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Vol. 2 of 2

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Preliminary Environmental Assessment for the Satellite Power System (SPS)

Volume 2
Detailed Assessment

October 1978

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 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 orbiting satellites, convert the energy to microwaves, and transmit the microwave energy via extremely directive transmitting antennas to large receiving antennas (rectennas) located on the earth. Present conceptual designs provide for microwave transmission at a frequency of 2.45 gigahertz and generation of 5 to 10 gigawatts-electric at each rectenna.

The impact of the SPS microwave transmission on the environment, as well as impacts related to other elements of the total satellite power system, are being determined by several research efforts funded by the Department of Energy. The goal of these programs is to advance the state of knowledge by the year 1980 to the point where the probability and severity of SPS impacts can be assessed. This two-volume document presents a preliminary evaluation of SPS environmental impacts and recommends impact-related research. More detailed and extensive assessments will be made of effects on the health and safety of the public and occupationally involved personnel, ecosystems, the upper and lower atmosphere, and communications systems.

If the 1980 assessments indicate that the impacts are acceptable or that feasible mitigating strategies can be implemented, and if other related assessments (the impact on society and a competitive comparison of the SPS with other energy alternatives) are favorable, a decision may be made to develop SPS-related technologies.

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PURPOSE

Volume II provides a preliminary assessment of the impact of the Satellite Power System (SPS) on the environment in a technically detailed format more suitable for peer review than the executive summary of Vol. I. It serves to integrate and assimilate information that has appeared in documents referenced herein and to focus on issues that are purely environmental. It discloses the state-of-knowledge as perceived from recently completed DOE-sponsored studies and defines prospective research and study programs that can advance the state-of-knowledge and provide an expanded data base for use in an assessment planned for 1980. Alternatives for research that may be implemented in order to achieve this advancement are also discussed in order that a plan can be selected which will be consistent with the fiscal and time constraints on the SPS Environmental Assessment Program.

INTRODUCTION

Because prospective research studies to evaluate the environmental impact of the SPS have only recently been initiated or are in the planning stage, very few new data are available to form the basis for the preliminary assessment. Therefore, in most cases, this assessment relies on the retrospective interpretation of data that form the present body of knowledge. In several areas the data bases are large but for various reasons are believed to be inadequate for the purposes of making an impact assessment, while in other task areas the data bases are virtually nonexistent; therefore, the preliminary assessment must be made under conditions of uncertainty and with explicit caveats.

Several unofficial documents are already in existence purporting to be SPS environmental impact assessments, which address environmental issues very lightly and tend to focus on issues that are not directly environmental in nature but rather are technological, societal, and comparative issues. Although it will be ultimately necessary to consider these other issues in making the final overall impact assessment, they will be discussed here only to the extent that they are relevant to the environmental assessment.

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1 HEALTH AND ECOLOGICAL EFFECTS OF MICROWAVE RADIATION

1.1 SCOPE

The effects of microwave radiation emmanating from the SPS on the following are considered in this section.

- General public outside exclusion zone for the rectifying antenna (rectenna) and in transit through the zone,
- Terrestrial workers involved in maintenance or operations at the rectenna site,
- Space workers involved in maintenance or operation of the SPS,
- Ecosystems both inside and outside the exclusion zone for the rectenna.

1.2 METHODOLOGY

1.2.1 Effects on Public and Workers

Although a sizeable effort has been expended on investigating the biological effects of microwave radiation, 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 hazards, and in many cases conflicting results have been obtained from similar experiments. The existing data base, however inadequate, will be used as a starting point to develop the information necessary for assessing the impact of the SPS microwave power transmission system (MPTS).

A combination of two types of studies must be used to arrive at an assessment of impacts. One, which we will call prospective, will be directed toward investigating research areas where no data currently exist and which pose serious questions about the advisability of using a microwave beam for transmission of energy from space. Principal among these is the effect of continuous exposure of the population to low levels of 2.45 GHz radiation. Several long-term studies using experimental animals will be the primary determinants in answering this question, but much of this work cannot be completed within the period from FY1978-80. However, short-term prospective studies will address several questions that can be answered in this time span.

The other type of study, which we will call retrospective, will address effects already documented in the literature. A major effort will be made to validate the apparently credible, published reports of potential adverse health effects of 2.45 GHz radiation. In addition, effects reported at certain other frequencies should be investigated to determine whether or not they will occur at 2.45 GHz. The intent behind the retrospective 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 in the design of the long-term experiments to be conducted after 1980.

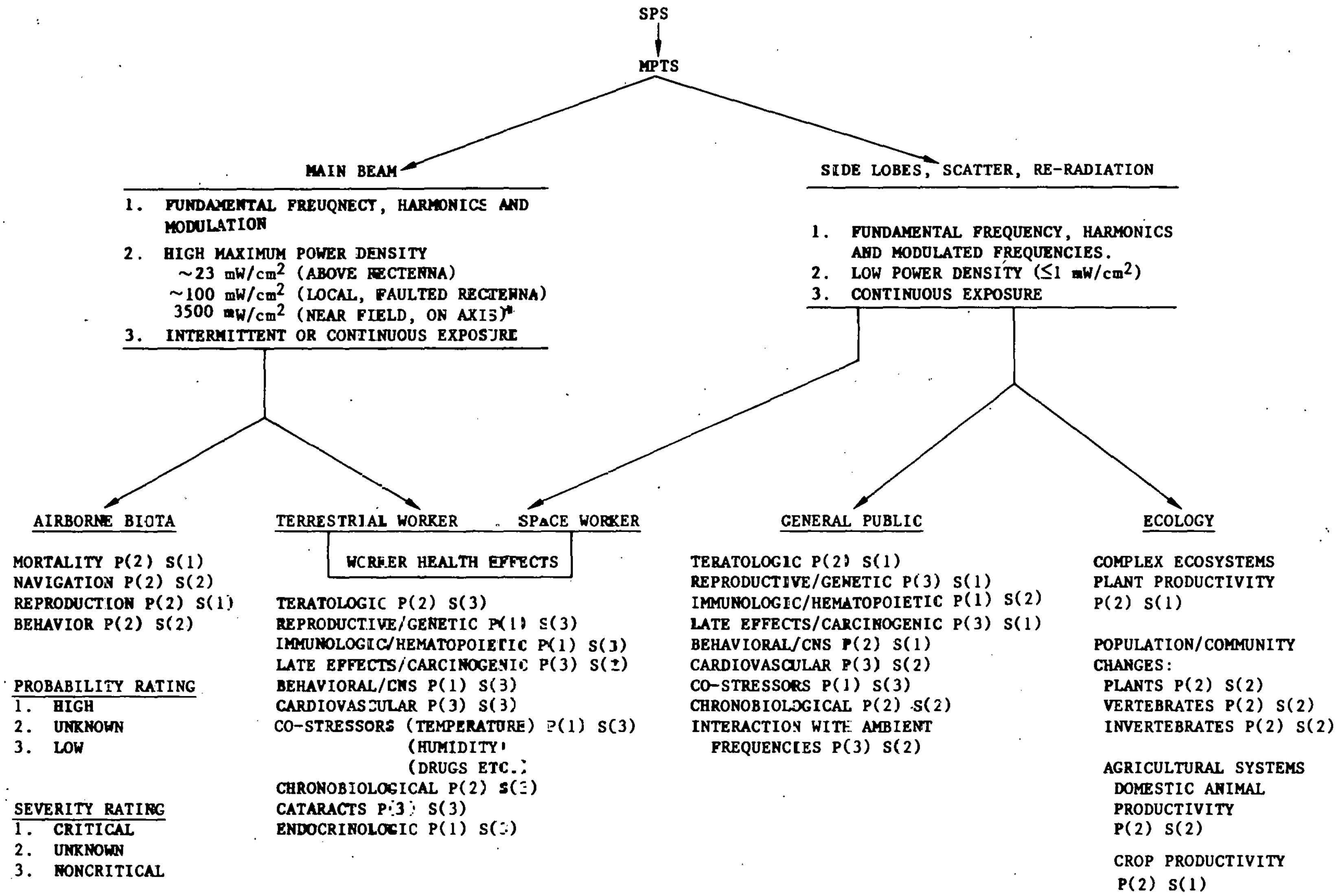
1.2.2 Effects on Ecosystems

Only rarely has microwave effects research with direct ecological implications been performed and never has the impact of microwaves on an entire ecosystem been attempted. Nevertheless, in a cursory review of the literature in this area, several reports have been identified which may have a bearing on the SPS program (Ref. 1.8.1). 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 have increased lethality, decreased reproductive success and alterations in normal behavior. However, data for the ecological effects of continuous, low level exposures expected to be associated with SPS are nonexistent.

As a first step, a comprehensive review and critical interpretation of the literature on the ecological effects of microwaves will be conducted. A computer-retrievable information system will be developed which will allow the identification of critical ecological information gaps. Ecological research protocols that address these gaps and are specific to SPS needs will be formulated during FY 1978-80. Particular emphasis will be on the relationship between rectenna operation and ecosystems.

1.3 CAUSE AND EFFECT RELATIONSHIPS

The cause and effect relationships for the microwave biological effects are shown in Fig. 1.1. Each effect is given a probability (P) rating and an issue severity (S) rating depending upon the expected probability of occurrence and the criticality of the effect as an SPS issue, i.e., how important the issue is to the SPS decision-making processes, if required mitigating strategies cannot be implemented.



*SPACE WORKER ONLY

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

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 (NIEHS, 1970) conservatively estimated that nearly one-half of our 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 as yet generated a data base upon which quantitatively sound and scientifically valid population exposure standards for microwave radiation (Ref. 1.8.3) can be established.

Research during the past five years has led to significant advances, both in research methodology and in knowledge of the effects of microwave radiation on living systems. This work 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/cm^2 (Ref. 1.8.12-15). At frequencies below 10 GHz, the full extent to which perturbations impact on living systems has not been determined nor are the conditions necessary to produce an observed alteration well defined. Even less is known about biological effects of microwaves at frequencies greater than 10 GHz.

Major difficulties in reliably evaluating consequences of exposure of humans to microwaves are the paucity of human data, difficulty in establishing dose distribution within a body, insufficiency of valid data on experimental animals, and the usual problems of extrapolating data from animals to humans. The current lack of understanding of basic mechanisms of how low-intensity fields interact with biological systems compounds the problem. Research to date has not resolved these difficulties, but it has helped to define the nature and scope of the problem and has provided directions for continuing research (Ref. 1.8.4). Only intensive experimental study of continuous wave (CW) radiation at the proposed frequency of 2.45 GHz can reveal whether the SPS concept can be implemented safely (Ref. 1.8.1).

A data base for making an ecological assessment is virtually nonexistent at the present time. A wide range of information is needed concerning quantitative and qualitative responses of an ecosystem to microwave exposure. This information must be directly related to the type and level of exposure to be found at and beyond the rectenna site. Critical areas for which information is currently lacking include effects on the survival, behavior and reproduction of airborne biota and on crop productivity.

The full impact of the effects of microwave radiation on ecosystems and human health will not be known until a determination of the spacial distribution and the 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 RESEARCH PLAN AND ALTERNATIVES

A draft research plan and schedule has been generated (see Ref. 1.8.5) by a group of peers in the field of microwave biological effects. It lists generic areas to be addressed and specific tasks to be undertaken during the next three-year period and assigns a priority to the research. A network diagram which incorporates the thinking of Ref. 1.8.5 is shown in Appendix 1A. The research is typed depending upon whether it is prospective or retrospective in nature and is aggregated in the categories specified in the plan.

Several sources have been important in developing the research plan for microwave ecological effects (Ref. 1.8.1 and Refs. 1.8.9-11). Of particular importance is the review of the biological effects of microwaves prepared at Pacific Northwest Laboratories (Ref. 1.8.1). As the most complete review of its type to date, it has helped establish research priorities. The siting document prepared by NASA (Ref. 1.8.9) has been useful and will continue to be so as mitigating strategies are developed.

1.6 PRELIMINARY ASSESSMENT

The state of knowledge dictates the preliminary assessment of the effect of SPS specific microwave radiation on health and ecology. In essence, the presently available information is too limited, contradictory, and incomplete to provide the requisite level of certainty which would permit an unqualified endorsement of the SPS concept.

In this preliminary assessment, the values presented in Ref. 1.8.6 were used as proposed limits of exposure of humans. Maximum power density from a single SPS were taken from Ref. 1.8.7. These values are summarized in Table 1.1.

1.6.1 Effects on Public Health and Safety

Public health and safety may be affected by the following factors:

Table 1.1. Ranges and Limits of Power Density for Microwave Exposure[a]

Impacted Biota	Ref. 1.8.6 Guideline Limit	Ref. 1.8.7 Expected P_D Max
Public	$\le$1.0 mW/cm^2 (continuous)	$\le$ 1 mW/cm^2 (Outside exclusion zone)
Terrestrial Worker	$\le$ 1.0 mW/cm^2 (continuous) No stated limit for Intermittent Exposure	$\simeq$ 23 mW/cm^2 (Inside exclusion zone. May increase to 100 mW/cm^2 under rectenna fault conditions.)
Space Worker	$\le$ 1.0 mW/cm^2 (continuous) $\le$ 10.0 mW/cm^2 (per 8-hr day)	$\le$ 3500 mW/cm^2 (near field on axis. See Ref. p. 1-15
Ecosystems	None	$\simeq$ 23 mW/cm^2 (Inside exclusion zone) $\le$ 1.0 mW/cm^2 (Outside exclusion zone)

[a] See Solar Power Satellite Baseline Review by MSFC-JSC, July 13, 1978

- Chronic exposure to low levels of microwave radiation ($\leq$1mW/cm^2) outside the rectenna exclusion zone.
- Short term exposure to higher levels of microwave radiation, e.g., in transit through the main beam in aircraft.
- Interaction with other biota of the ecosystem that are directly affected by the microwave radiation.

The effects that may occur, their assumed impacts based on the existing state of knowledge, their qualitative probability and severity ratings, proposed future research and possible mitigation strategies are listed in Table 1.2.

1.6.2 Effects on the Health and Safety of the Terrestrial Worker

The worker at the rectenna site will be exposed to both high and low levels of microwave radiation ($\sim$ 23 mW/cm^2) during work periods. Exposures may be increased by a factor of 4 under the conditions of rectenna malfunction, e.g., mismatch of the terminal electrical load. Such increases in power density levels to $\sim$100 mW/cm^2 could induce pronounced thermal effects in an unprotected worker. The effects which may occur in the range 23-100 mW/cm^2, their assumed impacts based on the existing state of knowledge, probability and severity ratings, proposed future research and possible mitigation strategies are listed in Table 1.3.

1.6.3 Effects on the Health and Safety of Space Workers

Space workers will be exposed to both high and low levels of microwave radiation during a tour of duty in space. Since the worker will be in close proximity to the transmitting array it is possible that exposure in near field at a power density near 3500 mW/cm^2 could occur. Diffraction of the fields at the edges of the transmitting array or the reflection of waves from local boundaries may also cause exposure of workers to fields in excess of ANSI* and guideline recommended limits listed in Table 1.1. 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 the existing state of knowledge, their probability and severity ratings,

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*American National Standards Institute, Standard C.95.4.

Table 1.2. Potential Effects of SPS MPTS on Public Health

Effect	Probability Rating[a]	Severity Rating[b]	Existing Knowledge	Proposed R&D[c] (Task)	Mitigating Strategies
Teratologic	2	1	Birth defects in mice and infant mortality in monkeys reported	1-5	● Implement safety standard ● Change baseline design ● Change operating mode
Immunologic/ Hemopoietic	1	2	Several reports of effects on white blood cells, both Western and East European literature	6-10	as above
Behavioral/CNS	2	1	Alterations in behavior and blood-brain barrier noted in rodents	11-18	as above
Reproductive/ Genetic	3	1	No effects noted at low exposure levels	5, 25, & 27	as above
Late Effect/ Carcinogenic	3	1	No data developed to date	20-23, & 26	as above
Cardiovascular	3	2	Change in heart rate noted <u>in vitro</u>	27 & 29	as above
Costressors	1	3	Effects demonstrated with temperature, humidity, and drugs	14 & 37	as above
Interaction with Ambient Frequencies	3	2	No data available as yet	36	● Limit environmental frequencies ● Change baseline design ● Change operating modes

[a] 1 - high; 2 - unknown; 3 - low.

[b] 1 - critical; 2 - unknown; 3 - noncritical.

[c] Task numbers taken from Ref. 1.8.5.

Table 1.3. Potential Effect of the SPS MPTS on Occupational Health (Terrestrial and Space Workers)

Effect	Probability Rating[a]	Severity Rating[b]	Existing Knowledge	Proposed R&D[c] (Task)	Mitigating Strategies
Teratologic	2	3	Birth defects in mice and infant mortality in monkeys reported	1-5	Screen out pregnant females
Immunologic/ Hemopoietic	1	3	Various effects noted at moderate dose, short exposures	6, 7, & 9	Provide shielding
Behavioral/CNS	1	3	Alterations in behavior and blood brain barrier noted after short exposures	12, 14, & 16	Provide shielding
Reproductive/ Genetic	1	3	Effects noted at moderate and high doses on male reproductive system	19, 25, & 27	Provide shielding
Late Effect/ Carcinogenic	3	2	No effects noted as yet	24 & 26	Provide shielding
Cardiovascular	3	3	Change in heart rate noted <u>in vitro</u>	29	Provide shielding
Costressors	1	3	Effects demonstrated with temperature, humidity and drugs	14 & 37	Provide environment control; limit exposure duration; screen for drugs, etc.
Cataracts	1	3	Cataractogenesis noted at high doses	28	Provide shielding; limit exposure duration
Endocrinologic	1	3	Changes noted at high dose, short exposure	31	Provide shielding

[a] 1 - high; 2 - unknown; 3 - low.

[b] 1 - critical; 2 - unknown; 3 - noncritical.

[c] Task numbers taken from Ref. 1.8.5.

proposed future research and possible mitigating strategies are listed in Table 1.3.

1.6.4 Effects on Ecosystems

The rectenna site ecosystems may be affected by chronic exposure to microwave radiation levels of approximately 23 mW/cm^2. Chronic levels of microwave radiation $\leq$1mW/cm^2 will be experienced outside the exclusion zone. Both high and low levels may produce effects. The possible effects, their assumed impacts based on the existing state of knowledge, their probability and severity ratings, proposed future research and possible mitigating strategies are listed in Table. 1.4.

As a result of a review of the biological effects of microwave radiation (see Ref. 1.8.1) 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 directed towards 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 may impose a sufficient additional thermal burden to be lethal. Furthermore, because birds apparently use the earth's magnetic field as a navigational aid, the strong electromagnetic beam may disturb their navigation patterns. Bees are important because of their impact on the pollenization process and therefore on man's food supply, and because they are similar to higher animals with respect to biochemical, physiological and behavioral characteristics. Bees are relatively easy to handle experimentally and have a short life cycle; therefore, they are attractive experimental subjects.

1.7 CONCLUSIONS AND RECOMMENDATIONS

Studies of the dependence of microwave biological effects on the complexity of fields established in standard exposure systems will also be undertaken. These studies are high priority since they will provide a method of correlating effects obtained at low microwave intensities but using different exposure systems and will aid in the retrospective interpretation of existing literature. It will also aid in defining exposure parameters for future experiments.

Table 1.4. Effects of the SPS MPTS on the Ecology

Effect	Probability Rating[a]	Severity Rating[b]	Impact Based on Present Knowledge	Proposed R&D	Mitigating Strategies
Change in plant productivity	2	2	Change in productivity could alter dynamics and composition of ecosystem; change in productivity of crops could have economic impact.	Literature search to determine susceptible species/ ecosystems and their locations. Perhaps some lab studies initiated.	Relocation of rectenna sites to avoid critical areas or selection of different crops.
Alterations of plant reproduction success	2	2	Change in reproduction could alter ecosystem composition and dynamics; also could affect crops.	As above	As above
Change in plant community structure due to species specific differences in sensitivity	2	3	Impact as above.	As above	As above
Impact on flying biota; birds, insects, bats	2	1	Potential for a variety of aesthetic and economic losses.	As above	Unable to address adequately at present time; perhaps siting changes.
Impact on invertebrates; insects, worms, etc.	2	2	Changes in ecosystem function/structure possible; potential for economic impact depending on effects on beneficial and pest species.	As above	As above

Table 1-4. (Cont'd)

Effect	Probability Rating[a]	Severity Rating[b]	Impact Based on Present Knowledge	Proposed R&D	Mitigating Strategies
Impact on decomposer organisms; fungi, bacteria, etc.	2	2	Alteration in productivity of system.	Literature search to determine susceptible species/ecosystems and their locations. Perhaps some lab studies initiated.	Unable to address adequately at present time; perhaps siting changes
Alteration of small mammal population 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.	As above	As above
Impact on reptiles and amphibians	2	3	Difficult to assess; general ecosystem change.	As above	As above
Impact on birds relating to low level exposure	2	1	Potential economic and aesthetic losses; general ecosystem change	As above	As above
Change in productivity of domestic animals; cattle, hogs, chickens, etc.	2	2	Difficult to assess.	As above	As above
Degradation of natural ecosystem quality	1	2	Fragmentation of terrestrial ecosystem by roads, power lines, etc. can reverse ecological succession.	Literature search to determine extent and severity of problem.	As above

Table 1-4. (Cont'd)

Effect	Probability Rating[a]	Severity Rating[b]	Impact Based on Present Knowledge	Proposed R&D	Mitigating Strategies
Disruption of ecosystems by electrical fields generated by power lines	2	3	Unable to predict.	Research is currently being conducted by various organizations outside SPS.	As above
Changes in plant communities as direct result of construction	1	3	Construction may destroy present plant communities, and lead to establishment of different types.	Review of literature concerning construction effects on ecosystems; obtain information on construction techniques projected for SPS.	Alternative siting; selection of least destructive methods of construction.
Change in small mammal populations	1	3	Changes in vegetation due to construction will affect mammal populations.	As above	As above
Impact on bird populations due to habitat change	1	2	Changes in habitat will alter bird populations.	As above	As above
Impact on reptile and amphibian populations due to habitat change	1	3	Changes in habitat will alter amphibian/reptile populations.	As above	As above

[a] 1-High; 2-Unknown; 3-Low

[b] 1-Critical; 2-Unknown; 3-Non-Critical

1.7.1 Public and Occupational Personnel

Knowledge of the effects of long-term continuous exposure to the SPS microwave transmission frequency is required before deployment of the system. There are no data of this nature currently available, and the necessary experiments are lengthy and costly. Because these data cannot be obtained quickly, it is prudent to consider first the apparently valid effects already demonstrated in the literature. Re-examination of these results under likely SPS exposure conditions can be accomplished in a 2-3 year period and will provide useful information as to the likelihood of these effects being a serious problem for SPS, as well as provide information to use in the design of the long-term experiments. In addition, there are some areas in which no data exist but which can also be addressed in the short term (see Table 1.2).

1.7.2 Ecosystems

SPS will require large areas of natural and man-altered ecosystems for rectenna sites. The ecological effects of long-term, low dose exposure to ecosystems 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 organisms would be speculative. Basic ecological field research will be required to answer critical questions for SPS.

The ecological research program will be a complex undertaking. In order to assure that all critical issues are addressed, a preliminary phase should be initiated. Phase I (through FY 80) will gather and assimilate data from various sources for the purpose of developing a subsequent research program which may be required after FY 80. The following task sequence is recommended to provide the required information.

(1) Determine potential critical ecological issues relating to SPS,

(2) Describe the level of knowledge that exists concerning the relationship of rectenna operation to ecological processes,

(3) Define technological and ecological data gaps, and determine research needs,

(4) Develop a computerized data base of technical

and ecological knowledge related to SPS that can incorporate new data as they become available. This information will be made available to organizations involved in SPS,

(5) Define research priorities for use in determining allocation of research funds, and

(6) Develop mitigation strategies or alternate siting patterns for areas that have potentially great impacts.

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APPENDIX 1A

MICROWAVE HEALTH AND ECOLOGICAL EFFECTS PROGRAM PLAN

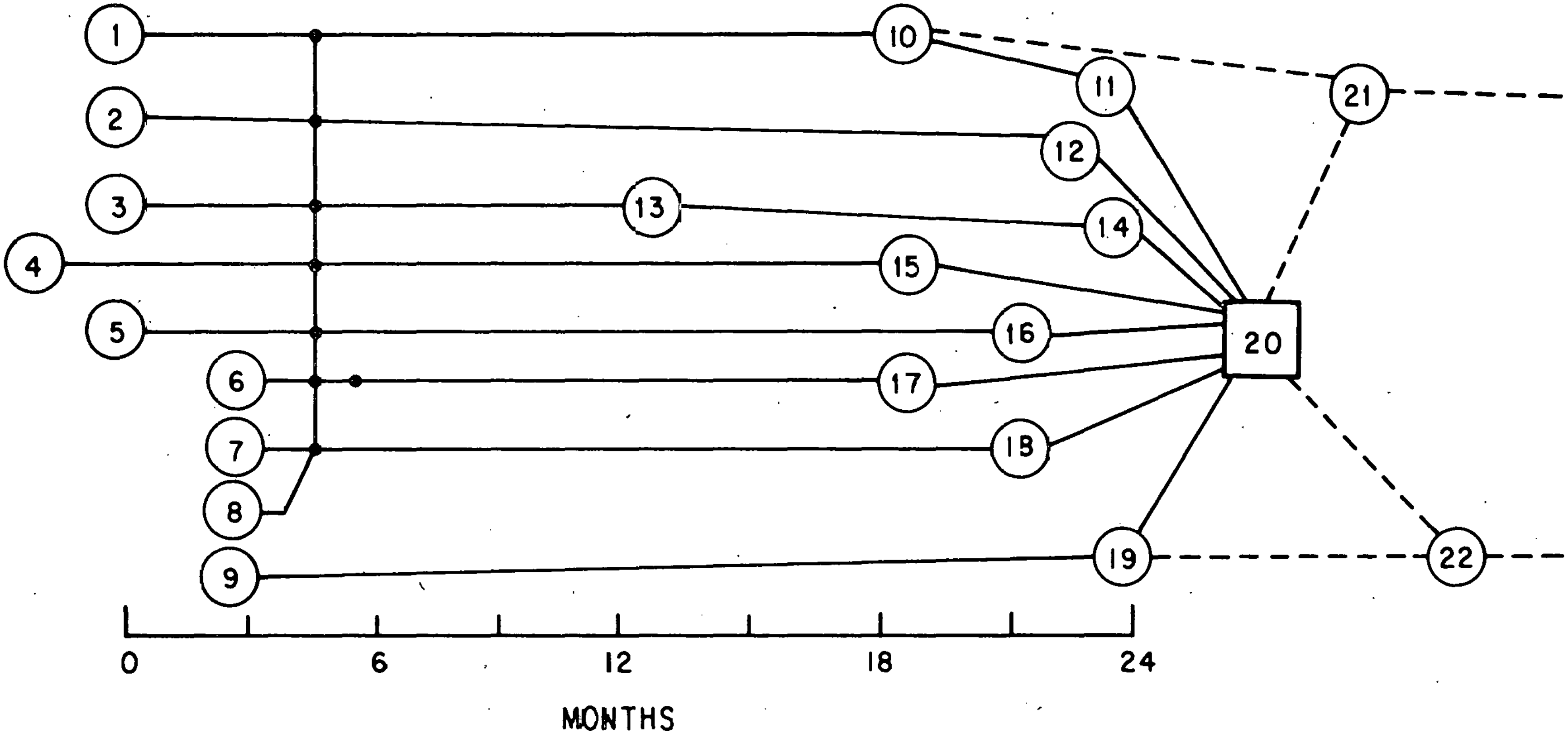

Fig. 1A.1. Microwave Health and Ecological Effects Program Plan

Key to Figure 1A.1

1. Begin comparison of biological endpoints using unipath and multipath sources.
2. Begin bird lethality and navigation study.
3. Begin validation study of immunological/metaological effects.
4. Begin bee lethality and behavior study.
5. Begin histophathological study of changes in central nervous system.
6. Begin validation study of teratology in rodents.
7. Begin validation study of changes in behavior due to drug-microwave interaction.
8. Begin quality assurance on all biological studies - continuing.
9. Begin assembling and computerizing ecological data base.
10. Complete comparison of unipath and multipath sources.
11. Re-evaluate existing biological data in light of unipath-multipath study.
12. Complete bird study.
13. Complete immunology validation study and begin follow-up phase.
14. Complete follow-up phase of immunology/hematology study.
15. Complete bee study.
16. Complete CNS histopathology study.
17. Complete teratology validation study.
18. Complete behavioral validation study on drug-microwave interaction.
19. Complete assembly of ecological data base.
20. FY80 evaluation of health and ecological effects.
21. Initiate long-term and selected short-term animal exposures.
22. Initiate long-term exposure of ecological park.

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2 OTHER EFFECTS ON HEALTH AND THE ENVIRONMENT

2.1 SCOPE

This section deals with nonmicrowave effects of the SPS on health, safety, and the environment. This includes the following:

- Terrestrial Operations

  Mining of raw materials
  Construction of terrestrial facilities
  Processing and fabrication of finished materials
  Transport of materials and equipment
  Ground station operations
  Flight operations

- Space Operations

  Orbital transfer of material and personnel
  Construction of SPS arrays
  Operation of arrays

Effects on the following are considered:

General public
Terrestrial workers
Space workers
Environment

The effects include direct and indirect effects on health, the creation of safety-related problems, and effects on the environment.

2.2 METHODOLOGY

The nature of effects of terrestrial operations dictates that they be treated in two ways. First, a number of the effects result from conventional processes that are used more extensively in the development of an SPS system (e.g., manufacture of steel). In these cases the assessment involves the evaluation of 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 system (e.g., effects of prolonged weightlessness). In these cases the assessment involves the identification of the potential effects, an evaluation of their possibility of creating health, safety, and welfare problems, and a review of the research needed to establish the magnitude of the effects more conclusively.

2.3 CAUSE AND EFFECT RELATIONSHIPS

Figure 2.1 shows the cause and effect relationships for various portions of the SPS system as currently understood. There are a multitude of possible interactions, and only the major pathways have been identified.

The Extraction, Processing, and Fabrication of Materials and Equipment activities result in impacts that are primarily conventional in nature; that is, the effects of air pollution generation, water pollution generation, land disturbance, and the like, are not unique to SPS deployment, but are common to all mining, construction, and manufacturing operations. The importance of considering these impacts as part of an SPS assessment comes from the need to evaluate the incremental effects caused by the SPS system requirements. This preliminary assessment will attempt to provide some very rough indications on the extent of the incremental impacts caused by the 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 will be involved in the manufacture of the solar arrays, and in the rocket propellants. As the assessment will show, there has been no systematic identification of the toxic materials involved, and a complete impact evaluation cannot be carried out at this time.

The Transport of Materials and Equipment activities 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 are conventional in nature, and the issue of interest is the incremental effect. Two unconventional and SPS-specific impacts are, however, significant. One is the exposure to toxic materials and the second is the potential for catastrophic accidents which results 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 assessed.

The 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 field effects are common to all electrical power systems and are not unique to the SPS.

SPS TERRESTRIAL OPERATIONS

Extraction, Processing, Fabrication of Materials and Equipment

Mining

- Land Disturbance (strip-mining, subsidence, spoil piles)
- Air Pollution Generation (fugitive dust)
- Water Pollution Generation (leaching, drainage modification)
- Toxic Materials Exposure
- Safety Hazards
- Noise
- Solid Waste Generation

Construction

- Land Disturbance
- Air Pollution Generation (fugitive dust)
- Water Pollution Generation
- Safety Hazards

Manufacturing

- Air Pollution Generation (stack emissions)
- Water Pollution Generation (process effluents)
- Solid Waste Generation
- Safety Hazards
- Toxic Materials Exposure
- Noise

Transport of Materials and Equipment

- Air Pollution Generation (vehicle exhausts)
- Water Pollution Generation (spills)
- Accidents (conventional, catastrophic)
- Toxic Materials Exposure

continued......

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

SPS TERRESTRIAL OPERATIONS

Ground Station (Rectenna Site) Operation and Maintenance	Flight Operations	
	Launch	Recovery
High Intensity Electromagnetic Fields	● Air Pollution Generation (vehicle exhaust, ground cloud) ● Water Pollution Generation (launch pad cooling) ● Noise (acoustic, sonic boom) ● Launch Emergency (abort, off-trajectory failure) ● Toxic Material Exposure ● High Acceleration/Deceleration ● Ozone Depletion	● Water Pollution Generation (residual propellant spills, ablative material removal) ● Noise (sonic boom) ● Recovery Emergency ● Toxic Material Exposure

Fig. 2.1. (Cont'd)

The Launch and Recovery Operations are similar to those undertaken in current space program activities; however, the deployment of the SPS system will require significantly larger launch vehicles and a significant increase in launch and recovery activity. The effects of these increases must be evaluated.

All of the SPS Space Operations 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 will 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 health and safety effects from deployment of an SPS system 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 an SPS system over existing levels of activity 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 SPS system definition.

Table 2.1 summarizes the state of knowledge of each of the effects. The references given should be considered as representative of the information available and are, by no means, an exhaustive compilation of the data.

2.5 RESEARCH PLAN AND ALTERNATIVES

Appendix 2A gives a research plan for evaluating the health, safety, and environmental effects of an SPS system.

2.6 PRELIMINARY ASSESSMENT

The preliminary assessment is divided into an evaluation of the effects of the effects on the public, terrestrial workers, space workers, and the environment.

Table 2.1. State of Knowledge of SPS Effects Exclusive of Microwave Effects

Group	Effects	Activities Involved	State of Knowledge	References
Public	Land Disturbance Effects Loss of Land Reduced property value	Mining, Construction	• Effects of mining, land reclamation potential under intensive study.	2.8.29
	Air Pollution Health Effects Respiratory disease Cardiovascular impairment Skin/eye irritation	Mining, Construction, Manufacturing, Transport, Launch	• Health effects of selected air pollutants well-documented from epidemiological and other studies. National standards established.	2.8.30
			• Emission rates of selected pollutants well-documented.	2.8.37
			• Atmospheric reactions and transport not completely understood.	2.8.38
			• Launch exhaust emissions and ground cloud dispersion not completely understood. Recommended limits available.	2.8.39
	Water Pollution Health Effects Intestinal disease Skin irritation Other ingestion effects	Mining, Construction, Manufacturing, Transport, Launch, Recovery	• Health effects of many water pollutants well documented.	2.8.40
			• Leaching into ground waters not clearly understood.	
			• Effluents from manufacturing processes are known.	
			• Water pollutants from transport, launch, recovery not completely known; estimated from other space program activities (i.e., shuttle).	2.8.9
	Noise Stress - psychological and physiological	Launch, Recovery	• Effects are known for both acoustic noise and sonic boom. Recommended standards are available.	2.8.42
	Safety Hazards Accidental injury/fatality	Transport, Launch, Recovery	• Conventional transport accident rates known.	2.8.41
			• Accident occurrence and extent of impact estimated for other space program activities (i.e., shuttle) but not for SPS.	2.8.9
	Solid Waste Generation Effects Sanitation problems	Mining, Manufacturing	• Extensive data available.	
	Toxic Materials Exposure	Mining, Manufacturing, Transport, Launch, Recovery	• Toxic materials involved in SPS not identified.	
			• Some materials have well-documented health effects, others have little or none.	
	High Intensity Electromagnetic Field Exposure	Ground Station Operation	• Effects unknown.	

Table 2.1. (Cont'd)

Group	Effects	Activities Involved	State of Knowledge	References
Terrestrial Workers	Occupational Air Pollution Health Effects Respiratory disease Cardiovascular impairment Skin/eye irritation Other occupational illness	Mining, Construction, Manufacturing, Launch	• Conventional occupational health effects well-documented. Threshold Limit Values established.	2.8.43
	Water Pollution Effects Skin/eye irritation Occupational illness	Manufacturing, Recovery (residual propellant spills, ablative material removal)	• Extent of effects unknown.	
	Noise Hearing impairment Stress-psychological and physiological	Mining, Manufacturing, Launch	• Noise effects available. Occupational exposure limits available for conventional activities.	2.8.42
	Safety Hazards Accidental injury/fatality	Mining, Construction, Manufacturing, Transport, Launch, Recovery	• Conventional occupational hazards and injury/fatality rates known. • Incidence and extent of occupational accidents from catastrophic transport accident and launch and recovery emergencies not evaluated.	2.8.7
	Toxic Materials Exposure	Mining, Manufacturing, Transport	• Toxic materials involved in SPS not identified yet.	
	High Intensity Electromagnetic Field Exposure	Ground Station Operation	• Effects unknown.	
Space Workers	Prolonged Weightlessness Effects Motion Sickness Balance Calcium loss Muscle deterioration Hormone, fluid, electrolyte imbalances Anemia Cellular immunity changes Cardiovascular changes	Orbital Transfer, Space Construction, Space Operation	• Data available from other space program activities.	
	Radiation Exposure Effects Cancer Genetic changes Cataracts Central nervous system damage Life shortening	Orbital Transfer, Space Construction, Space Operation	• Limited data available from other space program activities.	
	System Emergencies	Launch, Recovery, Orbital Transfer, Space Construction, Space Operation	• No data available on projected occurrence and extent of SPS emergency conditions.	

Table 2.1. (Cont'd)

Group	Effects	Activities Involved	State of Knowledge	References
Space Workers (Cont'd)				
	Emergency Medical/Dental Problems	Orbital Transfer, Space Construction, Space Operation	● No data available on projected occurrence rate for SPS.	
	High Acceleration/ Deceleration Effects	Launch, Recovery	● Some data available from other space program activities.	
	Extra Vehicular Activity Hazards Accidental Injury/ Fatality	Space Construction, Space Operation	● No data available on projected SPS occurrence.	
	Extended Confinement Psychological stress	Space Construction, Space Operation	● Some studies on confinement under other circumstances.	
	Thermal Extremes Hypothermia Injury/fatality	Space Construction, Space Operation	● Data on effects on earth available.	
	Plasma Arcing	Space Construction, Space Operation	● No data available.	
	High Intensity Electromagnetic Field Exposure	Space Operation	● Effects to be investigated.	
Ecology	Air Pollution Ecolcgical Effects	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, widespread ecological effects not known.	2.8.26
	Water Pollution Ecological Effects	Mining, Manufacturing, Construction	● Effects of many pollutants on aquatic ecosystems well known; may range from insignificant to severe.	2.8.23 2.8.24
	Solid Waste Ecological	Mining, Manufacturing	● Gross effects known and documented. Includes leaching of toxic chemicals from waste piles.	2.8.22
	Land Use	Mining, Manufacturing, Construction, Launch Sites, Transport, Rectenna Siting, Power Distribution System	● Land use changes known and documented for selected activities. Some constraint predictions dependent on system definition. Wildlife attraction to rectenna site appears probable for some species but no documentation exists.	2.8.25
	Noise	Launch, Recovery	● Very little information concerning effects on animals; information on ecological impact is lacking.	2.8.9
	Reflected Light Plant & animal cycles changed by reflected light	Space Operations	● Much is known about influence of light on biological cycles. Current SPS system definition information insufficient to predict effect.	2.8.28
	High Intensity Electromagnetic Field Exposure	Ground Station Operation	● Effects to be investigated.	

2.6.1 Effects on the Public

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

2.6.1.1 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 is attributable to the SPS system. Studies have been made of the materials requirements for an SPS system (Ref. 2.8.1–2.8.3). These can be used as a rough gauge of the increase in activity dictated by the SPS configuration. Table 2.2 shows the materials requirements of the two tentative SPS system designs from Ref. 2.8.1 (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 (e.g., aluminum, concrete) the increment is small (less than 2%).

Some attempts have been made to quantify the impacts of an SPS system on air pollutant emissions, water effluents, water requirements, solid waste generation, and land requirements. These data are presented on Table 2.3. It should be noted that these estimates were based on an earlier SPS configuration concept and do not represent the most recent design points of Ref. 2.8.1. Nevertheless, they give an order of magnitude estimate of the impact. Also, the U.S. annual totals are yearly data while the SPS data are for the entire system over its approximately 30 year design lifetime.

It is possible to compare the emission, effluent, and resource requirements to either U.S. totals or to alternative electrical generating systems. For example, the particulate air pollutant emissions of 3.32×10^6 metric tons are about 23% of the U.S. total in 1973; the SO_2, CO, and hydrocarbons are about 1.5%; and the NO_2 is about 0.2%. The SPS-related emissions, however, are totals and not annual rates and so the data are not directly comparable. As another example, the water pollutant burden of a coal-fired power plant is 8-600 metric tons per megawatt-year vs 0.2 metric tons per

Table 2.2. Incremental Material Requirements of SPS System

	Portion of U.S. Annual Production, %[a]	
Material	Silicon Design[b]	Gallium Arsenide Design[b]
GFRTP[b]	NA	NA
Stainless Steel	NA	NA
Glass	NA	NA
Silicon	NA	NA
Copper	0.12	0.07
Aluminum	1.24	1.28
Silver	0.42	17.02
Molybdenum	0.002	0
Mercury	73.7	73.7
Tungsten	1.63	1.63
Steel	0.23	0.23
Concrete[c]	2.10	2.10
Gallium Arsenide	NA	NA
Titanium	0.04	0.04
Ceramics	NA	NA
Misc. and Organics	NA	NA
Argon	10.28	2.44
Hydrogen	53.70	30.61
Oxygen	15.95	8.19
CH_4	NA	NA
Sapphire	NA	NA
Teflon	NA	NA
Krypton	NA	NA

[a] Unless otherwise indicated, materials requirements from Ref. 2.8.1, U.S. Production from Ref. 2.8.4. Values given are for one satellite.

Note: The SPS materials requirements are for the total system and the production rates are U.S. annual totals; caution must be used in interpreting these data.

[b] Glass fiber reinforced thermo plastic.

[c] Production measured as cement.

NA - Not available.

Table 2.3. Effects of SPS Deployment[a]

Type of Impact	SPS Total System Impacts[b]	U.S. Annual Total
	10^6 metric tons	
Air Pollutant Emissions[c]		
Particulates	3.32	14.46
SO_2	0.40	29.68
CO	1.25	88.08
Hydrocarbons	0.30	21.59
NO_2	0.03	19.74
Ammonia	0.008	NA
Water Pollutant Effluents[d]		
Bases	0.365	NA
Biological Oxygen Demand (BOD)	0.025	NA
Chemical Oxygen Demand (COD)	0.913	NA
Dissolved Solids	0.500	NA
Suspended Solids	0.661	NA
Organics	0.167	NA
Water Resources Requirements[e]		
Non-recoverable water use	102	1366
Solid Waste Generation[f]		
Waste Material	47.73	228.63
	10^3 km^2	
Land Requirements		
Land for Rectenna Sites Only	10.56	9363.17[g]

[a] The SPS impacts are for the total system and the U.S. totals are annual rates. Caution must be exercised in interpreting these data.

[b] Source: Ref. 2.8.3. Based on early version of SPS configuration (Scenario A). Does not reflect more recent designs.

[c] SPS data from mining, processing, fabrication. U.S. total data for all sources from Ref. 2.8.6, 1973.

[d] From steel, aluminum, copper, cement processes.

[e] SPS data from propellant manufacture, launch pad coating, construction. U.S. total from Ref. 2.8.4, 1975.

[f] SPS data from aluminum and steel processes. U.S. total data from Ref. 2.8.8, residential, commercial, industrial wastes.

[g] U.S. total land area.

NA - Not available.

megawatt-year for the SPS system (Ref. 2.8.5). This normalized comparison is also incomplete since it does not distinguish 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:

(1) The data available reflect an earlier SPS configuration and are useful only for addressing the scope of the potential problems.

(2) The impact-generating conditions (i e., air pollution generation, water pollution generation, etc.) 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.

(3) The impact-generating conditions have not been translated into public health and safety effects.

(4) 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 system designs. It can be stated tentatively that the available analyses indicate that the SPS system will have a measurable impact on air pollution, water pollution, water resources, solid waste, and land requirements. The public health and safety effects associated with these impacts appear to be non-negligible. The research program outlined in Appendix 2A is designed to provide the analysis needed to establish the extent of the effects.

2.6.1.2 Unconventional Effects on Public Health and Safety

The unconventional effects on public health and safety result from the exposure to toxic materials from mining, manufacturing, and transport; the potential accidental injury and/or fatality from the transport of highly explosive materials (e.g., rocket propellants); all of the launch and recovery activities; and exposure to high intensity electromagnetic fields (other than microwaves) at the rectenna site.

Toxic Materials. To date, no systematic identification of toxic materials involved in SPS deployment has been made. This materials list must be developed first, and then an assessment of the potential effects of SPS deployment can be made. It is expected that some of the materials will have a significant base of information upon which to carry out an assessment (e.g., mercury); however, there may be other materials where the dose-response relationships and the source-receptor pathways are unknown and additional research will be needed to carry out the assessment. The details of the research plan for toxic materials are presented in Appendix 2A.

Transport Accidents. A sizable quantity of highly explosive rocket propellants will 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 2.8.9 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 m^3 (850,000 gal) spill can produce thermal radiation sufficient to cause first degree burns and ignite light combustibles such as paper at a distance of 300 m. Radiation from a liquid pool fire is about a factor of 5 less. This sized spill is based on a launch pad accident of the space shuttle. A transport accident would probably not involve as much liquid hydrogen in one incident.

If immediate ignition did not occur, Ref. 2.8.9 indicates that the cloud of gaseous hydrogen could be dispersed downwind and ignited by some remote spark. However, this 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 and/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 is 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 would require an analysis of accident probability and an evaluation of probable transport corridors to determine public exposure to these hazards. This analysis is planned as part of the research program on safety hazard.

Launch and Recovery Air Quality. The launch activity results in air quality impacts from the exhaust products of the launch vehicle and from the formation and dispersion of a "ground cloud" at the launch platform 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 are emitted in the troposphere (0-11 km) although a sizable quantity is also emitted in the stratosphere (11-50 km) (Ref. 2.8.3). The ground cloud, on the other hand, is developed at the launch pad and will rise to between 0.7 and 3 km where its bouyancy is neutralized by a cooling of the gases.

The ground cloud has been the subject of extensive research, particularly with regard to its generation by the space shuttle program (Ref. 2.8.9). The ground cloud has the potential for creating direct public exposure 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 space shuttle operations. These results are not directly applicable to SPS operations because of the probable use ot liquid-fueled rockets (vs solid-fueled for the shuttle) and the significantly larger launch vehicle size. The model has not yet been exercised for the SPS launch vehicle configuration of Ref. 2.8.1.

As a result of previous work, it is possible to identify ambient concentration limits for various launch-related air pollutants. Table 2.4 gives the standards used for the space shuttle program based on the National Ambient Air Quality Standards promulgated by the U.S. EPA and on 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

Table 2.4. Exposure Limits for Selected Rocket Engine Combustion Products for Man

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 to 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 to 5 hr/day (3 to 4 days/mo)	15	--

Table 2.4. (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

[a] Code of Federal Regulations: 40 CRF 50

[b] Standard based on total suspended particulates

[c] Source: Ref. 2.8.9

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 ground cloud concentrations are below the STPL and PEL values.

In addition to these air quality impacts, the testing of rocket engines, testing of orbital maneuvering systems and reaction control systems, and test flights will also result in the release of air pollutants. The effects of these from SPS deployment have not been studied and will be as part of the research program.

Launch and Recovery Water Quality Impacts. No assessment has been made of the water quality effects of the launch and recovery of SPS vehicles; however, some information is available for the space shuttle (Ref. 2.8.9). Potential pollutants enter the water through contamination of the launch pad cooling water with engine exhaust products, removal of ablative insulation from reentry vehicles with high pressure water jets, and possibly from spillage of residual propellant if the launch vehicle is recovered from the ocean. The first two conditions can 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 2.5.

Table 2.5. Suggested Maximum Allowable Concentrations of Propellants in Water

Propellant Chemical Species	Suggested Maximum Allowable Concentration mg/liter
Hydrazine	90.7
Monomethylhydrazine (MMH)	0.35[c]
Nitrogen Tetroxide[a]	95
Aluminum perchbrate[b]	50

[a] Based on nitric acid

[b] Based on nitronium perchlorate

[c] Based on threshold limit values of hydrazine and MMH

Source: Ref. 2.8.9

Launch and Recovery Noise. Noise impacts from SPS operations will 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 from Ref. 2.8.2 shows the sound pressure levels of the HLLV, as compared to the Saturn V. The 130dB sound pressure contour is 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. 2.8.2 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 incur sound pressure levels of 125-130 dB. To assess the effects of these levels on the public, two conversion steps are necessary. First, the absolute sound pressure must 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

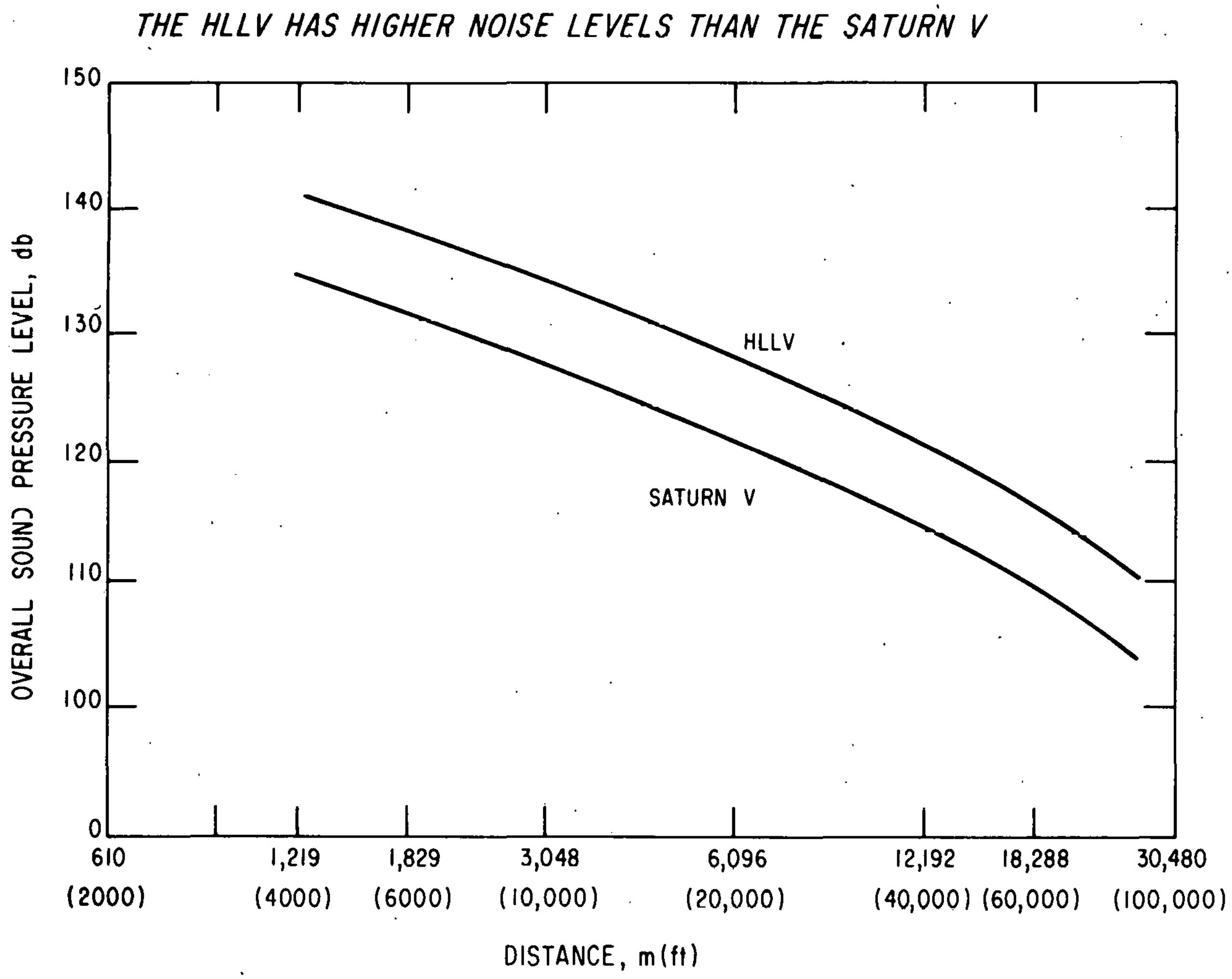

Fig. 2.2. Variation of Overall Sound Pressure Level with Distance from Launch Site

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. 2.8.2 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 will be similar to that of the Saturn as presented in Ref. 2.8.9. Thus, the conversion from absolute to A-weighted levels results in a reduction of approximately 30 dB (Ref. 2.8.9). 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 among some of the alternatives. Reference 2.8.9 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 95dB(A) for the frequency adjustment and further to 65dB(A) for the 24-hour weighted average (assuming a 1-minute duration and 60dB(A) background). This is compared to the 70dB(A) daytime guideline set by EPA and the 50dB(A) nighttime guideline. Considering that the overall sound pressure levels of the HLLV are estimated at about 7 dB over the Saturn V (Ref. 2.8.2) and that the frequency of launch is higher (as many as four per day as compared to one per day for the space shuttle), it appears that the EPA guidelines may be exceeded by the SPS launching program. More detailed system analysis will be required to verify this considering actual launch frequency and sound pressure levels.

The problems of sonic booms result from the supersonic flight of the space vehicles during ascent and reentry. The effects of sonic booms come from their abruptness causing a startle response in humans and the intensity of the overpressure causing property damage. Table 2.6, compiled from Ref. 2.8.9, shows the effect of sonic booms from several studies.

No information is available on SPS vehicle sonic boom generation but Ref. 2.8.3 gives some data on the space shuttle system. These are presented in Table 2.7. Considering the larger size of the SPS sysem components and the increased frequency of sonic boom occurence, it is evident that some problems will be encountred. An analysis of the SPS system sonic boom generation will be needed to evaluate the extent of these impacts.

Table 2.6 Effects of Sonic Boom

Overpressure (N/m^2)[a]	Effect of Simulated Boom on Test Subjects
International Civil Aviation Organization Results[b]	
<24	Not rated as annoying[c]
48	10% of sample rated this as annoying[c]
144	All considered this as 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
Federal Aviation Administration Results[d]	
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

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[a] 1 newton per square meter (N/m^2) = .00015 pound per square inch (psi)

[b] From Ref. 2.8.9. Primary source Ref. 2.8.10

[c] Based on 10-15 booms per day

[d] From Ref. 2.8.9. Primary source Ref. 2.8.11

Table 2.7. Space Shuttle Sonic Boom Generation

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

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[a] Distance measured from launch site.

[b] Where local gradient in speed of sound causes boom path to turn horizontal.

[c] Zone 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.

[d] Distance from landing site.

Source: Ref. 2.8.9.

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

Reference 2.8.2 presents a preliminary analysis that indicates the explosive potential of the HLLV to be about twice as much as the potential of a Saturn V. The peak side-on overpressure (PSOP) contour of 2760 N/m (0.4 psi) must be cleared of all personnel when explosion danger exists. For the Saturn V this contour extends to 2590 m and for the HLLV to 4267 m. 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 (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.

No analysis has been done on SPS launch abort or recovery landing accidents. The assessment of space shuttle operation from Ref. 2.8.9 concludes that these incidents are analagous to conventional aircraft accidents and that, in the case of launch abort, would occur over controlled range areas and thus present no unusual problems. An evaluation of accident probability would be required to estimate SPS effects.

High Intensity Electromagnetic Fields. At the rectenna site there will be an intense electric and magnetic field set up as a result of the high voltage power being transmitted to the site and from the site to load. The potential for public health effects from these fields has been evaluated only with regard to the microwave spectrum.

2.6.2 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 is an increment in conventional mining, construction manufacturing and transport impacts and a set of effects resulting from unconventional conditions.

2.6.2.1 Incremental Effects of Conventional Processes

Using the results of Ref. 2.8.2, which is an assessment carried out for an earlier SPS design, Table 2.8 shows the distribution of occupational illness and injury by various functional activities. These data were assembled using occupational illness and injury rates from the U.S. Department of Labor (Ref. 2.8.7) and labor requirements for the SPS system. Occupational fatality information was not included. The information shows that the material acquisition activities (i.e., mining) account for about half of the person-days lost for injury and illness and that the injury rate is much higher than the illness rate. These rates are totals over the 30-year life of an SPS system and cannot be directly compared to published annual rates.

2.6.2.2 Unconventional Effects

The unconventional effects on terrestrial worker health and safety result from exposure to toxic materials, safety hazards from the transport of highly explosive materials, all of the launch and recovery activities, and exposure to high intensity electromagnetic fields (other than micro-

Table 2.8. Distribution of Occupational Illness and Injury

Activity	Person-Days Lost, 10^6PDL[a] Occupational Injuries	 Occupational Illnesses
Material Acquisition	14.63	0.45
Ground Construction	9.04	0.29
Ground Operation and Maintenance	1.48	0.08
TOTAL	25.15	0.82

[a]Data are for conventional mining, construction, manufacturing only.

Source: Ref. 2.8.3. Based on early version of SPS configuration (Scenario A). Does not reflect more recent designs.

waves) at the rectenna site. These are the same effects as were discussed previously with regard to public health and safety. The difference between public and terrestrial worker impacts is one of degree and intensity.

With regard to toxic material exposure, it has already been stated that a toxic materials list has not yet been developed for SPS. The effects of these substances on the terrestrial worker will be more severe than on the general public because of the higher level of exposure, but a complete evaluation must be made when all of the materials have been identified.

In transport accidents involving catastrophic explosions or fire, the workers involved (e.g., railroad crewmen, emergency personnel, etc.) are more likely to suffer injury and/or fatality than is the general public, but this must be evaluated when a more detailed assessment of accident probability is made.

The occupational health and safety effects of launch and recovery operations are known only insofar as they can be compared to conventional industrial operations (e.g., the use of Threshold Limit Values for workroom air, the noise limits for workplaces, etc.). There has been no systematic assessment to date of the particular occupational health and safety problems created by SPS launch and recovery operations.

As with the public health effects, the effects of high intensity electromagnetic fields on rectenna site workers' health have not been evaluated.

2.6.3 Effects on Space Workers

The health and safety problems related to the uniqueness of the space environment can be grouped into three general categories. These are weightlessness (zero gravity), life support, and the effects of the radiation environment.

2.6.3.1 Weightlessness

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

The red cell mass was significantly reduced. This reduction was possibly due to reduced red cell survival, deformed red cells that may lead to their removal from the circulatory blood, increase in mean corpuscular volume and changes in osmotic regulation, total red cell lipids and/or bone marrow inhibition.[*] Reticulocytosis was delayed after return to earth, implying that erythropoietic mechanisms were insensitive to 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.)

There were some changes seen in the cellular immune system immediately post-flight 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 happening in the first few hours of weightlessness. This may be due simply to shifts between various fluid compartments due to weightlessness.

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[*] Mean corpuscular volume: size of red blood cells; osmotic regulations: 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.

[†] Endogenous compounds are those originating within the body.

[††] Plasma is the fluid component of the blood.

Calcium loss from bones while in the weightless state has been found to be continuous in all space flights so far studied. There appears to be no reversal in this trend even when extra calcium is added to the diet. This situation could lead to bone fragility, to urinary calculi, etc., and thus limit the time workers can 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. There is a possibility that with repeated trips to space there may be some irreversible damage to bone structure.

Muscle tissue reduction has taken place in all space flights to date. 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 changes 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, i.e., 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, etc., have affected a high percentage of space travelers. The physiological mechanisms underlying these sensations is 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 may be especially critical for construction workers.

There may be other problems of weightlessness that have not yet surfaced.

2.6.3.2 Life Support

Life support for long stays in space presents some problems which need careful evaluation.

The correct nutrients in a palatable form will have to be supplied to space workers, probably much of it dehydrated to lessen bulk for shuttle purposes. A possibility exists that some food could be grown on board, using recycled waste products. The amount that will have to be stored, its form, and the need for growing part of it will depend on the frequency of replenishment by shuttle flights and the amount of storage space engineered into space vehicles.

Recycling of water and air will have to be done as efficiently as possible. Systems for this need will have to go into the engineering development of space vehicles and stations.

Contaminants in the space vehicle environment from on-board outgassing of construction materials, waste products, coolants, etc., will have to be minimized and systems for air decontamination built in to remove, as far as possible, those unavoidably present. Various materials used in construction and operation of space vehicles need to be considered with the view of minimizing toxic materials in the atmosphere. Toxicology should also be considered in planning the disposal and recycling of waste products.

Medical and dental on-board support systems and emergency medical facilities will need to be built into the space vehicles to include: surgery, diagnostic equipment (X-ray machine, electrocardiogram equipment, etc.), a clinical laboratory for diagnostic procedures, and emergency dental work. Examples of the emergencies that should be prepared for in case the person cannot be returned to earth quickly are foreign bodies in eyes, fractured bones, ruptured peptic ulcers, heart problems, trapped air under a tooth filling, and kidney calculi.

Facilities for treatment of decompression problems (bends) should be built into space vehicles. The amount of EVA to be expected is unknown at present. However, in the process of construction work, it is possible that a space suit may get torn or punctured. It is also possible that compartments of the space ship may be penetrated by space debris or meteoroids.

The psychological stresses of confinement for long periods may present health problems. Literature searches on the effects of confinement should be made. Recreational facilities should be planned.

2.6.3.3 Radiation

The amounts and types of radiation to space workers will be a limiting factor in the length of time allowed in the space environment. NASA has in-house radiation research programs and, in addition, is supporting some research in other laboratories.

The approximate composition of galactic cosmic radiation is 85% protons, 13% alpha particles, and 2% high-energy heavy ions (Li-Fe). A great deal of research covering many years and many areas where problems may arise has been and is being done on the biological effects of protons and alpha particles. These data need to be reviewed to predict SPS radiation problems and time limits in space that will be imposed by the effects of these particles.

Data are very scarce, to date, on the biological effects of high-energy heavy ions (HZE). The unique characteristics (i.e., very high energy deposition at the path core surrounded by a penumbra of lower energy deposition) of this type of radiation make its effects unpredictable on the basis of results from research on other types of radiation. A few studies have been completed, some are in progress, and others have been proposed. It appears, tentatively at this stage, the HZE is more effective than other types of radiation in cell transformation, in inducing at least one type of tumor in mice, blocking nerve transmission, and damaging visual elements. However, some of these experiments have been done with much higher doses than will be encountered in space. Much more information is needed on carcinogenic effects, damage to non-regenerating tissues such as the central nervous system and visual elements, reproductive and genetic effects including teratology (birth defects), life-shortening effects, relative biological effectiveness as compared to other types of radiation, and possible synergistic effects with other types of radiation.

There appear to be some uncertainties about the composition of HZE in LEO and GEO, i.e., percentage of different ions, energies and fluxes. Firmer data on this may come from current research and information gathered on space shuttle flights. Data on the Relative Biological Effectiveness (RBE) or Quality (Q) factor are being collected and proposals for research to measure these have been made. From the few preliminary data it appears that the RBE ranges from 1 up to at least 10 (i.e., they may be 10 times more effective than X-rays in producing some types of damage). Physical methods of measuring HZE dose appear to have much uncertainty, be excessively time-consuming for read-out, are passive and may not accurately reflect "true" dose in terms that can be related to biological effects. More research is needed for real time read-out of dosage. Current methods of shielding against radiation appear to be ineffective for stopping HZE. Furthermore, it is possible that the secondary particles from interaction of HZE with shielding material may be as hazardous as unshielded HZE. The flux of electrons and protons in trapped radiation apparently remains fairly constant and is reasonably well-defined with regard to location, i e., geography and altitude. Revelance to space worker radiation and consequences to their health will depend on the orbit selected and the amount of time spent in any specific orbit.

Solar flare particle events consist mostly of high-energy protons. Forecast of these is not possible but onset of buildup can be detected. When buildup is detected, it appears that EVA should be discontinued and that probably all space workers should retreat to a heavily shielded area. NASA Systems Definition is planning such an area in the personnel vehicles.

There may be radioactive materials flown on space vehicles in instrumentation, as small power sources, and for diagnostic medical procedures. The extent of these materials is not yet known.

Preliminary assessment of thermal radiation is not possible until more information is obtained regarding expected termperatures in space vehicles and space suits.

Some other potential problem areas, in which assessment has not been done yet, are effects of magnetic fields, electrical fields, plasma arcing, space debris, and meteoroid collisions. NASA has information and/or research in some of these areas, but time has not permitted the obtaining of this information nor an evaluation of the extent of potential hazards to the space worker.

2.6.4 Ecological Effects

A variety of activities relating to construction and operation of SPS have potential ecological impact. These activities should be identified, and their impact predicted. Where warranted, mitigation procedures should be developed before such activities are initiated.

Construction activities,as well as the emissions of a variety of pollutants, are known to alter ecosystems by changing the character of plant and animal communities. These impacts can be assessed once specific development procedures and ecosystems are identified. Certain additional potential impacts will be more difficult to assess due to a lack of information in the scientific literature. These areas of concern include fragmentation of ecosystems, electric field effects, the possibility that some species of wildlife may be attracted to the rectenna in large numbers, and the possible disturbance of rhythmic cycle (e.g., reproduction, dormancy, etc.) in plants and animals by reflected light from satellites.

2.7 CONCLUSIONS AND RECOMMENDATIONS

Table 2.9 presents a summary of the non-microwave health and safety effects from this preliminary assessment.

2.7.1 Effects on the Public

The assessment indicates that there is a fairly large body of information that can be used to develop a complete assessment of conventional effects of SPS on public health and safety. The incremental effects of increases in conventional processes have been addressed to the extent that preliminary calculations of environmental residuals have been made, but these have not been translated into public exposure levels nor into public health effects. The objective of the ongoing assessment process should be to improve the accuracy of the residuals calculations and to make the necessary translations into actual health effects. This achievement will provide an adequate 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. For toxic materials, a systematic identification of the materials involved has not yet

Table 2.9. Summary of SPS Nonmicrowave Health and Safety Effects

Group	Effect	Probability[a]	Severity[b]	Impact Based on State of Knowledge	Proposed R&D	Mitigating Strategies
Public	Land Disturbance Effects	1	2	Some loss of and damage to land.	Review current research.	Land reclamation program. Alternative land uses.
	Air Pollution Health Effects	1	2	Some public exposure to increased air pollution Extent of effects not evaluated.	Air pollution impact analysis.	Emission control technology. Launch vehicle modifications. Launch site changes.
	Water Pollution Health Effects	1	2	Some public exposure to contaminated water. Extent of effects not evaluated.	Water quality impact analysis.	Effluent controls, spill prevention systems.
	Noise Effects	1	1	Possible acoustic noise levels above recommended maximums. Possible sonic boom problems.	Literature review, noise contour development, impact analysis.	Launch site change. Buffer Zones. Flight profile change.
	Safety Hazards	2	2	Possible public injury/fatality from accidents. Rates not evaluated.	Accident probability analysis.	Safety standards. Transportation corridor relocation. Flight path change
	Solid Waste Generation Effects	3	3	Possible sanitation problem.	Cursory evaluation	Waste disposal standards.
	Toxic Materials Exposure	2	2	Toxic materials not yet identified.	Develop list from systems definition. Review literature for effects. Conduct impact analysis.	Toxic materials handling procedures. Process changes to avoid use of toxic materials.
	High Intensity Electro-Magnetic Fields Exposure	2	2	Effects unknown.	Coordinate research with microwave efforts	Buffer zones. Rectenna siting.
Terrestrial Workers	Occupational Air Pollution Health Effects	1	2	Some worker exposure and occupational illness.	Literature review, impact analysis.	Workplace exposure standards. Process changes.
	Water Pollution Effects	1	2	Some worker exposure. Extent of effects unknown.	Literature review, impact analysis.	Spill prevention systems. Process changes.
	Noise	1	2	Some worker exposure. Extent of hearing problems and stress unknown.	Literature review, impact analysis.	Ear protectors for workers. Process changes.
	Safety Hazards	1	2	Worker injury/fatality from accidents. Rates not evaluated.	Accident probability analysis..	Safety standards. Safety equipment.
	Toxic Materials Exposure	2	2	Toxic materials not yet identified.	Same as public effects research.	Toxic materials handling procedures. Process changes to avoid use.
	High Intensity Electro-Magnetic Fields.	2	2	Effects unknown.	Coordinate research with microwave efforts.	Buffer zones. Rectenna siting.

Table 2.9. (Cont'd)

Group	Effect	Probability[a]	Severity[b]	Impact Based on State of Knowledge	Proposed R&D	Mitigating Strategies
Space Workers	Weightlessness					
	Immune System Changes	2	2	Possible increased susceptibility to infectious diseases.	Review of NASA findings-research on ways to challenge immune system.	Possibly challenge immune system of workers periodically.
	Anemia	2	2	Possible reduced efficiency, illness, residual effects on return to earth.	Review of NASA's findings and on-going research. Pursue recommend research.	Stimulate red cell production, hormones?
	Plasma Volume Reduction	2	2	Possible biochemistry, physical changes, work inefficiency, possible illness.	Review NASA Findings and research	Unknown
	Calcium depletion in bone-calcium excretion	2	2	Possible bone fragility and/or kidney calculi	"	Diet changes, hormone therapy.
	Muscle Tissue Loss-Nitrogen Loss	2	2	Decreased work efficiency residual problems on return tests.	"	Exercise, diet modification.
	Fluid and electrolyte Changes	2	2	Illness.	"	Unknown.
	Cardiovascular System Abnormalities	2	2	Illness, decreased efficiency, fatality	"	Unknown.
	Space motion sickness, spacial disorientation, etc.	2	2	Inefficiency, illness	"	Unknown.
	Radiation Exposure	2	2	May cause cancer, damage to central nervous system, genetic effects, visual damage, etc.	Peer review of literature and current research. Research based on recommendations of peer review.	Limit time spent in space. Provide best shielding available.
	System Emergencies	2	2	Not yet assessed.		
	Emergency Medical/Dental Problems	2	2	Illness, fatality.	Review systems design of facilities for adequacy.	Adequate medical and dental facilities.
	High acceleration/Deceleration Effects	2	2	Not yet assessed.		
	Extra Vehicular Activity Hazards	2	2	Not yet assessed.		
	Extended Confinement	2	2	Illness-may limit time spent in space.	Review literature on problems of confinement.	Recreational facilities in space vehicle
	Thermal Extremes	2	2	No assessment pending systems definition.		
	Plasma Arcing	2	2	Not yet assessed.		
	High Intensity Electro-Magnetic Field Effects	2	2	Not yet assessed.		

Table 2.9. (Cont'd)

Group	Effect	Probability[a]	Severity[b]	Impact Based on State of Knowledge	Proposed R&D	Mitigating Strategies
Ecology	Air Pollution, Water Pollution, Solid Waste Effects					
	Degradation of natural ecosystem quality by pollutants.	1	1	Air, water and solid wastes can change ecosystem structure and function.	Literature review.	Standard pollution abatement procedures.
	Land Use Effects					
	Changes in plant communities as direct result of construction.	1	3	Construction may destroy present plant communities and lead to establishment of different types.	Review of literature concerning construction effects on ecosystems; obtain information on construction techniques projected for SPS.	Alternative siting; selection of least destructive methods of construction.
	Changes in animal populations as direct result of construction	1	3	Changes in vegetation due to construction will affect animal populations.	As above.	As above.
	Attraction of wildlife of rectenna site	2	2	Warmth of rectenna, and its availability as a nesting site may attract birds, insects, other wildlife.	Literature review.	As above.
	Degradation of natural ecosystem quality by fragmentation	1	3	Fragmentation of terrestrial ecosystem by roads, power lines, etc. can reverse ecological succession.	Literature search to determine extent and severity of problem.	Unable to address adequately at present time; perhaps siting changes.
	Land use restrictions due to rectenna presence	1	2	Certain activities will be impossible due to presence of the rectenna.	Obtain updated specifications of rectenna.	Alter design to allow critical activities.
	Noise	1	2	Little information available.	Literature review.	Siting changes. Buffer zones.
	High Intensity Electro-Magnetic Field Effects					
	Disruption of ecosystems by electrical fields generated by power lines.	2	3	Unable to predict.	Research is currently being conducted by various organizations outside SPS.	Unable to address at this time: perhaps siting changes.
	Reflected Light Effects					
	Alteration of biological cycles in plants and animals due to reflected light from satellites.	2	2	Potential severity is great; no information on probability.	Literature review; limited research if warranted.	Unable to address at this time.

[a] 1 = High
2 = Unknown
3 = Low

[b] 1 = Critical
2 = Unknown
3 = Noncritical

been made. For transport accidents and for launch and recovery the only information available is from the limited prior space program activities and from projections for space shuttle operations. Substantially more work is needed to evaluate the data available and fill the gaps in the assessment.

2.7.2 Effects on Terrestrial Workers

As with the effects on the public, a good deal of data is available upon which to evaluate 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 trying to estimate the effects on the general public. The SPS program will, however, result in the involvement of a much larger work force in what has been considered a limited activity (e.g., launch and recovery) and will require the development of a broader data base upon which to measure occupational effects.

2.7.3 Effects on Space Workers

Some of the effects of weightlessness appear to be an adaptation to an unusual situation for humans. Eventually for these effects, it appears that a new equilibrium, suitable to the weightless state, is established and maintained (note, however that only 3-5 astronauts have been in space as long as 84 days, thus there could be space workers who, for physiological reasons, could not adapt). Other 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 in and post flight. The NASA in-house and supported research programs may be adequate for researching these problems, but there is a need to assess them in relation to SPS for adequacy of funding and content. NASA has ongoing research on Life Support Systems related to other planned flights. This research covers most, if not all of the expected problems. This work needs to be assessed for adequacy with regard to the unique aspects of SPS.

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

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

2.7.4 Ecological Effects

Construction and nonmicrowave operational aspects of SPS have the potential to impact large areas of natural and man-altered ecosystems. The responses of ecosystems to various types of physical disturbances are much better known than response to microwaves. For this reason, there is probably no need for a large, experimental ecological research program, for nonmicrowave effects. However, a preliminary, nonexperimental research program should be initiated.

Ecological impacts may vary with the specific construction techniques used, and even those methods that have minimal impact in one ecosystem might have a severe adverse impact when used in different ecosystem. It is possible that limited experimental research might be required to answer some critical nonmicrowave questions. A preliminary nonexperimental research program will determine if such questions exist, and establish priorities if they do.

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APPENDIX 2A

Nonmicrowave Health and Safety Effects Research Program

Table 2A.1. Research Program for Nonmicrowave Effects of SPS

Group	Effects	Research Tasks
Public	Land Disturbance Effects	1. Characterize land requirements for mining, construction from systems definition.
		2. Review literature and quantify extent of the problem.
		3. Identify and evaluate alternative land reclamation and other control measures.
	Air Pollution Health Effects	1. Quantify emission rates from systems definition.
		2. Apply models to estimate transport.
		3. Review EPA and other research on effects.
		4. Translate exposure into health effects.
		5. Identify and evaluate alternative control measures.
	Water Pollution Health Effects	1. Quantify effluent rates and spill probabilities from systems definition.
		2. Estimate public exposure to contaminated water.
		3. Review EPA and other research on effects.
		4. Translate exposure into health effects.
		5. Identify and evaluate alternative control measures.
	Noise	1. Review literature to determine acoustic and sonic boom effects.
		2. Apply models to determine SPS launch and recovery noise contours.
		3. Identify and evaluate alternative control measures.
	Safety Hazards	1. Quantify accident probability and extent from systems definition.
		2. Quantify public exposure to hazards.
		3. Identify and evaluate alternative control measures.
	Solid Waste Effects	1. Quantify solid waste generation from systems definition.
		2. Identify and evaluate alternative control measures.
	Toxic Materials Exposure	1. Prepare list of toxic materials from systems definition.
		2. Review literature to identify effects on health.
		3. Quantify exposure to toxic materials.
		4. Identify and evaluate alternative control measures.
	High Intensity Electromagnetic Fields	1. Coordinate efforts with microwave effects research.
Terrestrial Workers	Occupational Air Pollution Health Effects	1. Characterize occupational exposure.
		2. Review OSHA and other effects research.
		3. Identify and evaluate alternative controls.
	Water Pollution Effects	1. Characterize and quantify exposure to pollutants
		2. Review OSHA and other effects research.
		3. Identify and evaluate alternative controls.
	Noise	1. Review literature on occupational noise effects.
		2. Characterize noise exposure.
		3. Identify and evaluate alternative controls.
	Safety Hazards	1. Project accident probability and extent.
		2. Identify and evaluate alternative controls.
	Toxic Materials Exposure	1. Same as Public Effects tasks.
	High Intensity Electromagnetic Fields	1. Coordinate efforts with microwave effects research.

Table 2A.1. (Cont'd)

Group	Effects	Research Tasks
Space Workers	Prolonged Weightlessness Radiation Exposure System Emergencies Emergency Medical/Dental High Acceleration/Deceleration Extra Vehicular Activity Extended Confinement Thermal Extremes Plasma Arcing High Intensity Electromagnetic Field	1. Obtain information from NASA systems definition on SPS construction and operation to include frequency and extent of worker exposure to hazards in both low earth orbit and geosynchronous earth orbit. 2. Obtain information from NASA Life Sciences regarding: (a) The space environment and its effects on astronauts, and (b) NASA's research to identify causes and ameliorate effects. 3. Survey literature on pertinent subjects. 4. Convene peer Review Committees for recommendations on: (a) Extent of risks, and (b) Pertinent future research. 5. Quantify hazards using information obtained as above. 5. Evaluate increased mortality and morbidity. 7. Evaluate acceptability/unacceptability of health and safety risks.
Ecology	Air Pollution Ecological Effects Water Pollution Ecological Effects Solid Waste Ecological Effect	1. Review literature to determine effects. 2. Identify and evaluate alternative controls.
	Land Use Effects Changes in plant communities Changes in animal communities Attraction of wild life to site Fragmentation	1. Review construction effects on ecosystems. 2. Characterize construction required by SPS. 3. Identify and evaluate alternative.
	Noise Effects	1. Review literature.
	Electric Field Effects	1. Review research being conducted outside SPS.
	Reflected Light Effects	1. Review literature.

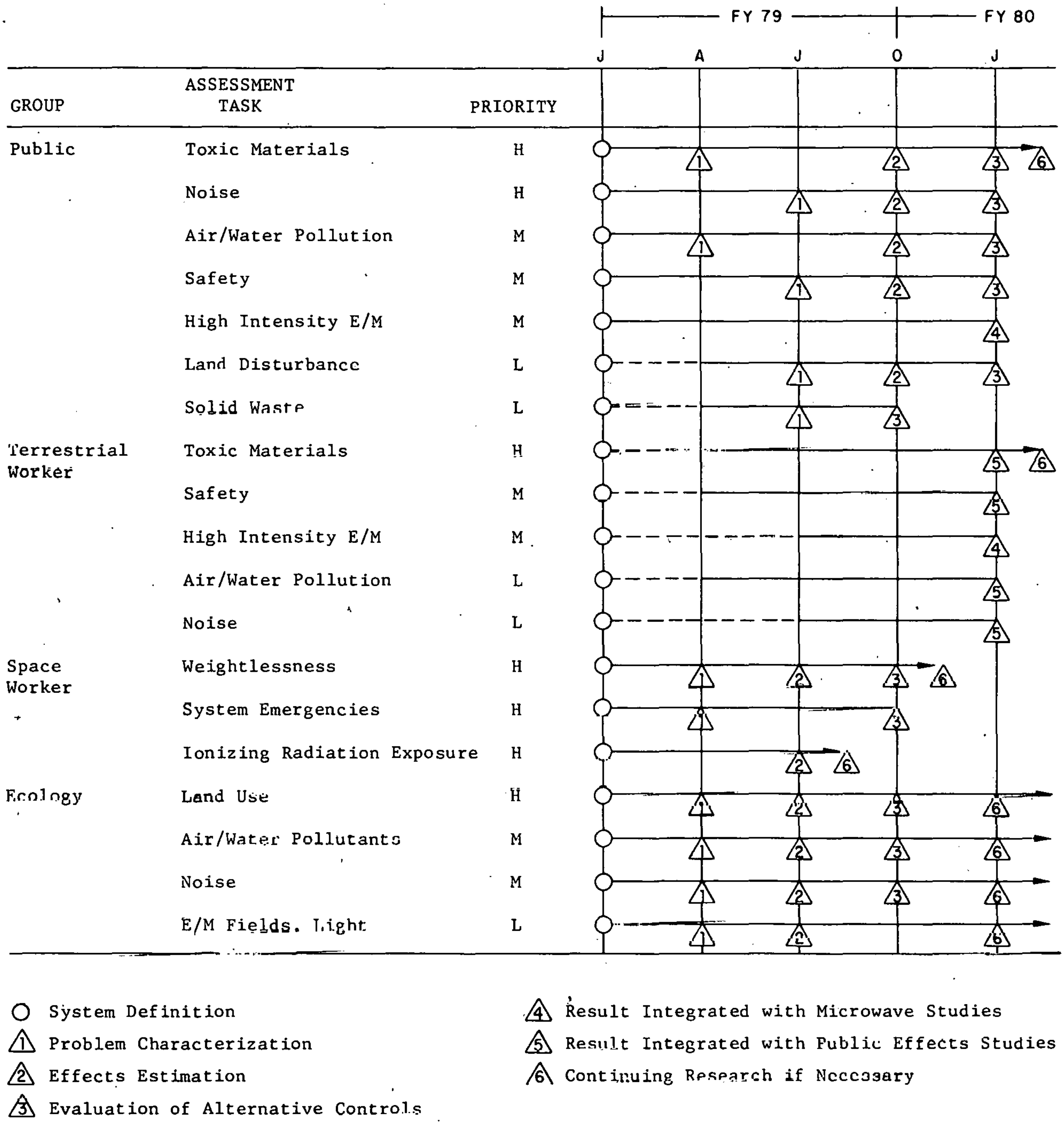

Fig. 2A.1. Schedule of Research Tasks for Nonmicrowave Health and Safety Effects

3 EFFECTS ON THE ATMOSPHERE

3.1 SCOPE

All levels of the Earth's atmosphere will be affected at least to some extent by the construction and operation of the satellite power system. The objective of this portion of the program is to identify which effects are important with respect to their consequences for the environment. Figure 3.1 shows a schematic diagram of the natural atmosphere that indicates the various levels referred to in the following text and the most commonly used terms. 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 the reader should refer to the *Handbook of Geophysics and Space Environments* (Ref. 3.1).

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 may result from the deposition of propulsion system effluents in various levels of the atmosphere. Below are listed some of the more obvious sources of atmospheric disturbance associated with the SPS:

- Thruster effluents in the lower and upper atmosphere (including neutral and ionized chemical species as well as thermal acoustic energy);
- Other effluents released into the upper atmosphere including waste heat and effluents from gas leaks, surface weathering, space manufacturing operations, debris, etc. (sometimes referred to as "fugitive emissions");
- Presence of large metal structures in orbit (source of reflected light, wake effects, etc.);
- Presence of large metal structure (rectenna) near the ground surface (change in surface roughness, surface albedo, atmospheric electric effects); and
- Microwave-related phenomena in the troposphere.

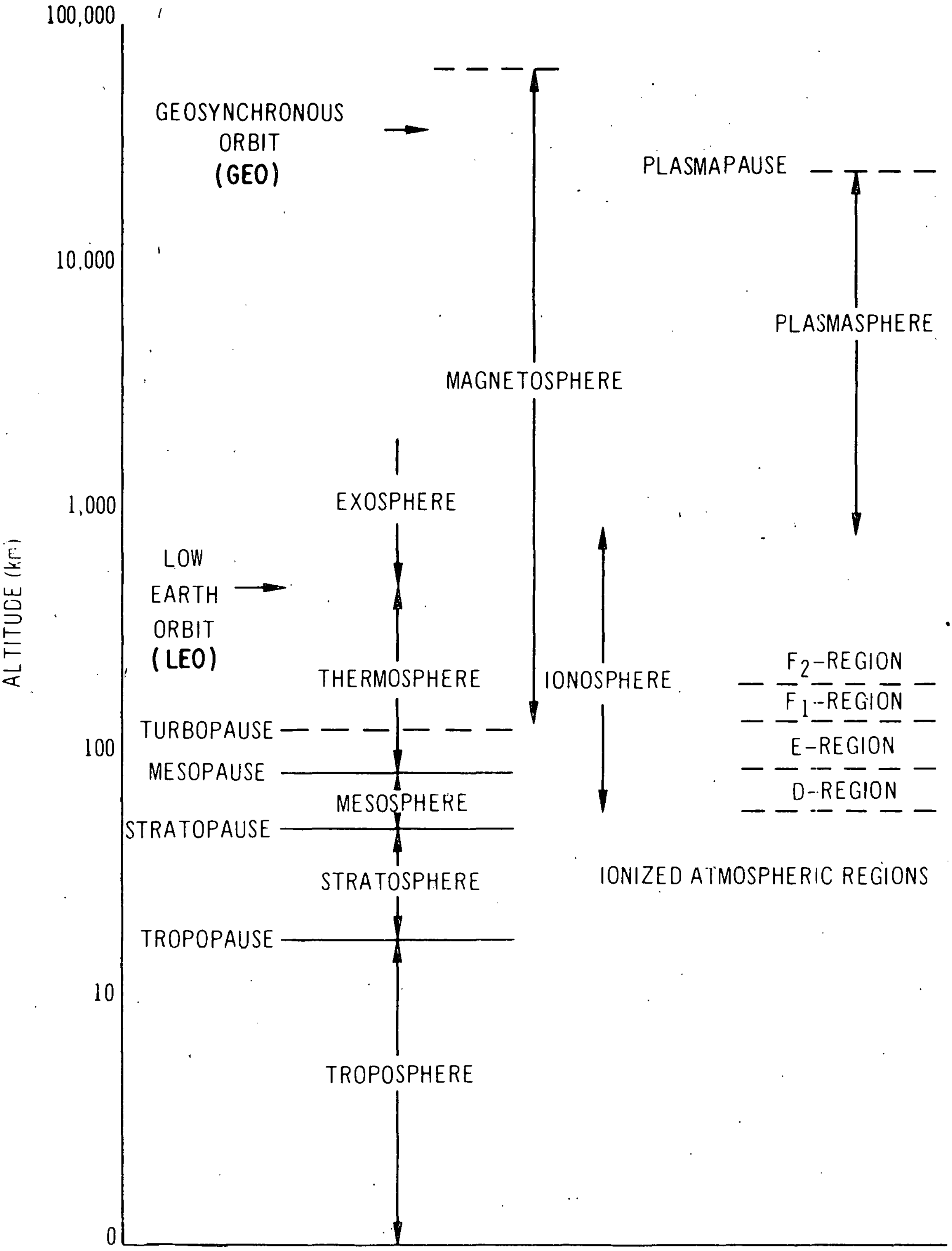

Fig. 3.1. Regions of the Atmosphere

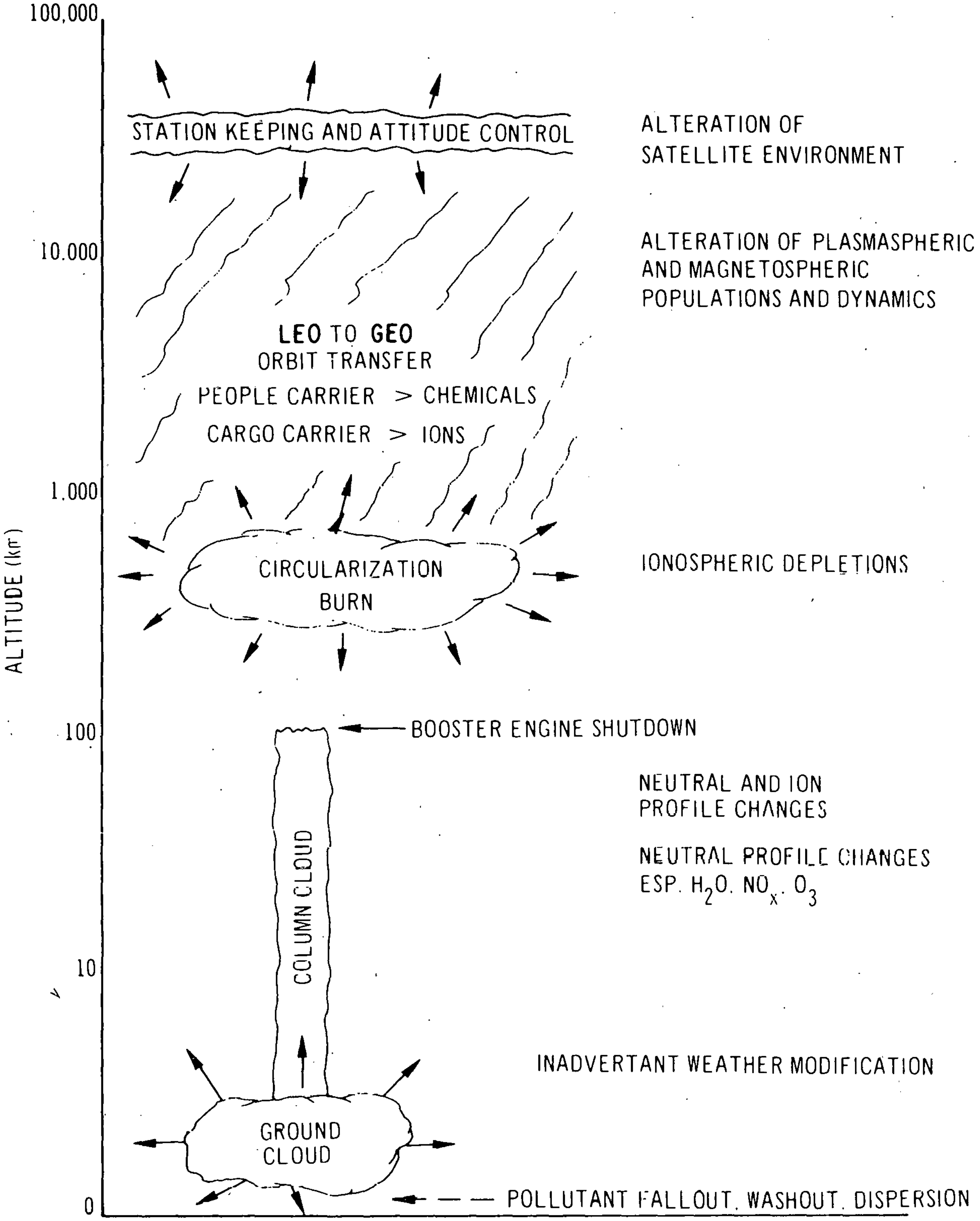

Fig. 3.2. Summary of Some Potential Atmospheric Effects Caused by Rocket Exhaust

The atmospheric effects assessment is conveniently divided into three major task areas:

- Non-microwave effects on the Upper Atmosphere (Mesosphere and Above),
- Microwave-Related Effects on the Lower Atmosphere (Primarily Troposhere), and
- Other Effects on the Lower Atmosphere (Troposphere and Stratosphere).

3.2 METHODOLOGY

The approach to the task areas defined above involves two major phases. The initial phase is one of identification of cause and effect relationships and preliminary assessment of the importance of such effects to mankind and to the environment based on existing knowledge. In addition to reviewing and compiling existing information, theoretical investigations will be conducted that include analysis of relevant existing data and simulation with existing modeling techniques. This phase will also identify areas requiring additional information (through experimental and theoretical investigations) and a list of priorities for future research. Several workshops have been held at ANL to solicit scientific opinions on effects in the:

- Upper Atmosphere (Aug. 28-30, 1978),
- Stratosphere (Sept. 6-8, 1978), and
- Troposphere (Sept. 12-14, 1978);

and those associated with

- Rectenna operations and microwave related phenomena in the lower atmosphere (Aug. 23-25, 1978).

The initial phase of the program is in progress and is expected to be completed by Oct. 1978.

Phase 2 of the approach will involve the acquisition and analysis of additional information necessary for the completion of the atmospheric effects assessment by the end of FY 80. This phase will include field and/or laboratory experiments in conjunction with theoretical modeling studies utilizing refined modeling methods as required. Section 3.5 describes the research plan for the program.

The plan for phase 2 is being refined in light of the output from the four workshops mentioned above plus additional solicited comments from other interested groups. In view of the short time available to complete the preliminary environmental assessment (less than 1.5 years), it is not likely that major new research programs can produce significant results before FY 80. Consequently, essential new information will have to be acquired through processing and analysis of existing data, theoretical calculations using existing or slightly refined computer models, and 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 will 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. For example, plans are already in progress to conduct ionospheric depletion* experiments that require special burns of the space shuttle rocket engines over locations on the ground where ionospheric observations are located. The exhaust products of these burns are expected to remove large numbers of electron-ion pairs from a region of the upper atmosphere called the F_2 layer of the ionosphere. Instrumentation located at the observatories will be used to study the nature and extent of these ionospheric depletions. Similar experiments are discussed more fully in Section 3.4.1.

3.3 CAUSE AND EFFECT RELATIONSHIPS

The cause and effect relationships that may play a significant role in determining the impact on the environment are in most cases not well-defined at this time. Those that are defined herein should be regarded as being not only preliminary in nature but also rather speculative. Figure 3.3 illustrates causes or disturbances and their potential immediate, intermediate and subsequent effects.

3.4 STATE OF KNOWLEDGE

3.4.1 Upper Atmosphere, Nonmicrowave Effects (above 60 km)

The state of knowledge regarding most of the cause and effect relationships indicated in Section 3.3 is not sufficiently advanced at this time to

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*Removal of electron-ion pairs.

make reliable estimates of the SPS impacts on the upper atmosphere and subsequently on the biosphere. The task of performing a preliminary assessment is especially difficult at this time for three reasons: (1) the basic physics and chemistry of the upper atmosphere and the processes that couple it to the lower atmosphere are under intensive investigation and much of our present knowledge* has resulted from relatively recent advances in ground-based (i.e., incoherent scatter radar) as well as rocket-borne instrumentation. Hence, to a certain extent, our ability to predict the consequences of perturbing the natural atmosphere depend upon progress in basic research on the natural atmosphere itself; (2) analytical (theoretical models) and experimental tools that can be used to investigate possible immediate consequences of perturbing the upper atmosphere are still in a fairly early stage of development and theoretical predictions have only been partially verified by experiment and observation; (3) the detailed information regarding the reference SPS design and especially the transportation system, including rocket propulsion systems, propellant exhaust products, launch schedules, etc., is now just becoming available.

3.4.1.1 Vehicle Effluent Effects

The area that has received the greatest attention (both theoretical and experimental) recently has been that of ionospheric depletion due to deposition of rocket exhaust in the upper atmosphere. The initial evidence that related rocket exhaust emissions to ionospheric depletion came about quite accidentally. In 1973, Skylab II was launched into orbit with an unusually long burn of the second stage of the Saturn V rocket, which passed through the ionosphere near the area where total electron content (TEC) observations were routinely made by ground-based radio observations as shown in Fig. 3.4.

Careful analysis by Mendillo et al. (Ref. 3.3) showed that the passage of the rocket through the F-layer could reasonably account for the observation that a 50% reduction in the TEC occurred, lasting for nearly four hours

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*For a good review of our present state of knowledge regarding the upper atmosphere, see Reference 3.2.

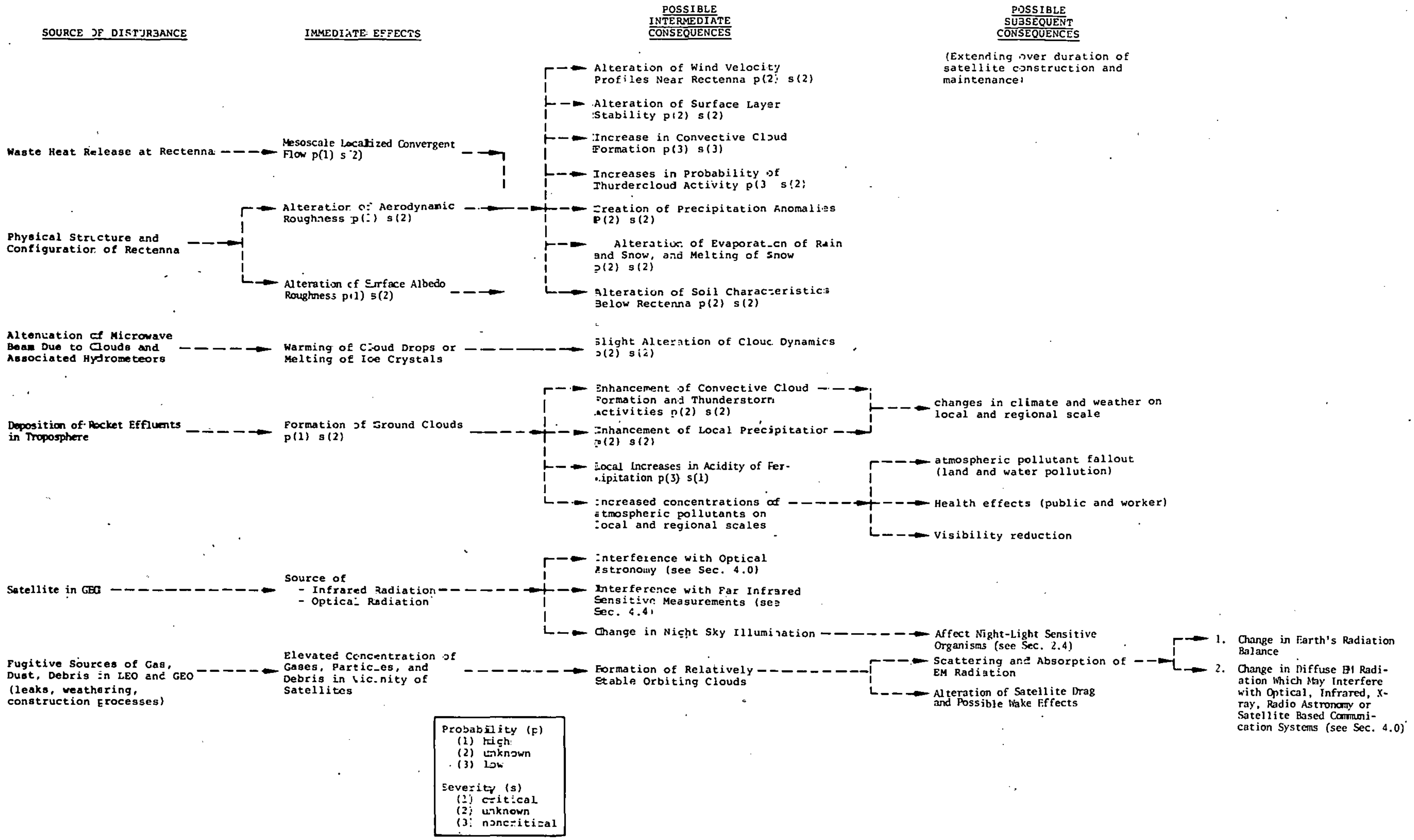


Fig. 3.3. Cause and Effect Relationships Due to the Impact of SPS on the Atmosphere

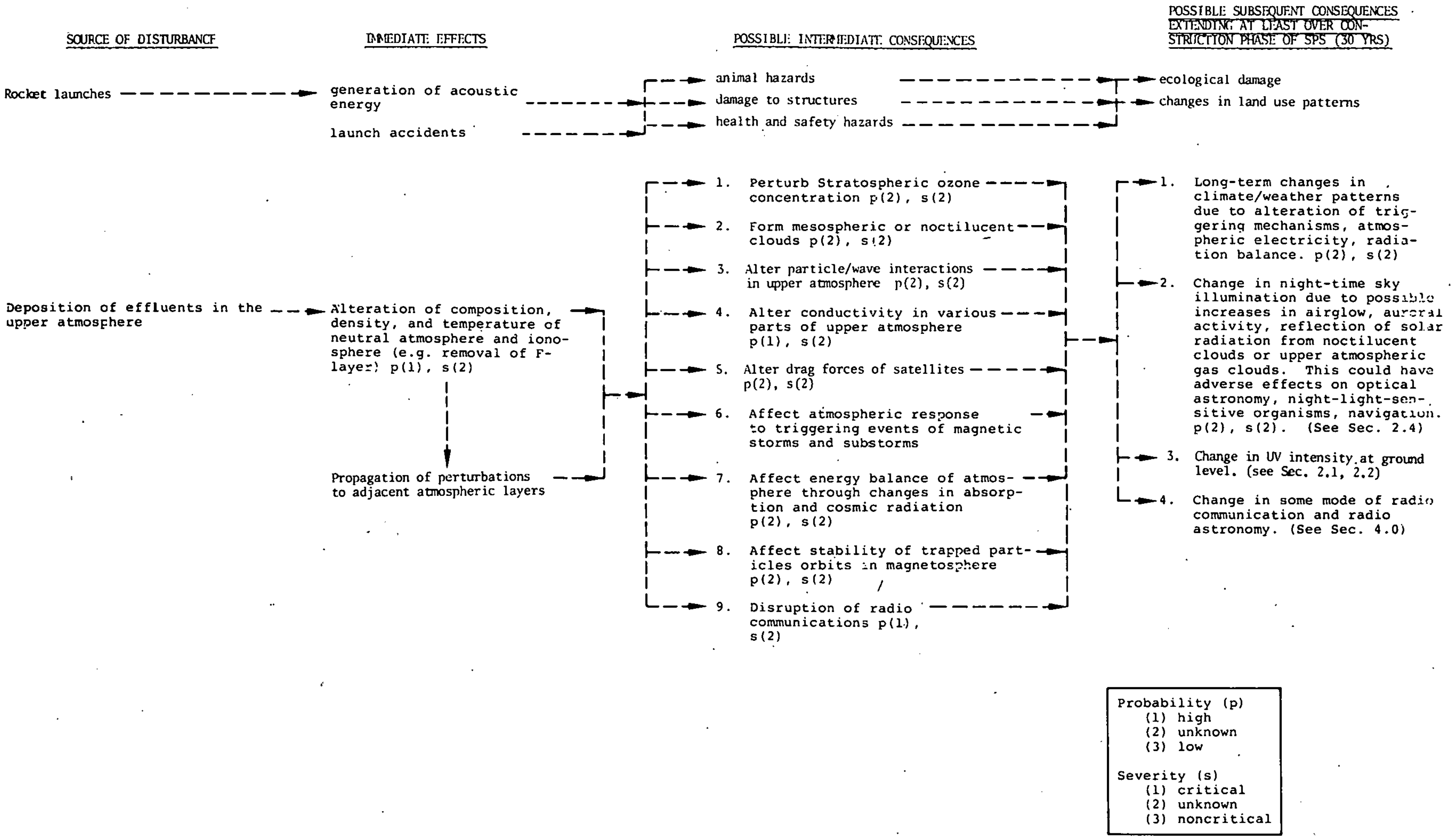
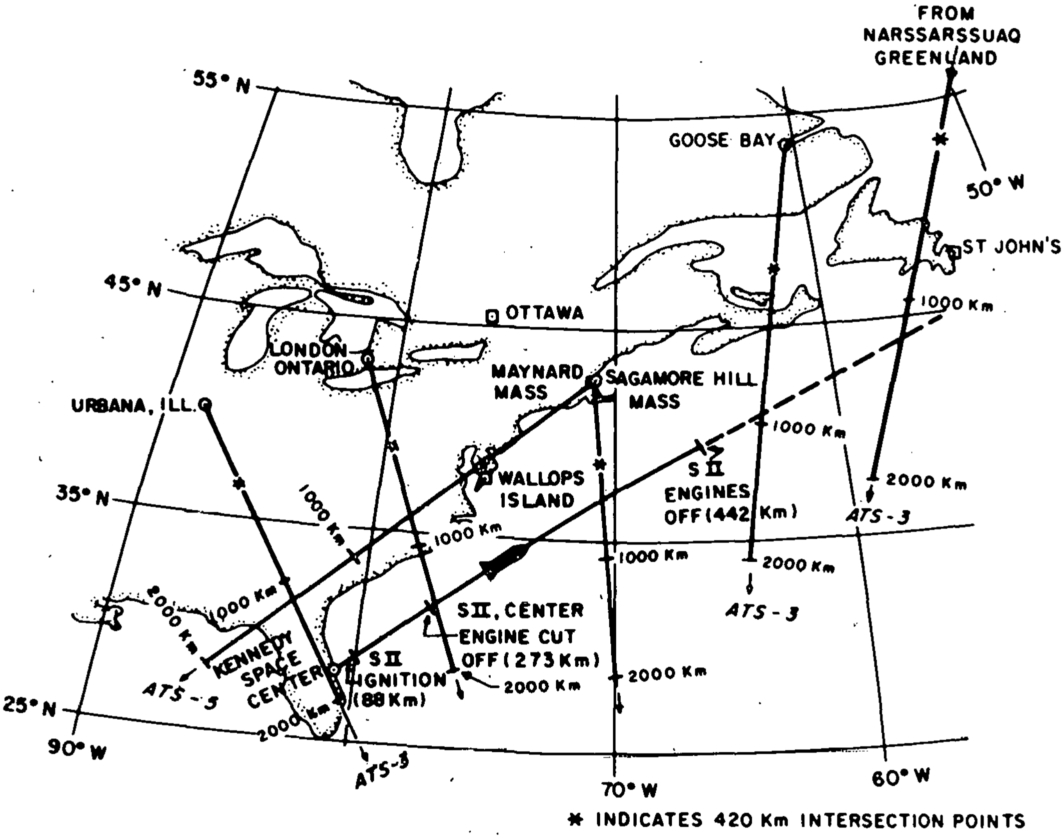

SOURCE OF DISTURBANCE
IMMEDIATE EFFECTS
POSSIBLE INTERMEDIATE CONSEQUENCES
POSSIBLE SUBSEQUENT CONSEQUENCES EXTENDING AT LEAST OVER CONSTRUCTION PHASE OF SPS (30 YRS)
Rocket launches
generation of acoustic energy
launch accidents
animal hazards
damage to structures
health and safety hazards
ecological damage
changes in land use patterns
Deposition of effluents in the upper atmosphere
Alteration of composition, density, and temperature of neutral atmosphere and ionosphere (e.g. removal of F-layer) p(1), s(2)
Propagation of perturbations to adjacent atmospheric layers
1. Perturb Stratospheric ozone concentration p(2), s(2)
2. Form mesospheric or noctilucent clouds p(2), s(2)
3. Alter particle/wave interactions in upper atmosphere p(2), s(2)
4. Alter conductivity in various parts of upper atmosphere p(1), s(2)
5. Alter drag forces of satellites p(2), s(2)
6. Affect atmospheric response to triggering events of magnetic storms and substorms
7. Affect energy balance of atmosphere through changes in absorption and cosmic radiation p(2), s(2)
8. Affect stability of trapped particles orbits in magnetosphere p(2), s(2)
9. Disruption of radio communications p(1), s(2)
1. Long-term changes in climate/weather patterns due to alteration of triggering mechanisms, atmospheric electricity, radiation balance. p(2), s(2)
2. Change in night-time sky illumination due to possible increases in airglow, auroral activity, reflection of solar radiation from noctilucent clouds or upper atmospheric gas clouds. This could have adverse effects on optical astronomy, night-light-sensitive organisms, navigation. p(2), s(2). (See Sec. 2.4)
3. Change in UV intensity at ground level. (see Sec. 2.1, 2.2)
4. Change in some mode of radio communication and radio astronomy. (See Sec. 4.0)
Probability (p)
(1) high
(2) unknown
(3) low
Severity (s)
(1) critical
(2) unknown
(3) noncritical

Fig. 3.3. (Cont'd)



SATURN / SKYLAB TRAJECTORY AND PATHS TO GEOSTATIONARY SATELLITES

Fig. 3.4. Geometry of the Skylab launch and ray paths to ATS-3 and ATS-5 from several sites in North America. For each station-satellite path, an asterisk marks the 420-km ionospheric point, and tick marks are placed at the 1000- and 2000-km altitude points along the ray path. The small squares mark the locations of ground-based ionosonde installations. (Diagram and caption from Ref. 3.4)

and covering an area 2000 km in diameter (see Fig. 3.5). The principal reactions responsible for the rapid and large-scale loss of the plasma were reported by the authors to be

$$O^+ + H_2 \rightarrow OH^+ + H$$

and

$$O^+ + H_2O \rightarrow H_2O^+ + O,$$

where H_2 and H_2O are the principal exhaust constituents of the LH_2/LO_2 Saturn V engines, and O^+ is the dominant ionic species in the F_2 region (above 150 km). The most important feature of these reactions is that they are much

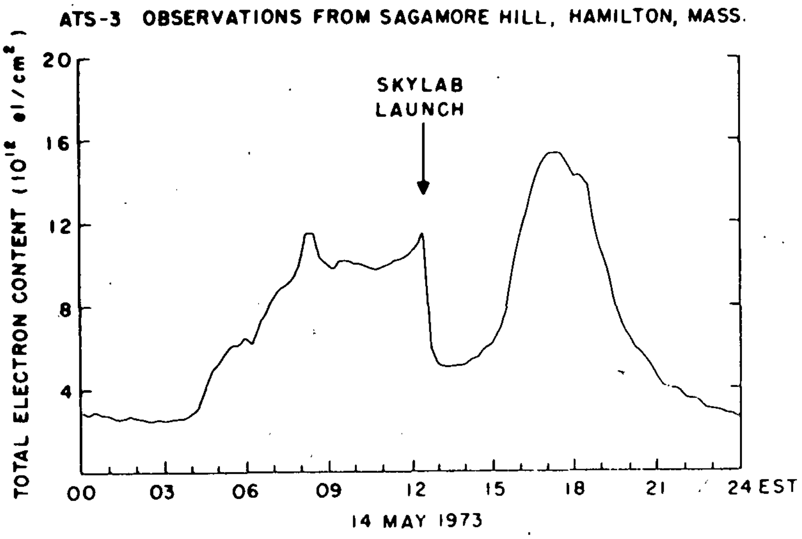


Fig. 3.5. Total electron content data obtained from the Sagamore Hill Radio Observatory in Hamilton, Mass., looking towards the geostationary satellite ATS-3 on 14 May 1973. (Picture and caption from Ref. 3.4.)

faster than the natural O^+ loss reaction mechanisms and therefore result in a considerable reduction in the O^+ concentration. Following the above reactions are a set of rapid charge recombination reactions that result in the removal of electrons:

$$OH^+ + e^- \rightarrow O + H$$
$$H_2O^+ + e^- \rightarrow H_2 + O$$
$$H_2O^+ + e^- \rightarrow OH + H$$

More recently, two deliberate attempts have been made to produce similar "holes" in the ionosphere. Codenamed LAGOPEDO (See Ref. 3.5), these experiments utilized rockets to carry explosive payloads into the ionosphere. The detonation products of the explosives were H_2O, CO_2 and N_2.

Both experiments successfully produced "holes" in the ionosphere that were accompanied by enhanced airglow as predicted by the calculation of Sutherland and Zinn (Ref. 3.6), and others. While the analysis of the data from LAGOPEDO is still in progress, some preliminary results were presented in 13 papers at a special session of the Spring Meeting of the American Geophysical Union in Miami in April (proceedings not yet available). Some of the results are summarized in a recent report by Zinn, Sutherland, Smith, and Pongratz (Ref. 3.7).

With respect to the airglow observations at LAGOPEDO, Pongratz and Smith (Ref. 3.8) reported it was still detectable after 400 sec. Sutherland and Zinn (Ref. 3.5) were able to fit the time-dependence of the observed airglow reasonably well with their ionospheric depletion model calculations but the spatial resolution is uncertain, since the data have not yet been reduced (this is being done as part of the SPS assessment program). Zinn et al. (Ref. 3.7) have pointed out that since their model does not include any treatment of condensation and evaporation, the simulation of processes involving water vapor is probably incorrect. They also mention, however, that since reactions involving carbon dioxide produce more than 50% of the airglow, the predicted airglow intensity is not very sensitive to water vapor chemistry.

Sjolander and Johnson (Ref. 3.9), on the other hand, described the expanding cloud through a simple spherical diffusion equation that incorporated a simple treatment of H_2O condensation and evaporation. They estimated that the snow* disappeared after about 80 sec. Their calculations for O^+, H_2O^+, NO^+ ions compared well with observations but their H_3O^+ results did not. Sjolander and Johnson found that the CO^+ data could be fitted without CO_2 condensation, in agreement with Zinn et al. (Ref. 3.7).

Hence, both the inadvertant Skylab II ionospheric depletion and the deliberate LAGOPEDO experiments demonstrated that the ionosphere can be depleted and that plausible mechanisms exist to explain the phenomena involved (at least in an approximate manner). What remains to be determined is what the nature and extent of this depletion is and how it will scale with increased rocket size and frequency of launches, and what the consequences are. Zinn et al. (Ref. 3.7) have carried out some preliminary calculations with a one-dimensional ionospheric chemistry model that suggest that daily launches of the type of HLLV envisioned in the SPS transportation system will result in continuous, substantial reduction in the total ionsphere.

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*Ice crystals formed initially during the rapid expansion and cooling of the water vapor cloud following detonation.

However, since Zinn's calculations are preliminary it will be necessary to perform additional calculations utilizing more appropriate models (two- or three-dimensional simulations that include more realistic treatments of the phenomena involved) before these predictions can be stated with any reasonable degree of confidence.

Our present state of knowledge is not sufficient to state with any degree of certainty what the consequences of such ionspheric depletions will be. Figure 3.3 does, however, indicate some possible consequences that must be examined as part of phase 2 of the program. These include alteration of particle-wave interactions, electrical conductivity, drag forces on satellites, response of the ionospheric-magnetospheric system to magnetic storms, location and behavior of the auroral region of the ionosphere, airglow intensity, electron temperature profile, and electromagnetic wave propagation properties.

Any influence that the thruster effluents released in the upper atmosphere might have on the lower atmosphere would either result from the direct migration of the effluents to the lower atmosphere or through triggering and/or coupling mechanisms that connect causal phenomena in the upper atmosphere with effects in the lower atmosphere. There is, at the present time, considerable interest in such cause and effect relations between the upper and lower atmosphere because of renewed interest in the so-called sun-weather effect. Such an effect presumably involves variations in the solar wind which in turn influence the behavior of the earth's magnetosphere and ultimately the troposphere weather through mechanisms as yet poorly understood. One mechanism for producing such an effect, suggested by Roberts and Olson (Ref. 3.10) involves intense fluxes of particles precipitated into the auroral zone during geomagnetically active periods; these fluxes may result in the formation of ions in the upper atmosphere that could subsequently serve as nuclei for the condensation of water, which would result in the formation of high altitude clouds. These clouds may then modify the earth's radiation balance. Another mechanism, more recently proposed by Markson (Ref. 3.11), involves changes in electric potentials in the atmosphere above thunderstorms caused by changes in electrical conductivity in the upper atmosphere. The changes in conductivity are thought to be brought about by the solar activity that modulates galactic cosmic ionizing radiation capable of reaching altitudes

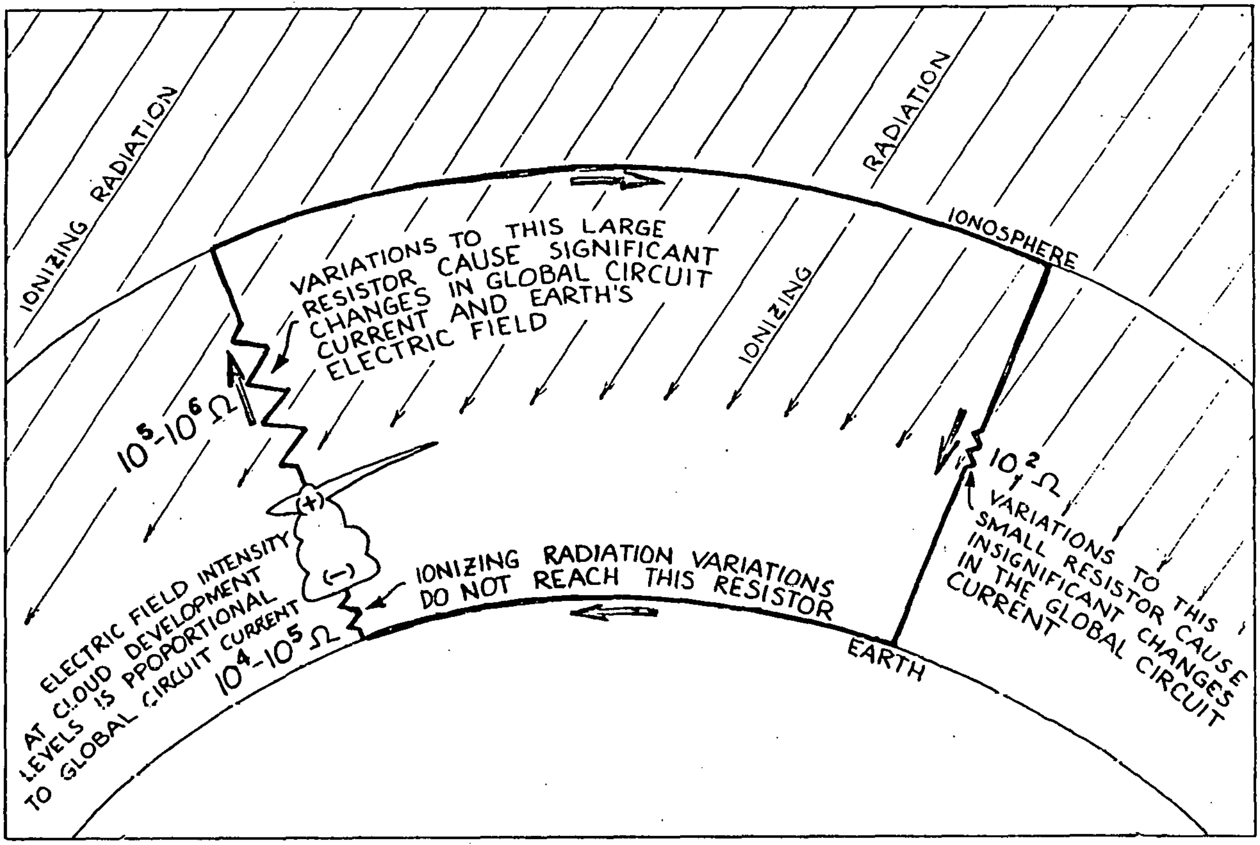

Fig. 3.6. Schematic diagram of global atmospheric circuit that indicates possible mechanisms for ionizing radiation to influence thunderstorm activity. (Picture contributed by Dr. Ralph Markson, Dept. of Aeronautics & Astronautics, Massachusetts Institute of Technology.)

of 20 to 30 km. This mechanism is illustrated in Fig. 3.6 along with a representation of the global electric circuit as envisioned by Markson. These topics as well as others form the subject matter of an international symposium/workshop, held July 24-28 at Ohio State University, entitled Solar-Terrestrial Influences on Weather and Climate (proceedings not yet available).

If the electrical mechanism proposed by Markson turns out to be valid for the solar-weather effect, then it may also be a reasonable candidate for a mechanism that could couple inadvertent changes in the ionosphere. The difficulty, according to Markson (private communication) is twofold. First, any alteration in the ionosphere would have to give rise to changes in conductivity in the region of 20-30 km. Second, it is not clear how changes in atmospheric electricity above thunderstorms influence cloud processes.

Considerably less well understood are the effects that rocket effluents have on the lower ionosphere, specifically the D&E regions. These regions are substantially more difficult to treat both because of the increased importance of collisions and because the neutral chemistry may be more important than the ion chemistry. This question has yet to be addressed in detail.

Another question that has thus far received only preliminary attention is the effect that the use of argon ions (Ar^+) as a propellant for orbit transfer from LEO to GEO will have on the upper atmosphere. Chiu, Ching, and Luhmann (Ref. 3.12) suggest that the large number of Ar^+ ions required will "profoundly alter the composition and dynamics of the ionosphere and magnetosphere." This remark is based upon their preliminary finding that, since Ar^+ has a very long charge-exchange lifetime in the natural plasmasphere, it will remain trapped for periods as long as 10 to 10 hours, during which time it can transfer its approximately 500 electon volts of energy via coulomb interactions to the ambient electrons. They estimate that about 80% of the Ar^+ ions will be released inot the plasmasphere (contained within about four Earth radii, while GEO is at about 6.6 Earth radii), and that the resulting Ar^+ ion concentration will substantially exceed the electron concentration at all altitudes where Ar^+ ions are released. Fig. 3.7 shows the relative positions and the general shapes of the plasmasphere and magnetosphere (the sun is off the picture to the left).

3.4.1.2 Other Effects

While in GEO, the satellite will be a source of visible light (reflected sunlight) as well as a source of infrared radiation, since a large portion of the incident solar energy will be rejected as waste heat. Douglas et al. (Ref. 3.12) from Maya Development Corporation have estimated that the reflected sunlight will cause the satellite to be the brightest object in the night sky next to the moon.

Their calculations show that 100 satellites together will produce about 1/10 the light of a full moon.

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*LEO - Low Earth Orbit (500 km)
GEO - Geosynchronous Orbit (35,800 km)

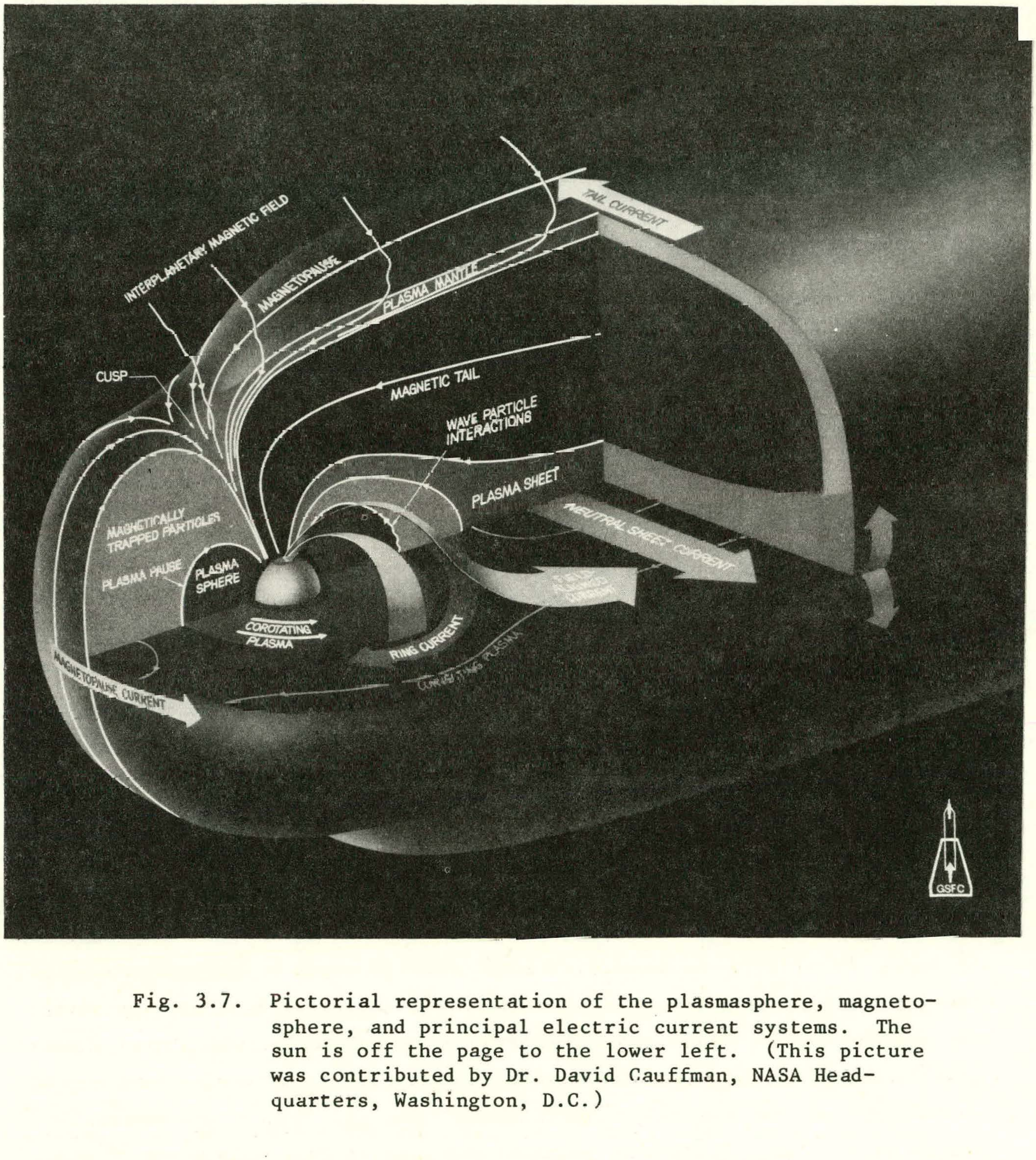

Fig. 3.7. Pictorial representation of the plasmasphere, magnetosphere, and principal electric current systems. The sun is off the page to the lower left. (This picture was contributed by Dr. David Cauffman, NASA Headquarters, Washington, D.C.)

In addition to potential influences on organisms (considered in Sec. 2), the additional night light, especially if it is diffuse, may interfere with ground-based optical astromony (considered in Sec. 4). If the reflected light were not diffuse but concentrated in a relatively narrow beam, it could be damaging to the naked eye.

Waste-heat rejection from the satellites will also make them the brightest objects in the night sky next to the moon in the far infrared region (peak radiation ≃ 9μ) Douglas et al. estimated that the intensity of the radiation from a satellite will be about equivalent to that of the moon throughout the infrared region, but they note that the moon occupies a much larger solid angle. However, they suggest that "even many hundred satellites should not be expected to cause a detectable sky illumination at far infrared wavelengths." This statement is based on the fact that as Douglas et al. point out, "the main component of sky radiation in this region of the spectrum is thermal emission from the lower atmosphere."

The satellites, due to construction operations, weathering by cosmic and solar ray bombardment, gas leaks, etc., will serve as relatively diffuse sources of assorted gases and particulate matter as well as of larger debris. Vondrak (Refs.3.14 and 3.15) has taken a preliminary look at the potential for forming relatively long-lived clouds of gas and dust in cislunar space (between Earth and Moon). Vondrak claims that (1) the dominant loss mechanism for gas clouds, if they are indeed formed, would be interactions with the solar wind; (2) the presence of such a gas cloud would become important when its mean density is large enough to divert the solar wind flow (this would require a gas leak rate of about 600 kg/sec); (3) significant absorption of the solar ultraviolet light would occur at comparable leakage rates; (4) interactions of solar wind with clouds of gas or dust may influence the Earth's weather and climate by altering the amount of solar radiation received by the Earth. In view of the large emission rates required to produce a significant effect, it is not at all clear whether or not the SPS will present a hazard along the lines Vondrak has suggested. Before such questions can be addressed it will be necessary to make some reasonable estimates of the strength of the source terms. If indeed clouds of gas or dust of significant mass density can form and remain in orbit for extended periods, then a possible consequence aside from the effect on the terrestrial environment may be the effects on the satellite environment that may impair its operation. Douglas et al. (Ref. 3.13) have examined the problem from this point of view. They mention four areas that they feel deserve quantitative investigation:

1. Sources, types and quantities of particulates emitted;
2. The concentrations that will build up and possible dispersal effects;

3. Effect of particles of various size and composition on operation of SPS and other satellites; and
4. Possible methods of control of particulates should they turn out to be a problem.

They also point out that very little information is available on items 1 and 3 above.

One problem of interest, since it is closely related to Vondrak's concern with influences on terrestrial climate, is the accumulation of enough mass in a cloud to reduce the sunlight received by a satellite by 10%. Douglas et al. estimate that about 4% of the SPS mass would have to be eroded away to form such a cloud. Assuming that surface erosion by meteoroids and sputtering (removal by charged particle impact) are the two main source of small particles, they estimate that perhaps in 10 years that amount of matter could be ejected into the satellite environment, but they go on to say that the ejecta would emerge with an angular distribution that would make an accumulation dense enough above the light collecting surface to obscure a significant fraction of the sunlight highly unlikely. Nevertheless, they suggest that the production of that much material by surface erosion (≃400 kg/day) seems rather large and its fate ought to be determined.

Douglas et al. also suggest, on the basis of a very simple model, that the ejected material mentioned above could potentially form a meteroid belt with a density roughly 10 times that of natural plasmasphere. If that is in fact true, then such a belt could have significant influence on magnetospheric processes. Such clouds of material may come into contact with the microwave beams but they judge that to be of negligible consequence.

Finally, Douglas et al. have identified three possible ways in which a satellite can influence the environment through which it travels:

- Production of electromagnetic (EM) radiation,
- Alteration of ambient particle distributions, and
- Generation of plasma EM disturbances.

These processes can have at least two possible environmental consequences according to Douglas et al.: alteration of the particle environment in the vicinity of other satellites by emission of disturbances by an SPS satellite, and production of electromagnetic interference. Consequences for the SPS itself are changes in its particle environment and in the drag forces and internal stresses on the physical structure. The satellite will experience both particle drag forces and induction drag forces. Douglas et al. conclude that the environmental consequences of satellite induced processes could be minimal but that the drag forces on an SPS during construction in LEO and during orbit transfer may be important.

3.4.2 Troposphere - Microwave Related Effects

The anticipated effects on the lower atmosphere are caused by waste heat released into the atmosphere by the rectifying antenna (rectenna) along with the heating of the atmosphere by absorption of the microwave beam. The possible consequences of this thermal energy release involve impacts on the weather and climate.

The effects of heat dissipation from an approximately 100-sq-km rectenna would be analogous to the effect of heat islands, which create mesoscale circulation patterns in the atmosphere on a horizontal scale closely related to the size of the heat islands themselves. For example, increases in the frequencies of occurrence of convective cloud formation and thunderstorm activity, and hence creation of precipitation anomalies, have been observed in many urban areas and their surroundings, and are thought to be due in part to the release of heat from within such areas.

The possible influence of microwave transmission through the troposphere is due to the absorption of microwave energy along the beam especially in clouds, causing local heating, enhanced turbulence, and possibly altering the dynamics of atmospheric circulation and contributing to microwave power beam spreading and wandering.

A preliminary assessment of the possible meteorological effects due to SPS rectenna operation was conducted by the Lyndon Johnson Space Center in 1977 (Ref. 3.16). The studies, mainly based on scale comparison and simple analytic estimates, are primarily qualitative in nature. The assessment was based upon the maximum power density of about 23 mW/cm^2 of microwave beam and an average of 0.75 mW/cm^2 of waste heat release at a rectenna covering approximately 100 km^2. The preliminary findings are that the effects of the SPS rectenna on weather and climate will be very small, and engineering considerations and the direct environmental consequences of construction will have much more significant impacts. A continuous release of 250 MW of waste heat from a 100 km^2 rectenna would be equivalent to the heat release associated with average suburban developments. This waste heat release is about 10 percent of the average natural energy conversion at the surface. The possible changes in aerodynamic roughness and rectenna's albedo would probably be more important than the waste heat release due to power conversion. 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 is negligible. Under most situations the heating by microwave will have no significant influence on the dynamics and thermodynamics of the clouds and associated hydrometeors.* Scattering by the particles, even in heavily polluted atmosphere, is also negligible.

A workshop on the atmospheric effects of rectenna operation was recently held (August 23-28, 1978) in Chicago.** Some of the panel's findings are highlighted in Appendix 3A.

3.4.3 Stratosphere, Nonmicrowave Effects

In recent years, considerable effort has been expended in a wide variety of research programs designed to advance the state of knowledge with respect to perturbation in the chemical composition of the stratosphere, particularly in connection with possible changes in stratospheric ozone concentrations. A wide variety of natural as well as human sources of chemical perturbation has been considered, including volcanic emissions, solar flares, subsonic and supersonic aircraft, chlorofluoromethane emissions, nuclear weapons testing, and biological production of nitrous oxide (N_2O). Each type of perturbation is characterized by the chemical nature of the emissions and by the given distribution of sources. Estimates of their impact on the stratospheric composition are based upon these particular characteristics. For this reason, the impacts on the stratosphere and mesophere due to the rocket exhaust emissions associated with the construction and operation of large space satellites cannot be estimated directly by simple extrapolation from previous assessments. The situation with regard to SPS-related rocket exhaust emissions differs in two significant respects from all other perturbations considered to date. First, the emissions will consist primarily of

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*Cloud water droplets, raindrops, hail, ice crystals, etc.

**Workshop report in preparation.

water and carbon dioxide, two substances which already exist in abundance in the atmosphere, together with much smaller amounts of other materials, including nitric oxide (NO). Second, the emissions are injected directly into the stratosphere and mesosphere simultaneously at all altitudes below approximately 120 km. Primarily because of these differences, it is not possible at this time to make reliable, quantitative estimates of the effect of SPS-related rocket emissions on the chemical composition of the stratosphere and mesosphere. While the frontiers of scientific knowledge concerning the lower stratosphere have been greatly expanded in recent years, as documented in Refs. 3.17 through 3.30, the state of knowledge concerning the upper stratosphere and mesosphere is not as advanced.

An initial evaluation of the potential for causing significant perturbations in stratospheric composition may be made by examining the relative magnitudes of the injection rates of the various exhaust components compared to rough estimates of "turnover rates" of the same materials at the altitudes of interest. The "turnover rate" is defined here as the total mass of the given substance within a one-kilometer deep layer, centered on the altitude of interest, divided by the residence time of that substance at the given altitude. The ratio of the emission or injection rate per kilometer to the turnover rate is a measure of the potential significance of the perturbation and will be termed the "perturbation ratio."

In order to compute perturbation ratios for the various exhaust components, estimates of their emission rates at various altitudes must be available. Table 3.1 shows the distribution of exhaust products for two alternate HLLV designs considered by the Boeing Aerospace Co. The numbers in the table represent emission rates at the mouth of the rocket motor and do not include the effects of afterburning in the rocket exhaust plume. It is assumed here that afterburning converts all carbon monoxide (CO) to carbon dioxide (CO_2) and all hydrogen (H_2) to water (H_2O). For purposes of estimating perturbation ratios, the two-staged winged design is used since the emissions are somewhat higher than for the two-staged ballistic vehicle. The former is also preferred by NASA for engineering reasons.

Table 3.1. Distribution of Exhaust Products in the Various Regions of the Atmosphere

	Magnitude of Exhaust Species/Flight - 10^3kg								
Region	H_2O	CHO	CH_4	H	CO	OH	CH_2O	CO_2	H_2
Two-Stage Ballistic Recoverable									
Booster									
Troposphere	1040	*	*	0.005	740	0.012	*	1193	36
Stratosphere	1096			0.005	780	0.013		1257	38
Mesosphere	440			0.002	313	0.005		504	15
Upper Stage									
Mesosphere	53			*	*	*		*	2
Ionosphere	1375	*	*	*	*	*	*	*	50
Two-Stage Winged									
Booster									
Troposphere	1275	*	*	*	577	*	*	1285	58
Stratosphere	1343				608			1354	61
Mesosphere	108				49			109	5
Upper Stage									
Mesosphere	279				*			*	10
Ionosphere	1936	*	*	*	*	*	*	*	70

Source: Boeing Aerospace Co., *Solar Power Satellite, System Definition Study Part II*, Volume V (December 1977).

*Less than 1 kg per flight.

Table 3.2 shows the estimated perturbation ratio for water as a function of altitude. These estimates are based upon the emission estimates given previously in Table 3.1, water concentration measurements of Masterbrook and coworkers (Refs. 3.31-3.33) as cited in NOAA et al. (Ref. 3.34), and the estimates of the residence time as a function of altitude also shown in Table 3.2. The values for the residence time are based upon consideration of vertical transport process only; the values up to 50 km are results of calculations presented by Oliver et al. (Ref. 3.35) using the Hunten 1974 vertical eddy diffusivity profile (Ref. 3.18, p. 19), and the values above 50 km have been adopted as a plausible but arbitrary extension of the results below 50 km. Examination of the table reveals that in the lower stratosphere the projected injection rate is small compared to the estimated turnover rate. At an altitude of about 35 km, the perturbation ratio is approximately 0.01. This indicates that the long term effect of a continuous injection

Table 3.2 Water Perturbation Ratio between 16 and 80 km

Altitude (km)	Assumed Residence Time (yr)	Water Perturbation Ratio (dimensionless)
16	2.2	1.6×10^{-4}
18	3.5	3.5
20	4.6	6.5
22	5.5	1.1×10^{-3}
24	6.3	1.6
26	6.8	2.5
28	7.3	3.6
30	7.7	5.2
32	8.0	7.3
35	8.4	1.3×10^{-2}
40	8.8	2.7
45	9.1	5.9
50	9.3	1.1×10^{-1}
55[b]	9.4	7.6×10^{-2}
60	9.5	1.3×10^{-1}
65	9.6	3.3
70	9.6	1.1
75	9.6	3.0
80	9.6	1.2×10^{1}

[a] Defined as $$\frac{\text{Water Injection Rate (mass/unit altitude/year)}}{\dfrac{\text{Total Mass of Water/unit altitude}}{\text{Residence Time}}}$$

[b] First stage emissions cease, second stage emissions begin.

of water at the rate indicated in Table 3.1 is to increase the water content at 35 km by approximately one percent. At 50 km, the increase in the water content is estimated to be 11 percent. Finally, at 80 km, an increase by a factor of 12 is predicted. These figures indicate that in the upper stratosphere and mesosphere, the potential clearly exists for significant perturbations in the water concentrations, given the anticipated level of spaceflight activity associated with SPS construction and operation.

This analysis is intended only to be suggestive of the effects that may result. More refined estimates will be necessary before reliable conclusions can be drawn. The photolysis of water vapor in the upper stratosphere and mesosphere, together with attack by excited oxygen atoms produced by ozone photolysis, may be expected, for example, to very significantly decrease the residence time and with it the perturbation ratio. At altitudes of 70-80 km, for example, the water residence time may be reduced to a small fraction of a year due to such chemical and photolytic processes. If the residence time is reduced to 0.1 year, the perturbation ratio would be correspondingly reduced to 0.12. The consequences, however, would be greater potential involvement in the complex set of chemical reactions which control the ozone concentration at these altitudes. Even the direction of the effect is not predictable without a much closer examination. The effects of vertical and horizontal transport must also be included. Finally, it should be pointed out that at the present time, the budget of water vapor in the stratosphere and above is only poorly understood. Considerably more information will be needed in this regard before reliable quantitative predictions of the effects of water from rocket exhaust can be made.

If similar calculations are made for carbon dioxide as were just discussed for water, the perturbation ratio for a one-year residence time is computed to be approximately 5.9×10^{-7} at 16 km, 1.2×10^{-5} at 35 km, and 1.0×10^{-4} at 50 km. Even allowing for more realistic residence times, it does not appear likely that the carbon dioxide emissions would have even a detectable effect. For example, using the residence times given in Table 3.2, the predicted change in the carbon dioxide concentration is 0.0001 percent at 16 km, 0.01 percent at 35 km, and 0.09 percent at 50 km. Of course, since carbon dioxide is emitted only by the first stage of the HLLV, emissions are zero above about 50 km.

Nitric oxide is formed from ambient nitrogen and oxygen in the hot rocket exhaust plume. Estimates of the amount produced in the exhaust of the space shuttle booster, as given in Refs. 3.36 and 3.37, amount to only 3-4 kg/km/flight at an altitude of 30 km. If the same estimate holds for the HLLV, the NO-injection rate at 30 km would be 1.2-1.6 metric tons/km/yr. The HLLV is expected to be significantly larger, however, and more nitric oxide is expected to be generated. Based upon more recent calculations of Gomberg

(Ref. 3.38) and taking into account the number of rocket engines to be used in the HLLV first stage, NO-injection rates have been estimated and are given in Table 3.3. Estimated nitric oxide perturbation ratios at these altitudes are also given in Table 3.3. The calculations were based upon observed odd nitrogen concentrations as given by Oliver et al. (Ref. 3.35) and Hudson (Ref. 3.17). These estimates indicate that, as in the case of carbon dioxide, nitric oxide injections from SPS-related spaceflight activity do not appear to be cause for concern at this time. Nitric oxide production due to reentry heating may be significant, however, and should be examined, but has not been considered in this preliminary analysis.

The discussion in this section has centered on the potential for significant chemical perturbations in the stratosphere and mesosphere. Water vapor emissions have been identified as a potential cause for concern, particularly at altitudes above 50 km. The effects of increases in the water vapor content of the atmosphere at these altitudes are not clearly understood at this time. In addition to the potential effect on the ozone concentration distribution alluded to previously, the possibility of significant climatic effects due to increased cloud formation, for example, deserves serious consideration, particularly in view of our present lack of understanding of the overall water budget. The need for additional research in this regard is particularly acute; until our understanding in this area is advanced beyond

Table 3.3. Estimated Nitric Oxide Injection Rates and Perturbation Ratios

Altitude (km)	Injection Rate (MT NO/km/yr)	Perturbation Ratio[b]
20	25.6	4.4×10^{-4}
30	14.7	1.2×10^{-3}
40	7.7	2.2×10^{-3}
50[a]	3.5	4.1×10^{-3}
60[a]	1.4	5.5×10^{-3}

[a] Extrapolated.

[b] Based upon residence times given in Table 3.2.

its current level, reliable predictions of the effects of water vapor injections due to SPS-related spaceflight activity will not be possible.

3.5 RESEARCH PLAN AND ALTERNATIVES

The research plan for the atmospheric effects portion of the environment assessment program consists of two phases. The first phase, which is expected to be completed at the end of FY 78, culminates in a preliminary assessment and a series of four workshops designed to identify issues requiring additional information and to make recommendations for specific near-term (i.e. 1980) objectives and approaches and more general, longer-term research objectives. The research plan for phase 2, which covers FY 79 and FY 80, is based primarily on the output of phase 1 and especially the outputs of the four workshops. Appendix 3B contains a task listing for FY 78 (tasks currently underway and nearing completion) and for FY 79 and FY 80. The tasks listed for FY 79 and FY 80 are preliminary and may require revision as more information becomes available. In particular, reports covering the workshops are currently in a state of preparation. Following initial drafts and circulation to workshop participants, the workshop reports will be sent to other agencies and interested persons for additional comments. The research plan for FY 79 and FY 80 may have to be updated as a result of revisions to workshop reports or other comments received.

3.6 CONCLUSIONS AND RECOMMENDATIONS

Since the atmospheric effects assessment effort is currently in phase 1, which is concerned with identification of issues and cause and effect relationships and preparation of research recommendations, it is somewhat premature to state conclusions at this time. However, based on our present state of knowledge and some results of the workshops recently completed (see Sec. 3.2), we can make the following draft conclusions and recommendations.

3.6.1 Upper Atmospheric, Nonmicrowave Effects (above 60 km)

The lowest layers of the ionosphere (D&E regions - see Fig. 3.1) can be affected by both rocket launches and spacecraft reentry. The effluents from these space operations include rocket exhaust products (primarily water and carbon dioxide) as well as some ablated materials and oxides of nitrogen produced during vehicle reentry. These effluents will modify the composition and properties of the natural atmosphere to a degree which has not yet been determined. Since such modifications may influence climate, satellite-based surveillance systems, radio communications, and navigation systems, microwave propagation (SPS microwave power beam stability) and magnetospheric processes, the likelihood and extent of these effects and their influences must be evaluated during FY 79 and FY 80.

The recently held workshop on Upper-Atmospheric Effects resulted in the following set of recommended approaches to problems in the D&E regions of the ionosphere:

1. Examine existing models of the atmosphere between 50 and 120 km to determine the extent to which they are capable of explaining existing data on the normal variations.

2. Use the best of the models and add the effect of the rockets (launch and reentry).

3. Consider particularly the role of horizontal transport processes (e.g., planetary waves) on the dispersal of the contaminents.

4. Use sounding rockets to examine effects of in-situ deposition of contaminents; particularly mass spectrometers to examine time-variations.

5. Use existing data from satellites and ground-based stations to search for effects from previous launches.

6. Participate in planned scientific experiments, such as those to be conducted during the 1979 solar eclipse.

7. Interact with other programs, such as the NASA space shuttle and the DOD SCATHA satellite.

A preliminary list of research tasks based upon the workshop findings is included in the research plan for FY 79 and FY 80 (see Appendix 3B).

The ionospheric layers above the D and E region are referred to as the F1 and F2 regions (see Fig. 3.1) or simply the F region for short. These regions are also subject to modifications in their composition and structure as a result of deposition of rocket effluents during launch, reentry, and space craft maneuvering operations in low earth orbit (LEO). The F2 region in particular overlaps the LEO.

Calculations have shown that injection of water and carbon dioxide into the F region results both in plasma reduction (electron-ion recombination) and enhanced airglow (visible emissions from excited molecules). These predictions have been verified both inadvertantly during the NASA 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 temperature variations could lead to thermal expansion that could modify satellite drag.

Recommendations addressing F-region problems made at the above-mentioned workshop include the following:

1. Obtain a quantitative description of <u>all</u> SPS rocket effluent terms as a function of space and time.

2. Develop three-dimensional simulation techniques needed to assess local effects of rocket effluents.

3. Utilize two-dimensional simulation models to assess global effects of multiple rocket launches following the SPS design schedule.

4. Perform rocket molecular release experiments to measure neutral, ion-neutral, and ion-ion diffusion coefficients and to test simulation predictions.

5. Conduct laboratory experiments to determine molecular ion dissociative recombination rates and products (specifically for H_2O^+ and OH^+).

6. Examine archived data taken during previous rocket launches to test simulation predictions and to search for radio scintillation effects and for traveling ionospheric disturbances associated with gravity waves caused by the rocket launches.

7. Monitor NASA and DOD rocket launches and space shuttle orbital flight tests to test simulation predictions and to search for radio scintillation effects and traveling ionospheric disturbances.

The magnetosphere which extends from the F1 region of the ionosphere (see Fig. 3.1) out to about ten earth radii on the sun-side and much further away on the dark-side is subject to a number of disturbances caused by:

- Ion engine exhaust from cargo orbit transfer vehicles (from LEO to GEO),
- Chemical exhaust from personnel orbit transfer vehicles,
- Ion and chemical exhaust from stationkeeping and attitude control thrusters,
- Various gases and particles emitted from satellites and vehicles in GEO, and
- Movement of the very large metal structures of the satellites through the ambient magnetic field and ionized plasma.

These disturbances can cause increased airglow, plasma turbulence, precipitation of Van Allen belt particles and perhaps even result in a change in location of the auroral zone. These atmospheric effects can in turn cause interference with optical sensors and radio communication and navigation systems as well as modification of the radiation belt dosage. (The SPS satellites will be located in GEO which overlaps the outer region of the second Van Allen belt.) Change in position of the auroral zone can result in power line surges in transmission networks and possibly changes in earth electrical currents. All of these effects and their impacts will have to be further investigated during FY 79 and FY 80. Specific recommendations for these two years were made at the recent workshop on Upper-Atmospheric Effects. These include the following:

1. Theoretically model the time-dependent response of the plasmasphere to argon ion injection.
2. Calculate the modification of the radiation belt high-energy electrons and the modification of the radiation dosage due to rocket effluents.
3. Calculate the expected increase in airglow intensity.
4. Experimentally observe ion beam-plasma interactions and plasma irregularity generation.
5. Measure the diurnal variations in the natural plasmaspheric temperature profile, etc. to compare with predicted variations resulting from SPS-related disturbances.

6. Consider the use of depletion experiments at auroral latitudes.

7. Utilize data from observations made using existing satellites (SCATHA, GEOS, PSEE).

8. Coordinate or combine modeling codes and establish uniform and consistent boundary conditions.

9. Use existing data to investigate mechanisms for dumping and replenishing trapped radiation (charged particles trapped in the magnetosphere).

In addition to the effluent effects mentioned above, the workshop also raised some issues regarding the satellites in GEO and possible impacts on the satellite environment and on the terrestrial environment. Issues that may require further investigation include the following:

1. Wake effects associated with the movement of the satellites through the ambient plasma and magnetic field.

2. Result of accidents involving formation of large amounts of debris or massive injections of propellants.

3. Bombardment of satellite structure by cosmic rays and meteoroids leading to formation of debris and possibly stable dust clouds.

4. Local magnetic and electric field distributions in vicinity of satellites that may trigger auroras, alter particle trajectories, short out magnetospheric electric fields, etc.

5. Hazards associated with debris accumulated during lifetime of 60 satellites in GEO.

6. Effect of visible and infrared radiation from 60 satellites on astronomical observations.

7. Potential for generation of relatively high energy electrons near satellite vicinity and hazards for personnel and equipment.

Present evidence suggests that the satellite-related effects are of either low or uncertain importance.

3.6.2 Troposphere - Microwave Related Effects

Preliminary qualitative analyses have indicated that the heat dissipation at the rectenna site would produce about the same heat island effects as a suburban area, and would be small compared with other man-made installations. Under most situations, the attenuation of the microwave beam in the troposphere will be small and will not produce disturbances of meteorological consequence on any scale.

However, careful analyses should be carried out to ensure that any possible unexpected consequences resulting from the processes initiated by such small perturbations have been thoroughly included. For example, even though the waste heat release from the SPS rectenna is small compared with the average natural energy conversion at the surface, the combination of this energy release with the possible alteration of aerodynamic roughness and albedo at the rectenna site may, in certain atmospheric situations, result in some undesirable meteorological effects. The effects of atmospheric electricity on tropospheric weather and climate may require investigation although the effects of SPS on atmospheric electricity have not yet been identified.

In the workshop on the atmospheric effects of rectenna operations* it was generally agreed that the direct atmospheric effects of the SPS will be small except during periods of beam misdirection, and that the effects of atmospheric heating need better definition--on both the mesoscale (regional and city size, 10 to 100 km) and "cloud scale" (10 km and less). The effects will vary from one atmospheric condition to another and will be site specific. However, not all conditions can be tested in the two-year feasibility study period and so a few typical configurations of flat land, ocean, and mountain-valley sitings should be focused upon. The longer term objectives are to consider site-specific items and define the effects of the SPS over various regions of the United States.

Variations in the refractive index of the atmosphere and the presence of hydrometeors in the atmosphere cause refraction, scattering and absorption of electromagnetic waves. At 2.45 GHz the refractive index of air at fixed pressure depends mostly on water vapor and temperature. In the presence of

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*Report in preparation.

convective or turbulent air motions a spectrum of atmospheric refractivity develops. These variations can lead to beam wandering and spreading.

The scattering and absorption by hydrometeors depends on their size, shape, number concentration, and composition. If these properties are specified, calculations can be made of atmospheric attenuation and of the spreading of the beam. Contributions to beam wandering and spreading from the planetary boundary layer, cloud systems, jet stream turbulence and stratified atmospheric layers must all be considered.

These atmospheric effects impact on the power beam and pilot beam stability problem. Slowly varying and drifting anomalies, large-area events, or numerous smaller-area anomalies in the power beam and the pilot beam cause spatial and temporal modulations that vary the illumination of the ground-based rectenna, and because of adverse geometry, cause large variations in pilot signal parameters. The latter have a strong potential for causing serious ambiguities in the control decisions and system stability considerations.

These considerations impact on the waste heat releases assumed in the feasibility studies mentioned above. The most useful studies will vary the heat releases and affected areas by an order of magnitude to account for loss of control in worst-case situations.

Studies should also include anomaly events appropriate to higher frequencies; in the 10 to 30 GHz range. Since the rectenna for these frequencies may be smaller than that of the 2.45 GHz system, the smaller anomalies become more directly important to fluctuation components. The higher frequencies would lead to increased atmospheric interactions, greater attenuation losses and refractive and scatter sensitivities.

Direct interactions with the atmospheric electricity fields are not thought to be crucial at the 2.45 GHz frequency. However, the mere physical presence of the rectenna may have some modifying influence on the occurrence and electrical behavior of thunderstorms over and around the rectenna.

The specific recommendations of the panel regarding research in the immediate future are to:

1. Conduct literature surveys and analytical calculations of the radiative and roughness characteristics of the

antenna; also make similar studies of the energy balance of typical sites.

2. Conduct model simulations on the mesoscale and "cloud scale" in nonsevere and severe weather situations of the effects of differential heating, evaporation and friction caused by the SPS rectenna.

3. Develop statistics at representative sites giving storm frequencies, dimensions, as well as rainfall and hail intensities and their spatial extents to help in communication studies.

4. Conduct studies using available data to estimate the effects of jet stream turbulence on the propagation of microwave radiation from the SPS satellite. Statistics on the frequency, extent and intensity of high level refractivity turbulence should be assembled.

5. Estimate the frequency of large humidity variations across stable layers in various geographical areas including coastal and continental areas.

6. Develop a research program to determine the meteorological variations in the atmosphere volume above the rectenna caused by tropospheric absorption and rectenna heating and associated interactions.

7. Consider the implications of changing to frequencies in the 10 GHz to 30 GHz range.

8. Determine those atmospheric conditions which would produce the maximum beam spreading and wandering and calculate the degree of bending. Do similar worst-case studies for Doppler shift. Determine the effects on the atmosphere and earth if the beam is displaced from the rectenna.

9. Conduct studies of microwave absorption in large storm situations to determine whether there are any significant effects on storm behavior.

10. Use existing or planned synchronous communication satellites and existing ground-based receiving stations to extract basic signal characteristics, with ground based coherent S-band radars acting as sensors of atmospheric structure.

11. Improve the existing data base regarding thunderstorms, such as frequency, location and intensity in order to determine the modifying effects on thunderstorms by the rectenna. Since important data regarding thunderstorms exist in Switzerland and South Africa, comparative studies should be made and results extrapolated

to the U.S. if appropriate. Of great importance is the improvement of methods for calculating ground strike density from the existing thunderstorm data base.

12. Conduct studies using existing thunderstorm electrical theories and models to help in determining the effects of normal perturbations in thunderstorms.

13. Carry out calculations of field enhancement for the rectenna to help determine changes in the dielectric properties of the earth's surface.

14. Conduct studies of corona production and enhancement of space charge and their effect on lightning processes.

3.6.3 Stratosphere and Mesosphere, Nonmicrowave Effects

In regard to the stratosphere and mesosphere, the potential exists for significant effects due to rocket exhaust emissions of water vapor at altitudes of 40 km and above, based upon a comparison of measured water vapor concentrations and projected injection rates. Much more detailed calculations are required, however, to properly assess the significance of this potential impact. In addition, because of inadequacies in our basic understanding of the water budget at these altitudes, a significant uncertainty must be associated with any prediction no matter which of the available models is used. The need for additional research in this area is great, and it is recommended that a substantial effort be directed towards increasing our understanding of the water budget in order to provide more reliable grounds for the prediction of effects due to SPS-related water vapor injections.

Emissions of the other principal rocket exhaust product, carbon dioxide, are not expected to have a significant impact, again based upon a comparison of the amount already present to that which would be injected.

Production of nitric oxide by afterburning in the rocket exhaust is not expected to have significant effects. This conclusion is based, however, upon injection rates estimated for solid-fueled rocket motors, and the estimates may therefore be considerably in error. If the nitric oxide production were increased by an order of magnitude or more, a marginal effect may be expected. It is recommended that estimates of the production of nitric oxide by afterburning effects be made for the specific rocket motors to be used in the HLLV in order to have more appropriate figures upon which to base an evaluation. Until such estimates are made, however, there is little reason to expect significant impacts from nitric oxide production by afterburning.

Production of nitric oxide in the mesosphere during reentry by the second stages of the HLLV and personnel launch vehicle (PLV) is also potentially significant. Estimates of the rate of nitric oxide production by this mechanism should be made as well as detailed calculations to assess its significance.

Finally, the climatic effects which may result from changes in stratospheric and mesospheric trace substance concentrations, including effects arising from a potential increase in noctilucent cloud formation, are not expected to be highly significant although much more extensive calculations are required for a detailed evaluation.

Appendix 3B includes a list of specific recommendations for both theoretical and experimental research that should be conducted over the next one-and-a-half to two years in order to provide as good a basis as possible, given the limited time available, for the evaluation of potential environmental impacts in the stratosphere and mesosphere. These specific recommendations should, however, be viewed within the context of three more general recommendations:

- With regard to experimental and observational measurement programs, it is recommended that ongoing programs, currently funded by NASA, FAA and other agencies, be identified which can be augmented and/or extended by DOE in order to provide additional or more timely data; in general, it is recommended that DOE participate in major experimental programs related to upper atmospheric research.

- It is recommended that a specific SPS-oriented modeling project be established in one or more of the experienced modeling groups.

- Finally, it is recommended that DOE begin planning for a longer term environmental impact assessment effort, assuming that work on SPS will continue beyond FY 1980, particularly in view of the fact that 20 years or so will elapse between the time that the current environmental assessment is made and the time at which actual construction will commence.

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APPENDIX 3A

HIGHLIGHTS OF AUGUST 23-28, 1978, WORKSHOP ON ATMOSPHERIC EFFECTS OF RECTENNA OPERATION

3A.1 RECTENNA WASTE HEAT EFFECTS

Construction of a rectenna will modify the thermal and radiative properties of the ground on which it is built; operations will introduce a heat source at the surface. Though the perturbations by the rectenna of the average surface heat exchange is of the order of 10%, a tenfold increase in perturbation should be considered on the occasions of microwave beam wandering and spreading due to atmospheric refraction effects. A nonnegligible effect invariably resulting from nonlinear interactions when the atmosphere is perturbed should be considered, though the nonlinear effects need better definition on both the regional scale (10 to 100 km) and "cloud scale" (10 km and less). The effects will vary from one atmospheric condition to another and will be site specific.

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 heat dissipation rates over comparable areas are 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 rectenna waste heat. It is therefore to be expected that meteorological effects of a rectenna would vary from site to site, and the central maximum heat dissipation (20 to 30 Wm^{-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 SPS system in the context of the increased energy consumption which 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 emissions of material into the troposphere. 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 construction of a rectenna are that they are generally small but detectable in some instances. The major immediate issue is to confirm these estimates by the most convincing methods now available. In an enterprise of the magnitude of the SPS any other approach to a question which might have an economic impact on the population at large, and which certainly impacts its peace of mind, would be inadequate. A second issue is that the possibilities of modifying weather and climate change by constructional manipulations not affecting system efficiency should be explored. A third is that 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.

3A.2 MICROWAVE PROPAGATION EFFECTS

It has been concluded that the passage of the microwave beam through the atmosphere will produce no significant meteorological consequence (Ref. 3.16). Much attention was focused, during the panel discussions, on the possible effects of the natural atmospheric conditions on the microwave beam propagation and the associated power beam and pilot beam stability problems.

Variations in the refractive index of the atmosphere and the presence of hydrometeors in the atmosphere cause refraction, scattering and absorption of electromagnetic waves. At 2.45 GHz the refractive index of air at fixed pressure depends mostly on water vapor and temperature. In the presence of convective or turbulent air motions a spectrum of atmospheric refractivity develops. The refractivity variations can lead to beam wandering and spreading.

The scattering and absorption by hydrometeors depends on their size, shape, number, concentration, and composition. If these properties are specified, calculations can be made of atmospheric attenuation and of the spreading of the beam.

In considering the effects of natural atmospheric conditions, it is convenient to examine various possible contributions from the boundary layer, cloud systems, jet stream turbulence and stable layers.

The Boundary Layer. As a result of heat, moisture and momentum exchanges at the ground, the lowest regions of the atmosphere can display a relatively high degree of refractivity turbulence. This activity is particularly the case during days when the air is humid and unstable or when the wind is strong. It appears, however, that over a 100 km^2 rectenna, the low-level refractivity variations will not have serious deleterious effects on the efficiency of the system.

Cloud Systems. Cloud systems represent regions where refractive indexes can be systematically different from those in the environment. This phenomenon is particularly true in the case of thunderstorms and squall lines. Such storms, especially when they produce heavy rain and hail, can cause very substantial scattering and attenuation of microwaves. It is essential that statistics be developed, at various representative sites, giving storm frequencies and dimensions, as well as rainfall and hail intensities and their special extents.

Jet Stream Turbulence. It has been found that clear air turbulent conditions, associated with the high level jet streams, can lead to significant scattering of S-band (wavelength around 10 cm) radiation. This is particularly likely when the humidity varies substantially with height through the turbulent region. It is recommended that available data be used to estimate the effects of jet turbulence on the propagation of microwave radiation from the SPS satellite. Statistics on the frequency, extent and intensity of high level refractivity turbulence should be assembled.

Stable Layers in the Atmosphere. Turbulence in the vicinity of the tropopause and other stable atmospheric layers can cause sufficiently intense fluctuations of refractivity to cause the scattering of S-band radiation. The effects are particularly important when the humidity varies substantially through the stable layer. The frequency of such conditions needs to be estimated in various geographical areas, including coastal and continental areas.

Beam control is impacted to a major extent by the interaction of both the power beam and the pilot beam with refractive-index anomalies in the atmosphere. 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 cause spatial and temporal modulations that vary the illumination of the rectenna, and because of adverse geometry, cause large variations in pilot signal parameters. The latter have a strong potential for causing serious ambiguities in control decisions and system stabiity considerations.

Current models based on satellite signal data demonstrate ranges of coupling of EM signal characteristics (amplitude, induced frequency modulation and phase) with general meteorological conditions. These satellite signal 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 atmosphere 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. These data are also required to support estimates of sidelobe variations caused by refraction, thus possibly expanding the interference problem for areas outside the rectenna exclusion zone.

The panel recommended that the following areas should be addressed during FY 79 and FY 80:

(1) Determine meteorological variations in the atmosphere above the rectenna caused by tropospheric absorption and rectenna heating and associated boundary interactions.

(2) Determine turbulent flow conditions in the atmosphere with humidity, pressure and temperature gradient ranges to allow development of refraction properties.

(3) Predict variations in relations with geographic areas.

(4) Modify existing models to provide adequate resolution for parametric analysis.

The indicated studies to expand atmospheric physical-parameter definition should include consideration of anomaly events appropriate to higher frequencies in the 10 GHz to 30 GHz range. Since the rectenna area for these frequencies may be smaller than that of the 2.45 GHz system, the smaller anomalies become more directly important to fluctuation components. The higher frequencies would lead to increased atmospheric interactions, greater attenuation losses and refractive and scatter sensitivities. An additional disadvantage in physical and control tolerances must be recognized. Some advantages accrue from the reduced potential for EM interference, negligible ionosphere effects, and smaller physical system.

Because we do not yet know the importance of the perturbations of the rectenna (in terms of heating and turbulence in the boundary layer), we cannot yet address the ways in which such perturbations will feed back to effect the system performance.

Problem 1: The effects of the atmosphere on beam wandering, beam spreading, and gain reduction.

Problem 2: The effects of the atmosphere on Doppler shift and Doppler spread of signals and the resulting impact on the ability of the pilot-control signal to minimize beam wandering, etc., and on the frequency control system.

Problem 3: The identification of the various atmospheric phenomena which may affect the factors listed in Problems 1 and 2. Some of the most important ones appear to be the following:

(a) Storms and clouds passing through the propagation path. It is expected that the important ones will be mainly of a convective type.

(b) Clear-air refractive index perturbations in stratified layers throughout the troposphere. Some initial indications suggest that the higher levels (i.e., near tropopause) may be most important, but the strong refractivity effects near lower level inversions should also be considered.

(c) Clear-air refractive-index perturbations associated with convective plumes and bubbles.

(d) Sharp horizontal discontinuities in refractive index associated with either dry (i.e., sea breeze fronts, dry lines) or moist fronts.

Problem 4: Possible heating of the ground and evaporation of soil moisture where the beam wanders off the rectenna, especially under conditions of failure of the control loop.

Problem 5: Atmospheric heating by absorption of the microwave energy by clouds, rain and hail and the probability of occurrence of effects of various magnitudes.

Problem 6: Possible effects on the signals at the rectenna of depolarization by nonspherical raindrops, hail, and snow crystals.

Problem 7: Use of the SPS system for remote sensing of winds, turbulence, and refractivity perturbations as a means of development of feedback signals to help control and system performance, and accommodate safety-related decision actions.

Problem 8: Wavelength considerations. By and large, the panel believed that while it may be desirable to move to higher frequencies to reduce antenna sizes and interference effects, the increased effects of attenuation and depolarization (among others) seem to preclude going to considerably higher frequencies. The meteorological studies should indicate the wavelength sensitivities of the cited absorption, scattering, and refractive effects.

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APPENDIX 3B

ATMOSPHERIC EFFECTS PROGRAM PLAN

Preliminary Atmospheric Effects Research Task List

Task	Priority	Est. Complet. Date
TROPOSPHERIC EFFECTS (Microwave-Related)		
1. Identification of possible issues and overall assessment of impact of rectenna operation.	High	9/80
2. Rectenna radiative properties, roughness characteristics and energy balance study.	High	3/79
3. Mesoscale model simulation of rectenna heat effects.	High	9/80
4. "Cloud Scale" model simulation of rectenna heat effects.	High	9/80
5. Effects of natural atmospheric phenomena on microwave beam propagation (meteo. factors that affect beam wandering, Doppler shift, etc.)	High	9/80
6. Effects of microwave beam on atmosphere including possible heating and evaporation of the ground under conditions of control failure.	Medium	9/80
7. Use of SPS and ancillary sensors for remote sensing of atmosphere.	Low	Continue
8. Effects of rectenna operation on atmospheric electricity and their associated meteorological phenomena.	Low	9/80
STRATOSPHERIC AND MESOSPHERIC EFFECTS		
1. Overall assessment of effects of rocket effluents in stratosphere and atmosphere.	High	FY 80
2. Prepare detailed rocket exhaust emission inventory, including calculations of after-burning effects.	High	FY 79
3. Estimate NO_x production rate due to reentry as a function of altitude for projected levels of spaceflight activity.	High	FY 79
4. Estimate (1-D Model) high altitude composition changes due to rocket launch and reentry emissions for various possible CO_2 and chlorofluoromethane (CFM) levels predicted for the year 2000 and beyond.	High	FY 80
5. Estimate (1-D Model) maximum acceptable level of injection of H_2O and NO_x, for various possible CO_2 and CFM levels.	High	FY 80

(Cont'd)

Task	Priority	Est. Complet. Date
STRATOSPHERIC AND MESOSPHERIC EFFECTS (Cont'd)		
6. Evaluate (1-D Model) effects of temperature feedback on high altitude composition changes, including effects of injections of CO_2, of fuel impurities such as sulfur, and of ablation material produced on reentry.	Medium	FY 80
7. Estimate (2-D and 3-D models) extent of "corridor effect" for various H_2O and NO_x injection rates.	High	FY 80
8. Evaluate importance of "corridor effect" and temperature feedback effects for climatic impacts, specifically changes in atmospheric dynamics and surface temperatures, for projected levels of spaceflight activity.	Medium	FY 80
9. Establish maximum acceptable H_2O and NO_x injection rates from point of view of climatic impacts.	Medium	FY 80
10. Estimate potential increase in noctilucent and nacreous cloud formation due to H_2O injections.	High	FY 80
11. Estimate extent of climatic effects arising from increase in noctilucent and nacreous cloud formation, taking potential corridor into account.	High	FY 80
12. Estimate effects due to localized energy injection due to rocket exhaust thermal energy and to microwave absorption.	Low	FY 79
13. Support suitable extension and/or augmentation of planned measurement program to provide calibration data for NIMBUS-G satellite H_2O and NO_x measurements.	High	FY 80
a. Additional high altitude H_2O and NO_x measurements.		
b. Extended and/or more timely data analysis and reduction.		
14. Augment ongoing NASA and FAA sponsored programs for CO_2 measurements above 35 km, to allow more accurate estimates of temperature profile in upper stratosphere and mesosphere.	High	FY 80

(Cont'd)

Task	Priority	Est. Complet. Date
IONOSPHERIC AND MAGNETOSPHERIC EFFECTS (Nonmicrowave)		
GENERAL		
1. Overall assessment of upper atmospheric effects and preliminary identification of issues.	High	9/80
2. Determine and monitor targets of opportunity including NASA and DOD rocket launches and space shuttle orbital flight tests.	High	9/80
3. Investigate perturbation of atmospheric electric field due to large-scale reduction in stratospheric and ionospheric conductivity.	High	9/80
D&E REGION		
4 . Determine electron density changes caused by ion composition changes resulting from water injection.	High	1/80
5. Determine magnitude of metal ion and atom ablation from space craft and impacts.	Medium	1/80
6. Determine if conductivity changes in dynamo region can significantly alter magnetospheric processes.	Medium	1/80
7. Determine the degree to which very low frequency (VLF) wave propagation is influenced by conductivity changes.	Low	1/80
F-REGION		
8. Obtain detailed description of source terms as a function of space and time.	High	1/80
9. Reduction of LAGOPEDO optical data.	High	9/78
10. Develop 3-D simulation technique needed to assess local effects. Assess local effects.	High	9/80
11. Utilize existing 2-D simulation models to assess global effects.	High	9/80
12. Perform rocket molecular release experiments to measure neutral, ion-neutral, and ion-ion diffusion coefficients and to test simulation predictions.	?	6/80

(Cont'd)

Task	Priority	Est. Complet. Date
IONOSPHERIC AND MAGNETOSPHERIC EFFECTS (Nonmicrowave) (Cont'd)		
F-REGION (Cont'd)		
13. Participation in already planned rocket launches (targets of opportunity). Add-on of ground based measurements, acquisition of SPS relevant data. Simulation of effects and comparison with observations.	High	6/80
14. Conduct laboratory experiments to determine molecular ion dissociative recombination rates and products (specifically for H_2O^+ and OH^+)	High	1/80
15. Examine archived data taken during previous rocket launches to test simulation predictions and to search for radio scintillation effects and traveling ionospheric disturbances (TIDs) associated with gravity waves caused by rocket launches.	High	1/80
MAGNETOSPHERE/PLASMASPHERE/SATELLITES		
16. Theoretically investigate time-dependent response of plasmasphere to argon ion injection and the impacts on electromagnetic wave propagation.	High	1/80
17. Determine modification of radiation belt high-energy electrons and associated radiation dosage environment.	High	1/80
18. Estimate changes in airglow.	Medium	9/79
19. Measure diurnal variations in natural plasmaspheric properties.	Medium	9/80
20. Conduct depletion experiments at auroral latitudes (add-on to planned experiment).	Medium	9/80
21. Use existing data to investigate mechanisms for dumping and replenishing trapped particles.	High	1/80
22. Investigate impacts on satellite and terrestrial environments of 30 to 60 SPS satellites in GEO. (Source of dust debris, plasma waves, induced electric and magnetic field effects, light reflection, diffuse infrared and microwave radiation.)	Medium	1/80

(Cont'd)

Task	Priority	Est. Complet. Date
TROPOSPHERIC EFFECTS (Non-Microwave)		
1. Qualitative assessment of inadvertent weather effects of rocket launches.	High	10/78
2. Overall assessment of effects of rocket effluents in troposphere.	High	9/80
3. Quantitative assessment of possible weather modification from rocket launches (model simulation).	High	9/80
4. Estimate field strengths near DC or AC power transmission lines and determine potential for adverse environmental impact if any.	Medium	2/79
5. Acquire meteorological data for proposed launch sites.	High	9/79
6. Develop climatic evaluation for proposed launch sites for surrounding possible impact areas.	High	9/79
7. Collect and summarize existing data on air background concentrations for pollutants at proposed launch sites.	Medium	9/79
8. Define, develop, and begin long-term ambient air quality monitoring activity at launch sites.	Low	12/79
9. Conduct cloud volume, composition, temperature, and moisture content measurements for launches to verify exhaust cloud source terms.	High	9/80
10. Apply and refine predictive atmospheric dynamics model for transport and dilution histories.	High	12/79
11. Apply and refine a validated photochemical model to characterize exhaust cloud species interaction with ambient air at proposed launch sites.	Medium	12/79
12. Apply and refine multicomponent cloud microphysical model to characterize interactions of gases, particulates and aerosols.	Medium	12/79
13. Nozzle and afterburning analysis to develop source terms.	High	9/79
14. Refine noise generation and sonic boom predictive techniques.	Medium	9/79

(Cont'd)

Task	Priority	Est. Complet. Date
TROPOSPHERIC EFFECTS (Non-Microwave) (Cont'd)		
15. Collect and summarize existing data on near-ground air quality impacts of past rocket launches.	High	1/79
16. Determine the effects of meteorological conditions on sound focussing, dust effects, and sonic boom transmission (use existing data).	Medium	1/79
17. Research on sonic boom/water interface effects.	Medium	12/79
18. Analysis of RP-1 fuel lots.	High	12/79

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4 EFFECTS ON COMMUNICATION SYSTEMS

4.1 ELECTROMAGNETIC COMPATIBILITY

4.1.1 Scope

The following are within the scope of this section:

- An assessment of the electromagnetic compatibility (EMC) of SPS with electromagnetic (EM) receiver systems.
- An evaluation of the EMC of electronic systems which would be degraded because of the high power of SPS.
- Analysis of the implications of the induced degradation.

4.1.2 Methodology

The potential EMC problem caused by the satellite power systems is recognized as one of the most critical in the SPS environmental assessment. Consequently, an aggressive 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 medical instruments and devices), because of SPS direct power coupling, and ionosphere and atmosphere media modification effects. These effects are depicted in Fig. 4.1. Primary evaluation areas include EM environment verification computations, coupling analysis, functional-operational priority categorization, degradation evaluations, and impact assessment. Subsequent tasks address mitigation methods for degraded systems, and guidelines for designers and planners of future systems.

Information was obtained from NASA on the SPS reference design (Ref. 4.1.3), including: single microwave power transmission system radiation characteristics, geostationary earth orbit (GEO) locations for multisatellite operation, emission power spectra, sidelobe structure, and candidate rectenna sites. A model is being used to predict field strengths at and near the surface of the earth from SPS microwave emissions. Priority rectenna sites will be analyzed from the candidates identified by NASA and DOE (Ref. 4.1.4). Equipment and systems near the rectenna sites that are susceptible to SPS radiation are identified by selective retrieval from existing files, and

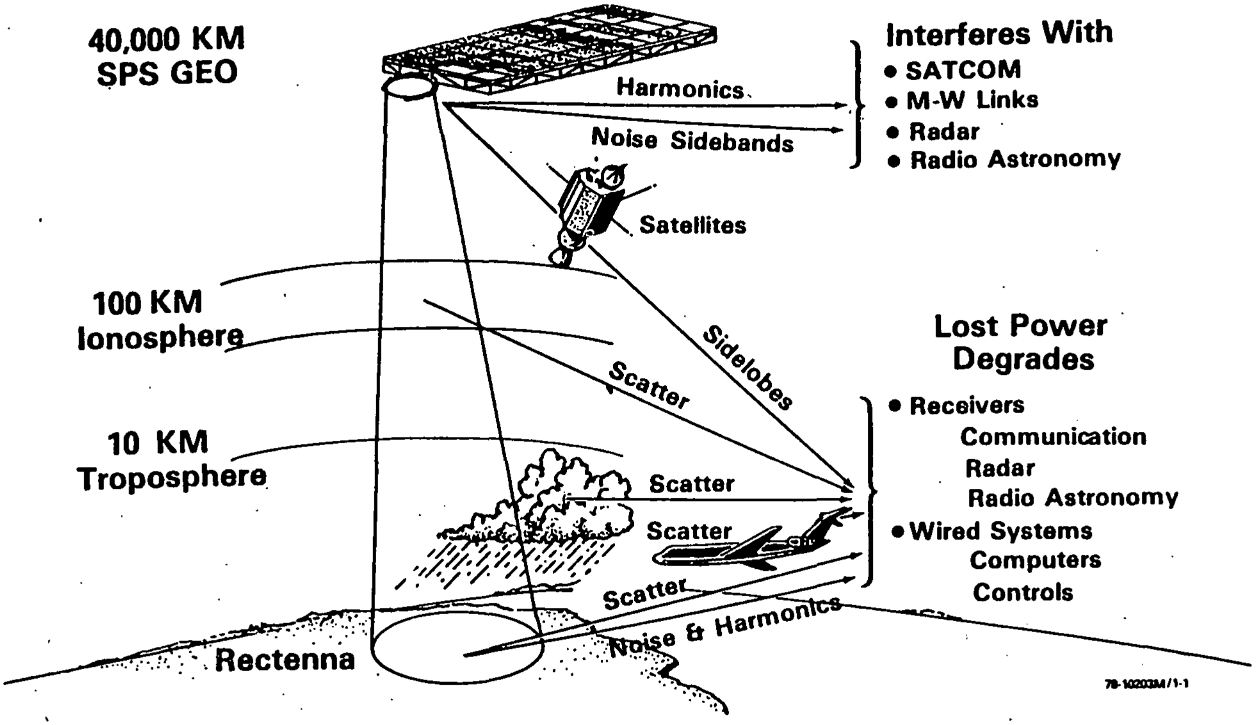

Fig. 4.1. SPS Radio Frequency and Electromagnetic Interference

categorized in relation to function, coupling modes, location, and interconnectivity. Signal/interference ratios (S/I) scoring models are multidimensional to allow adequate definition of the operational relationships. (These are demonstrated in the functional degradation summaries presented later in Table 4.7.) The (S/I) scoring models are being designed for "victim" systems, and confirmatory signal-SPS interference ratio tests will be conducted on candidate systems where data voids exist.

Subsequent to the degradation analyses, modification techniques applicable to affected continental U.S. (CONUS) systems will be developed to allow an acceptable operational capability within the SPS environment. Implementation procedures and cost estimates, with priorities, will be developed.

A basic study of SPS microwave energy distributions within habitable structures that could be located near the area of a rectenna site is being completed. This study is of interest to the microwave-related health and safety effects assessment as well as to the EMC analysis. The primary emphasis concerns defining the structural and geometric situations that would allow electromagnetic field maxima and the general range of penetration through materials and normal physical apertures (e.g., windows, skylights, unintentional gaps). This initial study identifies a rare likelihood of resources existing in the general classes of buildings and vehicles. General guidelines to minimize the probabilities of encouraging "hot spots" are included in the technical report for this task (Ref. 4.1.5).

The indicated communications impact would involve broadcast, commercial, recreation, and security services. Density variation predictions that apply depletion of the F-layer and the vehicle launch frequency of possibly one per day over a several-month period to establish operating power stations could result in several reduced or nonexistent ionosphere channels for the middle and upper frequency operations in the high frequency (HF) spectral regions.

4.1.3. Cause and Effect Relationships

Cause and effect relationships are shown graphically in Fig. 4.2. These indicate the atmospheric media effects on the SPS power and pilot beams, and the energy coupling to a number of electronic systems.

Various atmospheric parametric interactions affect the power efficiency of the SPS system as well as contribute to the electromagnetic compatibility problem. These are:

- Attenuation of the signal due to the atmosphere,
- Attenuation and distortion because of atmospheric gases and stratification,
- Attenuation and scatter due to precipitation, - rain, hail, etc.,
- Attenuation and scatter due to dust and other particulates, and
- Wavefront distortions due to turbulence with or without accompanying stratification.

These properties of the atmosphere vary with geographic location.

Atmosphere media effects are of two general types; long term variations where a time scale of "hours" is observed, and short term "transients" such as angels (drifting atmosphere refractive index anomalies and turbulence) would exhibit. Particulate and precipitation scatter would also be included in the latter category.

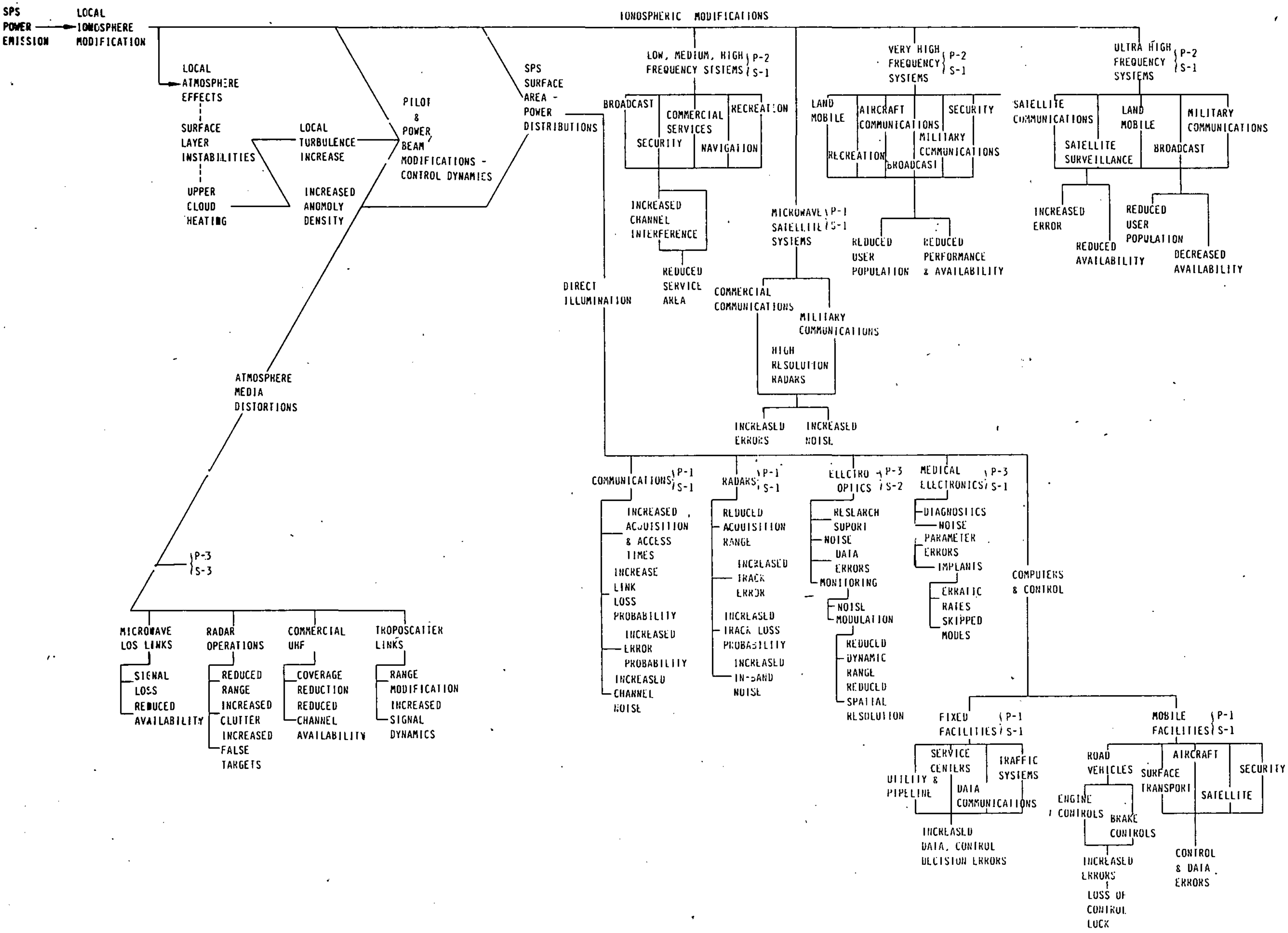

Fig. 4.2. Effects of the SPS MPTS on Electromagnetically Sensitive Systems

These categories represent different beam control response problems. Effect magnitudes and the statistical precessing of pilot beam parameters to extract atmosphere "signatures" must be carefully addressed in the pilot beam-array, control-loop design to positively minimize ambiguities and instability probabilities. These areas have important implications for future modular and subsystem laboratory testing.

Attenuation and scattering due to precipitation also reduces the amount of total power at the rectenna. This mechanism is generally proportional to rain rate and the problem varies with geographical location. Blowing dust or sand also contributes to beam power attenuation and scattering of energy away from the rectenna. Although each mechanism alone would have seemingly small effects stated as a percentage of main beam power or in dB power loss, because of the large power levels involved with SPS, the magnitude of power fluctuations due to these mechanisms may be unacceptable to the distribution system.

The pilot beam required for frequency/phase reference and orbital antenna control is also affected by these same atmospheric mechanisms. Under circumstances such as very heavy rain, severe sand storms, etc., any of these mechanisms could readily cause control-loop instabilities resulting in power beam wander and frequency fluctuations, which in turn adversely affect power transfer efficiency and greatly exaggerate the interference problems.

The above discussion addresses those mechanisms which cause degradation of received power at the rectenna and pilot carier modulation. Another major area of concern is the EMC problem. If no ionospheric or atmospheric effects were present, there would still be impact outside the rectenna area due to the power beam sidelobes, emission of harmonics of the primary frequency and spurious components, noise sidebands, and terrain reflections. The SPS emissions from these sources will cover the hemisphere (Ref. 4.1.6); however, EMC problems will most likely occur within 100 km radius of the rectenna where the power densities are highest.

Energy coupling to "victim" systems will involve in-channel and nonlinear responses by out-of-band components, relative to the primary receiver pass band, and coupling through cabling and circuit element apertures to other electronic circuiting. Different scoring procedures are required because of the wide variations in the latter in the characteristics of 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 metering applications. These define a range of performance characteristics, in terms of probability density functions for signal to interference ratios. Most of the EMC problems related to the SPS that represent a significant expenditure in victim equipment modification will be concerned with nonlinear response category.

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 surveillance and monitoring equipment required for military operations. Limited measurements will be required for the SPS problem to assure credibility in the predicted degradation and recommended functional modifications for these classes of equipment.

Additional EMC-related problems that will be addressed concern the infrared (IR) source and optical reflection characteristics of the SPS vehicle in temporary and permanent orbit locations. Functional impacts are anticipated for astronomy and space tracking/monitoring equipment because of the probable magnitudes of the emissions and reflections from the large orbiting platform.

4.1.4 State of Knowledge

Looking at the attenuation by the troposphere, it is expected on theoretical grounds that at a frequency of 2.45 GHz, radio waves suffer little attenuation, by the lower atmosphere of the earth. Gaseous absorption, due to both oxygen and water vapor absorption, is expected to contribute no more than about 0.1 dB, (Ref. 4.1.8) and rain absorption, no more than another 2 dB. This "worst case" total of 2.1 dB, although small, represents a loss of 38% of the originally transmitted power. On the average, one would expect about 0.02 dB of attenuation at a frequency of 2.45 GHz on a 30° elevation angle path to a satellite in a temperate climate characterized by a gaseous atmosphere with <u>no rain</u>. Even this, however, represents a 4.5% loss of power.

Clearly, annual variations in climate and temperature represent potential losses of several tens of millions of watt-years of energy during years of large excursions from mean conditions.

Scattering by refractive index fluctuations, termed "angel echoes" by radar meteorologists, are likely to be the most prevalent scatter effect at more arid SPS sites (Southwest U.S.). This is likely to be particularly true in view of the heating of the rectenna causing thermal instability in the layer of atmosphere directly over it.

A common appearance of these refractive-indexed-caused angel echoes is as a band or layer on a radar scope. Hence, they are often termed "turbulent layers."

In general, the systems most vulnerable to SPS emissions are those that operate in the vicinity of the main beam frequency and its harmonics. The main offenders would be:

Primary frequency	2.45 GHz
2nd harmonic	4.9 GHz
3rd harmonic	7.35 GHz
4th harmonic	9.8 GHz

Included in the band from 2.29-2.45 GHz are allocations to radio location and to space research. The radio location assignments have fairly strict Federal Communications Commission (FCC) requirements as far as radio interference is concerned. The amount of energy from SPS, possibly as far out as 200 km from the rectenna site, may exceed these FCC requirements (Ref. 4.1.10). The equipment itself could easily give erroneous information as to location due to this interference. The space research assignments are used for telemetry from missile tests, the space shuttle, space platform and other space related tests. These are vulnerable to SPS emissions because of high gain-directive antennas that will be looking skyward. Receiver sensitivity and bandwidth considerations indicate unacceptable "noise" effects for the space research class of energy receivers within 150 km of a rectenna site. Special filters could allow operation within about 100 km for the reduced bandwidth instrumentation where the band of interest was at least 100 MHz from the SPS frequency (primary and second harmonic). These interference effects apply to the radio astronomy band from 2.69-2.70 GHz.

From 2.45-2.69 GHz in addition to radio location, there are broadcasting satellite and fixed satellite assignments. Again, sensitive equipment would be vulnerable to SPS emission particularly for satellites in geosynchronous orbit since the receiving attennas would be oriented more-or-less towards the SPS.

From 2.7-5.0 GHz are assignments to aeronautical radio navigation, radio locations, maritime radio navigation, fixed satellite, radio astronomy, meteorological telemetry and other sensitive systems which again are subject to severe compatibility problems with SPS. Errors induced by SPS emissions into radio navigation systems can range from intermittent operation to limited position accuracy to total inability to determine position, depending on the type of system and the distance from SPS main beam. Most probably International Radio Consultative Committee (CCIR) and International Telecommunications Union (ITU) standards cannot be met for such systems within a 200-km radius of an SPS site.

Air traffic control communications, radar, and radio navigation aids have very strict interference regulation and standards. Because of safety sensitivities, all interference must be carefully controlled. At frequencies below about 1 GHz, and with receivers that are well designed, as are most FAA and aircraft receivers, degradation may not be serious until within 50 km of the rectenna site. Above 1 GHz serious problems may occur.

Surface communications within 100 km of the rectenna may be a problem unless very good receiver design is used. Many receivers will suffer from intermodulation problems at the millivolt-per-meter field intensities produced by SPS. For communications, noise and error effects will be serious for ultrahigh frequency (UHF) through microwave receivers. Surface resolution, degradation of target lock-on features, degradation guidance and control characteristics, etc. will be problems.

Tests are under way to determine the problems in a number of minicomputers and modular components. Previous experience indicates unacceptable control and data performance for large illumination levels without special shielding and grounding methods. Peripheral and processor modules have a similar range of responses for pulse and continuous wave illumination.

The medical electronics area has limited information for possible interference effects. A number of companies design equipment to operate in a field strength of 1 V/m. That would mean operations may be degraded within 60 km of the rectenna. Recent manufacturer data indicate that many of the latest pacemaker models would <u>not</u> be affected even by power densities anticipated near the rectenna. This information will be carefully reviewed and probably experimentally verified before final conclusions are published.

Degradation evaluation for many radar, communications, and control systems can be based on measurements and modeling of military and civil systems operating in collocation with high power radar, modulated continuous wave sources, or single frequency jammer equipment. Extrapolations for different coupling modes and nonlinear responses in the predetection and processing functions must be accommodated in this signal-interference scoring for SPS-induced degradation. Communications links and systems previously evaluated for collocated source degradation include analog and multiplexed digital configurations. Scoring of the latter is multifunctional because of the separate control, address, and data message components. Modification recommendations are affected by these functional sensitivities.

Imaging equipment degradation descriptors have been based on noise, detection threshold, and spatial resolution factors. Coupling is accomplished through detector (vidicon, semiconductor detector, multiplier tube), and associated control and signal circuitry usually physically located with the detector device.

4.1.5 Research Plan and Alternatives

Generally the EMC tasking involves application of propagation models describing the loss, scatter, and refractive properties of the atmosphere; and evaluating the CONUS electromagnetic receiver and other electronic equipment degraded because of SPS illumination. The electromagnetic compatibility implications of modified ionosphere regions (e.g., communications operating in the low through ultra high frequency spectrum) are discussed in Section 4.1.2.

Atmospheric propagation models have been developed to describe frequency dependent characteristics as listed in Table 4.1. The models relating these propagation and atmosphere characteristics must be modified to accommo-

Table 4.1. List of Propagation - Meteorology Parameters

Propagation Parameters	Meteorology Parameters
a. Attenuation	a. Temperature and pressure gradients
b. Rain, hail, particulate scatter	b. Humidity profiles
c. Refractive anomalies	c. Wind profiles
d. Refractive gradients	d. Turbulence properties
e. Terrain reflection	

date sensitivity analysis, particularly short-term power-beam scatter and refraction variations with local area meteorology. For a separate design support application, coherence properties will be provided so as to describe power density variations across the rectenna, and rectenna area terrain effects. This task involves no research; only organizational modification and meteorology parameter relationship definition. These modifications are included in the current EMC tasking.

Existing scoring models defining S/I functional degradation for various electromagnetic receivers and electro-optical (EO) devices will be selectively modified to accommodate continuous wave (CW), higher power illumination. This will involve extrapolation of current empirical models and additional simulation; limited sets of effects for a range of minicomputer, microprocessor, and control devices have been initiated. This task also involves no research, and is accommodated in the current EMC program.

From considerations of the EMC impact, two alternatives in SPS characteristics are to be noted. These concern modification of the transmission frequency from the current 2.45 GHz principal candidate and the potential for interference reduction through modulation of the power beam.

Frequency alternatives all relate to higher bands; 6 GHz through the 33 GHz regions. The EMC advantages primarily accrue in the regions above 10 GHz because of the reduced allocations and specific assignments in the military and civil sectors, and the predominant use of narrow beam antennas relative to electromagnetic systems in the lower spectral regions.

System performance would be impacted in varying degrees by operation at these higher frequencies, increased atmosphere attenuation, and scatter and refractive anomaly sensitivity. General expotential relationships prevail, with absorption windows available at discrete frequencies above 30 GHz. For the power ranges required for SPS, equipment development and operational uncertainties for the regions above 20 GHz presently are fundamental constraints. Planning for future operation at the higher end of this region would be dictated by the current system developments for the 10 GHz to 20 GHz region. The general allocation and assignment density in relation to the higher microwave spectral regions is shown in Fig. 4.3. One possible advantage to operation above 25-30 GHz is the probable efficiency and emission improvements attendant upon use of the gyrotron power amplifier.

For these higher frequencies, the system components would be physically smaller for parameters identical with 2.45 GHz operation (antenna array, rectenna). Control and operational stability problems would, however, be aggravated because of the increased atmospheric interactions.

Higher frequencies would also reduce the possible ionosphere beam distortion and parametric modification effects. Heating and dynamic perturbations would be negligible at frequencies higher than 30 GHz.

Lower frequencies cannot be considered because of the increased victim system densities within the continental United States. The increased

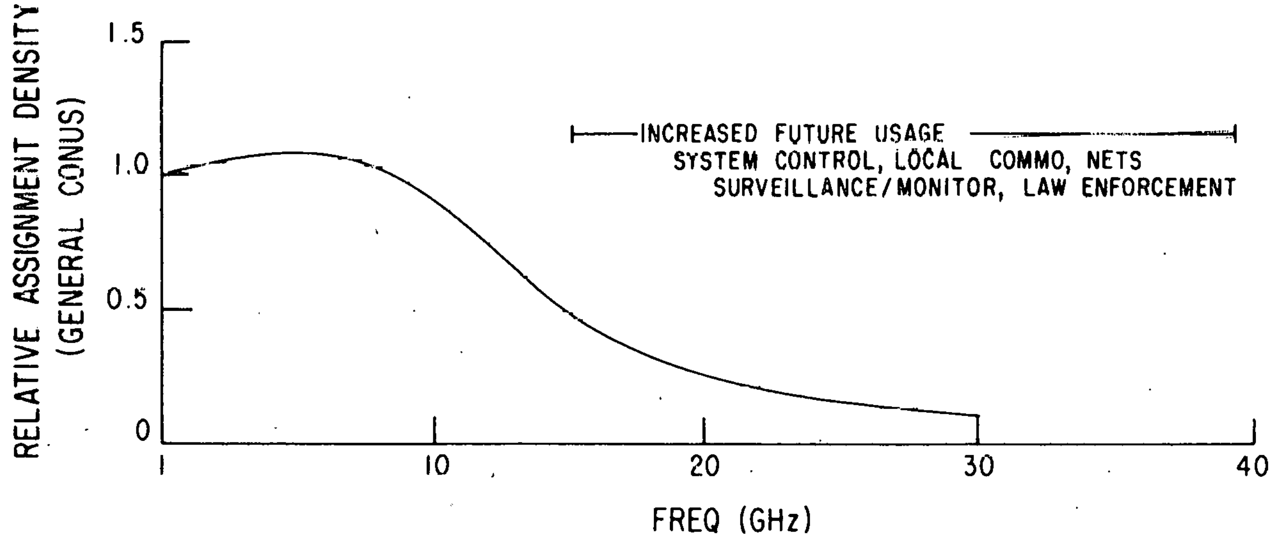

Fig. 4.3. General Spectrum Assignment Densities

interference would affect military and civil domains, and directly increase the susceptibility of VHF and sensor equipments because of circuit impedance and coupling aperture factors. Lower frequencies also represent higher ionospheric modification potential.

The present system configuration analyses emphasize the single frequency unmodulated mode. Modulation components will result from the noise characteristics of the frequency generation and power generation devices. Typical emission bandwidth displays for the primary, harmonic, and spurious frequencies for traveling-wave and crossed-field amplifiers have been presented in another section. As indicated elsewhere, one emphasis in amplifier tube design concerns the suppression of harmonic and spurious emission components to maximize usable power transfer and electromagnetic compatibility with other CONUS equipment operating in the higher microwave bands.

The single frequency mode with the very large output power of the SPS system causes various nonlinear responses from electromagnetically sensitive receivers (radars, communications) operated on the periphery of the rectenna sites as previously discussed. Since systems operating in these microwave regions are generally of wide bandwidth relative to the lower frequency voice or low rate analog operations, the effect of peak power is aggravated. From electromagnetic compatibility considerations, the advantages of increased bandwidth-lower peak power transmission modes for the SPS will be evaluated. Power delivery performance and control and media sensitivity aspects of the SPS will be addressed in these deliberations. Increased bandwidth introduces additional complexities in satellite array control, varying interactions with the troposphere and atmosphere relative to the frequency variation (e.g., selective fading), and also affects the efficiency of power conversion. Interference related factors include modulation sideband parameters, emission envelope distributions, spatial pattern stability, emission bandwidth, and peak-average amplitude ratios.

Two modes are being considered; noise modulation with a cosine spectral envelope, and linear chirp. Occupied bandwidth is one trade-off parameter; the minimum being the 50 MHz width of the industrial, scientific, and medical (ISM) band. Bandwidths in excess of this ISM band will obviously involve extensive reallocations becauseof existing government and nongovernment assignments. The EMC aspects and power system operational impact will be evaluated to support future decisions regarding SPS operational modes and additional allocation requirements during World Administrative Radio Conference (WARC) 79 and 80 proceedings. Interference-induced degradation analyses will include trade-off of bandwidth and modulation rates.

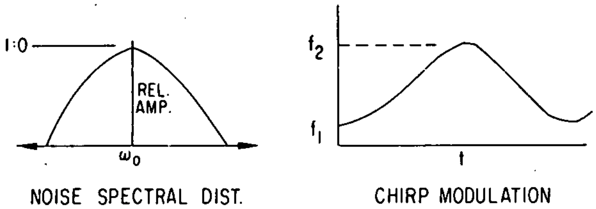

Fig. 4.4. Spectral Distribution for a Chirp Modulated Carrier

The noise modulated spectral distribution and chirp time modulation that will be examined are functionally indicated in Fig. 4.4.

The limited experience with radar systems having independent search and track modes, and time multiplexed communication links indicates the general trends in particular performance-S/I ratio characteristics for out-of-channel large interferer situations plotted in Fig. 4.5.

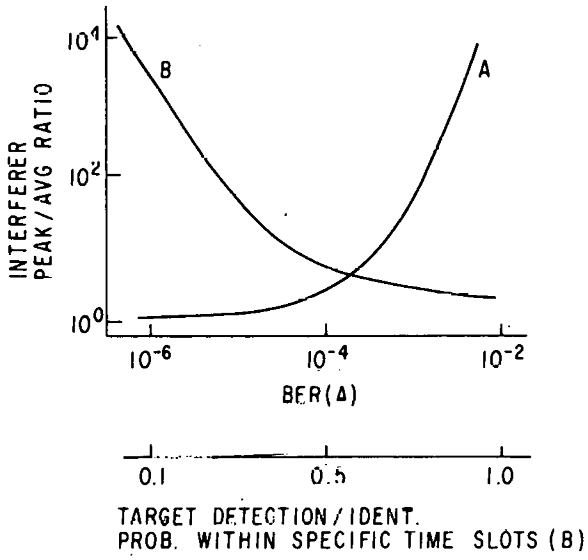

Fig. 4.5. Interferer Degradation Exemplary Trends

Relationships of similar form have been derived for communications synchronization delay and loss probabilities, and signal acquisition delays; and radar false target probabilities and tracking error distributions. For track-while-scan (TWS) radar systems (computer controlled phased array configurations), only performance predictions by computer modeling presently exist. A more complex functional scoring procedure is required because of the interdependencies of the detection, identification, and tracking functions; including the effects of the processing software.

Computer components and systems and electro-optical sensors are expected to have a degradation characteristic similar in form to that displayed for radars and communications receivers. Induced noise (band limited continuous and cross modulated periodic components), detection/identification thresholds and spatial discrimination (forms of modulation transfer function descriptors) will depend quantitatively on effective coupling apertures (frequency and mode dependencies), grounding circuit configurations, and aperture-circuit impedance relationships.

In the electro-optical area, the greatest imaging degradation because of illuminating high intensity microwave fields occurs with orthicon and similar multiplier type tubes. Spectrum spreading would provide the greatest improvement in noise and associated spatial responses since normal shielding and filtering could be employed.

An additional aspect of the SPS functional impact on EO systems concerns the infrared emission and spectral reflection properties of the orbiting power system satellites. Performance effects on astronomy and space tracking systems because of these "interferences" will be developed. For these systems, the total interference environment will include microwave power coupling and the cited emission and reflection sources.

If the initial electromagnetic compatibility analyses for these modulated formats indicates a significant reduction in induced degradation for the higher priority CONUS system categories with an emission bandwidth not in excess of the existing ISM band, the requirements for satellite transmission components will be submitted to NASA-Systems Definition to support a design trade-off study.

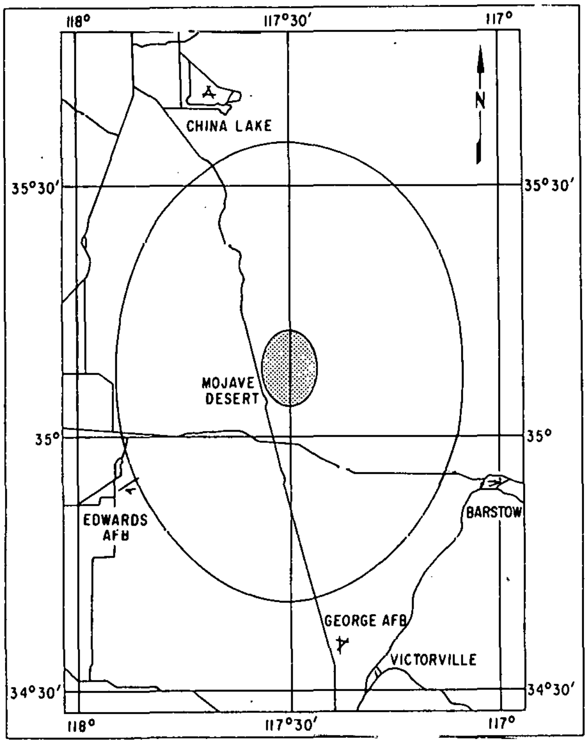

Fig. 4.6. Critical Mojave Rectenna Site

4.1.6 Preliminary Assessment

Candidate rectenna sites were identified by a previous NASA study (Ref. 4.1.4). Subsequent coordination with the NASA/MSFC Advanced Planning Office indicated an active study emphasizing the Mojave rectenna site. The initial EMC analysis exercise addressed this site so as to provide electromagnetic impact data to this site characteristic review, and contribute to the development of site selection criteria for NASA/DOE.

Figure 4.6 shows the Mojave site and the surrounding area which

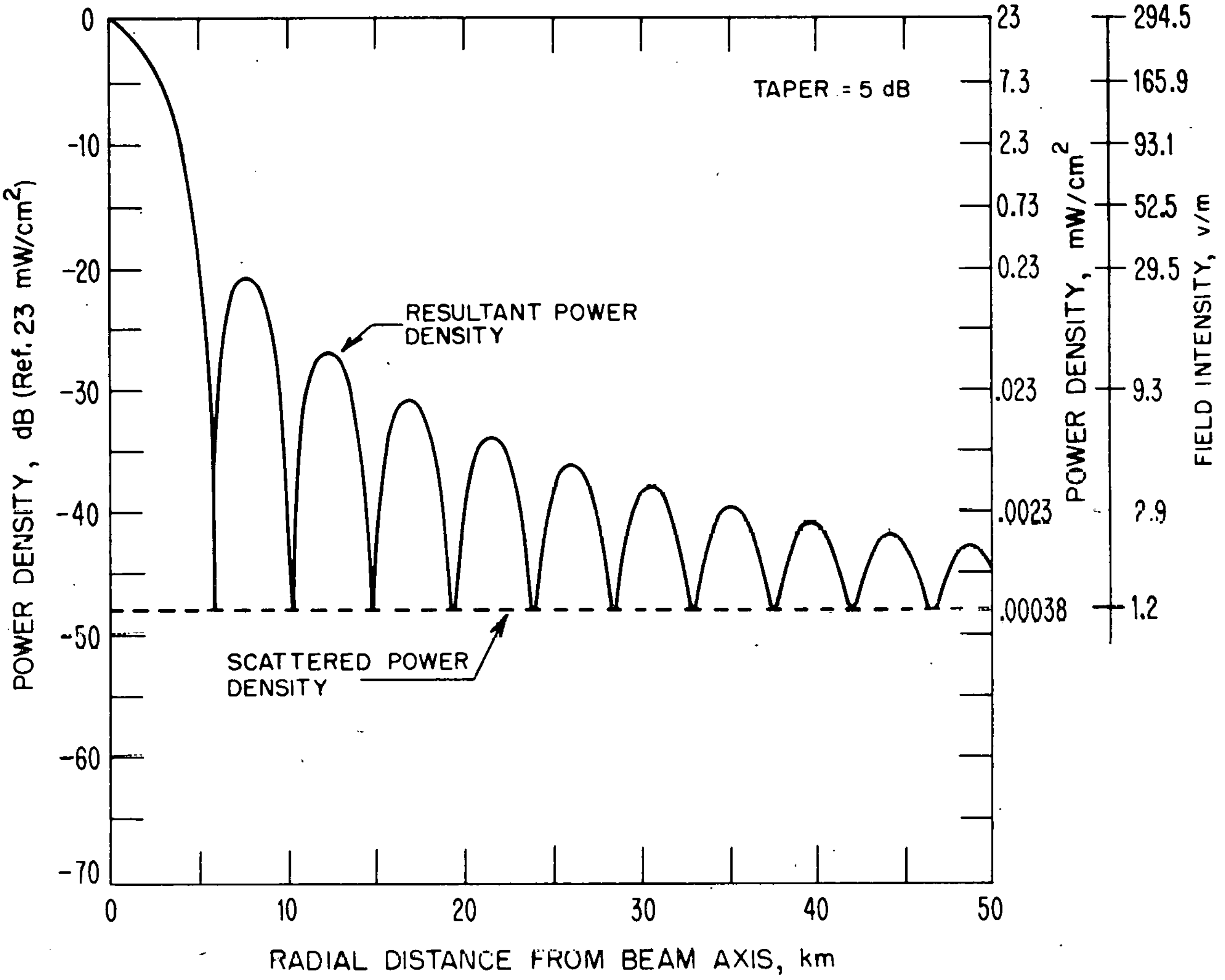

Fig. 4.7. SPS Transmitting Antenna Pattern

would be impacted by SPS emissions outside the rectenna enclosure. Figure 4.7 shows the main beam and sidelobe structure for the SPS using a 5 dB taper. Design literature for the SPS microwave power transmission system (MPTS) refers to the possible use of 5 dB, 10 dB, and 17 dB sidelobe tapers. The 5 dB taper was used for the studies here to allow worst case impact estimates.

The rectenna site is shown with center at 35° 8' North, 117° 30' West. The rectenna covers an area roughly 100 km^2. The outer elipse is roughly 49 km in radius and corresponds to the peak of the last sidelobe shown in Fig. 4.7. Generally, in dealing with communications systems, field intensities measured at an antenna are given in microvolts per meter (μV/m). For high power televisions or AM/FM broadcast stations, the field intensity beyond a mile, but within a few tens of miles, may be measured in millivolts per meter. Most likely for the average TV owner, the level of a field intensity measured at the home antenna would be in the microvolt per meter range. This will help to put the amount of energy beyond the rectenna site, due to sidelobe structure, in proper perspective.

Referring back to Fig. 4.7, the right-hand scale has two number values. One is power density in milliwatts per centimeter squared (mW/cm^2) and a corresponding scale is shown of field intensity in volts per meter which an antenna might see. If one were to connect the peaks of the sidelobes with a line, the result would be a curve which would approach the dashed line marked "scattered power density," asymptotically. It will be noticed that the field intensity beyond 50 km from the center of the rectenna site would still be 1 V/m at the 2.45 GHz frequency, representing a sizable input to communication systems operating within 100 km of the rectenna site.

Table 4.2. Selected Site Distances from Mojave Rectenna

SPS - China Lake Airstrip	64 km
SPS - Downtown Barstow	51 km
SPS - Edwards AFB Airstrip	43 km
SPS - Restricted Area R 2524	53 km
SPS - George AFB Airstrip	61 km

Table 4.3. SPS Incident Power At Mojave Sites

Site	Average Power Density	Field Intensity (mV/m)
China Lake Airstrip	1.21×10^{-7}	6.75
Downtown Barstow	1.91×10^{-7}	8.5
Edwards AFB Airstrip	2.69×10^{-7}	10.0
Restricted Area R 2524	1.77×10^{-7}	8.17
George AFB Airstrip	1.34×10^{-7}	7.1

Added to the electromagnetic field, due to sidelobes, is the power scattered from the main beam from media effects. Some preliminary assessments have been made at five sites surrounding the rectenna site in the Mojave. Those sites and the distance from the rectenna are given in Table 4.2.

Table 4.3 shows the predicted field intensity due to sandstorms occurring in the main beam. These results are for scattering by the largest possible common volume, that formed by the sandstorm and the SPS main beam, and would be considered worst case. A similar table was produced for duststorms which showed an insignificant amount of scatter.

Table 4.4. Atmosphere Anomaly - Turbulence Power Densities

Site	Power Density for 3 km Layer (mW/cm^2)	Field Intensity (mV/m)
China Lake Airstrip	6.78×10^{-9}	5.05
Downtown Barstow	1.07×10^{-8}	6.35
Edwards AFB Airstrip	1.50×10^{-8}	7.5
Restricted Area R 2524	9.87×10^{-9}	6.1
George AFB Airstrip	7.47×10^{-9}	5.3

Table 4.4 shows the predicted field intensity due to angel echo-turbulence scatter. This is computed for a layer 3-km thick extending from the surface, as an estimate of extreme conditions. Isotropic scatter is assumed. Other atmospheric scattering and multipath mechanisms include:

- Rain,
- Melting hail,
- Atmospheric layers (multipath), and
- Atmospheric aerosols.

In addition, energy will scattered by the terrain and by the rectenna itself. These latter two, however, will be primarily diffuse multipath, with little specular component at the angle of arrival ($R_{US} = 49.2°$) of the SPS energy. For this Mojave analysis, this component is not included. Diffuse reflection could not be neglected in higher conductivity and vegetated CONUS areas. Rain and hail would be serious problems if the rectenna were located someplace other than the California desert.

Bakersfield, California, is used as representative of rainfall to be found in the SPS receiving site vicinity (although it is still a considerable distance away and somewhat lower in elevation). Bakersfield receives a rain 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 incurs 19.3 mm/hr of rain rate, and incurs 47.2 mm/hr at the one-out-of-200 year extreme for five minutes of that year. Based on the work of Dutton (Ref. 4.1.11), the height of a storm that will produce the aforementioned rain rates at the earth's surface can be predicted.

The results are shown in Table 4.5 based on Bakersfield data, for average conditions, and in Table 4.6 for extreme, 99.5% confidence (one year out of 200), conditions.

Melting hail is usually present in every thunderstorm, convective type situation, to which the Bakersfield numbers used in Tables 4.5 and 4.6 pertain. Melting hail, however, because of the sparsity of the number of hail particles compared to the number of raindrops in a given volume of atmosphere, is expected to give results two or three orders of magnitude lower than the results of Tables 4.5 and 4.6.

Table 4.5. Scatter Power Densities - Average Rain Conditions

	Power Density (mW/cm^2)		Field Intensity (mV/m)	
Site	1 hr/yr	5 min/yr	1 hr/yr	5 min/yr
China Lake Airstrip	5.27×10^{-7}	2.07×10^{-6}	44.6	88.3
Downtown Barstow	8.30×10^{-7}	3.25×10^{-6}	55.9	110.7
Edwards AFB Airstrip	1.17×10^{-7}	4.58×10^{-6}	21.0	131.4
Restricted Area R 2524	7.69×10^{-7}	3.01×10^{-6}	53.8	106.5
George AFB Airstrip	5.80×10^{-7}	2.27×10^{-6}	46.8	92.5

Table 4.6. Scatter Power Densities - Extreme Rain Conditions

	Power Density (mW/cm^2)		Field Intensity (mV/m)	
Site	1 hr/yr	5 min/yr	1 hr/yr	5 min/yr
China Lake Airstrip	1.70×10^{-6}	1.05×10^{-5}	80	199
Downtown Barstow	2.67×10^{-6}	1.66×10^{-5}	100	250
Edwards AFB Airstrip	3.76×10^{-6}	2.33×10^{-5}	119	296
Restricted Area R 2524	2.48×10^{-6}	1.53×10^{-5}	97	240
George AFB Airstrip	1.87×10^{-6}	1.15×10^{-5}	84	208

The effects of trapping and multipathing by atmospheric layers will be inconsequential because the angle of arrival of the energy, $\theta_{os} = 49.2°$, is much larger than the critical angle for layer trapping.

Atmospheric aerosols consist of diminutive particles roughly 0.1μ in diameter. At that size, the scattering impact is even less than that for the duststorm scattering.

It can be seen that the amount of potential EM energy from all forms of scatter, including that from the rectenna itself (not yet calculated), added to the power from the sidelobes, presents a formidable problem 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 our data sample area. All government and nongovernment EM systems operating within this geographic boundary between 75 MHz and 5 GHz were tabulated. The active files showed 813 government systems and 685 civilian authorizations operational within these boundaries (N 1500 allocations).

For purposes of this initial environmental assessment, the equipment/ system categories identified in the file retrieval are as listed:

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 nets.
    - 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 equipment - 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 (law enforcement, management).
   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.

These system categories are in the frequency range cited for the file retrieval and are susceptible to SPS power densities previously displayed.

The quantitive functional degradation induced into particular major equipment categories deployed near the candidate Mojave site is indicated in Table 4.7. The derivatives of these performance factors are presented in the Mojave evaluation report.* Those functional systems included represent high priority operations that encompass relatively large geographic areas around the periphery of the rectenna site. The percentages indicate the characteristic changes for the various systems because of SPS illumination.

Various railroad, law enforcement, and emergency communication services will be incorporated into the functional categories as soon as degradation analysis is completed. The equipment presently uses very high frequency (VHF) and UHF analog voice or low data rate modes, and will therefore be minimally affected. Relays and base stations for these services could be readily modified where necessary by shielding and antenna pattern adjustments. Common carrier links will also be scored for future assessment analysis. These will include relays and mode stations.

The elements of performance degradation cited for the functional systems represent average overall operating modes and geographic range. For example, instrumentation radar systems detection and tracking performance includes operation over a full hemisphere coverage, and the range of cross section magnitudes for military target vehicles (e.g., tactical fighter

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*SPS EMC Evaluation - Mojave Rectenna Site, DOE report (to be published).

Table 4.7. Induced Functional-Degradation Summary - 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%)

and reconnaissance aircraft, target drones). Track score variations include low elevation angle modes, where the accuracy degradation and loss of lock probabilities expand by greater margins because of propagation factors. On-axis radar configurations are also represented, since this mode probably will be increasingly employed for these test range applications. The track error scores include normal smoothing, prediction filtering, and coordinate computations in real time and postmission processing software.

The communications system degradation cited includes single channel, and frequency and time multiplexed units operated by the military test ranges, the State of California, local county and municipal governments, and resource control and service industries.

This section relates the previously discussed performance degradation to operational compromises of the military instrumentation and systems employed in operational testing at China Lake, George Air Force Base, Edwards Air Force Base, and the Echo Range; and the command/control and other communications facilities associated with the resource management operations by utilities and municipal/county governments. The operational relationships must be discussed so as to demonstrate the effects upon national resources and major economic areas of the SPS-induced performance degradation, and the specific effects upon the major military operations in the Majove area because of the large power density illumination by the SPS source. These operational compromises and the specific areas of functional degradation will be expanded to provide the basis for subsequent recommendations in equipment and system operations to assure an acceptable level of performance when illuminated by this high power source.

For this Mojave site and others having a similar operational military/civil system ratio, modification recommendations will emphasize the civilian area. Support equipment (e.g., radar, telemetry, television, etc.) can be modified for operation within a range of 40-50 km from the rectenna site, assuming no media-induced instabilities in the SPS array control. Military operational EM systems cannot be modified because of the unacceptable probability of operational compromise; system performance or procedures in the test and evaluation exercises would have either little or a deceptive relation to combat operations.

4.1.6.1 Range Instrumentation

This equipment category includes the numerous types of radar and associated TV camera equipment employed for spatial position and orientation tracking at China Lake, Edwards AFB, and ECHO Range. The radar systems provide the basic tracking of airborne vehicles operating to test equipment effectiveness; including interaction in simulated engagement with surface defense units. The ones identified in the previous section include units that are slaved through command/ control networks for target acquisition and "hand-over" to cover large area flight operations. Telemetry data received from them includes rectangular spatial position coordinates, rectangular coordinate velocity data, and signal characteristics that are employed for diagnostics. These instrumentation radars must satisfy an accuracy requirement of 1.5-5.0 meters in position for elevation angles above 15°, and 5-15 meters for the lower elevation angle tracking modes. Where increased accuracy in lower angles is required the video records can be employed with the radar range and coordinate data to improve resolution. Video processing requires a two-station solution for this application. Previous accuracy requirements are based upon the use in the processing cycle of normal smoothing and predictive filtering processes.

As indicated previously the primary effects of the SPS power densities predicted for China Lake, Edwards AFB, and ECHO range cause increased noise in the predetection components of the receivers, reductions in target acquisition range, and increased data error during track. Considering the deployment of radars on these facilities, an increased gap in coverage would result because of the reduced detection range. These comments are also applicable to the TV cameras at Edwards AFB; primarily because problems in the TV detector would be reduced by a factor of 2-3 in particular cameras used at China Lake.

This tracking instrumentation must operate over an entire hemisphere to effectively support the operational exercises at these facilities. The SPS effect would be reduced if elevation were limited to approximately 50°, but this limit represents an impossible compromise for the military exercises.

The representative instrumentation time line for a normal test involving one or more aircraft includes premission calibration and coordinate slaving, acquisition command cycles, track confirmation, track, event tagging, and hand-over events. This time line indicates the general chronology of the radar and video equipment acquisition and track cycles. The interaction with command/ control networks is indicated in relation to the initiation of different modes. Typical effects of the SPS-induced degradation include uncertainties and delays in acquisition and additional communications activity necessary from the command/control network for instrumentation control and slaving data flow control, and hand-over. Increased gaps in radar coverage and data errors are certain to arise.

The primary effects, as noted, relate to signal acquisition and data error rates. These translate into operational problems in greatly increased activity through the data network because of synchronization and error effects.

The combination of error problems and increase in range net activity would reduce the capability to support simultaneous missions. It is particularly important to consider this apsect in engagement evaluation where numerous remote-controlled facilities may be involved and delays in communication events would represent an unacceptable experimental bias. Since such engagements generally involve event-related decision trees, the validity of most multiple vehicle experiments would be unacceptable. These comments are qualitatively correct on the basis of the deployment of command/control and instrumentation equipment, the magnitude of the SPS interference, and previous histories at other test ranges where an EMC situation caused similar compromises in instrumentation and network performance.

4.1.6.2 Operational Systems

The China Lake range generally evaluates weapons systems performance and operational engagements. The latter includes, for example, delivering of ordnance on the collection of surveillance data in the presence of a simulated hostile environment. These tests, therefore, are very dependent upon the EM support systems such as radar, command/control, and sensors. Considering the frequency range of military operational equipment employed for tactical aircraft, and the aperture of electro-optical devices supporting tactical emissions, the SPS power densities would eliminate effective testing except for very short ranges of deployment. Modifications to tactical equipment to accommodate the SPS are not possible because of the compromises and biases.

A representative surveillance and weapons delivery time line includes egress route command/control, reference point identification, entry maneuvers with radar and EW-scanner operations, penetration command/control, target entry communications, sensor search and track, weapons control or surveillance search operations, and regress communications. For multiple aircraft, for example, the previously cited command/control network activity increase represents severe constraints on the number of vehicles that can be supported and significantly increases the potential for missed events and thus destroys mission credibility.

The ECHO Range has the principal purpose of evaluating proposed EM penetration support equipment and procedures, and providing operational training and doctrine testing for tactical air force penetration against hostile air defense systems. Replicated environments are generated that interact with penetrating EM systems and control maneuvers and equipment operation for the testing and training purposes indicated. Time line critical events include signal detection, signal source recognition and mode analysis, and counteractive interaction events. The capability to detect specific signal characteristic changes is fundamental to the self-screening or standoff operations by penetrating aircraft.

The facility includes an operational monitoring capability to score all events relating to the survivability of penetrating air craft, and the "kills" for ordnance delivery and air defense actions. Facility operations would also be impeded in range of coverage and event recognition because of the SPS power densities.

The initial site analysis will present functional-operational time lines, with SPS induced functional and associated operational event compromises for mission envelopes. Geographic sensitivities will be indicated to support rectenna site modification recommendations.

4.1.7 Conclusions and Recommendations

The preliminary assessment of SPS microwave emissions on victim systems as given here demonstrates the operational degradation that would occur to electronic systems in the SPS-generated environment within approximately 100 km of the rectenna site. The Mojave site evaluation shows a wide range of performance degradation, particularly in those systems operated by the military. The basic functional and operational impacts of SPS are of such magnitude that in many instances they represent unacceptable or impossible compromises and biases to proper test and evaluation exercises performed by the involved facilities.

As mentioned previously, the evaluation of the Mojave candidate rectenna site provided impact data to NASA and contributed to establishing site selection and evaluation criteria, and allowed a limited exercise of the data retrieval and analysis procedures required for the EMC analysis of all candidate sites in the continental U.S. This Mojave site originally considered by NASA allowed a reasonable rectenna isolation from areas of even modest population density, but presents serious interference impacts upon surface and aircraft electronic systems. At this site, military operations represent the majority of the interference problems; the degraded systems being 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 degradations near the Mojave site and the inability to establish mitigating strategies without unacceptable probability of operational compromise, a second site north and east of the original site was proposed by the Institute for Telecommunication Sciences (ITS). A cursory look at the victim systems surrounding the new site indicates different functional classes that lend themselves to mitigating strategies. Modifications to most of the equipment could be accomplished to produce compatibility in the SPS-generated environment.

The functional degradation of military, nondefense government, and commercial systems in the Mojave area is basically characteristic of the effects that will be encountered in other areas in the continental U.S. Operational implications and therefore the associated economic impact will vary significantly because of the differing organizations and systems supported by the degraded equipment. Operational-functional relationships will exhibit differing sensitivities.

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, if not impossible, due to population density, terrain features, victim system density, etc.

Generally the northern and eastern CONUS regions will have a smaller military-nondefense equipment concentration in the rectenna areas than the original Mojave site reviewed. These regions will also include major transportation and commercial communications facilities. Because of the population and business densities, the total number of affected systems in the various operational categories will be larger.

A valid demonstration of rectenna site EMC analysis and impact evaluation has been developed. This project, shown to be fundamental in making site selections, will help determine system performance impacts, and help develop mitigating strategies for victim systems. It is recommended that several site evaluations in various geographical locations, particularly in northern and eastern CONUS regions, be carried out to establish a data base to be used in setting site selection criteria and geographically oriented mitigating strategies.

4.1.8 Reference Documents

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4.2 IONOSPHERIC HEATING AND LAUNCH VEHICLE EFFLUENT EFFECTS

4.2.1 Background

The ionosphere can be defined as that region of the earth's environment in which charged particles -- electrons and ions -- exist in sufficient abundance to have profound impacts on the chemical and physical mechanisms responsible for the formation and changes in the atmospheric structure. A graphic representation of the ionosphere is given in Fig. 4.8. In deference to historical development, the ionosphere is usually designated according to specific regions, D, E and F; each region being successively higher in altitude and usually greater in electron density. With the advent of the satellite era, the topside ionosphere, or the electron density above the F region, has become of importance, with no definite upper bound for altitude given.

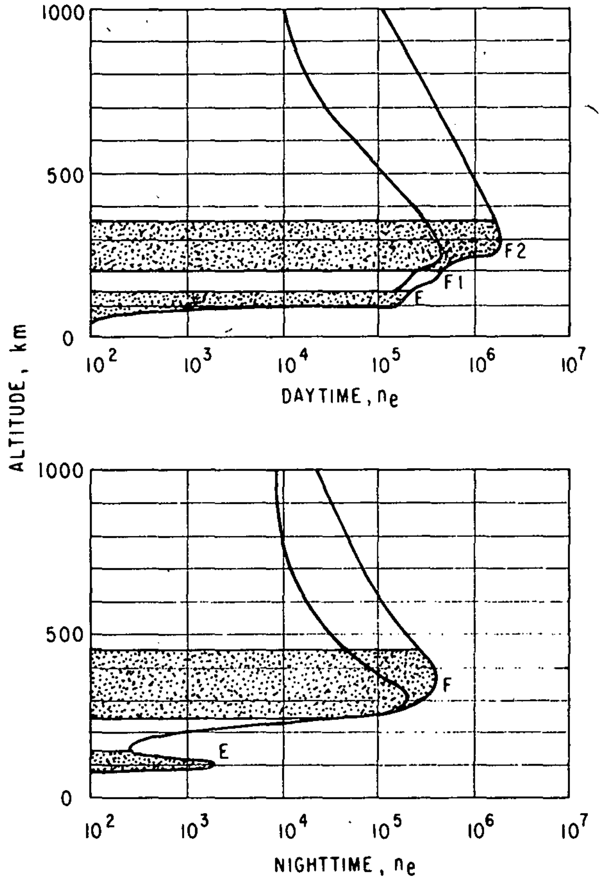

Fig. 4.8. Ionospheric Charge Density Distributions

All regions of the ionosphere display variations according to diurnal, seasonal, and solar cycle periods. In addition, geophysical disturbances associated ultimately with solar variations give rise to significant changes in the structure of the ionosphere. The ionsophere is at best a dynamic medium varying on time scales from a few seconds to tens of years.

Because of the presence of free electrons, the ionosphere causes electromagnetic energy that is sent into it to be refracted and slowed down.

The amount of refraction depends directly on the ionospheric electron density and is a function of the frequency of the electromagnetic wave sent into the ionosphere, the electron collision frequencies, 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 in fact permits long distance high frequency radio 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. Thus the waves arrive at reception points with travel times that are larger in the presence of the ionosphere. The travel time is related to the total number of electrons encountered along the propagation path.

Changes in the ionosphere, whether due to natural or artificial causes, give rise to changes in the performance of electromagnetic sensitive systems (i.e., telecommunication systems) whose energy is propagated within and through the ionosphere. Any change in the ionosphere potentially can change the performance of an ionosphere-dependent telecommunication system. 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 region. This could result in loss of information associated with changes in amplitude and phase of the radio wave.

The purpose of this section is to describe the impact of potential changes in the ionosphere that will result from the operation of the satellite power system microwave power transmitting system. These changes can evolve directly from heating of the ionsophere by the SPS power beam and also indirectly from the effluent material associated with the launch vehicles needed to place an operational SPS into geostationary orbit.

4.2.2 Methodology

4.2.2.1 Ionosphere Heating

Because of the large amount of power transmitted (greater than 5 GW) to the earth that is associated with each SPS, it is possible that substantial modification of the earth's ionosphere will result from direct heating of the ionosphere. If, in fact, this turns out to be the case, then telecommunications systems which transmit radio energy within and through the ionosphere may be severely affected and suffer possible performance degradation. Thus, it is necessary to assess accurately the potential for ionosphere modification resulting from SPS operation. Specific questions that must be answered are:

- Is the SPS transmission sufficient to cause harmful interference to telecommunication systems?
- Is the SPS transmission likely to give rise to interference effects that are not permissible by CCIR standards?
- Will the SPS power-beam transmission cause deterioration to the SPS pilot-beam transmission?

The results that follow from any effort to address these issues must provide quantitative information concerning effects on telecommunication systems caused by SPS-induced ionospheric modification.

In Table 4.8 are listed selected telecommunications systems that could be adversely affected by ionospheric changes associated with SPS operation. These systems are provided only as an example of the type of changes that could occur, as the table is not meant to be all inclusive. It must be pointed out, however, that not all potential telecommunications impacts will be adverse. As mentioned, frequencies above HF are propagated through the ionosphere with speed less than that of 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.

4.2.2.2 Vehicle Effluent Effects

The large launch vehicles and frequent surface-launch and near-earth orbit maneuver operations postulated to establish and maintain the SPS systems indicate a significant potential for transitory modification of regions of the ionosphere and magnetosphere because of effluent discharges. For SPS, the discharge rates and consequent ionospheric effects could exceed the F-layer density reductions noted following the Skylab launch.

The limited data available from this previous launch indicate that the exhaust from heavy lift launch vehicle (HLLV) engines would cause large depletion areas in the ionospheric F-layer. Recombination and stabilization periods could extend for several hours, impacting communications systems that

Table 4.8. Potential Systems Impact of SPS Operation

Telecommunication Systems Affected	Ionospheric Phenomenology	Possible Effect	Unresolved Questions
• HF Communications	Absorption	• Signal Loss for HF Communications	• Geographical Size and Magnitude
• Omega	Phase Change	• Modify VLF Signals Used for Navigation	• Location of Effect with Respect to Loran XMTR Locations
• Loran • AM Broadcast			
• HF Communications • Power Beam	Ionospheric Depletion (F-Region)	• Limit Frequency Window for HF Communications	• Geographical Size and Magnitude
• CB, HAM, Military Aeronautical Comm.		• Displacement of Power Beam	• Effect of Continuous Heating
• T.V. (VHF & UHF)	Ionospheric Irregularities	• Scatters Energy Propagating through Region	• Non-Linear Effects - Does it occur at 2.45 GHz
• Pilot Beam • Communications Satellite	Large Scale and Small Scale		- Function of power density
• Satellite Navigation (GPS)	(E&F Region)		• Lifetime and Geographical Distribution
• Radars (Spacetrak, Surveillance)	Travelling Waves	• Scatters Energy	• Over What Distances Do They Travel
• Radio Astronomy	(F-Region)	• Variations in Radar Target Location	
• All Telecom Systems	Ionospheric Induced RFI Harmonic Generation	• Increased Interference for Other Users	• Does it Occur?

rely upon upper region densities. This effect could extend over a 1000-2000 km region around the launch area depending on the actual launch trajectory.

The indicated communications impact would involve many of the same systems indicated in Table 4.8, such as commercial, recreation, and security services. Density variation predictions that imply depletion of the F-layer and the vehicle launch frequency of possibly one per day over a several month period to establish operating power stations could result in several reduced or nonexistent ionosphere channels for the middle and upper frequency operations in the HF spectral regions.

To make an assessment of this impact it will be necessary to utilize the theoretical information which will be obtained by studies such as discussed in Appendix 3B to make initial estimates of effects. The initial estimates will then be verified subsequently, observing effects of future launches of the space shuttle on telecommunications systems.

4.2.3 Cause and Effect Relationships

Cause and effect relationships are shown graphically in Fig. 4.9. One cause of ionospheric modification that may result from SPS operation is the large amount of energy that will pass through the ionosphere. Although a very small fraction of the energy will be absorbed, the energy densities presently associated with SPS passage (15-25 mW/cm^2) may be sufficient to give rise to 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.

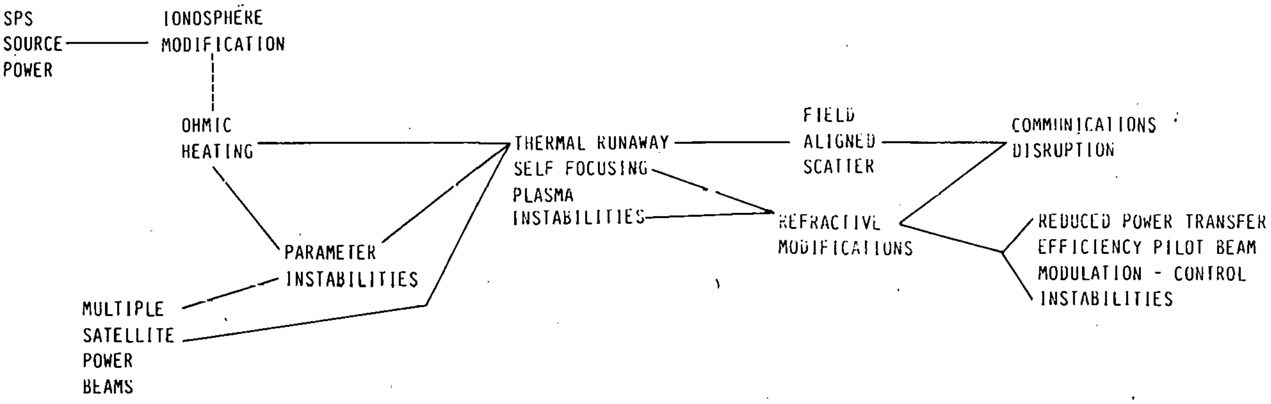

Fig. 4.9. Effect of the SPS MPTS on Ionosphere and its Consequences

- Thermal Runaway -- ionospheric heating at a rate faster than normal cooling resulting in an increased electron temperature at D-region heights (80-100 km).
- Plasma Striations -- formations of irregularities in electron density along magnetic field lines.

Other causes may be:

- Effluent from the heavy lift launch vehicles needed to construct the SPS which could result in significant depletion of the ionization density in the ionosphere. Such a depletion would have adverse effects on low and high frequency systems.
- Multiple power beams could give rise to gravity waves in the neutral atmosphere causing substantial changes in the ionosphere.

4.2.3.1 Ionosphere Heating

All of the SPS ionosphere/microwave interactions currently thought to be important are at least initially driven by ohmic heating. Ohmic heating of the ionospheric plasma and the resultant thermal forces may drive secondary phenomena such as an electron thermal runaway or thermal self-focusing of the microwave beam. These interactions do not necessarily scale linearly with their driving force (ohmic heating) and may occur on microscopic or macroscopic plasma-scale sizes.

Microwave radiation propagating through the ionosphere is collisionally damped by free electrons. Although the fraction of wave energy absorbed by the plasma is expected to be small, because this absorbed energy goes directly into the free electrons whose effective heat capacity is very small, the resulting ohmic heating can significantly affect the local ionospheric thermal budget.

Ohmic heating of the lower ionosphere by the SPS microwave beam increases the local electron kinetic temperature, which in turn increases the electron-neutral collision frequency but decreases the electron cooling rate.

Although collisions may prevent the formation of field-aligned irregularities in the lower ionosphere, plasma striations are a potential source of serious communications effects. In addition, strong local plasma heating frequently results in plasma turbulence, which contributes to scintillations of ground-to-satellite signals, including the uplink pilot beam. These striations can result from the self-focusing instability.

4.2.3.2 Vehicle Effluent Effects

The details of the changes in the ionosphere resulting from launch vehicle effluents have been provided in Section 3 and need not be repeated here.

4.2.4 State of Knowledge

4.2.4.1 Ionosphere Heating

Considerable knowledge exists concerning the effects of large amounts of heating on the ionosphere. Most of the theoretical and experimental work has been directed to the "overdense case," i.e., the case where the ionospheric density is sufficient to reflect the incident heating frequency.

The modification of the ionosphere caused by intense heating resulting from the transmission of electromagnetic energy has been confined primarily to heating using frequencies below 2 MHz. In fact, hardly any experiments have been performed that attempt to heat the ionosphere at frequencies greater than HF. Likewise, most of the theoretical work undertaken has been directed toward the response of the ionosphere to high-powered HF radio waves that are reflected from the ionosphere. Thus, in order to arrive at this preliminary assessment, it has been necessary to rely heavily on theoretical extrapolation of results (Ref. 4.2.7) obtained from HF heating to frequencies corresponding to the satellite power system operation.

The overdense heating experiments conducted at Platteville and Arecibo are well-documented in the literature. Both theory and experimental data are being investigated in order to resolve differences between observation and prediction. Very little has been done in the area of underdense heating from an experimental point of view.

4.2.4.2 Vehicle Effluent Effects

Current information regarding effluent effects on ionosphere characteristics 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 instrumentation producing the data. No information is available regarding transport processes in excitation or restabilization events.

4.2.5 Research Plans and Alternatives

4.2.5.1 Ionosphere Heating

In order to fully understand and predict the impact of SPS operation on the ionosphere (and magnetosphere), a coordinated program of theoretical, experimental and laboratory work must be undertaken. The experimental work will be concentrated around the Arecibo heating facility in order to assess the physical mechanisms giving rise to the creation of ionospheric irregularities and around the Platteville heating facility in order to properly assess the impact on telecommunication system performance.

The use of these facilities to simulate SPS effects relies on the fact that the rate of energy input to the ionosphere by ohmic (underdense) heating is inversely proportional to the square of the heating frequency. It is possible to utilize existing facilities such as Arecibo and Platteville to simulate SPS heating of the ionosphere in the D and E region. This simulation can be done at HF and the results extrapolated to the SPS operational frequency, subject to the condition that the heating is truly ohmic. For the F region simulations, modified and expanded facilities are needed in order to deliver the appropriate energy density to F region altitudes. These studies must be supported by detailed theoretical efforts devoted to establishing physically realistic models of the ionosphere/microwave interactions that can be used to provide sound extrapolation.

Tables 4B.1 through 4B.5, given in Appendix 4B, provide a listing of specific tasks that form the overall program of research and exploratory development geared toward assessing the effect of the SPS operation on the ionosphere and ionospheric dependent telecommunications systems. Details of this effort are given in Ref. 4.2.14. This program is broken down into five work areas:

- Simulation of telecommunications effects resulting from SPS operation
- Experimental studies of the physics of ionospheric heating
- Studies of the theory of ionospheric heating
- SPS impact on the pilot and power beams
- Development of advanced ground-based heater facilities

The efforts to be undertaken in these areas form a coordinated and cohesive program of providing the necessary data to determine the environmental impact of the operation of a microwave power transmission system on the ionosphere.

4.2.5.2 Vehicle Effluent Effects

The data to be developed by the atmosphere sciences tasks for the SPS concept study (see Section 3), including two dimensional modeling and subsequent testing during launches of large vehicles, will provide usable temporal and spatial transient and stabilization information for initial assessment of the communications degradation. A limited communications and sounder testing exercise is being planned during the shuttle launches to specifically measure F-layer depletion and stabilization transients (temporal and spatial) and confirm anticipated HF communications link reductions in availability. The possible utilization of existing OTH radar facilities to assist in tracking depleted volume characteristics will be investigated.

4.2.6 Preliminary Assessment

4.2.6.1 Ionosphere Heating

An initial experiment designed to produce and observe electron thermal runaway in the lower ionosphere was conducted at the Arecibo Observatory from June 4-13, 1978. The 430 MHz incoherent scatter radar was used both as a heater and as a diagnostic. 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 18 W/m^2 within a 300-meter beam at 100-km altitude. When the freqency is scaled to that of the solar power satellite, the

18 W/m^2 corresponds to a power flux of 58 mW/cm^2 at 2.45 GHz. This is well above the theoretically predicted threshold for an electron thermal runaway. Early predictions indicated limiting electron temperatures of nearly 2000K at altitudes below 100 km, 400 K at 110 km, and ambient (≃230 K) at 120 km and above.

The experimental results reported by L.M. Duncan (Ref. 4.2.13) show increases in temperatures that are less than predicted by theory. Temperature increases of 150-250 K above ambient were observed in the altitude range from 88 to 100 km (see Fig. 4.10) whereas theoretical considerations predicted increases on the order of 500 to 1000 K. The heating above 100 km fell off with height as predicted by theory, returning to ambient at approximately 120 km. Qualitative comparison of the measured heating and cooling time constants shows reasonable agreement with the theoretical expectations.

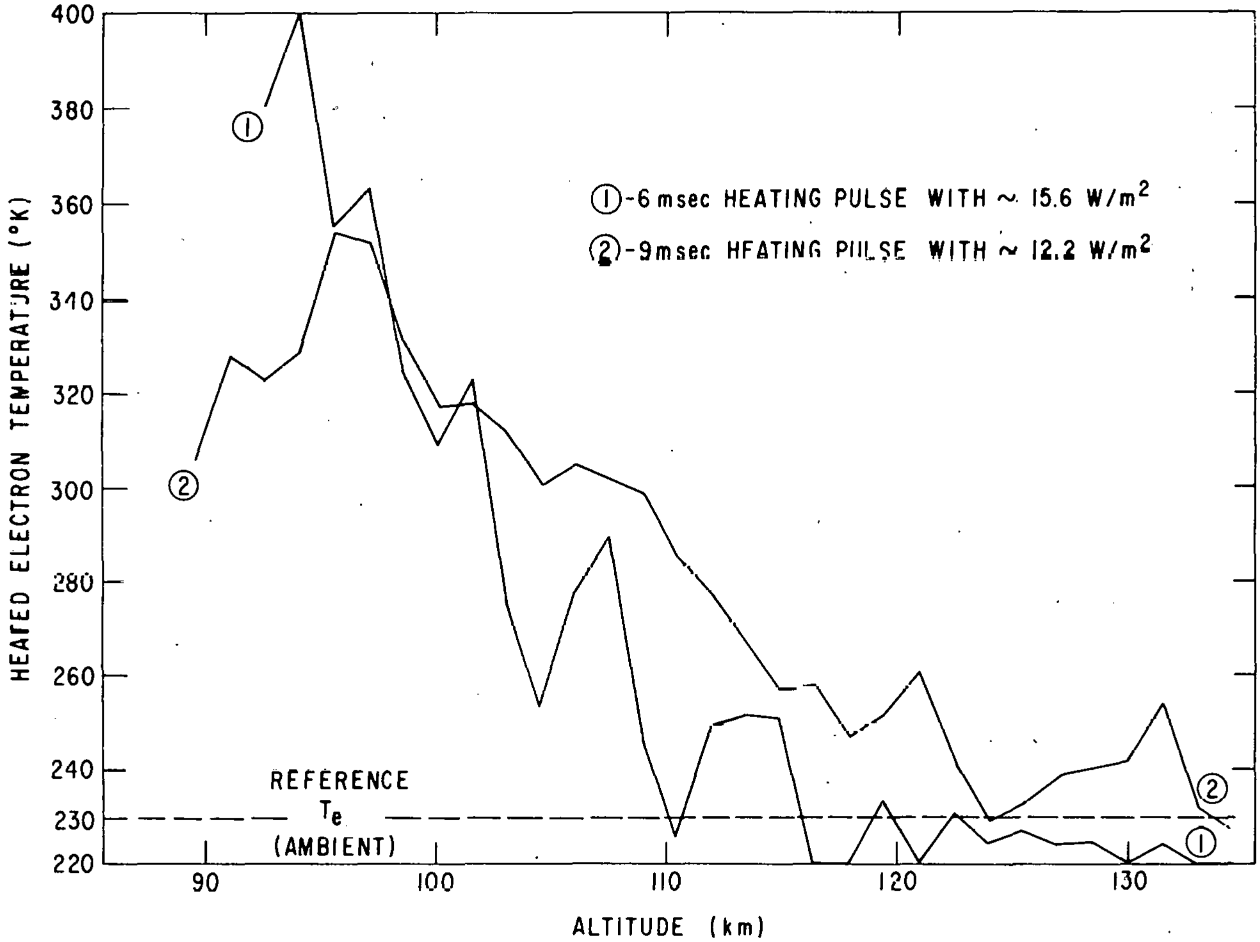

Fig. 4.10. Results of July 12, 1978, Ionospheric Heating Experiment at Arecibo Observatory

This experiment was not capable of generating any effects which might accompany continuous heating of the lower ionosphere. The discrepancy between experimental results and theoretical predictions indicates that the physical mechanisms of ionospheric heating and cooling need to be studied in greater detail. Areas for further research needed to understand ionospheric heating as it applies to SPS include: study of the role of nonMaxwellian electron energy distributions in ohmic heating, electron cooling interactions, and incoherent scatter interpretation, consideration of the role of thermal conduction within small beams (or on edges of large beams) in the collision-dominated lower ionosphere; a search for additional cooling mechanisms or improved estimates of accepted mechanisms; and a detail study of the frequency scaling of ohmic heating in the ionosphere.

These first results cast doubt that thermal runaway will occur at 15-25 mW/cm^2 as predicted earlier. Thermal self-focusing and the creation of plasma striations, however, are likely to occur for SPS energy densities. The spatial extent of these effects away from the immediate vicinity of the power beam cannot be assessed at this time, and must await experimental and theoretical verification. Likewise, the details of potential impact on telecommunications systems must await further work.

4.2.6.2 Vehicle Effluent Effects

The initial modeling predictions of F-layer depletion, and the Skylab and limited military 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 service impacts need to be identified by the F-layer characteristic predictions from two-dimensional model parameter analysis, and the physical property and communication link testing to be accomplished with the space shuttle launches.

4.2.7 Conclusions and Recommendations

4.2.7.1 Ionosphere Heating

At the present, the effects of heating the ionosphere and magnetosphere with high-powered radio waves in the high frequency portion of the frequency spectrum has been demonstrated. In addition, theoretical studies that were addressed to explaining the observed HF-induced effects have rendered a good general understanding of the response of the ambient ionosphere to high-powered high-frequency radio waves.

We are just beginning to obtain experimental results of the effects on the ionosphere of high-powered radio waves whose frequencies exceed the F-region critical frequency so as to give rise to underdense heating. Little is presently known about the phenomena of plasma generation that will result from the higher power density in the F region from the SPS. Many of the expected phenomena should produce communication effects similar to those already observed or which, it is believed, can be simulated and observed. It is necessary that further studies be carried out, both of a theoretical and experimental nature, to assess the impact of underdense heating on the ionosphere to determine what the resultant impact on telecommunications systems will be and to ascertain whether the SPS pilot beam will be adversely affected by the SPS power beam.

In recent years, numerous documents have appeared that address various aspects of the impact of the operation of a solar power satellite on the ionosphere and magnetosphere. A limited number of the more fundamental documents are listed in Section 4.2.8. These listed documents contain numerous references that can provide much more detailed information.

4.2.7.2 Vehicle Effluent Effects

The HLLV launches for establishment and operational support of SPS stations could impact on communications services that utilize F-layer refractions and significant signal margin reductions could exist for periods of 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 two-dimensional depletion and stabilization model studies, coupled with vehicle launch parameter and communications link measurements, should be coordinated so as to determine the typical range of frequencies and geographic extent of affected services. Ionospheric characteristics for input to communication prediction models should also be provided through the physical model and measurement efforts.

4.2.8 Reference Documents

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APPENDIX 4A

ELECTROMAGNETIC COMPATIBILITY EVALUATION PLAN

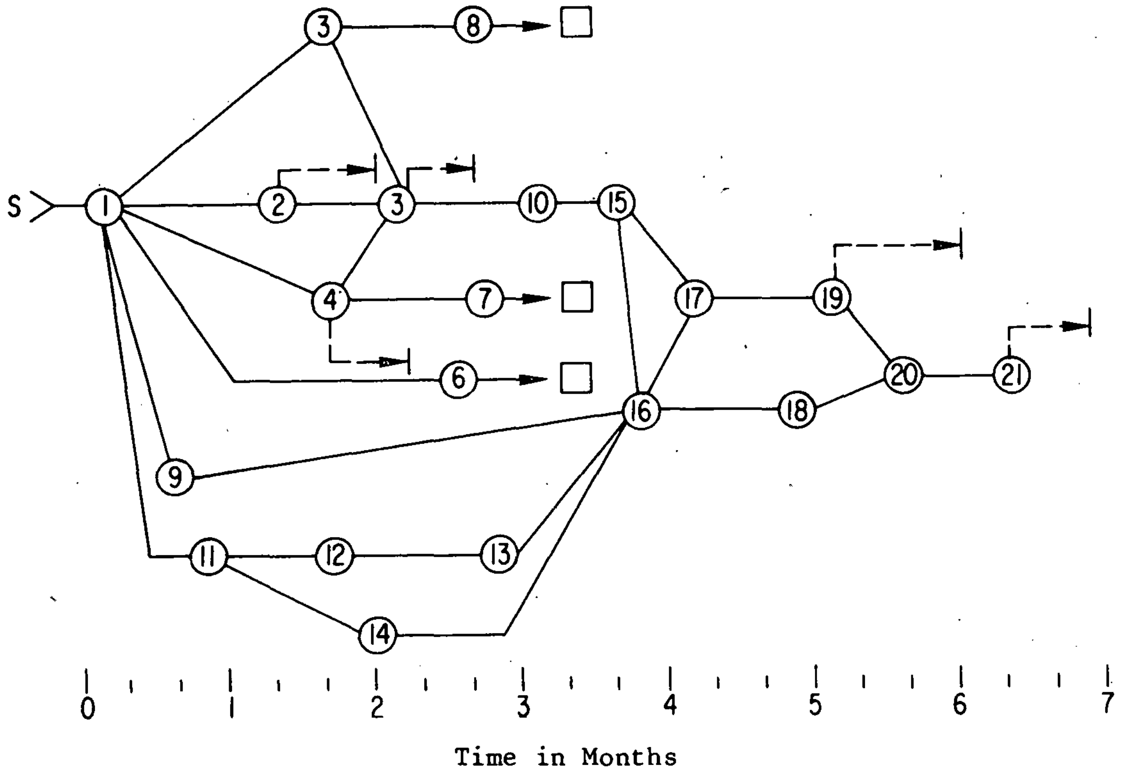
ELECTROMAGNETIC COMPATIBILITY EVALUATION PLAN

The principal tasks in the SPS electromagnetic compatibility analysis and evaluation program are listed.

1. Determine, i.e., compute or estimate, the microwave emissions from all components of the SPS MPTS, including the effects of propagation media.
2. Identify critical or high priority systems which are potential victims of radio frequency interference (RFI) or electromagnetic interference (EMI) from the SPS MPTS.
3. Quantify the effects on these systems and consequences.
4. Investigate means for mitigating harmful effects.
5. Provide design guidelines and recommendations to minimize RFI and EMI problems from the MPTS.

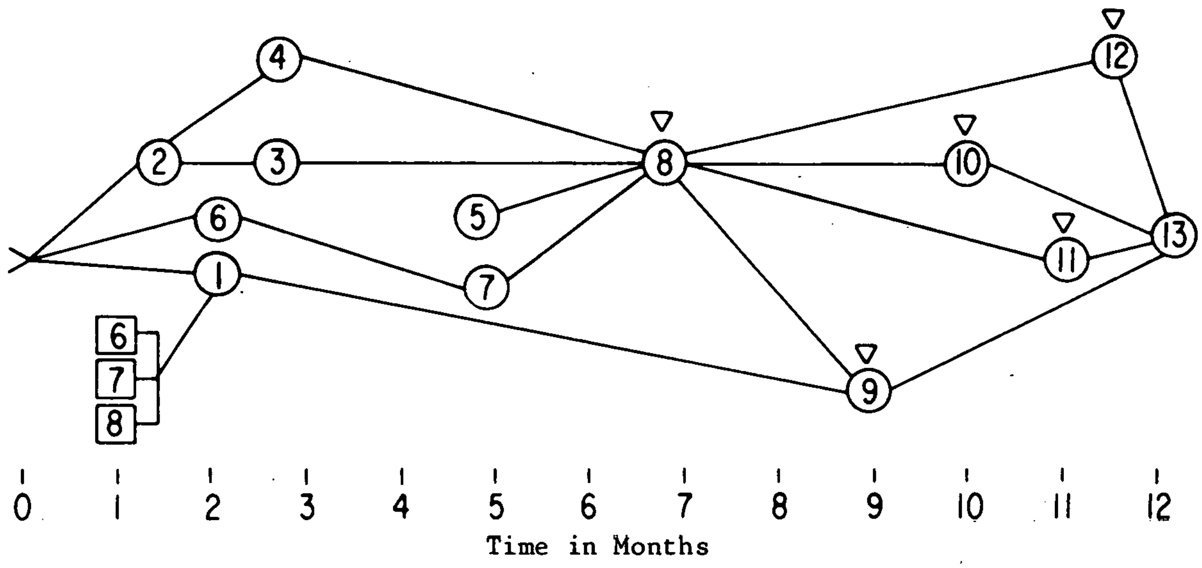
These general tasks provide power density contours, equipment/system degradation descriptors with related "national impact," functional modifications for degraded systems to accommodate the SPS environment, cost estimates for the recommended system modifications, and engineering guidelines and specifications for systems operating in the SPS environment.

The detailed tasking to accomplish this program is presented in the bubble diagram in Figs. 4A.1 and 4A.2.



1. Source file search and retrieval specifications.
2. Complete file search.
3. Complete commercial area search.
4. Complete military data search.
5. Functional and operational categorization.
6. Industry/commercial cost data.
7. Military cost data.
8. Commercial cost data.
9. Basic S/I vs Functional characteristic scoring model.
10. Couple mode analysis, radiative and conductive modes.
11. SPS spatial power computations (F_0, 2F, 3F, spurious components) with planned satellite antenna and 30% degraded.
12. Possible local meteorological variations - characteristics related to propagation effects.
13. Atmosphere propagation model modification.
14. Range of ionospheric parameter variations - input to IONCAP.
15. Select representative candidate equipment tabulations for operational functional categories.
16. Scoring model support for non-receiver systems (specific S/I parameters).
17. Design and implement models; design validation tests for data voids.
18. Score summary.
19. Complete models and testing - score summary.
20. Functional compromise summary.
21. Operational implications summary.

Fig. 4A.1. EMC Evaluation Tasks - Phase I



1. Current investment summary - category, priority, geo. area.
2. Function degradation categorization - coupling modes.
3. Shielding modification analysis.
4. Antenna modification analysis.
5. Circuit modification analysis.
6. Development/concept systems summary.
7. Development/concept system degradation mode analysis.
8. Modification tradeoff (performance/cost) - category, priority.
9. Systems investment prediction.
10. Functional modification recommendations.
11. DOD systems modification summary.
12. Design guidelines.
13. Summary report.

Fig. 4A.2. EMC Evaluation Tasks - Phase II

APPENDIX 4B

IONOSPHERIC HEATING PROGRAM PLAN OUTLINE

Table 4B.1. Simulation of Telecommunications Effects Resulting from SPS Operation

Title of Effort	Objective	Benefit to SPS
D-Region Communication and Navigation Experiment	Measure effects on signals affected by D-region	Determination of SPS operation will adversely impact on the performance of LORAN, OMEGA, and AM Broadcasting Systems
Analysis of Existing Data	Estimate telecommunication system vulnerabilities to potential SPS effects using available data	Identification of critical vulnerabilities and system impacts. Will provide guidelines for the direction of detailed experiments.
Phase Path Oblique Sounder Experiment	Measure effects of field aligned irregularities and density changes on HF communications	Early assessment of HF telecommunication system impact. Increased confidence in SPS HF system impact
Selected Telecommunication Demonstrations	Demonstrate performance impacts on actual telecommunication systems (T.V., CB: AM and FM)	Confirms predicted impact or lack thereof on selected high interest systems. Provides direct information to users vis-a-vis SPS operation
VHF Sounder Experiment	Measure the effects of SPS operations on frequencies between 30 and 200 MHz	Early assessment of potential impact on T.V., FM, Comm., and Radar. Increased confidence in SPS impacts.
Integration and Interpretation of Experimental Results	Analyze overall telecommunications impacts from combined experimental results	Provides estimate of overall telecommunications impacts.

Table 4B.2. Experimental Studies of the Physics of Ionospheric Heating

Title of Effort	Objective	Benefit to SPS
Experimental Studies of Self-Focusing Instabilities	Conduct an extensive program of experimental study of thermal self-focusing of electromagnetic waves in the ionosphere	Will provide direction and support to theoretical studies. Will provide information concerning the potential for SPS creation of irregularities due to self-focusing.
Experimental Studies of Electron Heating	Conduct an experimental program to assess importance of electron thermal runaway and the potential for parametric instabilities under conditions of simulated SPS operations.	Will provide information to support thermal runaway theory work and will provide information needed to assess pilot beam effects.
Experimental Studies of Parametric Instabilities and Short-Scale Striations.	Conduct an extensive experimental program of field-aligned plasma striations in conjunction with the experimental program devoted to thermal self-focusing. Satellite measurements of irregularities will be studied in conjunction with active experiments.	Will provide information needed in order to assess the probability of SPS production of plasma striations that would scatter EM waves in telecommunication systems.
A-1 Absorption Measurements for frequencies reflected from the F-region.	Determine the fraction of heater power that penetrates the E-region to heat the F-region.	Will provide information needed in the design of heaters to simulate SPS heating in the F-region.
Partial Reflection Experiments	Determine the spectrum of heated D-region ionization as a function of altitude	Will provide information on the existence of thermal runaway and its potential impact on D- and E-region.
A-1 Absorption Measurements for frequencies reflected from the E-region	Determine heater effects on E-region collision frequency	Will provide information on the probability of thermal runaway in the E-region.

Table 4B.3. Studies of the Theory of Ionospheric Heating

Title of Effort	Objective	Benefit to SPS
Plasma Instabilities Driven by Ohmic Heating-Thermal Self-Focusing and Stimulated Diffusion Scattering	Provide detailed model for underdense plasmas using both linear and non-linear theory Model for: Scaling in frequency Time and Space Scales Thresholds Prediction of Saturation level of electron density irregularities Determination of creation (and disappearance) of irregularities generated by self-focusing.	Will provide the theoretical basis to explain experimental results undertaken to observe effects of thermal self-focusing on radio waves. Will provide the only basis for extrapolating the experimental evidence to frequencies comparable to the SPS operating frequency.
Plasma Instabilities Driven by Ohmic Heating-Electron Thermal Runaway	Determine model for electron temperature and density changes for a realistic ionosphere subjected to intense heating.	Will provide the physical basis needed to address whether or not thermal runaway will be associated with SPS operation.
	Determine coefficients for ionospheric cross-modulation.	Will provide the only means to extrapolate experimental evidence of thermal runaway effects observed at lower frequencies to SPS frequencies.
	Determine changes in neutral and ion composition.	
Linear Instabilities in Intensely Heated Ionospheres	Determine if classes of instabilities (Plasma Wave Instabilities, Stimulated Raman Scattering, etc.) will occur during SPS operation and experimental program.	Will provide information needed to judge if experimental results can be confidently extrapolated to the SPS scenario.

Table 4B.3. (Cont'd)

Title of Effort	Objective	Benefit to SPS
Heating in Atypical Ionospheres	Determine the impact of additional heating in an ionosphere already heated by natural disturbances	Will provide information on the probability of SPS-related heating giving rise to adverse impacts on the ionosphere during natural disturbances such as storms, flares, etc.
Local Neutral Circulation	Determine the extent to which SPS heating of the ionosphere will affect the neutral atmosphere at ionospheric heights.	Will provide data and calculations on the degree to which the neutral atmosphere at ionospheric heights would display a modified circulation pattern as a result of SPS operation.

Table 4B.4. SPS Impact on the Pilot and Power Beams

Title of Effort	Objective	Benefit to SPS
Ionospheric Effects on the Stability of the SPS Pilot Beam	Determine phase and amplitude variations across the SPS array due to changes in the ionosphere occurring both naturally and as a result of heating.	Will provide information for the SPS phase control system, for the Pilot Beam pointing accuracy and on sidelobe levels.
Ionospheric Effects on the SPS Power Beam	Determine the energy, its magnitude and distribution scattered out of the power beam by ionospheric variations	Will provide information needed to assess overall transmission efficiency of the SPS. Will also provide information needed to address the potential for RFI.
Combined Pilot/Power Beam Test	Determine the uplink phase and amplitude variation on the pilot signal and interpret the resulting return signal.	Will provide a true test of uplink phase changes and the actual impact on a regenerated signal.

Table 4B.5. Development of Advanced Ground-Based Heater Facilities

Title of Effort	Objective	Benefit to SPS
Development of a Higher Power Heater at Arecibo	Build and construct a higher power heater at Arecibo, P.R., for use in SPS simulation studies.	Will provide a facility to supply SPS equivalent energy density to the F-region of the ionosphere for underdense heating.
Development of a Higher Power Heater at Platteville	Build and construct a higher power heater at Platteville for use in SPS telecommunication simulation studies.	Will provide a facility to supply SPS equivalent energy density to the F-region of the ionosphere for underdense heating.