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CONTAMINANT IONS AND WAVES IN THE SPACE STATION ENVIRONMENT

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Introduction

It is a difficult task to estimate, with any degree of certainty, the probable environment of any large space structure or system given that the system has not been firmly defined. This environment is a product of the natural environment and its interactions with that structure and system. We shall distinguish between the so-called induced environment, the molecular, particulate, photon and wave environment which results from the disturbing effects of a large object flying at orbital speeds through the ionosphere, and the contaminant environment which is produced when solids, liquids or gases are released from the system and interact with the induced environment in an array of chemical and physical processes. Our task is made particularly difficult by two important unknowns: a firm definition of the system and its contaminants; incomplete knowledge of the chemical and physical processes which can take place. In this paper we will address the probable plasma environment of Space Station. That is, we will discuss the particles (ions and electrons) and waves which will likely exist in the vicinity of the Space Station and how these may affect the operation of proposed experiments. Differences between quiescent operational periods (as defined by JSC 30426) and non-operational periods as well as probable effects from Shuttle operations will also be discussed. Areas which need further work are identified and a course of action suggested.

Background

Much of our knowledge about the interactions between large bodies and the ionospheric plasma had, until the time before Shuttle flights, been obtained from observations aboard small scientific satellites and various scaled laboratory investigations. The recent era of Spacelab-type payloads aboard the Shuttle orbiter has provided a wealth of heretofore unobtainable information. The Shuttle is not only the largest body flown to date but, as was discovered over a period of time, carries with it a large gas cloud. The discovery of "Shuttle glow" (Banks et al., 1983), broadband electrostatic noise (Shawhan et al., 1984a), heated electron populations (McMahan et al., 1983), a modified ion environment (Hunton and Carlo, 1985), and contaminant ions in the wake (Grebowsky et al., 1987) have begun to fill in pieces in what appears to be a complex puzzle associated with the large body induced environment and contaminant interactions. Recent studies of the neutral and ion population during thruster operations (Wulf and Von Zahn, 1986; Narcisi et al., 1983; Shawhan et al., 1984b), modification of the plasma during FES operations and H_2O dumps (Pickett et al., 1985), the discovery of pick-up ions consistent with chemistry of the H_2O, O^+ interaction (Paterson, 1987), as well as observations by neutral mass spectrometers (Wulf and Von Zahn, 1986; Miller, 1983), have helped to sort out the differences between interactions which are of the induced variety and those which result from release of contaminants by the orbiter. Observations by IR, optical, and UV instruments on board the orbiter (Torr, 1983; Torr and Torr, 1985; Koch et al., 1987), and by IR on the ground (Witteborn et al., 1987) have provided insight into the effects of both absorption and emission by this contaminant population. It is now clear as a result of these pathfinder experiments that in order to conduct experiments in plasma physics, provide long-term monitoring and a data base for the ionosphere, observe astronomical targets over a broad range of wavelengths, and provide sensitive remote sensing capability, the Space Station environment must be cleaner than that of the orbiter in many respects. Much work has already been done in assessing just how clean that environment must be in order to meet the minimum science requirements (Space Station Payload Contamination Compatibility Workshop, 1987). It will be the purpose of this paper to assess what the particle and wave environment might be and whether the current specifications are adequate in this regard. This assessment will be based on current contamination control requirements, knowledge of proposed space station configuration, and our best guess about the scaling laws for certain plasma interactions.

Particle Environment

A number of investigators have studied the composition of the Shuttle ion environment and compared it to that which was expected of the natural environment at the orbiter altitude (Grebowsky et al., 1987; Siskind et al., 1984; Reasoner et al., 1986). The studies observe large amounts of H_2O^+ which results from the rapid charge exchange reaction

$$H_2O + O^+ \rightarrow H_2O^+ + O$$

as well as smaller amounts of H_3O^+.

$$H_2O^+ + H_2O \rightarrow H_3O^+ + OH$$

The amount of H_2O^+ (and H_3O^+) observed appears to be directly proportional to the surface temperature leading to the conclusion that most of this observed water is offgassed from Shuttle tiles or other porous surfaces (Narcisi et al., 1983). The amount of water can be estimated by neutral mass spectrometers but caution must be taken since frequently these instruments can only observe molecules which are scattered back toward the orbiter either by collisions with ambient molecules or the cloud itself. Several attempts have been made to estimate water density or by observing the ion population and then doing a kinetic analysis. This has been done with observations obtained within the orbiter bay (Narcisi, 1983) and with data which were obtained during the PDP free-flight on Spacelab 2 (Paterson, 1987). Other estimates have been obtained by observing the infrared signature and then estimating column densities (Koch et al., 1987). The remarkable thing about all of these methods is that although they have shown some decay in the amount of water during the lifetime of the mission and variation among missions, the neutral observations, ion observations, and IR observations give a consistent picture which can be modeled within the accuracy of the known cross sections for the charge exchange reaction. The significance of this is that if we know one of the above parameters accurately, e.g., column density from IR observations, we can predict another, e.g., contaminant ion population, through a modeling of the chemistry and kinetics of the gas cloud. Several authors have developed models of this "gas-cloud" interaction; notably Patterson (1987) has modeled a steady state cloud and shown the production of H_2O^+ to scale with background O^+ density and Hastings et al. (1987a) have developed time-dependent models of clouds which would be associated with a brief gas release, such as the opening of a gas relief valve or a thruster operation.

This contaminant ion population can be a source of several problems.

(1) These ions create an additional wake which trails the object in a sense which is perpendicular to the magnetic field line instead of parallel to the velocity vector.

(2) Depending on the nature of the ions they may result in a deposition problem on some surfaces facing the ram direction.

(3) Depending on the excitation state of the ions, they may add to the IR, optical or UV spectrum which is sensed by a particular instrument.

(4) The current created by these pick-up ions is believed to be responsible for plasma instabilities which enhance the background wave environment.

(5) Molecules which have low ionization potential may be susceptible to the critical ionization velocity (CIV) process causing enhanced plasma density, production of wave turbulence, and possible photon emission.

Let us look at the above possibilities in light of Space Station operations. Although much of our shuttle experience has been gained by observing the H_2O/O^+ interaction, any process such as charge exchange, photoionization, ionization by CIV, etc., will produce the pick-up ion cloud and present a similar set of problems to experiments or the Space Station.

Figure 1 presents a cartoon of the composite nature of the Shuttle environment to illustrate the first point above. Superimposed on the induced environment (i.e., the neutral and plasma wake) is the wake produced by the pick-up ions. Generated in the orbiter rest frame they will appear to move past the vehicle perpendicular to field lines. Any experiment expecting to be in the neutral or plasma wake may in fact be in a location dominated by these contaminant ions. As mentioned in point 2, it is clear that these ions could interact with or stick to surfaces when they were presumed to be part of a freely expanding cloud. Possible surface degradation could result from the fact that they can strike the ram surfaces with near orbital velocity (their energy is dependent on the reaction that creates them as well as their mass). This implies chemistry which takes place in front of ram surfaces (e.g., glow) and that which takes place on surfaces must take these ions into account.

Regarding point 3, since these ions form an asymmetric distribution about the vehicle and since their column density is greatest in the wake direction, it is important to evaluate not only the atomic physics associated with the neutral molecule but its ionized and possibly excited state as well. If the ionized species has a particular emission line which is undesirable optically, this may be particularly noticeable in the wake direction.

We will discuss in more detail the effects described by points 4 and 5 in the next section. Let us first, however, summarize the primary contributors to the ion environment.

Molecular contaminants resulting from outgassed or vented products can interact with the ambient population through several processes creating an ionized cloud which will trail behind the Space Station much like the tail of a comet. If the ionizable contaminants are held to levels well below that of the Shuttle (how much below will be discussed in the next section), the ion environment during operational periods should be acceptable to most experimenters. However, a very important gap exists in our knowledge. A study of the OSSA Space Station waste inventory (Bosley et al., 1986) reveals a large number of possible waste gas and liquid products. Although interactions of simple molecules like H_2O, N_2, and CO_2 with the O^+ plasma are reasonably well understood, the chemistry of this large possible "soup" of waste products involves many unknowns. It would seem prudent to assess the possible interaction of some of these waste gases by realistic laboratory experiments before deciding that they are allowable vent gases.

Wave Environment

It will be difficult to assess whether the wave environment described in JSC 30420 and JSC 30237 can be met in its entirety. Analysis of the wave environment aboard the orbiter based on PDP data from OSS 1 and Spacelab 2 have led to the emerging picture, again depicted by the cartoon of Figure 1, that the broadband noise environment may be dominated not by the induced environment associated with the large body interaction as was originally believed, but by production of waves by the gas cloud itself. If this is the case it may be possible to correlate the general level of this background noise to the density of the water cloud. In Figure 2, we present data that have been compiled from the published literature (Pickett et al., 1985). The level of noise at 1 kHz (chosen as typical of the broadband noise spectra for these data) is plotted for three different cases of "small" gas cloud releases. The level of uncertainty in the measurement of H_2O density is represented by the vertical error bars. The three cases chosen represent almost 3 orders of magnitude in gas quantity. In all cases the dominant gas is H_2O. The first is the H_2O vapor cloud associated with the orbiter outgassing per se, the second an operation of the Flash Evaporator System (FES), and the third a typical operation of a VRCS thruster. In all cases the releases were on the dayside and in an ambient density of O^+ plasma of $\sim 10^5$ cm^{-3}. Note that the data indicate that the noise is linearly proportional to the density of gas released. The best fit to the data is that the intensity (at 1 kHz) of electrostatic noise is proportional to the product of H_2O and O^+ density. The constant of proportionality is such that at a 1 g s^{-1} release rate the measured electric field anywhere within the general interaction region will be ~ 1 mV m^{-1} in a 150 Hz bandwidth. (150 Hz is the approximate bandwidth at which these measurements were made.) This law is certainly not absolute but leads the author to believe that most of the observed noise can be tied to this contaminant release. Further examination of turbulence measured by the Langmuir probe and electrostatic waves observed near the orbiter wake by the PDP on Spacelab 2 leads one to speculate that the wake

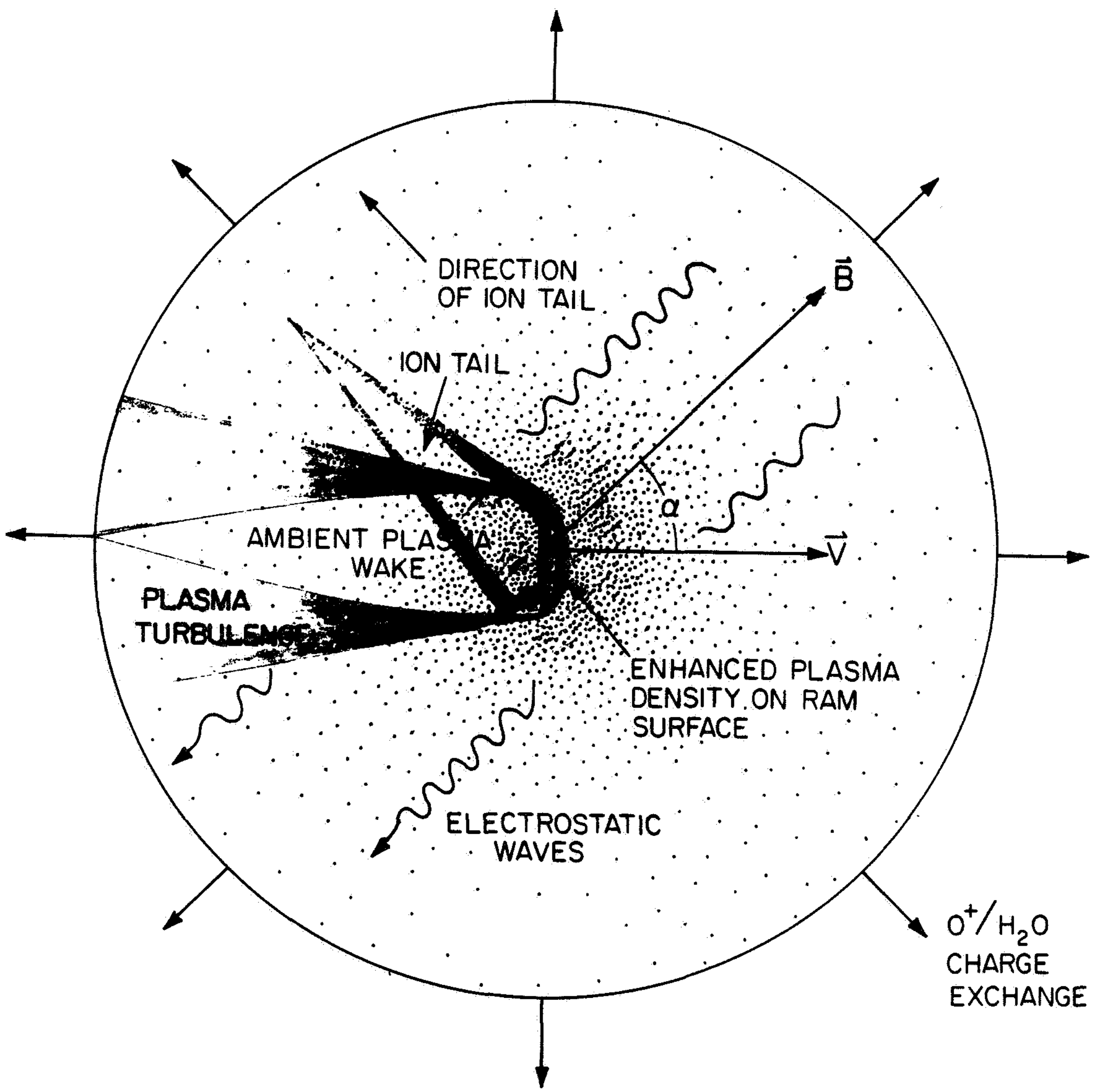

Fig. 1. The neutral cloud of gas which expands from the orbiter undergoes chemical interactions such as change exchange which results in an ion tail and creates plasma waves presumed to be driven by the ion currents.

noise is dominant only in a region confined to the wake and wake boundaries and most wake noise observed elsewhere is dominated by the production of noise associated with instabilities resulting from ion pick-up current generated by the contaminant water cloud.

In order to properly scale this phenomena we must establish more firmly the instability that causes the wave growth and the process that saturates the

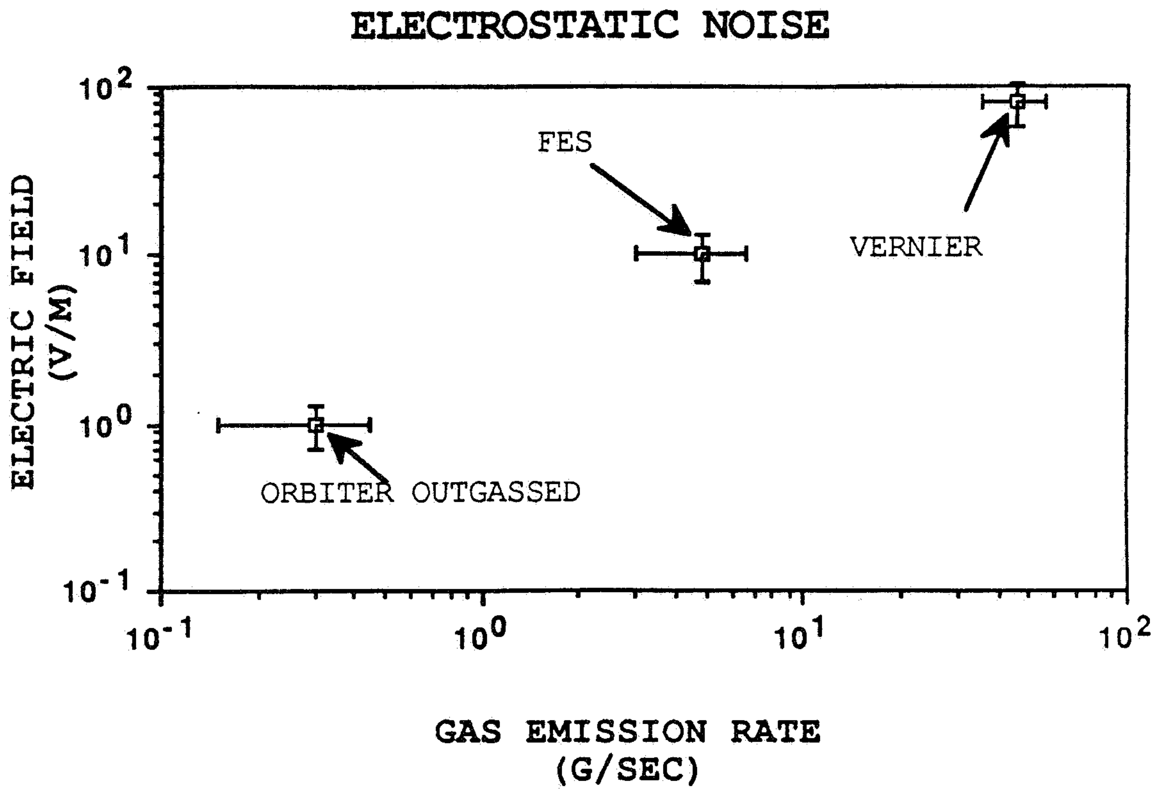

Fig. 2. Gas releases of three different magnitudes and the measured electrostatic noise show roughly a linear correlation. Estimates of outgassing rates for the first data point are a consensus of observations of inferred column density from IR and measurements of both ion and neutral densities. Emission rates of FES and VRCS are well defined.

instability. CIV may play a role in this process (Papadopoulos, 1984) but will again be very dependent on the gas composition. More experiments are required before we can definitely say that the above scaling law applies to molecules other than water, since the importance of a particular instability or CIV varies with molecular species.

Extrapolating this insight into the Space Station environment we are again led to conclude that the plasma environment will be acceptable and the JSC requirements met only during periods where ionizing components of the contaminant gases are minimized. Although the large modules and solar arrays may be a source of plasma noise generated by turbulence in their wake, at points midway along the transverse boom or on the upper or lower keel, this noise may be at an acceptable level at least for some geometric configurations of the velocity vector and magnetic field. Other sources of noise, currents carried by the structure to complete the $\vec{V} \times \vec{B}$ current loop (Hastings and Wang, 1987), radiation of noise by the cable trays or solar arrays or currents

(Hastings et al., 1987b), conduction of noise by sheath waves, etc. must be solved by appropriate design and are not within the scope of this discussion.

What numerical limits must be placed on the ionizing contaminants in order to meet the JSC 30237 specification and provide an environment free of this source of noise? Examining JSC 30237 for the spec on broadband emission for systems at standard locations, we find that at 1 kHz we must be less than 103 dB μV m^{-1} MHz^{-1}. Scaling to the 150 Hz bandwidth of the measurements taken in compiling Figure 2, we find that these emissions must be less than ~0.02 mV m^{-1} which, using the linear scaling law of Figure 2, implies an emission rate of water of <20 mg s^{-1}. This should be manageable for a structure like the Space Station which will not be covered with a material that continually outgasses water. The mass release rate of other ionizable molecules could be scaled appropriately depending on their cross section for ionization. The sum total of all of these easily ionizable molecules would then have to be such that their emissions are below JSC 30237 specifications. This compares favorably with recommendations from the Space Station Payload Contamination Compatibility Workshop which recommended lower column densities of most species.

In January 1987 the OSSA contamination compatibility workshop recommended several changes in JSC 30426, which included lowering total acceptable column densities of O_2, N_2, and H_2, as well as noble gases and other UV and non-IR active molecules. A further specification should be included which defines ionizable gases and the acceptable release rates for them. Furthermore, it is very important that we gain a detailed understanding of the chemistry and physics of reactions which occur between the ambient environment and the large shopping list of molecules which may be released during the non-operational periods to insure that experiments and the Space Station hardware are not subjected to effects described earlier.

Non-Quiescent Environment

JSC 30426 states that the Space Station be capable of supporting quiescent operation periods of up to 14 days. This period of minimum perturbation is essential for many science investigations and any disturbances during this period, however minor, must be noted. It is not clear that the requirement to record such disturbances is fully satisfied. Section 5.0 simply states that "...monitoring of the environment to a limited extent will be required." Since the IOC phase Space Station will not be gravity gradient stable, some fine tuning of attitude will be required. Whether it is accomplished with jets only or some combination of jets and gyros is unclear. It is clear, however, that during the long "quiescent" periods there will undoubtedly be some disturbances whether they be occasional jet firings, experiment vents, purges, or relief valve operations, EVA crew activity, etc. A clear requirement to monitor specific critical aspects of the environment must be in place. Space Station elements must have a way of "notifying the system" of an impending disturbance. Some monitoring can and should be real time and some may only be required after the fact. Whether PIMS or some other monitoring package is responsible is yet to be determined but the requirement must be a system responsibility with data accessable to all.

Non-quiescent periods, such as Shuttle docking, will provide significant disturbances. It is the concensus of a number of independent observations that the Shuttle orbiter carries with it a large amount of contaminant material, particularly water. Column densities near the orbiter of 10^{12} to

10^{13} should be expected. There is some disagreement over the decay time of the associated cloud. IECM observations (STS-2, STS-3, STS-4) indicated an initial decay time of ~10 hours. However, Narcisi et al. (1983) has observed wide variations in the water density cloud with some overall decrease in H_2O density with time, but a much stronger correlation between density and surface temperature. Raitt (private communication, 1987) reports that an ion signature, characteristic of H_2O^+ in his retarding potential analyzer, practically disappeared by the end of mission 51F. (51F spent a lot of time in a hot attitude due to a several day long solar observation cycle.)

The conclusion that may be reached from all of this is that the amount of contamination that will be carried into the space station environment by the orbiter may be reduced by simply waiting some minimum period of time ($\gtrsim 24$ hours) in a relatively hot attitude behind the station, then going to a cool attitude for several hours before beginning the approach and docking. Clearly it will not be possible to operate some experiments while the orbiter is in rendezvous phase, both because of the outgassed cloud and thruster plume impingement. Docking procedures which minimize plume impingement and thruster activity will be preferred. Operation of experiments while the orbiter is present may be possible and is dependent on the type of experiment.

Other disturbances to the environment, such as EVA activity, should be scheduled as much as is practical for the non-quiescent periods since gaseous products associated with the EVA suit can provide significant disturbances.

Summary

The developing requirements for Space Station must be responsive to the needs of the user and in line with the reality of Space Station logistics. They must also be internally consistent, be carried out to as full an extent as possible, and be "living documents" which can incorporate new knowledge as it becomes available. The PWWG (Particle and Waves Working Group) has been responsive to the user's needs in writing requirements and assuring that the proper tools are in place to implement them. The definition and control of the particle, plasma, and wave environment has incorporated specific needs from a wide range of potential users. The Contamination Working Group has likewise been responsive and JSC 30426 reflects the panel's concern for the cleanliness of the Space Station environment for the user, the Station safety and longevity, and for the preservation of the delicate natural chemical balance of the ionosphere. It is not clear whether some oversight group such as the CWG will be responsible for continual evaluation and enforcement of the requirements. Some mechanism will be required to do this.

Only minor modifications to the documents may be required, but the importance of these modifications cannot be over emphasized. Let us first deal with recommendations to changes in JSC 30426:

(1) Incorporate specific requirements relating to easily ionizable molecules which contribute to the plasma environment. This should be stated in g s^{-1} emission instead of column density; e.g. total water emission should be less than ~1 mg s^{-1} for adequate margin. Other common gases which contribute to this environment are N_2, CO_2, and H_2, e.g.:

$$N_2 + O^+ \rightarrow N_2^+ + O$$

$$N_2 + O^+ \rightarrow NO^+ + N$$

(2) Analysis of proposed vented products during non-operational periods must be performed to determine if the proposed contaminants are acceptable.

(3) More specific requirements for monitoring the environment should be in place. These should include real time or "warn" flags for certain releases which must be accounted for in data analysis or known about ahead of time.

JSC 30252, the Plasma Effects Control Process Requirements Document, must be consistent with the expected contamination levels and reflect the difference between operational and non-operational periods. Further recommendations in regards to operational considerations are the following:

(1) The orbiter should be allowed to outgas for $\gtrsim$24 hours before docking with the Station (the orbiter should be behind the Station).

(2) Procedures minimizing thruster activity and plume impingement should be implemented for docking activity.

(3) Any plan which includes continuous thrusting for reboost should be eliminated for environmental considerations.

(4) Brief gaseous releases, either by Station hardware or other equipment, must be minimized, documented, and made available in a common data base.

(5) EVA activity should be confined to non-quiescent periods whenever possible.

(6) It may be appropriate to include a section on operational guidelines in the JSC 30426 document.

Last of all, several recommendations regarding uncertainties about the physical processes involved are appropriate:

(1) The cross sections for charge exchange reactions of a broad range of molecules are not well known for O^+ at 5 eV.

(2) The susceptability of certain molecules to CIV at Space Station altitudes is unknown. Laboratory and Shuttle experiments are appropriate.

(3) The precise cause of "Shuttle glow" must be determined.

(4) Models which predict line-of-sight emissions and absorption must take into account possible ionized species that are present. In order to do this, accurate models of cross sections for reactions are required.

(5) The mechanism for production of broadband instabilities must be better understood so scaling laws can be used with more assurance.

All of the above physical considerations may also be applied to co-orbiting platforms. The environmental constraints may be similar or tighter depending on experiment complements.

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