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Environmental Effects of Space Systems

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This paper reviews the potential effects of large space systems, primarily the Satellite Power System (SPS), on the upper atmosphere. At altitudes of 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, rocket effluents cause 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. At altitudes of 500-36,000 km, rocket effluents and ion engine contaminants (primarily Ar+) could alter the magnetospheric and plasmaspheric structure and dynamics. One of the major impacts of these alterations could be perturbation of the stability of the Van Allen radiation belt, leading to changed radiation hazards to materials and personnel in space.

Introduction

CURRENT and promised additions to the launch vehicle arsenal, including the Ariane I and II rockets and the Space Shuttle, support the expectation that the broad spectrum of space activities will continue to proliferate. Proposals to use space systems as alternative sources of terrestrial energy—epitomized by the Satellite Power System (SPS)—add another dimension to the current scientific, commercial, industrial, and military exploitation of space. The increasing use of space has prompted increased concern about preserving the properties of space that stimulated its exploitation. Already man faces the formidable task of keeping track of thousands of pieces of hardware in low Earth orbit (LEO). According to Mokhoff,[1] 93 communications satellites now occupy or will shortly occupy geostationary Earth orbit (GEO). Add to this an anticipated 200 new satellites in the next decade[2] 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 helpful to review some pertinent details. The Ariane I is a conventional three-stage rocket with a gross liftoff weight of about 1.9×10^5 kg. 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 138-213 km, will burn liquid hydrogen (LH_2) with a liquid oxygen (LO_2) 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 reusable Space Shuttle will have a gross liftoff weight about 10 times that of the Ariane I. At 0-43 km, thrust will be provided by the three Space Shuttle main engines (SSME), which burn LO_2/LH_2, in combination with two solid-fuel booster engines. Between 43 km and typically 215 km only the SSMEs operate. Final orbit insertion, orbital maneuvering, and return are accomplished with the orbit maneuvering and reaction control systems, both of which use thrusters that burn monomethylhydrazine (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]

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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 and used to evaluate the environmental and socioeconomic impacts of the SPS, as well as its technical feasibility.[5] In the reference design, 60 satellites in GEO 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, projected to be in operation by about the year 2020, could supply approximately 20% of that year's total U.S. electrical energy demand. Conceivably, a larger system could be developed to help satisfy the global demand for electric power.

The types of rockets required for space transportation for the SPS are listed in Table 1. The heavy-lift launch vehicle (HLLV) will have a gross liftoff weight approximately 5.5 times that of the Space Shuttle. Its first stage will burn methane and oxygen to an altitude of about 56 km. Thereafter the second stage, consisting of 14 SSMEs, 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 LEO and GEO. The space components of the SPS (solar satellites, microwave generators, and transmitters) would be assembled in GEO from materials delivered to the LEO base station and then transferred to the construction site.

Figure 1 shows the scenario for construction of two 5 GW satellites per year. Note that two photovoltaic options for the solar satellites are indicated: Si, the use of silicon cells, and Ga, the use of gallium aluminum arsenide cells. If maintenance operations are included, as many as 500 HLLV flights per year are required to construct 60 satellites over a 30 year period.

The major potential impacts of SPS and other space vehicles and structures on the space environment derive from 1) transmission of the SPS microwave power beam through the atmosphere, 2) deposition of rocket effluents and ablated materials in the atmosphere, and 3) structures in orbit. This paper, which is an abbreviated and somewhat updated version of a review given in Ref. 6, summarizes present knowledge regarding these atmospheric impacts. Interference of SPS-generated microwaves with telecommunication systems is not explicitly addressed. Readers interested in this topic should consult Ref. 7.

Microwave Effects

The microwave power beam frequency of 2450 MHz specified in the SPS reference system design is essentially a compromise between increasing absorption by hydrometeors

Table 1 SPS space transportation vehicles

Vehicle	Transport function	Propellants	Launch[a] rate, $year^{-1}$	Operating altitude, km	Main exhaust products
Heavy-lift launch vehicle (HLLV)	Materials: Earth to LEO	CH_4/O_2 (stage 1) H_2/O_2 (stage 2) H_2/O_2 (circularization/deorbit)	375 375 375	0-57 57-120 450-500	CO_2,H_2O H_2O,H_2 H_2O,H_2
Personnel launch vehicle (PLV)	Personnel: Earth to LEO	Details not available (probably same as HLLV)	30	0-500	CO_2,H_2O,H_2
Cargo-orbit transfer vehicle (COTC)	Materials: LEO to GEO	Argon H_2/O_2	30	500-35,800	Ar^+ plasma H_2O,H_2
Personnel-orbit transfer vehicle (POTV)	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 per year.

	Silicon	Gallium
SPS Mass	$50{,}984 \times 10^6$ kg	$34{,}159 \times 10^6$ kg
Payloads		
HLLV	424×10^6 kg	424×10^6 kg
PLV	75 persons	75 persons
POTV	160 persons	160 persons
	400×10^6 kg	400×10^6 kg
COTV	$4{,}000 \times 10^6$ kg	$3{,}500 \times 10^6$ kg
Packing Factors		
Hardware	85%	95%
Propellants	95%	95%

Si and Ga refer to the Silicon and Gallium Aluminum Arsenide photovoltaic options, respectively.

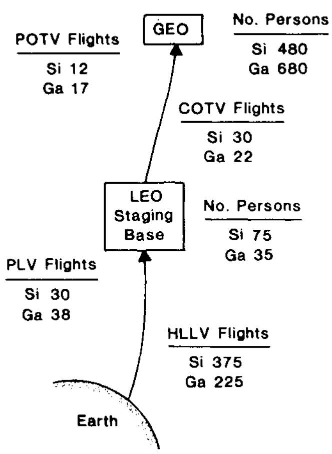

Fig. 1 Scenario for construction of two 5 GW satellites per year.

in the atmosphere at higher frequencies and increasing interactions with the ionosphere at lower frequencies. 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 of 10 W/m^2 at its edge. 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 and further increasing land use requirements.

The major concern regarding the transmission of microwaves through the atmosphere is interaction with the ionosphere.[8,9] 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 predicted to increase temperatures of local free electrons by several hundred degrees Kelvin.[8] An experiment to verify these predictions was conducted at Arecibo. However, because of frequency limitations, a scaling law stating 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 is thought to be that for near-threshold heating, the heating time constant becomes significantly longer than under normal conditions, resulting in the experimental radio wave pulse being too short in duration (9 ms) to reach the maximum heating value. In any case, before reliable estimates of SPS heating effects can be made, the scaling procedures used to extrapolate to the SPS reference design parameters must be verified.

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 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, self-focusing is expected to occur. Depending on the degree of induced density fluctuations, this instability could significantly modify propagation of high-frequency (hf) communications and the SPS pilot reference beam. 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."

Although no significant telecommunications effects have been identified, ionospheric modifications expected to accompany microwave power transmissions could affect the propagation of both the SPS microwave power and pilot reference beams. The pilot reference beam is used to maintain phase coherence at the transmitter 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.

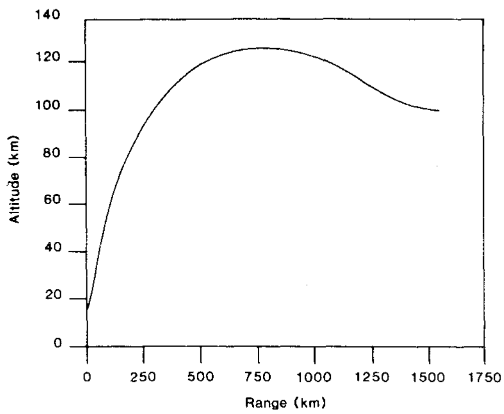

Fig. 2 SPS heavy lift launch vehicle trajectory.

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 typically will be confined to altitudes of 43-215 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, 450-500, and 500-36,000 km. Hence, for convenience in the following discussion, the upper atmosphere has been divided into three domains, A,B, and C, respectively. 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.

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 re-entry. Re-entry 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] The NO should be distributed between 55 and 100 km, with peak production at about 70 km.[11]

A less significant source of pollutants in this region is waste material and construction debris. Assuming that the equivalent of 1% of the total mass of two 5 GW satellite systems could 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.

Domain B Sources

The major sources of effluents in domain B are the circularization and deorbit burns of the HLLVs, PLVs, and personnel orbit transfer vehicles (POTVs). In each case, the propellant is LH_2/LO_2. Also expected are minor injections of combustion products from the Space Shuttle type of orbit maneuvering system and reaction control system engines, which presumably will burn MMH and N_2O_4. 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 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 a circularization burn of the second-stage rocket at GEO, a 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.

Stratospheric and Mesospheric Effects

Theoretical calculations[14,15] indicate that exhaust emissions of carbon dioxide and nitrogen oxides would not have detectable effects 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 re-entry of an HLLV second stage is expected to generally enhance the nitric oxide concentration in the mesosphere by up to 80% at some mesospheric altitudes.[15] Estimates of NO concentration enhancements are subject to substantial uncertainties about ambient levels as well as about the calculated changes. Changes in the total ozone column corresponding to enhanced NO levels have been estimated to be less than 0.1%.[15] In addition to these long-term effects, localized regions of high NO concentration may persist for 24-48 h after each re-entry. Higher than normal electron densities on both local and global scales are also expected in association with these enhancements in NO concentration.

The emission of substantial amounts of water and hydrogen is also expected to have some effects. Model calculations indicate that on a global basis the water concentration will be increased by about 8% at 60 km[15] and by much larger amounts at higher altitudes.[16] However, the enhanced concentrations of water vapor and NO concentration are not expected to alter the total ozone column by more than a few hundredths of one percent.[15] Such a change would be undetectable at ground level.

The injection of exhaust products near the mesopause, the region around 85 km corresponding to the lowest observed atmospheric temperatures, is likely to cause the formation of an artificial noctilucent cloud. Such clouds have been observed on several occasions following launches of rockets of various sizes, ranging from relatively small research rockets to larger ones intended to place a satellite in orbit.[17] 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 was illuminated by the sun. Theoretical estimates indicate lifetimes on the order of one day for an HLLV launch.[15]

In view of the predicted enhancement of water concentration 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,[15] the expected increase will 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 Changes

Preliminary calculations[15] suggest that the long-term global changes in the free-electron concentration in the D- and E-regions will probably be relatively small ($\lesssim 10\%$) owing to enhanced recombination of electron-ion pairs by increased positive ion-water clustering as well as enhanced production resulting from increased NO concentrations caused by re-entry. Changes of this magnitude probably could not seriously affect radio wave propagation. Changes in the Lyman alpha radiation intensity in both the daytime and nighttime D- and lower E-region conceivably could have a somewhat greater effect, but they have not been investigated in detail. On the other hand, short-term local changes due to water injection (promotion of ion-water cluster formation) and NO production by re-entry appear to be very large and to have lifetimes on the order of days. It remains to be determined through more sophisticated theoretical studies and field experiments focused on actual rocket launches whether these large-magnitude effects are real, what their actual temporal and spatial scales are, and what consequences they would have for radio wave propagation.

The only experimental evidence pertaining to very-low-frequency (vlf) propagation effects caused by a rocket launch is that obtained during the monitoring of the HEAO-C satellite launch by an Atlas-Centaur rocket in September 1979. One of the groups of participants in that monitoring campaign, Meltz and DarRold,[18] observed vlf propagation (10-13 kHz) using an operational radio navigation system (OMEGA) before, during, and after the launch. Such a system utilizes the Earth-ionosphere waveguide mode of propagation. For such a mode the observed vlf phase delay between the transmitter and receiver is sensitive to changes in the D- and lower E-regions. On the basis of their observations, Meltz and DarRold suggested that the exhaust products from the Centaur stage of the rocket (injected between 211 and 501 km) descended into the upper D-region and altered its composition. The observed phase advance suggests that the electron density and/or collision frequency was increased and in turn either increased the phase velocity or lowered the effective reflection height. A satisfactory theoretical explanation of these phenomena has not yet been put forward. The investigators observed vlf phase anomalies up to 24 h after the rocket launch and claimed they were caused by the launch. If such phase anomalies are indeed a characteristic feature of rocket launches, the extent to which they affect navigation should be examined further.

A somewhat more subtle concern regarding potential D- and E-region effects relates to the fact that the high-latitude conductivity distribution is especially important because the high-latitude ionosphere completes the electrical circuit that couples the auroral zone to the outer magnetosphere. The electrical currents that flow through this circuit undergo large fluctuations during magnetic substorms and have been known to induce damaging current surges in long telephone and power transmission lines. Alteration of the auroral zone conductivity (in the E-region) could modify the morphology of this current system and influence the location and occurrence or intensity of terrestrial current surges.

Markson[19] 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. Present knowledge regarding the alteration of the morphology of the auroral current system and Markson's suggestion does not permit an assessment of these effects.

F-Region Plasma Depletions

Rocket effluents (H_2O, H_2, CO_2) change the dominant $O+$ ions in the F-region 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 airglow, and the release of large numbers of hydrogen atoms. The rapid loss of electron-ion pairs creates an ionospheric hole that extends far beyond the local source of injected molecules

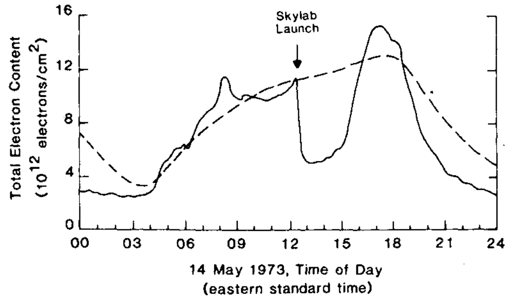

Fig. 3 "Hole" seen in the total electron content measurement of the ionosphere by the Sagamore Hill Observatory.

and that may extend to the conjugate ionosphere (i.e., may 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 F_2-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, Mass. The deep depression in the total electron content 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 were also intercepted by the resulting depleted region, it was reported that the ionospheric hole had a radius of about 1000 km and lasted for about 4 h.[20] Unfortunately, because the observations were not planned, they were somewhat incomplete.

The first successful attempt to produce a midlatitude, ionospheric depletion under controlled experimental conditions occurred in September 1977. Project LAGOPEDO, as it was called, involved two rocket-borne experiments.[21] Each rocket carried 88 kg of high explosives and an instrument package that was separated from the rocket prior to detonation of the explosive. The detonation products included about 30 kg of H_2O, 16 kg of CO_2, and 20 kg of N_2. 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 min and extending to a radius of 30 km or more. In addition to the rocket-borne instrument package, which sampled the disturbed area for 2-3 min, ground-based instruments monitored the hole for about 30 min until the satellite beacon was turned off. A major question that arose from these two experiments concerned the importance of the formation of ice crystals followed by gravitational settling to lower altitudes where the presence of the water was unimportant. Such formation would suppress the participation of the water molecules in the electron-ion removal process. The fraction of the water molecules that formed ice crystals was subject to considerable uncertainty.

The launching of the HEAO-C satellite in September 1979 provided an excellent opportunity to observe a large-scale ionospheric modification caused by the burn of an LO_2/LH_2-fueled rocket engine.[22,23] A monitoring campaign conducted by 17 separate research groups working with the cooperation of about 150 ham radio operators and several commercial station operators and listeners provided the most complete case study to date of a large-scale ionospheric modification.

Preliminary results have been reported[24-26] and more extensive investigations of the data acquired during this campaign are still in progress. The Centaur stage of the Atlas/Centaur launch vehicle burned its engines at 211-501 km altitude and injected about 7×10^{29} H_2O and H_2 molecules. For comparison, an HLLV circularization burn at 477 km altitude would inject about 9×10^{29} molecules.

The morphology of the ionospheric disturbance was investigated with satellite radio beacon studies of the ionosphere's total electron content, airglow studies using both airborne and ground-based facilities, and incoherent scatter radars. The combined results of these investigations[26] showed that the ionospheric hole followed the rocket's ground track, extending approximately 2500 km to the east of Cape Canaveral and 600-1000 km in the north-south direction (covering a surface area $\approx 1\text{-}3\times10^6$ km^2). More than 80% of the ambient electrons and ions were removed from the center of the hole within 2 min of the rocket's passage. The hole disappeared after local sunrise (4 h after launch) and no persistent F-region effects were observed thereafter. The dominant optical airglow emission enhancement seen was the oxygen red line at 6300 Å. The oxygen green line at 5577 Å was also observed to be enhanced, but to a lesser extent. The theoretically important emissions in the OH band near 6700 Å were not detected above background levels. However, an enhancement in the 2.9 μm OH band emission was observed.

Little, if any, evidence for plasma irregularities of characteristic size ≥ 1 km was found from geostationary satellite radio beacons and none was found from video data.[26] However, some fluctuations were seen in low-orbit satellite transmissions.[26] A traveling ionospheric disturbance consistent with a launch-induced origin was observed at Arecibo.[26] With regard to telecommunication effects, the preliminary conclusion from all of the hf radio experiments[26] was that no severe long-term effects were associated with the rocket launch. However, several observers did notice short-term signal fades or increased fading rates in the 7-21 MHz range during a time interval consistent with rocket-induced effects. However, these communication disturbances were not unlike those of natural origin that occurred before and after the launch.[26] Observations of vlf satellite beacons indicated disturbances in 14 kHz transmissions several hours after the launch; these could not be associated with known natural phenomena such as solar flares.[18]

Aside from the rocket launches mentioned here, very few additional archived launches have been reported for which either planned or accidental observations have shown any large-scale, F-region ionospheric disturbances.[27]

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 create an ionospheric hole similar to that produced by the September 1979 launch of the HEAO-C satellite. This has been supported by Zinn,[17] whose noontime circularization burn simulation indicated that the electron concentration would be reduced to one-third its normal daytime value over a 1000×2000 km region. The ionosphere would return to normal in about 5 h or after sunrise, as was the case with the HEAO-C hole. 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 (very high frequency) beacon propagation seem rather uncertain at this time and should be looked into further. If LEO for the SPS is to be located near the magnetic equator, observations should be made to verify or refute the predicted creation of artificial spread-F.[28,29]

SPS Predictions for a Single POTV Burn near LEO

A single POTV injection burn produces 10 times as many exhaust molecules (10^{31}) as does an HLLV circularization burn, or about as many exhaust molecules as were produced by the Skylab burn in 1973. If other things remain unchanged, the geographic area covered by the hole would be roughly 10 times that of the HLLV circularization burn hole or about 2×10^7 km^2 (twice the size of the United States). The Saturn V hole morphology is not completely known because of the incompleteness of the data. Mendillo[20] reported that it covered an area of about 4×10^6 km^2 and lasted for about 4 h after a noontime launch. However, Zinn[30] has suggested that if characteristic thermospheric winds prevailed at launch time (no actual wind data are available), the hole actually could have lasted until sunrise the next day. Zinn reconciles his estimate with the 4 h 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 about 3-4 h.

Hence, a noontime POTV burn is expected to produce a hole lasting 4-16 h. Since the hole will cover an area equivalent to that of the continental United States, the radio wave propagation effects would be more widespread but not necessarily more severe or long lasting than were those observed for the HEAO-C launch. The severity and duration of the fading of hf signals, beyond the observed effects of the HEAO-C launch, cannot be predicted with any confidence at this time.

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

Unfortunately, no data are available to assist in predicting the F-region depletion caused by an HLLV second-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 110-124 km. Zinn[30] has performed a calculation taking into account only those molecules released between 118 and 124 km (about 40% of the total second-stage emissions). Following a launch at noon from Cape Kennedy, some of the exhaust molecules slowly diffuse up to the F_2 layer where they react with $O+$ ions. After sunrise, the $O+$ ions are produced about as fast as they are destroyed, so the net effect is only a 10% reduction during the daytime. However, during the following night, the $O+$ and free-electron concentrations are gradually reduced to about 70% of their normal values. Since Zinn carried the calculation out for only about 36 h 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 second-stage engine burn is not expected to have any significant impact. In fact, it would probably be difficult to detect, except possibly during magnetically quiet times.

Multiple Launch Effects in the F-Region

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

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

It is therefore at least plausible that, in a belt-like region of the ionosphere surrounding the globe at the launch latitude, a roughly 10% or more chronically reduced free-electron density would be superimposed on severely depleted regions of size 1000×2500 km occurring twice daily. To this would be added one POTV burn per month producing a depletion on the order of 3000×8000 km. Such a chronic depletion belt could have a width of about 2000-10,000 km, corresponding to an overall electron-ion recombination efficiency of 0.2-1% for all of the HLLV exhaust molecules. The consequences of such a belt of depletion on hf communications have not been assessed.

Effect on the Global Hydrogen-Atom Cycle

A large fraction of the exhaust molecules injected by the second stage of the HLLV burn below 125 km will be converted into H atoms that will diffuse into the upper thermosphere and exosphere. This source of H-atom flux could double the exospheric density above about 800 km if HLLVs were launched twice daily.[15,30] Major uncertainties here are the magnitude of the natural flux of H atoms through the thermosphere and the effect of enhancement of this flux on the global escape rate. If the added H atoms were to accumulate and significantly increase the density above 800 km, important consequences could result. Since satellite drag has been used to detect variations in atmospheric density at altitudes at least as high as 1100 km, it is plausible that large chronic changes in density in the same range could slowly alter satellite orbits, especially sun-synchronous orbits at altitudes near 900 km. Although rather speculative, it has been suggested[30] 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 principal source of energy input to the high-latitude thermosphere.[31]

Magnetospheric Effects

Exhaust emissions from propulsion and stationkeeping activities of SPS spacecraft could 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: 1) the argon plasma jets from the solar electric propulsion modules of the COTV, and 2) the H_2O and H_2 neutral exhaust from the main LO_2/LH_2 engines of the POTV. The major part of the ion engine exhaust and a significant fraction of the POTV engines emissions are likely to be deposited in the magnetosphere.

The annual rate of injection of these effluents, assuming that two 5 GW satellites are 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 (4 R_e) is about 3×10^{32}. The natural Ar+ ion content is about 4×10^{25}.

Because of orbital mechanics, not all of the POTV emissions will remain in the magnetosphere. Of the 4.6×10^5 kg of propellant, about 2.5×10^5 kg will be injected at LEO where it will produce a large region of depleted ionosphere. About 140 T 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 nearly 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 a charge exchange with the magnetically trapped, high-energy charged particles. Hence, the population of trapped particles is likely to be reduced. The consequences of this reduction and of other possible effects of a long-lived orbiting cloud of neutral gas are 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. The immediate and ultimate fate of these Ar+ ions and their impacts on the near-space environment are currently the subjects of considerable controversy that is not likely to be fully resolved until more experimental data become available. Much of the controversy surrounds the nature of the interactions between the ion engine exhaust plasma and the ambient plasma embedded in the geomagnetic field. Depending upon details of these interactions, which are not fully understood, the exhaust beam could escape the geomagnetic field almost intact; portions could be stripped off and trapped in the geomagnetic field as a relatively hot, dense plasma; or the major portion of the beam's streaming energy could be dissipated by heating up the ambient constitutents and causing the beam to be brought to rest so that the Ar+ ions would enter the geomagnetic field as a cold, dense plasma. Which of these alternatives, if any, pertains determines to a large extent the impacts of the Ar+ ions as well as their ultimate fate. This issue is discussed in greater detail in Ref. 16.

Here the picture developed by Chiu et al.[32] will serve to illustrate a plausible early fate of the ion engine plasma and its corresponding impacts. While this picture is not universally accepted, it is supported by a number of investigators.[32] According to this picture, the interaction of the beam with the ambient plasma and geomagnetic field would stop 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-ultraviolet 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 may increase the intensity of radiation belt relativistic electrons, which may in turn require space system designers to provide greater shielding for equipment and humans in space.

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-ultraviolet 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 constitutents (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 ring current particles and the neutral exhaust cloud from the POTV, the Earth's response to solar activity may become shorter and weaker under SPS-modified circumstances.

However, the addition of cold, heavy ions (Ar+ by injection and O+ raised from lower altitudes by heating) could very well enhance ultra-low-frequency emissions. 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 in space communication systems. The currents induced in the ionosphere are of comparable magnitude to the auroral currents but are located at midlatitudes; thus they may adversely impact power lines and long telephone lines, as natural magnetic storms have.[33] The potential impacts are summarized in Table 2.[32]

Table 2 Satellite power system magnetospheric effects

Effect	Cause	Mechanism	System/activities impacted
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
Artificial ionospheric current	Ionospheric electric field induced by argon beam	Beam-induced Alfven shocks propagate into ionosphere	Power line tripping Pipeline corrosion
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
Artificial airglow	3.5 keV argon ions	Direct impact on atmosphere from LEO source	Interference with optical Earth sensors
Plasma density disturbance on small spatial scale	Plasma injection	Plasma instabilities	Signal scintillation for space-based communication

Effects of Large Space Structures in the Magnetosphere

Several authors, including Vondrak[34] and Rosen,[35] 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 cross-sectional area of 1.3-2.9 km^2. According to Rosen,[35] such a structure 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 are not clear at this time. Presumably there would be 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 will be distributed along an equatorial line over the U.S. on the magnetic shell defined by an L value of about 6.6. Hence, flux tubes passing through these satellites and perhaps even the whole region of the magnetic shell could be expected to suffer some plasma reduction. This, according to Vondrak,[34] 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 acceleration could lead to alteration of the ambient plasma and to enhanced radiation damage over and above that expected by unaccelerated particle bombardment. Project SCATHA[36] (Spacecraft Charging at High Altitudes) experiments have demonstrated that electric potentials established on spacecraft can accelerate and decelerate plasma components to tens of kiloelectron-volts. 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.[34,37]

The SPS satellite structure will dissipate most of the solar input energy as either reflected light or infrared radiation (at 310-398 K), 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. The effects of this radiation, as well as the effects of rf radiation on the astronomical community, could be important.[38]

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.[34,37]

Finally, the structures will be sources of various neutral contaminant gases (as well as Ar+ ions and electrons from attitude control and stationkeeping thrusters). Sources of neutral gases include: chemically fueled attitude control and stationkeeping thrusters used during eclipses of the sun by the Earth; leakage from pressurized chambers including living quarters, containment vessels, etc.; and satellite surface erosion and outgassing of volatiles.[34]

Conclusions

In the altitude range of 56-500 km, the major sources of SPS disturbance of the space environment are microwave transmission and rocket effluents. Although no significant telecommunications effects have been identified, ionospheric heating and density changes within the beam path are expected to accompany microwave power transmission through the ionosphere. These beam path changes could impact the performance of the SPS power and pilot reference beams. Rocket effluents can substantially alter the ion and neutral composition of this region, especially above 80 km. Telecommunications impacts observed to date appear to be rather small, although they have not been very thoroughly investigated. Most experimental work related to rocket effluent effects has focused on evaluating their duration and spatial extent in the F-region of the ionosphere.

Above 500 km, ion engine emissions, along with chemical effluents from rockets, are expected to be a significant factor in altering magnetospheric and plasmaspheric structure and dynamics. One of the major impacts of these alterations may be to perturb the stability of the Van Allen radiation belts; this prediction is, however, still quite controversial. This perturbation could change radiation hazards to space equipment and space workers, as well as alter high-energy particle precipitation. Very little experimental data are available.

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 from SPS space vehicles can be quite severe. It is not clear, however, how major alterations in this environment, which is known to vary by several orders of magnitude naturally, could affect the global climatic system. Although a connection between solar activity and climate, through interactions of the solar wind and the geomagnetosphere is believed to exist, this phenomenon is not at all certain or well understood. Thus, further research will be required in this region.

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