LABORATORY EXPERIMENTS OF RELEVANCE TO THE SPACE STATION ENVIRONMENT

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Introduction

One might expect that contamination effects would be negligibly small in the highly rarefied atmosphere appropriate to Space Station orbit. Observations taken over the several years on the Space Shuttle have demonstrated that this will indeed not be the case unless careful design measures are taken. Specifically, it has been found that the interaction between Space Shuttle and the ambient environment produces a "contaminant cloud" around Shuttle which can provide for deleterious effects. This interaction can provide for structural disfunction by material erosion as well as operational disfunction through oxidation or coating phenomena. Furthermore, the contaminant cloud can provide a more difficult environment for external probes to operate in because of increased radiative backgrounds due to surface and "cloud" glows, enhanced plasmas and surface charging, and also direct deterioration of diagnostic equipment. Although it is clearly desirable to reduce contaminant levels so as to obviate such effects there is a cost associated with such reductions and it is critical not to significantly overestimate the required levels of cleanliness for successful Space Station operation.

At the present time, the required contamination levels can only be specified by models which can be correlated with the available empirical data base. These models themselves require a significant amount of physical information for successful application. In the next section we will provide a brief overview of the phenomenologies which produce the contaminant cloud and review the physical data required to characterize it. This discussion will be followed by a brief description of laboratory techniques which can be utilized to provide the required data.

The Contaminant Cloud

Of course the dominant source of the contaminant cloud is the Space Station itself. Contaminant species are naturally introduced around Station and on Station surfaces during operational events such as thruster firings, water dumps and other vents. Furthermore, particles will shake off of surfaces and outgassing will occur. The ambient hard UV flux will also act to enhance desorption and outgassing, and indeed may interact with some species to provide polymerization on surfaces. As will be seen, the specification of the chemical form of these outgassed species is critical to determining their ultimate impact on Space Station performance.

Ambient species, primarily O and N_2, but also lesser species such as N, O_2, and H, will impact Station surfaces at orbital velocities of 8 km s^{-1}. It has been found that in many materials this interaction produces material erosion. It is generally assumed that this erosion is the result of oxygen atom attack and for many hydrocarbon materials mass loss is estimated to occur in one out of ten impacts (Leger and Visentine, 1986; Green et al., 1985). The reaction products of these interactions have not been measured, but in many cases can be estimated from mechanistic arguments. Erosion species identification is, of course, critical for specification of subsequent reaction, evaluation of deposition tendency, and understanding of erosion induced glows. It has been suggested in the past that limited key components could be protected from oxygen atom attack by the application of sacrificial coatings. The ultimate impact of these eroded materials on the local environment must be carefully evaluated prior to such applications.

Oxygen atom attack can also provide for functional deterioration in more insidious ways. For example, Leger and Visentine (1987) have recently pointed out that moly-disulfide, a common lubricant, will oxidize under oxygen atom attack, becoming abrasive. Such a transformation would provide increased particle loading and decreased mobility for moving parts. Other materials, while not eroding, will oxidize, resulting in changing thermal and radiative properties. Furthermore, possible synergistic effects on material erosion resulting from UV loading or surface charging remain to be evaluated.

The catalytic properties of various materials in high velocity interactions must also be evaluated. For example, knowledge of the surface accommodation coefficient for momentum is critical to specifying the local cloud density. Specifically if the ambient species accommodate their momentum on the surface they will then effuse away thermally, resulting in a higher local gas density than if they had scattered elastically from the surface. The momentum accommodation coefficient is a key parameter in contaminant cloud models. As another example, catalytic reactions of ambient species on surfaces have long been suggested (see, for example, Green et al., 1986) as possible sources for excited states which could then either further interact or themselves produce a surface glow. No data are presently available on such catalytic effects at orbital velocities for the various materials of importance to Space Station.

The ambient gasses will also interact with outgassed species around the Space Station. This interaction, initially occurring at orbital velocities but also of importance at lower velocities, will produce a scattering pattern which plays a role in defining the density profile and extent of the contaminant cloud. To the author's knowledge there are no measurements of the angular differential cross sections or momentum transfer resulting from such heavy body collisions. Furthermore, inelastic collisions will also occur producing radiation from direct excitation or chemi-excitation, as well as species transformation. The data base for such interactions is very sparse in the energy range of interest.

Lastly, the importance of positive ion reactions must be evaluated. Although ambient ion concentrations are typically small compared to neutral concentrations there can be charge buildup around the Space Station. One way this can occur is through reactions between ambient ions and contaminant neutrals. Many reactions of this type will move charge between species

without significant momentum transfer. Thus, charge initially at rest in the Earth frame may be swept along with Shuttle (see discussion in Caledonia et al., 1987a). Such reactions can also produce excited species which can radiate and new ionic species which are more likely to provide surface deposition. The efficiencies for ion neutralization on various Space Station materials remain to be evaluated. We note that enhanced ionization levels have been proposed as a source of Shuttle glow (Papadopoulos, 1974).

The various data requirements discussed above have been summarized in Table 1. Potential laboratory techniques for developing this data base are examined below.

Table 1. Required Data For Space Station Contamination Level Specification

Data Required		
· Material behavior under UV loading - Outgassing rates - Products - Surface effects - Particle formation · Material "erosion" studies under energetic species impact - Erosion rates - Passivation effects - nonlinear behavior - Species produced * state changes * deposition - Surface property changes - Erosion induced glows - Synergistic effects * UV loading * charged surfaces	· Ambient/surface interactions - Momentum transfer/ accommodation - Surface reactions e.g., fast $N_2 \rightarrow N + N \rightarrow N_2(A)$ - Surface collision induced glows - Material dependence of all above · Ambient/contaminant cloud interactions - Differential scattering cross sections - Inelastic collisions * chemical reaction * radiative inducing e.g., $O + M \rightarrow O + M^*$; $O + AB \rightarrow OA^* + B$	· Ionic interactions - Surface neutralization efficiencies - Ambient ion/ contaminant reactions * ion velocity separation * quasi-neutrality - Non-linear effects

Laboratory Studies

Material behavior under UV loading may be investigated by standard techniques and will not be reviewed further here. A research program in this area is presently in progress at NASA Lewis Research Center (S. Rutledge, private communication, 1987).

Development of the remaining data base requires the use of state-of-the-art neutral and ionic beams exhibiting characteristic velocities of 8 km s^{-1}. A number of neutral oxygen atom beams have been under development in response to the Shuttle observations of significant material erosion. These sources may be broken into four types:

(1) Thermal sources, such as microwave discharges or plasma ashers which can produce copious oxygen atoms at thermal or near-thermal energies. These devices are of no value in providing information of the type required.

(2) Plasma torches, where a gas is highly excited by RF, dc, or microwave sources and subsequently expanded through a free jet or supersonic nozzle converting the sensible heat to velocity. These devices can produce high fluxes of oxygen atoms, but are generally limited to oxygen atom energies below 1 to 2 eV (one investigator has proposed the potential to reach oxygen atom energies of 4 eV; however, see Table 2).

(3) Ion beam techniques, where sources of positive or negative oxygen ions are electrostatically accelerated and focussed to achieve the proper velocity, at which point the charge is stripped by various techniques such as charge exchange or surface neutralization. Such beams can readily achieve the appropriate velocity, however, are typically limited to low fluxes because of Coulombic repulsion effects. For standard ion sources achievable fluxes as high as 10^{15} cm^{-2} s^{-1} have been predicted but not demonstrated (note, however, the Princeton source in Table 2).

(4) Laser sustained plasmas, where lasers are used to produce a high temperature plasma which is subsequently expanded in a free jet or supersonic nozzle to produce a high velocity neutral beam. Such sources have been demonstrated to produce beams of the desired velocity of 8 km s^{-1} at flux levels of 10^{17} to 10^{18} cm^{-2} s^{-1} and thus are of great value for aging studies.

The status of neutral oxygen atom beams presently under development or in operation has recently been reviewed by Visentine and Leger (1987) and a slightly updated version of their tabulation is provided in Table 2. As can be seen a wide variety of sources should be available to develop various aspects of the required data base. At present for 8 km s^{-1} beam applications the laser discharge techniques appear to be the most mature and in the remainder of this text the PSI pulsed molecular beam source will be used for example. In principal alternate sources will provide similar utility.

The Physical Sciences, Inc. (PSI) source has been described in some detail elsewhere (Caledonia et al., 1987b; Caledonia and Krech, 1987) and will only be briefly reviewed here. In operation a fast acting valve is used to introduce a pulse of oxygen molecules into a previously evacuated supersonic nozzle. A pulsed CO_2 laser focussed near the nozzle throat is used to break down this gas and form a high temperature plasma. The plasma subsequently expands producing a high velocity beam made up primarily of oxygen atoms. A schematic of the PSI system, as it is used for material erosion studies, is provided in Figure 1. The laser beam enters from the left and the molecular beam propagates to the right striking material targets as shown. A mass spectrometer is available for beam characterization and radiative diagnostics are available to monitor both beam properties and radiation from the beam target interaction. A second mass spectrometer head will soon be installed to allow monitoring of erosion products.

Table 2. Extant Oxygen Beam Apparati
(Updated from Visentine and Leger, 1987)

Type	Technique	Source	Species	Energy
Microwave Discharge	Electrostatic accel.	LeRC, Ferguson	$O^+(O_2)$	0-50
Microwave Discharge	Free jet	Utias, Tennyson et al.	O,O_2(98%He,2%O_2)	2 eV
Plasma Torch	Free jet	Utias, Tennyson et al.	O(98%He,2%O_2)	~4 eV
Plasma Torch	Supersonic nozzle	Aerospace, Arnold and Peplinski	O,O_2(98%He,2%O_2)	1-2 eV
Plasma Torch	Supersonic nozzle	Ari, Freeman	O(He,O_2)	1.3 eV
Electron Bombardment	Electrostatic accel., focusing	Martin Marietta	O^+,O_2^+,O	5 eV
Electron Bombardment	Electrostatic accel., focusing	Vanderbilt U., Tolk and Albridge	O	5-10 eV
Electron Bombardment	Electrostatic accel., focusing	G.E., Amore	$O_2/O_2^+(O)$	3-10 eV
Electron Bombardment	Electrostatic accel., focusing	LeRC, Banks and Rutledge Albridge	$O+,O,O_2$	3-15 eV
Electron Bombardment (plasma toroidal)	Electrostatic accel., focusing	Princeton U.	$O,N(N_2/O_2)$	~10 eV
Electron Bombardment	Electrostatic accel., focusing	Aerospace, Mahadaven	O,O_2,N,N_2	3-100 eV
Laser Discharge	Pulsed breakdown	PSI, Caledonia and Krech	O(O_2)	2-14 eV
Laser Discharge	CW breakdown cross	Los Alamos	O(He/O_2)	2-5 eV
Laser Discharge	Laser blowoff	JPL, Brinza	O (solid films)	2-7 eV

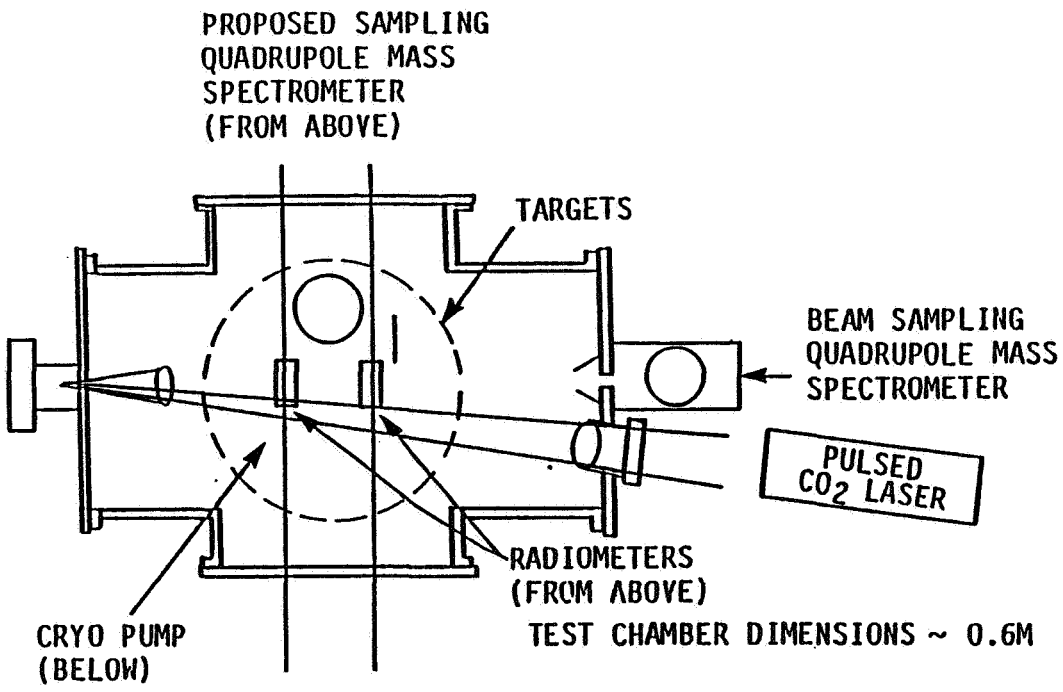

Fig. 1. PSI Oxygen Atom Test Facility under development.

A number of materials have already been studied with this device with spectrometer is available for beam characterization and radiative diagnostics are available to monitor both beam properties and radiation from the beam total 8 km s^{-1} O-atom irradiation levels typical of those encountered during a few weeks operation at Shuttle altitudes, $\leq 10^{21}$ O-atoms cm^{-2}. In general mass removal rates and surface properties have been found to be similar to those observed during Shuttle operation (Caledonia et al., 1987b; Caledonia and Krech, 1987). As soon as the second mass spectrometer head is operational this system will be capable of addressing many of the issues discussed in the previous sections. These include mass loss rates, erosion species identification, and surface property changes. Synergistic effects resulting from UV loading, heating cycles, stress, and flexing can also be investigated with modest system improvements.

Although the system was not developed specifically to study glows, such observations can readily be performed above irradiated surfaces using standard radiative diagnostic techniques. We have seen numerous material specific radiative signatures above surfaces both visually and using an optical multichannel analyzer (OMA). We are presently configuring an experiment to study erosion-induced infrared signatures above surfaces. An early study will involve oxygen irradiation of carbon surfaces which is expected to produce vibrationally excited CO. Possible catalytic surface glows can be studied in a similar manner. PSI has developed an 8 km s^{-1} beam of a mix of nitrogen atoms and molecules using similar phenomenology and anticipates no problem in incorporating oxygen in the mix as well. The neutral species mix in such beams will be evaluated using the mass spectrometer.

A ballistic pendulum was used within the PSI O-atom device as part of a calibration of the system flux. The pendulum can provide a measurement of the material momentum accommodation coefficient inasmuch as elastic collisions provide twice the momentum transfer as fully accommodating collisions. In our

previous measurements we could only use a pendulum material which was transparent to CO_2 laser radiation, we found that energetic oxygen atom collisions with Saran Wrap were largely elastic. The present system is not so limited and other materials can be readily investigated. More sophisticated techniques, for example, targets connected to stings mounted on pressure or torsion transducers can be envisioned. Note that pure beams rather than rare gas-seeded beams are decidedly more advantageous for such measurements.

Gas-gas interactions provide more of a challenge. In particular scattering cross sections are best measured in a crossed molecular beam experiment. A movable time-of-flight mass spectrometer would be a critical diagnostic in such an experiment. The present trend is to use pulsed beams at right angles to optimize detectability. Standard beam techniques cannot provide center of mass energies sufficiently high for the present application; thus, one of the energetic oxygen atom sources under development would be required. The ionic exchange beams are probably the most appropriate, although a skimmed laser discharge beam could also be used.

PSI has developed a crossed beam experiment to study infrared excitation resulting from energetic oxygen atom collisions with species such as CO, CO_2, and CH_4. A schematic of the device is shown in Figure 2. Here a skimmed beam of fast oxygen atoms is crossed at right angles with a skimmed pulse (again using a fast pulsing valve) of thermal target molecules. The IR detection system is downstream of the interaction zone since momentum transfer will sweep the excited molecules in that direction. This experiment design is challenging in that the measurement must be made under single collision conditions; i.e., both the target molecules and the oxygen atoms are required

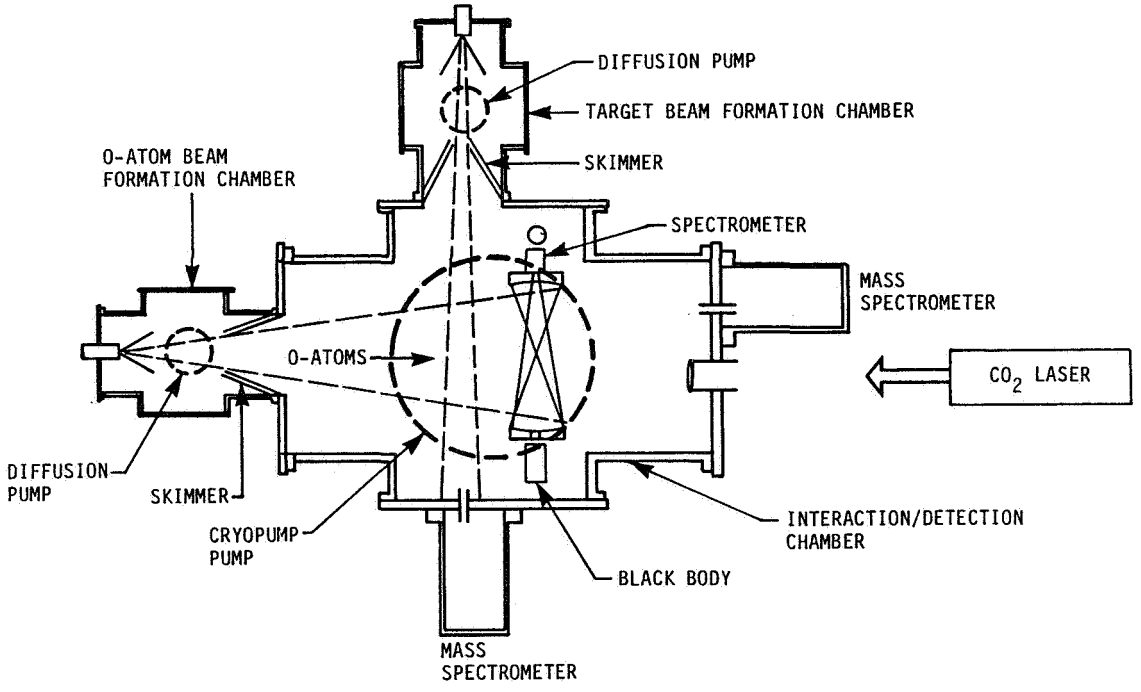

Fig. 2. Crossed beam system for excitation studies.

to experience only one collision in the interaction zone to ensure that the radiation is characteristic of fast atom impact. Similar techniques can be used to study visible excitation and chemical reaction in such systems.

The study of ionic reactions at interaction velocities of 8 km s^{-1} is straightforwardly performed using standard techniques. The data base for O^+ reactions with various contaminant species is limited at these energies, however, and the rate constants and products of such reactions should be evaluated. The evaluation of product energies is, perhaps, more stressing but also achievable.

Summary

A number of important quantities which must be evaluated in order to both understand and predict the contamination field about Space Station have been enumerated. It has been shown that the recent development of energetic oxygen atom sources enables the laboratory evaluation of the majority of these quantities. A number of potential measurement techniques have been briefly reviewed.

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