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Modification of the Aerospace Environment by Large Space Vehicles

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Space Shuttle-type transportation systems will be a source of repetitive modifications to the Earth's plasma environment due to the large amount of rocket exhaust that will be introduced on a routine basis into the ionosphere. The source of the perturbation lies in rapid ionospheric chemistry that leads to a large-scale "ionospheric hole." In this paper, it is shown that the number of ion-electron pairs removed due to rocket exhaust chemistry does not scale simply with the number of molecules contained in the plume. A perturbation source efficiency factor is defined to demonstrate how effects may be maximized or minimized depending on the rocket launch and/or orbital profile. Sample calculations are made for NASA's Space Shuttle and for the proposed heavy-lift launch vehicle envisioned for carrying solar power satellite components into low Earth orbit.

Introduction

WHILE the concern about rocket exhaust effects upon the Earth's upper atmosphere is not a new topic,[1] studies of plume-associated disturbances upon the environment remain an active area of investigation. Most of the rocket-induced aeronomic effects described in the early literature of the field were termed "localized," due mainly to the fact that the rockets examined were relatively small and thus their exhaust rates were low.[2-4] Of equal importance, however, was the fact that most of the early large-rocket flights were confined to lower ionospheric heights ($h<200$ km) where the dense neutral atmosphere causes the introduction of plume species to be relatively inconspicuous.[5,6] A new class of ionospheric disturbance became apparent during the Saturn V launch of Skylab in May 1973 when, for the first time in the U.S. space program, a very large rocket had its engines burning at high altitudes (200-450 km) where the tenuous ionospheric plasma is very sensitive to neutral molecular concentrations.

The Skylab effect was a rapid and large-scale depletion of the ionosphere due to greatly enhanced chemical loss rates between ions and electrons caused by the vast amounts of water (H_2O) and hydrogen (H_2) present in the Saturn exhaust plume. The "ionospheric hole" created by the Skylab launch involved nearly a 50% decrease in the total number of electrons within a 1000 km radius of the Saturn V launch path (see Fig. 1 and Mendillo et al.[7,8] for further details).

The purpose of the present paper is to describe two space transportation systems which require routine engine firings in the upper ionosphere and therefore the routine creation of large-scale ionospheric holes. The soon to be operational Space Shuttle program will include orbital configurations usually in the 250-450 km altitude range—at precisely the heights where the ionospheric plasma densities (O^+ and e^-) reach their maximum values. The Space Shuttle's engine exhaust rates[9] are considerably smaller than those of a Saturn V rocket and thus the very large spatial extent associated with the Skylab effect will not be found for the Space Shuttle-induced holes.

The launch vehicles required for the proposed solar power satellite (SPS) system represent a very substantial increase over "conventional" Space Shuttle cargo and support staff transportation modes. The regular transfer of material and personnel to low Earth orbit (LEO) and from LEO to geostationary Earth orbit (GEO) suggests that a routine modification of the ionosphere will be a consequence of the fully implemented SPS concept. The ultimate spatial and temporal extent of the SPS-induced ionospheric holes will depend on the specifics of the launch vehicles to be designed and the orbital flight plans that evolve. Ample opportunity exists to influence these decisions by model/simulation studies, as suggested by some of the preliminary results presented in the following sections.

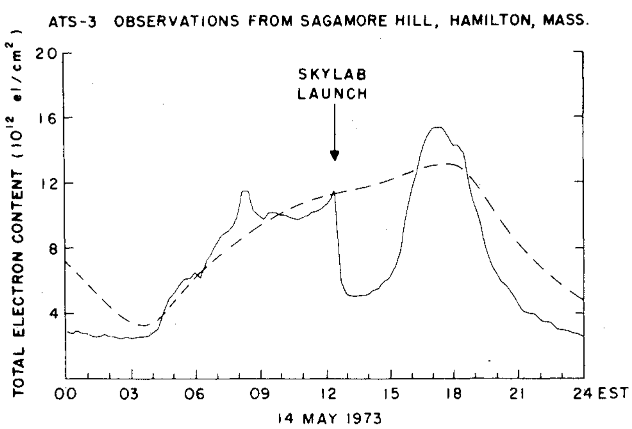

Fig. 1 Total electron content (TEC) data used to detect the "Skylab effect" on May 14, 1973. The dashed curve gives the anticipated diurnal TEC behavior based upon a monthly median prediction updated for geomagnetic storm effects (after Ref. 8).

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Description of Physical Processes

The main exhaust products of standard upper-stage rocket engines include molecular species of important ionospheric consequence. For example, a liquid oxygen-hydrogen engine (LH_2/LO_2), such as used in the Saturn V vehicles, has an exhaust plume of water vapor (H_2O) and unused fuel (H_2) in an abudance ratio of approximately 75/25% by molecular count. An alternate propulsion scheme, such as used by the Space Shuttle while in orbit,[9] burns monomethylhydrazine (MMH) and nitrogen tetroxide (N_2O_4) to produce, among other products, a significant amount of water (H_2O), hydrogen (H_2), and carbon dioxide (CO_2). The introduction of H_2O, H_2, or CO_2 into the upper ionosphere ($h > 200$ km, where the dominant ion is O^+) causes a chemical transformation to molecular ions at rates 100-1000 times faster than occur with the naturally occurring molecules of nitrogen (N_2) and oxygen (O_2). These important reactions are

$$O^+ + H_2O \xrightarrow{k_1} H_2O^+ + O \qquad k_1 = 2.4\times10^{-9}\text{cm}^3/\text{s} \tag{1}$$

$$O^+ + H_2 \xrightarrow{k_2} OH^+ + H \qquad k_2 = 2.0\times10^{-9}\text{cm}^3/\text{s} \tag{2}$$

$$O^+ + CO_2 \xrightarrow{k_3} O_2{}^+ + CO \qquad k_3 = 1.2\times10^{-9}\text{cm}^3/\text{s} \tag{3}$$

Once a molecular ion is formed, its dissociative recombination with an ambient electron occurs rapidly (see Banks and Kockarts[10] for a full treatment of normal ionospheric chemistry). For the above cases, the reactions are:

$$H_2O^+ + e^- \xrightarrow{\alpha_1} OH + \qquad \alpha_1 = 3.0\times10^{-7}\ \text{cm}^3/\text{s} \tag{4}$$

$$OH^+ + e^- \xrightarrow{\alpha_2} H + O \qquad \alpha_2 = 1.0\times10^{-7}\ \text{cm}^3/\text{s} \tag{5}$$

$$O_2{}^+ + e^- \xrightarrow{\alpha_3} O + O \qquad \alpha_3 = 2.0\times10^{-7}\ \text{cm}^3/\text{s} \tag{6}$$

Equations (1-6) describe the essential features of ionospheric hole formation. Several recent studies have examined the coupling of molecular diffusion and ionospheric chemistry in order to refine calculations aimed at specifying the development of molecular release scenarios.[11-14] For example, Forbes and Mendillo[11] treated the case of H_2 and H_2O molecules being lost via reactions with the neutral atmosphere before they could react with ionospheric ions. Their results showed that this effect is important only at very low altitudes in the F-region, and thus the neglect of these reactions in the present study is amply justified. In a similar way, the calculations of Anderson and Bernhardt[12] showed that, for regions very close to the release point and for very early

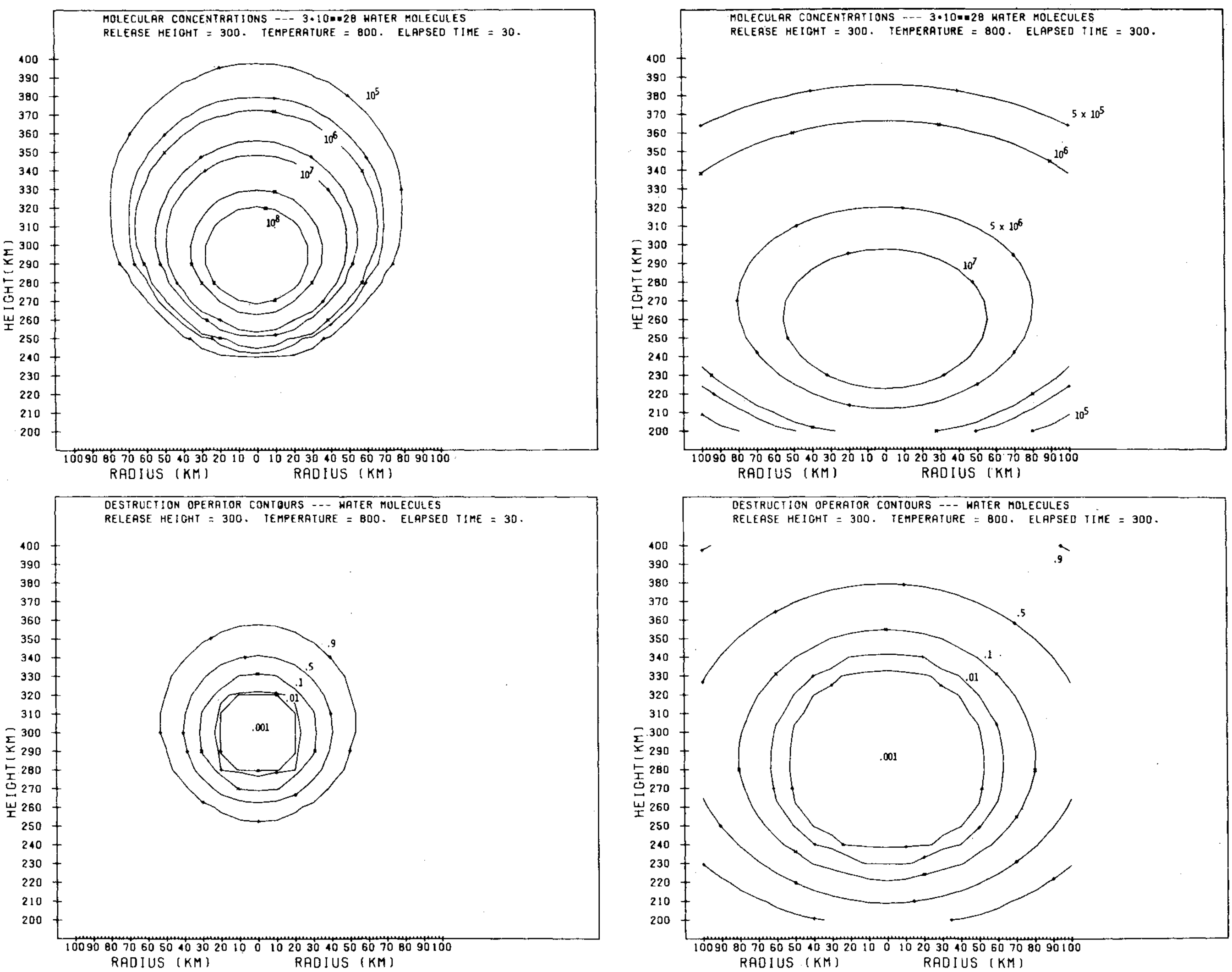

Fig. 2 Modification simulation results for a point source release of 3×10^{28} water molecules into a 800 K neutral atmosphere (after Ref. 15).

expansion times, high concentrations of H_2 can lead to the subsequent transformation of OH^+ and H_2O^+ to H_3O^+; this would lead to dissociative recombination rates that might be faster than the rates for the less complex molecular ions quoted in Eqs. (4) and (5). The neglect of these species in the present study should not appreciably affect the results for the total number of electrons removed over a large-scale region 900 s after the release.

For use in preliminary assessment studies such as this, Mendillo and Forbes[15] developed a relatively simple formulation whereby the hole-making potential of a release scenario may be computed by forming a set of O^+ "destruction operators" for each molecular species involved. Figures 2 and 3 give an illustration of the technique for the case of 3×10^{28} water molecules (approximately 1 ton of water—and similar to 1 s of Saturn V exhaust). Figure 2 describes the molecular diffusion results and their resultant effect upon the O^+ distribution. The top two panels show molecular concentrations (in cm^{-3}) at 30 and 300 s after the release, while the bottom two panels show O^+ destruction operators, defined as $D(t) = [O^+(t)]/[O^+(t=0)]$, at $t=30$ and 300 s. Note that the O^+ concentrations are not affected by H_2O concentrations of less than $10^5/cm^3$.

Figure 3 describes the consequence such a release would have upon the electron densities N_e of a typical mid-latitude winter nighttime ionospheric profile ($N_e(h,r)$ at $t=0$ is given in the upper left panel). The remaining three panels give $N_e(h,r)$ contours at $t=30$, 60, and 300 s. Note that the hole forms quickly and descends into the lower ionosphere as time progresses.

The techniques described by Mendillo and Forbes[15] do not include plasma diffusion or solar production effects and thus use of the multispecies destruction operator method provides a good estimate of the maximum possible hole that results from a release, but nothing about recovery times. Since the depletions form in the first few minutes following a release, these methods are well suited for assessing the environmental impact of large-scale rocket plume effects.

Assessment Scheme for Rocket Exhaust Effects

A concise and meaningful way of determining the potential consequence of any injected molecules is to specify the relationship between the total number of electrons lost within the geographical area surrounding the release and the total number of molecules available. Thus, a parameter called the total electron count (N_{tot}) may be defined to be

$$N_{tot}(t) = \int\int N_e(h,r,t)2\pi r\,dr\,dh$$

and

$$\Delta N_{tot}(t) = N_{tot}(t_0) - N_{tot}(t)$$

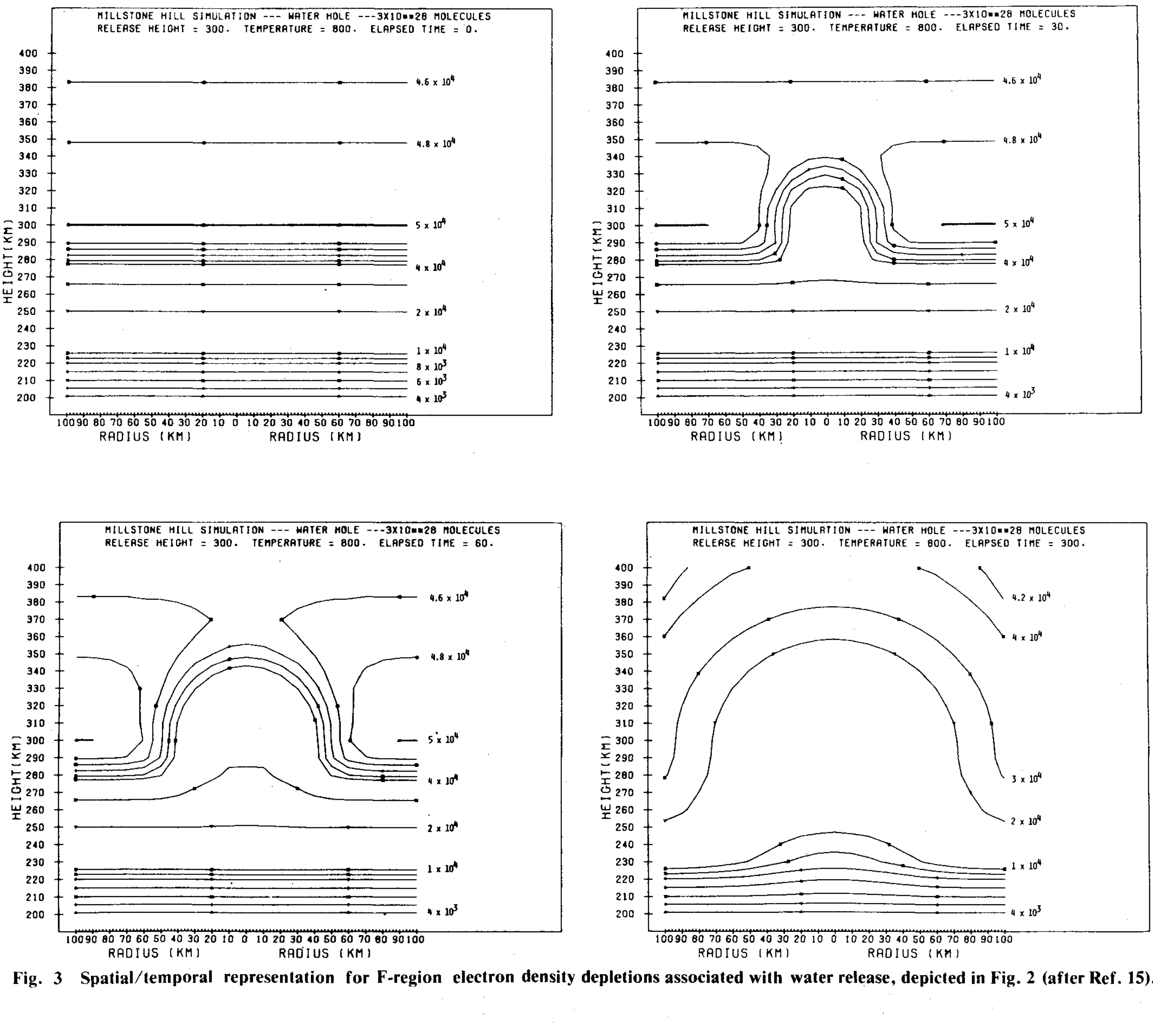

Fig. 3 Spatial/temporal representation for F-region electron density depletions associated with water release, depicted in Fig. 2 (after Ref. 15).

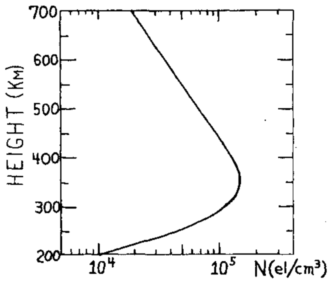

Fig. 4 Winter nighttime electron density profile, $N_e(h)$, for mid- latitudes during a solar maximum year.

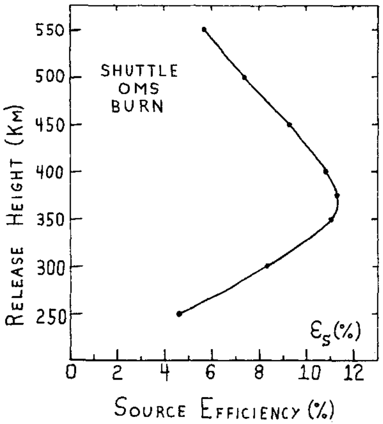

Fig. 5 Source efficiency results for an 11-s burn of the Space Shuttle OMS engines at various ionospheric heights; total source = 3.5×10^{27} H_2, H_2O, and CO_2 molecules.

The "efficiency" of the source (S_0) may then be defined as

$$\mathcal{E}_s(t) = [\Delta N_{\rm tot}(t)/S_0]\times 100$$

where $\mathcal{E}_s$ is expressed in percent as a convenient way of describing the actual units of electrons lost/molecules released. When defined in this way, the efficiency of the release gets larger as the source gets smaller. Thus, in the smallness limit of $S_0 = 1$ molecule, one electron would be lost and $\mathcal{E}_s$ would be 100%. The more interesting case occurs when S_0 is large and, in fact, approaches the total number of electrons found over large geographical areas.

The following two sections are devoted to a description of how the source efficiency factors $\mathcal{E}_s$(%) depend on the size and altitude of the release. For illustration purposes, use was made of the electron density profile $N_e(h)$ shown in Fig. 4, one typical of winter nighttime conditions at mid-latitudes during a solar maximum year. The vertical (columnar) total electron content (TEC $=\int N_e(h)\mathrm{d}h$) for this profile is 3.6×10^{12} electrons/cm^2.

Space Shuttle Effects

Table 1 presents a summary of the molecular flow rates anticipated from firings of the Space Shuttle's orbital maneuvering subsystem (OMS) engines. Following the scheme outline by Mendillo and Forbes[15] for handling multiple species destruction operators, computations were made of a set of source efficiency factors $\mathcal{E}_s(t)$ for 11 s bursts of OMS exhaust at various points over the 250-550 km altitude range. The $\mathcal{E}_s$ results were computed as a function of time after the release and for a variety of radii to test for the temporal and spatial extent of the hole-making process. The results in Fig. 5 give $\mathcal{E}_s$ at $t = 900$ s (by which time the hole formation had essentially stopped), using a radial extent of 175 km (beyond which negligible N_e changes occurred). Note that for this type of "small release" the $\mathcal{E}_s$ curve closely resembles the $N_e(h)$ curve in Fig. 4. The most efficient release height, $h(\mathcal{E}_{\rm max})$, is slightly above the height where the peak electron density occurs, $h(N_{\rm max})$, an effect due to the gravitational settling of the molecules, as shown in Figs. 2 and 3. The fact that only 10% of the molecules released actually led to the loss of an ion-electron pair should not be confused with the fact that severe N_e depletions have occurred near the release point. Thus, while an "overkill" situation exists near the release point, two factors limit the hole-making effectiveness of the molecules at more remote distances:

1) Vertical diffusion through an exponentially decreasing atmosphere results in the rapid escape of molecules before they can react with the O^+ in the topside ionosphere.

2) Horizontal diffusion through the Earth's tenuous upper atmosphere quickly results in molecular concentrations too low ($<10^5$ molecules/cm^3) to be of chemical importance.

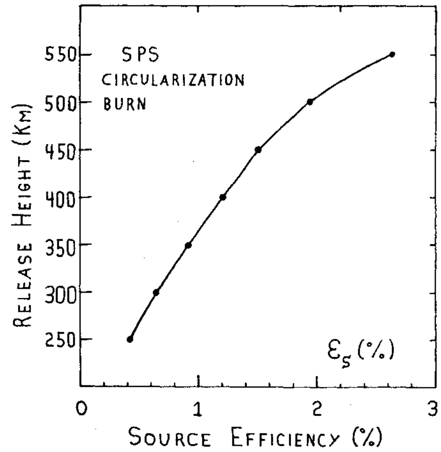

Fig. 6 Source efficiency results for an equivalent point source circularization burn of the HLLV proposed for the SPS program; total source = 10^{30} H_2 and H_2O molecules.

Solar Power Satellite (SPS) Related Effects

The launch vehicles being considered to ferry large amounts of material and personnel into space for SPS construction and maintenance are still in a very preliminary stage. The heavy-lift launch vehicle (HLLV) concept that has initially emerged[16] calls for a Space Shuttle-type vehicle with a multi-Saturn V equivalent lifting capability. The potential scenario of two HLLV launches per day on a continuous basis suggests an upper limit to the type of "large release" ionospheric modification effects that may be expected for the early 21st century.[14] As an example of what might be expected, Table 2 summarizes the type of exhaust breakdown proposed for a single HLLV orbit circularization burn using a liquid hydrogen/oxygen engine.

Table 1 Shuttle OMS exhaust rates by species

Species	Molecules/s
H_2O	1.36×10^{26}
H_2	1.20×10^{26}
CO_2	0.61×10^{26}

2 HLLV circularization burn exhaust charateristics

Species	Molecules
H_2O	7.5×10^{29}
H_2	2.5×10^{29}

Figure 6 contains source efficiency factor ($\mathcal{E}_s$) results at $t = 900$ s for equivalent point-source circularization burns by a single HLLV over the 250-550 km altitude range. Several features distinguished these "large release" results from those in Fig. 5:

1) The efficiencies are more than a factor of three smaller than for the Space Shuttle case.
2) The efficiencies increase with altitude throughout the ionosphere and thus no $h(\mathcal{E}_{max})$ is defined over the height range sampled.

The simulations carried out to obtain Fig. 6 required a radial extent of 1050 km to insure negligible effects at the outermost radius. Thus, while the efficiencies are low, the spatial extent of the resultant hole is obviously much larger than for the Space Shuttle case. The low $\mathcal{E}_s$ values for the SPS case are caused by the same "overkill" effects discussed with respect to the Shuttle. The curve in Fig. 6 does not go through a maximum simply because of the enormity of the SPS source function. Thus, even for an equivalent engine burn high in the topside ionosphere, diffusion and gravitational settling effects result in a significant number of molecules reacting with the ionospheric O^+ ions to form a hole.

Discussion and Conclusions

The plasma species (O^+ and e^-) which make up the F-region of the ionosphere ($h \approx 200$-1000 km) will experience significant modification effects ("ionospheric holes") with virtually every in-orbit engine burn of the Space Shuttle and the proposed HLLV's needed to construct an SPS program. The results presented here indicate that simple scaling arguments based on the number of highly reactive molecules (H_2, H_2O, CO_2) contained in a rocket exhaust plume cannot be used to estimate the number of electrons that will be lost due to an engine burn. For a source efficiency factor defined as $\mathcal{E}_s$ = number of electrons lost/number of molecules released, the trend clearly exists that $\mathcal{E}_s$ gets smaller as the size of the release increases—at least for point source releases in the 10^{27}-10^{30} molecules range appropriate for a small Space Shuttle OMS burn to a Saturn V/HLLV-type major orbital maneuver.

Rocket exhaust simulation studies should be extended from point source to line source perturbation scenarios for more realistic assessments. Mendillo and Forbes[15] investigated vertical line source effects in comparison to point source results for the same total number of molecules and found little difference between the two at $t = 10$ min after the release. A vertical line source at F-region heights is an unlikely scenario for an orbital vehicle since minimum energy (Hohmann type) requirements would utilize a cotangential engine burn to change orbital altitudes. From the modification perspective, the exhaust plume from such a burn would take the form of a horizontal line source. This may be treated as a succession of point releases and thus the source efficiency ($\mathcal{E}_s$) results presented in previous sections may be used to draw some preliminary, general conclusions about line source effects:

1) The maximum possible ionospheric perturbation (i.e., in terms of spatial extent) would be associated with a horizontal line source situated slightly above the peak of the ionospheric $N_e(h)$ profile (e.g., in the 350-450 km range). Such a configuration points to the most efficient dispersal of a molecular exhaust plume for the purpose of creating ionospheric depletions.

2) The opposite case of minimizing the spatial extent of an ionospheric hole would be achieved by requiring as concentrated a horizontal line source as is possible, and to locate that burn below the peak of the $N_e(h)$ profile. Note that the $\mathcal{E}_s$ results presented in Fig. 5 show a 50% reduction in hole-making efficiency for a point source release 100 km below $h(N_{max})$ in comparison to a release 100 km above $h(N_{max})$.

A new treatment of a moving, time-dependant horizontal line source has recently been carried out by Bernhardt.[17] The features described here and in Ref. 15 are essentially the same, although the spatial translation of a plume resulting from a moving rocket was shown to be significant for small sources—a point of some consequence for attempts to monitor plume effects with ground-based diagnostics.

The $\mathcal{E}_s$ results presented in Figs. 5 and 6 for small and large engine burns are in good agreement with the only experimental studies capable of addressing the spatial extent aspect of F-region depletions induced by the injection of highly reactive molecules. The Skylab effect[8] and the more recent Lagopedo experiments[18-20] pertain to large and small releases, respectively; the total electron content measurements made during each of these events point to low and high $\mathcal{E}_s$ factors, respectively, as the simulations presented here would suggest.

Finally, the opportunity to document in a more complete way the modification effects associated with a low exhaust rate horizontal line source will occur during the first day of the series of Spacelab-2 ionospheric modification experiments[21,22] scheduled for late 1982. The circularization burn for the Spacelab-2 mission is scheduled to occur along an approximately 800 km long path centered on the Millstone Hill Incoherent Scatter Ionospheric Observatory. A more immediate opportunity for assessing rocket exhaust effects was present during the Atlas/Centaur launch of the HEAO-C satellite in September 1979.[23] The wide variety of upper-atmosphere diagnostics scheduled to monitor these experiments should provide a much needed description for the largest type of Space Shuttle/Atlas Centaur perturbations that can occur and, indeed, set a baseline reference for any anticipated HLLV effects associated with the SPS program.

Acknowledgments

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References

[1] Kellogg, W.W., "Pollution of the Upper Atmosphere by Rockets," *Space Science Review,* Vol. 3, 1964, pp. 275-316.

[2] Booker, H.G., "A Local Reduction of F-Region Ionization Due to Missile Transit," *Journal of Geophysical Research,* Vol. 66, April 1961, pp. 1073-1079.

[3] Jackson, J.E., Whalen, H.A., and Bauer, S.J., "Local Ionospheric Disturbance Created by a Burning Rocket," *Journal of Geophysical Research,* Vol. 67, May 1962, pp. 2059-2061.

[4] Stone, M.L., Bird, L.E., and Balser, M., "A Faraday Rotation Measurement on the Ionospheric Perturbation Produced by a Burning Rocket," *Journal of Geophysical Research,* Vol. 69, March 1964, pp. 971-978.

[5] Arendt, P.R., "Ionospheric Undulations Following Apollo-14 Launching," *Nature,* Vol. 231, June 18, 1971, pp. 438-439.

[6] Arendt, P.R., "Ionospheric Shock Front From Apollo-15 Launching, *Nature,* Vol. 236, March 6, 1972, pp. 8-10.

[7] Mendillo, M., Hawkins, G.S., and Klobuchar, J.A., "A Large-Scale Hole in the Ionosphere Caused by the Launch of Skylab," *Science,* Vol. 187, Jan. 31, 1975, pp. 343-346.

[8] Mendillo, M., Hawkins, G.S., and Klobuchar, J.A., "A Sudden Vanishing of the Ionospheric F-Region Due to the Launch of Skylab," *Journal of Geophysical Research,* Vol. 80, June 1975, pp. 2217-2228.

[9] NASA Johnson Space Center, *Space Shuttle,* U.S. Government Printing Office, Washington, D.C., Stock No. 033-000-00651-9, 1976.

[10] Banks, P. and Kockarts, G., *Aeronomy,* Academic Press, New York, 1973.

[11] Forbes, J.M. and Mendillo, M., "Diffusion Aspects of Ionospheric Modification by the Release of Highly Reactive Molecules Into the F-Region," *Journal of Atmospheric and Terrestrial Physics,* Vol. 38, 1976, pp. 1299-1307.

[12] Anderson, D.N. and Bernhardt, P., "Modeling the Effects of an H_2 Gas Release on the Equatorial Ionosphere," *Journal of Geophysical Research,* Vol. 83, Oct. 1978, pp. 4777-4789.

[13] Bernhardt, P., "Three-Dimensional, Time-Dependent Modeling of Neutral Gas Diffusion in a Nonuniform, Chemically Reactive Atmosphere," *Journal of Geophysical Research*, Vol. 84, March 1979, pp. 793-802.

[14] Zinn, J., Sutherland, C.D., and Pongratz, M.B., "Effects of Rocket Exhaust Products in the Thermosphere and Ionosphere," Los Alamos Scientific Lab., Report LA-7926-MS/UC-34b, July 1979.

[15] Mendillo, M. and Forbes, J.M., "Artificially Created Holes in the Ionosphere," *Journal of Geophysical Research*, Vol. 83, Jan. 1978, pp. 151-162.

[16] DOE/NASA, "Satellite Power System Concept Development and Evaluation Program, Reference System Report (October 1978)," DOE/ER-0023, Jan. 1979.

[17] Bernhardt, P., "High-Altitude Gas Releases: Transition From Collisionless Flow to Diffusive Flow in a Nonuniform Atmosphere," *Journal of Geophysical Research*, Vol. 84, Aug. 1979, pp. 4341-4354.

[18] Pongratz, M.B. and Smith, G.M., "The Lagopedo Experiments—An Overview," *Transactions of American Geophysical Union*, Vol. 59, April 1978, p. 334.

[19] Clynch, J.R., Rushing, C., and Klobuchar, J., "Faraday and Differential Doppler Observations of the Lagopedo Ionospheric Depletions," *Transactions of American Geophysical Union*, Vol. 59, April 1978, p. 335.

[20] Klobuchar, J.A., Clynch, J.R., and Mendillo, M., "VHF Radio Wave Propagation Effects Observed During Lagopedo Ionospheric Modification Experiments," *Transactions of American Geophysical Union*, Vol. 59, April 1978, p. 334.

[21] Mendillo, M., da Rosa, A.V., and Bernhardt, P., "Spacelab-2 Plasma Depletion Experiments," *Transactions of American Geophysical Union*, Vol. 59, April 1978, p. 334.

[22] Rosendahl, J.D., "The Spacelab-2 Mission," *Sky and Telescope*, Vol. 55, June 1978, pp. 462-464.

[23] Mendillo, M., Baumgardner, J., and Klobuchar, J.A., "Opportunity to Observe a Large-Scale Hole in the Ionosphere," *Transactions of American Geophysical Union*, Vol. 60, July 3, 1979, pp. 513-514.