	Changes in ecosystem function/structure possible. Potential exists for economic impact depending on effects on beneficial and pest species.
Decomposer organisms	2	2	Alteration in productivity of system.
Small mammal population (alteration by direct effects of microwave exposure)	2	2	Changes in population size or community structure may affect ecosystem dynamics. Possible economic effects concerning pest and game species.
Reptiles and amphibians	2	2	Difficult to assess; general ecosystem change.
Productivity of domestic farm animals	2	2	Difficult to assess.

^aSome of these effects are not discussed in the text because knowledge has not advanced since publication of the Preliminary Environmental Assessment for the Satellite Power System, DOE/ER-0021 (Oct. 1978). See Ref. 2 for additional information.

^b1 = high; 2 = unknown; 3 = low.

^c1 = critical; 2 = unknown; 3 = noncritical.

As a result of a review of the biological effects of microwave radiation (see Ref. 2) a decision has been made to study the effects of microwave radiation on airborne species that are expected to inhabit or pass through typical rectenna sites. 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 pollenization process which is important to humans' food supply. Moreover, they are relatively easy to handle experimentally and have a short life cycle; therefore, they are attractive experimental subjects.

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.

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2 NONMICROWAVE EFFECTS ON HEALTH AND THE ENVIRONMENT

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2.1 SCOPE

The assessment described in Section 2 is designed to identify and, where possible, quantify the nonmicrowave-related health hazards and ecological impacts arising from the development and operation of the satellite power system (SPS) as defined in the current reference system.^{1*} The assessment covers the health and safety hazards 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, construction, and operation of the rectenna

2.2 METHODOLOGY

The nature of the effects of terrestrial operations dictates that they be assessed in two ways. First, a number of impacts result from conventional processes that would be used more extensively in the 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 prolonged weightlessness). 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.

*References for Section 2 are listed in Section 2.7.

2.3 CAUSE AND EFFECT RELATIONSHIPS

Figure 2.1 shows the cause and effect relationships for various portions of the satellite power system as currently understood.

The extraction, processing, and fabrication-of-materials-and-equipment activities would result in impacts that are common to all mining, construction, and manufacturing operations: air and water pollution, land disturbance, and the like. The importance of considering these impacts as part of an SPS assessment comes from the need to evaluate the incremental effects caused by SPS requirements. This assessment will attempt to provide some very rough indications of the extent of the incremental impacts caused by SPS deployment. The only significant exception to the conventional effects of these activities is the exposure to toxic materials that are unique to the SPS system. Some unusual materials would be involved in the manufacture of the solar arrays and in the rocket propellants but a complete impact evaluation has not yet been carried out.

The transport-of-materials-and-equipment activities 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 resulting from the need to move 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 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 significant increase

EXTRACTION, PROCESSING, AND FABRICATION OF MATERIALS AND EQUIPMENT		
Mining	Construction	Manufacturing
<ul style="list-style-type: none"> • Land Disturbance (strip-mining, subsidence, spoil piles) • Air Pollution (fugitive dust) • Water Pollution (leaching, drainage modification) • Toxic Materials • Safety Hazards • Noise • Solid Waste 	<ul style="list-style-type: none"> • Land Disturbance • Air Pollution (fugitive dust) • Water Pollution • Safety Hazards 	<ul style="list-style-type: none"> • Air Pollution (stack emissions) • Water Pollution (process effluents) • Solid Waste • Safety Hazards • Toxic Materials • Noise

TRANSPORT OF MATERIALS AND EQUIPMENT
<ul style="list-style-type: none"> • Air Pollution (vehicle exhausts) • Water Pollution (spills) • Accidents (conventional, catastrophic) • Toxic Materials

RECTENNA-SITE OPERATION AND MAINTENANCE
<ul style="list-style-type: none"> • Electromagnetic Fields • High Voltage

FLIGHT OPERATIONS	
Launch	Recovery
<ul style="list-style-type: none"> • Air Pollution (vehicle exhaust, ground cloud) • Water Pollution (launch pad cooling) • Noise (acoustic, sonic boom) • Launch Emergency (abort, off-trajectory failure) • Toxic Materials • High Acceleration /Deceleration • Ozone Depletion 	<ul style="list-style-type: none"> • Water Pollution (residual propellant spills, ablative material removal) • Noise (sonic boom) • Recovery Emergency • Toxic Materials

Fig. 2.1. Cause and Effect Relationships for Terrestrial SPS Operations

in launch and recovery activity. The effects of these increases are being evaluated.

All space operations would result in effects about which there is limited information. Both the type of individual exposed to the space conditions (i.e., construction worker instead of astronaut) and the exposure pattern would be significantly different from current space program experience. This assessment includes some preliminary information on potential problems.

2.4 STATE OF KNOWLEDGE

Many of the SPS health and safety effects would result from conventional processes, as indicated above. There is, in general, a considerable volume of information about these conditions and the data required for impact evaluation are well documented. In these cases an assessment of the incremental effect of a satellite power system must be made. In general, the state of knowledge about these incremental effects is not very far advanced because of the preliminary nature of the system design. The state of knowledge of each of the effects is summarized in Section 2.6.

2.5 ASSESSMENT

The assessment is divided into discussions of the nonmicrowave SPS effects on the public, terrestrial workers, space workers, and ecosystems.

2.5.1 Effects on the Public

SPS effects on public health and safety result from incremental impacts of conventional processes and nonconventional impacts of terrestrial operations that would be unique to the system.

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 have been made of SPS materials requirements.^{1,19-21} These can be used as a rough gauge of the increase in activity

dictated by the SPS configuration. Table 2.1 shows the materials requirements of the two tentative SPS designs from Ref. 19 (silicon system and gallium arsenide system) compared to current U.S. production of these materials. It is evident that some of the materials requirements represent substantial increments to current production rates (e.g., mercury, argon, hydrogen, oxygen); hence the effects associated with these processes are likely to be significantly increased by SPS deployment. For other materials the increment is small (less than 4%).

Some attempts have been made to quantify the impacts of a satellite power system on air pollutant emissions, water effluents, water requirements, solid waste generation, and land requirements. These data, presented in Table 2.2, were based on an earlier SPS configuration concept and do not represent the most recent design points of Ref. 1. Nevertheless, they give an order-of-magnitude estimate of the impact.

It is possible to compare the emission, effluent, and resource requirements to either U.S. totals or to the requirements of alternative electrical generating systems. For example, the particulate emissions of 110,000 metric tons 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 water-pollutant burden of a coal-fired power plant is 8-600 metric tons per megawatt-year vs. 2 metric tons per megawatt-year for the satellite power system.²² This normalized comparison is also incomplete because it does not identify the potential for locally severe problems caused by heavy loading of streams and aquifers. In essence, the surrogate comparisons cannot be made with the information currently available, and the basis upon which a comparison is to be made has yet to be defined.

To summarize the preliminary assessment of effects from conventional processes, the following points can be made:

- The data available reflect an earlier SPS configuration and are useful only for addressing the scope of the potential problems.
- The impact-generating conditions (e.g., air pollution) have been quantified in a rough form. The process by which these conditions are computed needs to be evaluated and the data reviewed for accuracy.

Table 2.1. Incremental Material Requirements
of Satellite Power System

Material	Portion of U.S. Annual Production, % ^a	
	Silicon Design	Gallium Arsenide Design
GFRTp ^b	NA ^c	NA
Stainless Steel	NA	NA
Glass	NA	NA
Silicon	NA	NA
Copper	0.94	0.66
Aluminum	7.3	7.4
Silver	6.9	170
Molybdenum	0.007	0
Mercury	22	22
Tungsten	48	48
Steel	2.6	2.6
Concrete ^d	4.0	4.0
Gallium Arsenide	NA	NA
Titanium	0.044	0.044
Ceramics	NA	NA
Misc. and Organics	NA	NA
Argon	7.8	1.9
Hydrogen	66.7	42.0
Oxygen	18.9	11.7
Methane	NA	NA
Sapphire	NA	NA
Teflon	NA	NA
Kapton	NA	NA

^aMaterials requirements are from Ref. 1 and U.S. production figures are from Ref. 23. Values given are for two satellites and it is assumed that two satellites are constructed per year.

^bGraphite-fiber-reinforced thermoplastic.

^cNA = Not available.

^dProduction measured as cement.

Table 2.2. Environmental Effects of SPS Deployment

Type of Impact	SPS Annual Impacts ^a	U.S. Annual Total
	<hr/> 10 ⁶ metric tons <hr/>	
Air Pollutant Emissions ^b		
Particulates	0.11	14
Sulfur dioxide	0.013	30
Carbon monoxide	0.042	88
Hydrocarbons	0.010	22
Nitrogen dioxide	0.0010	20
Ammonia	0.00027	NA ^c
Water Pollutant Effluents ^d		
Bases	0.012	NA
Biological oxygen demand	0.00083	NA
Chemical oxygen demand	0.031	NA
Dissolved solids	0.017	NA
Suspended solids	0.022	NA
Organics	0.0056	NA
Water Resources Requirements ^e		
Nonrecoverable water use	3.4	1366
Solid Waste Generation ^f		
Waste material	1.6	229
	<hr/> 10 ³ km ² <hr/>	
Land Requirements		
For rectenna sites only	10.56	9363 ^g

^aSource: Ref. 21. Based on early version of SPS configuration (Scenario A). Does not reflect more recent designs. The SPS annual figures were derived by averaging the total system impacts over a 30-year construction period.

^bSPS data from mining, processing, fabrication. U.S. total data for all sources from Ref. 24, 1973.

^cNA - Not available.

^dFrom steel, aluminum, copper, cement processes.

^eSPS data from propellant manufacture, launch pad coating, construction. U.S. total from Ref. 23, 1977.

^fSPS data from aluminum and steel processes. U.S. total data from Ref. 25: residential, commercial, industrial wastes.

^gU.S. total land area.

- The impact-generating conditions have not been translated into public health and safety effects.
- The basis upon which the effects are to be compared to either U.S. total conditions or to alternative system conditions has not been established.

Considering these conditions, it can be said that 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 and do not reflect the latest SPS designs. 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 considered.

Unconventional Effects

The unconventional SPS effects on public health and safety would result from the exposure to toxic materials from mining, manufacturing, and transport; the potential accidental injury or fatality from the transport of highly explosive materials (e.g., rocket propellants); all of the launch and recovery activities; and exposure to power-transmission-line electromagnetic fields near the rectenna site.

Toxic Materials. A materials list is being generated using the October 1978 reference system.¹ From this list the toxic materials will be extracted and their potential effects assessed. It is expected that for some of the materials there will be a significant data base that can be used in an assessment (e.g., mercury). However, for other materials the dose-response relationships and the source-receptor pathways are unknown and additional research will be needed to carry out the assessment.

Transport Accidents. A sizeable quantity of highly-explosive rocket propellants would need to be transported to the launch site in the course of SPS launch operations. The one of most serious concern is liquid hydrogen, which is currently transported by tank truck to launch sites but is under consideration for transport by barge or rail car. Reference 8 describes some of the problems with accidental hydrogen release based on projections

for the space shuttle program. Liquid hydrogen spills can ignite immediately or have a delayed ignition. Upon immediate ignition there is a flash as the gaseous hydrogen is consumed, followed by a burning of the liquid pool. The flash from a 3200 m³ (850,000 gal) spill can produce enough heat to cause first-degree burns and ignite light combustibles such as paper at a distance of 300 m. Thermal radiation from a liquid pool fire is about five times less. This size spill is based on a launch-pad accident of the space shuttle. A ground transport accident would probably not involve as much liquid hydrogen in one incident.

If immediate ignition did not occur, Ref. 8 indicates that the cloud of gaseous hydrogen could disperse downwind and be ignited by some remote spark. However, this possibility is limited by the lower flammable limit (the lowest concentration for which ignition could occur) and by the fact that an accident would likely involve some violent event sufficient to cause immediate ignition.

Other explosive or highly flammable materials include monomethylhydrazine, hydrazine, and nitrogen tetroxide used in chemical liquid propellants. These are of more concern for their highly toxic effects than for their flammability.

Spills of liquid oxygen could also create significant local impacts, primarily on ecosystems. The extreme cold would be the principal cause of damage.

Although data are available on the results of transportation accidents, these have not been translated into actual health and safety effects, i.e., injury rates. To do so will require an analysis of accident probability and an evaluation of probable transport corridors to determine public exposure to these hazards and to compare the hazards with those of conventional activities.

Launch and Recovery Effects on Air Quality. The SPS launch activity would result in air pollution from the exhaust products of the launch vehicle and from the formation at the launch platform and dispersion of a "ground cloud" made up of exhaust gases, cooling water, and some sand and dust. Because of launch trajectory and vehicle speed, the majority of the 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).²¹ The ground cloud, on the other hand, would develop at the launch pad and rise to 0.7-3 km, where its bouyancy 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.⁸ 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 (vs. solid-fueled for the shuttle) and the significantly larger launch-vehicle size. This is discussed further in Section 3 of this assessment.

As a result of previous work, ambient concentration limits can be identified for various launch-related air pollutants. Table 2.3 gives the standards used for the space-shuttle program based on the National Ambient Air Quality Standards promulgated by the U.S. EPA and exposure limits recommended by the Committee on Toxicology of the National Academy of Sciences (NAS)/National Research Council (NRC). The NAS/NRC recommendations include a short-term public limit (STPL) designed to avoid an irritation of the moist mucous membrane of the upper respiratory tract and a public emergency limit (PEL) related to accident conditions that might result in some irritation but with reversible effects. The space-shuttle study indicates that all SPS ground-cloud concentrations would probably be below the STPL and PEL values.

Test flights and the testing of rocket engines, orbital maneuvering systems, and reaction control systems would also produce air pollutants.

Launch and Recovery Water-Quality Impacts. The water-quality effects of the launch and recovery of SPS vehicles have not been assessed; however, some information is available for the space shuttle.⁸ 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 was recovered from the ocean. The first two conditions could be controlled by onsite water-treatment facilities and would not normally present a public health problem. Suggested maximum allowable concentrations for propellant spills are shown in Table 2.4.

Table 2.3. Human Exposure Limits for Selected Rocket Engine Combustion Products

Product	Type of Limit	Duration	Time-Weighted Average Concentration (mg/m ³)	Ceiling Limits (mg/m ³)
Standards set by the Environmental Protection Agency ^a				
Aluminum oxide ^b	National primary standards (for public health)	Annual average (geometric mean)	0.075	--
		Max. 24-hr, not to be exceeded more than once/yr	--	0.26
	National secondary standards (for public welfare)	Annual average (geometric mean)	0.06	--
		Max. 24-hr, not to be exceeded more than once/yr	--	15
Recommendations of the Committee on Toxicology ^c				
Hydrogen chloride	STPL	10 min	4	8
		30 min	2	4
		60 min	2	4
		1 hr daily	2	4
		5 hr/day		
		(3-4 days/mo)	0.7	--
	PEL	10 min	7	14
		30 min	3	6
60 min		3	6	
Carbon monoxide	STPL	10 min	90	135
		30 min	35	53
		60 min	25	38
		4-5 hr/day	15	--
		(3-4 days/mo)		

Table 2.3. (Cont'd)

Product	Type of Limit	Duration	Time-Weighted Average Concentration (mg/m ³)	Ceiling Limits (mg/m ³)
Recommendations of the Committee on Toxicology (Cont'd) ^c				
Carbon monoxide (cont'd)	PEL	10 min	275	275
		30 min	100	100
		60 min	60	60
Chlorine	STPL	10 min	1	3
		30 min	0.5	1
		60 min	0.5	1
	PEL	10 min	3	3
		30 min	2	2
		60 min	2	2
MMH	STPL	10 min	9	90
		30 min	3	30
		60 min	1.5	15
	PEL	10 min	90	90
		30 min	30	30
		60 min	15	15
Hydrazine	STPL	10 min	15	30
		30 min	10	20
		60 min	5	10
	PEL	10 min	30	30
		30 min	20	20
		60 min	10	10
Nitrogen oxides	STPL	10 min	1	1
		30 min	1	1
		60 min	1	1
	PEL	10 min	5	5
		30 min	3	3
		60 min	2	2

^aCode of Federal Regulations: 40 CRF 50.^bStandard based on total suspended particulates.^cSource: Ref. 8.

Table 2.4. Suggested Maximum Allowable Concentrations of Propellants in Water

Propellant Chemical Species	Suggested Maximum Allowable Concentration (mg/l)
Hydrazine	90.7
Monomethylhydrazine (MMH) ^a	0.35
Nitrogen Tetroxide ^b	95
Aluminum Perchlorate ^c	50

^aBased on threshold limit values of hydrazine and MMH.

^bBased on nitric acid.

^cBased on nitronium perchlorate.

Source: Ref. 8.

Launch and Recovery Noise. Noise impacts from SPS operations would come from the sound level generated by the heavy-lift launch vehicle (HLLV) during ascent and from sonic booms created during ascent and reentry. Figure 2.2 shows the sound pressure levels of the HLLV and the Saturn V. The 130 dB sound-pressure contour would be 5000 m from the launch pad for the HLLV, as compared to 2225 m for the Saturn V. Using a Cape Canaveral, Fla., launch site, Ref. 20 estimates that the city of Titusville would receive sound pressures of 128.9 dB and that other nearby cities of Cape Canaveral and Cocoa Beach would experience sound pressure levels of 125-130 dB.

To assess the effects of these levels on the public, the absolute sound pressure must first be converted to an A-weighted level to account for the sensitivity of the human ear to different frequencies. Second, the short-term sound pressure levels must be integrated into an overall sound level using weighting factors that account for time of day, frequency of occurrence, and duration of noise level. The first step is relatively easy. No data were presented in Ref. 20 as to the frequency distribution of the HLLV-generated noise, but since the information was based on an extrapolation of Saturn V data it can be assumed that the HLLV noise frequency spectrum would be similar to that of the Saturn as presented in Ref. 8. Thus, the conversion from absolute to A-weighted levels results in a reduction of approximately 30 dB.⁸

Fig. 2.2. Variation of Overall Sound Pressure Level with Distance from Launch Site (Source: Ref. 20)

The second conversion is not as straightforward as numerous methods are used to account for the other factors. Equivalent 24-hour weighted average, effective perceived noise level, and noise exposure forecasts are some of the alternatives. Reference 8 uses the 24-hour weighted average for the space-shuttle analysis and the 123-dB absolute sound level (measured at 6 km) is reduced to 95 dB(A) by the frequency adjustment and to 65 dB(A) for the 24-hour weighted average [assuming a one-minute duration and 60 dB(A) background]. This can be compared to the 70 dB(A) daytime guideline set by the U.S. EPA and the 50 dB(A) nighttime guideline. Considering that the overall sound pressure levels of the HLLV are estimated to be about 7 dB greater than those of the Saturn V²⁰ and the launches would be more frequent (perhaps two per day as compared to one per day for the space shuttle), it appears that the EPA guidelines might be exceeded by the SPS launching program. To

verify this conclusion more detailed system analysis will be required, considering actual launch frequency and sound pressure levels.

Sonic booms would result from the supersonic flight of the space vehicles during ascent and reentry. The effects of sonic booms come from their abruptness, which causes a startle response in humans and animals, and the intensity of the overpressure, which can cause property damage. Table 2.5 lists a number of effects of sonic booms.

No information is available on SPS-vehicle sonic-boom generation but some data have been reported for the space shuttle.⁸ These are presented in Table 2.6. Considering the larger size of the SPS components and the increased frequency of sonic-boom occurrence, it is evident that some problems would be encountered. An analysis of SPS sonic-boom generation will be needed to evaluate the extent of these impacts.

Launch and Recovery Accident. Several incidents could contribute to accidental injury or death during SPS launch and recovery operations. These include fire or explosion on the launch pad, launch abort, and landing accidents.

A preliminary analysis indicated the explosive potential of the HLLV to be about twice that of a Saturn V.²⁰ The peak side-on overpressure (PSOP) contour of 2760 N/m^2 (0.4 psi) would have to be cleared of all personnel when there was danger of an explosion. This contour extends to 2590 m for the Saturn V and to 4267 m for the HLLV. The analysis concludes that for a launch from Pad A of Launch Complex 39 at Cape Canaveral, the nearest city, Titusville, would experience a PSOP of 1930 N/m^2 (0.28 psi) during a catastrophic explosion of the HLLV. This would not result in structural failure but could blow out windows and doors, thus causing injury.

SPS launch abort or recovery landing accidents have not been analyzed. The assessment of space-shuttle operation in Ref. 8 concluded that these incidents would be analogous to conventional aircraft accidents and that, in the case of launch abort, they would occur over controlled range areas and thus present no unusual problems. An evaluation of accident probability would be required to estimate SPS effects.

Table 2.5 Effects of Sonic Boom

Overpressure (N/m ²) ^a	Effect of Simulated Boom on Test Subjects
<u>International Civil Aviation Organization Results^b</u>	
<24	Not rated as annoying. ^c
48	10% of sample rated this as annoying. ^c
144	All considered this annoying. ^c
48-144	Nonprimary structures (plaster, windows, bric-a-brac) sustained some damage.
<950	Primary (load-bearing) structures of acceptable construction and in good repair showed no damage.
<u>Federal Aviation Administration Results^d</u>	
16	Orienting, but no startle response. Eyeblink response in 10% of subjects No arm/hand movement.
30-111	Mixed pattern of orienting and startle responses. Eyeblink in about half of subjects Arm/hand movements in about a quarter of subjects; no gross bodily movements.
130-310	Predominant pattern of startle responses Eyeblink response in 90% of subjects. Arm/hand movements in more than half of subjects; gross body movement in about a fourth of subjects.
340-640	Arm/hand movements in more than 90% of subjects.

^aOne newton per square meter (N/m²) = 0.00015 pound per square inch (psi).

^bFrom Ref. 8. Primary source is Ref. 26.

^cBased on 10-15 booms per day.

^dFrom Ref. 8. Primary source is Ref. 27.

Table 2.6. Sonic-Boom Generation by the Space Shuttle

Flight Phase	Distance (km)	Overpressure (N/m ²)
Ascent ^a		
Shock wave first reaches ocean	60	290
Lateral cutoff ^b	59	85
Downrange	85	48
Focal zone ^c		
Center	-	1440
Lateral cutoff ^b	-	480
Booster Reentry ^a	280-370	96-144
Orbiter Reentry ^d	>650	<24
	185	48
	<44	101 max

^aDistance measured from launch site.

^bWhere local gradient in speed of sound causes boom path to turn horizontal.

^cZone where sonic boom is focused and reinforced because of in-flight maneuvers. Zone is approximately 300 m wide at the ground track and extends 75 km to either side.

^dDistance from landing site.

Source: Ref. 8.

Power-Transmission Electric and Magnetic Field Effects. People living and working in the vicinity of high-voltage transmission lines are exposed to electric and magnetic fields. Whether the voltage on transmission lines leaving an SPS rectenna would be higher than that currently used at conventional power plants has not yet been defined with certainty. 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. Should it appear that the SPS fields would be greater than conventional ones, possible effects on the public should be assessed.

Ozone Reduction - Skin Cancer. As pointed out in Section 3, preliminary calculations indicate that emissions from the HLLV would probably reduce the stratospheric ozone layer by a small amount (0.02%). For each 1% of ozone lost from the atmosphere, the biologically-harmful ultraviolet (BHUV) radiation is increased by approximately 2%. It is clear that the incidence of skin cancer is increased by an increase in BHUV, although there is a great

deal of uncertainty about the exact direct relationship between the amount of exposure to BHUV and the incidence of skin cancer. However, a number of studies are attempting to obtain more definitive data.

Acid Rain. If HLLV launches occurred during rainstorms, moisture falling through the exhaust cloud would produce acid rain. People exposed to this rain might experience eye and skin irritation or burns if the acidic moisture were not removed immediately. It is expected that this effect could be minimized by monitoring meteorological conditions and launching at appropriate times. For SPS, with many launches and high fuel use, scheduling launches to minimize acid rain might be limited.

Reflected Light. Preliminary calculations have been made of the intensity of specular and diffuse reflections from solar power satellites which would reach earth. These estimates need to be refined and the possibility of damage to the human eye should be studied. Eye damage could be of particular concern if a satellite was viewed through binoculars or telescopes.

2.5.2 Effects on Terrestrial Workers

The SPS effects on the health and safety of terrestrial workers can be measured in the same fashion as the effects on the public; that is, there would be an increment in conventional mining, construction, manufacturing, and transport impacts and a set of effects resulting from unconventional conditions.

SPS-related activities that would require materials or processes that would either be unique to the SPS or required in much larger quantities for the SPS than for conventional activities should be assessed in-depth to define and quantify unique hazards. Production activities that will require close examination are:

- Satellite components - manufacture, including processing of materials.
- Fuel - processing and transportation.
- Space vehicle - manufacturing, including processing of materials.
- Rectenna materials - manufacturing, including processing of materials.

Incremental Effects of Conventional Processes

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 2.7 illustrates the distribution of occupational illness and injury by various SPS functional activities, based on an earlier SPS design. These data were assembled using occupational illness and injury rates from the U.S. Department of Labor¹² and SPS labor requirements. 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-year life of the satellite power system and cannot be directly compared to published annual rates.

Table 2.7. Distribution of Occupational Illness and Injury

Activity	10 ⁶ Person-Days Lost ^a	
	Occupational Injuries	Occupational Illnesses
Material Acquisition	14.63	0.45
Ground Construction	9.04	0.29
Ground Operation and Maintenance	<u>1.48</u>	<u>0.08</u>
TOTAL	25.15	0.82

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

Source: Ref. 21. Based on early version of SPS configuration. Does not reflect more recent designs.

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) at the rectenna site. These are the same effects as were discussed on Section 2.5.1 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 which 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. Possible hazards due to toxic materials will be assessed.

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. This must be evaluated when a more detailed assessment of accident probability is made.

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 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 should be evaluated. Terrestrial workers at these sites would be exposed to high levels of noise; possible hearing damage and psychological effects should be studied.

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. The extent of this hazard will be assessed, based on the reference system,¹ and compared to similar risks in conventional power plants.

Should it be determined that the SPS worker at a rectenna site would be exposed to higher DC or low-frequency electric and magnetic fields than a conventional power-system worker, an assessment and comparison will become necessary.

2.5.3 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 current reference system¹ proposes 90-day tours in space, and a 5-year career for space workers has been contemplated. This schedule could involve 90 days in space alternated with 90 days on earth, but this is not yet a firm schedule. It has been roughly estimated that construction and maintenance of the satellite power system would require about 270,000 space-worker tours of 90-days duration. If the schedule suggested above (90-day tours, 5-year career) were followed, this rough estimate would mean that 27,000 persons would be exposed to the space environment with a cumulative total per person of 2.5 years in space. It is therefore imperative that all possible precautions be taken to avoid or minimize the health hazards for these space workers.

The health and safety problems of SPS space workers would be related to weightlessness (zero gravity), life support, and radiation. These three impact areas are discussed below.

Weightlessness

Weightlessness resulted in a number of physiological and biochemical alterations in astronauts during earlier space flights. NASA has ongoing research programs concerning the problems of weightlessness.

The red cell mass in astronauts was significantly reduced. This reduction was possibly due to reduced red-cell survival; deformation of red cells that led to their removal from the circulatory blood; increase in mean corpuscular volume;* and changes in osmotic regulation, total red-cell lipids, and bone marrow inhibition. Reticulocytosis** was delayed after return to earth, implying that erythropoietic mechanisms were insensitive to the loss of red cell mass during flight. (In the longest flights, it appeared red cell mass loss was at least partially arrested and that adaptation might be occurring.)

*Mean corpuscular volume: size of red blood cells; osmotic regulation: regulation of fluid flow between body compartments; bone marrow inhibition causes a slowing down or cessation of new cell production.

**Reticulocytosis: manufacture of young red blood cells; erythropoietic mechanisms regulate the manufacture of red blood cells.

There were some changes seen in the cellular immune system immediately after space flights, but the significance of these changes appears to be in doubt. These changes may have been stimulated by elevations of endogenous compounds,* such as cortisol and/or catecholamines.

Plasma** volume was decreased, apparently in the first few hours of weightlessness. This may be due simply to shifts among various fluid compartments due to weightlessness.

Calcium loss from bones while in the weightless state has been found to be continuous in all space flights studied so far. There appears to be no change in this effect even when extra calcium is added to the diet. This situation could lead to bone fragility, urinary calculi, etc., and thus limit the time workers could remain in space. There is a fairly rapid reversal upon return to earth, and it appears that the bone may return almost, if not completely, to normal. It is possible that repeated trips to space could result in some irreversible change in bone structure.

Muscle-tissue reduction has taken place in all space flights. There is some evidence from Skylab that a regimented exercise program may at least partially reverse this trend.

Fluid-electrolyte changes occur early in space flight and are sustained throughout flights up to 84 days in duration. These effects are accompanied by changes in hormones, some of which regulate kidney function. Thus, these changes may be a combination of fluid shifts due to weightlessness and hormonal changes with cause and effect interrelated.

Nutrition needs in the weightless state, in general, appear to be the same as those on the ground except that as time in space is extended there appears to be need for more nutrients (e.g., fat loss continued throughout the 84-day Skylab flight). Calcium loss (as discussed above) remains puzzling and protein intake may need to be lowered because of its possible effect on calcium metabolism. Nitrogen balance remains a puzzle, especially as related to muscle loss.

Vestibular middle-ear-balance-center problems such as "space-motion sickness," dizziness, vertigo, spatial disorientation, sensations of rotation,

*Endogenous compounds are those originating within the body.

**Plasma is the fluid component of the blood.

etc., have affected a high percentage of space travelers. The physiological mechanisms underlying these sensations are unknown. The motion sickness seems to lessen after about seven days; some of the other sensations persist longer. There is as yet no way to predict which persons will be most affected. Drugs used for other types of motion sickness have some effectiveness but are far from a completely satisfactory treatment of the problem. No ways are currently known to avoid or completely ameliorate the problem. It appears that these problems increase with increased physical activity and with increased space to move about in; thus they may interfere greatly with performance efficiency in space and might be especially critical for construction workers.

The NASA Life Sciences Directorate at Johnson Space Center will assess the possible deleterious effects, both acute and residual, on the health of SPS space workers living and working in a zero-gravity environment. This assessment will be based on:

- Previous experience with astronauts in manned space flight.
- Research on the causes and effects of changes in biochemical/physiological/medical parameters seen in previous manned flights.
- Results of steps taken to ameliorate, in later flights, the changes seen in earlier flights.
- Schedules of work and stay-times in space as projected in the current SPS reference system.¹

The assessment will include such effects as:

- Space motion sickness and vestibular problems.
- Reduction of red blood cell mass.
- Changes in the cellular immune system.
- Decreases in plasma volume.
- Cardiovascular changes.
- Calcium loss from the body (particularly from bones).
- Reduction in muscle tissue.
- Fluid shifts among body compartments.
- Effects of acceleration and deceleration.
- Acute problems in going from one g to zero g and vice versa.
- Other effects deemed pertinent by the assessment team.

The final report on the assessment will include medical/biological findings from earlier manned flights, pertinent research findings and proposed ways to ameliorate unwanted effects, and conclusions with respect to the probable effects of weightlessness on SPS space workers (based on the current SPS reference system) and the rationale for these conclusions.

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. When these designs have been put in the context of the SPS reference system¹ and have been developed in sufficient detail, an independent assessment should be made. This assessment should examine the designs for factors which may have been overlooked and for design features which may be improved. This evaluation should consider:

- Ventilation (supplying life-supporting gases, removing unwanted gases and noxious odors, and controlling humidity).
- Adequacy of personnel quarters and facilities.
- Recreations facilities.
- Foods (dietary and palatability aspects).
- Safety hazards.
- Health care facilities for emergencies, such as broken bones, bends, heart attacks, dental problems, etc.

Following are brief discussions of a number of possible life-support and safety hazards for SPS space workers.

Meteoroid and Space-Debris Collisions. No work in this area has been done specifically with respect to SPS. 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 which 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 studies.

Extravehicular Activity (EVA). In the case of the SPS, spacesuit activity would not be expected to be frequent, but it must be planned for in the 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 reference system is more fully developed.

Transport from One Satellite to Another. There has been a suggestion that it might be feasible for maintenance personnel to work on more than one SPS satellite. Transportation between satellites might create hazards which should be assessed if this option becomes viable.

Construction Accidents. Space workers may be more prone to conventional-type construction accidents than are terrestrial workers because of the possible awkwardness of working in the weightless state. The probability of accidents from this cause will need to be assessed and, if necessary, precautions taken to minimize hazards.

High Voltage Hazards. Some space workers would presumably work in the vicinity of equipment carrying high voltage. The hazards involved in this work, which need to be assessed, could be greater than those associated with the same kind of work in a terrestrial setting, due to weightlessness.

Transport Hazard. The space workers would be exposed to the hazards inherent in lift-off and landing of space vehicles. There could also be dangers in transferring between the launch vehicle, the orbital transfer vehicle, and the work stations. These risks will need to be compared with the conventional hazards of living and working on earth.

Spacecraft Charging and Environmental Interactions with Space Structures. These phenomena 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 both ground and satellite (SCATHA, in particular)

experiments in order to better understand 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.

Electric and Magnetic Fields. The collection and transmission of large amounts of electric power across the solar cells would generate electric and magnetic fields which 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. Some 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 previous 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.

Research on the biological effects of magnetic fields is in early stages. The space worker in geosynchronous earth orbit would be essentially out of the earth's magnetic field, so 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 be moving through, should be investigated.

The intensity of the electromagnetic fields to which space workers would be exposed needs to be calculated, and the possible biological effects of these fields should be assessed on the basis of the most recent research results.

Toxic Materials Handling. Toxic materials, such as gallium arsenide, might be used to construct the satellite. Possible health hazards for space-workers will need to be assessed after the handling of these materials is defined for the satellite power system.

Other Health and Safety Hazards. As the reference system is more clearly defined, some of the hazards outlined above may become trivial, but other hazards may emerge. The reference system will be reexamined periodically in order to define health and safety hazards.

Radiation

SPS Radiation Environment. A workshop on the "Radiation Environment of the Satellite Power System" was held at Lawrence Berkeley Laboratory in September of 1978. The conclusions of workshop participants, summarized below, dealt with sources and doses of proton and electron radiation, HZE particles, radiation exposure limits, shielding, radiation-emergency plans, and dosimeters.

In low earth orbit (LEO), nearly all of the radiation dose would come from the geomagnetically-trapped protons in the South Atlantic Anomaly. A preliminary estimate indicates that the 90-day mission dose behind approximately 2 g/cm^2 (0.3 in.) of aluminum would be about 20 rads at solar minimum and 10 rads at solar maximum. In the transfer from LEO to geosynchronous earth orbit (GEO), the trapped electron fluence would be responsible for most of the total dose, with trapped electrons dominating behind a shield thickness less than about 2 g/cm^2 aluminum and with electron bremsstrahlung dominating behind thicker shields. A preliminary estimate of the dose for a round trip from LEO to GEO and back to LEO (a total time of 10.5 hours) is typically 3 rad behind 2 g/cm^2 aluminum and 0.2 rad behind 5 g/cm^2 aluminum. In GEO, the dose from predictable radiation sources would come from penetrating electrons and the associated bremsstrahlung. A preliminary estimate based on the interim model (AEI-7) for the electron environment indicates that the 90-day mission dose behind 2 g/cm^2 of aluminum would vary from about 27 rad for the best parking longitude of 70° west to about 54 rad for the worst parking longitude of 160° west. Since the major contribution comes from electron bremsstrahlung, the doses could be reduced significantly by designing the walls of the work areas with an additional layer of heavy metal, such as tantalum or lead, to attenuate the electron bremsstrahlung more effectively.

A major uncertainty in the assessment of SPS radiation hazards results from the lack of information on the biological effects of the high-energy

heavy ion (HZE) radiation in GEO, particularly the cumulative effects on critical organs. This information needs to be obtained from experiments using available heavy-ion beams.

A critical question affecting the design and possibly the feasibility of the SPS is whether or not 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 by the National Council on Radiation Protection (NCRP) and International Commission on Radiological Protection (ICRP) for radiation workers. Since there would be a large number of workers who could receive a significant radiation exposure, the career limits established for astronauts by the National Academy of Sciences committee may not be appropriate. In any case, this question should be examined in detail in order to introduce stability into the planning for the SPS mission.

If radiation exposure limits are changed, the estimates of 90-day doses must be recalculated, using realistic shielding configurations, so that the spacecraft designer will have guidance in supplying sufficient shielding to appropriately limit radiation exposure from predictable sources. In addition, strategies for dealing with unpredictable sources must be developed at an early stage, as these may have significant impact on the final design.

Realistic calculations of 90-day HZE exposure for a "typical" space worker as a function of shielding thickness also are needed. For an adequate evaluation of HZE hazards to be made, an estimate would be needed of the fluences of the HZE component expected in various critical body organs. Although the number of variables involved precludes a precise determination, it is important that the spacecraft designer be aware of the consequences of increasing the thickness of shielding materials. Although it may not be possible to accurately determine the absolute magnitude of the fluences, the relative variation of fluence with thickness could give valuable information on the effects of a given increase in shielding thickness. This could impact the risk vs. cost analysis for the ultimate design chosen.

The radiation-shielding requirements for each portion of the SPS mission must be determined from the combined exposures for the total mission; for example, the allowable exposure within the vehicle at GEO depends on the exposures in LEO, during orbital transfer, during scheduled and unscheduled

EVA, and as anticipated from solar-particle events. It is necessary to reevaluate the radiation-shielding requirements in terms of the exposure expected for each portion of the mission. Since there are large uncertainties in the existing models of the space radiation environment, shielding requirements should be reviewed periodically as the models are improved. For example, an important improvement needed in the model of the electron environment for GEO is the dependence on the solar cycle. The preliminary estimates of doses quoted above do not take into account the uncertainties in models.

An important part of the radiation-protection design for the GEO base involves the hazard to personnel from solar-particle events. A heavily-shielded shelter is necessary to protect personnel from large solar-particle events, such as those of August 1972. 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 shielding, such as goggles to protect the eye lens and lead undergarments to protect the testes.

Both passive and active dosimeters are 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-particle events, 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.

Currently, there is apparently no single instrument or integrated group of instruments which gives real-time readouts of flux and energy (which, in turn, are related to dose) of all the various types of ionizing radiation which 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 will 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 for providing the information necessary to protect SPS personnel.

Effects of Ionizing Radiation. A panel of persons with expertise in the biological effects of radiation has been established. The panel, which consists of individuals from NASA, universities, and national laboratories, is investigating and will report on such radiation effects as:

- Genetic effects.
- Cancer induction.
- Visual damage (i.e., cataract induction, retinal damage).
- Blood disorders (i.e., anemia, leukemia).
- Central nervous system effects.
- Life shortening.

In its assessment, the panel will use existing information regarding:

- The biological effects of the types and fluxes of ionizing radiation expected to be encountered in transit from earth to LEO; in LEO, inside and outside space transportation vehicles; in transit from LEO to GEO; and in the working and living environments in GEO.
- Current reference system descriptions of:
 - Transportation times from earth to LEO, in LEO, and from LEO to GEO.
 - Work and construction schedules in LEO (construction personnel, transfer of materials and personnel between vehicles) and in GEO (construction, support, and maintenance personnel).
 - Types and thickness of radiation shielding in all areas of space transportation vehicles; in construction environments; and in living environments.

The panel also will assess the effectiveness of the shielding built into the space shuttle. This shielding is being used as the prototype for assessing the hazards of ionizing radiation to the SPS space worker along with a brief description in the reference system report¹ of a storm shelter that would be provided in GEO for high-radiation solar flares. It is possible that changes will be required in the materials used and the thickness of shielding. As the reference system is developed in more detail, further studies of shielding effectiveness will be needed.

2.5.4 Effects on Ecosystems

There may be adverse ecological impacts from almost all activities in the construction and operation of the satellite power system. The acceptability of these impacts must be assessed. If any effects are found to be unacceptable, then recommendations will be made for ameliorating them.

Rectenna Siting

A recently-initiated study is assessing the impacts of rectenna siting, 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 is typical of the surrounding terrain and is the subject of a comprehensive environmental statement being written for the Bureau of Land Management. The impact statement is being prepared because the area is a prospective site for a geothermal facility. Thus, much of the information needed for a rectenna impact assessment is being or has been obtained.

The study will produce a comprehensive prototype environmental assessment of the SPS-reference-design rectenna facility in both the construction and operation phases. (Microwave-related issues will not be addressed, as they are being studied elsewhere in the SPS research program.) This effort also will identify and calibrate, 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 will be defined in the context of actual baseline data for a specific site in an area with many characteristics that are optimal for an SPS rectenna (a sparsely-populated rural environment, not far from a major urban center). The study will provide specific impact data relevant to siting a rectenna facility in proximity to California's urban centers, and will significantly illuminate potential impacts of rectenna siting elsewhere.

Baseline environmental conditions and impacts of development will be available in the following areas:

- Air quality - baseline climatology, meteorology, and air quality; emissions inventory of the airshed; emissions inventory and dispersion modeling of emissions.

- Noise - baseline inventory, including field measurements and assessment of development impacts.
- Soils and geology - Order-3 soils survey; detailed geologic maps including seismicity, soil depth, soil family and slope class; hydrology setting and impacts including drainage, landslide potential, impacts on subsurface hydrology.
- Flora and wildlife - comprehensive baseline inventory of flora and fauna of the high desert, including presence of rare and endangered species; migration routes; flyways; and an assessment of impacts of development.

The site-specific study just described will point out possible detrimental environmental effects for areas with similar ecosystems. However, if satellite power systems are developed, there are expected to be 60 rectenna sites eventually, and they would need to be distributed in various areas of the country in order to supply populated areas with electricity. Thus, it is expected that areas with many different types of ecosystems 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 which would be unique or which would multiply considerably 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., toxic, flammable, and explosive. The same precautions would be needed as are now used with such fuels. However, the increment in hazards due to the amounts of fuel that would be used by the SPS needs to be assessed.

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, the possible effects of the SPS should be examined.

Air pollution from space transportation could affect not only wildlife, but also vegetation. The possible impacts should be studied, using projected amounts and types of pollutants for the satellite power system.

If HLLV launches occurred during rainstorms, moisture falling through the exhaust cloud could produce acid rain. There would be a possibility of damage to vegetation, including crop loss in the areas of this precipitation. The biota could be disturbed at launching and landing pads and rectenna sites and probably disturbed in adjacent areas.

The amount of ultraviolet radiation reaching the earth would be increased by the depletion of ozone brought about 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 the ultraviolet light might adversely impact the ecosystems. The extent of change and the resulting impacts should be evaluated.

Reflected Light from the Satellites

Since biota might be affected by this unusual light, i.e., by disruption of diurnal cycles in wildlife or growing cycles in plants, this aspect of the SPS needs to be investigated by zoologists and botanists.

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 voltage between the rectenna and the utility interface. The effects of the fields on the biota will need to be assessed.

2.6 CONCLUSIONS AND RECOMMENDATIONS

Tables 2.8-2.11 summarize the nonmicrowave health, safety, and ecological effects of the SPS, as determined by this preliminary assessment.

2.6.1 Effects on the Public (Table 2.8)

The assessment indicates that there is a fairly large body of information that can be used to develop a complete assessment of SPS effects on public health and safety due to increases in conventional activities. Preliminary calculations of environmental residuals from these increases have been made, but these have not been translated into public exposure levels or public health effects. The ongoing assessment process should improve the accuracy of the residuals calculations and make the necessary translations into actual health effects. This achievement will provide a quantitative basis for a system evaluation.

For the unconventional effects resulting from transport accidents, toxic-materials exposure, and launch and recovery operations, substantially less information exists upon which to base an assessment. The toxic materials that might be used in SPS components have not been systematically identified. The only information available on transport accidents and launch and recovery is from limited, prior space-program activities and projections for space-shuttle operations. Substantially more work is needed to evaluate the data available and fill the gaps in the assessment.

2.6.2 Effects on Terrestrial Workers (Table 2.9)

As with the effects on the public, a good deal of data is available for use in evaluating incremental occupational-health-and-safety effects from conventional processes. On the other hand, very little information is available to address occupational effects from unconventional activities, because prior analyses of space-program activities have been aimed at estimating the effects on the general public. The SPS program would, however, involve a much larger work force in what has heretofore been considered a limited activity (e.g., launch and recovery) and requires a broader data base upon which to base measurements of occupational effects.

Table 2.8. Potential Nonmicrowave SPS Effects on Public Health and Safety

Effects	Probability Rating ^a	Severity Rating ^b	Activities Involved	State of Knowledge	References
Land Disturbance Loss of land Reduced property value Psychological effects on health	1	2	Mining Construction	Effects of mining, land reclamation potential under intensive study.	2,17,20,28-32
Air Pollution Respiratory disease Cardiovascular impairment Skin/eye irritation	1	2	Mining Construction Manufacturing Transport Launch	Health effects of selected air pollutants well-documented from epidemiological and other studies. Emission rates of selected pollutants well-documented. Atmospheric reactions and transport not completely understood. Launch exhaust emissions and ground cloud dispersion not completely understood. Recommended limits available.	3-6,20,28,30,33-36
Water Pollution Intestinal disease Skin irritation Other effects of ingestion	1	2	Mining Construction Manufacturing Transport Launch Recovery	Health effects of many water pollutants well-documented. Leaching into groundwaters not clearly understood. Effluents from many of the manufacturing processes are known. Water pollutants from transport, launch, recovery not completely known; estimated from other space program activities (i.e., shuttle).	7,14,15,20,28,30
Noise Stress - psychological and physiological	1	1	Launch Recovery	Effects are known for both acoustic noise and sonic boom. Recommended standards are available.	9,20,30
Safety Accidental injury/fatality	2	2	Transport Launch Recovery	Conventional transport accident rates known. Accident occurrence and extent of impact estimated for other space program activities (i.e., shuttle) but not for SPS.	10,20

Table 2.8. (Cont'd)

Effects	Probability Rating ^a	Severity Rating ^b	Activities Involved	State of Knowledge	References
Solid Waste Sanitation	3	3	Mining Manufacturing	Extensive data available.	16,20,28,30
Toxic Materials Exposure	2	2	Mining Manufacturing Transport Launch Recovery	Toxic materials involved in SPS not completely identified. Some materials have well-documented health effects, others have few or none.	28,30
Electromagnetic Field Exposure	1	2	Rectenna Operation Power Transmission	SPS intensities yet to be defined.	37-43
Reflected Light Eye damage	2	2	Satellite Operation	Effects being assessed.	44-46
Ozone Reduction, Ultra- violet Increase Skin cancer	2	2	Launch Vehicle Landing	Many studies in progress on ultra- violet light and skin cancer. A specific study needed for effects of SPS.	31,47,48

^a1 = high; 2 = unknown; 3 = low.

^b1 = critical; 2 = unknown; 3 = noncritical.

Table 2.9. Potential Nonmicrowave SPS Effects on the Health and Safety of Terrestrial Workers

Effects	Probability Rating ^a	Severity Rating ^b	Activities Involved	State of Knowledge	References
Air Pollution Respiratory disease Cardiovascular impairment Skin/eye irritation Other occupational illness	1	2	Mining Construction Manufacturing Launch Landing	Conventional occupational health effects well-documented. Threshold limit values established.	11,20,22,28,30,49
Water Pollution Skin/eye irritation Occupational illness	1	2	Manufacturing Recovery	Extent of effects unknown.	14,15,20,22,28,30,49
Noise Hearing impairment Stress-psychological and physiological	1	1	Mining Manufacturing Launch Landing	Noise effects known. Occupational exposure limits available.	9,20,22,30
Safety Accidental injury/fatality	1	2	Mining Construction Manufacturing Transport Launch Recovery Rectenna Operation	Conventional occupational hazards and injury/fatality rates unknown. Incidence and extent of occupational accidents from catastrophic transport accident and launch and recovery emergencies not evaluated.	10,20,22,30
Toxic Materials Exposure	2	2	Mining Manufacturing Transport	Toxic materials involved in SPS not yet completely identified.	22,28,30
Electromagnetic Field Exposure	1	2	Rectenna Operation	SPS intensities yet to be defined.	37-43
High Voltage	3	1	Rectenna Operation	Standard employment practices well defined.	

^a1 = high; 2 = unknown; 3=low.

^b1 = critical; 2 = unknown; 3 = noncritical.

2.6.3 Effects on Space Workers (Table 2.10)

Some of the adverse effects of weightlessness appear to be temporary adaptations to an unusual situation for humans. It appears that a new equilibrium, suitable to the weightless state, is established and maintained (note, however that only a few astronauts have been in space as long as 84 days; thus there could be space workers who, for physiological reasons, could not adapt). Some effects -- such as spatial disorientation, anemia, and bone and muscle deterioration -- continue throughout space flight. These effects, if not ameliorated, could lead to major work and health problems both during and after space missions. Research programs conducted and sponsored by NASA may be adequate for evaluating these problems, but there is a need to assess them specifically in relation to the SPS. NASA has ongoing research on life-support systems related to other planned flights. This research covers most of the expected problems with the satellite power system. This work needs to be assessed for adequacy with regard to the unique aspects of the SPS.

The hazards of magnetic and high-voltage fields, plasma arcing, space debris, and meteoroids have not been assessed.

The effects of radiation depend a great deal on the length of stay in space. For radiation particles that have been studied in detail over the years, reasonably good predictions of effects can be made, given the expected dosages. From these predictions limits can be put on the length of stay in space. However, the biological effects of high-energy heavy ions are largely unknown. Studies of these particles, many of them funded by NASA, are just getting under way. Much more needs to be done in order to assess the hazards with more certainty.

2.6.4 Effects on Ecosystems (Table 2.11)

Construction and nonmicrowave operational aspects of SPS could impact large areas of natural and man-altered ecosystems. The responses of ecosystems to various types of physical disturbances are reasonably well known. For this reason, there is probably no need for a large, experimental ecological research program.

Table 2.10. Potential Nonmicrowave SPS Effects on the Health and Safety of Space Workers

Effects	Probability Rating ^a	Severity Rating ^b	Activities Involved	State of Knowledge	References
Prolonged Weightlessness Vestibular problems Calcium loss Muscle atrophy Hormone, fluid, electrolyte imbalances Anemia Cellular immunity changes Cardiovascular changes	1	2	Space Transportation Space Construction Space Operation	Data are available from other space program activities and NASA research, and are currently being put in the context of SPS Reference System by NASA Life Sciences, Johnson Space Center.	50-54
Radiation Exposure Cancer Genetic changes Cataracts Central nervous system damage Life shortening	1	2	Space Transportation Space Construction Space Operation	Data are available on the space environment from other space program activities, and from Proceedings of Workshop on Space Environment. Much data available on conventional radiation particles. Limited data available on high energy, heavy ions (HZE). Assessment of health consequences is currently being made.	51-63
System Emergencies	1	2	Launch Recovery Orbital Transfer Space Construction Space Operation	Designs for space shuttle available. No specific designs yet available for SPS.	52,53
Emergency Medical/Dental Problems	2	2	Orbital Transfer Space Construction Space Operation	No data available on projected occurrence rate for SPS.	52-54
High Acceleration/ Deceleration Effects	1	2	Launch Recovery	Some data available from other space program activities. Assessment in progress by NASA Life Sciences, Johnson Space Center.	52-54
Extra Vehicular Activity Accidental Injury/ Fatality	2	2	Space Construction Space Operation	No data available on projected SPS occurrence. Spacesuit EVA is to be kept to a minimum, but there will be construction work outside the module in beam builders, etc.	52-54

Table 2.10. (Cont'd)

Effects	Probability Rating ^a	Severity Rating ^b	Activities Involved	State of Knowledge	References
Extended Confinement Psychological stress	2	2	Space Construction Space Operation	Some studies on confinement under other circumstances.	
Thermal Extremes Hypothermia Injury/fatality	2	2	Space Construction Space Operation	Data on effects on earth available. Extent of extremes not yet defined for SPS.	
Spacecraft Charging/ Environmental Interactions	2	2	Space Construction Space Operation	Research in progress regarding other space activities.	64-70
Electromagnetic Field Exposure	2	2	Space Operation	Effects not entirely understood for space environment.	37-43
High Voltage	2	2	Space Operation	Effects not entirely understood for space environment.	
Meteoroid/Space Debris Collisions	2	2	Space Travel Space Construction Space Operation	Some studies on satellites. Needs study specific for SPS.	63,71

^a1 = high; 2 = unknown; 3 = low.

^b1 = critical; 2 = unknown; 3 = noncritical.

Table 2.11. Potential Nonmicrowave SPS Effects on Ecosystems

Effects	Probability Rating ^a	Severity Rating ^b	Activities Involved	State of Knowledge	References
Air Pollution	1	2	Mining Manufacturing Construction Launch Transport	Gross effects of selected pollutants are known and documented. Dose response of vegetation is poorly understood. Long-term, low-dose, wide-spread ecological effects not known.	2-6,13,20, 28,30-36, 72-75
Water Pollution	1	2	Mining Manufacturing Construction	Effects of many pollutants on ecosystems are well known; may range from insignificant to severe.	7,14,15,20, 28,30,74,75
Solid Waste	1	2	Mining Manufacturing	Gross effects are known and documented. Include leaching of toxic chemicals from waste piles.	16,28,30, 74,75
Land Use	1	2	Mining Manufacturing Construction Launch Sites Transport Rectenna Siting Power Distribution System	Land-use changes are known and documented for selected activities. Some constraint predictions depend on system definition. Wildlife attraction to rectenna site appears probable for some species but no documentation exists.	17,20,28-30, 72
Noise	1	2	Launch Recovery	Very little information concerning effects on animals; information on ecological impact is lacking.	9,20,30,75
Reflected Light Plant and animal cycles changed by reflected light	1	2	Space Operations	Much is known about influence of light on biological cycles. Current SPS reference system will be used to predict probable effects.	18,44-46,76
Ozone Reduction/ Ultraviolet Light Increase	1	2	Launch Landing of Space Vehicles	Evidence of the effects on biota is meager.	31
Electromagnetic Field Exposure	2	3	Rectenna Operation Power Transmission	Some evidence of effects on animals	37-43

^a1 = high; 2 = unknown; 3 = low.

^b1 = critical; 2 = unknown; 3 = noncritical.

Ecological impacts will vary from rectenna site to rectenna site and with specific construction techniques. Methods that have minimal impact in one ecosystem might have a severe adverse impact in a different ecosystem. It is possible that limited experimental research might be required to answer some critical questions.

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3 SPS EFFECTS ON THE ATMOSPHERE

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3.1 SCOPE

All levels of the earth's atmosphere would be affected to some extent by the construction and operation of the satellite power system. This assessment identifies the effects which are most important to the environment and estimates their consequences.

Figure 3.1, a schematic diagram of the atmosphere, indicates the various levels referred to in the following text and the most commonly used terms. The classification of atmospheric regions is most commonly made with regard to the observed variations of temperature with altitude, although if one is mainly concerned with ionic process, a different classification scheme is often used for altitudes above 60 km. The troposphere, in which people conduct their daily activities, contains approximately 85% of the total mass of the atmosphere.

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 sunlight side and far beyond that on the dark side, is defined as that 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.*

The variety of processes that occur naturally in the atmosphere is very large and many of these processes can be influenced by various aspects of the SPS. Figure 3.2 illustrates some of the disturbances that might result from the deposition of propulsion system effluents and the operation of a rectenna system.

3.2 METHODOLOGY

The initial step in this assessment is to identify cause and effect relationships and make a preliminary assessment of the importance of such effects to mankind and the environment based on existing knowledge. In

*References for Section 3 are listed in Section 3.7.

Fig. 3.1. Regions of the Atmosphere

Fig. 3.2. Summary of SPS Atmospheric Effects

addition to reviewing and compiling existing information, theoretical investigations are being conducted that include analysis of relevant existing data and simulation with existing modeling techniques.

At this time, preliminary studies have been completed, potentially important issues have been identified, research and assessment approaches and tasks have been defined, and contracts have been awarded and are in progress. It is not likely that current research will produce significant results before FY 1980. Consequently, new information will have to be acquired through processing and analysis of existing data and theoretical calculations using existing or slightly refined computer models, and by taking advantage of already-planned experiments (e.g., rocket launches) that could yield useful information. It is recognized, of course, that after 1980 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 and their subsequent impacts on the environment.

3.3 CAUSE AND EFFECT RELATIONSHIPS

This assessment is focused on those effects that may result from the implementation of the SPS reference system.² The reference system includes a schedule of space transportation operations that would use a variety of space vehicles. These are listed in Table 3.1. The transportation schedule is based on the assumption that two 5-GW satellites would be constructed per year. The numbers of flights of the various types of space vehicles required to construct two satellites per year are shown in Table 3.2 for both the silicon and gallium photocells currently being considered. These numbers do not include transportation requirements for maintenance operations, which could become substantial following construction and during system operation.

A summary of the cause and effect relationships for SPS impacts on the atmosphere is shown in Fig. 3.3. The principal concerns involve:

- Rectenna waste heat and surface roughness - the potential for weather modification.
- Rocket effluents - air quality and weather modification.
- Upper atmospheric activity - compositional changes in neutral atmosphere, ionospheric depletion, and effects on the plasmasphere and magnetosphere.
- Station-keeping - alteration of the satellite environment.

Table 3.1. Types of SPS Space Vehicles

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

Table 3.2. Scenario Data for Construction of Two 5-GW Satellites per Year

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

^aThese titles refer to the silicon and gallium options for the SPS photovoltaic cells.

Fig. 3.3. Cause and Effect Relationships for SPS Atmospheric Impacts

Fig. 3.3. (Cont'd)

3.4 STATE OF KNOWLEDGE

This assessment is organized by atmospheric region, as described in Fig. 3.1, starting with the tropospheric and ending with the magnetospheric effects. Under each region heading, introductory remarks of a tutorial nature describe the state of knowledge and are followed by a discussion of the specific issues that have been identified.

The assessment of the atmospheric effects of a satellite power system includes, among other things, effects due to rocket exhaust effluents. In view of the absence of more appropriate data, an analysis of the Atlas/Centaur fuel will be assumed for the heavy-lift launch vehicle (HLLV) fuel as well. This is a conservative assumption and may result in an overprediction of sulfur-dioxide and nitric-oxide emissions from that rocket. The types of fuel that would be likely to be used in the first stage of the HLLV are described in Table 3.3.

Table 3.4 lists the major chemical species that would be emitted by the HLLV engines at the nozzle-exit plane and for a plane 3 km (1.8 mile) downstream from the nozzle. The difference between the two sets of figures reflects the effect of afterburning within the rocket plume. The sulfur dioxide value in the rocket exhaust was calculated from the total sulfur content measured in the RP-1 sample taken from the fuel tank of the Atlas/Centaur (see Table 3.9). No values are available for the sulfur content of the liquid-methane fuel option. If liquid natural gas were used, the sulfur content would depend upon the source. On the other hand, if synthetic natural gas produced from coal were used, the sulfur content would depend both on the coal and the extent of desulfurization in the SNG process.

Table 3.3. Possible Propellant Combinations for the First Stage of the HLLV

Propellants	Oxidizer-to-Fuel Ratio	Chamber Pressure (psia)
Liquid methane/liquid oxygen	4.2	5000
Liquid methane/liquid oxygen	3.5	5000
RP-1 liquid oxygen	2.9	5000

Table 3.4. Estimated HLLV Exhaust Products

Chemical Species	Percent by Weight ^a	
	Nozzle-Exit Plane	Plane 3 km Downstream ^b
Atomic nitrogen	0	0.000003
Nitric oxides	0	0.00002
Carbon monoxide	0.53	0.0025
Carbon dioxide	51.92	55.0071
Hydrogen	0.016	0.0002
Hydroxyl	0.333	0.00002
Atomic hydrogen	0.0006	0.00002
Water	42.866	44.9898
Oxygen	4.317	- ^c
Atomic oxygen	0.016	0.0004
Sulfur dioxide	0.01	0.01

^aFor liquid methane/liquid oxygen fuel with an oxidizer-to-fuel ratio of 4.2, chamber-pressure of 5000 psia.

^bAfterburning is complete.

^cOxygen is assumed to be part of air.

Combustion products would be released into various layers of the atmosphere as the launch vehicle gained altitude. Table 3.5 shows the altitude distribution of combustion products in selected atmospheric layers for one possible propellant combination. Afterburning has been included in the calculations. Not included in Table 3.5 are nitrogen oxides and ablation products produced in the mesosphere during reentry of the upper stages of the HLLV and personnel launch vehicle (PLV). The amounts of these materials so produced are currently being estimated.

3.5 ASSESSMENT

3.5.1 Troposphere: Rocket Effluent Effects

The direct effects of the satellite power system on the troposphere will result from air pollutants released during manufacturing, transportation, rocket-engine test firing, and rocket launches. The major emphasis of this assessment is on HLLV rocket launches and their anticipated effects on air quality and weather. Other indirect effects will be addressed only briefly.

Table 3.5. Exhaust Products Emitted by the HLLV into Selected Atmospheric Layers^a

Atmospheric region	Altitude range ^a (km)	Quantity of Exhaust Products (kg) ^b									
		Mass of Propellant Emitted	Sulfur Dioxide	Hydrogen	Oxygen and Atomic Oxygen	Carbon Monoxide	Carbon Dioxide	Water	Atomic Hydrogen and Hydroxyl	Atomic Nitrogen	Nitrogen Oxides
Surface boundary layer	0-0.5	403,859	121	0.8	2	10	222,148	181,693	0.2	0.01	0.06
Troposphere	0.5-13	2,906,807	872	6	12	73	1,598,930	1,307,786	1	0.08	0.45
Stratosphere	13-50	3,068,846	921	375	31,198	12,760	1,654,573	1,361,904	10,297	0.02	0.11
Lower mesosphere	50-67	553,097	13	3,624	19,569	2,394	234,490	291,515	1,507	0	0
Mesosphere/thermosphere	>67	2,187,223	0	76,553	0	0	0	2,110,670	0	0	0

^aLiquid methane/liquid oxygen fuel, oxidizer-to-fuel ratio of 4.2, chamber pressure = 5000 psia. Staging occurs at 57 km. The second stage burns a liquid hydrogen/liquid oxygen propellant in accordance with the SPS reference system design.

^bAfterburning ceases at 19 km.

Figure 3.4 illustrates the environmental effects of rocket launches. The problem of launch and recovery noise is addressed in Section 2. To assess the effects of exhaust effluents, one needs detailed information about the nature and amount of the effluents, how they react with the ambient environment, and how they are transported to the sensitive receptors (plants, animals, people, and materials). The nature of the effluents depends largely on the fuels burned in the lowest-stage rocket motors and, to a lesser extent, on afterburning, which further oxidizes the exhaust products, and on ambient pollutant species with which the exhaust products can interact. The amount of effluent released in a given altitude range is primarily determined by rocket size, fuel flow rate, and the length of time the rocket spends in the given altitude range. Interaction with the ambient atmosphere and transport to sensitive receptors are controlled by thermodynamic properties of the effluent cloud and the ambient atmosphere, the chemical constituents of both, and local meteorology.

Rockets are powered by either solid or liquid propellants. Of the larger rockets studied (at least to some extent) from the environmental point of view, the Scout-Algol III, Titan, and space-shuttle first-stage boosters are all solid-fueled. The liquid-fueled rockets include the Atlas/Centaur, Saturn V, and the proposed SPS rockets (HLLV and PLV). Table 3.6 presents comparative data on some of these rockets.

The exhaust of solid-fueled rocket motors is distinguished by the presence of hydrogen chloride (HCl), chlorine gas (Cl_2), and aluminum oxide (Al_2O_3). These latter pollutants are of environmental concern as regards the space shuttle and, consequently, much of the work conducted in the past on rocket-launch effects has focused on solid-fueled rockets.

The exhaust of liquid-fueled rocket motors, on the other hand, consists mainly of water and, if a hydrocarbon fuel is used, carbon dioxide. These substances are very much less hazardous from an environmental point of view. As a result, reports of observations of liquid-fueled rockets are very limited. The launch of Apollo 16 in 1972 by a Saturn V vehicle was monitored, but the monitoring was limited to photographic coverage of the rise and growth of the ground cloud.³ Hence, it was considered necessary to conduct a field measurement program for the only liquid-fueled rocket presently in use -- the Atlas/Centaur. The opportunity to monitor such a launch occurred in November

Fig. 3.4. Environmental Effects of Rocket Launches

Table 3.6. Comparisons of Launch Vehicles

Rocket	Gross Lift-Off Weight (lb)	R/W Ratio at Lift-Off	Thrust at Lift-Off (lbf)	Mass Flow at Lift-Off (lb/sec)	Mass Flow to 4000 ft (lb)	Payload (lb)	Exhaust Products
Atlas/Centaur	311,000	1.17	365,000	1,440	20,160	7,000	CO, CO ₂ , H ₂ , H ₂ O, SO ₂ , NO _x
Saturn C-5	6,071,647	1.24	7,500,000	30,000	868,400	200,000	Same as Atlas/Centaur
HLLV	27,885,000	1.13	31,510,000	98,916	2,171,600	1,102,310	Same as Atlas/Centaur
Space Shuttle	4,400,000	1.53	6,710,000	23,825	412,849	65,000	CO, CO ₂ , H ₂ , H ₂ O, N ₂ , HCl, NO _x , Al ₂ O ₃ , Cl ₂
Titan III C	1,392,000	1.72	2,400,000	9,800	146,000	29,000	Same as Space Shuttle

1978 when an Atlas/Centaur was scheduled to place the HEAO-2 satellite in orbit. The results of the monitoring program are discussed briefly below.*

Air Quality Impacts

In the troposphere, the environmental effects of rocket exhaust are due primarily to the ground cloud (the cloud of hot rocket exhaust, steam from launch platform cooling, and sand and dust drawn into the cloud by vigorous turbulent mixing) formed in the first few seconds following ignition and lift-off. After the 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 adverse environmental effects associated with the exhaust emissions in the middle and upper troposphere have been identified. The ground cloud, on the other hand, is a source of potential air pollution and weather modification.

Because of the high temperature of the ground cloud, it rises to an altitude of 0.7 to 3 km, depending on the meteorological conditions and size of the rocket, where it stabilizes because of the cooling of the gases to the ambient temperature.

As the cloud rises, a substantial fraction of the heavy particles (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.

The amount of exhaust products contained in the ground cloud, excluding entrained dust and debris, is estimated to be that due to approximately the first 20 seconds of burn-time of the HLLV engines. This figure is arrived at by considering the ground cloud to be formed by the exhaust cloud emitted through the flame trench for the first 10 seconds after ignition plus the column of exhaust products formed during the following 10 seconds. The amounts of the principal exhaust constituents in a typical ground cloud at

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

stabilization (after neutral buoyancy is attained) are estimated to be: carbon monoxide = 2462 kg, water = 443,260 kg, sulfur dioxide = 99 kg, carbon dioxide = 541,762 kg, and suspended particulate matter after early fallout = 10-1,000 kg. The same calculations indicate that the amount of nitric oxide formed would be negligible. However, measurements made on the ground cloud of the Atlas/Centaur launch (see discussion below) indicate that a substantial amount of various nitrogen oxides is formed in practice.

The concentration of these species within the stabilized ground cloud is greatly modified by entrainment of the ambient air (the ground cloud is approximately 99% air) and steam from the flame trench and water sprays used to cool the launch platform and remove surface debris. Once the cloud has reached the stabilization altitude, it will grow in size because of atmospheric turbulent diffusion, and move with the prevailing winds at that altitude.

After stabilization, the surface and airborne concentrations of pollutants in the cloud can be predicted with an air pollution dispersion model called REED that has been developed especially for this process.⁴ The model has been tested against measured Titan exhaust clouds and found to be conservative in the sense that it overpredicts ground-level concentrations.

The model was used to estimate the potential effects of the HLLV ground cloud by calculating test cases for a variety of meteorological conditions. Much effort has been expended on diffusion calculations for the Kennedy Space Center (KSC) on the space-shuttle program; these calculations have been used for this assessment. Some meteorological conditions have been found to yield relatively high ground-level concentrations of air pollutants associated with the exhaust cloud. These meteorological conditions are associated with soundings taken during certain days in 1965. Some of these soundings were used as input to the REED program. The results of such calculations for the KSC are illustrated in Table 3.7, which shows the peak concentrations of sulfur dioxide experienced at ground level.

The highest ground-level sulfur dioxide concentration found for any of the cases (June 10, 1965) was 5 ppb. This concentration is one-fourth of the federal annual secondary standard and is thus not critical.

Atmospheric dispersion models such as REED can provide useful information about the effects on air quality of a specified source of pollution. It

Table 3.7. HLLV Diffusion Calculations for the Kennedy Space Center

Date	Time (EDT)	Cloud Height (m)	Elapsed Time (sec)	Results of Diffusion Calculations ^a		
				Range to Max. Conc. (m)	Azimuth (degrees)	SO ₂ Ground- Level Conc. (ppb)
3/7/65	115	1,673	252.8	10,530	115.4	3
6/10/65	1914	1,422	187.5	11,269	336.3	5
12/21/65	556	1,409	114.1	6,462	111.7	2

^aFor liquid methane/liquid oxygen fuel with an oxidizer-to-fuel ratio of 4.2, chamber-pressure of 5000 psia.

is considered desirable, however, to base an environmental assessment upon actual measurements, if relevant measurements are available, since dispersion calculations are subject to a wide variety of limitations. As indicated earlier, an opportunity arose to monitor the ground cloud of an Atlas/Centaur liquid-fueled rocket on November 13, 1978. Table 3.8 lists the quantities monitored in this program, and Table 3.9 gives a chemical analysis of the RP-1 hydrocarbon fuel used in the launch. A number of aerosol samples also were returned to the laboratory for investigation of size distribution and trace-metal content and for cloud-condensation-nuclei and ice-nuclei studies.

A total of 52 passes through the ground cloud were made over approximately 2.5 hours after launch, although after about 135 minutes the ground cloud was indistinguishable from an industrial plume in the area and the measurements were stopped shortly thereafter. The highest concentrations of the gaseous components were measured during the second pass, which took place five minutes after lift-off (on the first pass, the aircraft did not travel through the center of the cloud). The observed concentrations of NO, NO₂, and SO₂ were 635 ppb, 500 ppb, and 23 ppb, respectively. The cloud subsequently drifted downwind and dispersed until at 110 minutes after launch, the measured concentrations were 45 ppb, 65 ppb, and 7 ppb, respectively. The cloud grew in size primarily in the horizontal directions, dispersion in the vertical direction 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.

Table 3.8. Quantities Monitored⁵ in Ground
Cloud of Atlas/Centaur Launch,
November 1978

Temperature profiles
 Dewpoint profiles
 Physical dimensions of cloud
 Liquid water content of cloud
 Giant particles (10-1000 μm dia.)
 Large particles (0.1-10 μm dia.)
 Small particles (10^{-3} to 10^{-1} μm dia.)
 Cloud condensation nuclei (CCN)
 Ice nuclei (IN)
 Sulfur dioxide (SO_2)
 Nitrogen dioxide (NO_2)
 Nitric oxide (NO)
 Ozone (O_3)
 Methane
 Nonmethane hydrocarbons
 Ion concentration
 Vertical electric field
 Light scattering coefficient
 Turbulence
 Aircraft position

Table 3.9. Analysis⁶ of RP-1 Fuel Taken from
Atlas/Centaur Fuel Tank Just
Before November 1978 Launch

Element	Amount Present	
	%	ppm
Carbon	85.24	
Hydrogen	13.57	
Nitrogen	0.17	
Sulfur	0.047	
Calcium		5.1
Aluminum		1.7
Magnesium		0.46
Nickel		0.18
Lead		0.15
Zinc		0.14
Iron		0.09
Copper		0.08
Cadmium		0.05
Vanadium		<3 ^a
Chromium		<1 ^a

^aNot detected; detection limit given.

In view of the presence of sulfur as an impurity in the fuel, sulfur dioxide 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 to 10 ppm at a distance of one mile 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 to 5 ppm at a distance of about one mile 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 60 ppb, 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.

Acid rain may be an issue of concern near the launch area. Acid rain occurs when raindrops form in or fall through a region of the atmosphere containing a substance which, when dissolved in water, produces an acidic solution. The acidity of a solution is specified numerically by its pH; a pH value of 7 indicates a chemically neutral solution, with increasingly lower values corresponding to increasingly acidic solutions and with values above 7 corresponding to alkaline or basic solutions. Naturally-occurring rainfall generally has a pH between 5.5 and 6.5 and is therefore slightly acidic. In recent years, rain having a pH of 4 or less has been observed in the Scandinavian countries as well as in Canada and the northeastern United States. This 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. It is considered to be a large-scale effect, and the contribution from HLLV rocket exhaust emissions to regional- or continental-scale acid rain would be negligible, taking into account the magnitude of these emissions in comparison with the total SO_2 , NO , and NO_2 emissions from industrial and other sources in the southeastern United States.

A highly localized and temporary acid rainfall may occur in the vicinity of a launch area due to raindrops falling through the ground cloud. The effect can be easily mitigated by not launching during periods of adverse meteorological conditions. In the case of the HLLV, since any acidity would be due to SO_2 and nitrogen oxides in the ground cloud, and not to a principal exhaust product, the effect would be similar to the effect 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 continuous plume. An investigation into the expected magnitude of this effect is underway.

Inadvertent Weather Modification

The principal concerns about inadvertent weather modification by SPS rocket effluents are: (1) the possibility that the ground cloud formed by SPS rocket exhaust might temporarily modify local weather, and (2) the cumulative effects of nearly 400 launches per year on weather. The immediate dynamic and thermodynamic response of the ground cloud to heat and moisture from the rocket exhaust and the launch facility for a given meteorological condition is one possible effect. Another is the alteration of the microphysical processes of clouds in the general area due to rocket effluents, entrained debris, and cooling water during the launch.

Existing cloud models, validated by previous rocket-launch observations, can be used to simulate the convective activity and the possible associated precipitation under conditions favoring the latter. The inputs of interest are thermal energy and total water content of the ground cloud and column cloud. These input data are not generally available, so estimates must be made that are relatively uncertain. The potentially-significant, inadvertent weather modification in terms of changes of cloud microphysical processes is similar to that of planned weather modification. It depends upon the time of year, the site location, the origin of air mass, and various scales-of-weather patterns.

Effluent from solid- or liquid-fueled rockets would be expected to produce both cloud condensation nuclei (CCN) and ice-forming nuclei (IN) in the ground cloud. The addition of these nuclei can alter cloud microphysical processes which are significant for cloud and weather modification in Florida

and tropical regions. Cloud condensation nuclei are particles upon which water vapor condenses to form water droplets, which in turn form clouds and fogs. They play an important role in determining the colloidal stability of clouds and the formation of precipitation. In general, the addition of CCN may tend to slow down the warm rain-formation processes (those in which ice plays no significant role) if there are more than 1000 CCN/cm^3 . However, if very large hygroscopic particles (giant nuclei with radii $>25 \mu\text{m}$, 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 ice-forming nuclei per liter are added at a supercooled cloud temperature of approximately -10°C to -15°C for precipitation enhancement and one to several hundred IN per liter are added for thunderstorm modification.

To obtain data on the particle characteristics of rocket-exhaust ground clouds and their implications for inadvertent weather modification, a field program was conducted to measure particles and gases in the ground cloud from the November 1978 Atlas/Centaur rocket launch discussed previously. The Atlas/Centaur rocket is fueled by liquid hydrocarbons. The proposed hydrocarbon-fueled HLLV would be expected to have similar effluent characteristics. Data were acquired on the major particles and trace gas emissions from the combustion and entrainment processes. Similar measurements were made during the December 1978 Titan III rocket launch. Results of these measurements have been published.^{9,10}

These measurements indicated that the concentrations of ice-forming nuclei 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 of weather modification due to the production of ice-forming nuclei cannot be assessed with confidence at this time. The high concentration of cloud condensation nuclei observed in the rocket-exhaust ground cloud could alter the frequency and persistence of fogs and haziness on the surface. However,

the large amount of heat released by the rocket exhaust effectively lifts the ground cloud aloft until it reaches a stable layer of air that is several hundred meters to a few kilometers above the ground. Under situations conducive to fog occurrence it is unlikely that the later diffusion of the stabilized ground cloud toward the surface would take place soon enough to have a noticeable effect.¹¹

A rocket-exhaust ground cloud could be drawn into the convective cell of a large, developing natural storm. The large concentration of CCN entrained in the convective plume could delay the coalescence of the droplets in the developing cloud. With a delay in coalescence, the cloud would tend to grow larger and colder. The IN in the plume could then lead to the release of heat of crystallization, further increasing the size and intensity of the convective cloud system. This kind of modifying effect, though speculative, could occur any time in the year in Florida;¹¹ the same would be true in tropical regions.

The presence of convective elements and associated precipitation cells is the major concern about inadvertent weather modification from SPS rocket launches. Conditions which favor a potentially unstable boundary layer and the likelihood of such a layer combining with convective activity were identified for the Kennedy Space Center area in a theoretical study of the space-shuttle exhaust cloud.¹¹ The conditions include hurricanes; easterly wave 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 four hours after a rocket launch. The potential for inadvertent weather modification from HLLV effluents would be expected to extend beyond 24 hours after launch. The nearly 400 launches proposed per year therefore could be expected to have some cumulative effects. It is necessary to study this possibility further.

Other Effects in the Troposphere

Three additional issues involving possible modification of tropospheric weather have been identified:

- Possible perturbation of the atmospheric electric field due to large-scale reduction in ionospheric and stratospheric conductivity; this could have meteorological consequences.
- Possible modification of solar heating because of mesospheric cloud formation; this could result in variations of convection near the earth's surface and thus have weather effects.
- Direct-current, high-voltage lines carrying power from the rectenna would give off clouds of monopolar space charge due to corona; these might influence thunderstorm electrification and cloud physical processes.

All these issues involve effects whose likelihood of occurrence is unknown at this time, but whose consequences might be significant.

3.5.2 Troposphere: Rectenna Operation Effects

A preliminary assessment of the possible meteorological effects of SPS rectenna operation was conducted by the Lyndon Johnson Space Center.¹² The assessment was based upon the maximum microwave-beam power density of about 23 mW/cm² and an average 0.75 mW/cm² of waste heat release from a rectenna covering approximately 100 km². The preliminary findings are that the effects of an SPS rectenna on weather and climate would be small compared to the direct environmental consequences of construction, which would have more significant impacts. A continuous release of 750 MW of waste heat from a 100 km² rectenna would be equivalent to the heat release associated with average suburban developments. This waste heat release is about 10% of the average natural energy conversion at the surface. The possible changes in aerodynamic roughness and the rectenna's albedo would probably be more important than the waste heat release. The intensity of the atmospheric perturbation due to SPS rectenna operation should be very small compared with those of 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. Scattering by the particles, even in heavily-polluted atmosphere, would also be negligible.¹²

The above assessments, based mainly on scale comparison and simple analytic estimates, are primarily qualitative in nature. In order to identify possible new issues and to assess present knowledge and the need for additional research, a workshop was held in August 1978 to address the rectenna-

related effects. Three main topics were discussed: the effects of waste heat release on the atmosphere at the rectenna site, microwave interactions with the atmosphere, and the possible effects of the microwave beam on atmospheric electrification processes. A brief description of these subjects follows.

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%, a ten-fold increase in perturbation should be considered on the occasions of microwave-beam wandering and spreading due to atmospheric refraction effects.

It is possible to investigate the effects of the rectenna by studying the effects of land-use changes. The meteorological effects may be estimated on both the regional scale (or mesoscale) and the "cloud scale." On these scales, small temperature changes (of the order of 1°C) can be expected on occasions of light wind. Change in cloud populations can also be expected. Somewhat larger man-made 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 (the cloud scale), there are diurnally-varying changes in the surface energy budget which are larger than the projected rectenna waste heat. It is therefore expected that meteorological effects of a rectenna would vary from site to site, and the central maximum heat dissipation ($\approx 1.6 \text{ mW/cm}^2$) 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 the mesoscale 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, is in space. Furthermore, there are no significant emissions of material into the troposphere during operation. Of all major proposed power production systems, it is the least likely to have regional and global weather and climate effects.

In summary, preliminary estimates of the local and mesoscale weather and climate effects of rectenna construction are that they are generally small but detectable in some instances. The major immediate need is to confirm these estimates by the most convincing methods now available. The possibilities of avoiding weather and climate changes by construction manipulations not affecting system efficiency also should be explored. Some atmospheric effects are likely to 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.

To further quantitatively confirm the above estimates, a three-dimensional turbulence-closure model¹³ has been used to simulate the atmospheric effects of the construction and operation of a rectenna under a daytime, unstable-boundary-layer condition with logarithmic wind profile up to 4 m/s. It was found that increased roughness over the rectenna would considerably increase the surface heat flux (by a factor of 3.5) and friction velocity (by a factor of 1.9) at the center of the site in comparison with values located at the upstream boundary. This would be true if the thermal properties of the rectenna and the surroundings are such that the surface temperature of the rectenna area and the surrounding area are the same. An addition of 0.8 mW/cm^2 of waste heat at the rectenna would increase the surface temperature by less than 0.1°C and result in a maximum vertical velocity of approximately 7.4 cm/s.

The model simulation indicates that much larger effects would be expected if the local vegetation and roughness changes at a rectenna site were combined. For example, the simulation showed that magnitudes of perturbations for the surface heat flux could be double that caused by roughness alone if the surface air temperature excess over the rectenna were as much as 2°C . A maximum updraft of 15 cm/s was simulated downstream of the rectenna site. The meteorological analogy to this simulation can be found in theoretical and observational studies of the urban-heat-island effects of St. Louis.^{14,15}

For an extreme situation in which the waste-heat effects might be most apparent, consider the air over the rectenna to be calm and the effects of advection to be negligible. Under such conditions the ground temperature in the center of the rectenna site could increase by 2.9°C for a grassland and

4.6°C for a desert site during summer days, based on surface-energy-balance model calculations suggested by Bhumnalkar.^{16*} These thermal perturbations are significant in creating organized mesoscale convection. A three-dimensional boundary layer model which pays particular attention to energy balance at the surface with parameterized convective clouds and rain is currently being used to investigate the possible meteorological consequences.

Microwave Propagation

The atmospheric absorption of microwave energy at the proposed SPS wavelength is negligible in clear air for the projected tropospheric path lengths of about 20 km. However, some absorption by condensed water (clouds and precipitation) would occur when storms enter the beam path. Information is available regarding the amount of microwave absorption (the total attenuation of this wavelength being due predominantly to absorption) per unit path length as a function of rainfall rate.¹⁷ With the most extreme rainfall rate of 254 mm/hr as an example, the attenuation at the proposed 2.45-GHz frequency is estimated to be about 0.063 dB/km according to Bean et al. as cited in Ref. 17. 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 buoyant energy of a moderate cumulus cloud with an updraft of 10 m/s and temperature excess of 2°C. Therefore, it is reasonable to conclude that the absorption of SPS microwave power by a storm will have no significant influence on cloud dynamics and thermodynamics and the associated precipitation.

Since the passage of the microwave beam through the troposphere has been concluded to produce no significant meteorological consequence, much attention at the August 1978 workshop was focused on the possible effects of the natural atmospheric conditions on the microwave beam propagation and the associated power-beam and pilot-beam stability problems.

Beam control is affected to a major extent by the interaction of both beams with refractive-index anomalies in the atmosphere. Because of the reciprocity principle, the up-link (pilot) and down-link (power) beams should

*Personal communications with H.D. Orville, North Dakota School of Mines and Technology (1979).

follow essentially the same path, apart from possible effects of the small time delays involved. Slowly varying and drifting anomalies, large-area events, or numerous smaller-area anomalies in the power beam (main beam and principal sidelobes) and the pilot beam would cause spatial and temporal modulations that would vary the illumination of the rectenna, and, because of adverse geometry, cause large variations in pilot-signal parameters. The latter would have a strong potential for causing serious ambiguities in the control decisions and thereby affect system stability.

Current models based on satellite signal data demonstrate ranges of coupling of electromagnetic signal characteristics (amplitude, induced frequency modulation, and phase) with general meteorological conditions. These data allow parametric examination of beam effects and control configurations. Additional study is required to identify variations in refractivity anomaly characteristics and frequencies of occurrence resulting from SPS-induced atmospheric alterations. These data are needed in order to extend the parametric modes of current models. Information regarding the spatial and temporal characteristics of these anomalies would be used to develop signal-fluctuation statistics for the cited control decisions.

Atmospheric Electricity

Previous studies have considered the possibility that the SPS microwave beam might disrupt the ionosphere and consequently the atmospheric fair-weather electric field, thus influencing the frequency and intensity of thunderstorms. Current experiments and calculations presented at the August 1978 workshop indicated negligible disruption of the ionosphere. However, the mere physical presence of the rectenna might have some modifying influence on the occurrence and electrical behavior of thunderstorms over and around the rectenna.

3.5.3 Stratosphere and Mesosphere

The stratosphere and mesosphere are the lowest of the regions in the upper atmosphere (see Fig. 3.1). The classification of atmospheric regions is commonly made with regard to the observed variation of temperature with altitude. The mean temperature of the atmosphere decreases up to an altitude of approximately 11-12 km. The tropopause is the altitude at which the

atmospheric temperature stops decreasing, and marks the boundary between the troposphere and the stratosphere. The lower stratosphere (up to about 20 km) is nearly isothermal, but from 20 km up to approximately 50 km the temperature increases. The altitude at which this increase stops and the temperature begins to fall again is termed the stratopause and marks the boundary between the stratosphere and the mesosphere. The mesosphere is that region in which the temperature decreases with altitude again, and spans the range from 50 km to approximately 80 km. Above 80 km (the mesopause), the temperature increases with altitude; this higher region is termed the thermosphere.

Since the early 1970s, there has been much concern about the possible perturbation of the stratospheric chemical composition due to a wide variety of natural and anthropogenic sources, including volcanic emissions, solar flares, supersonic aircraft, chlorofluoromethane emissions, nuclear weapons testing, and increased biological production of nitrous oxide. The primary reason for concern over human health impacts has been the fact that the concentration of ozone (O_3) increases dramatically in the lower stratosphere, reaches a peak, and then decreases again in the upper atmosphere. Ozone absorbs ultraviolet (UV) radiation at wavelengths below approximately 300 nm, and the relatively high concentration of ozone in the stratosphere serves to filter out solar UV radiation below this wavelength. Ultraviolet radiation in this wavelength region has been implicated as a cause of skin cancer in humans, and any perturbation to the composition of the stratosphere which would decrease the total integrated ozone column density (which determines the flux of UV radiation at the earth's surface) may have serious effects upon human health. Furthermore, the chemistry of the upper atmosphere is quite complex, and the introduction of any of a wide variety of chemical compounds, including those found in rocket exhaust, may be expected to affect the ozone concentration. The magnitude of the impact depends upon the amount and chemical nature of the substance(s) being introduced, and must be evaluated separately for each particular type of source.

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 is due directly to the absorption of solar UV 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 and 70 km, the absorption of solar energy provides the main driving force for the dynamics of the atmosphere. Thus, perturbations in upper atmospheric composition may have an effect on meteorological variables as well, although in many respects these are less well understood.

Composition Perturbations

The most direct and obvious manner in which the proposed satellite power system might affect the upper atmosphere is through the direct injection of rocket-exhaust effluents. The projected level of spaceflight activity required to construct 60 solar-power satellites is unprecedented, as is the size of the launch vehicles themselves. The injection of relatively large amounts of rocket exhaust into the upper atmosphere 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 lead to the deposition of ablation materials and the production of nitric oxide in the mesosphere. The composition changes resulting from rocket-exhaust injections and reentry effects would be the most important primary effects expected in the stratosphere and mesosphere.

The most recent estimates of the masses of various exhaust products emitted into different regions of the atmosphere during one flight of the HLLV were given in Table 3.5. These values are not significantly different from those given by the Boeing Aerospace Co. in its SPS definition study¹⁸ which have previously been used to estimate the magnitudes of the expected atmospheric impacts. As indicated in the table, the primary exhaust products are carbon dioxide, already present in abundance in the upper atmosphere, and water. Other substances emitted in much smaller amounts result from fuel impurities, afterburning, and incomplete combustion.

Initial calculations indicated that carbon dioxide emissions due to 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.¹⁹ This assessment is still considered valid, and no detectable effects are expected from carbon dioxide emissions. To put the emission figures in Table 3.5 into

perspective, it should be noted that the total mass of carbon dioxide emitted per year would be 1.4 million metric tons (t) assuming 391 HLLV flights per year. This quantity is approximately 30% of the amount emitted into the atmosphere by a single 1000-MW coal-fired power plant in the same one-year period.

With respect to water-vapor emissions, the situation is different. Although water is abundant in the troposphere, it is present in only trace amounts in the upper atmosphere; the mass-mixing ratio is about three parts per million. 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 emissions. Recently, considerably more detailed calculations have been carried out to obtain more accurate estimates of the expected effects. These calculations, while still preliminary and incomplete, allow much more accurate estimates to be made of the impact of water injections.²⁰ Based upon these preliminary results, an increase in the globally-averaged water-vapor concentration of about 1% at 50 km and about 2% at 80 km could be expected for 391 HLLV flights per year. A higher launch rate would result in an approximately proportionally higher impact; thus, a total of 522 flights per year (two per day, five days per week) would be expected to result in increases of about 1.5% and 3% in the global water-vapor concentration at 50 km and 80 km, respectively. Below 50 km, the water-vapor perturbation would decrease to much less than 1% in the lower stratosphere.

Corresponding perturbations occur in the concentration of other trace substances because of the complex system of atmospheric chemical interactions. The globally-averaged ozone concentrations could be expected to decrease by approximately 1-2% in the mesosphere, and by much less than 1% in the stratosphere. With regard to ozone, the total, vertically-integrated ozone concentration may be of greater concern. This integrated concentration determines the flux of near-ultraviolet radiation at the earth's surface. Preliminary results indicate that the expected change in the total ozone column due to SPS space flights would be only about -0.02%, a change which is currently undetectable.

The calculations also took into account the effect of nitrogen oxides deposited in the upper atmosphere by afterburning in the rocket-exhaust plume.

The results indicated that the effects on composition are totally negligible, due to the relatively small amount of nitrogen oxides actually produced in this manner.

Figure 3.5 shows some results from one set of calculations. The figure gives the estimated percent change in the globally-averaged ozone, water, and nitrogen-oxide concentrations as functions of altitude for an assumed 391 HLLV flights per year. Rocket-exhaust emissions above 80 km were not taken into account, and the estimated perturbations near that altitude and above are lower bounds to those that would actually be expected. The figure clearly illustrates however, that the most significant perturbations are expected to occur in the mesosphere and that the impact on the stratosphere is minimal.

No quantitative assessment is yet available for the effects of nitrogen oxides produced by reentry. Rough estimates indicate that the amount produced could be on the order of 1-2% of the total global natural production from auroral activity, molecular-nitrogen photodissociation, and meteoroids. As indicated earlier, work is underway to make more accurate estimates of the amount that would be generated by reentry. The effects on atmospheric chemistry would also occur predominantly in the mesosphere, with no significant effect expected in the stratosphere.

Thus far, quantitative estimates of the impacts expected from injections of rocket exhaust into the upper atmosphere have been restricted to calculations of the global or hemispheric average concentrations. Such estimates may be made with available one-dimensional atmospheric models and are relatively easy to carry out. However, because of the high expected launch rate, a significant "corridor effect" may exist. The term "corridor effect" refers to a significant dependence of the composition perturbations on latitude, the perturbation being largest near the latitude at which injection takes place. This effect would be expected whenever the exhaust injection occurred over a narrow latitude band and at a rate which was significant compared to the rate of north-south atmospheric transport. As a result of the corridor effect, the composition perturbations near the latitude at which injection takes place could be significantly greater than the same perturbation averaged over all latitudes. A similar argument holds for reentry-produced nitrogen oxides. Quantitative estimates of the corridor effect for

Fig. 3.5. Estimated Changes in Ozone, Water Vapor, and Total Nitrogen Oxides Concentrations (Source: Ref. 20)

HLLV flight activity are not yet available. The calculations involve the use of a two- or three-dimensional atmospheric model and are considerably more difficult and expensive to carry out, although work is currently underway to provide such estimates for the SPS environmental assessment. Such calculations have been made to estimate the magnitude of the corridor effect expected from the space-shuttle flight program; results show significant variations with latitude.

In addition to the principal exhaust products, water and carbon dioxide, any impurities in the fuel 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 of 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 may be produced rather easily with today's technology. Current liquid-fueled rockets do not use

methane, however; instead, a higher-molecular-weight hydrocarbon mixture is used. 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 could result in the emission of up to 750 t/yr of sulfur dioxide into the stratosphere. This injection rate may be compared to sulfur-dioxide emissions in the stratosphere from the current fleet of nine Concorde, estimated to be at most 3500 t/yr, or to the injection of sulfur compounds into the lower stratosphere during the 1963 eruption of Mt. Agung in Bali (estimated at 4×10^6 t). Based upon these comparisons, the presence of a sulfur impurity at the 0.05% level would not be considered likely to have any significant effects, and a similar conclusion may be reached regarding any other known potential fuel impurity.

Climatic Effects

The effect on the tropospheric climate of perturbations of the natural composition of the upper atmosphere has not been studied in detail. However, information is available which allows estimation of some quantities of interest; one such quantity is the change in surface temperature resulting from changes in high-altitude composition. Estimates of surface temperature changes indicate that the impact of the anticipated upper-atmospheric-composition perturbations on the earth's surface temperature would be completely negligible.²⁰ The estimates are based on the composition perturbation results described above and results available in the scientific literature using one-dimensional radiative equilibrium models. Thus, only the direct effect of composition perturbations upon the earth's radiation budget is taken into account. Neither a possible corridor effect nor the possibility of increased noctilucent cloud formation were considered, although it is unlikely that their magnitudes would be changed significantly by more detailed calculations.

With regard to more general climatic or weather effects, the possible existence of a corridor effect complicates the picture. A more extensive analysis will be required to assess the climatic effects of composition perturbations which are latitudinally dependent and which are expected to be most significant on a relative basis in the mesosphere. In addition, 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. In any case, even a qualitative assessment must await detailed model predictions of the altitude- and latitude-dependence of the expected composition perturbations.

A more specific question that has been raised is the extent to which increased water-vapor concentration at mesospheric altitudes would affect the formation of noctilucent clouds. An increase in water concentration could give rise to increased cloud formation near the mesopause, at an altitude of about 80 km. To accurately assess this possibility, better information about the mesospheric environment than is currently available is needed, particularly with regard to temperature and existing water-vapor concentration. Again, an assessment of SPS-related effects must await predictions of the altitude- and latitude-dependence of the expected increase in water concentration.

It seems highly probable that transient noctilucent clouds would be induced in the vicinity of the launch site following the launch of an HLLV or PLV. Examples of such artificially-induced noctilucent clouds have been reported several times 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.²¹ The persistence and growth of the clouds only near the mesopause indicates 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 (100% relative humidity). To put the emissions into perspective, a single HLLV launch would inject approximately 13 t of water into the same 10-km altitude range, i.e., 50,000 times as much as the French rocket. In view of the large amount of water involved, it must be concluded that very substantial artificial noctilucent clouds would also be generated by HLLV and PLV launches. The expected lifetime of these clouds is not known.

The significance of the noctilucent-cloud question from the point of view of climatic effects is that atmospheric clouds and aerosol affect the earth's radiation budget through their ability to absorb and scatter electro-

magnetic radiation. Noctilucent clouds tend to be optically thin, however, and the subsequent effect of an increase in noctilucent-cloud formation on the tropospheric climate is unknown. Thus, it is not clear that the formation of additional clouds would have a detectable impact on anything else. These questions definitely require further investigation, based upon more detailed water-vapor concentration predictions. Work is in progress to provide some of the answers needed for the environmental impact assessment.

Energy Injection

The construction and operation of the satellite power system would result in the direct injection of 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.

On a localized basis, a dramatic increase in temperature would certainly occur in the vicinity of the HLLV exhaust plume for a short time after the passage of the rocket. However, because of the relatively high rate of atmospheric dispersion, the actual plume, together with any associated temperature perturbations, would be rapidly dissipated. Calculations are underway which are expected to confirm that, taken individually, HLLV and PLV launches would have no significant thermal impact on the stratosphere and mesosphere. Also, due to the intermittent nature of this thermal-energy injection and the transient nature of the resulting temperature rise, the time-averaged energy flux into the upper atmosphere would be small compared with 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 1×10^{-7} mW/cm² for an assumed 500 HLLV flights/year. This figure should be compared to the average 4 mW/cm² energy input due to solar UV absorption.

Estimates are available for the upper-atmospheric absorption of microwaves at the SPS frequency of 2.45 GHz. The fractional absorption of microwaves with a frequency of 2.45 GHz vertically incident on the atmosphere has been reported to be approximately 0.01, of which only 0.001 occurs in the stratosphere and mesosphere.^{22,23} The peak power in the microwave beam is

expected to 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 UV absorption input, and may be considered negligible. When averaged over the globe, even assuming the presence of sixty 5-GW rectennas, the average energy flux to the upper atmosphere would be only $6 \times 10^{-5} \text{ mW/cm}^2$.

Microwave attenuation at 2.45 GHz above the troposphere is due almost entirely to absorption by molecular oxygen,²³ with an absorption cross-section of approximately $1.3 \times 10^{-31} \text{ m}^2$ (estimated from results presented in Ref. 23). Using this cross-section together with data on the variation of atmospheric number density with altitude,²⁴ the microwave attenuation values for both the stratosphere and mesosphere have been independently calculated and the results are in agreement with the total value given in Ref. 22 for altitudes above the troposphere. A total absorption rate of 0.0056 mW/cm^2 (0.14% of the solar input of 4 mW/cm^2) is estimated in the stratosphere, and an absorption rate of 0.0001 mW/cm^2 (0.4% of the corresponding solar input of 0.025 mW/cm^2) is estimated in the mesosphere.

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 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 negligible.

3.5.4 Ionosphere

The position of the ionosphere in the atmosphere was shown in Fig. 3.1. It is a region in which the population of ions and free electrons, although small relative to neutral particles, is large enough to be physically significant. In particular, 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 about 60 to 90 km and is roughly coincident with the mesosphere. The

E-region extends from about 90 to 150 km and coincides with the lower portion of the thermosphere. Two rather important transitions occur in this altitude range. First, the dominant transport mechanism changes from eddy diffusion to molecular diffusion at the turbopause (≈ 110 km). Second, the influence of the earth's magnetic field begins to play an important role relative to diffusion processes in the motion of charged particles at around 150 km. This marks the beginning of the magnetosphere. The F-region of the ionosphere begins around 140 to 150 km and extends upward into a highly-ionized region called the plasmasphere. The plasmasphere is terminated in a narrow region called the plasmopause wherein both the electron and ion populations drop rather sharply, by an order of magnitude or more. The plasmopause defines a doughnut-shaped region extending out to about four earth radii in the equatorial plane and reaching into the F-region at mid-latitudes (see Fig. 3.6). The F-region itself is subdivided into the F_1 -region (140-200 km) and the F_2 -region (200-1000 km).

The entire ionosphere is characterized by a relatively rich variety of chemical, physical, and electromagnetic phenomena involving the mutual interactions of solar and cosmic radiation, neutral particles and ions, and the earth's magnetic and gravitational fields. These interactions give rise to both periodic and random variations in upper-atmospheric properties that have significant impacts on man's environment. Because of the relatively delicate balance of forces involved, and the relatively small numbers of particles contained in the ionosphere, the possible effects of large quantities of rocket-propellant exhaust products, on a scale much larger than heretofore experienced, must be assessed.

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 nitric oxide (NO) by solar UV and to a lesser extent by hard x-rays and energetic electrons in the upper portion of the region. Below 70 km, galactic cosmic radiation is the dominant source of ionization. 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

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Fig. 3.6. Cross Section of Magnetosphere and Plasmasphere

lower region. During the nighttime hours many of the remaining free electrons form negative ions so that below 90 km the free-electron population essentially disappears. This has a significant influence on the reflection height, absorption, and polarization of radio waves.

The major potential perturbations of the D-region resulting from the proposed SPS would be associated with the HLLV rocket effluents that would be injected once or twice per day for a 30-yr period during the construction phase.² These effluents would include water vapor, hydrogen gas, and thermal energy during launch, and ablated materials, oxides of nitrogen, and thermal energy during reentry.

Figure 3.7 provides an overview of the cause and effect relationships of rocket-exhaust emissions in the lower ionosphere. Several of the issues relating to these cause and effect relationships are briefly described below.

Fig. 3.7. Rocket-Effluent Effects in Lower Ionosphere --
D-Region and Lower E-Region (50 to 120 m)

Effect of Water Vapor on Ion Concentration. Water vapor emitted by launch-rocket engines may alter ion and electron 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. The extent and persistence of such anomalies must be determined. 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.

Effect of Nitric Oxide Production During Reentry. Nitric oxide produced (principally) during the reentry phase of rocket operations could enhance the D-region of the ionosphere. Sporadic-E* layers might occur more frequently if the metal ion layers between 100 km and 110 km were augmented by ablation products. It is unlikely, however, that the rate of mass input to the E-region by ablation would be competitive with the normal meteoric influx, except perhaps locally. Thus, any effects would have to be highly localized. Effects resulting from ablation do not appear to be important at this time.

Possible Changes in Atmospheric Electrical Conductivity in the D- and E-Regions. Changes in electrical conductivity in the lowest part of the ionosphere may produce significant changes in the propagation characteristics of very-low-frequency radio waves, creating potential problems for communication and navigation systems using these frequencies. The probability of occurrence and significance of this issue are unknown at this time.

E-Region of the Ionosphere

The E-region is formed principally by soft solar x-rays. The main positive ions are O_2^+ , NO^+ , and O^+ . 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. Historically, this was the region of the ionosphere 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 one approaches the top of 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 120 km, only the lower E-region would be subject to the direct rocket effluents. (Details regarding the PLV trajectory are not yet available.) 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-

*Sporadic-E refers to the formation of thin layers (1 or 2 km thick) of greatly enhanced electron concentration.

and F-regions. In addition, effluents from the HLLVs, PLVs, and personnel orbit-transfer vehicles (POTVs) injected near LEO might enter this region by downward diffusion and gravitational settling of ice crystals. Because the E-region completes the plasmaspheric circuit at the base of magnetic flux tubes (the so-called dynamo region between 90 and 150 km), the conductivity here is critical to plasmasphere characteristics and magnetosphere-ionosphere coupling. This coupling involves the precipitation of energetic particles into the lower atmosphere, with possible implications for ozone and air conductivity at low altitudes. Climate effects are therefore possible.

The probability that rocket effluents could modify the electrical conductivity in the dynamo region to the extent necessary to cause climatic effects is unknown. However, this problem is being examined further.

F-Region of the Ionosphere

The electron-density profile in the F_1 -region reaches a peak (or shoulder) during the daytime and undergoes quite a large reduction at night. The F_2 -region contains the highest electron-density profile peak, $\approx 10^6$ electrons/cm³, which is reduced by about a factor of 10 at night. Beyond the F_2 peak, the electron density continues to fall off with altitude. It undergoes a rather sharp ten-fold reduction at the plasmopause (≈ 4 earth radii near the equatorial plane). The positive-ion population in the F_2 -region is dominated by O^+ ions which recombine rather slowly with electrons. Solar extreme-ultraviolet radiation is the principal source of ionizing radiation in the F-region and peak production occurs at around 160 km. The increase in electron density beyond 160 km arises from the fact that the reduction in the electron-loss rate is greater than the reduction in the ionization rate. Still higher in the ionosphere, a gradual transition to the plasmasphere occurs in which the ion population becomes dominated by protons (hence the alternate name protonosphere).

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, which begins to play a dominant role in charged-particle motion above 150 km. The mean free path between collisions increases from about 40 m at 150 km to 80,000 m at 500 km. In addition to gyrating about magnetic field lines, charged particles are

subject to drifts caused by electric fields and drag by the dense neutral atmosphere. Neutral winds (thermospheric winds) are highly variable and subject to opposing, driving energy sources that arise from near-equatorial solar radiation heating on one hand, and high-altitude, or auroral-process heating, on the other. This latter point is made to recall the fact that while electromagnetic forces control ion/electron motion, strong mechanical- and thermal-energy sources drive the coexisting neutral atmosphere. 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.

Figure 3.8 indicates some of the many plausible steps, or intermediate effects, through which the release of rocket-exhaust products may impact the environment. The ultimate impacts are depicted as ellipses. The major issues and the current understanding of them are summarized below.

F-Region Plasma Depletions. Rocket effluents (such as H_2O , H_2 , and CO_2) cause the dominant F_2 -region ions (O^+) to quickly form molecular ions (e.g., H_2O^+) which very rapidly recombine with electrons. This depletion or "ionospheric hole" can extend far beyond the local source of injected molecules and thus affect radio communication and navigation systems over a wide geographical area. The perturbation may be extended to the conjugate ionosphere (i.e., at the opposite end of the geomagnetic field line passing through a hole) via draining effects on a plasmaspheric tube or by allowing enhanced photoelectron escape from the depleted region.

The deposition of rocket-exhaust products in the F_2 -region has now been well established as a cause of ionospheric depletions. The mechanisms involved in this "hole-making" process are reasonably well-understood in general terms, but specific details require further investigation.

A detailed investigation of archived data on past launches has been undertaken in an attempt to uncover as much information as possible on upper-atmospheric effects of rocket launches. To date the investigation has found that the open literature regarding pre-Skylab (1973) rocket launches indicates that:

Fig. 3.8. Rocket-Effluent Effects in the F-Region of the Ionosphere

- Rocket injections of gases into the F-region produced localized, short-lived regions of depleted free-electron density by physically pushing the ambient plasma aside. The spatial and temporal extent of such a "snow-plow" effect was determined by the time required for the injected material to expand to ambient densities. These effects are thus altitude-associated with time scales ranging from a few seconds to minutes and spatial scales up to several kilometers from the burning rocket. No significant consequences were associated with these effects.
- Chemistry effects between rocket exhaust and the ambient ionosphere were never considered in conjunction with pre-Skylab observations of rocket effects. These are, in fact, the cause of longer-term (i.e., for periods longer than hours) and spatially-extended (hundreds of kilometers) effects, as described below in connection with the Skylab event.
- Even extremely large injections of water into the 100-150 km region distinguished themselves only by the size of the ice clouds produced.

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. The trajectory of that rocket accidentally intercepted radio-signal ray paths connecting the ATS-3 communication satellite with the ground-based observatory at Sagamore Hill in Massachusetts. The deep depression in the total electron content (TEC) observed at Sagamore Hill after the rocket passed the intersection point is shown in Fig. 3.9. Based on observations made at four other ground-based observatories whose lines-of-sight with ATS-3 also were intercepted by the resulting depleted region, it was reported that the "ionospheric hole" had a radius of about 1000 km and lasted for about four hours.²⁵ An attempt to simulate or more appropriately "match" the observed data of that ionospheric depletion found that a hole observed by ground-based stations could have drifted out of the line-of-sight of the observations along magnetic field lines. Furthermore, if typical thermospheric winds existed at the time (unfortunately no observations were in progress), then the residual rocket-exhaust products not consumed in the initial depletion process could have been transported to adjacent ionospheric regions to eat away additional electron/ion pairs. This effect of winds, or movement of neutral atmospheric constituents (which are far more abundant than the ions and electrons), would result in the effective displacement of the hole.

Fig. 3.9. "Hole" Seen in Total-Electron-Content Measurement of Ionosphere by Sagamore Hill Observatory (Source: Ref. 25)

The first successful attempt to produce an ionospheric depletion under controlled experimental conditions occurred in September 1977 (see Ref. 26). Project "Lagopedo," as it was called, involved two rocket-borne experiments. Each rocket carried 88 kg of high explosives and an instrument package that was separated from the rocket prior to detonation of the explosive. The detonation products included about 30 kg of H_2O , 16 kg of CO_2 , and 20 kg of N_2 .²⁷ These experiments generally confirmed theoretical predictions of an initial period of several seconds during which the ambient plasma was swept away by the rapidly-expanding detonation cloud over a distance of less than 1 km followed by a much larger-scale plasma-depletion process lasting for at least 30 minutes and extending over a radius of 30 km or more. In addition to the rocket-borne instrument package, which only sampled the disturbed area for two to three minutes, ground-based instruments monitored the "hole" for about 30 minutes. A major finding of these two experiments was the importance of the suppression of 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).

Efforts to understand the hole-making phenomena are now underway at several laboratories. As a result of these efforts a variety of one-, two-, and three-dimensional models are now available that treat the various physical, chemical, and electromagnetic processes that occur in both the natural and perturbed ionosphere. But additional work will be required before the consequences of even single rocket launches can be predicted with confidence. The major points of uncertainty at this time seem to be the combined effects of phase changes, horizontal advection by neutral winds, horizontal and vertical diffusion, and gravitational settling. These combined effects must be understood in order to predict the transition from an isolated, local, spherically-expanding cloud of chemically-reactive injectants to the realistic picture of pollutants being periodically injected along rocket trajectories and subjected to complex physical transport and chemical processes.

The evaluation of the environmental significance of forming "holes" once or twice per day remains to be done. Some other effects associated with "hole" formation and some possible consequences of these effects are summarized below.

Model calculations show that ionospheric depletions produce 2000°K and 50°K increases in electron temperature during the day and night, respectively.²⁸ These temperature changes have a small effect on the plasma concentration and may consequently affect navigation or communication. Neutral atmospheric temperatures are not expected to be affected by these electron-temperature changes because the neutral density is a thousand times greater than the electron density in the F-region.

Another effect is the draining of the plasmasphere due to the depleted F-region. Plasma diffusing parallel to the earth's magnetic-field lines would attempt to fill in the F-region hole. A large portion of the plasmasphere could be affected. Absence of this plasma may increase the lifetime of Van-Allen belt energetic particles which would increase the energetic-particle radiation dosage of satellites. This possible chain of events is illustrated in Fig. 3.10. It is unknown whether these events would in fact take place and affect particles in the Van Allen Belt.

Generation of Plasma Instabilities. Both the ionospheric depletions described above and disturbances caused by acoustic gravity waves generated in

Fig. 3.10. Possible Chain of Events Linking F-Region Depletion to Atmospheric Effects

the wake of a rocket or by its rapidly expanding exhaust cloud can cause plasma instabilities or irregularities in the equatorial ionosphere. Such irregularities may give rise to a form of radiowave interference called "spread-F." The main characteristic of spread-F is that it yields a widened echo trace on the ionosonde record (radio frequency reflections vs. altitude). The widened echo trace results from the alignment of the irregularity structures along the magnetic field lines, which are horizontal in the equatorial region. The occurrence of spread-F as a result of rocket-produced ionospheric depletion has been predicted.^{29,30} During the Spacelab-2 mission (currently planned for 1981), plans call for monitoring the ionosphere during a specially-designed burn of the space-shuttle orbital engines near the geomagnetic equator in order to look for the predicted spread-F.

Enhanced Visible Air Glow. As described earlier, rocket-exhaust effluents enhance the formation of molecular ions that rapidly recombine. The dissociative recombinations of the molecular ions and other secondary processes lead to airglow emissions. The dominant visible airglow would be the emission at 630.0 nm from the singlet-D state of oxygen atoms $O(^1D)$. These atoms are produced in the excited singlet-D state by the reaction $O^+ + H_2 \rightarrow OH^+ + H$, followed by the dissociative recombination reaction $OH^+ + e^- \rightarrow O(^1D) + H$. Intensities could range up to 10 kilo-Rayleighs. The airglow is quite useful

for ground-based diagnostics of the aeronomy of the ionospheric depletion processes and has been observed in a number of cases, including the Lagopedo experiments.²⁶

Changes in the Hydrogen-Atom Cycle of the Upper Atmosphere. The injection of large amounts of H_2O or H_2 could ultimately lead to two hydrogen atoms per molecule being added to the thermosphere. Increased hydrogen abundance in the topside ionosphere (above 300 km) could enhance satellite drag at high altitudes, affect Van-Allen-Belt precipitation rates, and thus possibly influence radio communication systems sensitive to plasma irregularities (scintillation effects) caused by energetic particles.

Recent calculations indicate that the number of hydrogen atoms that could reach the upper thermosphere because of injection of H_2O and H_2 during the second-stage burn of an HLLV from 60 to 120 km is larger than previously thought. These calculations showed that, during the first 30 hours after the launch, about 1.3×10^{31} hydrogen atoms would be produced at the expense of about 20% of the exhaust molecules. This means that over a five-day period the number of H atoms produced would about equal 15% of the total thermospheric H-atom inventory above the mesopause. Because an HLLV would be launched once or twice per day, the total H-atom production after five days would about equal the total number of hydrogen atoms naturally present. However, the real question is, "How rapidly are water molecules injected relative to the rate at which they naturally migrate upward from the lower atmosphere across the mesopause?" The natural flux of water molecules across the mesopause leads to a rather large natural flux of H atoms upward through the thermosphere to the exosphere, where they replace those H atoms that naturally escape from the earth's gravitational field into outer space. Hence, the problem is to obtain a better understanding of this natural process and then to examine the effect of the perturbation caused by the exhaust products.

Alteration of Ion Mixture in the F_2 -Region. The decreased electron concentration in the F_2 -region caused by the introduction of water leads to a decrease in the rates of chemical reactions involving electrons. This results in substantially larger-than-normal concentrations of NO^+ . Practical consequences of this phenomenon are unknown.

Effect on the F₂-Region of Modifying the Magnetosphere. Perturbations in the magnetosphere are likely to alter the rate of precipitation of high-energy particles into the F₂-region. The natural precipitation process causes both ionization and heating in the mid- or upper-latitude thermosphere, as mentioned earlier. The impact of artificial changes in the precipitation rate is unknown at this time. Presumably, satellite drag (thermospheric orbits) and radio communications could be affected, as illustrated in Fig. 3.11. The nonauroral F-region has horizontal magnetic-field components that could contribute to the formation of structured irregularities (resulting from the ionization produced by precipitation) that could produce radio-wave scintillations. These effects are judged to be relatively unimportant at this time.

Heat-Balance Effects of Injected Water in the Upper Thermosphere. The infrared emissivity of water is orders of magnitude larger than the emissivity of the normal thermospheric constituents O, H, or N₂. Therefore, the introduction of water molecules in the 150-500 km altitude range could increase the radiative cooling rate and consequently lower thermospheric temperatures. This could lead to a decrease in the thermospheric density and a lowering of low-energy-trapped-particle precipitation rates and an increase in radiation flux levels within the Van Allen Belts (possible impact for space

Fig. 3.11. Changes in the Magnetosphere and Consequences for the F₂-Region of the Ionosphere

operations). Because there are several competing mechanisms that operate to raise or lower the thermospheric temperature, the net effect of all of these mechanisms must be evaluated together. Such an evaluation has not yet been made.

Increase in Infrared Emission Density. Molecular species in the rocket exhaust could react in the F-region, producing vibrationally-excited molecules, for example: $\text{CO}_2 + \text{O}^+ \rightarrow \text{CO}^* + \text{O}_2^+$ or $\text{H}_2\text{O}^+ + \text{e}^- \rightarrow \text{OH}^* + \text{H}$. The CO^* or OH^* could radiate blanketing infrared radiation. This could interfere with space and optical systems, including infrared astronomical observations. The likelihood of this occurring is unknown at this time, but the potential impacts could be important.

3.5.5 Plasmasphere and Magnetosphere

As was shown in Fig. 3.1, the plasmasphere and magnetosphere are the outermost regions of the atmosphere. Fig. 3.6 (page 118) presented a simplified cross-sectional view of these regions in a plane perpendicular to the earth's orbital plane. Note that the sun is to the left of the picture and that the dotted line passing through the object labeled SPS represents a magnetic flux tube. The orbital plane of the SPS satellite is perpendicular to the page. The rather dramatic departure from a simple magnetic dipole field results from the interaction of the earth's field with the stream of charged particles that constitutes the solar wind. Aside from distorting the field lines, this interaction plays an important but not completely understood role in various auroral and perhaps other processes that influence upper-atmospheric dynamics and terrestrial radio communications. Recently, serious consideration has been given to the role that such interactions may play in tropospheric weather. In fact, the so-called "solar weather effect" was the subject of a symposium/workshop entitled "Solar-Terrestrial Influences on Weather and Climate" held at Ohio State University in July 1978.³¹

The two SPS-related sources of disturbance of the natural plasmasphere and magnetosphere would be (1) the rocket effluents used to propel the cargo-carrying vehicles and personnel-carrying vehicles from low earth orbit to geosynchronous orbit, and (2) the presence of the satellite structures themselves (including debris). Figure 3.12 illustrates these sources of distur-

Fig. 3.12. Identified Causes and Effects of Magnetospheric Impact

bance and some potential impacts. Based upon the anticipated relative importance of these two sources of disturbance, most of the efforts during FY 1979 and FY 1980 are being devoted to the rocket effluents. It is hoped that Project SCATHA (Space Charging at High Altitudes), along with other targets of opportunity, will address some of the issues of lesser priority under the second category of sources of disturbance.

The expected rocket effluents would be of two types: chemical exhaust products from the POTV and argon ions (Ar^+) and electrons from the ion propulsion system of the cargo orbit-transfer vehicle (COTV). Some additional chemical and Ar^+ propellants would also be used to control position and attitude during occultations of the satellites and COTVs. The annual rate of injection of these effluents, assuming that two 5-GW satellites would be constructed per year, has been estimated to be:³²

$\text{H}_2\text{O}/\text{H}_2$: 1×10^{33} (H atoms)

Ar^+ (& e^-): 4×10^{32}

Energy $\equiv$ 15 megatons of high explosive (MT-HE)

To place these numbers in perspective, one can compare them with ambient loading of material:³²

500-1000 km	2×10^{32} H atoms
1000 km-4 earth radii (plasmopause)	1×10^{32} H atoms
4-7 earth radii (GEO)	3×10^{29} H atoms
500 km-GEO	4×10^{25} Ar^+ ions
Thermal kinetic energy	0.01 MT-HE
Energy involved in magnetic substorms in the vicinity of the plasmasphere	7-70 MT-HE

In terms of particle numbers alone, the SPS input would obviously be quite significant. However, to be more physically meaningful, one ought to include in such comparisons some consideration of effluent rates relative to natural residence times, more specifically, the use of a perturbation factor (PF) defined by:

$$\text{PF} = (\text{injection rate} \times \text{residence time in region}) \div \text{ambient loading}$$

The residence time is a difficult quantity to estimate. It is the average interval between a molecule's deposition in the region and its removal by either chemical reaction or transport out of the region. Bauer³² suggests the following residence times based on Ref. 33: 500-1000 km, 1 day; 1000 km-plasmopause, 10 days; and plasmopause-GEO, 100 days. In order to roughly estimate PF for H atoms and Ar^+ ions, one can input the total values for the entire region from 500 km to GEO and use a transport time of 10 days. This leads to values of about 10,000 and 200,000 for H atoms and Ar^+ ions respectively. These values suggest that the Ar^+ -ion input would be quite important and that the H-atom input might be important, especially at the higher altitudes. In addition to this direct input of H atoms, the HLLV second-stage rockets, which would burn up to 120 km, and the circularization and deorbit burns also would inject H atoms at 500 km, some of which would diffuse upward into the 500-1000 km region. The annual injection rates for these sources would be 7.4×10^{34} and 1×10^{33} H atoms for the HLLV second stage and circularization-plus-deorbit burns, respectively. If a significant fraction of the H atoms from these latter sources did indeed migrate into the plas-

masphere, they, when combined with the direct plasmaspheric sources, would yield a larger PF value. The implication of PF values of 0.1 to 1.0 is unclear. Of primary concern is the effect that such additions of H atoms might have on the natural H-atom-cycle processes. It is likely, for example, that the addition of large quantities of H_2O and H_2 could influence the energy balance in the upper thermosphere and plasmasphere as well as the escape rate of H atoms into outer space.

The injection of Ar^+ ions as indicated above could potentially be an important disturbance above 500 km. The results of this injection are currently being examined in some detail using available information and state-of-the-art modeling methods. Theoretical studies indicate that as the beam of Ar^+ ions and free electrons is ejected from the ion engines, it interacts with the earth's magnetic field in an inelastic manner, transferring energy to the field and subsequently to electric currents at the point in the auroral regions where the field lines enter the ionosphere. These currents are partially dissipated due to ohmic losses and consequently heat energy is transferred to the thermosphere in a manner similar to natural, high-latitude thermospheric heating processes.

One consequence of this energy transfer process is that the ion beam may be stopped, relative to the field lines, within about 1000 km of the ion engines before charge exchange has taken place. The proposed stopping process is illustrated in Figs. 3.13 and 3.14. The distribution of the ions and electrons after ejection over a short segment of the rockets' trajectory around the earth is shown in Fig. 3.13. Note that the effluents are restricted to a relatively thin shell in the radial or "y" direction, but are spread out along the entire field lines from pole to pole (only the northern hemisphere is shown). Figure 3.13 also shows a wavy line on one of the magnetic field lines. This is supposed to represent an Alfvén wave as it propagates along the field line. Alfvén waves are low-frequency, transverse plasma waves that can be generated when a plasma is embedded in a magnetic field. Figure 3.14 schematically represents the process of generating these waves. Not unlike a boat moving through water and generating surface water waves in its wake, the beam deforms the field lines as it moves through the magnetic field. This distortion can be represented as the production of Alfvén waves that propagate poleward along the field lines. In the polar

Fig. 3.13. Dispersion of Ar^+ Ions after Beam Injection

regions electric currents are set up so that part of the energy carried by these waves is reflected back along the field lines and part is transferred to the polar atmosphere via ohmic heating. Therefore the process of distorting the field lines results in the ion beam doing work on the magnetospheric system. This heat energy source is estimated to be comparable to that which naturally accompanies magnetic storms.

Recalling that such auroral processes are an important source of heating of the thermosphere (along with the absorption of solar-UV radiation

Fig. 3.14. Ar^+ -Ion Beam Wake in Magnetosphere

in lower latitudes), such a perturbation may have important consequences. For example, the heat input associated with the Ar^+ exhaust might have a tendency to change the plasmaspheric composition by allowing the naturally-present O^+ ions to be forced up higher into the plasmasphere where the radiation belts are located. Principal components of the plasmasphere before and after the hypothesized heating process are shown in Fig. 3.15. A possible consequence of this is that the mechanisms naturally contributing to the instability of the Van Allen Belts are suppressed. This implies that the lifetime of trapped particles will be increased and that the corresponding radiation levels in the Van Allen Belts will be enhanced. This could lead to adverse effects on materials and people passing through or residing in these regions. (The lower Van Allen Belt lies within the plasmasphere while the outer belt

Fig. 3.15. Principal Components of Plasmasphere Naturally and after Heating

lies just below GEO.) It is estimated that the suggested suppression mechanism could lead to an increase of the radiation-belt electron level by as much as a factor of two or three.

Main Issues Associated with Rocket Effluents

Injection of Ar^+ Ions. Ar^+ -ion engine exhaust may alter the time-dependent dynamics, thermal structure, and composition of the plasmasphere. Based on the work described above, such effects seem highly likely and are expected to be quite important.

Generation of Plasma Instabilities. Thermalization of the exhaust ion beam or a portion thereof and subsequent diffusion of the exhaust plasma cloud by plasma instabilities could cause plasma striations and global-scale scintillation of space-based communication and navigation signals. It is unknown at the present time whether significant communication interference would arise. However, if it did, this could be an important impact.

Alteration of Physical Structure of Magnetosphere and Plasmasphere. An argon-contaminated plasmasphere may alter mid-latitude, ionospheric-trough formation processes and coupling processes between the ionosphere and magnetosphere. There is a possibility that multiple plasmapauses would form at the equatorial plane. This would change the magnetospheric convection pattern and consequently the location of the auroral oval. This, in turn, could induce power-line surges at population centers in the event of magnetospheric storms. The probability of occurrence of these phenomena is unknown, but the consequences could be important. Electric current surges in power lines and long-haul telephone lines resulting from natural magnetic storms have been reported in North America.³⁴⁻³⁶ Therefore, there is a connection between natural disturbances of the magnetosphere and terrestrial impacts. What is lacking is any concrete evidence that manmade disturbance will be of sufficient magnitude to cause similar impacts and, furthermore, whether the location of the auroral oval can be shifted by such disturbances.

Enhancement of Airglow. Increased airglow due to precipitated 500-eV Ar^+ ions and 5-eV thermalized electrons may impact space-based optical sensors

for military, scientific, weather, and earth resources applications. The probability of occurrence and the severity of the impacts, if any, are unknown.

Disturbance of Van Allen Belts. The Van-Allen-Belt particle distribution may be affected by rocket activity. The addition of "cold" heavy ions (such as Ar^+) may stabilize trapped relativistic electrons and increase energetic particle density. Cold plasma with light mass (such as photoelectrons emitted from the SPS) would dump Van Allen particles. An alteration of trapped radiation could have an effect on the lower atmosphere (e.g., cause a change in the character and frequency of relativistic electron precipitation, possibly affecting ozone and atmospheric electricity). The probability of this effect occurring is unknown but the potential impacts are important.

Plasma-Sheet Disturbances. Ion exhaust and chemical exhaust gases from attitude-control systems could interact with plasma-sheet particles. Magnetospheric convection patterns or ionospheric conductivity might be altered. If so, then the auroral oval might be located over population centers. During magnetospheric storms, power-line surges may be induced, as mentioned above. The likelihood of this effect is unknown, but the impact could be significant.

Changes in Auroral Current Systems. Would exhaust gases deplete the F-region at auroral latitudes? If so, they could affect auroral field-aligned current systems by either altering ionospheric conductivity or depleting sources of current carriers. Both the probability of occurrence of this effect and the severity of any impact are unknown.

Magnetosphere/Solar-Wind Interaction Changes. Rocket-exhaust gas or ion-engine exhaust in GEO might alter the solar-wind flow past the magnetosphere. Variations in the magnetosphere or solar wind could affect terrestrial weather. Such effects are highly uncertain, but any effect on climate would be considered important.

Main Issues Associated with Satellite Structure

The SPS satellite structures themselves may have some effects, at least on the satellite environment, if not on the lower terrestrial environment.

Several issues regarding such effects are summarized below. None of these issues are considered sufficiently important with respect to the SPS environmental assessment project to warrant a high priority for near-term study.

Obstruction to Plasma Flow. Large space structures would physically obstruct the plasma flow, causing, for example, the absorption of ions or electrons on the structure surface. This would deplete ionization in the Van Allen Belt (the rate of replenishment is uncertain). Passage of a solar-power satellite through the GEO environment would also generate plasma waves and form a large wake behind the structure (this could impact the orbital placement of multiple solar-power satellites or other GEO satellites).

Catastrophic Accidents. A "worst-case" analysis should be made of possible catastrophic SPS accidents, such as an impulsive release of all its fuel at GEO. Although unlikely to occur, such a failure could have dangerous effects.

Surface Weathering as a Source of Particles. The exposure to high-energy particles and solar radiation would result in ion emission, sputtering, and weathering of SPS surfaces. This would greatly enhance pollutants and dust at GEO.

Electromagnetic Disturbances. Local magnetic and electric field distortions in the vicinity of the SPS could trigger auroras, alter particle trajectories, short out magnetospheric electric fields, and otherwise affect magnetospheric convection.

Space Debris. The physical presence of 60 SPS satellites in GEO and their assorted space debris would result in a miniature asteroid belt representing a significant navigational hazard.

Visible and IR-Radiation Source. The system of satellites would represent a source of light and infrared radiation. This source could interfere with astronomical observations in and near the equatorial plane. This issue is addressed in Section 5.

High-Energy Electron Generation. High energy electrons would be generated in and near the SPS-microwave transmitters. Not only would these particles be a potential hazard to personnel, they would ultimately enter the environment near the solar-power satellite as a contaminant population.

3.6 CONCLUSIONS

3.6.1 Troposphere: Rocket Effluent Effects

An assessment of the air quality impacts of the HLLV, if launched from Kennedy Space Center, has shown that:

- The sulfur dioxide concentration would not be a critical problem.
- Nearly all of the carbon monoxide would be oxidized to carbon dioxide.
- The amount of nitric oxide formed would probably be negligible.
- Acid rain might occur near the launch site if sulfur was present in significant quantities in the fuel. Nitrogen is also a potential source for the formation of acid rain but thus far this possibility has not been evaluated.

Future study should include assessments for other generic geographic launch sites, improved estimates for accumulative effects, and characterization of aerosols and particulate matter in the launch cloud.

Valuable but limited information has been gathered regarding inadvertent weather modification due to rocket launches. Because the possibility for inadvertent weather modification by the SPS rocket effluents would be rather high and because cumulative effects would be possible, continuing monitoring of rocket-exhaust ground clouds is needed. Simulations (using computer models) of inadvertent weather modification by HLLV launches under various meteorological conditions are also required to improve the assessment.

3.6.2 Troposphere: Rectenna Operation Effects

Estimates of the local and mesoscale weather and climate effects of waste heat from an SPS rectenna indicate that impacts would generally be small, but would be detectable in some instances. The absorption of

microwave power in the troposphere is expected to be worst during rain storms, but even then would have a negligible effect on the weather. The possible effect of natural atmospheric conditions on microwave-beam propagation and the associated power-beam and pilot-beam stability needs further study.

3.6.3 Stratosphere and Mesosphere

Carbon dioxide emissions due to rocket launches would be expected to have no detectable effect on the upper atmosphere. However, water vapor concentrations could be significantly affected by SPS-related rocket-exhaust emissions. The change in the total ozone column due to SPS spaceflights would be expected to be undetectable, as would the effects of nitrogen oxides. 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. Corridor-effect calculations are important to an improved assessment of the SPS perturbations of the upper atmosphere's composition.

The global impact of the anticipated upper-atmospheric-composition perturbation on the earth's surface would be negligible. Reliable assessments of general climatic effects due to SPS perturbations of the upper atmosphere must await model predictions of altitude and latitude dependence. It is probable that transient noctilucent clouds would be induced in the vicinity of the launch site but they would not be expected to have a detectable impact on anything else.

Injection of energy into the stratosphere and mesosphere due to thermal energy from rocket exhausts or absorption from the microwave beam would not be expected to cause significant environmental impacts.

3.6.4 Ionosphere

The lowest layers of the ionosphere (the D- and E-regions) could be affected by both rocket launches and spacecraft reentry. The effluents from these space operations include water vapor, hydrogen gas, and thermal energy during launch, and ablated materials, oxides of nitrogen, and thermal energy during reentry. These effluents would modify the composition and properties of the ionosphere and might influence climate, satellite-based surveillance systems, radio communications, navigation systems, microwave propagation (SPS power-beam stability) and magnetospheric processes. While the likelihood of

altering the electron and ion composition seems to be fairly high, the magnitude of the impacts is uncertain. The effects of nitrogen oxides formed during reentry and ablated materials do not appear to be important at this time. The probability of changes occurring in atmospheric electricity and the importance of such changes are also unknown. The F₁- and F₂-regions of the ionosphere are also subject to modifications in composition and structure as a result of deposition of rocket effluents during launch, reentry, and spacecraft maneuvering operations in low earth orbit. The F₂-region in particular overlaps LEO.

Calculations have shown that injection of water and carbon dioxide into the F-region results in both plasma reduction (electron-ion recombination) and enhanced airglow (visible and IR emissions from excited molecules). These predictions have been verified both inadvertently during the Skylab launch and deliberately during the Lagopedo experiments. Further work is required to determine if other phenomena, including plasma-temperature variations and instabilities, also accompany such depletions. Enhanced airglow, while not a serious matter at ground level, can contribute to the noise level of satellite-based surveillance systems. Plasma instabilities may be important sources of interference with radio communication and navigation systems. Plasma and neutral atmosphere temperature variations could lead to thermal expansion that could modify satellite drag.

3.6.5 Plasmasphere and Magnetosphere

The issues associated with SPS rocket effluents in the plasmasphere and magnetosphere include the following:

- Injection of Ar⁺ ions. Effects would be likely and would be expected to be important.
- Generation of plasma instabilities. Possibility of communication interference is unknown.
- Enhancement of airglow. Probability of occurrence and severity of impacts are unknown.
- Disturbance of Van Allen Belts and plasma sheet. Probability of occurrence is unknown but potential impacts are important.
- Changes in auroral current systems. Probability of occurrence and severity of impact are unknown.
- Magnetosphere/solar-wind interaction changes. Effects are uncertain but may be important if associated with climate.

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, electromagnetic disturbances, space debris, visible and IR radiation source, and high-energy electron generation.

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4 SPS EFFECTS ON COMMUNICATIONS SYSTEMS DUE TO IONOSPHERIC DISTURBANCE

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4.1 SCOPE

The ionosphere is the region of the earth's atmosphere in which charged particles -- electrons and ions -- exist in sufficient abundance to have profound impacts on the chemical and physical mechanisms responsible for forming and changing the atmospheric structure. The ionosphere is usually designated according to specific regions: D, E, and F, as described in Section 3.5.4. The characteristics of all regions of the ionosphere vary daily, seasonally, and in response to solar cycles (sunspots). Geophysical disturbances ultimately associated with solar variations also cause significant changes in the structure of the ionosphere.

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 sufficiently great to cause the incident EM wave to be totally reflected and returned to the earth's surface; this property permits long-distance, high-frequency, radio-wave propagation systems to operate. 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 electromagnetic-sensitive systems (i.e., telecommunication systems) whose energy is propagated within and through the ionosphere. In addition, small-scale (meters to kilometers) irregularities in the ionospheric electron density can give rise to 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.

Changes in the ionospheric structure due to SPS operations could result either from the interaction of the ionosphere with the SPS power beam (heating) or from interactions with effluent material from the launch vehicles needed to build and maintain the satellite power system.

4.2 METHODOLOGY

4.2.1 Ionospheric Heating

In order 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 the Arecibo Observatory of the National Astronomy and Ionosphere Center in Puerto Rico and the Institute for Telecommunication Sciences Ionospheric Heater Facility in Platteville, Colorado. Both facilities use high-frequency (HF) transmissions to heat the ionosphere. The energy that they deposit in the ionosphere is such that, for the D- and lower E-regions (80-100 km), equivalent SPS energy can be achieved for underdense (ohmic) ionospheric heating (i.e., heating an ionospheric region with a radio wave whose frequency exceeds the largest plasma frequency of the region). For F-region simulations, modified and expanded ionospheric heating facilities would be needed to deliver the appropriate energy density to F-region altitudes.

One area of experimental work is the simulation of SPS effects on telecommunications. These studies are conducted at Platteville, because of favorable logistics and because the communications environment of Platteville 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," which enable direct measurement of electron density and temperature in the ionosphere.

The results of the simulation of SPS effects on telecommunications can be extrapolated to the SPS operational frequency, subject to the condition that the heating is truly ohmic. The experimental work is supported by detailed theoretical studies designed to establish physically-realistic models of the ionosphere/microwave interactions that can be used to provide sound extrapolation.

SPS heating of the D- and E-regions is simulated and the effects of this heating on specific, ionospherically-reflected signals are assessed

using the Platteville facility. Signals such as those of LORAN-C (100 kHz), OMEGA (10.2 kHz), WWVB (60 kHz), WWV (2.5 MHz), and an AM broadcasting station are monitored during times when the Platteville facility is heating the ionosphere. Data obtained from heating experiments in the early 1970s also are being analyzed in order to improve the assessment of potential SPS-related effects.

In the studies of the physics of ionospheric heating, using the Arecibo facility, the thresholds for the onset of large ionospheric changes associated with heating are analyzed. The amount of enhanced heating in the lower ionosphere under SPS operational conditions is simulated and the effects of heating on ionospheric irregularities, such as sporadic-E patches, are evaluated.

The 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 link between observed telecommunications and experimental-physics effects and predicted SPS operating conditions. The changes in the lower ionosphere expected from absorption of the SPS microwave beam will be assessed. A model of thermal self-focusing effects also will be developed so that the electron-density perturbations that would be produced by SPS operation can be predicted.

4.2.2 Vehicle Effluent Effects

Techniques and data developed by the atmospheric sciences tasks of the SPS program (see Section 3) -- including two-dimensional modeling and subsequent model testing with data collected during rocket launches -- will provide usable temporal and spatial information as well as transient and stabilization information for an initial assessment of the degradation of communications systems. A limited communications and sounder-testing exercise is planned during the NASA space shuttle launches to specifically measure F-layer depletion and stabilization transients (temporal and spatial) and confirm anticipated reductions in availability of high-frequency communications links. The possible utilization of existing over-the-horizon radar facilities to assist in tracking depleted volume characteristics is being investigated.

4.3 CAUSE AND EFFECT RELATIONSHIPS

Cause and effect relationships for the interaction of SPS microwaves and the ionosphere are shown in Fig. 4.1. One cause of possible ionospheric modification by the SPS would be the large amount of energy passing through the ionosphere. Although a very small fraction of the energy would be absorbed, the energy densities presently associated with SPS passage (15-25 mW/cm²) could be sufficient to cause certain plasma/microwave interaction effects. These include:

- Thermal self-focusing: focusing of electromagnetic waves in the ionosphere, producing large-scale, field-aligned density irregularities in the F-region.
- Enhanced heating: ionospheric heating at a rate faster than normal cooling, resulting in an increased electron temperature in the D-region.
- Plasma striations: formations of irregularities in electron density along magnetic field lines.

Effluent from the heavy-lift launch vehicles needed to construct the SPS also could result in significant depletion of the ionization density in the ionosphere. Such a depletion would have adverse effects on low- and high-frequency communications systems. Although unlikely, multiple power beams from adjacent rectennas could give rise to gravity waves in the neutral atmosphere. They could cause changes in the ionosphere.

Fig. 4.1. Cause and Effect Relationships for Ionosphere Impacts of SPS Microwave Beam

4.4 STATE OF KNOWLEDGE

4.4.1 Ionospheric Heating

Because of the large amount of power (5-10 GW) that would be transmitted to the earth by each satellite, substantial modification of the ionosphere could result from direct heating. If this would occur, telecommunications systems which use the ionosphere to transmit radio energy might be affected and suffer performance degradation. Thus, the potential for ionosphere modification resulting from SPS operation must be assessed. Specific questions that need to be answered are:

- Could the SPS microwave transmission cause harmful interference effects in telecommunication systems?
- Would the microwave beam be likely to give rise to interference effects that are not permissible by standards set by the Consultative Committee on International Radiocommunications (CCIR)?
- Would the SPS power-beam transmission cause the SPS pilot-beam transmission to deteriorate?

The results of any effort to address these issues must provide quantitative information concerning SPS effects on telecommunication systems.

4.4.2 Vehicle Effluent Effects

The large launch vehicles and frequent spaceflights postulated to establish and maintain the SPS indicate a significant potential for transitory modification of the ionosphere by rocket effluents. The discharge rates and consequent ionospheric effects could exceed the F-layer density reductions noted following the Skylab launch (see Fig. 3.9). The limited data available from this previous launch suggest that the exhaust from heavy-lift launch vehicles (HLLVs) might cause large depletion areas in the F-layer of the ionosphere. Recombination and stabilization periods could extend over a 1000-2000 km region around the launch area, depending on the launch trajectory.

Potential variations in electron density resulting from SPS space-vehicle activity could lead to reduced ionosphere channels for operation of middle and upper frequencies in the high-frequency (HF) portion of the spectrum. To assess this impact it will be necessary to use the results of

theoretical studies. Initial studies will be verified subsequently by observing effects of future space-shuttle launches on telecommunications systems.

Table 4.1 lists the types of telecommunications systems that could be adversely affected by ionospheric changes associated with SPS operation. It must be pointed out, however, that not all potential telecommunications impacts would be adverse. Frequencies above HF are propagated through the ionosphere at a speed less than that in free space. If SPS operation caused a substantial decrease in the ionospheric density, these waves would not be slowed down as much, and conceivably an improvement in the performance of such systems could result (see Ref. 1*).

Table 4.1. Potential Telecommunications Impacts of the SPS

Ionospheric Effect	Systems Affected	Impact
D-region absorption	HF communications	Signal loss
Phase-path change	VLF navigation	Position errors
Electron depletion	HF communications	Reduced maximum usable frequencies (MUF)
	SPS	Displaced beam
	High-frequency direction-finding (HFDF), HF radar	Position errors, tilts
Irregularities	HF, VHF, UHF broadcast	Cochannel interference
	HF communications	MUF, coverage modifications
	VHF, UHF communications	Long-range propagation
	HF, VHF, UHF radar	Spread clutter
	Satellite communications	Signal scintillation
	Satellite navigation	Position errors
	HFDF	Position errors
Traveling waves	HF communications	MUF changes, fading
	HFDF, HF radar	Position fluctuations, fading
Intermod, harmonics	Radio astronomy, others	Radio frequency interference

*References for Section 4 are listed in Section 4.7.

4.5 ASSESSMENT

4.5.1 Underdense Ionospheric Heating

All of the SPS ionosphere/microwave interactions currently thought to be important would at least initially be driven by ohmic (underdense) heating. Ohmic heating of the ionospheric plasma and the resultant thermal forces may drive secondary phenomena, such as enhanced electron heating or thermal self-focusing of the microwave beam.² These interactions do not necessarily increase linearly with their driving force (ohmic heating) and may occur on microscopic or macroscopic scales. Microwave radiation propagating through the ionosphere would be damped by collisions with free electrons. The fraction of wave energy absorbed by the plasma would be expected to be small; however, because the absorbed energy would go directly into the free electrons, whose effective heat capacity is very small, the resulting ohmic heating could significantly affect the local ionospheric thermal budget.

Ohmic heating of the lower ionosphere by the SPS microwave beam would increase the kinetic temperature of local electrons, which in turn would increase the electron-neutral collision frequency but decrease the electron cooling rate. Collisions should prevent the formation of field-aligned irregularities in the lower ionosphere. Plasma striations, although unlikely, could cause communications effects in the upper ionosphere. Strong, local plasma heating frequently results in plasma turbulence, which contributes to scintillations of ground-to-satellite signals. The uplink pilot beam between a rectenna and an SPS satellite could be affected if this occurred. These striations can result from the self-focusing instability.

Considerable knowledge exists concerning the effects of large amounts of heating on the ionosphere. However, most of the theoretical and experimental work has focused on the "overdense case," i.e., the case where the ionospheric density is sufficient to reflect the incident heating frequency (see Section 4.5.2). The experimental studies have been confined primarily to heating using frequencies below 10 MHz. Hardly any experiments have been performed that attempt to heat the ionosphere at frequencies greater than HF. Most of the theoretical work has considered the ionosphere's response to high-powered, high-frequency radio waves that are reflected from the ionosphere. Thus, in order to arrive at this preliminary assessment of SPS-

induced heating, it has been necessary to rely heavily on theoretical extrapolation of results obtained from HF heating³ to frequencies corresponding to the satellite power system. The overdense heating experiments that have been conducted at Platteville and Arecibo are well-documented in the literature.⁴ Both theory and experimental data are being investigated in order to resolve differences between observations and predictions.

An initial experiment designed to produce and observe enhanced electron heating in the lower ionosphere was conducted at the Arecibo Observatory in June 1978. The 430-MHz incoherent scatter radar was used both as a heater and a diagnostic tool. The transmitter is capable of pulses up to 10 ms in length with a peak pulse power of 2.5 MW. This system yields a peak power flux of approximately 1.8 mW/cm^2 within a 300-meter-diameter beam at an altitude of 100 km. When the frequency is scaled to that of the solar power satellite, the 1.8 mW/cm^2 corresponds to a power flux of 58 mW/cm^2 at 2.45 GHz. This is well above the theoretically predicted threshold for enhanced electron heating. Temperature increases of 150-250 K above ambient were observed in the altitude range of 88-100 km.⁵

The Arecibo results have recently been studied in detail; it has been shown that the pulse lengths used in the 430-MHz experiment (6-9 ms) were too short for the electrons in the lower ionosphere to be heated to steady-state temperatures.⁶ Thus the additional heating observed during the June 1978 experiment is not indicative of what could occur as the result of SPS operation, which would involve continuous heating of the ionosphere. Pulse lengths of 15-20 ms are believed to be needed in order to achieve steady-state temperatures in the ionosphere at heights of 100-120 km.⁶ Using the continuous heating capabilities of the Platteville and Arecibo facilities, the ionosphere will be subjected to high-powered radio waves that can produce the steady-state temperature needed to simulate SPS operations.

Attempts to simulate the SPS effects on the performance of specific telecommunications systems have been undertaken recently at the Institute for Telecommunication Sciences. Using the electron density profiles generated by Perkins and Roble³ as indicative of the ionospheric structure resulting from the passage of an SPS power beam, the Institute has numerically simulated the performance of a high-frequency circuit operating from Washington, D.C., to Albuquerque, New Mexico. Similar profiles, generated for conditions

when SPS operation is absent,³ have also been used to simulate HF-circuit performance in order to help assess SPS impact on such circuits. The results show that the maximum usable frequency could be reduced by 15% and the overall reliability decreased by 20% if the HF circuit passed through the SPS-heated ionosphere.

4.5.2 Overdense Ionospheric Heating

As indicated in the previous section, almost all attempts to heat the ionosphere using high-powered radio waves have been undertaken for the "overdense" case. This is particularly the case for F-region heating. The heating that is caused by radio waves reflected from the ionosphere results from deviative absorption of the radio waves.⁷ This contrasts markedly to the ionospheric heating that would result from the passage of the SPS microwave power beam through the ionosphere - the "underdense" case. It is believed that SPS-induced heating would be purely ohmic in nature and the resulting changes in ionospheric electron density and temperature would be due to instabilities related to thermal processes.

There is substantial reason to believe that the spectrum of ionospheric irregularities produced by overdense heating differs significantly from that anticipated from underdense heating. Similarly, the effects of overdense heating on the performance of telecommunications systems cannot be extrapolated with any degree of confidence to those of underdense heating. It is worthwhile, however, to briefly review telecommunications impacts that were observed during the intensive overdense ionospheric-heating experiments conducted in the early 1970s. This review will indicate how ionospheric heating can affect telecommunications systems performance. Only coordinated telecommunications and underdense ionospheric heating experiments can lead to a realistic simulation of SPS-induced effects.

The primary source for the material summarized below is a special issue of Radio Science from November 1974 dealing with ionospheric modification by high-powered radio transmissions.⁴

Effects Observed at Very Low Frequency (VLF) and Low Frequency (LF)

Observations have indicated that the modulation radiated by a high-frequency, high-powered radio transmitter can be transferred to VLF and LF radio waves reflected from the D-region of the ionosphere.⁸ The observations reported were of conventional cross-modulation effects wherein the modulation of a high-powered radio wave was transferred to another wave that passed through the region of the ionosphere that was disturbed by the modulating wave. Cross-modulation effects were observed on frequencies of 20 kHz and 60 kHz when the Platteville high-powered transmitter was operating at 5.1 MHz and 7.4 MHz.

The heating frequencies used in the experiments (5-10 MHz) were not reflected by the lower ionosphere but passed through it. The lower ionosphere was heated using modulating frequencies that involve processes that rather closely approximate ohmic processes. The increase in electron temperature in the lower ionosphere resulted in an increase in electron-collision frequency, which in turn affected the propagation characteristics of the VLF and LF waves that were reflected from the region where substantial heating was taking place. The ionospheric heating was produced by processes that are believed to be similar to those expected for the underdense SPS ionospheric heating. More recent analysis of VLF and LF data taken during times of high-powered, HF heating has been undertaken.⁹ A theory has been developed that demonstrates that the reflection process of VLF and LF waves in the D-region is changed by the passage of high-powered, HF waves through the D-region.

Effects Observed at Medium Frequency (MF)

No observations of telecommunication systems operating at medium frequency in conjunction with intentional ionospheric heating have been reported in the literature.

Effects Observed at High Frequency (HF)

A substantial amount of data has been collected that deals with the effects of F-region changes induced by overdense heating on the performance of HF radio systems. The first direct evidence of intentional ionospheric modification was obtained using a vertical-incidence ionosonde.¹⁰ The ionosonde measures the time delay between transmission and subsequent reception of

a radio wave after it is propagated vertically into and reflected by the ionosphere. Such phenomena as artificial spread-F (a manifestation of heater-induced irregularities in electron density) and wide-band attenuation appeared to be regular and repeatable occurrences.

Substantial ionospheric effects caused by heating have been observed using a high-frequency, phased-array radar.¹¹ The phased-array radar was chosen for the experiment because of its sensitivity to heat-induced changes in the ionosphere. The radar was used to study the angular spectrum of spread-F returns from the ionosphere modified by the Platteville heater. The observations obtained indicated that the radar signal was broadened in range and Doppler and angular extent by the irregularities produced by the heater.

High-frequency (and VHF) backscatter-radar observations have been made in experiments that used the Platteville heater along with radar located in New Mexico.¹² Irregularities produced by the heater gave rise to signals that were scattered back to the radar (backscatter) directly from the modified region of the ionosphere. The principal characteristics of the scattered return signals included:

- The echos generally appeared and disappeared with the turning-on and turning-off of the heater.
- The range depth of the scattered return was comparable to the size of the heater beam in the ionosphere.
- The Doppler spectrum of the returns was narrow (2 Hz at 30 MHz).
- The equivalent scattering cross-section of the heated volume varied substantially with time of day and decreased monotonically with increasing frequency.

These measurements, as well as others using a network of oblique HF sounder paths operating in the southwest United States,¹³ clearly demonstrated that the ionospheric irregularities that caused the observed HF effects were aligned along the earth's magnetic field lines. The results of the experiments using the network of sounder paths demonstrate a strong aspect sensitivity; i.e., the propagation path was nearly perpendicular to the field line that contained the electron-density irregularities. The radar cross-sections obtained from both of the studies mentioned above indicate that cross-sections on the order of $1 \times 10^5 \text{ m}^2$ to $1 \times 10^8 \text{ m}^2$ between frequencies of 20 MHz and 70 MHz could result from the heated ionospheric volume.

Detailed models of the irregularities that give rise to scattering of radio waves in the HF (and VHF and UHF) portion of the frequency spectrum have been developed.^{14,15} These models are based on the observations discussed above and are dependent upon the fact that the radio waves heating the ionosphere are reflected from the ionosphere.

Effects Observed at Very High Frequency (VHF) and
Ultra High Frequency (UHF)

Radio waves propagated at VHF and UHF have been observed to be scattered by irregularities in electron density that were created by overdense ionospheric heating. Radar located at White Sands, New Mexico, that illuminated the ionosphere above the high-powered Platteville transmitter was used to observe backscatter at VHF and UHF.¹⁶ The frequencies employed were 157.5 MHz and 435 MHz. Two distinct scattering modes were determined: one at the radar frequency, f_R , and the other at a frequency shifted from f_R by an amount equal to the heater frequency f_H . The scatter mode observed at f_R was highly aspect-sensitive. The mode corresponding to the shifted frequency, $f_R \pm f_H$, depended much less on the magnetic aspect. Both of the scatter modes were found to turn off and on in response to ionospheric heating and the spectral width of both modes was observed to be rather narrow - on the order of 10 Hz.

VHF and UHF scatter modes of propagation have also been observed using a bistatic radar system.¹⁷ These experiments utilized transmitters and receivers located at White Sands, New Mexico, and Stanford, California. The results obtained support the findings mentioned above (Ref. 16) that there are two different scatter modes. The scatter cross-section for the mode that was highly aspect-sensitive was found to be largest for the lower frequencies employed in the experiment: $4 \times 10^6 \text{ m}^2$ at 49.8 MHz compared to $3.2 \times 10^3 \text{ m}^2$ at 423.3 MHz. The scatter cross-section for the mode that was independent of the geomagnetic aspect was found to increase with increasing frequency (4 m^2 at 49.8 MHz to 16 m^2 at 435 MHz).

The aspect-sensitive, field-aligned ionospheric irregularities created by overdense ionospheric heating could be used to design point-to-point VHF communication circuits.¹⁸ Experiments have shown, for example, that facsimile can be transmitted via 30 MHz and 50 MHz scatter from heater-induced iono-

spheric irregularities.¹⁹ While the usefulness of such a communication system would be severely limited by the geometrical considerations concerning irregularity location and aspect sensitivity, as well as by the locations of the transmitter and receiver, inadvertent interference to existing systems would be possible, particularly under selected geometrical conditions.

Detailed studies have been undertaken to obtain realistic estimates of the scattering cross-section of the irregularities created by overdense ionospheric heating. In addition to the references already mentioned, two other articles have described attempts to model VHF/UHF scattering cross-sections.^{15,20} The scattering cross-section is very dependent on the electron-density irregularity, which in turn depends on the causative mechanisms accompanying overdense ionospheric heating.

Effects Observed on Satellite-Ground Signals

A limited program of satellite-ground reception observations has been undertaken, including an experiment that obtained observations from both geostationary and orbiting satellites whose signals passed through a region of the ionosphere modified by the high-powered Platteville transmitter.²¹ The observations indicate that scintillation (rapid fading of signal amplitude) of VHF/UHF signals occurs and that the depth of scintillation varies inversely with frequency and is in agreement with the phase-path theory of satellite scintillation.

Conclusions

As was discussed at the outset of this section, the effects of ionospheric heating on telecommunications system performance have generally been obtained for the case of overdense heating. The results described for effects observed in the F-region are valid only for ionospheric heating wherein the heating EM wave is reflected from the ionosphere. The SPS microwave beam would heat the ionosphere as it passed through the earth's atmosphere. Currently there is no physically-based rationale to extend the observed results to SPS operations.

4.5.3 Vehicle Effluent Effects

Current information regarding effluent effects on the ionosphere is based on limited Skylab launch data, and the minimal relatable data from military missile launches where ionosphere transients are employed for detection or warning. No detailed temporal or spatial characteristics can be inferred because of the limitations of the instrumentation producing the data. No information is available regarding transport processes in excitation or restabilization events.

The initial modeling predictions of F-layer depletion, and the Skylab and missile data, indicate that communications services using F-layer support could experience outage periods and subsequent marginal-signal periods with the ionosphere upper-layer "hole" extending about 1000-1500 km around the trajectory, depending on the actual launching scenarios. Specific SPS impacts have not yet been identified. This can be done using predictions from models and results from testing to be accomplished with the space-shuttle launches.

4.6 CONCLUSIONS

The effects of heating the ionosphere and magnetosphere with high-power, high-frequency radio waves have been demonstrated experimentally, and theoretical studies have rendered a good general understanding of the ambient ionosphere's response to these radio waves. Experimental results are just beginning to be obtained on the ionospheric effects of high-power radio waves whose frequencies exceed the F-region critical frequency and cause underdense heating. Little is known about the plasma irregularities that would result from the higher power density in the F-region from the SPS. Many of the expected phenomena could produce communication effects similar to those already observed or which can be simulated and observed. Further theoretical and experimental studies are needed to assess the impact of underdense heating on the ionosphere and determine the resultant impact on telecommunication systems.

The HLLV launches needed to construct and operate the SPS could also impact communications services that utilize F-layer refractions. Significant signal-margin reductions could exist for hours after each launch for links using the 1000-1500 km area around the launch trajectory. A major operational

impact could develop for broadcast, commercial, and security services operating in the upper-HF spectral regions. The depletion model studies (see Section 3), coupled with vehicle-launch parameters and communications-link measurements, should help determine the typical range of frequencies and geographic extent of affected services. Ionospheric characteristics that can be used in communication-impact-prediction models can also be obtained through the physical model and measurement efforts.

Studies of the effects of the ionosphere on the SPS microwave pilot beam and power beam are important. Irregularities in the ionospheric structure that arise from natural causes can cause significant signal fading. This fading, known as scintillation, can lead to loss of these signals. It is anticipated that irregularities created by the passage of the power beam through the ionosphere could magnify the effects of ionospheric scintillation on both the pilot beam and the power beam. Energy from the power beam could be scattered as a result of ionospheric irregularities and the phase stability of the pilot beam could be adversely affected by both naturally-occurring and artificially-induced ionospheric irregularities.

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5 ELECTROMAGNETIC COMPATIBILITY

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5.1 SCOPE

The electromagnetic compatibility (EMC) assessment evaluates the possible interference of the satellite power system with other electromagnetic equipment. Electromagnetic equipment includes both devices that use radiated electromagnetic energy, such as radio and radar, and systems that use wired connections, such as computers and control and sensor systems. In environments where a large number of electronic systems operate together (particularly if transmitting equipment is included), it is necessary to analyze unintentional interactions. Modifications are frequently required to eliminate harmful interference.

The SPS microwave power transmission system (MPTS) would radiate unprecedented amounts of electromagnetic energy from space to earth. The power radiated as microwaves from a single satellite would be comparable to the present world total of artificially-generated radio energy. Most of the power would be captured by the rectenna, but a small amount would be "lost." The intensity of the microwave power lost from the MPTS would be highest near rectenna sites and decrease rather rapidly with distance from these sites. Electromagnetic compatibility problems would be most likely within about 100 km of each rectenna site.

A small fraction of SPS power would be radiated in directions far removed from the power beam and would increase microwave power densities across the hemisphere of the earth below the satellite and throughout near-earth space. An additional fraction of the radiated power could appear at frequencies not assigned to MPTS operation (i.e., noise sidebands and harmonics).

The large sunlit areas of an SPS satellite would also cause it to appear brighter than any objects in the sky except the sun and moon and could possibly present problems for astronomy.

The potential EMC effects of the SPS are illustrated in Fig. 5.1.

5.2 METHODOLOGY

A comprehensive program has been initiated to analyze the functional and operational degradation of electromagnetically-sensitive systems (e.g., communication, radar and navigational systems, computers, sensors, electronic

Fig. 5.1. Overview of Potential SPS Electromagnetic-Compatibility Impacts

medical instruments and devices). Primary areas of effort include computations to verify the electromagnetic environment, coupling analysis, categorization of functional-operational priorities, degradation evaluations, and impact assessment. Other tasks address mitigation methods for degraded systems and develop guidelines for designers and planners of future systems that might be affected by the SPS.

5.3 CAUSE AND EFFECT RELATIONSHIPS

The SPS MPTS could 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 and noise components.
- Ionospheric heating (discussed in Section 4).

In addition to the effects of the MPTS, sunlight scattered and reflected from the solar-power satellite might affect optical astronomy. A wide variety of electronic systems may be affected by SPS microwave power. Some of these systems are shown in Fig. 5.2, along with some of the possible effects.

5.4 STATE OF KNOWLEDGE

The production by the SPS of substantial microwave field strengths over extremely large areas would present a unique EMC condition. Existing high-power radar and communications systems produce similar field strengths, but only in small areas. The high field strengths would result from small power losses from the MPTS, losses due to a number of separate causes, none of which could be completely eliminated.

The transmitting antenna could not direct all the microwave energy to the rectenna. A few percent of this energy would be distributed in undesired directions, covering a hemisphere of the earth and extending through near-earth space. There would be a fundamental limitation in confinement of the beam due to the finite size of the antenna and unavoidable diffraction effects. There are a number of practical problems which would, however, probably be more significant for the SPS. The excitation (or illumination) of the transmitting aperture would have a discretely-stepped taper (see Section 5.5.1 for a discussion of the effects of this taper). It would also be necessary to operate with some level of failure in the driving elements, further departing from ideal excitation. All elements of the array must be properly phased to realize optimum gain and minimize side lobes. Phasing accuracy would inevitably be compromised by mechanical tolerances in element alignment, element and overall array pointing, and errors and failures in the phase-control electronics. The phase-control problem is further complicated by the required ground-phase-referenced retrodirective control, with potential problems introduced by the temporal and spatial variations in ionospheric and tropospheric propagation and by the more than 0.1-second earth-to-space

Fig. 5.2. Effects of SPS Microwave Transmission on Electromagnetically-Sensitive Systems

propagation delay. Many of these concerns are addressed in the SPS reference system report.^{1*}

Scattering in the troposphere, which would be expected from a number of phenomena, could degrade performance of the retrodirective phase control; this in turn would increase power in the transmitted side lobes in addition to the scattering produced by the troposphere. Major phenomena of interest are:

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

These phenomena have wide geographic and seasonal variations as well as temporal variations on scales ranging from hours to minutes. They also represent different beam-control response problems. The magnitudes of the effects and the statistical processing of pilot-beam parameters to extract atmosphere "signatures" must be carefully addressed in the pilot-beam/array-control-loop design to minimize ambiguities and possible instabilities. These phenomena have important implications for future modular and subsystem laboratory testing.

Attenuation and scattering due to precipitation would also reduce the amount of total power at the rectenna. This reduction would generally be proportional to the rain rate and the problem would vary with geographical location. Blowing dust or sand also might contribute to attenuation and scattering. Each mechanism alone would have small effects, stated as a percentage of main-beam power or in dB power loss; however, because of the large power levels involved with the SPS the magnitude of the cumulative 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 rectenna would not be a perfect absorber but would scatter or reradiate a few percent of the incident power and, with present designs,

*References for Section 5 are listed in Section 5.7.

pass about one percent, some of which would be scattered from the underlying surface. Terrain outside the rectenna site would also partially scatter or reflect power from the transmitted side lobes, resulting in wider distribution. Scattered microwave fields at 2.45 GHz would be most severe within about 100 km of a rectenna site, both because power flux in the transmitted beam would decrease rapidly away from the rectenna (see Section 5.5.1 and Ref. 1) and because most scattering would be expected below 10 km altitude. Electronic systems within a 100-km radius of a rectenna would be more likely to be affected by SPS microwave power than those farther away. Some of the effects possible near the rectenna are discussed in Sections 5.5.1 and 5.5.2.

Energy coupling to "victim" systems would involve in-channel and nonlinear responses by components out of the primary-receiver pass band and coupling through cabling and apertures to other electronic circuitry. Different scoring procedures are required for SPS coupling than for other types of coupling because of the wide variations in energy coupling and the intermodulation of components of the interferer with the desired signal. Scoring procedures applicable to this problem can be derived by extrapolation of existing empirical and analytical degradation models for receiver systems employed for communications, radar, or a general range of applications. These scoring procedures define a range of performance characteristics, in terms of probability density functions for signal-to-interference ratios. Most of the SPS-related EMC problems that would require significant modifications of victim equipment would be concerned with nonlinear-response effects.

Computer devices, optical equipment, and medical instrumentation present unique scoring descriptives that relate to effective apertures and energy coupling into signal and control circuitry. These types of problems can, to a lesser degree, be extrapolated from experience with high-power radar illumination of military surveillance and monitoring equipment. Limited measurements will be required for the SPS problem to assure credibility in the predicted degradation and any recommended functional modifications for these classes of equipment which might be necessary.

Beyond about 100 km from rectenna sites, relatively few electromagnetic systems would be affected by SPS emissions. Systems identified to date that could be affected are sensitive microwave receivers, particularly those with antennas pointed near an SPS satellite. Services possibly affected

could include radio astronomy, deep-space research, and satellite communications. These problems are discussed in Sections 5.5.3 and 5.5.4. Aircraft and spacecraft passing through the SPS microwave power beam would be exposed to high levels of microwave radiation (23 mW/cm^2 , and higher for spacecraft) with consequent potential for effects on on-board electronic systems. These effects are considered in Section 5.5.3.

SPS radiation at frequencies outside the band allocated for the MPTS could, if not kept below specified limits, impact other users of the electromagnetic spectrum. Any DC-to-microwave conversion devices in the satellite and microwave-to-DC converters at the rectenna would inevitably generate some power at undesired frequencies, as harmonics (i.e., multiples) of the intended frequency and noise. The level of harmonics and noise generated would depend on the components used. The radiation of these spurious frequencies is very sensitive to details of the design of transmitting and rectenna systems. Present knowledge of the SPS permits only estimates of some of these emissions.

The MPTS antenna in space would produce substantially different radiation patterns at different frequencies. Spurious emissions from the satellite could thus be evident throughout the hemisphere of the earth from which it would be visible and conceivably throughout near-earth space. For reasonable MPTS designs, problems from emissions at unintended frequencies should be confined to possible interference with receiving systems operating at these frequencies. Such problems would be most severe for systems with directional antennas which would always be pointed toward the solar-power satellite (i.e., satellite communications systems) or which might be so pointed (i.e., radio astronomy, deep-space research, radar systems). It must be noted that many directional antennas have significant sensitivity (side lobes) in unintentional directions so that interference would be possible even if such antennas were not pointed toward the solar-power satellite. Spurious emissions from rectennas would be expected to be a problem only in limited areas on the earth or possibly for spacecraft with earth-directed antennas or aircraft passing near them.

The SPS satellites, as very large, usually sunlit objects, would scatter and reflect sunlight. Computations indicate that each satellite would appear brighter than any object in the sky except the sun or moon. (The

amount of power scattered as light is comparable to the microwave power transmitted.) The presence of 60 of these objects in the sky, fixed in position relative to the ground, would affect optical astronomy or other observations requiring a dark sky, such as auroral photometry. Scattering in the atmosphere would cause the sky to appear brighter in all directions. SPS effects on optical astronomy are considered in Section 5.5.4.

5.5 ASSESSMENT

5.5.1 Electromagnetic Environment Summary

Antenna Patterns for the Satellite Power System

The most recent SPS concept proposes to use a 2.45-GHz beam of about 6.85-GW power beamed from a 1-km-diameter array in geostationary orbit with a Gaussian amplitude taper across the aperture.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 14-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 and flux densities in the ionosphere would be less than 23 mW/cm².

The radiation pattern of circular apertures is well understood and many references are available for cases in which the distribution across the aperture is uniform in amplitude and phase. Born and Wolf² give a derivation for the radiation pattern for the case of uniform illumination. We extend their analysis to the case where the amplitude across the aperture consists of a finite number of steps in the radial direction and is circularly symmetric, as shown in Fig. 5.3. As currently conceived, the SPS MPTS would have a 10-dB, quantized, Gaussian amplitude taper designed to yield optimum beam efficiency.³ The analysis of the radiation pattern from a circularly symmetric aperture with radially-stepped amplitude is developed fully in Ref. 4. The results of this analysis for the proposed SPS transmitting antenna are given in Figs. 5.4-5.6.

Fig. 5.3. Amplitude Taper across Circularly-Symmetric Aperture

Fig. 5.4. SPS Power Gain Envelope versus Angle from Boresight, in $\phi = 0$ Plane (on-axis gain is about 87.65 dB; boresight is at $\theta = 90^\circ$) (Source: Ref. 4)

Fig. 5.5. SPS Power Gain versus Angle from Boresight, Showing Side-Lobe Detail (Source: Ref. 4)

Fig. 5.6. Power Gain versus Theta for an Angle 90° from Boresight (Source: Ref. 4)

Attenuation and phase delay for moist and dry air also have been estimated.⁵ At 2.45 GHz, at an altitude of 5 km and for 50% relative humidity, the attenuation is 0.003 dB/km and the phase delay is 8.68 radians/km. For dry air the corresponding values are essentially zero.

A detailed characterization of the SPS MPTS radiated power is the basis for the electromagnetic compatibility evaluation of the system. It provides the parameters and limits for testing and simulation programs as well as for analytical efforts.

Microwave Fields Inside Habitable Structures

It is necessary for the EMC analysis 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 very 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.⁶ This study analyzed the relevant physical processes, produced measured values for many of the quantities involved, 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:

Structure	% Transmission	
	Dry	Wet
Wooden Wall	15	6
Frame Wall	40	15
Window (wood sash)	70	40

Metal walls or screening, or even foil, transmits very little 2.45-GHz microwave energy (less than 1%) if openings or joints are substantially less than an inch 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 locally-increased 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 that 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 of people, who are significant microwave absorbers and reflectors, modifies reflection patterns, in a time-varying way as the people move and absorb energy, reducing the field increases possible due to reflections.

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.⁸ 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 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.

5.5.2 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 center coordinates of the site are 35°, 8' North latitude and 117°, 20' West longitude; the proposed rectenna would cover roughly 100 km². The evaluation of SPS electromagnetic compatibility for this site provided impact data for one possible site, helped establish site selection and evaluation criteria, and allowed a limited exercise of the data retrieval and analysis procedures 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 5.7 shows a main beam and side-lobe structure for the assumed SPS space antenna. Note that the field intensity beyond 30 km from the center of the rectenna site would be 1 V/m at the 2.45-GHz frequency. This would represent a sizable input to communication systems operating within 100 km of the rectenna site. In dealing with communication systems, field intensities measured at an antenna are given in microvolts per meter (V/m). For high-power television or AM and FM broadcasting stations, the field intensity beyond a kilometer, but within 30-50 kilometers, 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 side lobes 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, for example, statistics were gathered from Bakersfield, California, the nearest site where records are kept.

Fig. 5.7. SPS Transmitting Antenna Pattern

Bakersfield receives rain at a rate of about 9.1 mm/hr on the average of about one hour per year, and at the extreme (one year out of 200) receives 17.3 mm/hr for one hour during a year. For about five minutes of an average year, Bakersfield receives 19.3 mm/hr of rain, and 47.2 mm/hr at the one-out-of-200-years extreme for five minutes. Based on the work of Dutton, scattered power densities can be predicted as a function of rain rate.⁹ Results are shown in Table 5.1, 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.

Table 5.1. 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	5.27	20.7	44.6	88.3
Downtown Barstow	51	8.30	32.5	55.9	110.7
Edwards AFB Airstrip	43	1.17	45.8	21.0	131.4
Restricted Area R2524	53	7.69	30.1	53.8	106.5
George AFB Airstrip	61	5.80	22.7	46.8	92.5

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 site, an area 145 km by 145 km with the proposed rectenna site at the center was chosen as a data sample area. All EM 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:

1. Military Development and Operational Test and Evaluation

- a. Instrumentation radars - conical scan and monopulse modes
- b. Traffic monitor/control radars
- c. Radar transponders
- d. Radar signal and functional replicators
- e. Wideband monitor receivers with recognition/decision software-scan instantaneous-frequency modes
- f. Television cameras for target position track
- g. EM system operational monitors - multiple wideband receivers with processing software
- h. Range command/control communications networks
- i. Range telemetry communications networks

2. Industrial Communications

- a. Utility network command/control and telemetry
- b. Pipeline network command/control and telemetry
- c. Water resource telemetry
- d. Multiplexed carrier networks - two major service systems

3. Transportation Support Systems

- a. Railroad mobile equipments - yards and enroute complex
- b. Air traffic control network
- c. Emergency services - mobile, base station, and relay equipment - medical and general emergency applications
- d. Railroad "car condition" monitors

4. Public Service Communications

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

5. Specialized Services

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

The character of functional degradation that would be induced by an SPS into major equipment categories deployed near the Mojave site is indicated in Table 5.2. 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.

The performance degradation indicated in Table 5.2 would compromise the operation of the military instrumentation and systems employed in operational testing at the military sites listed in Table 5.1 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 EM equipment and system operations to assure an acceptable level of

Table 5.2. Induced Functional Degradation Summary for the Mojave Area

Function	Characteristic Effects
Instrumentation Radar (military test ranges)	a. Cooperative target acquisition range: -(8-20%) b. Skin target acquisition range: -(13-28%) c. Cooperative target track error: +(15-40%) d. Skin target track error: +(22-65%) e. Loss of track loop lock (skin mode) probability increase: +(10-40%)
Command/Control and Telemetry Communications (military test ranges)	a. Signal acquisition threshold: +(5-20%) b. Data error: +(5-28%) c. Sync loss probability: +(3-25%)
Tactical Signal Identification - Analysis Systems	a. False alarm probability outside mission zone: +(3-25%) b. False alarm probability within mission zone: +(18-60%) c. Receiver noise threshold: +(5-40%) d. Signal processing time: +(45-115%) e. Software overload probability increase: +(2-26%)
IR Scanner (tactical system)	a. Video noise threshold: +(2-26%) b. Target detection/identification probability: -(5-33%)
Utility and Pipeline Command/Control/Telemetry Communications	a. Signal acquisition threshold: -(5-15%) b. Data error: +(10-30%) c. Link noise: +(5-20%)
Image Intensifiers	a. Video noise level: +(10-45%) b. Standard target detection/identification range: -(5-30%) c. Multiple target spatial resolution: -(2-60%)
Non-Federal Government Communications	a. Channel noise: +(5-15%) b. Data error: +(8-35%)

performance if illuminated by an SPS source. Implementation procedures and cost estimates, with priorities, are being prepared.

For the Mojave rectenna site analyzed and other sites with a similar operational military/civil system ratio, modification recommendations will 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, assuming no media-induced instabilities in the SPS array control. Military operational EM 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 "victim" 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, military operations would suffer most of the interference problems; the systems that would be degraded are integral components of complex development and operational test 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 which 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 geographic areas would not be as simple, and might be impossible, due to population density, terrain features, victim-system density, etc. Generally the northern and eastern regions of the United States have smaller military-nondefense equipment concentrations in potential rectenna areas than the Mojave site. These regions 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.

5.5.3 Satellite Effects

Satellites in Geosynchronous Earth Orbit (GEO)

Satellites in GEO include civilian and military communications relays that support intercontinental and intracontinental services. Data, voice, and entertainment services are provided through these satellites. Satellites that could suffer interference degradation because of SPS operation (and their longitudes) include:

- SATCOM - 119°W, 135°W, 132°W
- COMSTAR - 128°W, 95°W
- WESTAR - 99°W, 123.5°W, 91°W
- TDRSS - 171°W, 41°W
- MARISAT - 15°W, 176.5°E, 73°E
- SBS - 122°W, 106°E
- INTELSAT - 61.4°E
- ANIK - 108.5°W, 114°W

The SPS interference with INTELSAT has been analyzed as representative of the interference situations that could arise:

The SPS space antenna patterns presented in Figs. 5.4-5.6 indicated the spatial energy distribution without considering media-induced, small-level oscillations and wander. Spatial relationships for a pessimistic geometry between a space antenna and INTELSAT with line-of-sight passing near an earth-surface tangent are depicted in Fig. 5.8. This represents a pessimistic geometry because of the minimum possible space antenna angle relative to the main beam. The space antenna gain at the INTELSAT line-of-sight angle is about -18 dB; the resulting interference signal into the INTELSAT antenna being -73 dBm at 2.45 GHz.

The INTELSAT uplink frequency is in the 5.93-6.42 GHz band. Direct in-band interference from the SPS second and third harmonics (4.9 GHz and 7.35 GHz) would be attenuated by about 16 dB and 20 dB, respectively, because of selective-filter characteristics of the transponder-receiver radio-frequency (rf) amplifier. The SPS primary-frequency power at the INTELSAT antenna would be attenuated by about 40-45 dB by the input rf amplifier, with some leakage directly through the tunnel diode amplifier degrading the attenuation of the

Fig. 5.8. Pessimistic INTELSAT-SPS Geometry

passband filter. A leakage coupling of -36 dB for frequency ratios of 3/1 to 4/1 is typical for tunnel diode amplifiers operating in the 2-8 GHz region.

The INTELSAT transponder is functionally diagrammed in Fig. 5.9. This diagram indicates the frequency translations involved in the uplink/downlink conversion. For the cited transponder characteristics and anticipated out-of-channel coupling, the SPS signal thresholds for INTELSAT are: SPS fundamental frequency, -57 dBm; and SPS second harmonic, -75 dBm. Since these threshold amplitudes were derived from a most disadvantageous space antenna-INTELSAT geometry, other INTELSAT orbital locations could tolerate interference magnitudes at the antenna that were larger in direct relation to the reduction in antenna gain.

Fig. 5.9. INTELSAT Satellite Transponder

The SPS-amplitude thresholds for other GEO satellites are:

- SATCOM: $-62 \text{ dBm} - f_0$; $-77 \text{ dBm} - f_2$
- COMSTAR: $-60 \text{ dBm} - f_0$; $-74 \text{ dBm} - f_2$
- WESTAR: $-58 \text{ dBm} - f_0$; $-74 \text{ dBm} - f_2$
- MARISAT: $-62 \text{ dBm} - f_0$; $-76 \text{ dBm} - f_2$
- SBS: $-62 \text{ dBm} - f_0$; $-78 \text{ dBm} - f_2$
- ANIK: $-62 \text{ dBm} - f_0$; $-78 \text{ dBm} - f_2$
- TDRSS: $-54 \text{ dBm} - f_0$; $-68 \text{ dBm} - f_2$

TDRSS is 9 dB less susceptible than other commercial satellites at the same orbital position because of processing gain afforded by wideband signal structure. The susceptibility of military communications satellites is now being addressed. There should be reduced degradation in existing systems relative to commercial satellites because of signal-processing gain. Satellites planned for the 1990 time period will have additional protection because of adaptive antenna modes.

Antenna and transmitter amplifier configurations for the listed communications satellites indicate no intermodulation effects in the transmitted signals due to SPS primary or anticipated harmonic emissions. There is a margin of about 55 dB for such effects.

The SPS amplitude margin at the "worst case" INTELSAT coordinate was 15 dB. Considering the cited threshold for SPS pattern stability and the characteristics of communication-satellite antennas and receivers, a minimum orbital separation of 2° between SPS and communication satellites would be appropriate.

Satellites in Low Earth Orbit (LEO)

Two LEO satellites are discussed here: LANDSAT and GPS. They are representative of satellites in LEO which could be expected to be most likely to be affected by SPS interference.

LANDSAT. The LANDSAT satellite program is intended to develop and demonstrate capability for global monitoring support for earth resources management. Launch of LANDSAT-D is scheduled for late 1981. A subsequent launching is anticipated during 1982-83, and an advanced system, LANDSAT-H, is also planned.

The LANDSAT-D will provide imagery from a sun-synchronous, circular orbit at an altitude of 705.3 km with a 98.2° 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 directly and through TDRSS. These communications links are diagrammed in Fig. 5.10. A power density-time plot for the case of orbit coincidence with the

Fig. 5.10. LANDSAT Communications Links

SPS main beam is presented in Fig. 5.11; this situation would occur frequently because of LANDSAT's 6-8 orbit tracks per day over the continental United States. The SPS energy coupling paths into LANDSAT systems are indicated in Fig. 5.12. As diagrammed, the communications, sensor, power bus, and attitude-control functions could be affected. Coupling would occur through the solar cells, communications antennas, attitude-sensor optical apertures, and the optical apertures and thermal louvers of the multispectral scanner and thermal mapper. The exposed area and scanner locations on the satellite indicate that the optical aperture would be the principal coupling mode for these sensors.

Star-tracker noise and angle error ranges in relation to microwave illumination levels are indicated in Fig. 5.13. The LANDSAT star tracker

Fig. 5.11. SPS Microwave-Beam Geometry at LANDSAT Orbit Altitude

Fig. 5.12. LANDSAT Functional Impact Modes

provides error data to the attitude-control software. Attitude error would accumulate over a period of about 4-5 seconds within the SPS beam. This attitude deviation (pointing deviation magnitude and rate, hemisphere orbit distance for the error increase and restabilization phases) will be estimated for SPS main-beam and primary-side-lobe illumination of LANDSAT orbit passes.

The satellite-earth uplinks use an S-band channel (direct and through TDRSS at 2.1064-GHz with wideband modulation modes through TDRSS). Other satellite receiver channels include a 13.775-GHz track signal from TDRSS, and the 1.2276-GHz and 1.5754-GHz transmissions from GPS. For the direct earth-station to satellite S-band link a bit error rate (BER) increase of 70-85% would occur for an SPS main-beam exposure period of approximately 16 seconds. For the wideband TDRSS channel, the BER increase would be 20-40%, the higher range caused by nonlinear responses in the first conversion and amplifier stages of the receiver during exposure to SPS power densities $\geq 8 \text{ mW/cm}^2$.

For perhaps one to three SPS satellites dispersed over the continental United States, the LANDSAT mission profile could be modified to eliminate

(a) Increase in Signal Noise vs. Interference Power Density at 2.45 GHz

(b) Increase in Average Angle Error vs. Power Density at 2.45 GHz

Fig. 5.13. Image-Dissector Star-Tracker Error Characteristics

command-control transmission during the specific orbit time slots corresponding to SPS illumination. This obviously would not be a satisfactory mode, except on a temporary basis for an operational satellite while functional modifications were being incorporated into future vehicles. These modifications should eliminate the BER effects for the narrowband and wideband transmissions to the satellite, thus removing all mission dependencies between LANDSAT and SPS operations. Mitigation techniques to be investigated include rejection filters and antenna modifications. Filters are preferred because of the relative simplicity and the elimination of antenna-control-command and steering-software additions. The filters should have a bandwidth of about 10 MHz and an out-of-band insertion loss of less than 2 dB.

For the multispectral scanner and thermal mapper, mitigation techniques include circuit filters, noise extraction (spectral density-correlation models) in the data analysis process, and extended shielding for the detectors and colocated video amplifiers. Additional shielding for the video channel and scan-control circuitry may be necessary to eliminate jitter in the line scans, if the coupling is proven to be directly into these circuits and not through internal common connections. For the star tracker, circuit shielding and optical aperture mesh shielding might be useful. The latter is applicable since focusing optical components are used in front of the photomultiplier tube. Effects on the sun sensor are insignificant (approximately a 2% increase in noise); this noise should cause less than a 2-5° orientation change of the solar panels over a period of 1-1.3 seconds of maximum SPS beam exposure, and would be corrected within 2-5 seconds after LANDSAT left the SPS beam. The error magnitude would be limited by the solar-panel-control bandwidth and the small aperture of the sun sensors. If sun acquisition by the sun sensors occurred during SPS main-beam exposure, the solar panel transient time would be extended by approximately 3-5 seconds because of the signal channel noise and related angular uncertainties (the sun/SPS illuminating power ratios would also be minimal during this event).

GPS. The GPS is a navigation and position-fixing system being implemented by the Department of Defense to support worldwide strategic and tactical combat system operations. A decision is expected to allow nondefense uses of GPS within a few years. By 1982, 24 satellites will be in a 17,500-km circular orbit, with a 12-hour orbit time.

This system provides a passive operational mode for users (receive only). The satellites provide two frequency transmission, at 1.2276 GHz and 1.5754 GHz in a QPSK format. Signals include time correlation, ephemeris, identification, and data to compute propagation errors. Users include satellites, aircraft, surface vehicles, and individuals through man-pack receiver and display units.

Earth-to-satellite communications provide ephemeris update, orbiting clock corrections, and command-control data to the satellite computer, directly and through TDRSS relay. The uplink communications use S-band. The satellite has conical, spiral receiver antennas located on the space- and earth-pointing planes.

The GPS power-density variations for SPS beam interaction are plotted in Fig. 5.14. Power coupling modes into the GPS satellite are diagrammed in Fig. 5.15; this diagram indicates a coupling to sensors and communications similar to that for LANDSAT. The GPS vehicle has the additional mode of direct entry through the louvers that control the temperature of the principal electronic functions: clock, computer, and command-control receiver and decoder components. As indicated in Fig. 5.15, this direct penetration energy would primarily couple to the various electronic functions through cables and interface circuits.

Maximum and average SPS power levels reflected into the satellite electronics would be 25 W and 2.8 W, respectively, for power densities of about 0.1 mW/cm^2 (see Fig. 5.14) and louver openings of 10° , 30° , and 45° . Induced jitter in the internal clock and message-decoder logic is estimated to be in the 10% to 65% range for SPS power of 10-25 W. These initial estimates will be validated in future tests of modular logic components configured to represent GPS systems.

The S-band communications receiver and associated processor would experience a BER increase of 50 to 1000 if the antennas were exposed to SPS power densities of 10-100 mW/cm^2 . The probability of losing signal lock is also being examined; this could occur because of mixer-stage intermodulation products, in-channel noise, and gain compression.

Mitigation techniques that will be tested for the GPS communications receivers are identical to those indicated for LANDSAT. Functional dif-

Fig. 5.14. SPS Microwave-Beam Geometry at GPS Orbit Altitude

Fig. 5.15. GPS Functional Impact Modes

ferences would result from the increased SPS maximum power density and the broad-band GPS signal mode. Sun-sensor control of solar-panel orientation would be affected in the same manner as discussed for LANDSAT. The short exposure times and the low control bandwidth limit the possible roll of the solar panels because of signal noise. The conclusion regarding LANDSAT sun acquisition when exposed to SPS illumination is also applicable to GPS.

The earth sensors on GPS would be effectively shielded from SPS exposure by the satellite structure for all possible SPS/GPS geometric relationships over the western hemisphere. For geometries with GPS over Europe or Asia with a line-of-sight to an SPS side lobe, the power densities on the earth sensor would be at least a thousand times below any upset threshold. (For power densities, refer to SPS/INTELSAT discussion.)

The GPS transmitters would be unaffected by SPS penetration at the levels indicated. Power and driver amplifier circuitry and the physical configuration indicate no possibility of induced phase-modulation jitter on the transmitted signal attributable to coupling into transmitter circuitry. Transmitter antennas would be shielded from direct SPS power exposure by the body of the GPS. The 50-ohm power amplifier impedance, the wideband-output-tuned filters, and the output/input coupling of the power and driver stages indicate a net coupling of -40 dB to -65 dB for the SPS fundamental frequency, and values of -70 dB to -80 dB for the SPS second harmonic.

Future Satellites

Environmental specifications similar to those displayed for LANDSAT and GPS will be developed for future resource-monitoring satellites currently in the concept definition phase at NASA. Estimates of possible functional degradation because of SPS operation will be provided as guidance to the preliminary specification and design development. These systems include:

- Earth Watch - orbit altitude approximately 10,000 km, mapping and microwave monitor.
- Microsat - passive L-band radiometer.
- Radar Holographer - bistatic radar (GEO illuminator with LEO collector).
- GEOSAR - GEO synthetic aperture radar.
- Ellipsometer - bistatic radar for moisture measurement.
- LANDSAT-H - Multispectral scanner and synthetic array radar.

5.5.4 Effects on 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, and this could thus limit or hinder astronomical observations.

Radio Astronomy

There are two main concerns for radio astronomy: (1) microwave flux levels at 2.45 GHz could be high enough to affect low-noise receivers located several hundred kilometers from a rectenna site and perhaps throughout an entire hemisphere, and (2) noise and harmonics from the SPS could further restrict the spectrum available for observations.

Microwave power density from a single SPS satellite is expected to be -30 dB W/m^2 as far as 300 km from a rectenna site, with regularly-spaced grating lobes of up to -10 dB W/m^2 . A 0-dB-gain antenna (i.e., isotropic, effective aperture of about 10 cm^2 at 2.45 GHz) or equivalent side lobe of a high-gain antenna in a -30 dB W/m^2 radiation field will deliver about one microwatt to a receiver. This is 30 dB above the gain compression point for some parametric amplifiers. Unavoidable beats between carriers from different satellites would modulate the gain compression, generating spurious signals in the receiver passband which could easily counterfeit the data being sought. Although parametric amplifiers represent a worst case for gain-compression sensitivity, the other possible receiver-input stages show qualitatively similar overload and intermodulation effects. All such effects would be most evident in receivers operating at frequencies near the SPS frequency.

Filters could be used ahead of the receiver input to reject the SPS frequency, at the cost of some insertion loss and degradation in noise performance. Filters of any given performance might permit useful operation when an astronomical antenna was pointed well away from any SPS satellite. However, there would be a region of the sky surrounding the line of satellites in which useful measurements might not be possible. Distances to the nearest rectennas, and details of attainable antenna, filter, and receiver performance would determine the size of this region, and of a smaller region which would need to be avoided to prevent damage to the receiving equipment.

and filter. A series of measurements on existing receiving facilities and available filters would allow the sizes of the excluded regions to be estimated with reasonable confidence for representative facilities.

The SPS MPTS would inevitably generate noise sidebands near the power-beam frequency and its harmonics. The amount of such radiation permitted under international radio rules in the assigned radio astronomy bands is outlined in Ref. 11. These radiation limits should be regarded as performance requirements for the MPTS. If these limits were observed in all of the protected astronomy bands and were not exceeded by any great amount just outside these bands, then SPS noise radiation would not interfere with current radio astronomy in-band operation.

There could, however, be two kinds of substantial effects on current observations. First, if the radiation standards were actually met in those bands closest to the SPS carrier and harmonics, it would likely be done by source filtering, which results in a very steep noise spectrum adjacent to the astronomy band. Useful operation under these conditions might require better adjacent-channel selectivity than is compatible with the lowest-noise receiver designs. Again, filters may be required. Second, a great deal of radio astronomy is done at frequencies of opportunity and at radio spectral lines lying outside the protected bands. The SPS noise sidebands might exclude a portion of the spectrum from such operation as, of course, other radio transmitters operating at their assigned frequencies presently do. The difference is that terrain shielding, routinely used to protect existing observatories from such transmitters, would be ineffective against SPS satellite radiation.

Optical Astronomy

Even with conservative assumptions about the reflectance of SPS surfaces, it seems that solar-power satellites would be very bright objects. Assuming a diffuse albedo of 4% for the 54 km² area of the SPS solar arrays, each satellite would appear from the earth to be as bright an object as the planet Venus at its brightest and brighter than any other object in the sky except the sun and moon. The combined light from 60 satellites would be as bright as the moon halfway between the new and quarter phases.

The primary effect of the SPS on optical astronomy would be to increase the brightness of the night sky against which astronomical objects are observed. The effect of increased night-sky brightness on observations is best understood if one defines a quantity P as the ratio of the brightness of the night sky with the SPS to its brightness without the SPS. The effect is to reduce the aperture of all earth-based telescopes by the factor $P^{-1/2}$ when making sky-limited observations. The actual value of P would be a function of position in the sky, being very large near the satellites and somewhat less away from them. The minimum effect of the current reference system would be to create, for each observatory that could see the satellites, a contaminated band approximately 60 degrees by 10 degrees in which P would be greater than 2. Within this zone, astronomical observations of faint objects such as galaxies would be impaired. Further, because of the geostationary character of the SPS orbits, the apparent position of the satellites would remain fixed. For northern observatories in the western hemisphere a good fraction of the contaminated zone would be in the prime observing window, the region greater than 30° above the horizon, where atmospheric transparency is high. Because of the way the atmosphere would scatter sunlight reflected by the SPS, it would be difficult to reduce the size of the contaminated zone, but small increases in the apparent brightness of the satellites would increase the zone's size proportionately.

Specular reflections from the solar collectors and the metallic surface of the transmitting antenna would cast bright, narrow beams of light which would sweep across the earth. These beams would be brighter than full moonlight with consequent, effects on optical observations, possibly extending to damage of sensitive sensor systems. Fortunately, the motion of these beams could be made regular and easily predictable.

Finally, there would be some as-yet-unknown effect of the LEO structures that would be used in conjunction with SPS construction and support. These objects, if very bright, would also create a contaminated zone. The orbit of the structures would carry them over a large portion of the sky and would not only impair observations but make the scheduling of observations difficult.

5.6 CONCLUSIONS

The satellite power system, like any other system, must be designed for maximum compatibility with other electromagnetic systems. The SPS reference system design is being used as a basis for the assessment of potential degradation of sensitive systems. Future work will address interference mitigation techniques for affected systems and develop guidelines for system designers and planners.

The microwave field which would be produced by the SPS is unprecedented in its coverage. Scattering of the fundamental and harmonic frequencies as well as the radiated noise power requires intensive electromagnetic compatibility analysis and assessment. SPS design criteria would include the minimization of scattering and spurious emissions.

Several potential problem systems and situations are being studied. The possibility that incident microwave energy might be concentrated by habitable structures has been suggested. An analysis of this problem has shown that the probability of such field enhancement is low.

A representative, candidate rectenna site in the Mojave Desert was evaluated for electromagnetic interference impact. The functional degradation of military, nondefense government, and commercial systems that could be caused in the Mojave area by SPS is basically characteristic of the effects that would be encountered in other areas in the continental United States. Operational implications, and therefore the associated economic impact, would vary significantly because of the differing organizations and systems supported by the degraded equipment.

Procedures for rectenna-site EMC analysis and impact evaluation have been developed and demonstrated. These have shown EMC considerations to be important in site selection and will be useful in determining system performance impacts and developing mitigating strategies for victim systems.

Impacts of the SPS on LEO and GEO satellites also have been considered. Functional and operational degradation has been assessed and potentially useful mitigation techniques have been suggested but need further study and validation. Future investigations will address the energy-coupling and performance effects for military satellites and a range of possible LEO-GEO satellite programs currently in the concept development phase within NASA.

The effects that SPS would have on radio and optical astronomy have also been addressed. Results from a recent workshop on this topic will be published soon and reflected in the 1980 revision of this environmental assessment for the SPS.

5.7 REFERENCES FOR SECTION 5

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