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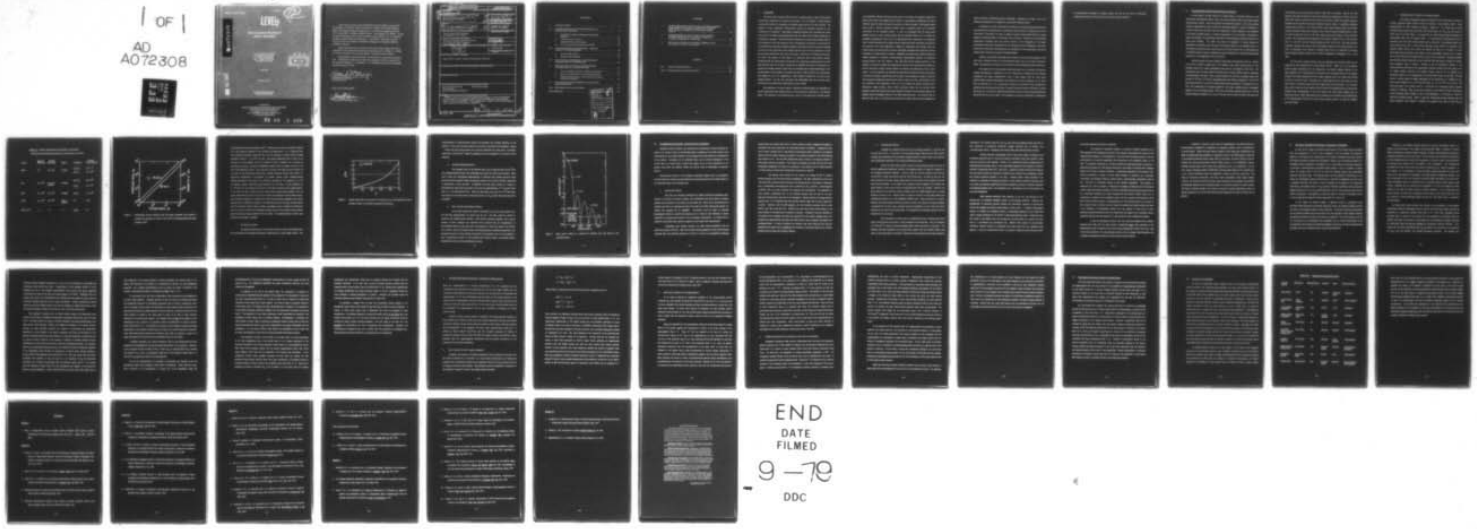
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**Environmental Factors of
Power Satellites**

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Interim Report

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Prepared for
**SPACE AND MISSILE SYSTEMS ORGANIZATION
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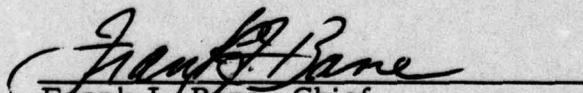
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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.



Gerhard E. Aichinger
Project Officer

FOR THE COMMANDER



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I. Introduction

The solar power satellite (SPS) system is a proposed project which would involve considerable expenditure of resources and money. If it is feasible, it would provide considerable benefits in satisfying our national energy needs in the 21st century. For projects of such magnitude, environmental factors are essential elements in any evaluation of the program. Historically, ecological disasters were inevitably the result of the lack of foresight and planning rather than the result of the intrinsic properties of civilization or progress. The construction and operation of a solar power satellite system is no exception to this rule; indeed, as will be developed in this chapter, the necessity of considering these questions in systems design is accentuated because we shall be dealing not only with the interactions with earthly biota but also with the operations of other space systems sharing the use of near-earth space. Therefore, in this larger environmental sense, the purpose of this paper is to delineate those environmental factors associated with the construction and operation of a solar power satellite system in order that they may turn out to play a central role in defining the limits of the system in a positive and integral manner, rather than as a subsidiary and remedial afterthought. Our considerations in this chapter are pursued with such a view in mind; and consequently, this chapter is not to be regarded as a mere listing of impacts for the solar power satellite system. As such, our treatment will undoubtedly miss some specific topics which may be considered as of high priority by some readers.

The importance of space systems interaction notwithstanding, the possibility of harmful interactions with earthly biota is perhaps of greater importance to the general public. The treatment of environmental interactions of the solar power satellite system

is an especially difficult task since issues such as the effects of long-term exposure of biota to low microwave dosages and the effects of stratospheric modification by rocket effluents upon the earth's climate and weather are rather complex. The situation about these issues is further worsened because there is presently little or no scientific observation on the biological effects. It must be recognized that the solar power satellite system is such a unique project that its physical effects, not to mention its biological consequences, have yet to be determined from experiments of comparable scale. Political debates will no doubt revolve around such issues; therefore, we shall not be concerned with value judgments in regard to interactions with earthly biota but merely review the present state of proven knowledge, although what constitutes "proven knowledge" is further subject to debate. Originally, the solar power satellite design was evolved partially to overcome environmentally objectionable features of alternative energy sources in the 21st Century. This view may still be correct; however, in this chapter, we shall not consider the comparative severity of the environmental impacts of various alternative energy sources because we believe that objectivity must be maintained. Lest some readers may consider our discussions of possible harmful interactions with biota as casting a negative tone on the system, we encourage the reader to make his own comparative judgments based on facts which we hope to review, and bearing in mind that subjective value judgments of this sort must balance the merits and demerits of alternative energy sources, which involve emotional issues such as nuclear waste disposal, excess heat disposal and carbon-dioxide buildup in the atmosphere, against the possible harmful biological effects of the SPS mentioned above. We reiterate that we shall not take a pro or con stand on any issue, but we shall stand behind our judgment of

what constitutes scientifically proven knowledge. Discussion of a topic is not to be construed as argument for or against the solar power satellite system.

In Section II, we shall summarize the possible environmentally intrusive factors in the construction and operation of a solar power satellite system. Sections III to VI will be devoted to discussions of what we regard as major environmental factors in spatial regions in increasing order of remoteness from the earth. These are: a) the biospheric environment extending from the earth's surface to the tropopause, b) the upper atmospheric environment extending from the stratosphere to the turbopause, c) the near-earth space environment extending from the turbopause to the magnetopause, and d) the cislunar space environment beyond the magnetosphere.

Finally, we emphasize once again that, because of the scale and uniqueness of the solar power satellite system, the environmental factors are by no means well-determined. Consequently, we cannot do much more than the identifying of issues at present.

The importance of environmental assessment prior to or concurrent with systems concept development is realized by the U.S. Department of Energy and the National Aeronautics and Space Administration since a joint program plan for solar power satellite (SPS) concept development and evaluation has been developed for the years 1977 to 1980 (Ref. I.1). It is stated that "a period of intensified study is proposed to synthesize and extend previous results, to obtain resolutions insofar as possible to several key issues, and to provide an adequate information base from which recommendations for future SPS efforts can be made." In this chapter, we hope to emphasize the importance

of environmental feedbacks on design criteria, not just for the sake of minimizing environmental impact itself but also for the sake of systems function.

II. Characteristics of Environmentally Important Elements

In this section we shall discuss the characteristics of specific elements of the construction and operation phases of the solar power satellite which would cause possible environmental impacts. Since the physical and functional aspects of the various power satellite components have been reviewed in preceding chapters, it would be redundant to re-iterate these here; however, since the magnitude of impact depends on the magnitude of the power satellite system, it would be appropriate for us to specify, in as general a manner as possible, the quantitative features of environmentally important factors for a basic power satellite. The reader may scale the magnitude of impact upwards or downwards in accordance with the size of his system relative to our standard model. In this regard, the reader must be made aware of the further caveat that our discussions are of necessity based on current technology or current assessment of expected technological progress up to the beginning of the 21st Century.

Current concepts of power satellite construction and operation focus on a system in the form of either a single unit or two separate units which would provide 10 GW, adequate power for a large metropolitan area such as Los Angeles or New York. The construction time for such a system is between six to twelve months, while the operating life expectancy is 30 years. Such a power satellite unit will have a payload mass in the vicinity of 10^7 kg ($\sim 10^4$ tons) at geosynchronous orbit (GEO), consisting of ~ 60 km² of solar panel area and a microwave transmitting antenna operating at a frequency of 2.45 Ghz. The construction of the space segment of the power satellite system is generally planned to be a two-stage process. First, heavy lift launch vehicles (HLLV) of 4×10^5 kg payload capacity, launched at the rate of one per day for about 100 days, will boost the

total payload into low-earth orbit (LEO) at about 500 km altitude. Second, the final payload is partially assembled at LEO and is subsequently transported to GEO by means of cargo orbit transfer vehicles (COTV) which are powered by argon ion engines using the assembled power satellite solar panel elements as power source. In addition, subsidiary transportation vehicles of the shuttle orbiter type, using chemical fuels, will perform personnel transport duties; and ion engines will be used for station keeping duties at GEO. The final construction work at GEO will require about 500 workers in extra-vehicular activity. The major ground-based segment of the system consists of one or two rectenna sites of $\sim 130 \text{ km}^2$ area and a launch-landing site for the HLLV's. The above baseline component concepts may evolve with technological advances in the future; however, the order of magnitude of the concept is probably fairly firm, as is indicated in the Solar Power Satellite Baseline Review held at NASA Headquarters, Washington, D.C., in July 1978.

For the power satellite system, there are basically four elements which may be important in the consideration of environmental factors. These are: 1) the propulsion system exhausts associated with the construction and station keeping activities of the space segment, 2) the transmission and reception of the microwave beam, 3) the physical structure and debris associated with the space segment and 4) the launch and landing activities at the HLLV base. Obviously, for a large project such as this, there are many other facets of activities which may have impacts upon the environment. For example, issues such as land use in the vicinity of HLLV launch and landing sites are not drastically different from considerations of the same issues near other major projects such as airports and dams. Since these issues do not represent new elements in the consideration of the environmental factors of the solar power satellite system, we shall not consider them any further.

1. Propulsion System Exhausts of the Space Segment.

The chemical propulsion systems envisioned for the SPS consists of HLLV's, COTV's, personnel launch vehicles (PLV) and attitude control systems (ACS). Some characteristics of these vehicles are listed in Table II.1. The break-down of these chemical rocket exhaust products below LEO include H_2O , CO , CO_2 , H_2 , and traces of CHO , CH_4 , H , OH and CH_2O . It is noted that the orbit insertion burns envisioned are considerably lower than the Skylab launch. If environmental considerations deem it necessary, even lower orbit insertion burns may be considered. The propulsion systems for orbit transfer from LEO to GEO include chemical O_2/H_2 rockets for personnel orbit transfer vehicle (POTV), and COTV's, the options for which are at present not well-determined primarily because these depend on the technological advances on ion engines and on solar cells; thus the figures listed in Table II.1 are tentative. Generally speaking, orbit transfer mission objectives are best achieved with high specific impulse ion engines since propellant mass is reduced. Further, as will be developed in Section V, the environmental interactions in the magnetosphere depend critically upon the energy of the ion engine exhaust; therefore, the specific impulse assumed for ion engines is an important element in the considerations of environmental factors of the SPS. We shall assume a nominal argon ion engine operating at an ion temperature of $\sim 1000^{\circ}K$ and at a beam current density of 2.5×10^{-2} amp/cm² (Ref. II.1) or 1.6×10^{17} Ar⁺/cm² sec. The streaming speed of the exhaust beam is ~ 60 km/sec for a nominally assumed specific impulse of ~ 6000 sec. Thus, the ion beam exhaust is a very dense, but fairly cool plasma whose streaming kinetic energy of 500 eV (corresponding to ~ 60 km/sec Ar⁺ ions) far exceeds the thermal energy. Figure 1 shows the relationship between payload mass and argon propellant mass needed to transport the payload from LEO to GEO with an

Table II. 1. Vehicle Characteristics (according to Preliminary

NASA Solar Power Satellite Baseline Concept Review, July 1978)

Vehicle	Ignition Mass (Kg)	Payload Mass (Kg)	Engine	Propellant	Exhaust Rate (Kg/sec)
HLLV	10^7	3.9×10^5	2-stage	O_2/CH_4	2.8×10^3
				O_2/H_2	4.7×10^2
PLV	2.5×10^6	75 person module	2-stages	O_2/CH_4	2.8×10^3
				O_2/H_2	4.7×10^2
POTV	8.1×10^5	3.6×10^5	2-stages	O_2/H_2	1.0×10^2
COTV	4.4×10^6	3.5×10^6	Argon Electric	Ar^+	0.04
COTV-ACS	—	—	—	O_2/H_2	0.1

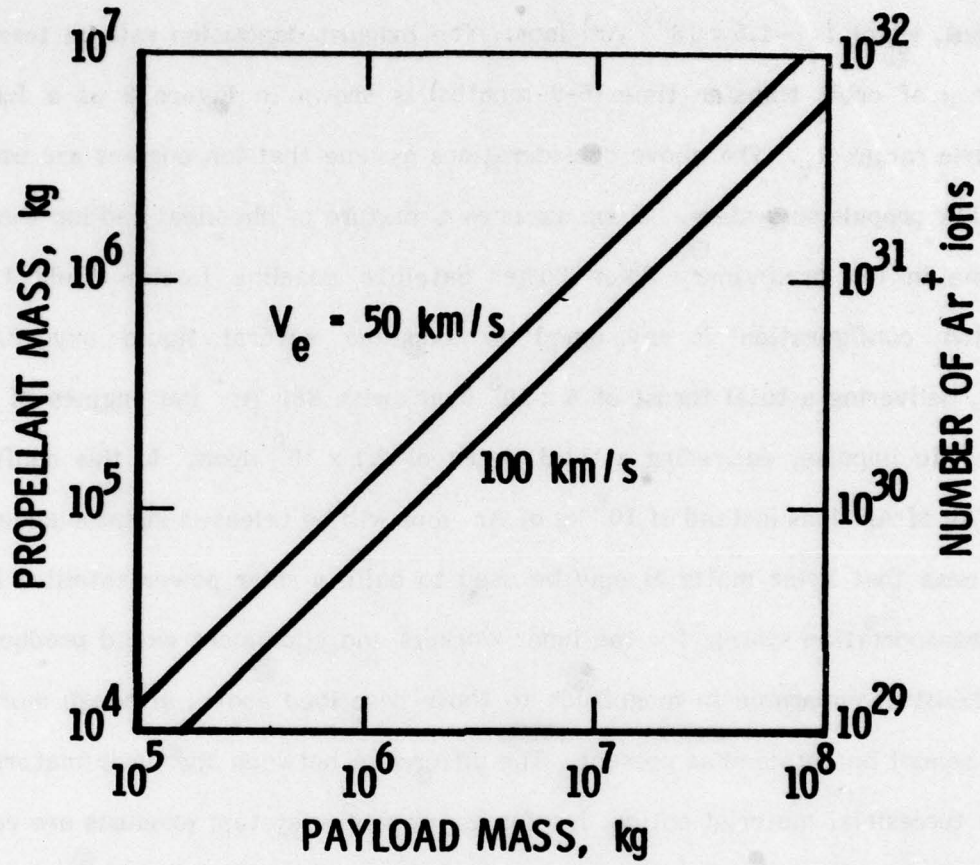


Figure 1. Relationship between payload mass and argon propellant mass needed to transport the payload from LEO to GEO with an accompanying orbital plane change of 28.5° .

accompanying orbital plane change of 28.5° . Obviously, the amount of propellant required for a given payload depends on the ion-beam streaming speed. For a minimum Solar Power Satellite payload of about 10^7 kg, it will be necessary to expend 10^6 kg of argon propellant, which is $\sim 1.5 \times 10^{31}$ Ar^+ ions. The exhaust deposition rate in terms of the fraction μ of orbit transfer time (6-9 months) is shown in Figure 2 as a function of geocentric radius R_E . The above considerations assume that ion engines are used as the sole COTV propulsion system. If one assumes a mixture of chemical and ion thrusters, as was done in the preliminary Solar Power Satellite Baseline Review (July 1978), the propulsion configuration is envisioned to combine several liquid oxygen/hydrogen engines, delivering a total thrust of 4×10^8 dyne, with 880 Ar^+ ion engines of 1.3×10^4 sec specific impulse, delivering a total thrust of 2.1×10^8 dyne. In this configuration, 2×10^5 kg of Ar^+ ions instead of 10^6 kg of Ar^+ ions will be released in the magnetosphere. In the case that lunar material may be used to build a solar power satellite fleet, the space transportation system for the lunar workers and equipment would produce propulsion exhausts comparable in magnitude to those described above, although more precise figures cannot be obtained at present. The difference between the lunar material option and the terrestrial material option, insofar as propulsion system exhausts are concerned, is not in the first mission but in subsequent missions since the first mission of both options require boosting of large payloads from the earth. The characteristics of lunar mass drivers are unavailable at present.

2. The Microwave Beam

The physical parameters of the microwave beam are quite well-defined since the transmission and reception-rectification requirements are major design factors. The

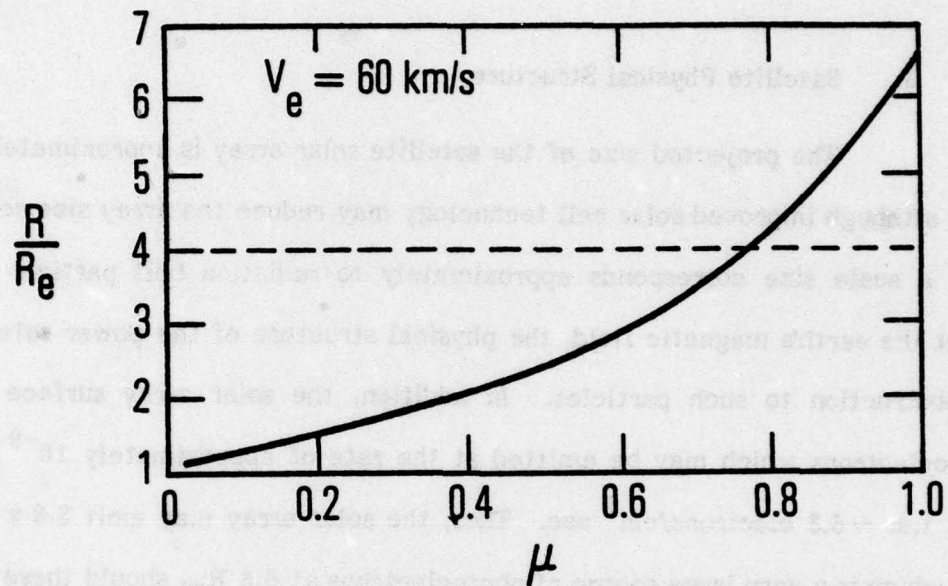


Figure 2. Exhaust deposition rate in terms of the fraction μ of orbit transfer time (6-9 months) is shown as a function of geocentric radius R_E .

characteristics of environmental concern are primarily the rectenna diameter on the ground (~ 10 km) and the power density of the beam at and below the ionosphere. Figure

3 shows the beam power density as a function of distance from the center. In addition, waste heat of $20\text{--}30 \text{ Wm}^{-2}$ might be dissipated into the atmosphere at the center of the rectenna.

3. Satellite Physical Structure

The projected size of the satellite solar array is approximately 60 km^2 (Ref. II.2), although improved solar cell technology may reduce the array size somewhat. Since such a scale size corresponds approximately to radiation belt particle gyration radius about the earth's magnetic field, the physical structure of the power satellite represents an obstruction to such particles. In addition, the solar array surface is a source of photoelectrons which may be emitted at the rate of approximately 10^{-9} amp/cm^2 (Ref. II.3), i.e. $\sim 6.3 \text{ electrons/cm}^2 \text{ sec}$. Thus, the solar array may emit $3.8 \times 10^{12} \text{ electrons/sec}$, which is a very large source of photoelectrons at $6.6 R_E$, should these electrons leave the sheath.

4. HLLV Launch and Landing Activities

At the HLLV launch site, which is envisioned to be a man-made lagoon (Ref. II.4 and II.5), approximately one launch per day for ~ 100 days would be needed to construct one standard power satellite. These launch activities, together with a similar number of HLLV landings, may introduce sonic elements into the consideration of environmental factors, since each HLLV may generate 4 times the thrust of the Saturn moon rocket. Since the detailed launch and landing scenario, especially operations in the troposphere, have not been precisely determined at the present time, it is not possible to give a quantitative account of the possible sonic sources, unless the detailed vehicle configurations and the thrust scheduling are known.

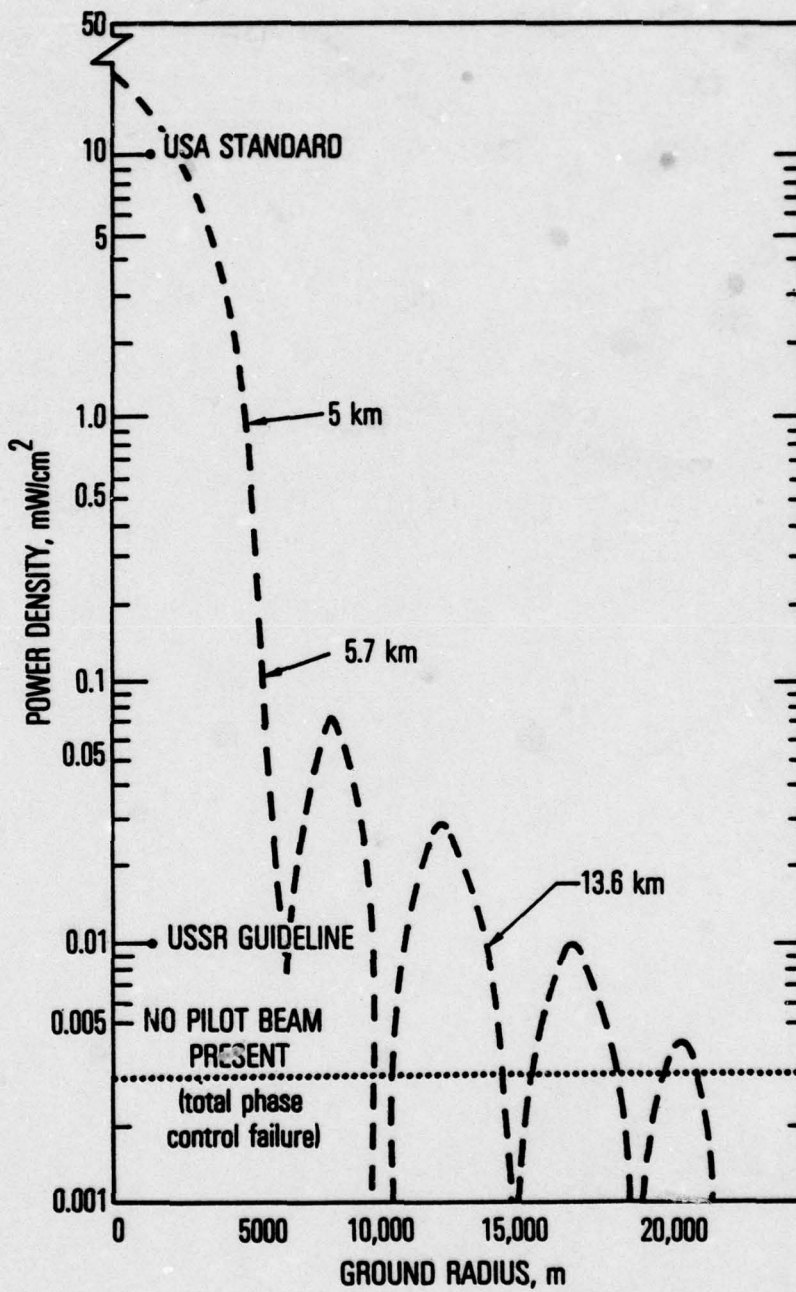


Figure 3. Beam power density as a function of distance from the center of the microwave beam.

III. The Biospheric Environment: Ground Level and Troposphere

Biospheric effects related to the construction and operation of power satellites are likely to be critical factors in determining public acceptance of the SPS concept since such effects are most easily related to by the populace that must finance the development of the system. Obviously, not all potential issues can be treated adequately in this review, and so we shall focus on issues that appear to be of most importance at the present time, given the baseline system and present state of knowledge of pertinent factors.

Environmental factors in the biosphere essentially separate into two categories: (1) those related to launch activities during the construction phase and (2) those related to the microwave beam at the rectenna site.

1. Launch-Site Effects

The noise and vibration resulting from engine testing and launching, particularly of the heavy lift launch vehicles, will undoubtedly have some effect on people, animals, and structures in the vicinity of the launch site. Since one to several heavy lift vehicles will need to be launched per day at the peak of the SPS construction period, the effects will probably not be negligible. Precautions could be taken to minimize physiological effects on launch-site personnel, but it would be more difficult to impose regulations on persons and animals in the surrounding communities. It is likely that an extensive noise buffer zone would be required to meet noise-level requirements.

Potentially more serious, however, are sonic booms associated with the ascent and reentry of HLLV's. Since the formation and propagation of sonic booms depend critically upon the thrusting schedule of the HLLV as well as on atmospheric conditions

during launch and reentry (Ref. III.1), it may be possible to devise mitigation strategies to minimize sonic boom generation by monitoring weather conditions. Unexpected sonic boom events occurring over a long period are potentially rather annoying to the general public, as the so-called "mystery air quakes" in the eastern seaboard of the United States have proven to be. For the SPS construction phase, however, the surprise element of sonic booms may not be present. The effects on animals and marine life have not been extensively researched, but there is no indication at the present time of serious impacts on either human or animal life, provided that occurrence is episodic.

The ground cloud formed at the launch site during lift-off is another potential problem that will need further investigation. The high temperature of the cloud will cause NO_x , formed by after-burning in the exhaust plume, to rise before it disperses; thus, a considerable surrounding area may be affected by NO_x problems. Meteorological conditions will, of course, influence the dispersal rate and pattern. The possibility of local weather modification due to the extensive ground cloud as well as the heat generated during launch will need to be investigated. Studies related to the Space Shuttle program (Ref. III. 2) indicated that such weather effects might last for only 2 days after a launch. However, with the SPS program, the time between launches will be much shorter than this 2-day lag time. Whether this may have serious ramifications on the local weather at the launch site is unknown at present. Although it would be difficult at the present time to predict the nature and magnitude of the weather changes, data to be obtained from Space Shuttle launches will likely provide much necessary information for modeling studies. It must be pointed out, however, that since LH_2/LO_2 and CH_4 are projected to be used as HLLV propellants, the toxicity of the ground cloud is not a severe problem as is the case with the Space Shuttle.

2. Rectenna Site Effects

Although the required land area for the receiving antenna is $\sim 100 \text{ km}^2$ and the heat loss will be ~ 15 percent of the incoming energy, these land and heat burdens compare quite favorably with alternative energy sources of similar output and therefore are not generally considered to be critical environmental issues.

By far the most serious issue in terms of both potential impact and lack of data for appropriate assessment concerns the biological effects of long-term exposure to low-intensity microwave radiation. Concern exists not only for workers at the site but for all forms of plant and animal life near the rectenna site. As shown in Fig. II.3, the power density of the beam quickly drops below the U.S. safety level as distance from the beam center increases. At the edge of the rectenna, which is roughly 5 km in radius, the power density is more than an order of magnitude below the U.S. standard. However, the power density in the side-lobe maxima remains above the USSR standard out to a radial distance of about 12 km. Barriers could of course be erected to keep large animals and unauthorized persons out of any designated "hazard" area. These would have no control, however, over little animals, insects, plant life, or birds. The lifetime of a power satellite is projected for 30 years; thus, constant low-level irradiation of those lower life forms could go on for many of their generations. The biological and ecological impacts of such a situation are not yet known.

The discrepancy of three orders of magnitude between American and Soviet safety levels has been the source of much discussion and controversy. The U.S. standard of 10 mW/cm^2 is based on thermal heating effects which commence at that level. The Russians and East Europeans, on the other hand, believe that non-thermal effects may occur at flux levels below 10 mW/cm^2 , affecting the nervous system and hence behavior.

According to the Russian literature (see e.g. Ref. III.3) neurological effects give rise to such symptoms as headaches, irritability, fatigue, insomnia, loss of memory, and decreased sexual ability. Complaints also include chest pains and shortness of breath.

Western scientific methodology tends to lend little weight to subjective and amorphous symptoms such as those listed above, particularly when they could be easily caused by numerous other agencies. Further, U.S. research has failed to substantiate the Russian/Eastern European claims to the statistically significant level required by Western scientific methodology (Refs. III. 3, III.4, III.5). A general criticism is that Soviet research into non-thermal effects of microwave irradiation has suffered from inadequate controls and limited statistical analysis of the data. Another factor, which certainly is not conducive to resolving the opposing viewpoints, is that Russian scientific reporting tends to be brief and sketchy; experimental details considered important by Western scientists are frequently glossed over or not discussed at all. (Admittedly, part of the problem may lie in the translation.)

Until recently relatively little research in the U.S. was devoted to non-thermal and low-intensity biological effects of non-ionizing radiation. However, the proliferation of microwave devices coupled with preliminary evidence of non-thermal effects has changed the picture dramatically in recent years. A Federal multi-agency program to evaluate the biological effects of nonionizing radiation in the 0-3000 GHz range is being coordinated by the Office of Telecommunications Policy. Relatively little data exists at the present time, and the goal for the near future is to improve the data base in a coordinated and systematic way. Shorter term studies on low-intensity microwave exposure effects on salmonella virus and honey bees are presently being pursued. It must be noted however that it is critical to separate purely thermal effects

from those caused by microwave irradiation.

The question of biological impacts of microwave radiation associated with SPS operations will undoubtedly stimulate more research, particularly into areas such as long-duration exposure of microorganisms in the soil, flora and fauna; however, with the proliferation of microwave appliances, such concerns are not necessarily unique to the SPS. The proposed utilization of the land beneath the receiving antenna for grazing or agricultural purposes may also depend somewhat on the results of research into biological effects of low level microwave radiation. A preliminary assessment of the problem (Ref. III.6) has identified a number of areas where research is required; e.g., teratology, hematology, immunology, behavior, nervous system, endocrinology, reproductive system, etc. The area of cumulative effects is also virtually unexplored. The problem of dosimetry (i.e., how to measure or determine the dosage of radiation and its distribution within a body) will require attention, as will the distinction between truly thermal effects (i.e., reactions resulting from tissue heating) and non-thermal effects (those due to interaction or response of the biological system with the imposed electromagnetic field). Since thermal effects depend on characteristics of the irradiated body (e.g. texture of skin, amount of hair or feather, size and shape of irradiated part) great caution will have to be exercised in extrapolating results from test species to other forms of life. Similarly, external conditions such as air temperature and degree of air circulation will be important since the thermal response of a body depends on heat dissipation processes.

It must be emphasized, however, that the microwave dosages at the rectenna (receiver) site (Fig. II.3) are many orders of magnitude below those expected at the high-powered radar transmitter sites where human physiological effects have from time to time been reported. For small animals, however, the low dosage characterization will no longer be appropriate because of the small body volume involved.

In general, it should be noted that the establishment of an effect should not automatically be regarded as a dangerous or undesirable condition without consideration of actual impact. Unlike the Space Shuttle Program which relies upon modification and usage of existing facilities contiguous to population centers, the SPS program is expected to use dedicated facilities whose access could be controlled. For such a reason, we do not consider the local non-microwave related effects above to be of significant impact, although nonlocal issues such as sonic boom generation may be of importance. For the same reason, mesoscale weather modification, (the heat island effect) at the rectenna site is not of great importance since its magnitude is similar to that of a small city. The issues of microwave interaction with biota would undoubtedly induce public debate; however, we remind the reader that such issues and effects are not unique to the SPS but are generally associated with increasing usage of microwave devices in modern society. The study of genetic damage over durations measured in species generations will be of special importance not only for SPS environmental assessment but also for modern life in general.

IV. The Upper Atmospheric Environment: Tropopause to Turbopause

We use the term upper atmospheric environment for the altitude region extending from the tropopause (~15 km) to the turbopause (~120 km) because its dynamical behavior is dominated by the interactions of the neutral molecular and atomic species. This region is sometimes called the "homosphere." Indeed, even the dynamical behavior of ionospheric layers embedded in this region, the D- and E-layers, are primarily dependent on the direct photoionization of available neutral species. This is in contrast to regions above the E-layer level (~120 km) in which the charged species play increasingly important dynamical roles. The photochemistry and the dynamical interactions of this region are exceedingly complex; and therefore, it would not be appropriate for us to give a simplified summary here since it would invariably not do justice to the dynamical interactions; and possibly worse, it may generate mistaken conceptions when emotionally charged issues such as the CO₂ greenhouse effect and the ozone depletion (skin-cancer) effect are discussed. Consequently, we refer the reader to a number of excellent reviews of the composition and dynamics of this region (Ref. IV. 1 and IV. 2).

In this region the thermal budget is regulated mainly by polyatomic trace molecules whose absorption and emission properties control the radiation balance between the earth and atmosphere subject to solar insolation. The global temperature distribution sets up pressure gradients and thereby affects the wind patterns in these regions, although the general circulation is neither well known nor understood. The major gases (O₂ and N₂) are well-mixed in the stratosphere and mesosphere but the vertical distributions of the all-important minor species are influenced largely by chemical and solar photoabsorption processes and do not necessarily have a well-mixed distribution.

Because of the delicate balance between the various atmospheric layers it is thought that perturbation in one region could potentially trigger a response in another region, particularly an adjacent region, although a complete understanding of atmospheric coupling mechanisms does not exist as yet. For this reason much attention has been given to the stratosphere, which overlies the troposphere, in terms of trying to fully understand its structure and behavior and its coupling to the troposphere. The stratospheric constituent that has received the lion's share of attention is O_3 . Ozone is important for two reasons: (1) its absorption of solar ultraviolet radiation provides the major heat source in the stratosphere and establishes the stable positive temperature gradient, and (2) the absorption of the solar ultraviolet radiation shields the surface of the earth from those wavelengths which, it is believed, are an important source of skin cancer among humans. Effluents that are released in the troposphere (~ 15 km) are "washed out" fairly rapidly, on the order of weeks, owing to weather conditions. In the stratosphere and above, however, the life time of pollutants is quite long, on the order of years, and thus the injection of ozone-destroying agents directly into this region poses a potentially serious problem.

In recent years much attention has focused on the possibility of stratospheric modification owing to anthropogenic activity such as the use of aerosol spray cans and the operations of a supersonic transport fleet (Ref. IV. 3). What these seemingly diverse activities have in common is the release into the atmosphere of molecules which can interact with ozone and reduce its total abundance in the atmosphere, thereby, weakening our ultraviolet shield and perhaps changing the atmospheric thermal structure. Compounds that can react catalytically with O_3 and produce a net reduction in its population are NO_x , HO_x and fluorine- and chlorine-containing molecules. The exhaust from

chemical rockets typically contains one or more of these substances or compounds that eventually would evolve into them. Consideration of the possible effects of HLLV exhausts has led to the baseline specifications that O_2/CH_4 and O_2/H_2 propellant combinations be used for the first and second stages of the HLLV. Basically, then, the problem that needs to be investigated for the SPS concerns the impact of water vapor and molecular hydrogen injection into the upper atmosphere. Carbon monoxide and carbon dioxide are also first-stage products, but they are released in a region below 25 km, where the natural abundance is large and they do not enter in the main ozone cycle.

The supersonic transports and the Space Shuttle program have generated much interest in the study of troposphere-stratosphere-mesosphere effects (e.g., Ref. IV.10 and IV.11). The main concern, of course, is whether changes in trace gas concentrations in the upper layers could influence climate and biospheric processes at the earth's surface. Because so many chemical reactions are involved in determining the steady-state distribution of minor species in the upper atmosphere, and since the life-cycles of the different molecular species are inter-related, it is virtually impossible to predict how the O_3 content would be affected by the increase or decrease of another molecule without considering the whole family of aeronomic reactions and physical processes. For example, while O_3 is catalytically destroyed by NO_x , the resultant increase in ultraviolet radiation in the troposphere would enhance the destruction of nitrous oxide, thereby reducing a natural source of stratospheric nitric oxide (Ref. IV. 4). Thus, one cannot draw the simple conclusion that injection of NO_x will lead to a net reduction of O_3 ; the feed-back mechanisms are crucial in determining what the ultimate impact will be. In a similar vein, the injection of water vapor into the stratosphere was thought to be unimportant relative to NO_x pollutants. A recent study has shown, however, that water vapor may be

very important to the ozone question if chlorine pollutants are present (Ref. IV. 5). Again, this illustrates the necessity for considering all factors, not just independent processes. For a deeper understanding of the O₃ issue, the reader is referred to the treatise: "Environmental Impact of Stratospheric Flight" (Ref. IV. 3).

At the present time the state of knowledge of the stratosphere and mesosphere is far from being complete. Although research to date has fairly well defined the global time-dependent behavior of macroscopic properties such as density, temperature, pressure, not enough is known about the distribution of minor species (whose importance has already been pointed out), global dynamics and heat sources, or aeronomic reaction rates. Basic research is needed in all these areas in order to be able to make accurate assessments of environmental impacts. For example, even the sign of the change in ozone resulting from NO_x injection is in question owing to uncertainties in current 1-dimensional models (Ref. IV. 6). Nevertheless, since H₂O in HLLV exhausts comprise increasing proportions of the naturally occurring H₂O as one goes up in altitude (private communications, DOE Environmental Assessment Workshop, Aug. 1978), the question of H₂O in the upper atmosphere is the major issue concerning SPS impact in this region.

A possibly important, but mostly speculative, issue in the consideration of HLLV exhausts in the homosphere is the potential greenhouse effect of CO₂ injection. However, if one compares the HLLV traffic model, in which CO₂ is released below 50 km altitude only (Table II. 2), to that of stratospheric flight and to the burning of fossil fuels, it is seen that CO₂ injection of HLLV's is inconsequential.

Just as the concentrations of atmospheric constituents are related, so are the atmospheric layers; the atmosphere itself knows no boundaries. Thus, while the ozone layer maximizes in the stratosphere, its origins are in the mesosphere, where the

photodissociation of O_2 and the subsequent recombination of atomic oxygen provide the source of O_3 . To completely understand the upper atmospheric behavior, one must include the mesosphere.

In addition to its role in the ozone cycle, the mesosphere is important in environmental considerations also because of the presence of the ionospheric D-layer and the polar scattering layer (Ref. IV. 7), both of which may be affected by large-scale injection of water vapor from rocket engines. The lower D-layer is composed mainly of water-cluster ions: $H^+ \cdot (H_2O)_n$; the polar scattering layer is thought to be composed of ice particles (noctilucent clouds are thought to be the equatorward extension of the polar layer). The properties of both these phenomena would conceivably be modified if the abundance of water vapor were to suddenly increase. Investigations to determine the effectiveness of water vapor in altering the properties would of course have to take into account processes that destroy H_2O , such as photolysis in the upper stratosphere and the mesosphere. It is not clear, however, what effects the modification of the D-layer and the polar scattering layer would have on natural processes and human activities.

The ionospheric E-layer (~100-120 km), on the other hand, is of some importance to HF radio propagation; and, at the auroral zone, it is of crucial importance to the dynamical processes of the earth's response to solar flares, i.e. the geomagnetic storms. Solar flares inject energetic plasma into the earth's magnetosphere where they travel along magnetic field lines and are deposited in the auroral zone ionosphere. In the ionospheric E-layer, these energetic particles not only cause the aurorae but also generate strong auroral currents which have been documented to be possible sources of powerline surges in North American and Canadian power grids (Ref. IV. 8). Since HLLV exhausts are likely to increase NO_x in the E-region, it is thus likely that the E-region

composition and conductivity would also be modified because the E-region ions are primarily molecular. If so, then there would be serious potential concern that the magnetic storm current system may be modified (Ref. IV. 9). Whether such modifications of E-region conductivity can cause powerline surges to move to population centers at lower latitudes is entirely speculative at present. However, the possible social and economic impacts of such "hidden" issues need to be dealt with.

In summary, it appears that at least two potentially serious impacts in the homosphere may be tied to the release of H_2O and NO_x formation by HLLV exhausts. A number of other minor issues may be identified, but these are probably of little consequence. It is perhaps important to remind the reader that it is not known that such impacts would occur, for it is not known exactly how the upper atmosphere would be modified by launch vehicle chemical exhausts. The only thing we are sure of is the potential for perturbation; the rest is speculation and extrapolation. However, the ramifications as discussed above are so serious that the importance of studying atmospheric pollution problems should not be underestimated or disregarded.

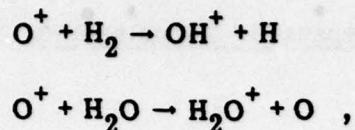
V. The Near-Earth Space Environment: Turbopause to Magnetopause

Since the magnetosphere is a tenuous environment, it is not surprising that the construction and operations of the SPS may turn out to have major effects upon the ionospheric-magnetospheric environment. Insofar as we can determine, the ionosphere and magnetosphere do not have scientifically proven effects on the natural systems on the earth; however, magnetospheric effects of the SPS system impact human activities which utilize the near-earth space environment. For the same reason, environmental issues for the ionosphere and magnetosphere may be more amenable to mitigation by careful systems design.

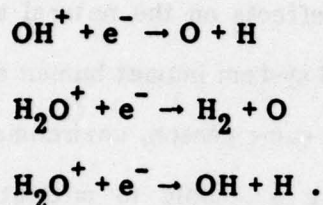
Instead of listing a large number of ionospheric and magnetospheric impacts, we have selected three, which we deem to be more clearly identified at present, for detailed discussion, although mention will be made of a number of other issues, which are presently less well-identified. In our judgment, the three major magnetospheric issues are: 1) effects of HLLV exhaust interaction with the F-region ionosphere, 2) effects of spacecraft emissions, such as COTV and POTV ion engine exhausts and chemical engine exhausts, upon the magnetospheric environment and 3) possible interactions of the microwave beam with the ionosphere.

1. HLLV exhausts and the F-region ionosphere.

Accidental observation of F-region ionospheric density depletion co-incident with the launch of Skylab II in 1973 (Ref. V. 1) has focused observational and theoretical attention upon the possible creation of an ionospheric "hole" by the H_2 and H_2O exhausts of LH_2/LO_2 chemical rocket engines. The principal reactions responsible for depletion of the dominant F-region O^+ ions are the charge transfer reactions



which results in molecular ions with fast loss reaction mechanisms such as



More recently, two deliberate attempts have been made to generate such an ionospheric hole by explosive release of H_2O , CO_2 and N_2 from a rocket payload (Ref. V. 2). The inadvertent observations of the Skylab launch and the successive attempts to create ionospheric holes in the above mentioned LAGOPEDO experiments have amply demonstrated that the above ionospheric chemical reactions were probably taking place, leading to a depletion of O^+ ions. The major questions in the assessment of the environmental factors of SPS, however, remain to be answered. Namely, what are the duration and extent of such holes generated by HLLV's whose thrust schedules are substantially different from the Skylab launch; and what are their effects upon human activity. Neither of these questions have been answered, although the effects of possible radio wave interference have been looked for and found inconclusive in the LAGOPEDO events. Since the ionospheric chemical processes involved in these O^+ depletions are of intrinsic scientific interest, many proposed experiments will probably be carried out in the 1980's. Insofar as SPS environmental impact is concerned, such effects can be mitigated to a

certain degree by changing the HLLV thrusting schedule so that the orbit insertion burns take place below the O^+ dominant F-region. Such a mitigation technique has been noted in the NASA Baseline SPS Design Review, July 1978.

2. Spacecraft emissions in the magnetosphere.

As is noted in Section II, spacecraft emissions in the magnetosphere involve exhausts from orbit transfer vehicles (COTV and POTV) in the form of Ar^+ ions and H and O atoms, exhausts from station keeping activities and photoelectrons emitted from the solar array surface. Of these three sources of emissions, the orbit transfer vehicle emissions would probably be the most serious source because photoelectrons are likely to form a sheath near the spacecraft surface, being held back by the spacecraft charging potential.

Argon ions injected into the plasmasphere during the construction phase of a single SPS of 10 GW power capacity are comparable in number to the entire content of the plasmasphere (Fig. II. 1). Since Ar^+ ions are injected in the form of a beam, the environmental effects of Ar^+ ions in the magnetosphere are also associated with the evolution of the collective state of Ar^+ ions, starting with the thermalization of the beam and ending with the loss of Ar^+ ions in the atmosphere (Ref. V. 3). First, the plasma turbulence connected with the thermalization of the beam (Ref. V. 4) and with the diffusion of the plasma cloud, amply demonstrated by barium release experiments in space, generate small scale plasma irregularities aligned with the earth's magnetic field. Such striations are known to cause communication/navigation signal scintillations, thus interfering with the function of other space systems. Second, the Ar^+ ions are sufficient in number and are sufficiently long in residence time that the composition and structure

of the plasmasphere may be altered (Ref. V. 5). According to a model developed for the natural plasmasphere (Ref. V. 6), injection of Ar^+ together with deposition of its energy would alter the plasmaspheric composition in which O^+ rather than H^+ would be the dominant ion (Ref. V. 3). Cornwall and Schulz (Ref. V. 7) have pointed out that the composition and density of magnetospheric plasma control the lifetime of the Van Allen radiation belt electrons. Since the Van Allen radiation belt environment is a major design element for most space systems, thorough investigation in this area of research would be needed to assess the modification of the Van Allen radiation environment. This is an issue of major importance since it is expected that about five hundred workers will be performing extra-vehicular construction activities in GEO during the construction phase. Finally, the loss in the atmosphere of primary-beam Ar^+ ions and the loss of heated second-generation plasma stimulate airglow, which would impact earth sensing systems at infrared and other frequencies. Since earth-sensors in space are major elements in civilian and military space applications programs, careful coordination and mitigation strategies may be needed during the construction phase of the SPS.

3. Possible interactions of the microwave beam with the ionosphere.

Ionospheric heating by radio waves at frequencies above and below the ionospheric plasma frequency is an active subject of research and experimental facilities have been constructed at a number of sites, Arecibo (Puerto Rico) and Boulder (Colorado) among them. We shall limit our discussion to studies specifically applicable to SPS. The ionospheric heating effects of the microwave beam can be classified into two types: a) resistive heating and b) self-focussing heating. Ching (Ref. V. 8) pointed out that resistive heating in the microwave beam was comparable to solar EUV heating of the thermosphere. Perkins and Roble (Ref. V. 9) investigated resistive heating in a realistic beam

configuration and came to similar conclusions. Experimental observations of such resistive heating effects at Arecibo produce temperature rises which are, however, considerably below those predicted. A serious problem of microwave beam heating of the ionosphere due to the onset of the self-focusing instability was pointed out by Perkins and Valeo (Ref. V. 10). When the beam intensity is sufficiently strong, the heating causes a change of the refractive index which in turn focuses the beam into more intense heating. Experimental verification of such self-focusing instability has been achieved (Ref. V. 11). This unstable situation results in plasma turbulence which in turn raises the question of whether the beam would remain coherent under these circumstances. The present baseline SPS design for the microwave beam with a central intensity of $\sim 23 \text{ mW/cm}^2$ is supposed to have taken the factor of self-focusing into account; however, in our opinion this design criterion may need further verification with heating experiments.

In the evaluation of SPS impacts upon the magnetosphere and ionosphere, a major question to be asked would be: how extensive are the identified impacts? In this regard, we note that the effects associated with exhaust emissions in the ionosphere and the magnetosphere are necessarily of larger scale in dimension and energy content than the effects of ionospheric heating by the microwave beam. On the other hand, the exhaust emissions, with the exception of stationkeeping thrust activities, are episodic rather than steady in character. On the whole, it seems that ionospheric heating by the microwave beam is a potentially serious problem for the functioning of SPS itself; whereas, exhaust emissions are potentially serious problems for the functioning of other space systems and for the health of space workers.

Aside from the above clearly identified impacts there are still a large number of issues which are quite plausible but are as yet of a more speculative nature. For example,

the modification of the magnetosphere by rocket exhausts and the injection of large quantities of H₂O in the thermosphere may cause changes in their convective circulation. If magnetospheric convection can be modified to the extent that ionospheric currents associated with geomagnetic storms were not confined to high latitudes, then powerline surges caused by such magnetic storm currents may provoke serious political considerations. Further, the physical structure and debris of the SPS pose navigational problems at GEO where the proliferation of communication satellites is already causing problems of crowding. Clearly there are many such issues, some are speculative and some are not necessarily environmental factors, but all of them need further investigation.

VI. The Cislunar Environment Beyond the Magnetopause

For earth-based SPS missions the question of cislunar environmental factors beyond the magnetopause does not arise, except for the possibility of magnetopause modification by the direct interaction of station keeping exhausts with the solar wind (Ref. VI. 1). However, because of the total mass of effluents required for this interaction to take place, such considerations are perhaps more appropriate for the case of a SPS fleet. Nevertheless, this question needs to be investigated in the future.

For moon-based SPS missions, the mass-drivers (Ref. VI. 2) may be a potentially serious environmental factor in cislunar space beyond the plasmopause, as well as for the atmosphere of the earth (Ref. V. 1). Quantitative assessment of the driven-mass as a source of particulate matter for cislunar space as a whole cannot be made without more design information on the assumed mass drivers. However, a qualitative idea can be obtained by noting that the design must meet launch velocity requirements accurate to one part in 10^6 and targeting requirements at the collecting point accurate to 100 meters (Ref. VI. 3). With such stringent requirements, it would not be too difficult to recognize that such mass-drivers may be a potentially serious source of particulate matter for the terrestrial and lunar atmospheres (Ref. VI. 1). Increase of particulate matter in the earth's atmosphere does not necessarily imply an automatic response in the climate because episodic particulate increases in the recent past, associated with the Krakatoa and Agung eruptions, did not seem to have significant climate consequences. Continuous increases are a different matter since this is an issue not only applicable to moon-based SPS missions but also to inevitable factors in post-industrial societies.

VII. Discussion and Conclusion

As with all large-scale human ventures, there are necessarily environmental factors involved in the construction and operation of a solar power satellite system. In this chapter, we hope to have discussed those presently identified environmental factors of the SPS, which, in our opinion, may have major impacts upon biota and upon human activities, with the intention of organizing the issues in perspective. Since such an objective necessarily requires a certain amount of subjective judgment over and above the simple statement of facts, we shall presume to do so in Table VII. 1, in which we characterize what we judge to be the more important issues identified. In this table, the word "episodic" is used to characterize construction phase effects in contrast to "steady" effects associated with SPS operations. We have assumed a conservative scenario in which SPS construction is only "episodic" rather than continuous. The word "synoptic" is used in the meteorological sense, i.e. of scale ~1000 km or larger. Hopefully, the reader may then form his own judgment as to the comparative severity of environmental impact in regard to alternative energy sources and to other human activity in general. Clearly, the issues discussed in the text and summarized in Table VII. 1 are not to be construed in the incriminatory sense because the ultimate evaluation of SPS environmental impact would depend upon comparative severity rather than upon a simple enumeration.

An equally important objective of this chapter is the raising of the designer's awareness of environmental issues so that mitigation strategies may be contemplated. Even at the present early stage of design conceptualization such mitigation strategies have already been called upon, for example, to minimize the generation of F-region depletion by scheduling the orbit insertion burns of HHLV's at below F-region heights.

Table VII. 1: Important Environmental Factors

Possible Effects	SPS Source	SPS Specificity	Duration	Scale	Characterization
Sonic Booms	HLLV	No	Episodic	Synoptic/ local	Biological
Ground cloud, NO _x	HLLV exhausts	No	Episodic	Local	Meteorological
Low-intensity irradiation	Microwave beam	Yes	Steady	Local	Biological
High-intensity irradiation	Microwave beam	Yes	Steady/ episodic	Local	Biological
Ozone modification	HLLV/H ₂ O	No	Episodic	Synoptic	Biological
Powerline surges/E-region conductivity	HLLV/NO _x	No	Episodic	Synoptic	Technological
F-region depletion	HLLV/H ₂ O	Yes	Episodic	Local/ synoptic	Technological
Magnetospheric modification	Ion engines	Yes	Episodic/ steady	Synoptic	Technological/ Biological
Ionospheric heating	Microwave beam	Yes	Steady	Local	Technological
Cislunar dust	Mass Drivers	Yes	Episodic/ steady	Synoptic	Meteorological/ Technological

Since very few of the identified effects are presently fully understood, it is premature and presumptuous for us to suggest mitigation strategies at the present time. However, we consider our mission to be fulfilled if designers are made aware of the need to keep current on the activities of those considering the environmental factors. Indeed, mitigation is not the sole reason to integrate environmental factors into the basic design; environmental feedback being what it is, a design which relegates environmental factors to that of an afterthought may find its function completely negated by the modified environment. For the SPS, the modification of the radiation belt environment by ion engine effluents and the possibility of thermal self-focusing of the microwave beam may potentially feedback respectively upon the efficient operations of the solar array and the coherent collection of energy by the rectenna.

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