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Effects of Thruster Firings on the Shuttle Environment 1: Neutral Gas Composition

DONALD E. HUNTON

19 January 1990

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The changes in the neutral gas composition surrounding the Space Shuttle caused by the Shuttle's Vernier Reaction Control System (VRCS) and Orbital Maneuvering System (OMS) rocket engines were measured with a quadrupole mass spectrometer aboard STS-4. There are substantial differences between the measured composition changes in the payload bay and the calculated composition of the thruster exhaust plumes. These differences can be explained by kinematic effects that occur as the exhaust products collide with surfaces and other gas phase species in the Shuttle environment. Hydrogen, because of its light mass, is enriched in the return flux to the spacecraft, and tends to permeate the Shuttle environment during thruster firings more easily than heavier species. The effect of the thruster firings on the mass spectrometer also depended on the attitude of the instrument with respect to the velocity vector. When the mass spectrometer was pointed into the velocity vector, decreases in atomic oxygen concentration were detected during the engine firings.

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1: Neutral Gas Composition

1. INTRODUCTION

Three neutral mass spectrometers have been flown in the Space Shuttle payload bay. The Induced Environment Contamination Monitor (IECM), which flew on STS-1, -2, -3, and -4, was designed to evaluate the properties of the environment in the Shuttle bay.[1] This group of instruments included a quadrupole mass spectrometer to measure the neutral gas composition.[2,3,4] The Air Force's Geophysics Laboratory (GL) provided a quadrupole mass spectrometer of different design for another instrument

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(Received for publication 18 January 1990)

[1] Ehlers, H.K.F., Jacobs, S., Leger, L. and Miller, E. (1984) Space Shuttle Contamination Measurements from Flights STS-1 Through STS-4, J. Spacecraft and Rockets, Vol. 21: 301-308.

[2] Carignan, G.R. and Miller, E. R. (1983) Mass Spectrometer, in STS-2, -3, -4 Induced Environment Contamination Monitor (IECM) Summary Report, Miller, E.R., ed., NASA TM-82524, Feb. 1983, pp. 87-101.

[3] Miller, E. R. (1982) Mass Spectrometer, in STS-2 Induced Environment Contamination Monitor (IECM) Quick-Look Report, Miller, E.R., ed., NASA TM-82457, January, 1982, pp. 67-69.

[4] Miller, E.R. and Carignan, G. R. (1982) Mass Spectrometer, in STS-3 Induced Environment Contamination Monitor (IECM) Quick-Look Report, Miller, E.R. and J.A. Fountain, eds., NASA TM-82489, June, 1982, pp. 38-41.

pallet aboard the STS-4 mission.[5] This instrument, called the Quadrupole Ion/Neutral Mass Spectrometer (QINMS) measured both the positive ions and the neutrals with higher time resolution than was possible with the IECM. Finally, von Zahn and coworkers[6,7] designed a high sensitivity, double focusing sector instrument with a closed ion source for shuttle use. The Bonn Neutral Mass Spectrometer (BNMS), as it was called, was flown on STS-7 and mission 41-B.

The data from all three experiments showed that the environment near the Shuttle is considerably different from the natural atmosphere.[8] Surface outgassing, and cabin and payload gas leakage have all been shown to modify the Shuttle environment considerably. Other Shuttle operations such as water dumps and flash evaporator operations presumably also affect the environment, though these effects have not been measured in the payload bay by the mass spectrometers.

The various types of maneuvering thrusters on the Shuttle appear to have a larger instantaneous effect on the neutral environment than any other source of contamination. The IECM instrument did not measure the effect of the vernier RCS engines (see description of the engine types below), but recorded order of magnitude increases in water concentration that correlated with primary RCS engine firings.[2] Narcisi et al,[5] in a preliminary report on the GL STS-4 data, discussed neutral composition changes during vernier RCS and the OMS engine firings. The effects of the firings were very short-lived. Species concentrations returned to unperturbed levels within seconds after the firings ended. The three major exhaust products observed were H_2, H_2O, and N_2. The OMS plume was enriched in hydrogen, a fact

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[5] Narcisi, R., Trzcinski, E., Federico, G., Wlodyka L. and Delorey, D. (1983) The Gaseous and Plasma Environment Around Space Shuttle", AIAA-83-2659, (1983), AIAA Shuttle Environment and Operations Meeting, Oct. 31 - Nov. 2, 1983, Washington, DC.

[6] Von Zahn, U. and Wulf, E. (1985) The Gaseous Environment of the Shuttle, As Observed by Mass Spectrometer Inside the Payload Bay of the Shuttle Orbiter, AIAA-85-6097-CP, AIAA Shuttle Environment and Operations II Conference, Nov. 13-15, 1985, Houston, TX.

[7] Wulf, E. and von Zahn, U. (1986) The Shuttle Environment: Effects of Thruster Firings on Gas Density and Composition in the Payload Bay, J. Geophys. Res., Vol. 91: 3270-3278.

[8] Green B.D., Caledonia G. E. and Wilkerson, T. D (1985) The Shuttle Environment: Gases, Particulates and Glow, J. Spacecraft and Rockets, Vol. 22: 500-511.

attributed to the higher scattering cross section of the light hydrogen molecules. The importance of scattering was emphasized by Wulf and von Zahn[7] who have written the most complete analysis of the thruster firing effects. They conclude that the effects of the thruster firings are not observed if there are no surfaces to redirect the thruster exhaust plume toward the payload bay, and that the composition of the gas entering an instrument in the payload bay may be considerably different from the calculated composition of the exhaust plume.

The purpose of the present report is to extend the analysis of the thruster data discussed by Narcisi et al,[5] and to examine a number of other instances of thruster firings that took place throughout the STS-4 flight in July, 1982. Many of the phenomena reported by previous investigators are confirmed in the QINMS data. In addition, hydrogen is shown to be an important constituent of the return flux to the spacecraft, and an example of the "snowplow" effect of the thruster plume, in which ambient atomic oxygen is scattered away from the payload bay, is discussed.

2. INSTRUMENTATION

The GL Quadrupole Ion/Neutral Mass Spectrometer (QINMS) is, as the acronym suggests, a small, quadrupole instrument capable of measuring both positive ions and neutral species. Periodic commands from the ground switched it between these two types of measurements. Only the neutral measurements will be discussed in this paper. The design and operation of the instrument have been described in more detail in previous publications.[5,9,10,11] Figure 1 is a schematic drawing of the instrument that

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[9] Hunton, D.E. and Calo, J. M. (1985) Gas Phase Interactions in the Shuttle Environment, AIAA-85-6055-CP, AIAA Shuttle Environment and Operations Meeting II, Nov. 13-15, 1985 Houston, TX.

[10] Hunton, D.E., Trzcinski, E., Wlodyka, L., Federico, G., and Dorian, J. (1986) Quadrupole Ion/Neutral Mass Spectrometer for Space Shuttle Applications, AFGL-TR-86-0084 ADA 172000.

[11] Hunton, D. E. and Swider, W. (1988) Variations of Water Vapor Concentration in the Shuttle Environment, J. Spacecraft and Rockets, Vol 25: 139-145.

shows the principal components, including the motor driven cover, ion source, quadrupole rods, electron multiplier, and electronics housing.

The mass spectrometer was mounted in the payload bay on a cross-bay support pallet, slightly above the level of the payload bay door hinges. Its field of view was over the right wing at a 12° elevation above the plane of the wings. In this position, shown in Figure 2, part of the field of view was of unobstructed space, while the rest was of Shuttle surfaces such as the inside of the payload bay and portions of the right wing.[11]

Pre- and post-flight neutral calibrations were performed using stagnant test gases. After the flight, the sensitivity of the instrument was found to have drifted somewhat as a function of its temperature.[11] All data discussed here have been corrected for the temperature drift.

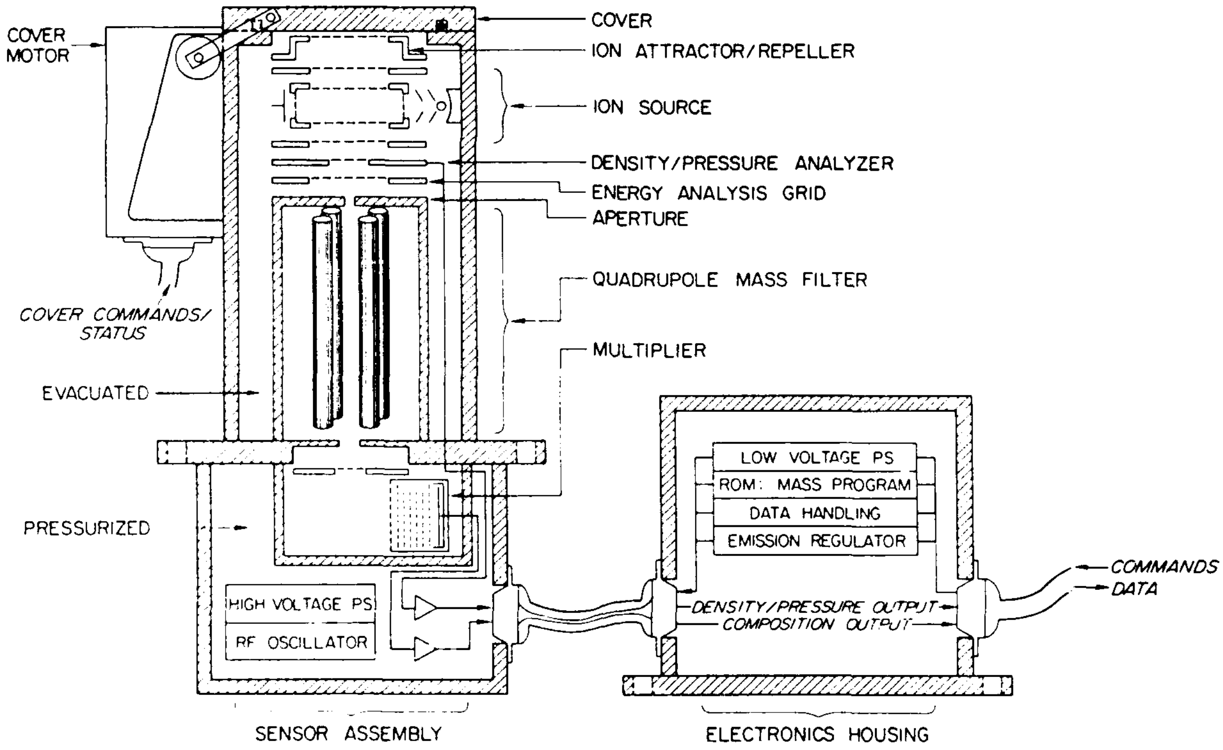

Figure 1. Schematic Drawing of the QINMS Instrument

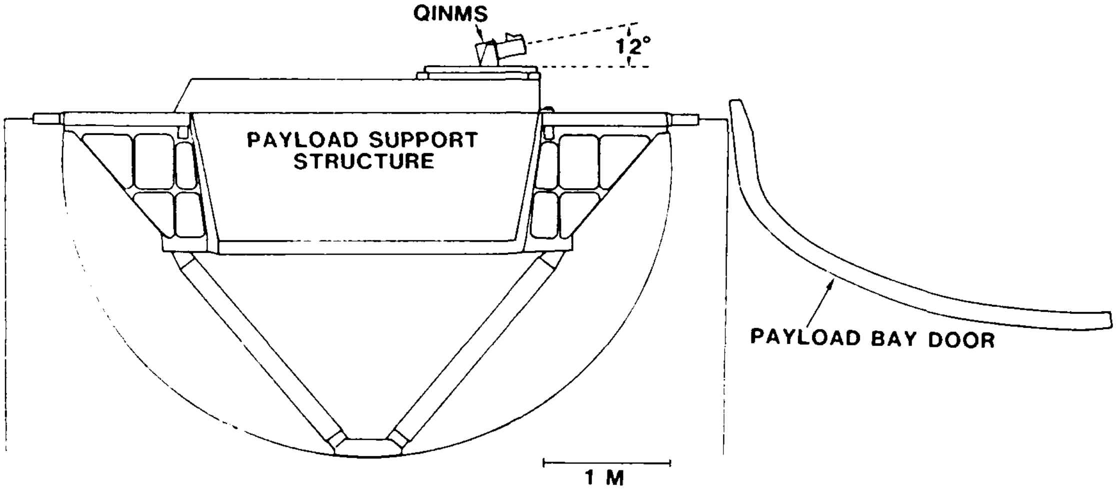

Figure 2. Position of QINMS in the Shuttle Payload Bay

As mentioned above, the only other detailed measurements of the effect of thruster firings on the neutral environment were made by Wulf and von Zahn.[7] The important differences between their instrument and the GL mass spectrometer are in mass range, sampling speed, and sensitivity.

The GL instrument measured masses 1 to 67, whereas Wulf and von Zahn reported on masses 12 to 80. The BNMS takes eight measurements per second, whereas QINMS takes 100. Much of the BNMS thruster effects data were taken in the sawtooth mode where an entire mass spectrum was collected in 256 seconds. The effects of the thrusters appeared as spikes superimposed on the individual mass peaks. The change in the concentration of one species at a time is measured with 0.125 s time resolution. Gas composition changes during thruster firings were inferred from comparison of the effects on different masses during many different firings. In contrast, because QINMS recorded only the intensities at the top of each peak, an entire mass spectrum was collected every 1.28 seconds. Several entire mass scans were collected during the longer individual thruster firings.

Finally, the BNMS was much more sensitive than the GL instrument. The detection limit of the BNMS is estimated to have been approximately three orders of magnitude lower than for QINMS.

3. ORBITER THRUSTER TYPES

The Orbiter has three types of rocket engines that are used in orbit to control attitude and position. The Orbital Maneuvering System (OMS) engines are the largest. With a thrust of 25,000 lbs, they are used to make large changes in the orbital altitude of the Shuttle. The two OMS engines are located in the rear engine pods, and point away from the Shuttle along the Shuttle's longitudinal axis.

The Reaction Control System (RCS) is composed of two types of engines that are used to change the attitude of the Orbiter. Both types, the Primary RCS engines, with 870 lbs of thrust, and the Vernier RCS engines, with 25 lbs of thrust, are located in various positions and orientations. The vernier RCS thrusters are used much more frequently in flight than the primary engines. There are six verniers, two in front and two in each rear engine pod. They are labeled with the number 5 (the primaries are labeled with numbers 1-4) and with two letters giving their location [F=front, R=right (rear) and L=left (rear)] and pointing direction [D=down, R=right and L=left]. For example, the vernier in the right rear engine pod that points down is labeled R5D. Drawings of the Orbiter thrusters can be found in References 7 and 12. The QINMS instrument collected data for one burn of the OMS engines and for many vernier thruster firings, but did not collect any useful data during primary RCS engine firings.

4. RESULTS

The vernier thrusters fire, on the average, once every 15 seconds throughout a flight.[5] Because of this, much of our STS-4 neutral data show the effects of thruster firings. Unfortunately, a complete analysis of all the thruster data has been frustrated by two instrumental characteristics. The sampling time of the instrument (10 ms per measurement) is only slightly faster than the average firing time of the vernier thrusters (80 ms). A typical firing does not affect even one complete 1.28 second measurement sequence, but only a few mass measurements. The timing accuracy is not sufficient to discern which measurements were taken during the firing. Thus, it is difficult to separate the effect of the thruster from the scatter in the data for these short thruster firings. Also, the drift in the sensitivity caused by temperature changes[11] makes it difficult to compare data taken at different times and temperatures.

Because of these problems, we have limited quantitative analysis of the thruster data to Orbit 4.6, an early orbit that contains particularly favorable data. Both the Vernier RCS engines and the OMS engines were fired during orbit 4.6, allowing the effects of the two types of engines to be compared. Also, the engine firings were long enough to allow the mass spectrometer to sample each species several times. The "thruster-on" data can be averaged to give more confidence in the quantitative composition measurements. Finally, the temperature of the instrument was optimal (21° C) during this orbit. The drifts in sensitivity caused by low temperatures were negligible.

Qualitative thruster firing effects data are presented for several other orbits. Hydrogen data from Orbit 67.0 allows comparison of the different effects of thrusters on the left and right sides of the spacecraft. In addition, the QINMS instrument was in a ram orientation (pointed into the velocity vector as the Shuttle flew sideways) during orbits 29.3 and 51.8. Thruster firings during these data periods shows the effect of the cloud of thruster exhaust gases on the flow of ambient species into the payload bay.

Returning first to Orbit 4.6, the effects of the thruster firings are very clearly seen in Figure 3. The firing history for the six vernier RCS engines is indicated at the top of the figure, and the fourth burn of the OMS engines is marked explicitly. Signal increases during the thruster firings were measured at masses 1, 2, 4, 14, 16, 17, 18, 19, 28 and 30. Masses 2, 4, 18, 28 and 30 are the parent ion peaks from molecular hydrogen, helium, water, nitrogen and nitric oxide, respectively. The other masses are due to dissociative ionization of these same molecules in the ion source, or in the case of mass 19, to ion-molecule reactions occurring in the ion source. Thus, all of the signal increases can be attributed to only five species: molecular hydrogen, helium, water, molecular nitrogen, and nitric oxide (NO). In the five main panels of Figure 3, the parent ion signals (in amps) for these

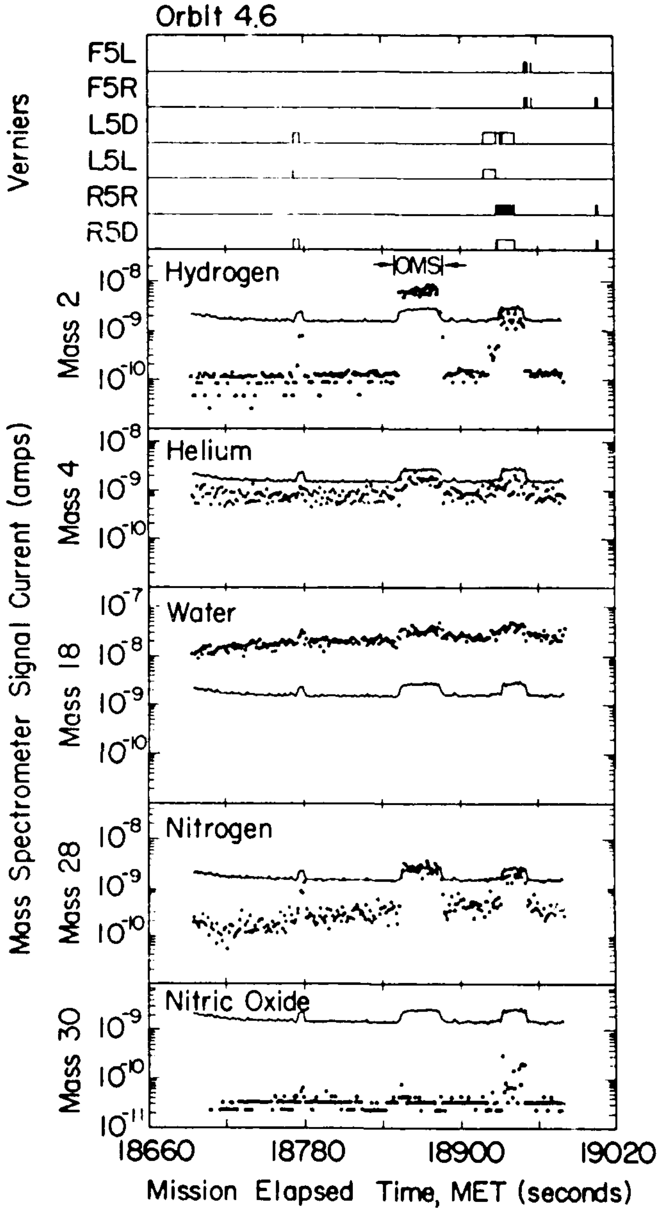

Figure 3. Thruster Firing Data for Orbit 4.6. Mass spectrometer signal currents for the five major exhaust products detected by the instrument are plotted against Mission Elapsed Time (MET) in seconds. The solid line in each panel is the data from the total pressure monitor. The firing history for the six Vernier Reaction Control System (VRCS) engines is marked in the top panel. The fourth burn of the Orbital Maneuvering System (OMS) engines occurred approximately between MET 18850-18880, and is marked explicitly in the hydrogen panel.

detected components of the thruster exhaust are plotted against Mission Elapsed Time (MET) in seconds. The total pressure signal, measured with an ion collection grid in the QINMS ion source, is drawn in each panel of the figure as a reference.

To compare the results of our measurements to thermodynamic calculations of the composition of the exhaust plumes, we have calculated the mole fraction of each of the four main species detected by the QINMS instrument (hydrogen, helium, water, and nitrogen). Average parent ion currents were calculated during the vernier thruster and OMS engine firings and during the adjacent unperturbed times. The differences between the thruster-on and the thruster-off currents were converted to changes in pressure by dividing by the laboratory calibration factor for each gas. Finally, the mole fraction of each of the four main gases was calculated from the pressure increases. Nitrogen was differentiated from carbon monoxide (both mass 28 species) by examining the intensity of the fragment ions N^+ and C^+, produced by dissociative ionization of the parent species.

Table 1 shows the results of these calculations for the OMS engine and for the second of the two R5D vernier thruster firings in Orbit 4.6. (The two

Table 1: Thruster Exhaust Composition (Mole Fractions)

	Experiment	(Orbit 4.6)	Calculation
Species	VRCS (R5D)	OMS	CONTAM 3.2
H_2O	.70	.37	.33
N_2	.06	.07	.31
H_2	.14	.40	.17
CO	0	0	.13
CO_2	0	0	.04
H	0	0	.02
He	.10	.16	0
NO	trace	0	0

vernier thruster firings gave nearly identical results.) In addition, the table shows the results of thermodynamic equilibrium calculations of the composition of the exhaust plume of a vernier RCS engine done with the CONTAM 3.2 computer model.[12] This model only predicts the composition of the gas at the center of the exhaust plume, and agrees very well with recent measurements (see below). However, the model does not account for variations in composition with position in the plume, and in particular, does not calculate the backflow region composition.

Many of the observations about thruster firings that have been reported earlier in the QINMS data[5] and in the BNMS data[7] are reiterated in Figure 3 and Table 1. These are listed here briefly for completeness.

1) The effects of the thrusters are very short-lived. All five signals increase markedly as soon as the thrusters fire, and decrease to background levels within a second or two after the firing stops.

2) The magnitude of effect that any thruster has on the mass spectrometer and the payload bay environment depends on where that thruster is located. Two examples of this cited by Wulf and von Zahn[7] can also be seen in the QINMS data. First, the front vernier thrusters have no measurable effect on the QINMS instrument; only the verniers in the rear engine pods affect the mass spectrometer. Second, the signals from the OMS burn in orbit 4.6 are approximately the same magnitude as those from the rear vernier RCS burns, which is surprising given that the OMS engines are approximately 1000 times larger than the VRCS engines. Both observations have been explained by the fact that neither the plumes from the front verniers nor the OMS engines have any Shuttle surfaces with which they can interact, whereas the rear verniers direct their plumes onto the tops of the wings. The plume molecules scatter off these Shuttle surfaces and are redirected toward the payload bay.

3) The gas returned to the payload bay from the OMS plume is highly enriched in hydrogen, due to the high scattering cross section for that species.

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[12] Segal, A., Hoffman R. J., and Miller, W. (1987) Chemical Species and Reactions of Importance in Assessment of Bipropellant Plume and Contamination Effects, Air Force Rocket Propulsion Laboratory Technical Report AFRPL TR-86-102.

4) Increases in the measured amounts of species that *are not* produced by the engines are observed during thruster firings in addition to actual exhaust products. In the QINMS data, the increase in the helium signal is the best example of this. Helium is not produced by the thrusters at all, but clearly increases in concentration at the mass spectrometer during the thruster firings. A second example is the high mole fraction of water in the VRCS plume. The concentration of water in the Shuttle environment during orbit 4.6 was high due to outgassing of Shuttle surfaces. Some of this "ambient" water was scattered into the mass spectrometer during the thruster firing in addition to the water produced by the thruster itself.

Hydrogen stands out as the most pervasive of the thruster exhaust products in the Shuttle environment. The hydrogen enrichment of the OMS exhaust plume return flux to the mass spectrometer, already mentioned above, is an excellent example. The same phenomenon is seen in the VRCS data from Orbit 4.6. Even though the VRCS return flux is dominated by water, the enrichment of the return flux in hydrogen can been seen by comparing the mole fraction of hydrogen to nitrogen. The measured fraction of hydrogen is considerably higher than nitrogen, which is the reverse of what is predicted by the equilibrium codes.

In addition, there are many instances where an increase in the amount of hydrogen during a thruster firing is the only signature of the event detectable by QINMS. For example, the hydrogen data from Orbit 4.6, plotted in Figure 3, shows that the amount of hydrogen detected by the mass spectrometer increased by about a factor of 3 at MET 18920, about 10 seconds before the right side verniers began to affect the other species concentrations. This increase coincides with the firing of the two left side verniers, L5D and L5L. At MET 18930 when the right hand verniers turned on, the hydrogen signal increased by approximately another factor of 3. In this case, as is frequently true throughout the flight, hydrogen is the only species detected from the left side verniers. No other signals besides Mass 2 increased at MET 18920. As discussed below, this fact is attributed to the pointing orientation of the QINMS instrument.

The effects of the two left side VRCS engines can be differentiated in another example of thruster data. Figure 4 shows the firing histories of the four rear verniers along with the mass 2 signal from a portion of orbit 67.0. The downward-pointing verniers on both sides of the Shuttle (R5D and L5D) have approximately the same effect on the total pressure monitor and the hydrogen signal, whereas the left-pointing vernier on the left side (L5L) had no effect at all. A tiny increase in the mass 30 signal, corresponding to NO, was also noted during these thruster firings, but the quality of the data was not sufficient to tell which engine produced the signal.

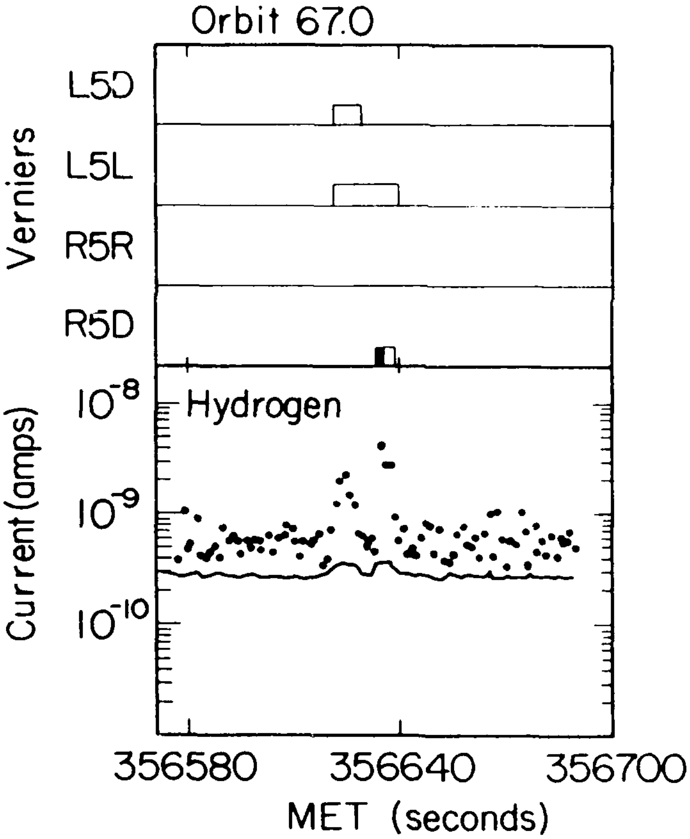

Figure 4. Effect of Downward-pointing Rear Vernier Thrusters on Hydrogen Signals in Orbit 67.0. The hydrogen concentration increased distinctly when the two downward-pointing thrusters, L5D and R5D fired, but did not respond to L5L, the left-pointing thruster on the left side.

The downward-pointing thrusters on both sides of the Shuttle cause the largest return fluxes to the payload bay, as Wulf and von Zahn[7] have pointed out, because their exhaust plumes can bounce off the wings of the Shuttle. However, QINMS was much more sensitive to the heavier species from the right side vernier. The reason for this left-right asymmetry is that the instrument pointed toward the right side of the Shuttle bay. It was positioned to measure the return flux from the thrusters on that side more easily. Because the BNMS pointed vertically out of the payload bay for many of the thruster effects measurements, it was affected equally by the thrusters on the left and right side of the Orbiter.

However, the two examples discussed above show that hydrogen behaves qualitatively differently from the heavier species. In the case of hydrogen, the left side thrusters had nearly as large an effect on the mass spectrometer as the right side thrusters. These data indicate that the heavier species form directed fluxes across the payload bay, and that the effect of that flux depends on the position and pointing direction of the instrument. In contrast, hydrogen appears to envelop the Shuttle in a cloud of molecules whose directions are well randomized.

A final example of thruster data shows the dependence of the effect of thrusters on QINMS angle of attack. The data of Orbit 4.6 was taken with the Shuttle in the so-called "airplane" attitude, with the nose toward the velocity vector. This attitude gives our instrument an attack angle of approximately 90°. In two other orbits, 29.3 and 51.8, the instrument was in a ram attitude (that is, the sensor pointed into the velocity vector) during thruster firings.

When the mass spectrometer is in a ram attitude, natural thermospheric species, atomic oxygen in particular, can stream directly into the instrument and give rise to large signals; most of the pressure in the ion source is then due to these ambient species. The sensitivity of the mass spectrometer to ambient species is strongly dependent on angle of attack, whereas the sensitivity to Shuttle contaminant species is less angle dependent.[11]

The QINMS data show that thruster firings extensively modify the location of the "plow cloud" ahead of the orbiter, and hence affect the flow of ambient species into the instrument. In both examples of thruster data taken in the ram attitude, the total pressure showed a decrease of about 50 percent during the firing. In orbit 51.8, the R5R vernier thruster was responsible for the decrease in signals; R5D caused an effect of similar magnitude in orbit 29.3.

Only the data from Orbit 51.8 shows changes in individual species concentrations; the data from Orbit 29.3 was inexplicably noisy. Atomic oxygen, mass 16, the most prominent ambient neutral species at Shuttle altitudes, showed a dramatic decrease of a factor of 30-35 in orbit 51.8 during the R5R firing. The mass 32 signal, due to molecular oxygen formed by atomic oxygen recombination in the mass spectrometer ion source, also showed a small decrease, though not as large as the drop in mass 16. Molecular nitrogen, at mass 28, is the second most prominent neutral species at Shuttle altitudes. The mass 28 data in Orbit 51.8 were noisy for some reason, but may show a small decrease at the time of the thruster firing. The mass 14 signal, which is due to dissociative ionization of N_2, decreased by a factor of 3 or 4. It is not clear why the drop in 14 was larger than the decrease in 28.

As has been the case in the other examples of data discussed earlier, the molecular hydrogen signal behaved very differently from the other signals. At the same time that the total pressure, the mass 16 and the mass 14 signals were decreasing, the molecular hydrogen concentration increased significantly. The total pressure, atomic oxygen and hydrogen data are shown in Figure 5 for the orbit 51.8 case. Note that the drop in atomic oxygen signal at the end of the data period is due to a change in attitude away from the ram direction and not to any thruster effects.

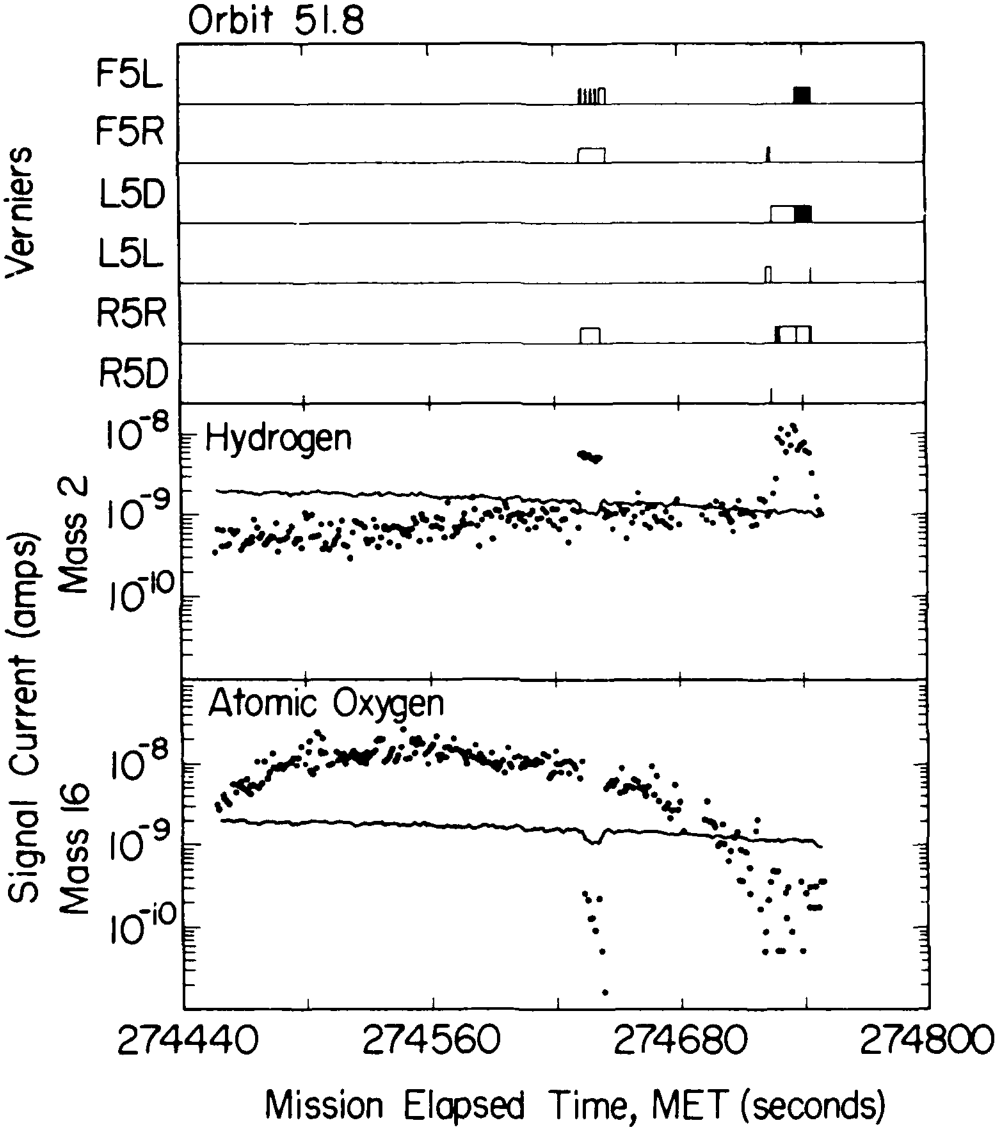

Figure 5. Changes in Hydrogen and Atomic Oxygen Signals Caused by Thruster R5R During Orbit 51.8. The instrument was pointed into the velocity vector during most of the orbit. Hydrogen concentrations increased as in other examples, but atomic oxygen concentrations and total pressure decreased markedly. The fall-off in atomic oxygen signal at the end of the orbit was caused by a change in instrument attack angle away from ram.

5. DISCUSSION

Wulf and von Zahn[7] have reported that there is no simple correlation between the neutral gas composition changes measured by a mass spectrometer in the payload bay and the actual composition of the thruster exhaust. They identify scattering of the thruster exhaust plumes off Shuttle structures such as the surfaces of the wings as an important mechanism for re-directing the plume flux back to the Shuttle bay. The present data corroborates this observation, as there are substantial differences between the thermodynamic calculations of thruster exhaust composition and the mass spectrometer measurements.

In addition to surface scattering, gas phase scattering is another major mechanism for transport of the thruster exhaust to the mass spectrometer. Because of the kinematics of gas phase collisions, such interactions are more likely to produce changes in return flux composition than surface scattering. In a collision between a light molecule and a heavy one, the light molecule will experience a larger change in both direction and momentum, and is therefore more likely to be returned to the spacecraft. Conversely, neither specular or diffuse scattering nor adsorption/desorption from a surface should favor either light or heavy species unless there are molecule-specific differences in the adsorption properties.

Most of the exhaust gases from a thruster move away from the engine in the same direction as the thruster nozzle is pointing. A small fraction of the exhaust is scattered out of the main plume, crosses back over the plane of the engine exhaust nozzle, and actually goes behind the exhaust nozzle. This flux of gas in the backflow region of the engine is of particular concern in Shuttle bay contamination studies, because the backflow flux is pointed directly at the payload bay.

In addition to such self-scattering within the plume, the exhaust molecules may interact with other contaminant species in the Shuttle environment and with ambient thermospheric species. Collisions with these species could also lead to a return flux that is kinematically enriched in light species such as hydrogen.

The variation of plume gas composition as a function of angle from the plume axis has been investigated in recent laboratory experiments[13,14] at the Technical University of Hamburg-Harburg. An MBB 10N thruster, which is similar in size to the VRCS thrusters on the Shuttle and uses the same bipropellant fuel/oxidizer mixture, was fired into a large vacuum chamber. A variety of diagnostics were used to characterize the plume flow field. In particular, a mass spectrometer measured the composition of the plume gas at three distances away from the nozzle exit and at angles between 0 and 125° with respect to the plume axis.

The plume composition was found to vary significantly with angle. Close to the plume axis, at angles less than 50°, the measured composition did not vary appreciably with angle, and agreed very well with the predictions of the CONTAM 3.2 computer model listed in Table 1. At angles greater than 50°, however, the relative amount of hydrogen increased significantly. In the backflow region, that is, at angles greater than 90°, the exhaust was made up almost entirely of hydrogen.

The preponderance of hydrogen in the return flux measurements made by QINMS substantiates these laboratory measurements. Because of its position in the payload bay, the QINMS instrument was in the backflow region of all the thrusters aboard the Shuttle. In agreement with the TUHH results, the flight mass spectrometer measured more hydrogen than any other species from all but the R5D vernier in Orbit 4.6. This particular case is discussed below.

It is not possible to distinguish between self-scattering in the plume and scattering from other contaminants using the present data. Nevertheless, it is clear that both mechanisms, along with surface scattering, are required to understand all the experimental results. Because of its orientation, if the QINMS instrument were simply measuring unperturbed backflow from the thrusters, then it would not detect any signals from the left side thrusters. The instrument was pointed away from that flow of gas. In fact, the near

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[13] Preliminary data is from Trinks, H. (1989) Plume Contamination: TUHH Experimental Investigation, Progress Report #1, Air Force Armament Laboratory AFATL/SAI Interim Technical Report, Jan 20, 1989.

[14] Trinks, H., and Hoffman, R. J. (1983) Experimental Investigation of Bipropellant Exhaust Plume Flowfield, Heating and Contamination, and Comparison with the CONTAM Computer Model Predictions, AIAA-83-1447, AIAA 18th Thermophysics Conference, June 1-3, 1983.

left-right symmetry in hydrogen measurements that is not seen for other species seems to require that surface and non-plume gas phase collisions randomize the flow of the hydrogen. It may be better to think of the Shuttle being enveloped in a cloud of hydrogen during thruster firings than to think of directed hydrogen flows.

A second effect of gas phase collisions, in addition to returning the thruster plume species to the vehicle, is to increase the backscattered flux of "non-plume" contaminants. For example, the mass spectrometer recorded an increase in the amount of helium during firings even though helium is not one of the exhaust products. Narcisi et al[5] observed that helium was a major contaminant throughout the flight. The increase in the total gas density caused by the thruster firing increased the probability of helium collisions with other species. The mass spectrometer measured the resultant larger backscattered flux. Wulf and von Zahn[7] made the same observation, reporting a signal increase at all masses when the thrusters fired.

A similar effect can be seen in the water vapor measurements during the vernier RCS firings. The composition of the gas entering the mass spectrometer from the vernier thrusters was enriched in water compared to the levels expected from the calculations. Orbit 4.6 occurred early in the STS-4 flight and surface outgassing led to high levels of water.[11] There are three sources of water signals in the mass spectrometer: internal ion source outgassing, directed outgassing flux from external surfaces, and backscattered return flux from gas phase collisions. Thruster firings probably do not affect the first two sources. However, the thruster plume appears to have enhanced the return flux of contaminant water.

If the mole fraction of light species is high, the mole fraction of heavier species must necessarily be low. Indeed, for both the OMS and VRCS engines, the measured mole fractions of heavier species such as nitrogen, carbon monoxide and carbon dioxide in Table 1 are much lower than the calculations suggest they should be. At first glance, this would seem to contradict the measurements of Wulf and von Zahn,[7] who saw substantial concentrations of N_2, CO and CO_2.

In fact, it is very difficult to make quantitative comparisons between the BNMS and QINMS data. The main reason is the difference in background pressure. Wulf and von Zahn calculate a background number density in the payload bay of 7×10^{14} cm^{-3}, which is equivalent to a pressure of approximately 2×10^{-8} torr. The QINMS pressure measurements taken during orbit 4.6 indicated a pressure two orders of magnitude higher, 2×10^{-6} torr.

Because the background pressure was so much higher for the QINMS measurements than for the BNMS measurements, the effects of backscattering of non-plume species were much more important for QINMS. Perhaps the best way to interpret the Orbit 4.6 results is to picture a return flux from the thruster plume, consisting mostly of hydrogen, carrying with it a small fraction of the contaminant gases, water, nitrogen, and helium, that were already in the environment before the thruster fired. The other thruster products such as CO and CO_2 were probably in the return flux, but at a level below the detection limit of QINMS. The water and helium signals detected by QINMS were high because the background concentrations of those gases were high. The large differences between the measured and calculated composition in Table 1, therefore, are largely artifacts of the environment in which the measurements were taken.

Contrast this situation with the much cleaner environment where the BNMS made its measurements. The return flux from the thruster plume did not interact with the background contaminants to nearly as large a degree, and so the BNMS measured a more true representation of that return flux. Species such as CO and CO_2 were seen by the BNMS because of its much higher sensitivity. The present data suggest that the BNMS would have seen very large hydrogen signals had the instrument made that measurement.

The QINMS data from Orbit 67.0 may be more similar to the BNMS data. The pressure monitor measurement was nearly a factor of 10 lower than Orbit 4.6, and most individual species signals were low. The only changes observed during the thruster firing were a factor of 5 increase in H_2 and a tiny increase in NO. It is not known why nitrogen and water were not observed. Nevertheless, these data serve to emphasize qualitatively that significantly more hydrogen is returned to the payload bay than other species.

We turn finally to the decrease in the measured flux of ambient atomic oxygen during thruster firings that was observed in Orbit 51.8. In the ram attitude, the Shuttle is flying sideways with the right wing pointed in the direction of motion. The total pressure and the atomic oxygen signal in the mass spectrometer are due primarily to ambient species streaming directly into the instrument. The thrusters on the right side of the Shuttle, particularly those in the rear, create a cloud of exhaust molecules when they fire, through which the beam of ambient species must pass on the way to the instrument.

In principle, both reactive and non-reactive collisions between the atomic oxygen and the exhaust species could occur, and both could reduce the flux of atomic oxygen to the mass spectrometer, as seen. However, there is no evidence for reactive scattering in the mass spectrometer data in the form of increases in the signals of possible reaction products. This suggests that non-reactive collisions sweep the atomic oxygen out of the beam, a phenomenon that has been nicknamed the "snowplow effect."

A very rough estimate of the exhaust plume column density can be made by assuming that the atomic oxygen intensity can be described by a simple Beer's Law equation and by ignoring multiple scattering effects. In that case, the fraction of the original oxygen atom intensity detected during the thruster firing, I/I_0, is equal to the negative exponential of the collision cross section, σ, times the column density, ρ_c.

$$\frac{I}{I_0} = e^{-\sigma\rho_c}$$

From the data in Figure 5, I/I_0 is approximately 1/35, or 3×10^{-2}. This requires the exponent $\sigma\rho_c$ to be approximately 3.5. If we take the hard sphere radius of an atomic oxygen to be[15] $r_0 = 0.6$ A and the hard sphere

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15. Moses, A. J., The Practicing Scientist's Handbook, (Van Nostrand Reinhold, New York, 1978), p. 43.

radius of a typical exhaust molecule such as H_2O or N_2 to be[16] $r_m = 1.6$ A, then the total hard sphere scattering cross section, $\sigma = \pi(r_o + r_m)^2$, is equal to 1.5×10^{-15} cm^2. The column density of thruster exhaust plume species in front of the mass spectrometer must then be approximately 2×10^{15} cm^{-2}. A more accurate calculation of column density would require a multiple scattering contamination program.

Because hydrogen is so much lighter than oxygen, it is backscattered in the collisions and detected in larger amounts by the mass spectrometer during the thruster firings. An order of magnitude estimate of the return flux of hydrogen to the payload bay can be made by converting the hydrogen signal increase shown in Figure 5 to a number density of hydrogen in the instrument ion source, by assuming that the flow of hydrogen out of the instrument is effusive, and by equating the effusive flow out of the source with the flux entering the source. This calculation gives the hydrogen return flux as slightly more than 10^{14} $cm^{-2}s^{-1}$. Unless the velocity distribution of the hydrogen is known, this flux cannot be converted to a number density.

6. CONCLUSIONS

The thruster engines used to change Shuttle attitude and orbital position are among the most important sources of gaseous contamination in the payload bay. Even the effects of the smallest vernier RCS engines are easily detected by mass spectrometers mounted in the payload bay.

An analysis of the data from the quadrupole mass spectrometer flown on STS-4 by GL has confirmed many of the observations reported earlier by other investigators. The effect of the thrusters is very short lived. The concentrations of neutral gas species return to unperturbed levels within a few seconds after the thruster firing is complete. The exhaust plumes of the engines are, for the most part, directed away from the Shuttle. Because of this, surface and gas phase scattering are important mechanisms for returning the exhaust species to the Shuttle payload bay. Only those

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[16] Chemical Rubber Company, Handbook of Chemistry and Physics, 52nd Edition, 1971, p. F-170.

thrusters that have large surfaces to interact with, such as the wings, cause large changes in the payload bay gas composition. Finally, the concentrations of species not found in the exhaust plumes, such as helium and water vapor, also increase during the thruster firings.

Two new observations have also come out of this study.

1) The kinematics of gas phase collisions cause light species such as hydrogen to be favored in the return flux. The composition of the gas returning to the payload bay from the OMS engines is clearly enriched in hydrogen. Also, the hydrogen from the vernier thrusters appears to pervade the Shuttle environment more easily than the other exhaust products. Only the right hand, downward-pointing vernier, R5D, gave detectable signals for water and nitrogen. However, the right and left side, downward-pointing verniers, R5D and L5D, gave nearly equal hydrogen signals. This result is in excellent agreement with recent laboratory measurements of significant enhancements in relative hydrogen concentrations in the backflow region of the thruster.

2) When the instrument was pointed into the ram direction, the ambient atomic oxygen streamed directly into the ion source to give large mass 16 signals. These atomic oxygen signals were decreased by a factor of more than 10 during firings of the R5R thruster. Collisions between the oxygen and the counterstreaming exhaust products appear to have scattered the oxygen out of the "beam" that entered the instrument. Total pressure was also reduced by a factor of 2. However, at the same time, the hydrogen signals increased significantly, again indicative of the ease with which hydrogen is scattered back into the payload bay. These measurements allowed rough estimates of the column density of exhaust molecules (2×10^{15} cm^{-2}) and the return flux of hydrogen (10^{14} cm^{-2} s^{-1}) to be made.

The QINMS instrument is currently scheduled for two more flights aboard the Space Shuttle. The Air Force Program 675 experiment is planned for STS-39 in January, 1991 and the NASA JSC Evaluation of Oxygen Interactions with Materials (EOIM-3) experiment is slated for STS-46 in September, 1991. In both of these experiments, the mass spectrometer will measure the neutral and ion environment for extended periods of time. We hope to measure the effects of the thruster firings under a wide range of orbital conditions and thus obtain enough data to perform a statistical analysis of many thruster firings. Such an approach should give a more complete view of the effect of the thrusters on the Shuttle environment than the individual case studies presented here.

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