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MASTER

ENVIRONMENTAL EFFECTS OF SPACE SYSTEMS

by

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ENVIRONMENTAL EFFECTS OF SPACE SYSTEMS

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Abstract

This paper reviews the potential effects of large space systems, primarily the Satellite Power System (SPS), on the upper atmosphere. From 56-500 km, the major contaminant sources are SPS microwave transmissions and rocket effluents. Although no significant effects have yet been found for microwave transmissions, deposition of rocket effluents causes compositional changes, most of which appear to be associated with the release of large amounts of water. The formation of "ionospheric holes" is an example of a modification resulting from the injection of propellant exhaust in the F-region. From 500-36,000 km, rocket effluents and ion engine contaminants (primarily Ar+) could alter magnetospheric and plasmaspheric structure and dynamics. One of the major impacts of these alterations could be perturbation of Van Allen radiation belt stability, leading to changed radiation hazards to materials and personnel.

I. Introduction

The unique properties of the Earth's space environment make it an attractive place for a broad spectrum of scientific, commercial, industrial, and military activities. Current and promised additions to the launch vehicle arsenal including the Ariane I and II and the Space Shuttle support the expectation that these activities will continue to proliferate in the foreseeable future. The proposal to use space as an alternative terrestrial energy source as epitomized by the Satellite Power System (SPS) adds yet another dimension to this exploilation of space. Such proliferation has resulted in increased concern about preserving the very unique properties of space that stimulated its exploitation in the first place. Already we are confronted with the formidable task of keeping track of literally thousands of pieces of hardware in low earth orbit. According to Mokhoff[1], 93 communications satellites occupy or will shortly occupy the geostationary orbit (GEO) environment. Add to this an anticipated[2] 200 new satellites in the next decade and the possibilities for crowding of both the physical and the electromagnetic environment are obvious.

To place the scale of the proposed activities in proper perspective it is worthwhile reviewing some pertinent details.

The Ariane I is a conventional 3-stage rocket with a gross lift-off weight of about 207 tons. The first two stages will burn unsymmetrical dimethyl hydrazine (UDMH) fuel with a nitrogen tetroxide (N_2O_4) oxidizer. The third stage operating in the altitude range of 138 to 213 km, will burn liquid hydrogen with a liquid oxygen oxidizer. According to present plans, the Guiana Space Center from which the Ariane will be launched can handle up to four or five launches per year.[2]

The reuseable Space Shuttle will have a gross lift-off weight about ten times that of the Ariane I. From 0 to 43 km thrust will be provided by the three space shuttle main engines (SSME's) that burn LO_2/LH_2 in combination with two solid-fuel booster engines. Between 43 km and typically 215 km only the SSME's operate. Final orbit insertion, orbital maneuvering, and return are accomplished with the orbit maneuvering and reaction control systems, both of which utilize thrusters that burn monomethylhyrazine (MMH) with N_2O_4 as an oxidizer. Up to 60 launches per year are anticipated. One of the early uses of this system could be for SPS technology verification.[3]

Continuing up in size and launch frequency, Glaser has proposed that the SPS produce baseload power for the utility electric power grid.[4] A reference design has been developed by the National Aeronautics and Space Administration (NASA) and is being used in a Department of Energy (DOE)-sponsored program to evaluate the environmental and socioeconomic impacts of the SPS, as well as its technical feasibility.[5] Briefly, the NASA reference design utilizes 60 satellites in geosynchronous orbit to collect solar energy, convert it to microwave energy, and transmit it to the Earth's surface, where receiving antennas (rectennas) rectify the microwave radiation to DC power. Each satellite delivers 5 GW of power to the grid. The total system is projected for operation around the year 2020 and is expected to supply approximately 20% of that year's total U.S. electrical energy demand.

One should not lose sight of the fact that an international SPS could conceivably be much larger and contribute significantly to the fraction of global demand for electric power that could be satisfied by all forms of solar energy.

The types of rockets required for space transportation for the NASA reference design are listed in Table 1. The largest of the proposed space vehicles is the HLLV. It will have a gross lift-off weight approximately 5.5 times that of the space shuttle. It's first stage will burn methane and oxygen to an altitude of about 56 km. Thereafter the second state consisting of 14 SSME's will burn to an altitude (adjustable) of 124 km. Circularization and deorbit burns near 500 km will use these same engines. The initial construction phase involves building base stations at low Earth orbit (LEO) and geosynchronous earth orbit (GEO). The space components of the system (solar satellites, microwave generators and transmitters) would be constructed in space from materials delivered to the LEO base station and then transferred to the GEO construction site.

Figure 1 shows the scenario for construction of two 5-GW satellites per year. Note that two photovoltaic options are indicated: (1) the use of silicon cells (si) and (2) the use of gallium

Table 1. SPS space transportation vehicles.

Name	Abbreviation	Function	Propellants	Launch Rate[a] ($year^{-1}$)	Operating Altitude (km)	Main Exhaust Products
Heavy-lift launch vehicle	HLLV	Transport of materials earth surface to LEO	CH_4/O_2 (Stage 1)	375	0-57	CO_2, H_2O
			H_2/O_2 (Stage 2)	375	57-120	H_2O, H_2
			H_2/O_2 (circularization/deorbit)	375	450-500	H_2O, H_2
Personnel launch vehicle	PLV	Transport of personnel earth surface to LEO	Details not available (probably same as HLLV)	30	0-500	CO_2, H_2O, H_2
Cargo-orbit transfer vehicle	COTV	Transport of materials LEO to GEO	Argon H_2/O_2	30	500-35,800	Ar ion plasma H_2O, H_2
Personnel-orbit transfer vehicle	POTV	Transport of personnel LEO to GEO	H_2/O_2	12	500-35,800	H_2O, H_2

[a]Assuming construction of two (silicon option) 5-GW satellites/year.

aluminum arsenide cells (Ga). If maintenance operations are included, as many as 500 heavy lift launch vehicle (HLLV) flights per year are required to construct 60 satellites over a 30-year period.

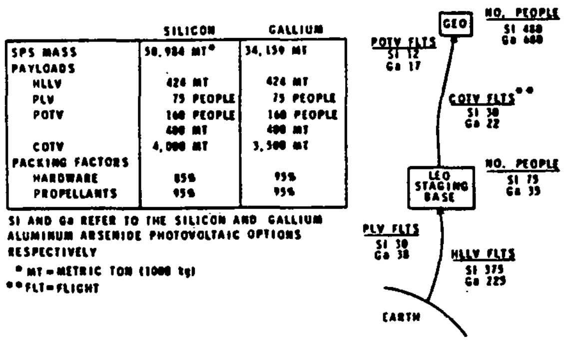

Fig. 1 Scenario for construction of two 5-GW satellites per year (Source: Ref. 5).

The major potential impacts on the space environment of the SPS and the space vehicles described above derive from: (1) SPS generated microwave interference with telecommunication systems, (2) transmission of the SPS microwave power beam through the atmosphere, (3) deposition of rocket effluents and ablated materials in the atmosphere, and (4) structures in orbit.

This paper, which is an abbreviated and somewhat updated version of a more detailed review given in Ref. 6 summarizes our present state of knowledge regarding the atmospheric effects of the SPS and other space vehicles (items (2), (3), and (4), above). Interference with telecommunication systems, while an ultimate impact of various atmospheric effects described here is not explicitly dealt with. Readers interested in this latter topic should consult Ref. 7.

Section II contains a summary of the effects of transmitting power through space. The impacts of rocket effluents and ablated materials being injected into various regions of the upper atmosphere are addressed in Sec. III. Section IV describes some of the anticipated effects of large space structures in the magnetosphere.

II. Microwave Effects

The greatest benefit of a system designed to collect solar energy in space for subsequent transmission to the Earth's surface is the essentially constant exposure (except for occultations) to direct solar radiation (1350 W/m^2) as opposed to the diurnally varying, attenuated solar radiation received on the Earth's surface (150-570 W/m^2). Several proposals have been made for the transmission of energy from the space environment to the Earth's surface. These include solar radiation reflected from large mirrors, infrared laser beams, and microwave beams. The advantage of microwaves over the other alternatives is the relative transparency, even during storm conditions, of the atmosphere to the reference system frequency of 2450 MHz. This power transmission frequency is situated in the middle of the IMS user band (2450 ± 50 MHz) and is just above the upper limit of the Eastern European IMS band (2375 ± 50 MHz). It is essentially a compromise between increasing absorption by hydrometeors in the atmosphere at higher frequencies and increasing interactions with the ionosphere at lower frequencies.

The major concern regarding the transmission of microwaves through the atmosphere is interaction with the ionosphere.[8,9] Modifications to the ionosphere could affect the propagation of both the SPS microwave power and pilot reference beams, as well as the propagation of other frequency bands used by terrestrial and satellite communication systems. The pilot reference beam is used to maintain phase coherence and was originally designed to be transmitted from the center of the rectenna to the power beam transmitter in GEO. However, due to potential control problems associated with changes in propagation properties through the column of the atmosphere exposed to the power beam, the point of emanation of the pilot beam will probably be shifted to a location remote from the rectenna.

The power beam has a Gaussian shape with a center power flux density of 22,000 W/m^2 at the transmitting antenna (1-km diam) and 230 W/m^2 at the rectenna. The rectenna is roughly 10 km in diameter and has a power flux density at its edge of 10 W/m^2. The rectenna's shape is adjusted according to the angle of incidence of the power beam. The maximum power flux density at the rectenna, which is approximately equal to that in the ionosphere, represents a compromise between exceeding the threshold for enhanced electron heating in the ionosphere (discussed below) and further increasing land use requirements.

The two main phenomena are enhanced electron heating, which results in elevated free electron temperatures and a plasma instability called thermal self-focusing, which results in plasma density and beam density irregularities.

Enhanced electron heating is a lower ionospheric phenomenon that results in increased temperatures of local free electrons. These temperatures were predicted to be on the order of several hundred degrees Kelvin.[8] An experiment to verify these predictions was conducted at Arecibo. However, because of frequency limitations, a scaling law saying that ohmic heating scales inversely as the square of the driving frequency was employed to simulate SPS effects. The heating experiment resulted in about a 100 K temperature increase. According to Duncan,[8] most of the discrepancy between theory and experiment has been resolved. One reason for the low experimental value was thought to be a heating pulse that was too short in duration (nine million-seconds) to reach the maximum value. In any case, before reliable estimates of SPS heating effects can be made, it will be necessary to verify the scaling procedures used to extrapolate to the SPS reference design parameters.

The thermal self-focusing instability is an F-region plasma effect that can give rise to large-scale variations in both the ambient plasma and in the beam profile. The threshold for exciting this instability is about 50 W/m^2 for the SPS frequency of 2450 MHz and is therefore, according to Duncan,[8] well below the proposed peak power density of 230 W/m^2. Hence, one can expect self-focusing to occur. Depending on the degree of induced density fluctuations, this instability could cause significant modifications to high frequency (HF) and pilot reference beam propagation. It has not yet been possible to verify these effects with existing experimental facilities. However, as reported by Duncan, planned upgrading of the Arecibo and Platteville facilities will permit simulations of SPS power beam effects. Therefore, Duncan concludes that "no significant telecommunications or climatic effects have yet been experimentally demonstrated."

III. Rocket Effluents and Ablated Materials Effects

Direct deposition of rocket effluents can, of course, occur throughout the entire space environment. Upper atmospheric releases from the Space Shuttle missions will be typically confined to the altitude range of 43 to 215 km.[9] Orbit circularization and other maneuvering will vary widely with specific missions. The SPS transportation vehicles will routinely operate in three altitude ranges: 56-124 km, 450-500 km, and 500-36,000 km. Hence, for convenience, the upper atmosphere has been divided into the following three domains:

Domain A 56-124 km,
Domain B 124-500 km, and
Domain C 500-36,000 km

Since the SPS vehicles will be the dominant source of rocket exhaust in the foreseeable future, emphasis will be placed on effluents from those vehicles in the following discussion.

A. Sources

Domain A. Sources

As shown in Table 1, the major source of rocket exhaust in Domain A is the second stage of the HLLV, with the primary combustion products being H_2O and H_2. Because of the shape of the HLLV trajectory, (Fig. 2) a substantial fraction of the total effluent is injected between 110 and 124 km, i.e., just above the turbopause. The personnel launch vehicle (PLV) also burns its engines in this region, but details regarding its trajectory are not available. In any case, the HLLV exhaust will dwarf that of the PLV.

The other main source of pollutants in Domain A is vehicle reentry. Reentry results in ablation of materials from the vehicles and heat shields and in production of nitric oxide (NO). Estimates by Park suggest that the mass of NO produced should equal about 22% of the mass of the vehicle.[10] With peak production at around 70 km, the NO should be distributed between 55 and 100 km.

A less significant source of pollutants in this region is waste material and construction debris. Assuming that the equivalent of one percent of the total mass of two 5-GW satellite systems sould be lost each year. Whitten[12] estimates that this source would amount to about 10^6 kg/yr of material ranging in size from fine dust to relatively large objects that might reach the Earth's surface intact. Approximately half of this material might be metallic, with the remainder being oxides of aluminum or silicon. Based on estimates by Park and Menees,[13] however, the annual injection rate of meteoritic material (4×10^7 kg/yr) would exceed this man-made source by more than an order of magnitude.

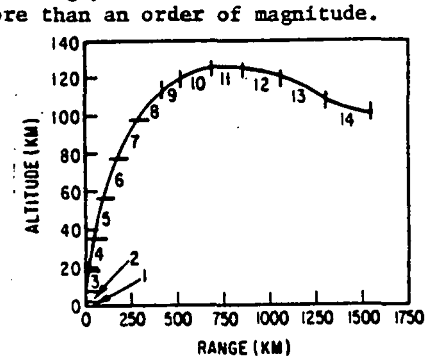

Fig. 2 SPS heavy lift launch vehicle trajectory. (Source: Ref. 5).

Domain B Sources

The major sources of effluents in Domain B are the circularization and deorbit burns of the HLLVs and PLVs, as well as similar burns of the personnel orbit transfer vehicles (POTV). In each case, the propellant is LH_2/LO_2. One can also expect minor injections of combustion products from the space-shuttle-type orbit maneuvering system (OMS) and reaction control system (RCS) engines that will presumably burn monomethylhydrazine and nitrogen tetroxide. In addition to these chemical rockets, the electric ion engines of the cargo orbit transfer vehicle (COTV) deposit some argon ions and electrons in the region near Domain B, although most of these effluents are injected at higher altitudes.

Domain C Sources

There are five engine burns in all for each POTV round trip between LEO and GEO. A typical scenario includes a deorbit burn of the first stage rocket at LEO, stage separation and circularization burn of the second stage rocket at GEO, deorbit burn of the second stage at GEO, circularization of the second stage at LEO, and circularization of the first stage at LEO. In addition to the two burns at GEO, other effluent sources in Domain C include the electric ion propulsion system and the chemical rockets used on the COTV for control during eclipses of the sun by the Earth.

B. Effects

Stratospheric and Mesospheric Effects

Theoretical calculations indicate that exhaust emissions of carbon dioxide[14] and nitrogen oxides[15] would have no detectable effect on the composition of the stratosphere or mesosphere, due to the relatively small quantities of these substances that are emitted compared with the amounts already present in the natural atmosphere. On the other hand, periodic reentry of an HLLV second stage is expected to result in a general enhancement of the nitric oxide concentration in the mesosphere by a factor of approximately two in a 45 degree-wide corridor centered on the reentry latitude.[15] In addition, localized regions of high NO concentration may persist for 24-48 hours after each individual reentry event. Higher than normal electron densities on both local and global scales are also expected in association with this enhancement in the NO concentration.

The emission of substantial amounts of water and hydrogen are also expected to have non-negligible effects. Model calculations indicate that on a global basis, the water concentration in the upper mesosphere will be increased by approximately 0.4% and the ozone concentration at the same altitude is expected to decrease by approximately 0.4%. The corresponding decrease in the total integrated ozone column density is only about 0.02% globally, and about 0.1% within a 40 degree-wide corridor centered on the launch latitude. This decrease would be undetectable, and the resulting increase in the incidence of solar ultraviolet radiation at ground level would also be undetectable. In addition, theoretical calculations[15] indicate that within the same corridor, the water concentration at the top of mesosphere will increase by about 15% above the normal level. Composition changes in the stratosphere would be much less than 1% and no large-scale atmospheric effects are expected at those altitudes.

The passage of a large rocket such as the HLLV through the mesopause, the region around 85 km corresponding to the lowest observed atmospheric temperatures, is likely to result in the formation of an artificial noctilucent cloud. Such clouds have been observed on several occasions following the launching of rockets of various sizes, ranging from relatively small research rockets to larger ones intended to place a satellite in orbit.[16] These observations have been made at middle latitudes, where natural noctilucent clouds have never been observed. The lifetimes of such clouds are uncertain, since observations must be made after sunset and in all cases to date the cloud has persisted beyond the point at which it is illuminated by the sun. Theoretical estimates indicate lifetimes on the order of several hours for clouds produced during an HLLV launch.[17]

In view of the predicted enhancement of water near the mesopause, the possibility of a buildup of noctilucent clouds around the launch latitude must be considered. Based upon the theoretical calculations discussed above, the expected increase will still not be sufficient, by a considerable margin, to cause the formation of a permanent global-scale cloud. In light of this expectation, no significant climatic or other effect is expected due to noctilucent cloud formation.

D- and E-Region Plasma Depletions

The participants in the Ionospheric and Magnetospheric Workshop[18] held in August 1978 suggested that water injection will tend to convert the region from ≈ 80 to 100 km from one dominated by light molecular ions to one dominated by heavier water-cluster ions that can recombine more rapidly with the free electrons. This will lead to a reduction in the daytime free-electron density. This idea has since received further support both by participants at the La Jolla Workshop[19] and by calculations recently performed by Forbes[20] and those in progress by Whitten et. al.[15] Forbes has estimated that water vapor concentrations ≃ 100 ppmv (parts per million by volume) would lead to a near complete conversion to the water cluster ions within a cylindrical volume between 70 and 100 km altitude and having an area of 20,000 km^2. Combined with the loss of electron production caused by screening of UV radiation by water molecules, Forbes estimates a 75% reduction in the daytime free-electron density over this same volume. If such depletions were indeed limited to such small volumes they would not be expected to be of much concern. The size of the region affected is critically depended on a number of parameter values used by Forbes including neutral wind speeds, diffusion rates, and the photolytic lifetime of water (~ 2 days). Using the same parameter values, Forbes also estimates that the size of the high concentration region is not expected the grow even for several launches per day.

Another effect of the large injections of water is that by photolysis it will greatly enhance the populations of OH radicals and H atoms

The hydroxyl radicals are important sources of airflow in the near IR. The H atoms will participate in mesospheric chemistry to some extent, but most will tend to diffuse into the thermosphere. A qualitative estimate by Forbes suggests that this upward flux of H atoms will result in about 10% or more attenuation of UV radiation on a global scale. This would probably produce a small chronic reduction in D- and E-region daytime ionization. On the other hand, increased concentrations of H atoms in the geocorona will scatter UV radiation at nighttime and this will cause an increase in nighttime D- and E-region ionization. It is not known what impacts such long-term changes in the diurnal pattern of ionization would have. However, it has been noted that such patterns are related to electromagnetic coupling between the E- and F-regions.

A possible compensating effect on the D- and E-region plasma density reductions could result from the production of NO by reentering space vehicles and debris. Since ionization of naturally occuring NO is the main source of free electrons in the D- and lower E-region, enhanced NO concentrations could increase the free electron content. Whitten, et al.,[15] conclude that production by reentry will increase ambient NO concentrations by a factor ≤2 in a global 45°-wide corridor centered on the reentry latitude. This may more than compensate the plasma reduction and lead to a net enhancement of D- and E-region plasma density. Hence, it will be necessary to evaluate the net effects of these compensating mechanisms more closely.

The consequences of substantial changes in D- and E-region plasma density and therefore electrical conductivity have only been conjectured. If the large plasma reductions are confined to small areas as indicated above (≈ 20,000 km^2) it is unlikely that they would significantly affect VLF, HF or VHF wave propagation or coupling between the upper and lower atmosphere in a manner that would influence climate or weather. On the other hand, and this is quite speculative, if the electrical conductivity were to be altered on a large scale as in F-region depletions, then it is plausible that such changes could lead to alteration of radio wave propagation, especially VLF, and possibly to large-scale changes in electric fields and current systems. The high latitude conductivity distribution is especially important because this part of the ionosphere completes the electrical circuit that couples the auroral zone to the outer magnetosphere. The currents that flow through this circuit undergo large fluctuations during magnetic substorms and have been known to cause damaging current surges in power transmission lines and long telephone lines. Alteration of the auroral zone conductivity could modify the morphology of this current system and influence the occurrence or intensity of terrestrial current surges, perhaps moving them to more populated areas. Markson[21] has suggested that, since the lower ionosphere is part of the global atmospheric electric circuit through which currents are driven by thunderstorms, large-scale perturbations in the conductivity, especially if they reach down to the middle stratosphere, may influence thunderstorm processes and therefore weather and climate. It is not possible to assess these speculative effects at this time.

F-Region Plasma Depletions

Rocket effluents (H_2O, H_2, CO_2) change the dominant O^+ ions to molecular ions, which very rapidly recombine with the free electrons. The net results are the removal of electron ion pairs at a rate 1000 times faster than normal, the production of prompt, intense chemical air low, and the release of large numbers of hydrogen atoms. The rapid loss of electron-ion pairs results in an ionospheric hole that extends far beyond the local source of injected molecules and may be extended to the conjugate ionosphere (i.e., cause a hole at the opposite end of the geomagnetic line that passes through the initially depleted region).

The 1973 launch of Skylab with a Saturn V rocket injected a substantial amount of rocket exhaust into the F2-region of the ionosphere. The trajectory of that rocket accidentally intercepted radio-signal ray paths connecting the ATS-3 communication satellite with the ground-based observatory at Sagamore Hill in Massachusetts. The deep depression in the total electron content (TEC) observed at Sagamore Hill after the rocket passed the intersection point is shown in Fig. 3. Based on observations made at four other ground-based observatories whose lines-of-sight with ATS-3 also were intercepted by the resulting depleted region, it was reported that the ionospheric hole had a radius of about 1000 km and lasted for about four hours.[22] Unfortunately, because the observations were not planned, they were somewhat incomplete.

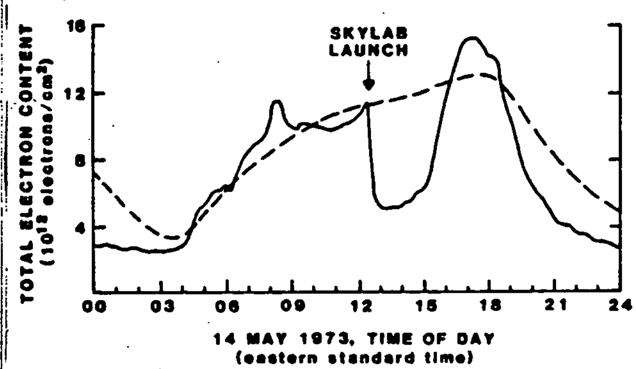

Fig. 3 "Hole" seen in the total electron content measurement of the ionosphere by the Sagamore Hill Observatory (Source: Ref. 22).

The first successful attempt to produce a midlatitude, ionospheric depletion under controlled experimental conditions occurred in September 1977. Project "LAGOPEDO",[23] as it was called, involved two rocket-borne experiments. Each rocket carried 88 kg of high explosives and an instrument package that was separated from the rocket prior to detonation of the explosive. The detonation products included about 30 kg of H_2O, 16 of CO_2, and 20 of N_2. These experiments generally confirmed theoretical predictions of a signature effect, i.e., an initial period of several seconds during which the ambient plasma was swept away by the rapidly expanding detonation cloud over a distance of less than 1 km followed by a much larger-scale, plasma-depletion process lasting for at least 30 minutes and extending to a radius of 30 km or more. In addition to the rocket-borne instrument package, which sampled the disturbed area for two to three minutes, ground-based instruments monitored the hole for about 30 minutes until the satellite beacon was turned-off. A major question that arose from these two experiments was the importance of the suppression of the participation of the water molecules in the electron-ion removal process through initial formation of ice crystals followed by gravitational settling to lower altitudes where the presence of the water was unimportant.

Hence, through 1978, the sum total of relevant data consisted of an incomplete set of accidental observations made of the Skylab launch of 1973 and the planned, but rather short-term and small-scale observations of the two explosive releases of the Lagopedo Experiments. Fortunately, the planned launching of the HEAO-C Satellite in September 1979, was discovered in the Spring of 1979 to be an excellent opportunity to observe a large-scale ionospheric modification caused by a LO_2/LH_2-fueled rocket engine burn.[24,25] Through careful planning and coordination a monitoring campaign involving some 17 separate research groups plus the cooperation of approximately 150 Ham radio operators and several commercial station operators and listeners provided the most complete case study of a large-scale ionospheric modification to date.[26] Fig. 4 shows the ground track of the rocket launch trajectory through the ionosphere and several of the ray paths used to monitor the ionospheric disturbance. The disturbed region of the ionosphere is shown as a dashed, kidney-bean-shaped area. The Centaur stage of the Atlas/Centaur launch vehicle burned its engines from 211 to 501 km altitude and injected about 77×10^{29} H_2O and H_2 molecules. For comparison, the HLLV circularization burn at 477 km altitude will inject about 9×10^{29} molecules. Hence, the magnitude of the injections are nearly equal but in the case of the HLLV circularization burn the injection occurs at a higher mean altitude and therefore will result in a somewhat larger dispersion of exhaust molecules and larger depletion region.

SPS Predictions for a Single HLLV and PLV Circularization Burn

A single HLLV circularization burn and to a lesser extent a PLV circularization burn will produce an ionospheric hole not greatly different from that produced by the September 1979 launch of the HEAO-C Satellite. This has been confirmed by a noontime circularization burn simulation by Zinn.[17] He predicted a 1000 km x 2000 km region over which the electron concentration would be reduced to 1/3 its normal daytime value. The ionosphere would return to normal in about 5 hours. A nighttime hole would, of course, remain until sometime after sunrise as did the HEAO-C hole. Based upon experience with the HEAO-C launch, a hole of at least the size predicted by Zinn and perhaps one somewhat larger can be expected. In addition, one would expect airglow intensities and radio wave propagation effects similar to those seen in the HEAO-C case. The radio wave effects would probably be detectable if looked for, but would not be expected to seriously degrade amateur or commercial short wave radio operations. Effects on VLF and VHF beacon

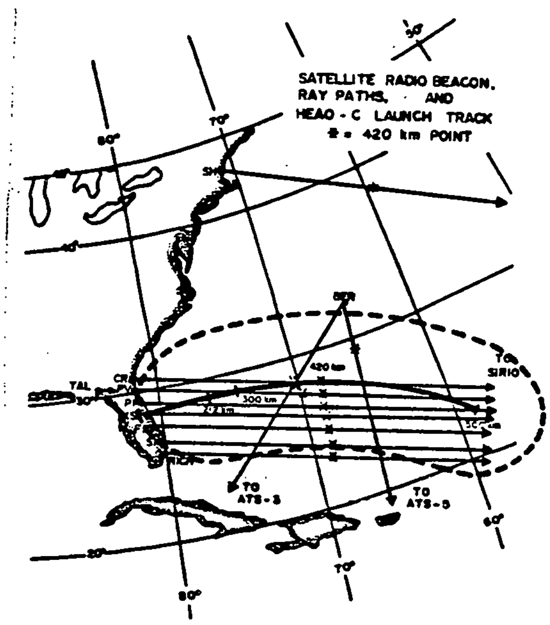

Fig. 4 HEAO-C Satellite Launch of Sept. 1979 produced an ionospheric hole indicated by the dashed kidney-bean-shaped region. Straight lines depict ray paths to satellites in GEO. Heavy curved line represents the rocket trajectory.

propagation seem rather uncertain at this time and should be looked into further. If LEO is to be located near the magnetic equator then observations should be made to verify or refute the prediction of creation of artificial Spread-F.[27,28]

SPS Predictions for a Single POTV Burn Near LEO

A single POTV injection burn produces ten times as many exhaust molecules (10^{31}) as the HLLV circularization burn. That is, about as many exhaust molecules as the Skylab burn of 1973. If other things remain unchanged then the geographic area covered by the hole would be roughly ten times that of the HLLV circularization burn hole or about 2×10^7 km^2 (twice the size of the U.S.). The Saturn V hole morphology is not completely known because of incompleteness of the data. Mendillo,[22] reported that it covered an area of about 4×10^6 km^2 and lasted for about four hours after a noon-time launch. Zinn,[17] however, has suggested that, if characteristic thermospheric winds prevailed at launch time, (no actual wind data is available) the hole actually lasted until sunrise the next day. Zinn reconciles his estimate with the 4-hour lifetime reported by Mendillo by pointing out that the hole was probably blown out of the observatory's line of sight with the ATS-3 satellite after 3 or 4 hours.

Hence, we expect a noontime POTV burn to produce a hole lasting for 4 to 16 hours. Since the hole will cover an area equivalent to the Continental U.S.A., the radio wave propagation effects would be more widespread but not necessarily more severe or long lasting. The severity and duration of the fading of HF signals beyond that observed in the HEAO-C launch cannot be predicted with any confidence at this time.

SPS Predictions for a Single HLLV 2nd Stage Burn (56-124 km)

Unfortunately, no data is available to assist in the prediction of the F-region depletion caused by the HLLV 2nd Stage burn. Hence, it is necessary to rely entirely on the theoretical model calculations. Each such burn releases about 2×10^6 kg of exhaust, most of it in an altitude range of 110 to 124 km. Zinn[17] has performed a calculation taking into account only those molecules released between 118 and 124 km (about 40% of the total 2nd stage emissions). Following the launch at noon from Cape Kennedy, some of the exhaust molecules slowly diffused up to the F2 layer where they reacted with O^+ ions. After sunrise, the O^+ ions are produced about as fast as they are destroyed so that the net effect is only a 10% reduction during the daytime. However, during the following nighttime the O^+ and free electron concentrations were gradually reduced to about 70% of their normal values. Since Zinn only carried the calculation out for about 36 hours, it is unclear whether this low-level depletion process would continue into the next night, etc. However, since the H_2O and H_2 molecules would eventually be photolyzed (in a few days) the depletion process would cease after a few days. This low-level, long-lived depletion from a single 2nd stage engine burn is not expected to have any significant impacts. In fact, it would probably be difficult to detect, except possibly during magnetically quite times.

Multiple Launch Effects in the F-region

No detailed calculations have been possible of the effects of multiple launches on the F-region. Existing models are not adequate to handle the global scale processes. Hence, for the purposes of this assessment, only relatively simple, crude estimates can be made.

The total number of electrons and ions in the ionosphere is of the order of 10^{32}. Taking into account 2 HLLV launches per 24-hour period and the fact that each exhaust molecule can potentially recombine 2 electron-ion pairs, the theoretical maximum number of pairs that could be removed, assuming that the exhaust molecules were ideally distributed (100% efficiency), is 4 times as great as the number present. If the HLLV exhaust distribution system were 2.5% efficient, the total global ionosphere would suffer a chronic 10% depletion (this would vary with time of day and location).

It is therefore, at least plausible that a belt-like region of the ionosphere surrounding the globe at the launch latitude would have superimposed on twice daily severely depleted regions of size 1000 x 2500 km a roughly 10% or more chronically reduced free-electron density. To this would be added one POTV burn per month producing a depletion of the order of 3000 km by 8000 km. Such a belt could have a width of the order of 2,000 to 10,000 km. This would require an overall electron-ion recombination efficiency of between 0.2 and 1% for all of the HLLV exhaust molecules. The consequences of such a belt of depletion on HF communications have not been assessed as yet. Again, it must be stressed that these global-scale effects are based on little more than scientific guesses at this time.

Effect on the Global Hydrogen Atom Cycle

A large fraction of the exhaust molecules injected by the 2nd stage of the HLLV burn below 125 km will be converted into H atoms that will diffuse into the upper thermosphere and mesosphere. Zinn's calculations[17] indicate that this source of H-atom flux could lead to a doubling of the exospheric density above say 800 km if HLLV's were launched twice daily. A major source of uncertainty in these calculations is the magnitude of the natural flux of H atoms upward through the thermosphere and how enhancement of this flux would affect the global escape rate. If these added H atoms were to accumulate and significantly increase the density above 800 km then important consequences could result. Since satellite drag has been used to detect variations in atmospheric density at altitudes as high as 1100 km or more it is plausible that large chronic changes in density in the same range could slowly alter satellite orbits especially sun-synchronous orbits operating near 900 km altitude. Although rather speculative, it has also been suggested that substantially increased upper thermospheric densities may alter wind patterns at those altitudes and also may affect ionospheric-magnetospheric coupling processes especially those involving the precipitation of high energy particles. Such processes are believed to be a principle source of energy input to the high latitude thermosphere.

Magnetospheric Effects

Exhaust emissions from propulsion and stationkeeping activities of SPS spacecraft are expected to induce substantial modifications of magnetospheric processes on both the local and the global scale. This is primarily because of the relatively large mass and energy contents of these emissions when compared with the total mass and energy contents of the inner magnetosphere. The sources of these emissions are: (a) the argon plasma jet from the solar electric propulsion modules of the cargo orbit transfer vehicle (COTV), (b) the H_2O neutral exhaust from LO_2/LH_2 main engines of the personnel orbit transfer vehicles (POTV). The major part of the ion engine exhaust and a significant fraction of the POTV engines emissions are likely to be deposited into the magnetosphere.

The annual rate of injection of these effluents, assuming that two 5-GW satellites would be constructed per year, has been estimated to be: 10^{33}H atoms (in the form of H_2O and H_2) and 4×10^{32} Ar^+ ions and electrons. The kinetic energy associated with these particles would be about three orders of magnitude greater than the thermal energy normally present in the plasmasphere and roughly comparable to that injected by magnetic substorms during relatively quiet periods. The normal H-atom content between 500 km and the plasmapause (4Re) is about 3×10^{32}. The natural Ar^+ ion content is about 4×10^{25}. Hence, the mass and energy additions are indeed large compared with the natural plasmasphere. However, because of orbital mechanics, not all of the POTV emissions will remain in the magnetosphere. Of the 460 metric tons (MT) of propellant about 250 MT will be injected at LEO where they will produce a large region of depleted ionosphere. 140 MT will be injected at GEO and will go into a gravitationally-trapped elliptical orbit centered around 15,000 km altitude. The remainder will probably escape into outer space. Because of the near collision-free environment of the magnetosphere the trapped neutral exhaust molecules will remain in orbit for a long time. However, since this orbiting cloud will overlay regions of the magnetosphere containing large numbers of charged particles (Van Allen belts and ring current), it is expected that the low-energy neutrals will undergo charge exchange with the magnetically-trapped high-energy charged particles. Hence, a reduction in population of trapped particles is likely to occur. The consequences of this and possible other effects of a long-lived orbiting cloud of neutral gas is not presently known.

The plasma ejected from the COTV ion thruster array would comprise a dense beam of 3.5 keV Ar^+ ions and electrons that would not be expected to recombine within the beam. Expected modifications of such an injection are briefly summarized in Table 2. According to Chiu et al.[29] the interaction of the beam with the ambient plasma and geomagnetic field would result in the stopping of the beam within about 1000 - 2000 km of the engines. The stopping process would convert the streaming energy of the beam into thermal energy of those regions where the geomagnetic field lines enter the denser portions of the ionosphere and thermosphere. Since auroral processes are an important source of heating of the thermosphere (along with the absorption of solar-UV radiation in lower latitudes), such an additional input of heat energy, which is comparable in magnitude to the natural processes, may have important consequences that have not yet been analyzed. The energy released by the ion engines is also sufficient to cause turbulent response in the magnetospheric plasma. As this free energy evolves, the magnetospheric composition is modified not only by the presence of argon ions but also by the heating. This physical evolution of injected energy and mass can cause an increase in the intensity of radiation belt relativistic electrons which may require mitigation on the part of systems design in space equipment and human activity. At (LEO), a substantial fraction of the energetic argons may escape magnetic confinement and impact the atmosphere in the form of an intense beam. The optical emissions stimulated by such a beam may be more than an order of magnitude more intense than the aurora at near UV wavelengths. The possible interference with space-borne optical sensors induced by such a strong source of artificial atmospheric emissions may require further technological assessment by the sensor community. The earth's response to solar disturbances, in the form of auroral magnetic storms, depends on the density and composition of the magnetospheric constituents (plasmas and neutrals); modification of the magnetospheric density and composition is likely to change the magnetospheric response to solar activity. Because of the rapid rate of charge exchange interaction between energetic particles of solar wind origin and the neutral exhaust cloud from the POTV, we expect that the earth's response to solar activity may become shorter in duration and weaker in intensity under SPS-modified circumstances. Further, some plasma disturbances caused by the transformation of injected free energy involve density irregularities and cause currents to form in the magnetospheric and ionospheric plasma. If these density irregularities cover sufficiently large areas, they may cause signal scintillation effects in space communication systems. The ionospheric currents induced in the ionosphere are of comparable magnitude to the auroral currents but are located at mid-latitudes; thus they may adversely impact powerlines and long telephone lines, as has been observed in connection with natural magnetic storms.[30]

IV. Effects of Large Space Structures in the Magnetosphere

Several authors, including Vondrak[31] and Rosen[32] have suggested that large structures in the magnetosphere will serve as sinks for particles striking them. The COTV, depending upon which photocell option is chosen will have a

Table 2 Satellite Power System Magnetospheric Effects

Effect	Cause	Mechanism	System/Activities Impacted
1. Dosage Enhancement of Trapped Relativistic Electrons	O^+ and Ar^+ in magnetosphere due to exhaust and plasmasphere heating	Thermal heavy ions suppress ring current ion cyclotron turbulence, which keeps electron dosage in balance in natural state	- Space equipment - Modification of human space activity
2. Artificial Ionospheric Current	Ionospheric electric field induced by argon beam	Beam induced Alfvén shocks propagate into ionosphere	- Powerline tripping - Pipeline corrosion
3. Modified Auroral Response to Solar Activity	Neutrals and heavy ions in large quantities	Rapid charge-exchange loss of ring-current particles	- May reduce magnetic storm interference with earth and space-based systems
4. Artificial Airglow	3.5 keV argon ions	Direct impact on atmosphere from LEO source	- Interference with optical earth sensors
5. Plasma Density Disturbance on Small Spatial Scale	Plasma injection	Plasma instabilities	- Signal scintillation for space-based communication

cross-sectional area of 1.3 to 2.9 km^2. Such a structure according to Rosen[32] could have a sweeping effect on the inner Van Allen belt particles as it moves back and forth between LEO and GEO. However, the extent of such a sweeping action, and the impact on the space environment is not clear at this time. Presumably it would have a net positive influence through the reduction of ionizing radiation levels.

The 60 SPS satellites will each cover an area of ≈ 55 km^2 and be distributed along an equatorial line over the U.S. on the magnetic shell defined by an L value of about 6.6. Hence, one would expect that flux tubes passing through these satellites and perhaps even the whole region of the magnetic shell could suffer some plasma reduction. This, according to Vondrak,[31] would be analogous to the "sweeping" of the Jovian radiation belts by the Galilean satellites.

The satellites are expected to become charged and, consequently, will accelerate ambient charged particles. This could lead to alteration of the ambient plasma and to enhanced radiation damage over and above that expected by unaccelerated particle bombardment. (The satellites will reside in the outer portion of the outer Van Allen Belt.) Project SCATHA (Spacecraft Charging at High Altitudes), (see Garrett[33]) is relevant to this issue. For example, SCATHA experiments have demonstrated that electric potentials established on spacecraft can accelerate and decelerate plasma components to tens of KeV. These experiments have also indicated that klystron operations can be adversely influenced by the plasma environment, which may be modified by gaseous and particulate emissions in GEO.[31,34]

The SPS satellite structure will dissipate most of the solar input energy as either reflected light or infrared radiation, since the proposed solar cells are expected to be, at most, 17-19% efficient. In addition, the DC-to-RF converters will dissipate approximately 1.2 GW of waste heat, probably at relatively high temperatures (>500° C). The effects of this radiation, as well as the effects of RF radiation on the astronomical community, could be important.[35]

Satellite structural members will be exposed continuously to direct solar and cosmic radiation and are expected to be sources of photoelectrons and other charged and neutral particles. The ejected neutral particles could form relatively long-lived, orbiting, dust clouds or rings near GEO.[31,34]

Finally, the structures will be sources of various neutral contaminant gases (as well as Ar^+ ions and electrons from attitude control and station-keeping thrusters). Sources of neutral gases include: (a) chemically-fueled attitude control and station-keeping thrusters used during eclipses of the sun by the Earth, (b) leakage from pressurized chambers including living quarters, containment vessels, etc., and (c) satellite surface erosion and outgassing of volatiles.[31]

In addition to these satellite structural sources, there will be both chemical and ion propellants injected near GEO from the POTV circularization and deorbit burns, from COTV operations, and from thrusters required in space construction operations and maneuvers. Based on exhaust and escape velocity, it is anticipated that the POTV circularization burn neutral effluents will be gravitationally trapped, while those from the deorbit burn will escape into outer space. The other sources of neutral gases probably will have relatively low exhaust speed and be more randomly directed. Thus, they probably will be trapped and may form gas clouds in the GEO environment. The minimum gas releases rates needed to produce significant effects have been evaluated by Vondrak.[31] Garrett and Forbes also have performed some calculations relevant to this topic.[34] They suggest that it may be possible to measure an actual contaminant cloud (Xe^+ ions) during the 1979-1980 time frame by using the GEOS II satellite.

Finally, space operations between GEO and lunar orbit (a region referred to as "cislunar space") also may have complicating environmental consequences. Vondrak[31] has suggested that released gases in this region could form a ring around the Earth at approximately lunar-orbital distance similar in structure to the Jovian ring associated with gaseous emissions from the Jovian satellite IO. A total leakage rate $\geq$ 600 kg/sec could lead to significant effects, such as the alteration of the solar wind flow pattern and, consequently, the structure of the outer magnetosphere. However, this value is probably well above that expected from space operations in the foreseeable future.

V. CONCLUSIONS

In the altitude range of 56-500 km, the major sources of disturbance of the space environment are SPS microwave transmission and rocket effluents. Although no significant effects have yet been found for microwave transmissions, the deposition of rocket effluents is known to cause compositional changes. Current work has focused on evaluating the duration and spatial extent of these perturbations. Most appear to be associated with the release of large amounts of H_2O in regions where it is not usually found.

Above 500 km, along with chemical effluents from rockets, ion engine contaminants (anticipated to be primarily Ar^+) are expected to be a significant factor in altering magnetospheric and plasmaspheric structure and dynamics. Although still quite controversial, one of the major impacts of these alterations may be to perturb the stability of the Van Allen radiation belts. This could lead to changes in radiation hazards to space equipment and space workers, as well as alteration of high energy particle precipitation events.

In the outer magnetosphere, current knowledge of environmental changes is limited. The space environment is very low in density and energy, and the environmental loading can be quite severe. It is not clear, however, how major alterations in this environment, which are known to vary by several orders of magnitude naturally, could affect the global climatic system. Although a connection between solar activity and climate is believed to exist through subtle changes in geomagnetic activity, this phenomenon is not at all certain or well understood. Thus, further research will be required in this region.

In summary, the ambient density falls rapidly and the potential for significant environmental alterations increases as one goes outwards from the Earth's surface. Correspondingly, as the altitude increases our current knowledge of environmental change processes and their importance decreases. Hence, the reader is cautioned that, unless specifically indicated to the contrary, the probability of occurrence of the potential atmospheric effects of large space systems and their significance for the terrestrial environment should be regarded as uncertain and requiring further research.

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