Variations of Water Vapor Concentration in the Shuttle Environment

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A quadrupole mass spectrometer was used on STS-4 to measure the water vapor concentration in the Shuttle's vicinity. During the flight, the water concentration varied by at least a factor of 100, and correlated very well with the temperature of the bay. Water dumps and Shuttle attitude had little effect on the measured water signals. Estimates of total water concentration can be made from both the ion mode and the neutral mode data. Though the two types of data show qualitatively similar behavior, there is not enough ion mode data to confirm the detailed trends observed in the neutral mode. The ion mode and neutral mode estimates appear to bracket the true water concentration. A lower limit estimate of the highest water concentration at the instrument is 5×10^{-7} Torr.

Introduction

A NUMBER of neutral mass spectrometers have been flown in the Shuttle's payload bay. These include the quadrupole instrument in the Induced Environment Contamination Monitor (IECM) that flew on the first four Shuttle flights,[1-3] the Quadrupole Ion-Neutral Mass Spectrometer (QINMS) built by the Air Force Geophysics Laboratory for STS-4,[4] and the University of Bonn neutral gas mass spectrometer (BNMS) that has been flown twice, once on mission STS-7 and again on mission 41-B.[5,6] Measurements of water concentrations were stressed in all of these experiments. Each investigation has shown that water vapor is one of the most important contaminants in the Shuttle environment.[1-8]

The present paper focuses on the water vapor measurements made by the QINMS on STS-4 in June and July of 1982. Several other aspects of the data from this experiment have been presented previously in the literature.[4,9,10] Large variations in water vapor concentrations were observed throughout the seven-day STS-4 flight. Possible causes of these variations were temperature, attitude, time, and water dumps. Our analysis of the data shows that temperature was the dominant controlling influence.

An important feature of the QINMS instrument is that it measured the amounts of both the ionic and neutral species in the Shuttle environment. Estimates of water concentrations can be made from both types of data. The neutral mode data appear to underestimate while the ion mode data seem to overestimate the true water concentration. In the discussion section, the ion mode and neutral mode data are compared to each other and to the results of the other mass spectrometer experiments.

Instrumentation

The mass spectrometer is composed of two units. As shown in Fig. 1, the evacuated part of the sensor contains the ion source and focusing grids, the quadrupole rods, and the electron multiplier. The radiofrequency and high voltage power supplies are housed in the sealed part of the sensor. The electronics box contains the low voltage command, telemetry, and programming circuits. Further details can be found in other publications.[4,9-11]

The instrument measures both neutral species and positive ions. In the neutral mode, the grids in the ion source are biased to reject ambient ions and electrons. A transverse electron beam ionizes the neutral species that enter the ion source. In the ion mode, the electron beam is turned off, and the grids are biased to attract the positive ions. The sequences of measurements are preprogrammed and stored in EPROMs. Commands from the ground switch the instrument between the two modes.

The field of view of the instrument is an important consideration in the analysis of the data. Because ions tend to be neutralized when they strike surfaces, the ion mode field of view was defined by the physical geometry of the apertures in the ion source grids. This field was a cone along the axis of the sensor with a 10 deg half angle. Conversely, because nonreactive neutrals can reflect off surfaces in the ion source, the field of view for these neutral species was considerably larger and may have approached a 90 deg half angle cone, i.e., a nearly complete hemisphere. The larger field of view does not apply to reactive neutrals such as atomic oxygen, because these species can react with surfaces in much the same way as the ions.

On STS-4, the instrument was located approximately three-quarters of the way back in the payload bay. It was slightly above the level of the payload bay door hinges, and was 1.5 m from the right edge of the bay. The sensor pointed out over the right wing at a 12 deg elevation above the plane of the wings. Figure 2 shows the position and orientation of the instrument in the payload bay. This position was chosen to give the instrument an unimpeded view of space in the ion mode. In the neutral mode, however, a number of Shuttle surfaces, particularly the inside of the payload bay wall and perhaps a portion of the right wing tip, were within the field of view.

Water Concentration Measurement Techniques

Indications of the concentration of water near the mass spectrometer can be obtained both from neutral mode and ion mode data. In the neutral mode, the 18-amu signal is directly proportional to the pressure of the water in the ion source. Laboratory calibration experiments were done before and after the flight to measure this relationship. For water vapor, the conversion factor was approximately 10^{-1} A/Torr.

Because these laboratory calibrations were accomplished with a stagnant gas in the ion source, they are not directly applicable to the Shuttle environment. The low ambient gas pressure at Shuttle altitudes allows most of the contaminant gases to move away from the Shuttle as a directed outgassing flux. Because the mass spectrometer is mounted in the midst of this directed flow, it is difficult to relate the water pressure inside the ion source to the fluxes of water outside.

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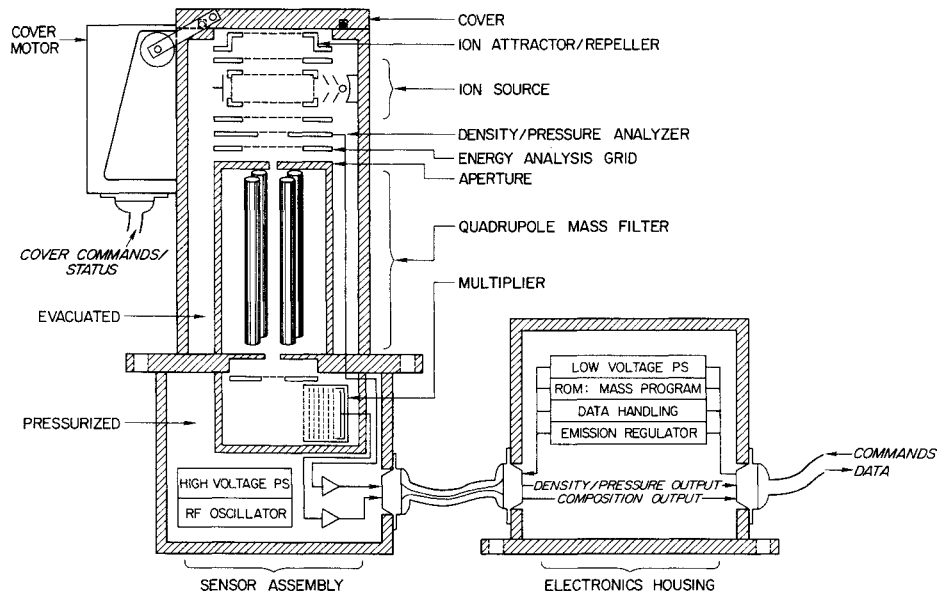
There are three mechanisms by which water molecules can enter the mass spectrometer ion source: desorption from surfaces inside the ion source, directed outgassing flux from orbiter surfaces in the field of view, and gas phase collisions which backscatter the water into the ion source. Robertson[12] has examined the contribution of self-scattering (water-water interactions) to return flux in the vicinity of a spherical vehicle. He estimates that backscattered flux is only a few percent of the total concentration. In a return flux experiment[13] performed on Atmospheric Explorer D, a known amount of neon gas was released from the satellite. Measurements of neon intensity made with a mass spectrometer showed that the return flux due to both self-scattering and ambient scattering was less than one percent of the total amount of neon. In the case of the IECM instrument on the early Shuttle flights, a large difference in water concentration was observed when the instrument was pointed in the ram direction as compared to the wake direction.[1] This particular instruments had a narrow field of view and did not observe any Shuttle surfaces. This result shows that ambient scattering is probably more important than self-scattering.

The importance of outgassing from Shuttle surfaces in the field of view of the mass spectrometer can be seen in the BNMS data. That instrument was mounted on a swivel and could be pointed either toward the forward bulkhead of the Shuttle payload bay or vertically out of the bay. In the latter position, no surfaces were in the field of view, and the total pressure was nearly a factor of 10 lower than when the bulkhead was in the field of view.[5]

The inner surfaces of the QINMS instrument itself undoubtedly contributed some water to the total gas phase number density in the ion source. However, we conclude, in agreement with Wulf and von Zahn,[5] that this is not the dominant source of water. Our observation of large water ion signals can only be accounted for if there is a substantial concentration of water outside the source.

Because both the gas phase collisions and the direct surface outgassing mechanism for transporting water into the ion source involve directed flows of material, neither can assure equilibration of the number densities inside and outside the source. The deconvolution[7,8] of these effects to give an accurate water concentration requires the use of complex scattering programs such as SPACE-2.[14] Qualitatively, however, we believe that true water vapor concentrations are underestimated if the laboratory calibration factors are applied to the Shuttle data. The QINMS instrument was mounted so that much of its field of view, even in the neutral mode, was of empty space rather than payload bay surfaces. Those surfaces that were in the field



QUADRUPOLE ION-NEUTRAL MASS SPECTROMETER

Fig. 1 Schematic diagram of the quadrupole mass spectrometer.

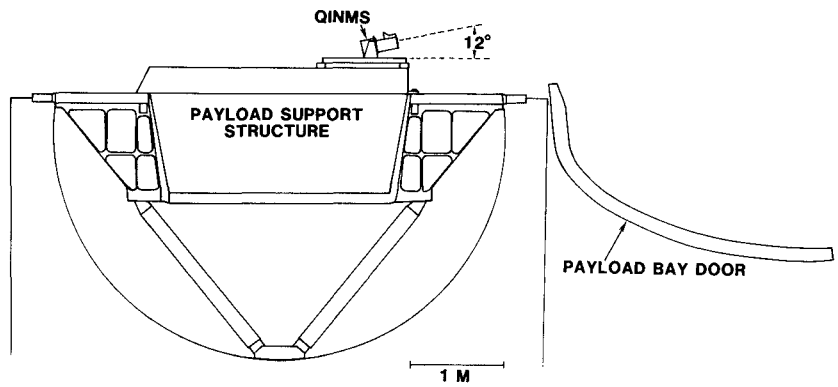


Fig. 2 Simplified sketch of the QINMS instrument payload showing the position of the sensor in the payload bay. The view is toward the front of the Shuttle; the instrument is pointed over the right wing. The payload was about three-quarters of the way back in the bay and carried several other instruments besides QINMS.

of view did contribute to the water signal. However, the outgassing flow from other surfaces to the side of and behind the instrument, out of the field of view, could not enter the mass spectrometer. These surfaces contributed to water number density in the vicinity of the mass spectrometer without increasing the measured signal. Thus, the water that entered the mass spectrometer ion source did not represent all the sources, and the water signal underestimates the total amount of water.

Uncertainties in calibration factors and sampling characteristics are perhaps the largest problems in analyzing the neutral mass spectrometer data. Narcisi[15] suggested that these uncertainties could be eliminated if species concentrations could be related to ratios of mass spectrometer signals rather than to the signals themselves. He showed that the water concentration in the vicinity of a sounding rocket is proportional to the ratio of H_2O^+ (18 amu) to O^+ (16 amu) ion signal intensities. In the following paragraphs, an expression equivalent to his is derived. However, there are a number of problems encountered when applying this method to the STS-4 QINMS data.

Water ions are formed from neutral contaminant water in the charge exchange reaction

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

O^+ is the most prevalent positive ion at Shuttle altitudes. The measured intensity of the oxygen ions, $I(O^+)$, is proportional to the total flux of oxygen ions entering the instrument. When the sensor is pointed into the velocity vector, this intensity is

$$I(O^+) = Cn(O^+)v_sA \tag{2}$$

where $n(O^+)$ is the number density of oxygen ions, v_s the velocity of the Shuttle, A the effective area of the instrument's sampling orifice, and C a calibration constant describing the sensitivity of the instrument.

For the sake of the derivation, we assume that all of the water ions detected by the mass spectrometer are formed within a well-defined sampling volume in front of the mass spectrometer entrance grid. This volume is created by the $-10V$ draw-in potential placed on the front grid of the mass spectrometer. We further assume that single collision conditions exist within the sampling volume. With these assumptions, the water ion intensity can be written

$$I(H_2O^+) = Cn(H_2O)n(O^+)\sigma v_sV \tag{3}$$

where $n(H_2O)$ is the number density of water, σ the cross section of reaction (1), and V is the sampling volume. The calibration constant, C, is taken to be the same for the water ions as for the oxygen ions.

The ratio of the water and oxygen ion intensities is the ratio of Eqs. (2) and (3).

$$\frac{I(H_2O^+)}{I(O^+)} = n(H_2O)\sigma\frac{V}{A} \tag{4}$$

To the degree that V and A are constant, the intensity ratio is proportional to the water concentration. Relative changes in the water concentration are reflected accurately by the intensity ratio.

If the draw-in field is perpendicular to the entrance grid at all points of interest (i.e., if the motion of all ions is perpendicular to the grid), then A is the actual area of the sampling orifice, and V is that area times the distance that the field extends into space, ℓ. Substituting $V = A\ell$ into Eq. (4) and rearranging gives

$$n(H_2O) = \frac{I(H_2O^+)}{I(O^+)} \cdot \frac{1}{\sigma\ell} \tag{5}$$

Equation (5) is equivalent to the expression derived by Narcisi[15] for calculating the concentration of water near mass spectrometers on sounding rockets.

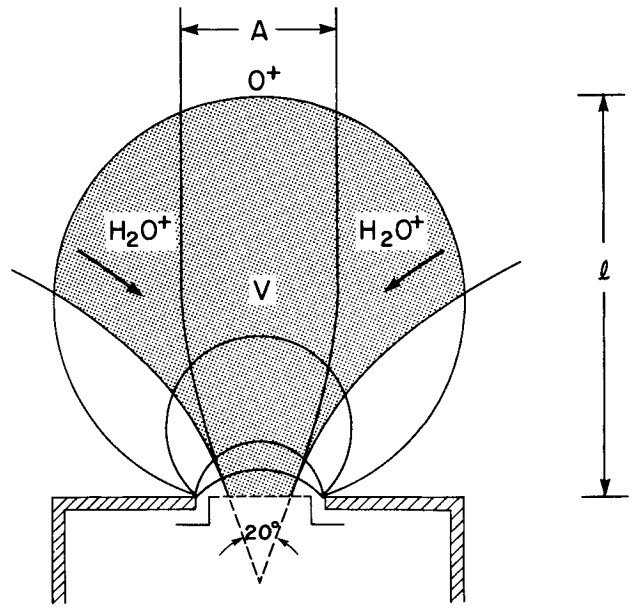


Fig. 3 Sketch of the draw-in field, showing the effective aperture for collection of O^+, A; the collection volume for H_2O^+, V; the length of the draw-in field, ℓ, and 20 deg geometric acceptance angle into the source.

The cross section for reaction (1) is well known from laboratory experiments;[16] for 5 eV oxygen ions the value is 2.6×10^{-15} cm^2. Determining the length of the sampling volume, ℓ, is more difficult. Without any plasma shielding effects, the potential due to the draw-in grid along the axis of the instrument is [17]

$$U(z)/U_o = 2/\pi \tan^{-1}(r_o/z) \tag{6}$$

where U_o is the $-10V$ potential placed on the draw-in grid and r_o, the radius of the grid, is 1.3 cm. An ion moving away from the instrument along the axis will be drawn into the instrument if $U(z)$ is greater than the ion energy. For example, Eq. (6) can be used to show that a water ion moving away with thermal energy (0.025 eV) will be drawn back toward the mass spectrometer from distances as great as 300 cm.

If there is a plasma in front of the sampling orifice, $U(z)$ falls off considerably faster than Eq. (6) predicts. Sugimura and Vogenitz[18] and Sugimura[19] have performed extensive Monte Carlo calculations of the flow of ions into a mass spectrometer mounted on a sounding rocket. Their calculated axial fields generally fall off at least a factor of three to four times faster than Eq. (6) shows. We feel reasonably confident that the length of the sampling volume along the instrument axis is between 10 and 100 cm (i.e., 30 cm within a factor of three).

Substituting $\ell = 30$ cm and $\sigma = 2.6 \times 10^{-15}$ cm^2 into Eq. (5) gives

$$n(H_2O) = \frac{I(H_2O^+)}{I(O^+)} \cdot 1.3 \times 10^{13}\ \text{cm}^{-3} \tag{7}$$

The first problem in using Eq. (7) for estimating water concentrations has to do with the actual shape of the draw-in field. The draw-in grid is 2.5 cm in diameter, a size that is probably small compared to the sampling volume. The field from such a small grid, sketched in Fig. 3, has considerable focusing properties. The effective sampling area for O^+, A, is somewhat larger than it would be in the absence of the draw-in field, but the focusing effect is probably not large because of the high kinetic energy of the incoming oxygen ions. Water ions, on the other hand, are thermal with respect to the instrument, and the draw-in field can collect ions from a much larger volume. As

shown in the figure, V is substantially larger than the product of A and ℓ. If so, Eq. (7) overestimates the number density of water within the draw-in field, because the water ions are actually being drawn from a larger volume than the equation assumes.

A second problem is that the analysis above addresses only one mechanism for transport of water ions into the mass spectrometer: collection of ions formed within the draw-in field. In analogy with the neutral mode, water ions formed outside the draw-in field volume can also enter the mass spectrometer, either by gas phase scattering or by line-of-sight motion of water molecules from the Shuttle surfaces. Neither of these mechanisms affect the flux of oxygen ions entering the instrument. Therefore, if water ions do enter the instrument by means of direct surface outgassing or by collisions, then Eq. (7) again overestimates the water content in the sampling volume, because the equation assumes that all the water ions were formed within the small sampling volume. It is not known how important this effect is.

Neutral Mode Results

The mass spectrometer was operated for 128 separate neutral mode data collection periods. These were spaced fairly evenly throughout the flight and were 5–15 min long. The instrument collected one full mass spectrum approximately every second. To reduce this large amount of data, we first omitted the data taken when the RCS engines were firing and then calculated the average intensity of each species for each data collection period. This method reduces the full set of flight data to a 128-point flight history for each species which shows how the overall species concentrations changed during the flight.

Such a flight history for neutral water vapor is shown in the top panel of Fig. 4. The horizontal scale is time measured in orbits (which were 90 min long) and the vertical scale is the intensity of the water signal measured by the mass spectrometer. The prominent features in Fig. 4 are the large peaks at orbits 5, 18, and 32 where the water intensity rises an order of magnitude above adjacent levels. In the rest of this section, temperature changes are shown to be the cause of these large features. Water dumps and attitude changes had little effect.

The times when water dumps occurred during the STS-4 flight are shown with asterisks in Fig. 4a. Supply and waste water dumps are not differentiated. The flight history of neutral water concentrations might be expected to show higher intensities during and immediately after each water dump. In fact, no correlation is apparent between the times of the water dumps and the changes in the amount of water observed by the instrument.

Because the QINMS was not a primary instrument in the STS-4 payload, we had no influence over the attitude of the Shuttle during the flight. Hence, the data in Fig. 4 were taken at many different instrument angles of attack (the angle between the centerline of the quadrupole assembly and the velocity vector). The 128 different values of water concentration in the flight history were sorted into twelve 15 deg angle-of-attack bins. An average intensity for each bin was then calculated.

The variation in water signal with angle of attack is plotted as the solid line in Fig. 5. A least-squares line drawn through these data would indicate a decrease of about a factor of 4 in water concentration between ram and wake. This change may not be significant in view of the large error bars on the data points. In any event, the small change in water intensity with angle of attack implies that the large changes in water intensity in Fig. 4 are not due to Shuttle attitude changes.

For comparison, the angle of attack variation in the neutral atomic oxygen signal at 16 amu is also plotted in Fig. 5 (dashed line). In the first 45 deg the intensity of the atomic oxygen falls off by approximately three orders of magnitude and then flattens out into a long tail that extends to 180 deg. The large signals near ram (0 deg attack angle) are due to ambient atomic oxygen. The magnitude of the smaller signals at higher

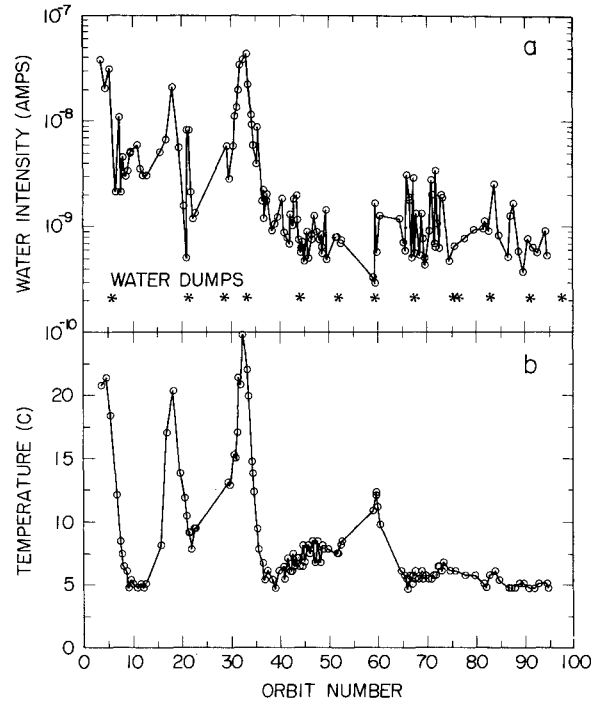


Fig. 4 Total neutral mode water intensity (a) and mass spectrometer sensor temperature (b) as a function of time (in orbits) during the STS-4 mission. The times of water dumps (both supply and waste) are marked with asterisks in the upper panel.

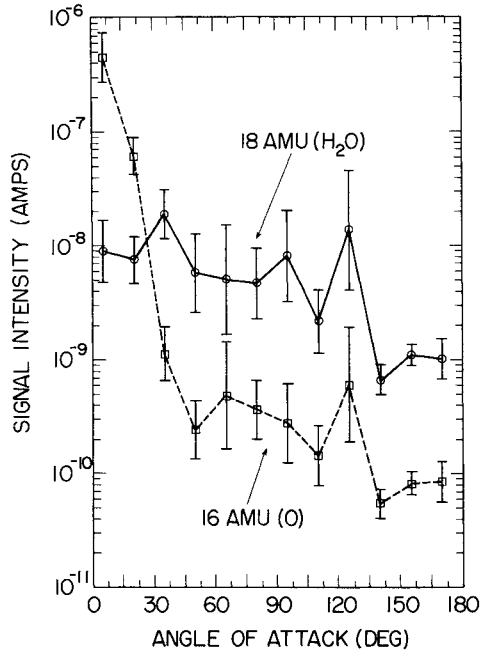


Fig. 5 Variation of the neutral water signal (18 amu, solid line) and of the neutral atomic oxygen signal (16 amu, dashed line) as a function of the instrument angle of attack (ram = 0 deg and wake = 180 deg).

attack angles is approximately 5–10% of the water signal intensity at the same angles. This signal level is consistent with production of the mass 16 species by dissociative ionization of water in the ion source.

A final factor that must be considered in analyzing the concentration of water in the vicinity of the instrument is the payload bay temperature. As Narcisi et al.[4] have shown, the variations in water intensity are well correlated with the changes in the temperature of the mass spectrometer. The average temperature of the mass spectrometer sensor for each of

the 128 data collection periods is plotted in the lower panel of Fig. 4. The three large features at orbits 5, 18, and 32 are nearly identical in shape and location to the features in the water vapor flight history. Several smaller features appear in both sets of data as well. Temperature sensors in other parts of the payload bay gave flight histories with very similar peaks, but with 100°C excursions.[4]

To summarize, there is little or no correlation between the measured water concentration and either the times of water dumps or the attitude of the Shuttle, but there is a strong correlation between water concentration and temperature. This leads us to conclude that the surface outgassing rate, which is a function of temperature, is the dominant factor controlling the amount of gaseous water in the payload bay.

Ion Mode Results

The mass spectrometer was commanded to take ion mode data on 56 occasions during the flight. Unfortunately, the instrument was in a ram attitude in only eight of these cases. Because Eq. (7) is valid only for ram data, the history of water vapor concentration changes from the ion mode data is much sparser than the neutral history.

Table 1 presents values of $I(O^+)$, $I(H_2O^+)$ and $n(H_2O)$ for the eight ram ion mode orbits. Equation (7) has been used to calculate $n(H_2O)$, which is given in both number density and pressure units. The ion intensities are the output currents of the electron multiplier in amps. Orbits 11.2, 12.2, 13.2, 27.1, and part of 24.6 were in sunlight, which accounts for the higher $I(O^+)$ values observed for those periods.

Discussion

In a quadrupole mass filter, the ions that are able to pass through the filter are selected via the amplitude of the rf and dc voltages applied to the quadrupole rods. During flight, these voltages were not scanned continuously over the whole mass range but rather were stepped from one discrete voltage to the next. The instrument only sampled the tops of the mass peaks. After the flight, these rf and dc voltages were found to have drifted slightly from their preset values. The amount of drift was an inverse function of temperature. As a result, each mass peak had shifted slightly from underneath the single measurement point selected for that mass, and measured ion intensities were lower than they should have been.

Table 1 Estimated water number densities [from Eq. (7)]

Orbit	$I(O^+)$, A	$I(H_2O^+)$, A	$n(H_2O)$, cm^{-3}	$P(H_2O)$, Torr
3.6	2(−8)[a]	2(−9)	1(12)	4(−5)
11.2	3(−7)	9(−8)	4(12)	1(−4)
12.2	3(−7)	7(−8)	3(12)	9(−5)
13.2	3(−7)	5(−8)	2(12)	6(−5)
15.7	7(−8)	7(−9)	1(12)	4(−5)
24.6	5(−7)	2(−8)	5(11)	1(−5)
27.1	1(−6)	2(−8)	3(11)	7(−6)
49.7	3(−7)	< 7(−9)	< 3(11)	< 9(−6)

[a]Read 2(−8) as 2×10^{-8}.

Table 2 Temperature correction factors for neutral water intensity

Temperature, °C	Correction factor, f
28	1.0
17	1.3
15	2.7
11.5	5.1
9.5	51
7.5	73
4.5	124
2.0	340

This temperature drift problem was reproduced in the laboratory after the flight. Its cause was eventually traced to a potting compound that had not cured properly. An extensive series of post-flight temperature calibration experiments led to correction factors for the intensity of each mass at each temperature. Because the temperature of the instrument was recorded during the flight, these correction factors were able to be applied to the flight data. The corrected current, I_c, for each mass, was taken to be

$$I_c = f(I_u - I_b) \tag{8}$$

where I_u is the uncorrected current, I_b the background current, and f the temperature correction factor. The background current for each orbit, taken to be the intensity of the 25 amu channel, was 1×10^{-10} A within a factor of 2 for the neutral mode in the entire flight and somewhat lower for the ion mode. The temperature correction factors for water are listed in Table 2. At room temperature, the instrument remained well calibrated. At lower temperatures, the measured water intensity was too low by up to two orders of magnitude.

All of the data from the flight, including the points plotted in Figs. 4 and 5 and listed in Table 1, have been corrected for the temperature drift problem. This correction does not compromise the conclusion that the temperature of the Shuttle is the dominant factor controlling the amount of water vapor. Because the correction factors are larger at low temperature, the variation in water intensity with temperature is even larger in the uncorrected data than in the corrected data of Fig. 4.

The temperature corrections do present a problem in determining the actual background level in Fig. 4. After the middle of the flight, the temperatures were usually in the 5°C range. The uncorrected water data during this period were only slightly above the background level of 1×10^{-10} A. Figure 4 shows these signals as about 1×10^{-9} A because of the very large correction factor at the low temperatures. It seems clear that after about orbit 37, the water signals were at or below the detection limit of the instrument.

In contrast, the measurements made at the temperature peaks at orbits 5, 18, and 32 were substantially above the detection limit and were subject to much smaller temperature correction factors. These are much more valid measurements.

Because of the scarcity of ion mode data, it is very difficult to make any detailed comparisons between the ion mode and neutral mode estimates of water concentration. Further, the ion mode measurements were generally taken at different times and at different orbit locations than the neutral measurements. As an example of this problem, consider the fact that the highest ion mode water estimates in Table 1 occur at orbits 11–13, whereas Fig. 4 shows a minimum in the neutral mode estimates at this time. We expect that the ion mode measurements should also have followed the temperature profile in the same way that the neutral measurements did. Unfortunately, there is insufficient ion data to demonstrate this: With one exception, there are no ion mode measurements at the temperature peaks. The one exception is orbit 3.6, which shows a high neutral mode water signal but a relatively low ion mode estimate. Orbit 3.6 was the first time the instrument was operated in orbit. The neutral mode measurements may have been artificially high because of ion source outgassing.

As was pointed out in the section on water concentration measurement techniques, the neutral mode measurements very likely underestimate the true water concentration whereas the ion mode measurements are probably overestimates. The only orbit where both ion mode and neutral mode data were taken, other than orbit 3.6, is orbit 15.7. Though this is not an ideal choice for comparison because of the low temperature (7.5°C), the data support the bracketing analysis. The neutral mode water intensity at this time was 5×10^{-9} A. This corresponds

to approximately 5×10^{-8} Torr, if the laboratory calibration factor of 10^{-1} A/Torr is used. For the same orbit, the ion mode data in Table 1 give a pressure of 4×10^{-5} Torr, a considerably higher value.

It is not possible to calculate exactly where in this range the actual water vapor concentration was. However, the pressure of 5×10^{-8} Torr calculated from the neutral mode measurements can be taken as a lower limit on the water concentration in orbit 15.7. In the same way, the ion mode estimate of 4×10^{-5} Torr can be taken as an upper limit. As shown in Fig. 4, the highest water concentrations were approximately 10 times larger than those in orbit 15.7. Therefore, we take 5×10^{-7} Torr to be the lower limit on the maximum water concentration for the whole STS-4 flight.

The data from the IECM mass spectrometer were used to derive column densities for water. For the STS-4 flight, the maximum column density was calculated to be 3.2×10^{13} cm^{-2} (Ref. 3). It is impossible to compare this column density with the present local number density (pressure) without knowing the length of the column, i.e., how far the water extends into space away from the Shuttle. On the other hand, it is possible to calculate what column length would be required to force agreement between the two measurements. Assuming a constant number density throughout the column, a pressure of 5×10^{-7} Torr corresponds to a column density of 3.2×10^{13} cm^{-2} in a distance of 18 m. This at least a plausible column length, indicating that there may be agreement between the IECM and QINMS data. The agreement may be misleading, however, because the neutral mode data underestimates the neutral number density and must be viewed as a lower limit.

Previous water measurements within the Shuttle payload bay have indicated that the amount of water decreases quite rapidly with time, dropping to instrument background levels within 10–40 h of launch.[3,7,20] The suggestion was that the sources of water were depleted in this time, i.e., that the surfaces had cleaned up. The flight history in Fig. 4 does show an overall decrease to background levels by orbit 37, in agreement with the earlier results. Interestingly, the present neutral mode data indicate that this decrease is due entirely to temperature changes and not to actual decreases in the amount of water adsorbed to the Shuttle surfaces. The effect of temperature on instrument sensitivity and on the water concentration can be eliminated by considering data from only a narrow temperature range. For example, the temperatures in orbits 4, 5, 18, and 31–33 were within one degree of 21°C, a temperature range where the instrument calibration was reliable. The measured water intensities at these times were all equal to 3×10^{-8} A within a factor of 2 and show no decrease at all. This observation is in significant disagreement with Scialdone's prediction (Ref. 20, Fig. 6) of a factor of 7 decrease in water column density over the same 30 orbit period. Similar comparisons of water intensities taken from other narrow temperature ranges also show little variation with time. Our tentative conclusion is that the quantity of water adsorbed to the Shuttle surfaces did not decrease substantially during the first half of the seven day STS-4 flight. This conclusion is not supported by the ion mode data which do show a decrease from orbits 11–13 to 49.7, and clearly must be verified in later flights.

Finally, consider the somewhat surprising result that water dumps have virtually no impact on the overall history of water concentrations. The mass spectrometer collected neutral data during a total of nine of the water dumps marked with asterisks in Fig. 4. Examination of the full set of data rather than the reduced data from each orbit (the single average intensity points plotted in Fig. 4) shows how the water concentration changed during each orbit. Narcisi et al.[4] reported an eightfold increase in water concentration during the water dump at orbit 6.7. However, the dump at orbit 6.7 is the only one where a statistically significant increase in water concentration was recorded. In three other cases, orbits 29.3, 59.9, and 67.9, very small increases in water concentration were observed, but the overall signals were essentially at the background level. There is no obvious correlation between the observed increases in water vapor during water dumps and temperature or attitude.

Other neutral mass spectrometers in the Shuttle bay have also failed to see conclusive effects of water dumps.[7] There are no definitive explanations, but several suggestions have been proposed.[7,21] According to crew members, the water leaves the dumping ports as a well-collimated stream with a half angle of perhaps 5–10 deg. Much of the water is in the form of ice crystals rather than vapor. Ambient scattering may be insufficient to redirect the flux of water back toward the payload bay. Further, the ports are located below the level of the payload bay door hinges. When the doors are open, the flux of water may bounce off the door and be directed away from the bay.

These results suggest that the increase in water observed during the dump at orbit 6.7 may have been due to a cause other than the water dump. The Shuttle had just passed into the Earth's shadow as this data was obtained, so increases in the Shuttle surface temperatures are an unlikely explanation for the water increase. However, orbit 6.7 was only the fourth time the instrument was operated in the neutral mode. Perhaps the increase in water signal was due simply to increases in ion source degassing as the source itself warmed up during the orbit.

Summary

The Air Force Geophysics Laboratory quadrupole mass spectrometer on STS-4 made water vapor measurements throughout the flight. The water concentration can be estimated from both the ion mode data and the neutral mode data. Though the two types of data show similar trends in a qualitative and general way, making detailed comparisons or calculating an absolute water concentration is very difficult. However, the two types of data appear to bracket the actual concentrations in that the ion mode data overestimates the water concentrations while the neutral mode data underestimates them. An estimated lower limit of 5×10^{-7} Torr is calculated for the water pressure at the highest water signal intensities.

There is a strong correlation between the intensity of water and the temperature of the instrument and the Shuttle bay. Increased outgassing rates of water adsorbed to Shuttle surfaces is the most likely explanation of this observation. The water density was high at the beginning of the flight and dropped to near the instrument background by mid-flight. This drop is attributed entirely to the corresponding drop in temperature. There is some evidence in the present data that the amount of water adsorbed to the Shuttle surfaces did not decrease substantially during the first half of the flight.

Water dumps appear to have essentially no effect on the water vapor measurements in the Shuttle bay. Possible explanations include scattering of water off the open payload bay doors, formation of ice crystals rather than vapor, and good collimation of the beam of water leaving the dumping port.

Postscript

The Shuttle spacecraft was rained on heavily very shortly before the launch of the STS-4 mission. The protective tiles on the Shuttle's surface had not been treated with water repellant, and absorbed a large quantity of water. This water was carried into orbit. For this reason, the STS-4 water concentration measurements reported here were probably anomalously high, and should not be regarded as typical of all Shuttle flights.

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