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Space Power Systems – What Will be Their Impact on the Upper Atmosphere and Ionosphere?

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Interim Report

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This technical report has been reviewed and is approved for publication.

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Space power systems are currently receiving widespread attention because of the significant contributions that they could make toward meeting our country's energy needs in the 21st century. Although the systems are environmentally "clean" relative to alternative or complementary concepts, some effects may be produced in the earth's atmosphere and ionosphere that could ultimately have impact on other activities of our society and on the biosphere as a whole. Specifically, we must consider 1) interactions of the microwave radiation with the thermosphere and ionosphere, and 2) pollution of the entire atmosphere up over

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through the thermosphere as a result of the high volume of space traffic that will be required to construct and then service and maintain the power satellites. Microwave propagation effects could result in ionospheric modification that would have adverse effects on communications systems. Pollution effects, particularly in the stratosphere, could lead to changes in the spectral properties of ultraviolet radiation at the earth's surface, which would alter a number of biospheric processes. These factors must be taken into account in the design and development of space power systems so as to minimize their impacts. In addition, since the pollution problem is not unique to power satellites alone, a careful assessment of this problem is necessary taking into account all advanced space systems concepts that require a high level of support by space transportation vehicles.

CONTENTS

SPACE POWER SYSTEMS – WHAT WILL BE THEIR IMPACT ON THE UPPER ATMOSPHERE AND IONOSPHERE?

Among the prospects for meeting our country's energy needs in the 21st century, perhaps the boldest, and certainly the most exciting, are the space power systems. As currently envisioned, huge power stations, each capable of serving a large city, would orbit at geosynchronous altitude (35, 800 km) and either transmit space-generated power to earth or relay power between distant ground-based sites. If these concepts prove to be feasible and cost effective and become operational, there is no doubt but that they will more than pay back the billions of dollars that have been invested in space research and the development of aerospace technology.

Preliminary studies indicate that space power systems are viable concepts that could become both economically and technologically feasible by the end of this century.[1,2] No scientific "breakthroughs" are required, but significant advancements in the technology in various fields need to be accomplished. A number of technological problem areas have already been identified that require detailed evaluation and analysis before a systems feasibility decision can be reached. In addition, a number of sociological, political, ecological and environmental issues need to be examined. The obstacles are many and complex, but since they seem to be surmountable, given adequate time and funding, there is great enthusiasm on the part of proponents of the concepts to initiate a definitive phased program of study and development that hopefully would culminate in the first operational space power station before the end of this century.

Considering the dwindling supply of fossil fuels on earth, the ever-increasing demands for energy, and the even more questionable feasibility of nuclear fusion power sources, the demands for serious consideration of satellite power systems seem well justified. Initial studies were sufficiently encouraging that a joint $5-million study of satellite solar power stations has been undertaken by NASA and ERDA during the current fiscal year.

Both "active" and "passive" space power systems are presently under consideration. In the passive concept, geosynchronous satellites would relay energy between distant ground-based sites. In this way, remotely located power-generating stations, such as nuclear or solar power facilities in the desert, could serve the populated urban regions as shown in Figure 1. Energy-rich countries could also utilize the relay system to deliver power to customer nations. In contrast, an active power satellite would actually generate the power in space, by either solar or nuclear energy conversion, and then transmit the power to earth.

In either active or passive systems, the transmission of energy between space and earth would utilize the microwave portion of the electromagnetic spectrum. This choice is dictated by a number of factors: the technology is well advanced, efficiency of transmission is high, ionospheric and atmospheric interactions are minimized, and surface weather conditions have negligible impact on transmission properties. Current baseline designs call for a transmission frequency of 2.45 GHz, which is equivalent to a wavelength of 0.122 m.

The outstanding feature of power satellites, and the source of a number of major problems, is the enormous size that is required of the structures. For a surface power delivery of 5000-10,000 MW, a solar

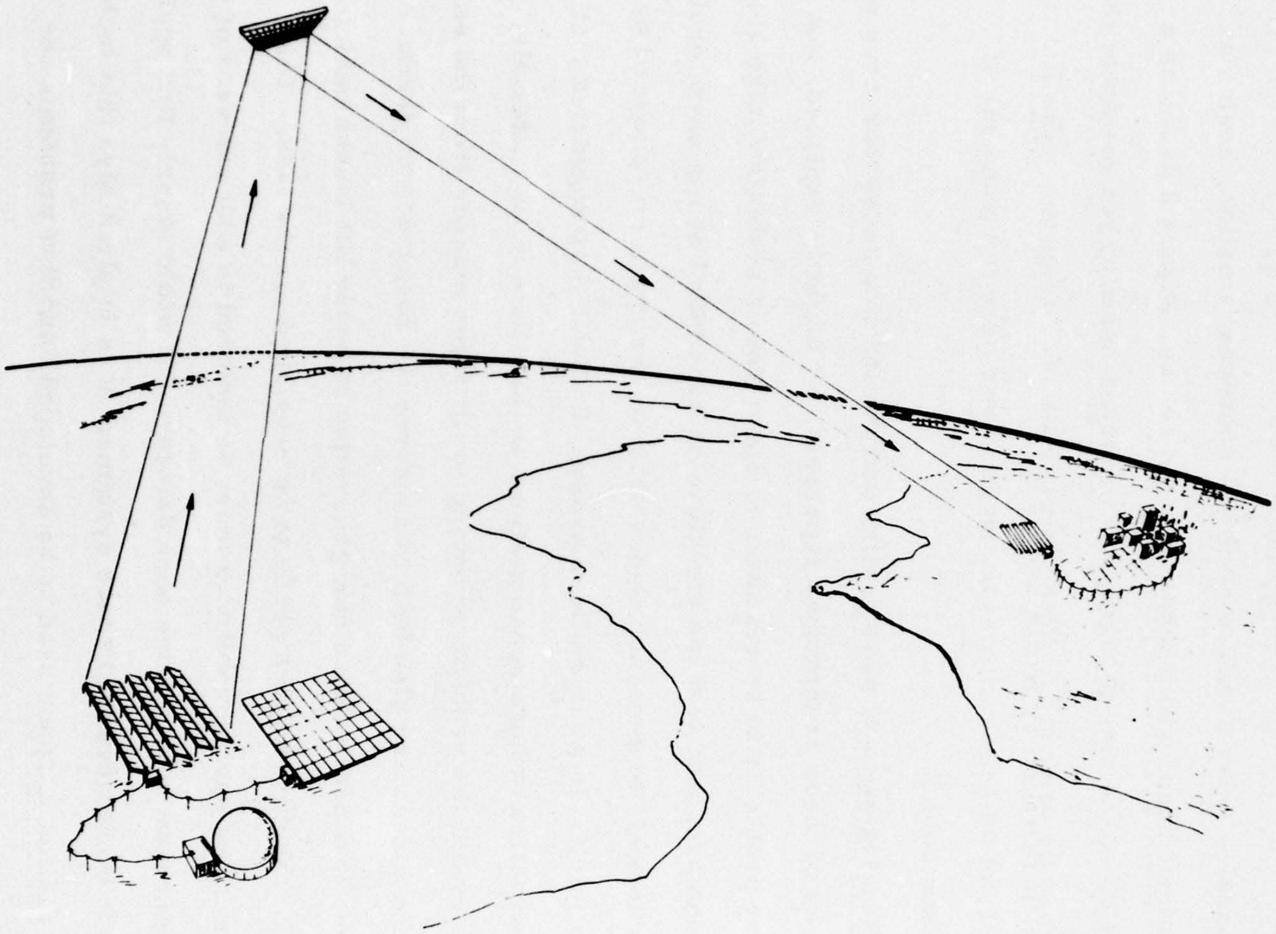

Fig. 1 Power Relay Satellite

power satellite requires on the order of 50 km^2 of solar cells or solar collectors and concentrators, and its mass would be on the order of 10^7 kg. A passive relay satellite would be somewhat smaller, having an area of about 1 km^2 and a mass of about 10^5 kg. Figure 2 provides a perspective of the size of Glaser's[2] proposed solar power satellite; the Shuttle may be seen in the lower left corner of the figure. (The Shuttle orbit will not be geosynchronous. It is shown here for purposes of comparison only.)

The logistics of constructing and putting into geosynchronous orbit structures of these proportions represent, as might be expected, one of the major problems to be resolved by space power systems design studies. It has been proposed that the structure be assembled at low earth orbit and then "tugged" to geosynchronous orbit by the space tug, powered by the satellite itself. In a futuristic approach, O'Neill[3] has suggested that the construction of huge space stations could utilize lunar materials. This would alleviate the problem of having to lift large masses from the earth's surface to space, and also help to conserve the resources on earth. With any approach, it appears that a new generation of heavy lift launch vehicles and orbit transfer vehicles needs to be developed for the task. The development of such capabilities must be included in cost analyses of space power concepts, even though such development would clearly find applicability in other advanced space systems. It is implicit also that techniques of construction in space need to be developed, and that problems concerning the large scale and long-term use of men in space need to be resolved.

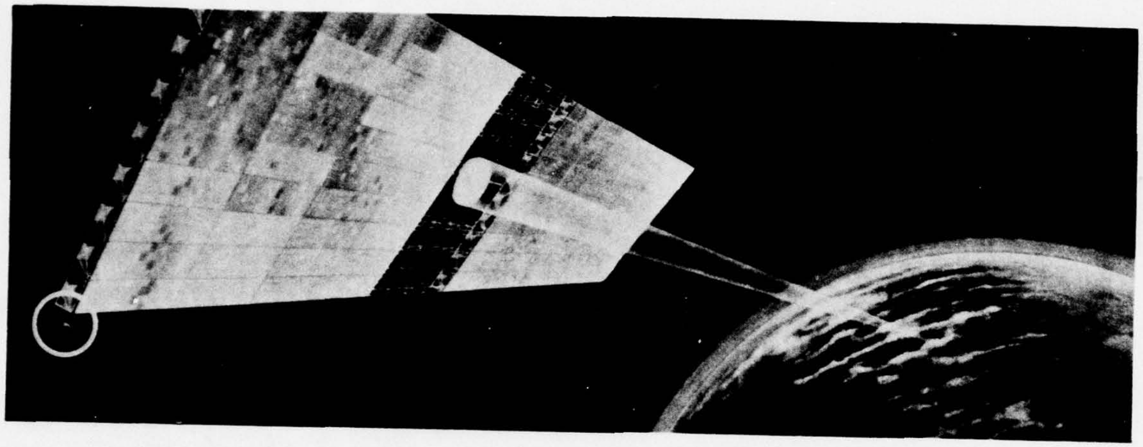

Fig. 2 Glaser's Solar Photovoltaic Power Satellite

Even assuming that the technological problems can all be resolved or circumvented, the acceptability of space power concepts will also depend on their projected impacts on (1) the sociological and political structure of our society, and (2) the surface and near earth environment. The former impacts are, or course, subjective in nature and impossible to quantify. The latter are more amenable to quantitative or, in some cases, at least semi-quantitative treatment.

There are many ways in which life and the environment can be affected by space power systems, either directly or indirectly, and the design of the systems, in particular the transmission power levels, will be strongly influenced by consideration of such factors. Problems of great concern include the effects on humans, animals, microorganism, and the flora and fauna of prolonged exposure to microwave radiation. Thermal pollution effects (i.e. the "heat islands") on the environment also need to be considered. In the atmosphere above the receiving antenna, the problem is dual-natured in that one must consider both the effect of the beam on the atmosphere as well as that of the atmosphere on the beam. In addition to effects directly related to the power transmission system, the impact on the atmosphere and biosphere of the pollutants emitted by the space vehicles in support of the power stations also needs to be assessed.

The impact of space power systems on the earth's atmospheric environment from ground level out to the far reaches of the ionosphere is a subject that has not been dealt with to any depth in the many review articles that have been written on the power satellites. Indeed, since the microwave spectral region was selected for power transmission largely because of the atmosphere's transparency to such wavelengths, it would appear that there should be no impact of any significance on the atmospheric environment. Preliminary space power systems studies [2,4] have, however, identified potential ionospheric problems, and it is these and related atmospheric problems that shall be addressed in this article.

To obtain a better perspective of potential atmospheric/ionospheric problems, it is necessary to delve into greater detail on the design and projections of the sytems, in particular, the characteristics of the microwave beam. Based on considerations of cost effectiveness, size of the space and ground structures, safety levels for the microwave flux intensities at the receiving antenna, the baseline design of a solar power satellite[2] calls for a 1-km diameter antenna in space and a total power delivered to earth of 5,000 MW. The size of the beam at the surface of the earth is about 7-km in diameter, and the average flux of the order of 100 W/m^2. The dimensions of the beam and the flux level through the major part of the atmosphere (i.e. out to about several hundred km) can be taken to be essentially the same as at ground level. The average intensity of the microwave beam when it reaches the earth's surface is much less than the solar constant, which is about 1350 W/m^2.

The ionosphere will absorb on the order of only about a thousandth of one percent of the energy in the beam, which means that the ionosphere will have virtually no impact on the transmission power levels. On the other hand, 0.001% of an average flux level of 100 W/m^2 corresponds to 1 mW/m^2 of energy deposited in the ionosphere, which is of the same order of magnitude as the solar energy contained in the spectral region below 100 nm (the extreme ultraviolet) that represents the major source of heat and ionization in the atmosphere-ionosphere system above an altitude of about 100 km. Figure 3 compares the rate of absorption of energy from the sun with that from a microwave beam of uniform flux 100 W/m^2 at a frequency of 2.5 GHz. These profiles were computed assuming nominal atmospheric and ionospheric models[5,6] representative of average conditions. The neutral upper atmosphere and the ionosphere are actually highly variable in time and space, but the curves should give a reasonable representation of the energy deposition rates on average. The microwave absorption profile does not reflect possible anomalous absorption, which might result if the response of the medium to the additional energy input triggers further enhanced absorption and instabilities.

Of course, microwave and extreme ultraviolet radiations interact in completely different ways with the atmospheric medium, the microwave photons being much less energetic and unable to produce ionization or dissociation of the ambient molecules and atoms. In fact, the solar extreme ultraviolet photons interact initially with the molecules and atoms, whereas the microwave radiation reacts primarily with the ambient electrons. Despite this fundamental difference, energy considerations alone indicate a potentially significant impact on the thermal state of the atmosphere-ionosphere system. It is recognized that such a situation could have portentous ramifications[4], but it is not known exactly what the induced effects will be, and further studies, both theoretical and experimental, need to be conducted.

Cause for concern over potential microwave-induced perturbations of the ionosphere may be attributed in large part to the results of recent radio-frequency ionospheric modification experiments conducted at Platteville, Colorado and at Arecibo, Puerto Rico.[7] Since many unanticipated phenomena

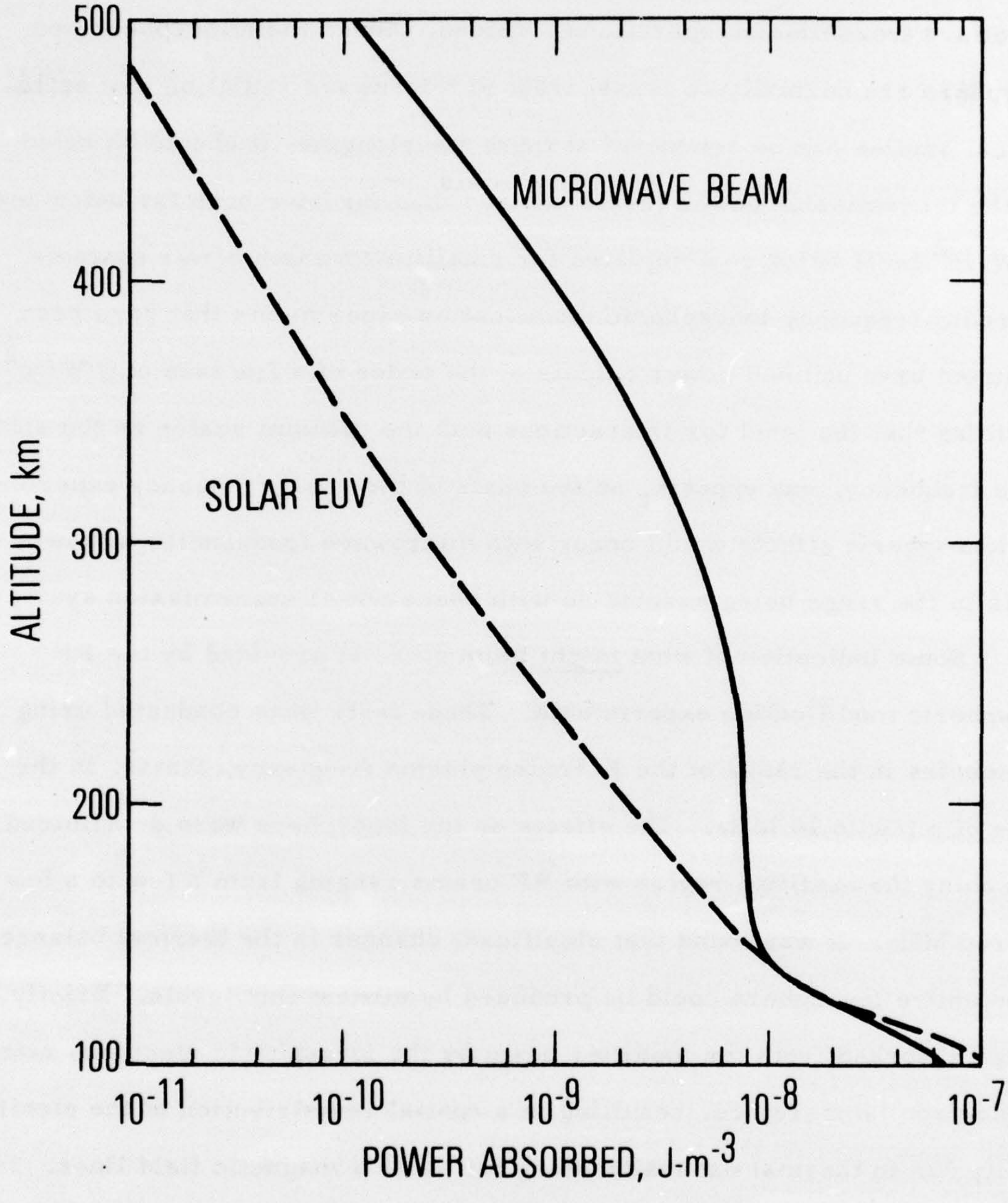

Fig. 3 Solar EUV and Microwave Beam Absorption

were observed in these experiments, similar "surprises" could result from microwave transmission operations. Indeed, though the atmosphere and ionosphere are normally so transparent to microwave radiation that astronomical studies can be conducted at these wavelengths, it should be noted that the transmission power levels utilized thus far have been far below the 100 W/m^2 level being contemplated for satellite-to-earth power systems. The radio-frequency ionospheric modification experiments that have been conducted have utilized power outputs of the order of a few tens of μ W/m^2. Assuming that the level for interactions with the medium scales as the square of the frequency, one expects, on the basis of the radio frequency experiments, that ionospheric effects would occur with microwave frequencies at power levels in the range being associated with space power transmission systems.

Some indication of what might be in store is provided by the RF ionospheric modification experiments. These tests were conducted using frequencies in the range of the F-region plasma frequency, that is, in the range of a few to 10 MHz. The effects on the ionosphere were determined by probing the modified region with RF beams ranging from a few to a few hundred MHz. It was found that significant changes in the thermal balance of the entire ionosphere could be produced by modest flux levels. Briefly, energy absorbed from the modifier beam by the ionospheric electrons raises the electron temperature, resulting in a spatial redistribution of the electron density due to thermal expansion along the earth's magnetic field lines. In the upper ionosphere, this is manifested as a depletion in the electron density, since the electrons diffuse up the field lines. In the lower ionosphere (the D-region, between 80 and 100 km), the increased electron temperature lowers the rate of electron-ion recombination, resulting in an increase in the electron density.

With increased power levels, plasma instabilities are excited that produce additional nonlinear (or anomalous) absorption of the heater beam and result in the generation of field-aligned density irregularities. These irregularities give rise to a number of scattering phenomena, of which the best known is spread-F. This is a condition such that a frequency normally reflected from a well-defined height in the F-region ionosphere is reflected, instead, from a wide range of altitudes due to spatial irregularities in the plasma. The spreading of echos has been observed in the E-region ($\sim$110 km) also. The phenomenon of sporadic-E, the existence of very thin layers of greatly enhanced ionization in the E-region, has been observed to occur concomitant with ionospheric heating experiments, but it has not been firmly established that those sporadic-E events were directly related to the RF experiments.

A number of scattering phenomena have been observed to occur in the modified region. The nature of the phenomena depends on the heater frequency. For example, the scattering region extends beyond the limits set by the heater beam pattern if the heater frequency exceeds the F-region maximum plasma frequency, but at lower heater frequencies the modified region conforms to the heater beam width. Probing frequencies as high as a few hundred MHz were found to be affected by the heated region.

In addition to radio frequency phenomena, optical phenomena have also been observed that are indicative of the physical processes taking place in the modified ionospheric region. Changes in the airglow emission at 630 nm, which is excited by photoelectron impact on atomic oxygen, are caused by the redistribution of electron energies. Enhancement of molecule oxygen infrared emissions at 1.27 μm have also been observed, but the mechanism is not fully understood. The effect occurs not in the primary modified region, but in a region removed from it but along the same magnetic flux tube. This illustrates the complexity and interdependence of atmospheric and ionospheric processes.

Whether the forementioned phenomena would occur if the ionosphere were heated by microwaves is a question yet to be answered. Theoretical studies have not yet been accomplished, but even if they were, one would be reminded that theoretical studies did not accurately predict all the effects observed in the RF heating experiments. A possible ameliorating factor is that microwave frequencies are far-removed from the range of plasma frequencies of the ionospheric regions. While this might lead one to intuitively expect that nothing drastic is likely to occur as with nearly resonant frequencies, the factor of the high flux levels could be counter-active if the levels are sufficient to trigger instabilities in the plasma. In addition to creating problems of concern to communications systems that transmit via the ionosphere, ionospheric modification could affect the space power system design via its influence on the phase and amplitude of the microwave beam.

Of course, any modification of the ionosphere by the microwave beam will be localized in nature and will not have impact on a global-scale. The absorption of energy from the microwave beam will be confined to the beam width, roughly 7 km, but the subsequent interactions and the excitation of instabilities increase the sphere of influence beyond the limits set by the beam width. In the RF ionospheric heating experiments the recovery of the ionosphere to its normal state occurred fairly rapidly following the heater turn-off. For microwave power transmission systems, however, the power will be "on" for the lifetime of the satellite, which is projected to be some 30-100 years, depending on the specific design. Another pertinent point is that the beam position will be essentially fixed in geographic space, due to the use of geosynchronous orbits, and thus any perturbations induced by the microwave beam will not be very effectively diluted as might be the case with a non-geostationary beam.

As part of the systems feasibility and evaluation studies, it will be necessary to determine, both theoretically and experimentally, the nature of the microwave interactions with the ionosphere and its impact on other users of the electromagnetic spectrum. For a single satellite power station, the impact would not be particularly disruptive, but since a fleet of some 50-100 satellites is projected for the USA, and since it is likely that other nations would put power satellites into orbit, the problem takes on new proportions. It may well be that if plasma instabilities can be excited, which would produce ionospheric irregularities and concomitant scattering phenomena that would affect communications as well as the transmitted microwave beam, then the flux level for commencement of such phenomena would serve to define the maximum level for microwave power transmission.

If power were to be transmitted at a level that would produce some perturbation in the ionosphere but still be tolerable by the power system and other users, then it is possible that a good deal of science may be performed as an extra benefit. It is known that fluctuations of both large and small scale occur at all times in the ionospheric electron density, but the study of the physical mechanisms producing the disturbances is usually hampered by the lack of knowledge of the source or driving function. In the case of microwave-beam induced perturbations, the source characteristics would be well-defined, allowing studies of the type of the RF ionospheric heating experiments. A new dimension is provided by virtue of the fact that the microwave source function will be constant in time, whereas in the RF experiments the heater was on for only short intervals.

The ionosphere can also be affected by the exhaust products of the various space vehicles used in the construction and maintenance of the space power stations. A striking example of the consequences of interaction between the ionosphere and booster exhaust gases was provided by the launch of NASA's Skylab 1. The second-stage burn of the Saturn 5 engines deposited large quantities of hydrogen and water vapor molecules in the ionosphere. Rapid ion-atom interchange reactions occurred between the exhaust molecules and the ambient atomic oxygen ions, and the positively charged molecules formed thereby recombined rapidly with the ambient electrons. The net effect was a substantial depletion (≥ 50%) of the total height integrated electron density that persisted for several hours and encompassed a region on the order of 2000 km in diameter. Such "holes" in the ionosphere would certainly create problems for communications systems. Although one or a few of such events might be tolerable, the projected 10 or more Shuttle flights <u>per day</u>[1] in support of the power satellite fleet (mainly for construction, but also for inspection and maintenance purposes) could probably cause serious and troublesome disruption of communications if each flight were to create an ionospheric hole. Clearly, measures would need to be taken to avoid such occurrances.

The molecular effluents from booster engines, particularly water vapor, could also affect the D layer of the ionosphere. This layer is composed mainly of water-cluster ions [i. e. $H^+ \cdot (H_2O)_n$], and thus any increase in the abundance of H_2O is likely to affect the formation rates of the ions and, as a result, the ion density. This problem needs to be investigated in order to determine whether significant alteration of the D region is a possibility.

Another potential pollution problem is presented by the orbit transfer vehicles that will move the completed (or partially completed) power satellites from low earth orbit to geosynchronous orbit. An advanced high performance propulsion system is required for the task, and the one that is favored by many is the solar electric propulsion system, which operates basically by the acceleration and then expulsion of a heavy ionized metal. Preliminary studies have not indicated any serious problems, but further investigation using realistic traffic models is necessary[9].

Thus far, we have considered only perturbations of the ionized component of the atmosphere. What of the neutral component? Of the major atmospheric gases, only O_2 absorbs in the microwave spectral region, but the absorption is not strong enough to affect either the beam or the thermal balance of the atmosphere. Of the trace gases, H_2O is the dominant absorber, but again the impact will not be very great owing to the low abundance of the molecule in the earth's atmosphere. Thus, direct absorption by the neutral atmosphere is not expected to affect either the beam or the atmosphere.

In the upper atmosphere, between about 100 and 400 km, the neutral atmosphere will be indirectly affected by microwave transmission via its coupling to the ionosphere. Some of the energy gained by the ambient electrons from the microwave beam will be transferred to the neutrals either directly by collisions or by intermediary collisions with the heavier positive ions. This transfer of energy would raise the neutral atmospheric temperature. In addition, changes in the ion density would affect neutral wind speeds, as the ions, which are constrained by the earth's magnetic field, provide a "frictional" force that regulates the winds.

The effects on the neutral atmosphere will of course be spatially localized and no significant changes in the global balance of the upper atmosphere are expected. Since the upper atmosphere and ionosphere interact, there will be some feedback to the ionosphere as a result of the neutral atmospheric perturbations, and this feedback or coupling will need to be taken into account in any thorough treatment of ionospheric modification by the microwaves. For example, heating of the neutral atmosphere causes an upwelling (i.e. thermal expansion) which would result in a relative enrichment of molecular species at F-region altitudes and an increased rate of recombination of electrons and ions. Thus, the electron density within the beam-heated column of air would differ from that in the surrounding region. The distribution of the electrons and ions would also be affected by the perturbed neutral wind pattern, since the ions are moved along the earth's magnetic field lines by the neutral wind. It is also likely that the heated column of air, which presents a discontinuity in the medium, will give rise to atmospheric gravity waves. The wave structures, whose scale size and properties would need to be determined, would be impressed on the ionized component and would thereby affect communications systems.

The effects of microwave transmission on the ionosphere and atmosphere above 100 km are summarized in Table 1. The mutual coupling effects are also included.

The major impact on the neutral atmosphere that could have repercussions affecting the biosphere would stem from the effluents of the space vehicles that are need to lift, assemble, and then service and maintain the power stations. The sheer mass of a single power station, some 10^7 kg, clearly indicates that a high rate of Shuttle launches and orbit transfer vehicle activity will be necessary. At the present time only rough estimates can be made, but the projected rate of about 10 Shuttle launches per day in the early 21st century, at the peak of the construction phase of the power satellite fleet, should be indicative of the volume of traffic to be expected.

The biospheric problems that may arise as a result of the release of booster exhaust products are similar to those widely discussed in connection with stratospheric pollution by SST's and other high flying aircraft. However, the Shuttle problem is accentuated by the fact that the exhaust is released throughout the atmosphere from ground level up to at least the thermosphere. In the troposphere, residence times of injected compounds are relatively short, typically of the order of weeks, so that "cleansing" is rapid. However, the residence time increases with altitude, and ranges from about a year in the lower stratosphere to about 10 years in the upper stratosphere. Thus, the accumulation of exhaust products becomes a critical factor.

TABLE 1

POSSIBLE EFFECTS OF MICROWAVE BEAM PROPAGATION

IONOSPHERE

- Electron temperature increase
- Electron density decrease in D-region, increase in F-region
- Modification of electron energy distribution
- Anomalous absorption and heating, leading to field-aligned irregularities and radio scattering phenomena

THERMOSPHERE

- Neutral temperature increase
- Modification of relative composition
- Modification of airglow characteristics
- Excitation of atmospheric gravity waves

MUTUAL COUPLING EFFECTS

- Neutral composition affects the electron-ion recombination rate
- Ion density affects the neutral wind system
- Neutral winds and gravity wave structure affect the ion distribution

Although effluents will be released over a wide range of altitudes, the region of greatest concern is the stratosphere (~ 10-50 km), because it provides the protective layer of ozone that shields the earth's surface from solar ultraviolet radiation. It is well known that an increase in the ultraviolet flux at ground level will result in an increase in the incidence of skin cancer among humans. However, the consequences are of even greater scope, encompassing the biosphere as a whole, since any change in the ultraviolet spectral characteristics is likely to affect other forms of plant and animal life and microorganisms as well. The potentially dangerous exhaust products that could reduce the ozone content if injected in sufficient quantities are the NO_x and chlorine compounds.

Besides affecting the ultraviolet absorption characteristics, any modification of the structure of the atmosphere is likely also to have impact on the surface climate, since the radiative balance of the earth-atmosphere system is strongly regulated by infrared-active molecules and aerosols in the atmosphere. The populations of both of these components can be altered by large-scale pollution. An assessment of the climatic impact is by no means simple. On the one hand, one must consider the increase in IR absorbers and radiators (molecules like H_2O, CO_2, CO, O_3) that would enhance the "greenhouse effect" and produce an increase in the average surface temperature. On the other hand, certain effluents would react photochemically and form aerosols, which partially shield the surface from the incoming solar rays and thereby counteract the greenhouse effect. Other feed-back mechanisms (such as temperature-induced changes in the snow and ice cover, which would alter the earth's albedo) add to the complexity of the problem.

A large number of studies have been performed on the problem of stratospheric pollution from aircraft, and similar studies would need to be repeated for the advanced space transportation system envisioned for the future. The SST studies were not conclusive or totally satisfying to all critics, and, if anything, they highlighted the uncertainties in current knowledge of the structure and dynamics of the stratosphere and of the relevant chemical reaction rates. Although a good deal of research on chemical reaction rates and stratospheric composition has been initiated as a result of the SST problem, substantial gaps in knowledge still exist, particularly concerning the global behavior of stratospheric circulation, and thus an assessment of the environmental impact of the advanced space transportation system will not be an easy task.

A list of the ways in which booster exhaust products may affect the stratosphere and ionosphere is presented in Table 2. The list is by no means complete, particularly with regard to effects on the higher atmospheric layers (the mesosphere and thermosphere), but since virtually no research has been done concerning pollution effects at such high altitudes, it probably is best not to speculate at this time on the possible consequences.

NASA's Satellite Power Team, headed by Dr. William B. Lenoir of Johnson Space Center, has recently assessed the critical areas of satellite power systems concepts[9], and, in connection with microwave beam propagation and transportation system pollutants, the following objectives of required efforts were identified:

TABLE 2

POSSIBLE EFFECTS OF SPACE TRANSPORTATION POLLUTION

- Creation of ionospheric "holes"
- Modification of D-region water cluster ion chemistry
- Modification of stratospheric-mesospheric trace gas composition, aerosol distribution, thermal balance

Microwave Beam Propagation

- Preliminary design studies with meteorologists and atmosphere-ionosphere experts to define propagation environments.
- Detailed analysis and calculation of propagation effects; measurements and experiments; determination of flux density limitations.

Transportation System Pollutants

- Determination of all emissions of stages and boosters considered for satellite power systems.
- Determination, using an appropriate traffic model, of the impacts of the various exhaust products (including NO_x produced by the plume), of heavy ion injection, and of ionospheric F2-layer interruption (the ionospheric "holes" caused by launches).
- Study and classification of short, medium, and long-term effects.
- Identification of secondary impacts.

The recommended studies are part of an overall near-term "get smart" program to examine and evaluate those aspects of space power concepts "that presently constrain our ability to project the economic viability of satellite power systems". Assessment of the ionospheric propagation and atmospheric environment effects will no doubt have impact on decisions related to microwave power levels and the propellants and propulsion systems to be used by the transportation system.

It is of great significance to note that in the 21st century the power satellite fleet will probably be only one of a number of space systems that will be operating to serve mankind[10]. Ultimately, and in the near future, an assessment of the pollution problem related to space transportation will be required that will encompass not only the activities associated with the power satellite fleet, but with all other large-structure space concepts as well. Realistic traffic models, including allowance for growth on an international basis, will be crucial for a realistic assessment of potential impacts. The utilization of space holds great promise for improving the quality of life on earth, but we should ensure that such activities do not precipitate events that could ultimately have adverse effects on life.

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