The Shuttle Environment: Gases, Particulates, and Glow

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Introduction

THE growing number of Space Shuttle missions has presented the aerospace community with an unprecedented body of data on the Shuttle environment itself, as well as new data on astrophysical domains far from the Earth. This paper focuses attention on selected Shuttle environmental phenomena that may impact plans for future observations from the Shuttle platform. In this review data from STS 2-4 which have recently become available will be compared and contrasted. These data have all been presented previously, although not largely in the open literature.

Among the many environmental factors that will interest users of the Shuttle, three factors have been selected that must be reckoned with for a broad range of instruments and measurements:; gases, particulates, and vehicle glows. We leave aside other issues such as mechanical structure, vibroacoustics, thermal excursions, electromagnetic interference, and materials degradation; the first three of these appear to be well understood at this time, and the last two are active research areas.

Gases, such as H_2O, surrounding the Shuttle can potentially absorb light from astronomical sources giving false, partially attenuated spectra (visible, i.r.), and can contaminate those types of particle/optical detectors that are open to the vacuum. Particulate matter can settle out on optical surfaces, reducing their transmission, and can scatter unwanted light from the sun or the Earth into the line of sight of a telescope. Vehicle glows may stand in the way of a telescopic line of sight, adding spurious signals and limiting the sensitivity of astronomical or Earth observations.

While a great deal of attention[1] has been given to the Shuttle environmental parameters as potential problems for Shuttle users, we wish to stress that so many of the original requirements on the Shuttle have been met that perhaps undue emphasis can now be seen to have been given to these "problem areas." This emphasis may have been strong enough to make it hard for users to know, a priori, that the Shuttle is, in fact, a working spaceship ready to convey many successful instruments into space over the years ahead.

Two elements currently important for users of the Shuttle are 1) to have a candid and complete description of the environment in the payload bay on-orbit, controversies notwithstanding, and 2) to make sure that the Shuttle environment is not only consistent with any given set of measuring instruments but also steadily improves with successive launches. In an effort in this direction, Scialdone[2] has recently presented a baseline model for the gaseous and particulate environment of the Shuttle bay. The developing Shuttle bay data base provides both a test bed for such models and a means for extending them.

In this paper we concentrate on the data (and interpretation thereof) from various early STS flights, with regard to the gaseous envelope surrounding the Shuttle, the particle populations in orbit with the Shuttle, and the optical interferences from local (rather than astronomical) sources. It seems that many design goals for the on-orbit environment have been met. On the other hand, the environment is very variable, depending upon angle of attack, thruster events, water dumps, solar angle, and payload bay activities. We will attempt to highlight the role of these effects whenever possible.

Gaseous/Plasma Environment Around the Space Shuttle

Several different instruments have been used to sample the on-orbit neutral/ionic gas composition in the Shuttle payload bay. These include: a neutral mass spectrometer,[3] which was part of the Induced Environment Contamination Monitor (IECM); a Bennett rf ion mass spectrometer,[4] which was part of the Plasma Diagnostics Package (PDP) on STS-3; and a fast sampling quadrupole mass spectrometer[5] used in both ion and neutral sampling modes on STS-4.

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These devices were backed up with additional diagnostics such as pressure monitors and electron density probes (see, for example, Ref. 6). In general, the Shuttle contaminants were apparently no more severe than anticipated[1]; however, very large variations in species/densities are observed during the course of flight, most of which can be related to either orbital considerations, i.e., angle of attack, solar attitude, spin, etc., or Shuttle events such as engine firings, water dumps, and bay door operation. While a sampling of the available data base has appeared in Refs. 3-5, no detailed comparison or interpretation of the results has yet been presented. A brief overview of these results is provided below.

The Natural Atmosphere

These composition measurements must be interpreted in light of the natural atmospheric constituents in order to separate the Shuttle-induced component. Shuttle missions 2-4, which we consider here, had on-orbit altitudes of 240-300 km. Both higher and lower altitude orbits have been achieved during later missions. At these altitudes atmospheric densities are on the order of 10^9 particles/cm^3. Representative atmospheric compositions[7] at altitudes of 240 and 305 km are given in Table 1. Atomic oxygen is the dominant constituent, although N_2, O_2, and He are present in significant quantities. At these altitudes the atmospheric kinetic temperature is comparable to the exospheric value and ranges between 800-2000 k. This tenuous atmosphere has a collisional mean free path of about 1 km. The dominant characteristic of the atmosphere at these altitudes is its variability. Even the most simplistic treatment of the atmosphere must consider its dependence on diurnal, latitudinal, and solar activity effects. The ionosphere is a multiconstituent plasma whose behavior is linked with that of the neutral atmosphere through solar ionizing radiations, and with electrodynamic influences of the magnetosphere. Shuttle missions occur in the midst of the F2 region, which is the ionospheric layer having the highest plasma density—up to 10^6 ions/cm^3. The dominant ion is O^+ produced from absorption of solar uv ionizing radiation; on the order of 0.1% of the O atoms are ionized. The ionosphere exhibits even more extreme variability than the neutral atmosphere, with the F2 peak generally being at lower altitudes during the day, and higher at night. It is within this very variable natural environment that the Shuttle operates. Thus, it is obvious that care must be taken in generalizing any specific observational finding.

The Shuttle will perturb this natural environment both by its flowfield and its emissions: leakage, evaporation, outgassing, desorption, and orbital control thrusters.

The Orbiter carries a vernier thruster system of six rockets that provide 1.1×10^7 N of thrust and a reaction control system consisting of 38 main thrusters that can produce up to 3.8×10^8 N each. All of these hypergolic engines utilize monomethylhydrazine (MMH) as fuel and N_2O_4 as oxidizer. The exhaust products are modeled to be predominantly H_2O, N_2, H_2 and CO with traces of CO_2, H, unburned fuel, and O_2 (see Table 2). The mean exhaust velocity is 3.5×10^5 cm/s.

Neutral Measurements

Carignan and Miller[3] have reported neutral species observations taken on STS – 2, -3, and -4. Their device spanned the mass range from 2 to 150 amu and used a three-stage skimmer pumped by zirconium oxide getters to limit the instrument field of view to 0.1 sr.

Both ambient atmospheric and contaminant species were observed by the mass spectrometers. Species identified from the measurements include He, H_2O, N_2/CO (mass 28), NO (presumably), O_2, Ar, CO_2, Freon 12 and 21, trichloroethylene, and other heavy hydrocarbons (cleaning agents). Statistically significant quantities of masses 11, 19, and 36 were also observed but not identified. (Note that mass 19 could be H_3O^+ produced from a reaction between H_2O^+ and H_2O.) Although O_2, N_2, He, and Ar are ambient molecules, the latter three were also found to be significant contaminants. The heavier species, with the exception of Freon 21 which is used in the thermal control systems, were typically in low concentrations and the CO_2 was primarily at instrument background levels, although some contribution from the Shuttle environment was observed. Interestingly enough, methane was also seen, with its presence correlated with thruster activity. It has been suggested that this observation reflects the presence of unburnt monomethyl hydrazine which is catalyzed to methane by the zirconium oxide getters.[3] An alternate mechanism, proposed by a reviewer, is that methane is released from the getters in the presence of increased water vapor during Reaction Control System (RCS) firings. In any event, Narcisi et al.[5] observed no evidence of CH_4 in their measurements.

The absolute concentrations of contaminants in the Shuttle bay are not well evaluated as yet. For most of the measurements the mass spectrometer was pointed upward out of the bay; thus, contaminants originating from Shuttle surfaces must scatter off of ambient gases into the instrument. Accounting for this effect is both complicated and uncertain, and self-calibration techniques have been employed. These calibrations have only been partially successful to date, and the results are not yet fully analyzed. Suffice it to say that ambient pressures are $\sim10^{-7}$ Torr, and bay pressures between 10^{-7} and 10^{-4} Torr have been observed[6] during various Shuttle activities with the higher pressures correlating with ram observations and thruster firings. The principal contaminants observed were H_2O and He, and much of the mission was dedicated to the study of H_2O. The envelope of H_2O flux into the spectrometer during the STS-4 flight is shown in Fig. 1. The values within the envelope are strongly modulated by the instrument angle of attack. The large spikes have been correlated to specific RCS firings,[3] although the vast majority of such firings do not lead to such large excursions in H_2O concentration.

The initial decay time for H_2O after launch is about 10 h, corresponding to outgassing from surfaces conditioned by the prelaunch environment. Interestingly enough, later spikes in the H_2O count rate apparently exhibit similarly long decays, in contradiction with the observations of Narcisi et al.[5] described below. These long decay times may be an instrumental artifact, for example, reflecting vapor histories over the zirconium oxide getters. Alternately these measurements may reflect outgassing over Shuttle surfaces.[9] Additional testing with the instrument would be required to resolve this issue.

Estimates of the H_2O column density for the three flights are provided in Table 3. The maximum limits correspond to observations at early times. Note the large variations from flight to flight. STS-2 and STS-4 were subjected to heavy rains prior to launch, and this may account for the higher observed column densities in the early orbits.

It is expected that ambient species will behave quite differently than contaminants as the spectrometer angle of attack is varied. This is borne out in Fig. 2 where the He and Ar count rates vs time are shown for a particular STS-3 orbit. (These species are not collimated by the getters.) The system angle of attack varies from 170 to 10 deg over the time shown, and the He and Ar concentrations are seen to be largest in the near-ram position, in keeping with the presence of these species in the ambient gas. [The bump in the Ar trace is due to flow interference from the Remote Manipulator System (RMS)[3].] These observations, along with many others not shown, are in good agreement with model atmosphere expectations.

On STS-4 the IECM was picked up by the RMS and moved around to enable it to look down at the Shuttle bay and adjacent surfaces. Measurements were performed for 15 different orientations, as shown in Fig. 3a; each with a 10 deg half-angle field of view. The corresponding average count rates for H_2O are shown in Fig. 3b, the spikes represent changes due to RCS

Table 1 Atmospheric composition (from Ref. 7), molecules/cm^3 [$1.7 \times 10^9 = 1.7(9)$]/fractional composition

Altitude, km	O	N_2	O_2	He	A	H
240	1.7(9)/70.1%	6.8(8)/28.0%	3.7(7)/1.5%	1.0(7)/0.4%	2.5(5)/0.01%	1.3(5)/0.005%
305	5.0(8)/84.2%	8.3(7)/13.9%	3.3(6)/0.6%	7.4(6)/1.25%	1.3(4)/0.002%	1.0(5)/0.02%

Table 2 Modeled thruster exhaust thruster exhaust products (from Ref. 8)

Species	Mole fraction
H_2O	0.328
N_2	0.306
H_2	0.17
CO	0.134
CO_2	0.036
H	0.015
O_2	0.0004
$MMH\text{-}NO_3$	0.002

Table 3 H_2O contaminant column density (from Ref. 3)

	Maximum[a]	Final
STS-2[b]	2.0×10^{13}	2.7×10^{12}
STS-3	1.5×10^{11}	4.0×10^{10}
STS-4	3.2×10^{13}	1.0×10^{12}

[a]Except for RCS firings and payload bay door closings.
[b]The STS-2 values are considered upper limits.

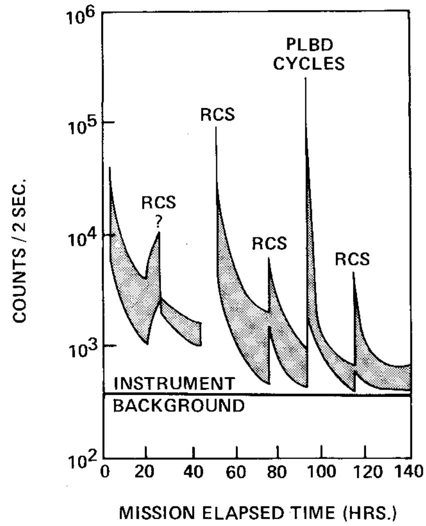

Fig. 1 Envelope of H_2O count rate over the duration of the STS-4 flight.[3]

thruster firings. Measurements for helium were quite similar; however, Freon 21 exhibited a distinct signature, reflecting perhaps the position of specific leaks. With the exception of freon the contaminants appear to be well distributed throughout the bay, peaking slightly in the aft section.

Narcisi et al.[5] also report Shuttle contaminant species measurements acquired using a quadrupole mass spectrometer. This instrument was positioned to look horizontally over the right wing of the Shuttle, although pitched slightly upward, and had a 2π field of view for neutrals. Measurements were made in both ram and nonram modes. During the ram mode, measurements are made with (R mode) and without (NR mode) a grid-retarding potential of 2.5 V to distinguish between ambient and contaminant species. Ambient species, having no directed kinetic energy, cannot penetrate beyond the retarding barrier.

Typical observations during vernier (VCS) and Orbiter Maneuvering System (OMS) burns are shown in Fig. 4a. Note that the H_2O and N_2 histories follow the total pressure, with signals decaying back to steady levels within seconds, quite unlike the bay observations by Carignan and Miller.[3] It is to be remembered that Narcisi's instrument has a significantly different viewing configuration and a much broader field of view. Narcisi's data will observe species scattered off wing structures and, thus, it will be susceptible to surface-induced effects, but may more closely represent the actual bay environment. H_2, an exhaust species not observed in the IECM measurements, was found by Narcisi to behave in a manner similar to N_2 and H_2O during thruster firings (see Fig. 4b). These species are the three major components expected in thruster exhaust. (See Table 2.)

One of the more intriguing measurements reported by Narcisi et al.[5] is shown in Fig. 5. Here the average H_2O signal for a given scan is plotted vs mean MET (mission elapsed time) and compared with the spectrometer sensor temperature measurements. There is a remarkable correlation between these two histories. Although the local variation in temperature is small, thermistors placed throughout the pallet exhibit significant variations, on the order of 100°C, while maintaining a temporal structure similar to that shown in Fig. 5. Since the instrument has a large field of view, it can sample the outgassing from a wide surface area. Indeed, Narcisi et al.[5] conclude that the spacecraft surface temperatures seem to be a significant controlling factor in the water vapor environment. Note that measurements made in the more confined interpayload areas within the bay may exhibit different dependencies. Additional measurements on future flights should resolve this issue. Again, absolute calibrations are difficult because of the scattering problem. As discussed below, Narcisi et al.[5] have suggested that absolute H_2O concentrations may be deduced more appropriately from ionic observations.

Helium was once again found to be an important species. Approximate helium pressures were found to vary between 4×10^{-9} and 2×10^{-7} Torr. Since typical ambient ram He pressures were $\sim 6 \times 10^{-9}$ Torr and the observations were primarily made in nonram operation, substantial helium leaks, apparently from payloads, were evident. Higher molecular weight species, > 50 amu, were also observed, and the total "heavy" pressure was estimated to be $< 10^{-9}$ Torr. In these latter measurements contamination by ion source outgassing cannot be excluded, particularly since no mass discrimination was attempted.

Positive Ion Measurements

Narcisi et al.[5] also operated their instrument in the ion mode; instrument field of view in this case was 20 deg, and a typical scan time for amu 1-67 and TI (total ions) > 50 amu was less than 1 s. Species observed include O^+, H_2O^+, H_3O^+, N^+, N_2^+, NO^+, O_2^+, and OH^+.

A typical scan of H_2O^+, O^+, and N^+ vs time is shown, contrasted to the density monitor, in Fig. 6. These measurements were performed during daytime, at an altitude of 298.5 km, and with an instrument angle of attack ranging between 33 and 38 deg. The O^+ and N^+ are ambient species, and

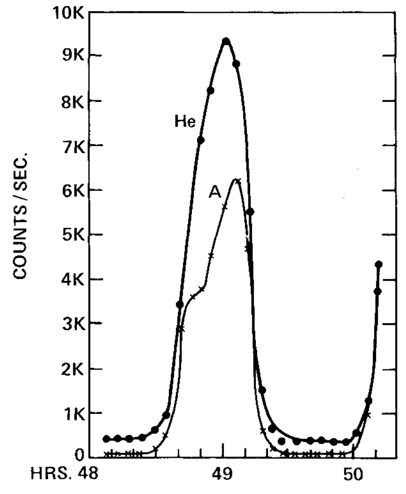

Fig. 2 Variation in measured helium and argon as instrument angle of attack varies from 170 to 10 deg.[3]

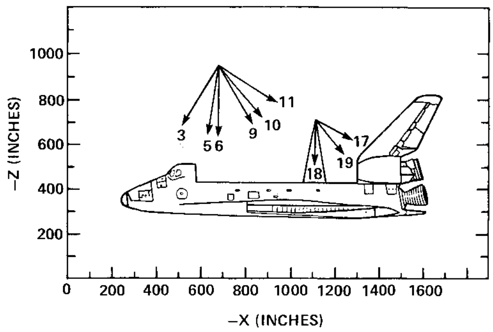

Fig. 3a STS-4 geometry of some contamination survey positions.

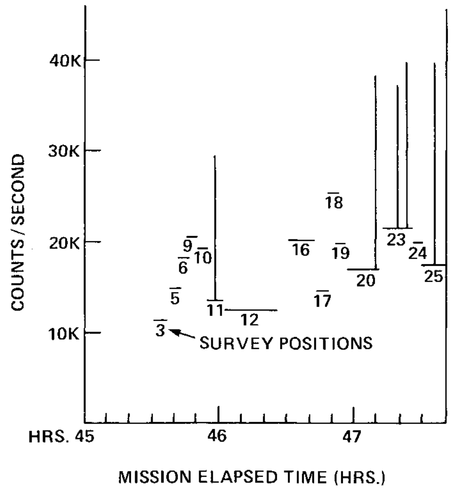

Fig. 3b STS-4 H_2O counts during contamination survey.[3]

H_2O^+ is a contaminant species most likely formed via

$$O^+ + H_2O \rightarrow H_2O^+ + O \tag{1}$$

Note that the O^+/H_2O^+ ratio typically is of order unity (factor of 2). This ratio is sensitive to angle of attack and was found to be ~ 10 with the instrument looking in the ram direction in an earlier orbit. Nighttime concentrations of H_2O^+ were found to be lower, reflecting lower ambient O^+ densities.

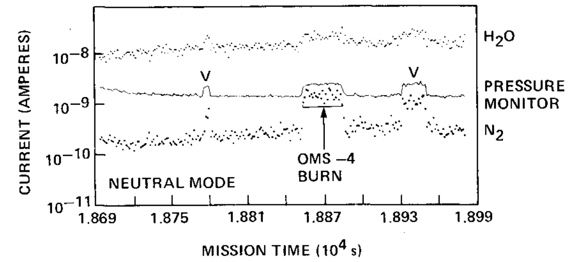

Fig. 4a Orbit 4.6 measurements of N_2, H_2O, and the pressure monitor exhibiting effects of the Vernier and OMS burns.[5]

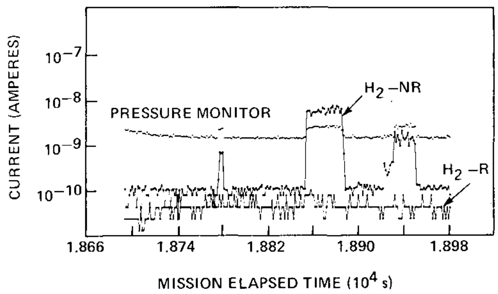

Fig. 4b Orbit 4.6 measurements of hydrogen showing clear increases due to engine firings.[5]

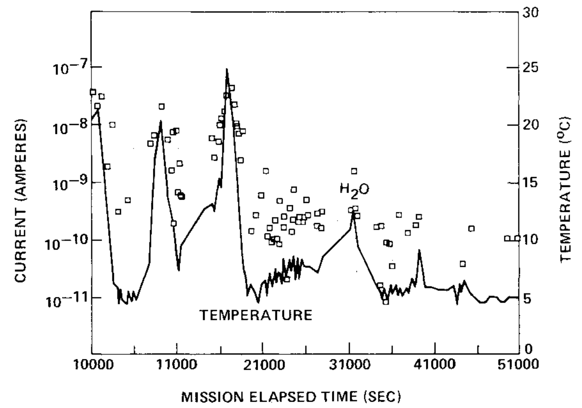

Fig. 5 The average H_2O currents and sensor temperature measurements throughout flight.[5]

The H_3O^+ current falls about one order of magnitude below that of H_2O^+ for the conditions of Fig. 6. This species is most likely produced via the reaction.

$$H_2O^+ + H_2O \rightarrow H_3O^+ + OH \tag{2}$$

It has been suggested[5] that these data may be used to estimate neutral H_2O concentrations via a kinetic analysis.

The spikes seen in Fig. 6 in the vicinity of 23,210 and 23,270 MET correspond to VCS firings. At these times, positive ion depletions of an order of magnitude are observed in the total density monitor and reflected in the O^+ and N^+ observations. Thus the thruster exhaust gases tend to displace or "blow away" the ambient atmosphere. Enhancements in the N_2^+, NO^+, and OH^+ concentrations were noted at these times. These species correspond to anticipated products of reactions between O^+ and the thruster exhaust gases N_2 and H_2. The decrease in H_2O^+ concentrations is attributable to the decrease in O^+, its precursor. The H_2O concentration is already large and the thruster event does not alter the H_2O concentration sufficiently to overcome the O^+ depletion.[5]

We note that ion measurements during thruster firings may be complicated by concomitant changes in vehicle potential.[10] Narcisi et al.[5] have performed measurements on O^+ and NO^+

where their retarding potential was swept over ranges of 12 and 19 V, respectively; although these data have, for the most part, not yet been analyzed. They have demonstrated the ability to measure spacecraft potential in this manner, however.

Grebowsky et al.[4] have performed thermal ion measurements in the Shuttle bay on STS-3 using a Bennett ion mass spectrometer that was part of the Plasma Diagnostic Package. The STS-3 mission was in a transequatorial orbit (inclination of 38 deg) with a mean altitude of 244 km, and the ion measurements reported were specific to a nose-to-sun attitude orbit. The spectrometer was positioned within the PDP in the bay so that it faced the interior port bulkhead. The instrument scanned 1-64 amu in 2.4 s.

Ions observed include O^+, H_2O^+, H_3O^+, NO^+, O_2^+. A typical observation is shown in Fig. 7. Note that a signal is only shown for 50 min out of the 90-min orbit; no thermal ions were observed during the unplotted portion of the orbit.

As can be seen, the ion concentrations all increase sharply as the Shuttle proceeds through the dawn terminator. On other orbits, a brief (~10 min) precursor enhancement of the ion currents is observed followed by a decrease just prior to sunrise. These observations are quite different from those of Narcisi et al.,[5] and more difficult to interpret because of the positioning of the instrument and possible interference from other payloads. In particular, for most of the orbit the majority of ambient ions would scatter off of the Shuttle's outgassing layer or Shuttle/payload surfaces prior to entering the spectrometer. Surface scattering would most likely result in ion neutralization. The observed daytime dropoff in ion concentrations can be correlated with a similar drop in bay pressure, occurring as the bay faces the Shuttle wake. It would be expected that the wake would exhibit depleted ion concentrations.

The day/night ion variation does not scale with PDP pressure and is not well understood, although it may also be due to ram-wake variations. Grebowsky et al.[4] originally suggested that the variation may result from photoionization of the Shuttle cloud. This appears unlikely given anticipated photoionization rates at Shuttle altitudes. Indeed one would anticipate that the contaminant ions would be produced via reaction with ambient species. Perhaps geometric effects preclude such reactive events within the instrument field of view during specific portions of the orbit. On the other hand, the day/night behavior is reminiscent of F_1 region collapse that can occur at Shuttle altitudes in the equatorial region. Nonetheless, Grebowsky et al.[4] argue that the observed predawn precursor ion currents result from ambient ions entering the instrument, confusing the issue further. It is clear that these observations require further investigation.

Variations in ion concentrations were also correlated with Shuttle activities such as water dumps and thruster firings. For example, enhancements in H_2O^+, H_3O^+, and NO^+ have been observed in thruster firings. Narcisi et al.[5] observed similar enhancements in exhaust-related species, although reporting a concomitant drop in total plasma density. Such a drop is not reported by Grebowsky et al.,[4] perhaps because their scan time was considerably larger than typical burn times. In any event, the interpretation of the measurements of Ref. 4 in terms of ambient ions is complicated by surface scattering effects.

It appears that during thruster events significant increases in contamination levels occur that largely dissipate on time scales of 1 s. If this is indeed the case, thruster firings may be viewed by Shuttle experimenters as a short-term inconvenience whose effects may be removed by appropriate filtering. On the other hand, because thruster events are so frequent (approximately once every 15 s on average), a cooperative arrangement between experimenters and the Shuttle crew may be required for sensitive observations.

There have been several measurements of the electron densities and energies that we have not addressed here. Shawhan et al.[6] and Murphy et al.[10] have reported factors of 2-10 increases over ambient in the thermal electron concentrations as compared to the nearly parallel observations of the Dynamics Explorer satellite.[11] Indeed unusual electron energy ditributions have been observed[11,12] and interpreted to indicate the presence of a Shuttle-induced plasma above vehicle surfaces in the velocity vector.

In summary, it is apparent that the Shuttle neutral/plasma environment is very sensitive to both the ambient atmosphere and Shuttle activity, and that the species observations strongly reflect both instrument positioning and angle of attack. Very few of the data have been analyzed to date, and most of the published results highlighted here are presented as particle fluxes rather than concentrations. A number of interesting, and in some instances unexplained, observations have been provided. It seems likely that at least some of these differences can be attributed to atmospheric variability between missions or even during a mission. Further analysis and additional careful measurements should aim to provide a sound basis for comparison so that agreements are believable, and explanations can be found for real differences. Then, finally, we will

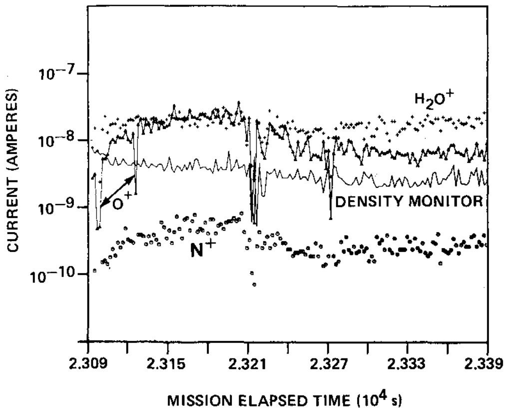

Fig. 6 Orbit 5.4 daytime measurements of O^+, N^+, and H_2O^+, and the density monitor.[5]

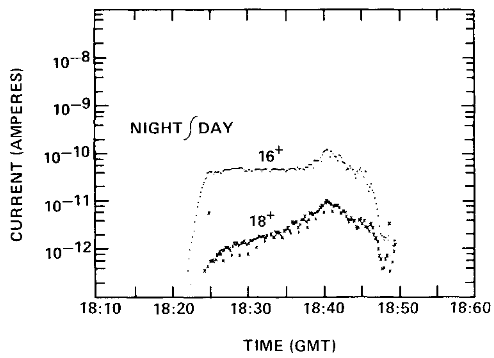

Fig. 7a The collected ion currents in the bay for the ion species with atomic masses of 16 and 18 for orbit 34.[4]

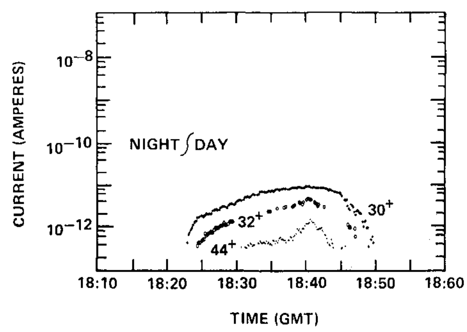

Fig. 7b The heavy mass ions measured on orbit 34. The ions with masses 18 (H_2O^+) and 44 (CO_2^+) are STS-3-borne contaminants.[4]

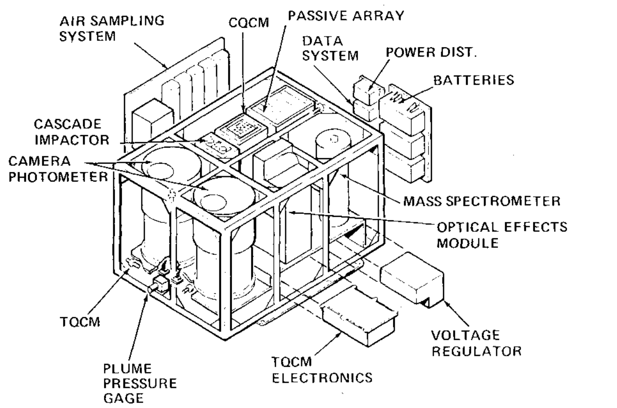

Fig. 8 Induced-environment contamination monitor which was onboard STS-2-3,-4 and Spacelab missions.[19] (TQCM and CQCM are temperature-controlled and cryogenic quartz crystal microbalances, respectively.)

be able to increase our understanding of the dynamic Shuttle environment.

Particulates

In this section, we summarize data[3,13,14] from the IECM for STS-2, -3, and -4 flights. Also we include data from a different source,[15] namely, video tapes of the field of view looking aft of the forward cargo bay on STS-3. Figure 8 shows components of the IECM. First, we will discuss briefly IECM data from the passive sample array, cascade impactor, and camera/photometer.

The passive sample array is a series of witness plates that present time-integrated exposures. Size distributions of particulates deposited on the passive sample array at various times are shown in Fig. 9. These are averaged over the three flights in question. Exchanging the sample trays and using control samples make it possible to distinguish the amounts and distribution of particulates for 1) the preflight environment at the Orbiter Processing Facility (OPF) at Kennedy Space Center, 2) the ferry flight that returns the Shuttle from the landing site, and 3) the orbital mission per se. Note that the OPF and ferry flight distribution are quite similar, and that the mission distribution displays three principal peaks near 5, 13, and 22μm. The OPF and Ferry distributions are not representative of a natural dusty environment, but are more smokelike in character.

The absolute degree of cleanliness can be estimated by comparison of the size distributions with MIL-STD-1246A for product cleanliness. This is shown in Fig. 10 for STS-4 where, to state the worst case, all of the points are seen to be below the standard line whose intercept represents the obscuration equivalent to one particle of 750 μm/ft^2. (A 300 μm normalized distribution was the goal set by the Contamination Requirements Design Group, CRDG.) Below the 100 μm particle size, the distributions are more consistent with the 300-μm clean air standard.

The cascade impactor data for periods during the ascent and descent of STS-2, -3, and -4 are shown in Table 4. This is a differential volumetric sampling of airborne particulates separated into three size ranges for the Shuttle altitude range 0-23 km, and is also compared here with the requirements for class 100 K clean air which was the CRDG goal. (We realize that relating cascade impactor particulate measurements in the bay during liftoff to a class 100 K clean air environment can be inexact. For example, collection efficiency can be a function of particle size.) The concentrations of the largest particles were well below those goals for all three missions. The intermediate and smallest particle concentrations are low for missions with dry prelaunch and takeoff weather, and seem to be greatly enhanced under wet conditions. The rationale for this apparent correlation is unclear.

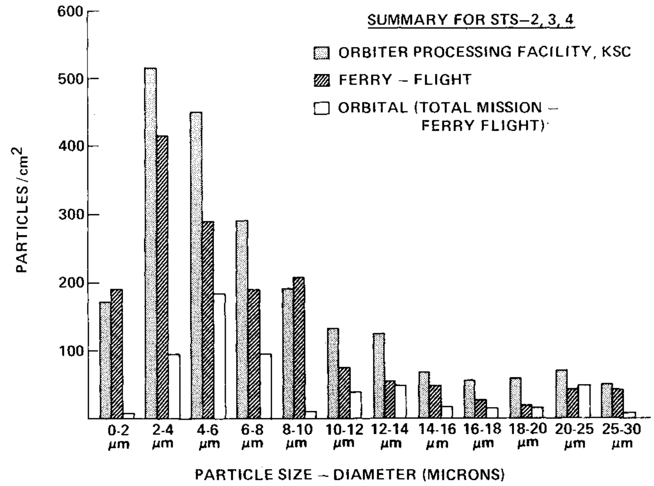

Fig. 9 Passive sample array particle distributions.[13]

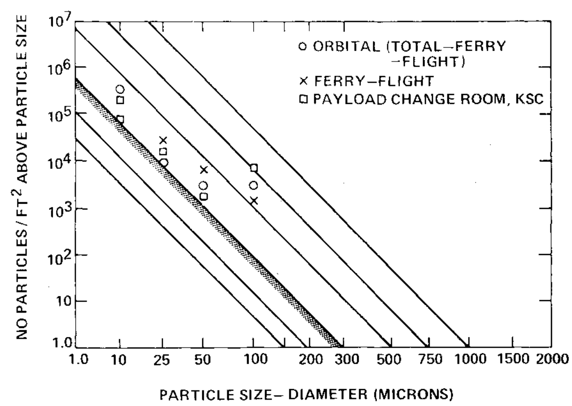

Fig. 10 Passive sample array: particle-size distributions for STS-4, combined mission operations.[14]

Table 4 Cascade impactor particulate measurements (taken from Ref. 13)

Particle size, μm	Class 100 K air, μg/m^3	Flight results, μg/m^3
>5	<375	STS-2 Ascent 30
		Descent 10[a]
	(assuming $\bar{d}=25$ μm, $\rho=2$ g/cm^3)	STS-3 Ascent 10
		Descent 10
		STS-4 Ascent nonfunctional
		Descent 20
1-5	<100	STS-2 Ascent 500
		Descent 250
	(assuming $\bar{d}=5\mu$m, $\rho=2$ g/cm^3)	STS-3 Ascent 10
		Descent 10
		STS-4 Ascent 300
		Descent 10
0.3-1	<10	STS-2 Ascent 250
		Descent 115
	(assuming $\bar{d}=1$ μm, $\rho=2$ g/cm^3)	STS-3 Ascent 10
		Descent 10
		STS-4 Ascent 90
		Descent nonfunctional

[a]Descent values should be considered upper limits due to errors introduced by thermal effects.

The on-orbit environment was probed by a camera/photometer experiment. Data from the IECM provide time-resolved information on the particulates orbiting with the Shuttle in the payload bay. The camera/photometer is actually a stereo pair of devices taking 32-deg field-of-view (FOV) films of contaminant particulates as small as 25 μm, as they are illuminated by the sun against a dark sky or Earth background. The photometers also provide data on the background levels of brightness not only when the illuminated particles are being photographed, but also during orbital nighttime when only the star field is observed.

Figure 11 presents curves reflecting the time histories of particle concentrations. During the first hours of Shuttle flights, the frequency diminishes for seeing many particles per frame, while the likelihood of seeing no particles per frame increases to virtually 100%. These data specifically do not include the time periods of water dumps, which are the major source of photographed particulates on-orbit (count rates >100 per frame). The decay of water dump particles is very rapid, however, and is characterized by an *e*-folding time constant of 5 min, so that return to predump levels takes 15-25 min.

After about 15 MET, the background sky brightness due to molecular and particulate scattering is not measurable (below threshold) with the camera/photometer system in the IECM. Again, we emphasize that this does not include the times of water dumps or RCS/VCS thruster firings. With the scattering so low that there is no discernible day/night (orbital) difference in the sky background, one-tenth-magnitude stars are readily seen, and it is integrated starlight that then controls the exposure time of the camera/photometer films.

Thus, the particulate environment of these Shuttle flights seems to be quite manageable after about 15 MET, with the exception of ≤½-h periods immediately following water dumps. In the clean periods, the observable particulate abundances, according to the IECM, are approximately equivalent to one 25-μm particle event every two orbits (~3 h), per 1 deg FOV. Recently photometric data from STS-4 have become available from Smith et al.[17] Their preliminary analysis indicated that particulate concentrations remained higher during the mission and that particulates were larger than the IECM data indicate.

A different observation[15,16] on STS-3 has caused some concern about populations of large particles that may orbit with the Shuttle once they are created by an unexpected or accidental event. Such an event might be, for example, RCS plume impingement on the Shuttle body flap that was suggested by Leger during NASA's Shuttle Environment Workshop.[1] During the second day of the STS-3 flight, a television camera looking aft from the cargo bay recorded many frames showing large particles (1-7 mm diameter) suspended well forward of the tail assembly and having velocities in the range ½-4 cm/s. For one of the episodes studied, a typical number of particles larger than 5 mm, in a 4-deg half-angle about the long axis of the Shuttle, was about 60. There were many more smaller particles that could not be reliably resolved and counted. Possibly larger particles were also seen, but this is not completely certain owing to assumptions that had to be made in the data reduction.[15,16]

Although particulates have often been observed around spacecraft (Voyager, Viking, Mariner-Venus-Mercury, Skylab), the STS-3 episode is particularly striking in appearance. We do not have additional information at this time on this or other Shuttle flights. This phenomenon could prove troublesome if left unexplained and unfixed. Further analysis or additional observations to resolve this issue would be valuable for assessing the local environment and particle production mechanisms.

In summary, the level of scattered light from particles fell below the natural background levels and detectability limits after the first day on orbit. Changes in procedures in the OPF are scheduled and, hopefully, will improve the preflight environment. Nevertheless, apertured doors or purging are recommended to protect very sensitive instruments.

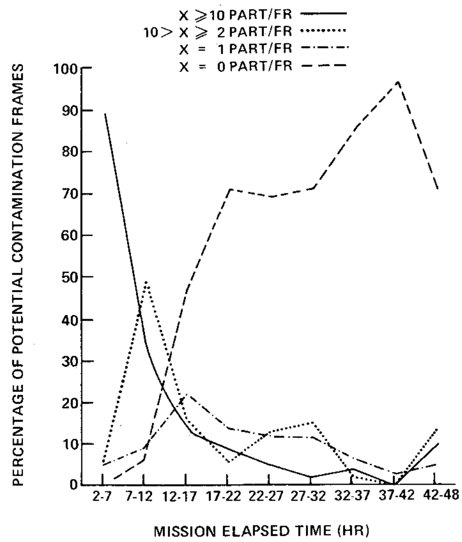

Fig. 11 Summary of the contamination observed during the first 48 h combined from the STS-2, -3, -4 missions.[13]

In general, the particulate environment looks acceptable on the basis of the IECM data, while the other STS-3 and STS-4 data raise doubts about a totally optimistic conclusion. The particulate question is extremely important for infrared observations from the Shuttle, since very demanding i.r. applications have been proposed that could be compromised by fluctuating intensities of scattered terrestrial or solar i.r. radiation. Models have been developed that either describe these early measurements[2] or try to predict on-orbit particulate release rates.[18] Further measurements will be required to validate these models.

The Optical Environment

Thruster Glow

The optical environment surrounding the STS was recognized as a potential problem area and was the subject of extensive modeling years before any launch.[8,19] These models mainly considered attenuation and self emission by the gaseous and particulate effluents arising from thrusters, dumps, and outgassing. Perhaps the most fascinating observations from the early Shuttle missions was the appearance of the continuous glow over Shuttle surfaces during passive operation conditions, and the spatial extent and brightness of the thruster firings. Both of these glow mechanisms raise important questions about the integrity of optical measurements performed from the STS Orbiter.

The observations of the Shuttle Induced Atmosphere (SIA) experiment, as reported by Weinberg,[20] indicate that brightest part of the Milky Way. (In additon, solar radiance reflected from Orbiter/payload-induced particulates can be of comparable brightness.) The SIA telescope had an instan-reflected from Orbiter/payload-induced particulates can be of comparable brightness. The SIA telescope had an instan-taneous field of view of 6 deg, but could scan azimuthally from viewing just over the engine pods through zenith to 30 deg past zenith toward the cabin. One-color scans consistently showed an enhanced radiance peaking just above the tail. Periodically, a large brightness feature was observed near zenith and could always be directly correlated with a thruster firing. The SIA experiment also observed radiance associated with a series of thruster firings while scanning the sky at 420 nm. They indicate a widely spread glow—the entire sky flashes brightly immediately following vernier thruster firings. Observations of the glow on STS-4 by Mende et al.[21] indicate that the thruster glow near the tail is strongest in the red end of the spectrum, stretching from 720 nm to the system cutoff at 800 nm. Near the tail, thermal emission from the hot exhaust products [such as $CO(v)$, $H_2O(v)$] may dominate, while farther from the nozzle photochemical or energetic collisions with the ambient atmosphere may give rise to molecular electronic transitions in the blue (such as $NO_2 A \rightarrow X$). Yet another glow in the violet has been observed after thruster firings. Temporal behavior suggests its relation to re-encroachment of the ambient atmosphere into the thruster exhaust plume. Obviously better measurements of the spectral and spatial characteristics of these thruster-related glows are required to quantify these fascinating observations.

Surface Glow—Observations

Even more surprising, however, was the presence of a glow above the surfaces of the Shuttle during passive operational periods. This phenomenon was observed by Banks and coworkers[22] on STS-3. A series of observations on later Shuttle missions has been performed by Mende et al.[21,23,24] in an attempt to quantify its nature. A visible glow has also been observed by the Atmospheric Explorer (AE) C and E satellites,[25] and by the Dynamics Explorer (DE) B satellite.[26,27] The large satellite data base has permitted a fairly convincing assignment of OH emission as the source of that glow, the vibrationally excited OH being formed by the chemical reaction of energetic atmospheric O atoms with H on the surface. It is not at all clear that the source of the glow above Shuttle surfaces is also OH. In fact, the limited Shuttle data indicate that it probably is not $OH(v)$ emission.

Both Shuttle and satellite glows are seen on surfaces undergoing energetic collisions with the ambient atmosphere, i.e., in the ram direction. Data from STS-4[23] clearly showed a dependence of intensity with respect to the angle of attack. No glow was observed from surfaces in the wake or shadowed by Shuttle structures. Surfaces exposed to the velocity vector exhibit substantial intensity even at large angles of attack. On the other hand, Atmospheric Explorer data exhibit a sharp $\cos^3\phi$ dependence of intensity on angle of attack.[25] Yee and Abreu[25] reported the altitude dependence of the AE glow to track with the atomic oxygen profile between 190 and 280 km. Between 140 and 180 K the AE glow tracks with neither N_2 nor O concentration profiles, increasing more rapidly than either concentration. Shuttle observations of absolute intensity are difficult, and a definitive altitude scaling with the O or N_2 profile cannot be determined.

The photographic data on the Shuttle has permitted the spatial distribution of the glow to be quantified. Preliminary estimates[22] of an extent of 5-10 cm above the surface have been revised to 20 cm in a careful analysis by Yee and Dalgarno.[28] This distance represents the region over which excited species (atoms or molecules) are emitting. The extent of the glow has been interpreted to represent the product of the emitter velocity and radiative lifetime of the excited state. If radiators leave the surface at thermal velocities, then the corresponding radiative lifetimes are less than 1 ms. If their exit velocity is faster, the lifetime becomes shorter still, approaching 50 μs if the atmosphere/surface interaction is elastic and the reflected velocity is comparable to the incident velocity. The various chemical processes that could give rise to this emission are considered below. If a plasma process is responsible for the glow, its extent represents the perpendicular relaxation length of the plasma.[29] The likely emissions resulting from a plasma over the Shuttle surface have been considered.[30]

The spectral distribution of the glow has also been measured. Mende et al. [21,23] have reported that the glow is a nearly continuous spectrum (for a resolution of ~ 15 nm) and increases in intensity to the red out to a 800-nm detection limit. (The Shuttle glow seems to have a spectral distribution that does not vary appreciably with distance from the surface.[28] Witteborn[31] has observed the 1-3-μm infrared emission of the entire Shuttle from the Earth's surface. He concludes that the glow intensity is 2-3 times brighter in that spectral region than in the 500-800-nm region.

Surface Glow—Possible Mechanisms

Atomic oxygen is by far the dominant atmospheric component at orbital altitude. Thus, it has been widely considered to be the reactive source of the Shuttle glow. Molecular nitrogen is present in significant concentrations also (see Table 1). The Shuttle orbital velocity is 8×10^5 cm/s. Thus, as the Shuttle sweeps through the tenuous atmosphere, the atmospheric species energetically impact the surface. For oxygen atoms, the energy of the collision is 5 eV on average, but the atomic oxygen velocity vector ($\bar{c} = 10^5$cm/s) will provide a distribution of collision energies (3.8-6.3 eV). These energetic O atoms could react with Shuttle surfaces to produce new chemical species that could give rise to the glow. Nitrogen molecules will have a collisional energy of 9.3 ± 2 eV, comparable with their dissociation energy of 9.8 eV, and, thus, may dissociate upon impact, with the atoms remaining adsorbed to the surface. Let us now consider the interactions of atoms and surfaces.

The energy partitioning in the interaction of gases with adsorbed atoms has been studied for many years. Two different types of processes are possible. In the first, the Langmuir-Henshelwood (LH) process, both atoms are adsorbed on the surface after collision. They then migrate over the surface, react, and escape into the gas phase. The level of excitation of the escaped molecule depends both on the reaction exothermicity and the nature of the surface adsorption.[32,34] When surface coverage by adsorbed atoms is great, an incident gas-phase atom is likely to strike an adsorbed atom and form a molecule that escapes into the gas phase. This is called a Rideal process. Here the interaction time is short (10^{-12}s) and little energy partitioning with the surface can occur. Consequently, the newly formed molecule can possess a large fraction of the bonding energy. The gas-phase molecular products are observed to have highly nonstatistical, non-Boltzmann energy distributions.

Surface-catalyzed emissions have been the subject of several laboratory studies. In particular, O-atom bombardment of surfaces is observed to give rise to $O_2(b \rightarrow X)$ and $(A \rightarrow X)$ bands.[35] It is suspected that a gas-phase atom reacted with an adsorbed atom (bound to the surface by only 0.5 eV) to give rise to this emission. However, even LH processes have been observed to give rise to electronically excited molecules, such as N_2, over a variety of surfaces including glass[36] and metals.[37] The creation of these recombined molecules into electronically excited states suggests a very short surface residence time for the newly formed species, and indicates that recombination and desorption are part of a single physical process.[38] In those laboratory studies the N atoms recombine to form the $A^3\Sigma_u^+$ state at high vibrational levels. The molecules then collisionally transfer into the $B(^3\Pi_u)$ state. Strong $B \rightarrow A$ (first positive) emission is then observed above the surfaces. A detailed investigation of the energy accommodated by N atoms have been studied by Halpern and Rosner.[39] They found that both Rideal and LH processes occur over a single surface under different physical conditions. Thus, the level of product excitation will depend upon the nature of the surface and surface coverage and temperature.

Recently, laboratory experiments have begun to examine the reaction of energetic oxygen atoms and ions with solid materials. Experiments are ongoing to measure the interaction of $\sim$1-eV O atoms with carbon by Arnold and Peplinski.[40] Ferguson[41] has observed the degradation of Kapton by energetic (O-1 keV) oxygen ions. Kapton is a long chain polyimide composed of substituted benzene rings linked by O and N atoms. In Ferguson's experiments, samples of Kapton bombarded by O^+ ions changed in appearance and microscopically resembled orbitally exposed Kapton from STS-2. Hydrogen was not detectable in these experiments, and the major detectable change in composition was a severe loss of carbon. The weakest bonds are the C-N (3.2 eV) and C-O (3.7 eV) bonds that may have suffered preferential attack by the 5-eV O^+ ions resulting in chain breakage and materials properties degradation. A variety of species, including CO and OH, can be products of this bombardment. The interactions of the ambient atmospheric O atoms with other STS materials have been studied in some detail by Leger.[42] Mass loss was found to be very variable from material to material. For the worst case (Mylars, graphites), 10% of the O-atom collisions led to mass loss.

With these observations as background, we will now consider the possible emitting species resulting from chemical reactions of energetic atmospheric components on Shuttle surfaces, specifically, vibrationally excited OH and CO, and electronically excited N_2, O_2, and NO. We will also briefly consider the plasma process. Slanger[43] has postulated hydroxyl radicals above Shuttle surfaces as a glow source. Vibrationally excited OH would be created in the reaction of 5-eV O atoms with atmospheric H or Shuttle-produced H_2O adsorbed on surfaces or by direct attack on hydrogen-containing surface materials. Vibrational states emitting in the red ($v'=6$-8, $\Delta v=5$) have radiative lifetimes between 4 and 10 ms.[27,44] Although spectral analyses support OH as a good candidate for the glow source above AE and DE satellites, a careful radiative lifetime analysis of the Shuttle glow by Yee and Dalgarno[27] yielded a lifetime of 0.67 ms for thermal velocity emitters, suggesting that OH is not the Shuttle glow source unless the Shuttle environment provides an unexpectedly large degree of collisional de-excitation. Specifically, even for a gas kinetic rate coefficient, densities in excess of $10^{12}/cm^3$ would be required to quench OH in 1 ms. The OH Meinel bands (vibrational overtones) do have the proper coarse spectral distribution to match both satellite and Shuttle glow observations. On the other hand, they exhibit a considerable spectral structure that should have been at least partially resolved in Mende's[24] spectral observations. Thus, OH seems to be precluded as the source of the Shuttle glow due to radiative lifetime and spectral structures.

Carbon monoxide is another molecular species that could give rise to the glow. Surface materials containing carbon have been shown by Leger[42] to undergo appreciable mass loss on orbit. Vibrationally excited CO has been observed in the reaction of O atoms with carbon adsorbed on platinum.[34] Thus vibrationally excited CO could arise from the interaction of energetic O atoms with carbon-containing Shuttle surfaces. Vibrational transitions with $\Delta v=6$-8 would fall into the 600-850-nm region, and should rise in intensity to the red as the transition probability increases with decreasing Δv. These overtones are not likely to be as strong as the corresponding transitions in OH. The radiative lifetimes for vibrational levels 5-11 are 4-7 ms, comparable to those for OH, and, thus, perhaps too long to explain the Shuttle observations. Unlike OH, however, the CO spectral distribution would be more continuous because the bandwidths are comparable to their separations. Thus, CO emission could be a constituent of Shuttle glow over surfaces that undergo appreciable mass loss. The glow, however, is observed even over surfaces not containing carbon (such as aluminum) and that do not suffer significant mass loss (painted surfaces), as shown by Mende.[24]

We have recently suggested another possible source for the glow:[45] atomic recombination into electronically excited molecular states. Atmospheric N_2 can dissociate upon its energetic collision with Shuttle surfaces. The N atoms then may recombine to form highly vibrationally excited $N_2(A)$ molecules. The surface will incompletely accommodate the 9.8-eV reaction exothermicity and the molecule will leave highly excited. The degree of energy accommodation, and, thus, residual excitation, will depend on the nature of the surface. Some fraction of the exciting molecules will leave in the $A^3\Sigma_u^+$ state. Recombination into the ground state and other electronic states is possible (see below). The gas-phase emissions observed by Mannella et al.[37] were the result of collisional processes quenching high-lying A vibrational states to form vibrationally excited B-state molecules (see energy levels in Fig. 12). The molecules then rapidly radiate (first positive transitions) back to lower levels of the A-state manifold. [These radiative lifetimes of the vibrational levels of the $B(^3\Pi_u)$ state are in the 6-8-μs range.]

Collisional processes probably will not be significant above Shuttle surfaces. At Shuttle altitudes, the mean ambient free path between collisions is kilometers. The effect of surface reflections and thermalized velocities may decrease this pathlength by an order of magnitude.[46] In the absence of collisions, highly excited A-state molecules can still decay radiatively to lower levels of the B state as indicated in Fig. 12. These reverse first positive ($A \rightarrow B$) transitions have not been observed, but have been estimated to occur and to be important in auroras.[47-49] These transitions are less strongly allowed than B-A, and radiative lifetimes are estimated to be a few orders of magnitude slower—in the 10^{-2}-10^{-4}-s range. Thus, the postulated mechanism is that the N atoms recombine on the Shuttle surfaces with varying degrees of energy accommodation. The newly formed N_2 molecule then leaves the surface in the A state with a considerable portion of the reaction exothermicity. These highly vibrationally excited A-state molecules slowly radiate (in the infrared between 2 and 6 μm) into vibrationally excited B states. These, in turn, rapidly radiatively decay giving rise to first positive band radiation. Nearly all of the 9.8-eV reaction exothermicity may be available in the N_2 product. Some small (< 1 eV) energy will be lost to overcome bonding to the surface.

A spectrum of $N_2 B \rightarrow A$ emission with 5-nm resolution is presented in Fig. 13. This spectrum was obtained by electron irradiating an N_2/O_2 mixture of total density 1×10^{13} molecules/cm^3 (0.25 m Torr).[50] The spectral intensity in each band reflects both the transition probability and the excited

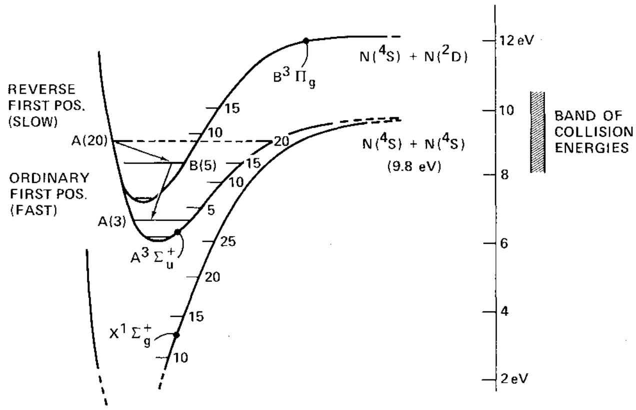

Fig. 12 Potential energy diagram for X, A, and B electronic states involved in nitrogen recombination glow mechanism.

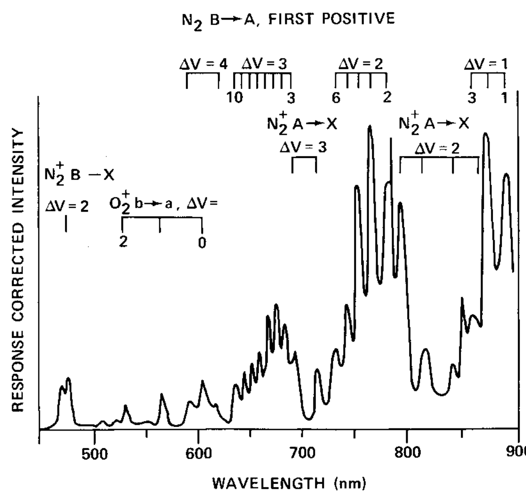

Fig. 13 Emission from electron-irradiated air at ¼ mtorr pressure.[48]

state populations. Thus, this particular spectrum is not meant to accurately represent the N_2 recombination glow above the Shuttle surfaces, but merely to demonstrate the possibility that this process may play a role.

In addition to $N_2 B \rightarrow A$ features, various ionic bands are present in the laboratory spectrum due to energetic electron impact. These molecular states would not be created in molecule/Shuttle collisions because of energetic constraints. If plasma processes play a role in the Shuttle glow, these transitions may be expected.[30]

The intensity onset in the red and the rise to longer wavelengths agree with Shuttle glow spectral observations.[24] The observed structure in the laboratory spectrum will decrease as resolution becomes poorer and as rotational and vibrational temperatures increase, as would be the case for the Shuttle.

Torr and Torr[51] recently presented some preliminary findings of emissions that were observed by their Imaging Spectrometric Observatory during the Spacelab mission. The bright glow they observed was above surfaces of their experiment and not the Shuttle surfaces per se, but they tentatively assigned a number or N_2 first positive transitions in their spectrum. Indeed N_2 first positive bands are the dominant contributor to their spectrum in the red/near-infrared region. This fascinating observation may indicate that the postulated collisional excitation mechanism plays a role over Shuttle surfaces.

Because of the many difficulties associated with absolute intensity measurements, this aspect of the Shuttle glow is perhaps the hardest to quantify. Mende[23] has stated that the glow on the STS-5 rear engine pod was several hundred kilorayleighs within the bandpass of this instrument.

Based on this observation, the efficiency required to produce N_2^* from collisions of ambient N_2 with the Shuttle surface has been estimated.[45] The observed radiances correspond to fluxes off the surfaces on the order of 10^{10} emitters/cm^2-s. It was shown[45] that only a small fraction of the energetically allowed dissociative collisions must result in vibrationally excited metastable state formation to give rise to the above emitter flux.

Other possible emissions could arise from recombination of O and/or N atoms on adsorbed Shuttle surfaces. It is assumed that the adsorbed atoms are not electronically excited due to rapid quenching by the surface. In N-N recombination, the A, the ground $X^1\Sigma_g^+$ and a $^5\Sigma_g^+$ state correlate to N(^4S) atoms. Although recombination has been the subject of much study (see Ref. 52 and references therein), it is not yet understood. $N_2(A)$ formation seems to be the preferred excited state channel. In the absence of collisions the $^5\Sigma_g^+$ state cannot populate any other molecular states (no allowed transitions), and under collisionless conditions surrounding the Shuttle only emissions arising from the A state should be expected.

If energy partitioning between the accessible electronic states occurs as the newly formed molecule leaves the surface, numerous other allowed transitions would result from population of the $W^3\Delta_u, a'^1\Sigma_u$, and $a^1\Pi_g$ states. These states are populated in laboratory studies where collisional redistribution occurs.[52] The most notable emissions from these states are: the Lyman-Birge-Hopfield bands ($a \rightarrow X$) which peak at 140 nm; the Wu-Benesch ($W \rightarrow B$) bands in the infrared; and the McFarlane infrared bands ($a \rightarrow a'$).[53] Based on their lifetimes, all of these transitions would have the same spatial extent. The larger the role of the surface in the reaction, the less likely the molecule is to leave the surface electronically excited. Thus, the collisional mechanism forming $N_2(A$, high $v)$ would be the favored source for N_2 emissions in the Shuttle glow. The presence of other electronic states as detected by vuv-i.r. emissions observed in future measurements will provide insight into the nature of the different surface-molecule interactions.

Oxygen atoms from the ambient flux will also be adsorbed on Shuttle surfaces. Unlike N_2, all six O_2 electronic states lying below the dissociation energy (5.2 eV) correlate with ground state atoms, and, thus, could be directly populated by O-atom recombination. Unfortunately, no allowed radiative transitions connect these states. The $A \rightarrow X$ is the most prompt ($\tau_A = 0.2$ s) and has been observed weakly in the upper atmosphere and in the laboratory.[35] The radiative lifetimes of the other states are thought to be 10-100 s so that they are not likely sources of the 20-cm glow layer. The c, A', and $A \rightarrow X$ bands lie in the uv-blue spectral region. The $b \rightarrow X$ transition at 762 nm was observed by Mende et al.[21] in the Earth's airglow layer. It is difficult to assess if it is a component of the Shuttle glow layer. The b state radiative lifetime is ~ 13 s, which would give rise to a much more extended glow. Thus, O_2^* emission does not seem a likely source of the observed Shuttle glow due to spectral distribution and radiative lifetimes, and susceptibility to collisional dissociation by energetic atmospheric species. Nonetheless, if these states are created, they could pose a serious optical problem because their lower intensity glow layer could extend many tens of meters, thus potentially interfering with measurements from any Shuttle location.

Heterogeneous recombination of N and O atoms can form NO in the excited $\mathbf{a}^4\Pi_i$ state as well as the ground state, although several other electronic states lie below the dissociation energy.[54] The **a** state only has allowed transitions in the infrared to the $b^4\Sigma^-$. If electronic energy partitioning occurs near the surface, then the $A^2\Sigma^+$, $B^2\Pi_r$, and $C^2\Pi_r$ states, which rapidly radiate in the uv to the ground state,[54] could also be formed. The $C \rightarrow A$ band at 1.22 μm has also been observed in the laboratory. Thus neither the spectral distributions nor lifetimes of NO* fit the observed glow. Moreover, if the surface does not play a role in partitioning the energy, we would expect to see only emission in the infrared. It must be stressed that the glow may depend upon the nature of the surface and that NO emission may appear brightly in a thin layer over certain surfaces.

Plasma processes have also been suggested as a source for the Shuttle glow.[29] The physical mechanism involves the atmospheric ions being reflected off the Shuttle surfaces, creating an unstable ion distribution which then interacts collectively to heat the electrons. The more energetic electrons then can collisionally ionize more of the background gas resulting in more ions to propagate the unstable cycle. The net effect is to enhance the number of electrons in the energetic tail of the distribution. This mechanism is appealing because it fits many of the observations. It predicts the perpendicular relaxation length of the electrons (the extent of the excitation) to be 10-20 cm. It also agrees with observations of Murphy and Shawhan[10] and Murphy et al.[55] in which enhanced electron densities were observed in the ram direction, and with the number of energetic electrons enhanced.[12] Papadopoulos[29] predicts that the electron concentration, however, should depend linearly on the ambient plasma and the total pressure. The enhanced glow intensities associated with thruster firings are a direct consequence of total pressure enhancement according to this mechanism. The predicted altitude scaling of the surface glow is more complex. Although total pressure decreases with increasing altitude, the ion density could be constant or even increasing over the 240-300-km Shuttle altitude range, depending upon the atmospheric conditions. Altitude scaling of the plasma mechanism is not inconsistent with the sparse Shuttle data base. The spectral character of the plasma glow should reflect the excited species, dominantly O and N_2. In a thorough review, Kofsky and Barrett[30] found no spectral evidence to support this mechanism. Laboratory studies of beam plasma discharges[56] in N_2 and air reveal structured first positive bands as described above, but also exhibit the presence of higher electronic state emissions ($C \rightarrow B$) and ionic bands of N_2 (and O_2), such as shown in Fig. 13, and which extend considerably to the blue. Indeed, Papadopoulos suggests monitoring 391.4 nm ($N_2^+ B \rightarrow X$) and 337.1 nm ($N_2 C \rightarrow B$) emissions as a sensitive test for this theory.

In summary, it is likely that several mechanisms involving O or N_2 are simultaneously occuring over various Shuttle surfaces and that any one may dominate under certain conditions. The key to our understanding the glow phenomenon lies in an extended data base that includes improved spatial, spectral, and surface specific observations. It is clear that a number of processes, including those discussed above as well as chemical/erosive mechanisms, can provide for unique glows of differing characteristics under the wide range of on-orbit conditions. Atomic recombination as a source of the glow depends upon the interaction of the Shuttle with the ambient atmosphere and, unlike contamination-induced glow, cannot be overcome by simple preventative measures. Consequently, the glow could have a significant impact over a wide range of altitudes on the instruments that hope to use the Shuttle as a remote optical observatory.

Conclusions

In this paper we have singled out for special attention the Shuttle-environmental issues of gases, particulate matter, and vehicle-induced glow phenomena. We now have an elementary understanding of the gaseous atmosphere that surrounds the Shuttle. It appears to be acceptable for most measurement functions envisioned for the Shuttle. Nonetheless, much remains to be understood. For example, even with several observations taken, the total rate of water vapor desorption and the cause(s) of its variability remain to be defined. The existence of a Shuttle-induced enhancement of the Plasma density is still unclear. The vehicle glow is the most puzzling and intriguing phenomenom observed, and several possibilities have been put forth as an explanation. A full evaluation of the glow as an interference to optical measurements is not available and is very important. Much more comprehensive spectroscopy and spatial photometry will be needed just for the empirical documentation of the glow and definition of its potential for interference with other work. The particulate environment looks promising, with regard to cleanliness for most optical applications, yet there are disturbing hints from the video data on STS-3 and camera data of STS-4 that the particulates may pose a problem for some experiments or after certain on-orbit procedures.

It appears that the large variabilities in the natural and Shuttle-induced environment in these early missions have created additional complications in correlating the measurements of different observers. Thus, many questions remain. Nevertheless, it is clear that the Shuttle environment is a hospitable one for many applications, and it still remains to be clarified how far one can go with the most environmentally demanding Shuttle payloads.

Note Added in Proof

Discussions of several aspects of the Shuttle environment during the early missions are now appearing in the literature. These include Refs. 57-60. Recent observations of the glow above Shuttle tile surfaces indicate a broad spectral emission. Excited nitrogen dioxide (NO_2) catalytically formed upon Ram surfaces has been suggested as a potential source of the gas phase emission by Swenson, Mende, and Clifton.[61]

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