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Midcourse Space Experiment Contamination Measurement During Cryogen Phase

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In-orbit measurements with contamination-monitoring instruments were used to validate the Midcourse Space Experiment contamination model and to investigate the phenomenon of molecular and particle generation in space. Measurements from the first orbit contact through the first 10 months showed water vapor as the largest gaseous species, with argon gas from a venting source important only during the first week in orbit. Simple reporting tools were used for rapid assessments of the spacecraft environment during early operations. The contamination levels and the decay rate of water vapor around the spacecraft were found to be in excellent agreement with prelaunch predictions. Future measurements include validation of the model of the aging spacecraft and investigation of the degradation of thermal radiators.

Introduction

THE optical sensor performance of the Midcourse Space Experiment[1] (MSX) can be degraded when molecular films and particulates are deposited on mirrors and windows. The major source of this contamination is the spacecraft itself, although condensation of ambient gaseous species, especially at low Earth orbit, is possible at low operating temperatures such as those of the Space Infrared Imagers and Telescope III (SPIRIT III) primary mirror. Molecular self-contamination results from spacecraft materials outgassing in vacuum and is exacerbated by solar radiation. Particulate contamination can come from redistribution of particles carried from the ground or can be generated in orbit by discrete events such as door openings or by material abrasion as a result of thermal cycling or terminator crossings.

To minimize self-contamination, only low-outgassing materials were used in the fabrication of the MSX spacecraft, and a rigorous contamination control plan[2] was implemented during fabrication, testing, and launch procedures. A suite of contamination-monitoring instruments was included to identify and measure the contamination environment,[3] to measure the decay rate of molecular species such as water vapor and to identify the particle-generating mechanisms and locate their sources. The contamination experiment will serve as a functional demonstration for similar spacecraft by assessing the effectiveness of the ground contamination control plan, quantifying the long-term effects of contamination on long-life, long-wave, infrared radiation sensor performance,[4,5] and validating the preorbital contamination model[6] used to predict the contamination environment.

The overall approach of the MSX contamination experiment is to compare a prelaunch contamination model, which itself is based on the materials used and their measured outgassing rates, with the actual measured values in orbit. The model can then be modified so that results agree with in-flight measurements. More important, the instruments' performance must be calibrated carefully so that the quantities measured are accurate and can be compared with other types of measurements. For brevity, only a brief description of the monitoring instruments and their ground calibration procedures is presented.

Contamination Monitoring Instruments and Their Ground Calibrations

The MSX contamination monitoring instruments consist of a quadrupole mass spectrometer [the neutral mass spectrometer (NMS)], a cold cathode pressure gauge [the total pressure sensor (TPS)], a Bennett-type mass spectrometer [ion mass spectrometer (IMS)], a water vapor photodissociation/radiometer instrument [the krypton radiometer experiment (KRE)], a particle detector based on a pulsed xenon flashlamp [xenon flashlamp experiment (XFE)], the ultraviolet and visible imagers and spectral imagers (UVISI) wide field-of-view imager (IVW), a quartz crystal microbalance (QCM) within the cryogenically cooled SPIRIT III primary mirror [cryogenic quartz crystal microbalance (CQCM)], and four thermoelectrically controlled QCMs (TQCMs) located around the spacecraft. These instruments have been adequately described previously.[3]

The NMS and TPS were calibrated at the National Institute of Standards and Technology (NIST) with absolute pressure standards for various gases, focusing particularly on their calibration with water vapor. The characterization of the NMS in water vapor was important to the MSX program because it was expected to be the primary contaminant in the spacecraft environment.[5,6] The spacecraft itself is the primary source of the water vapor, which is adsorbed onto all blankets and exposed surfaces. The NMS was calibrated

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for water vapor by using an NIST prototype water vapor source connected to the vacuum chamber through a precision leak valve.[7] The NMS response to water vapor was essentially linear, although CO, H_2, CO_2, and CH_4 were observed. The presence of these gases was attributed to chemical reactions occurring on the filaments because their concentrations increased at a rate similar to that of water vapor during initial measurements at low pressure.[8]

The TPS flight and spare units were calibrated by measuring their responses to the known pressure changes of various calibration gases. To minimize calibration uncertainty, measurements of instrument output were made at increasing values of calibration gas pressures. This method of increasing gas pressures was used to avoid the error generated by slow desorption of gas from the walls of the calibration chamber, which occurred when pressure was decreased. The selection of calibration gases was based on the expected on-orbit environmental constituents. In addition, nitrogen was used so that orbital results could be compared with the calibration results of other flight pressure sensors. Gauges were calibrated in He, H_2O, N_2, and Ar for pressures ranging from 1×10^{-5} to 1×10^{-10} torr. These results have been published elsewhere.[9]

The expected ionospheric and contaminant species were used to identify the types of ions to be measured in the IMS spectral calibration.[10] Ionospheric species at the MSX altitude of 900 km are predominantly H^+, He^+, and O^+ based on the International Reference Ionosphere.[11] Because the contaminant ion species and flux expected in the vicinity of long-duration satellites such as MSX are unknown, the expected ion species were based on the expected dominant neutral contamination species, H_2O, and charge–exchange cross sections. Charge–exchange reactions with ionospheric O^+ are expected to lead to H_2O^+ and H_3O^+ contaminant ions.[10]

The operations and sensitivity of the cryogenic quartz crystal microbalance (CQCM) to mass deposition are well established.[12] The CQCM is expected to be commanded in orbit to perform a controlled warm-up to identify the composition of the films deposited on it. This is commonly called a thermogravimetric analysis because the mass is also measured by the crystal frequency. Thermogravimetric analysis calibration measurements were conducted on each of the flight and spare QCMs with various films, especially water.[4] The CQCM, as a surrogate for the primary mirror of SPIRIT III, is expected to slowly accumulate a water vapor film with time, which will degrade its optical performance. A calibration of the water vapor film as a function of optical scatter has been done,[13] and this calibration will be used toward the end of the MSX mission to measure the effect of water film on the observed optical performance.

The calibration of the krypton lamps and radiometer for water vapor responsivity began by measurement of the absolute vacuum ultraviolet irradiance of the krypton lamps with a cesium iodide (CsI) photodiode having an NIST-traceable calibration. The OH radiometer was calibrated for absolute radiance sensitivity with a 1000-W tungsten irradiance standard having an NIST-traceable calibration. The instrument was also fully characterized for linearity of response, dark current, field of view, temperature effects, and voltage effects. An ultraclean, all-stainless-steel, all-metal-sealed thermal vacuum chamber with cryopumps was used.[14] The dynamic range of the krypton lamps and OH radiometer spans approximately six decades. However, the H_2O calibration could be performed only over approximately two decades in the center of the dynamic range (10^9–10^{11} H_2O molecules/cm^{-3}). The calibration was extrapolated over the entire dynamic range based on independent calibrations and characterizations of the krypton lamps and radiometer. From this calibration, the instrument constant was determined with an uncertainty of $\pm 23\%$.

The xenon flashlamp and the UVISI IVW were calibrated[15] with a 1000-W tungsten irradiance standard with a NIST-traceable calibration against which its spectral irradiance is compared. Pulse-to-pulse intensity variation, temporal pulse shape variation, and temperature and voltage effects were characterized. An end-to-end performance test was conducted with the xenon flashlamp and UVISI IVW in joint operation. The test was performed in a clean room certified to class 10,000 but that typically approaches class 1000. The two instruments were bolted to a mock instrument pallet, which ensured that they would be in their relative flight geometry.[15]

Three latex spheres (50-, 14-, and 5-μm radius) were introduced into the measurement volume. The spheres were provided as a suspension in a solvent. The 5-μm sphere was introduced with a nebulizer that evaporated the solvent and essentially dispensed particles on a current of air. The larger spheres were introduced with a pipette after evaporation of the solvent in ambient air. Results of these calibration measurements are published elsewhere.[15,16]

Results During Early Flight Operations

The term *operations* was defined by MSX as the period of time between launch and the ejection of the SPIRIT III solid argon-cooled door. Because the argon cryogen was expected to have a lifetime of about 10 days, the early operations plan consisted of a series of spacecraft check-outs and instrument turn-ons for 7 days with the contamination instruments as the main local environment monitors. The contamination experiment principal investigator's team was tasked to report twice daily during this early operations phase on the state of the contamination environment, i.e., a weather report. The team then constructed several charts in response to this task for each of the relevant contamination instruments, including the levels predicted by the MSX contamination model,[6] as well as to the level where the contamination would be unacceptably high (Go/NoGo) based on the mission requirements of optical sensors.

Figure 1 shows the early operations chart for the TPS, which shows the initial pressure from the first orbit to 108-h mission elapsed time (MET). During the first 6 h, the TPS agreed almost exactly with that predicted by the MSX model.[6] After about 6-h MET, the pressure rapidly increased by about two orders of magnitude, indicating that the supercooled argon cryogen started to sublime via its vent port. Argon as the major gas species was verified by the mass spectrum obtained from the neutral mass spectrometer several hours later (Fig. 2), which showed a very large mass 40 argon peak and the normal gases as a result of water vapor and residual gases. The argon pressure was above the Go/NoGo criterion for water vapor, but because we knew that the pressure was due to argon, no change in plans was recommended to the program.

The water vapor density was plotted from the measurement of the NMS (Fig. 3), which again was in surprisingly good agreement with our MSX model[6] predictions and several orders of magnitude lower than the Go/NoGo level. The level of volatile organic

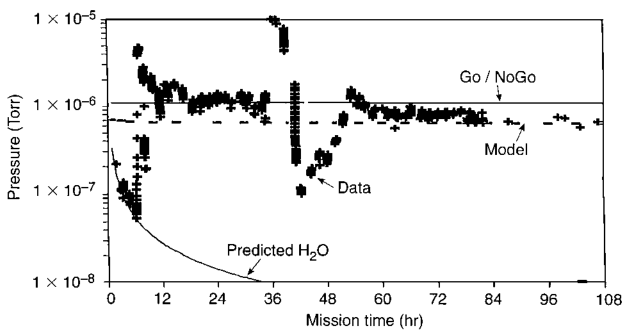


Fig. 1 Early operations chart for the total pressure sensor.

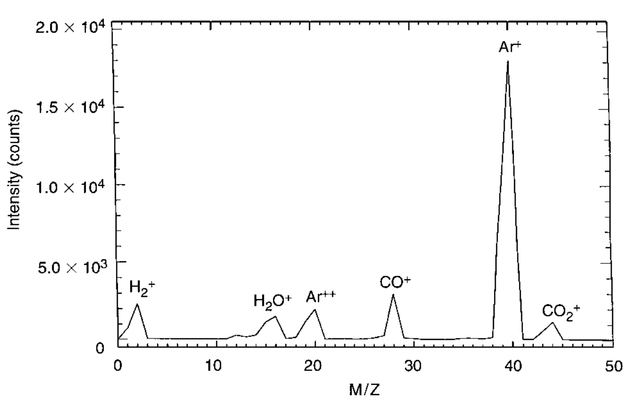


Fig. 2 Early operations mass spectrum of the atmosphere above MSX, showing a large presence of argon.

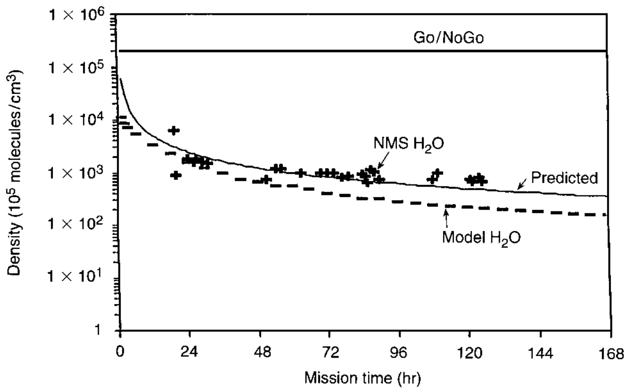


Fig. 3 Early operations water vapor measurements with the NMS.

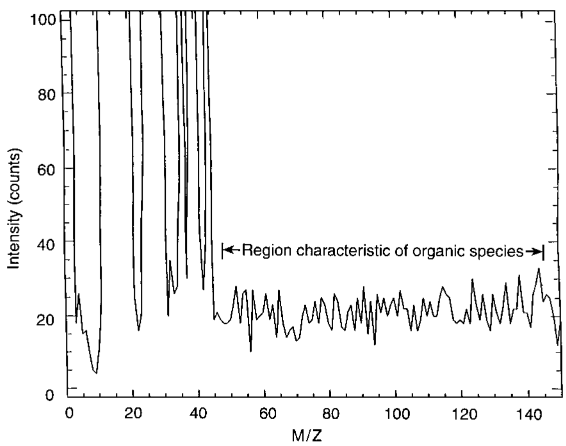


Fig. 4 Mass spectrum showing lack of higher masses above 45.

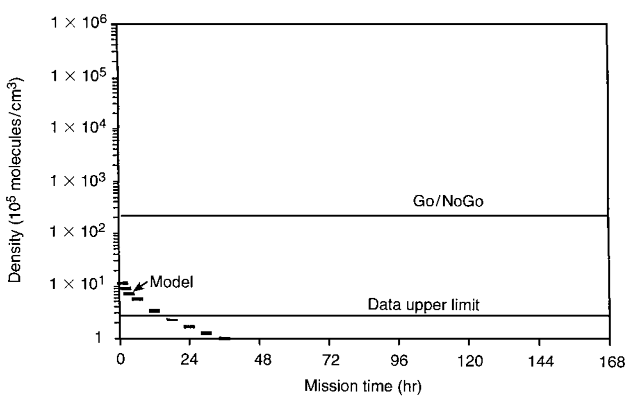


Fig. 5 Inferred total organic densities during early operations.

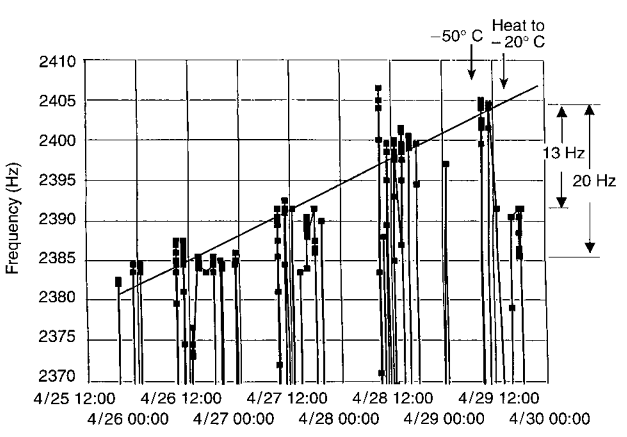


Fig. 6 TQCM 4 measurement showing decreased deposition when heated to − 20°C.

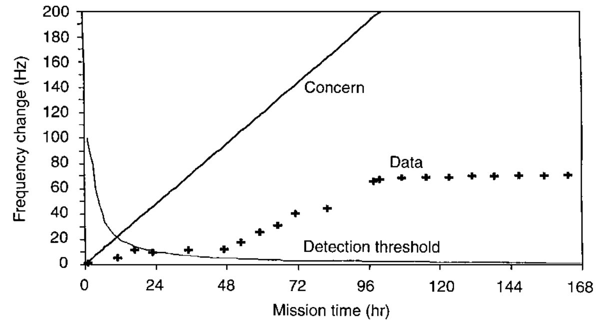


Fig. 7 Early operations accretion rate on the CQCM.

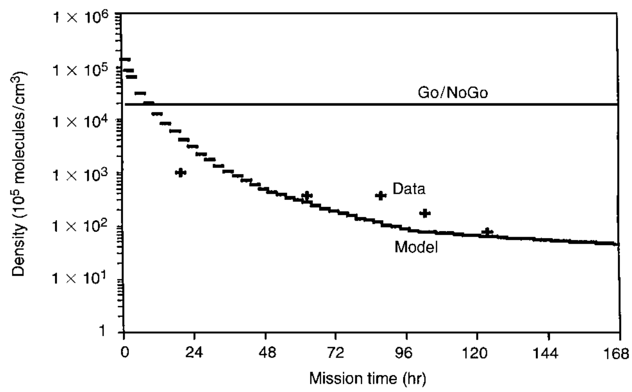
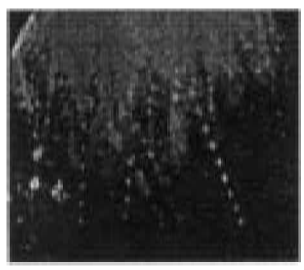
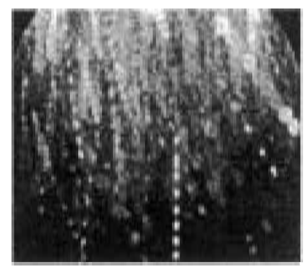


Fig. 8 Early operations measurements for water vapor by the KRE.





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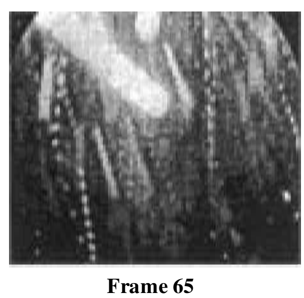

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Fig. 9 Particles measured by the XFE during the SPIRIT III door opening; particle velocities were several meters per second.

molecules (defined as the sum total of molecules with amu > 45, Fig. 4) also showed no organic contamination beyond 24-h MET, and the amount detected during the first day of orbit was not of concern to UVISI (Fig. 5). This observation was verified by the amount of deposit that was shown by the TQCM to volatilize when heated to the temperature of the UVISI (Fig. 6), when 13 out of 20 Hz was lost when the TQCM was commanded to heat up from −50 to −20°C. The TQCMs were designed to operate in orbit at −50°C.

The CQCM, mounted adjacent to the SPIRIT III primary mirror and operating at around 30 K, measured an accretion rate several times lower than that which the MSX model[6] would indicate as a concern (Fig. 7). The water density measured by the KRE similarly agreed well with the MSX model[6] prediction but was several orders of magnitude lower than the Go/NoGo level (Fig. 8).

The early operations plan called for the door of the space-based visible instrument to be opened first, then the nine UVISI doors in

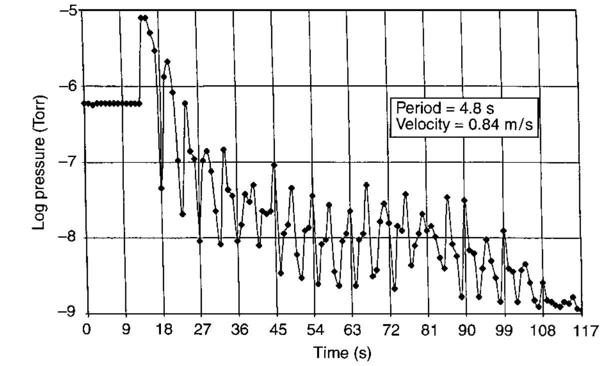

Fig. 10 Rapid pressure decay and fluctuations of the argon gas as the SPIRIT III door was ejected.

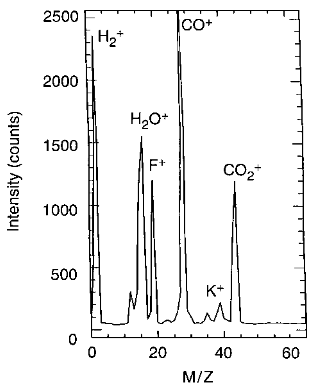

Fig. 11 Mass spectrum above MSX after SPIRIT III door ejection, showing absence of the argon peak.

groups of three, and, finally, the SPIRIT III door. The particulate generation during these door opening operations was dramatic, as shown in Fig. 9 for the SPIRIT III door opening, as measured by the XFE. Moreover, it was shown that the clearing times were on the order of 5 min and that the spacecraft was essentially quiescent during the opening of the SPIRIT III door to start the cryogen phase of MSX. During the actual SPIRIT III door opening, the TPS measured the rapid pressure decay of the argon gas as the door was tumbling away from MSX (Fig. 10). The ejection of the cover and the subsequent loss of the source of argon gas were immediately verified by the NMS, which showed no peak at mass 40 (Fig. 11).

Results During Cryogen Phase

MSX operated successfully for 10 months with the SPIRIT III telescope under solid hydrogen cooling. The contamination monitoring instruments, starting with the TPS, began collecting data after the first few orbits. Early operations results for each of these instruments have been reported previously,[8,9,14–19] and a more complete data analysis for the entire 10-month cryogen phase is being reported here. The general compilation of on-orbit results is reported here in terms of the water vapor, films, particles, and spacecraft charging as measured by MSX.

The total gas pressures measured by the TPS[8] (Fig. 12) around MSX was identified by the NMS as mostly water vapor after the SPIRIT III argon-cooled cover was deployed[8] (Fig. 11). Figure 12 shows the pressures measured by the TPS from the first day on orbit through 4000-h MET of the cryogen phase. The TPS measurements showed excellent reproducibility with respect to solar illumination, and Fig. 13 shows one data collection event (DCE), which was correlated to solar heating of surfaces on the $+X$ face of MSX. Each DCE can be characterized by the pressures induced due to solar heating. These pressure bursts have been identified positively by both the NMS and the KRE as water vapor.[17]

Although initial pressure measurements showed that the rate of water vapor was t^{-1} during the first week, the rate slowed to about $t^{-0.5}$ after the first month. It is hypothesized for MSX that surface evaporation of water films carried from the ground was substantially completed after one week in orbit; subsequent water vapor outgassing must come from the bulk or interior layer of the multilayer insulation that continually equilibrates on the outside surfaces

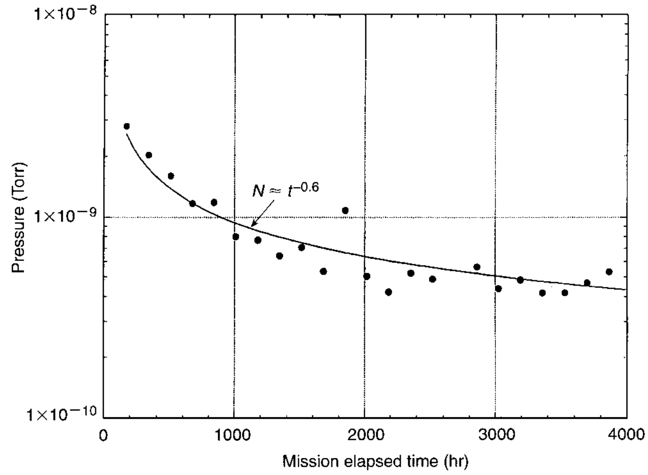

Fig. 12 Total pressures measured by TPS at 4000-h MET during the cryogen phase.

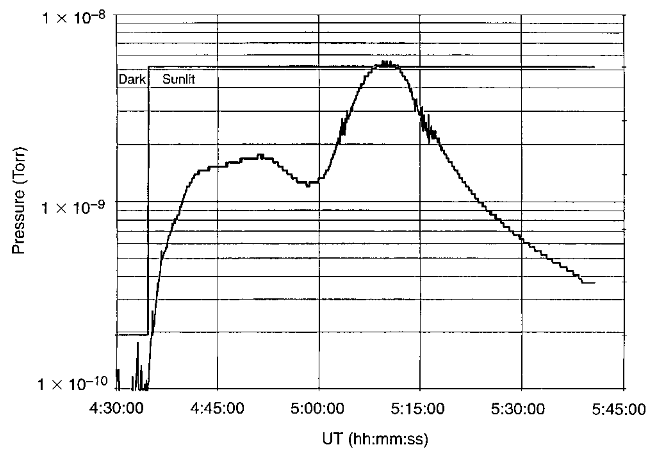

Fig. 13 Pressures induced by solar heating.

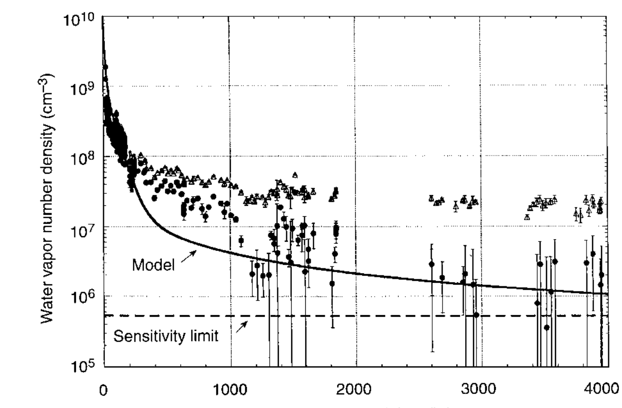

Fig. 14 Water vapor densities measured by NMS, showing large variations due to different solar illumination during each DCE.

during times when they are not solar illuminated. These were significant pressure variations, however, and were dependent on the solar illumination of the spacecraft surfaces close to the TPS. It appears that the water vapor pressure environment around spacecraft such as MSX is not static nor does it have simple monotonic decay behavior, but it is rather more variable than expected because of orbital conditions. Nevertheless, the water vapor predictions by our MSX external contamination mode[6,20] were largely accurate when averaged over time such as a week.

The NMS measured a much larger time variation for water vapor density (Fig. 14), which is also correlated to a different area being solar illuminated during spacecraft maneuvers and a different volume being observed.[18] The effect of solar illumination on the data

Table 1 Film thickness on the QCMs after 10 months

QCM	Thickness, Å	Location and direction
TQCM 1	105	$(+Y, +Z)$ solar panel
TQCM 2	132	$(+Z)$ ram
TQCM 3	8	$(+Y, -Z)$ wake
TQCM 4	55	$(+X, +Z)$ optical instrument axis
CQCM	158	(SPIRIT III) primary mirror

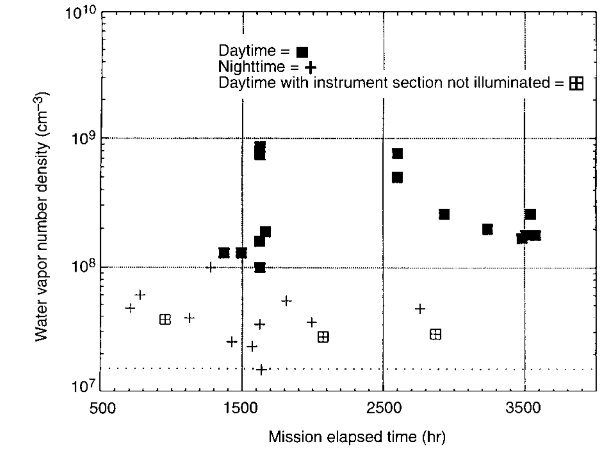

Fig. 15 Water densities measured by KRE correlated with solar illumination.

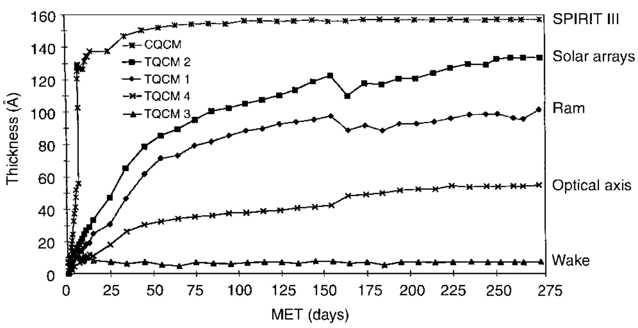

Fig. 16 Mass deposition converted to thickness (assuming density = 1.0 g/cm³) during the cryogen phase for all QCMs.

from the KRE is shown in Fig. 15, which shows that higher water vapor measurements significantly clustered around observations as the spacecraft exited the umbra.

In general, the water vapor data measured by the TPS, NMS, and KRE were mutually consistent. They initially followed the prelaunch model[6,20] prediction of $t^{-1.0}$ and were dominated by outgassing of the multilayer insulation on the $+X$ side of the spacecraft, where these instruments are mounted.

The four temperature-controlled TQCMs around the spacecraft, as well as the single CQCM mounted adjacent to the SPIRIT III primary mirror, continue to function well as expected by measuring the amount of mass deposition on their surfaces. The film thicknesses measured by each QCM after 10 months in orbit are listed in Table 1, and individual mass depositions with time are shown in Fig. 16. As seen in both Table 1 and Fig. 16, the total contaminant film depositions varied from 8, 55, 105, and 132 Å, respectively, on TQCMs 3, 4, 1, and 2. The ordered film depositions agree with prelaunch predictions,[6,19] which indicated that TQCM 3 (which was facing the wake most of the time) would have the least deposition and that TQCMs 1 and 2 would show more deposition because TQCM 1 had a direct view of the solar panels whereas TQCM 2 is oriented at the ram velocity vector most of the time. TQCM 4 is facing in the direction of the optical instruments. The CQCM, which is located next to the cryogenically cooled primary mirror inside SPIRIT III, has accumulated 158 Å of deposit since launch, but this will not have a measurable effect on the bidirectional reflectance distribution function (BRDF) because it would take close to 10,000 Å of

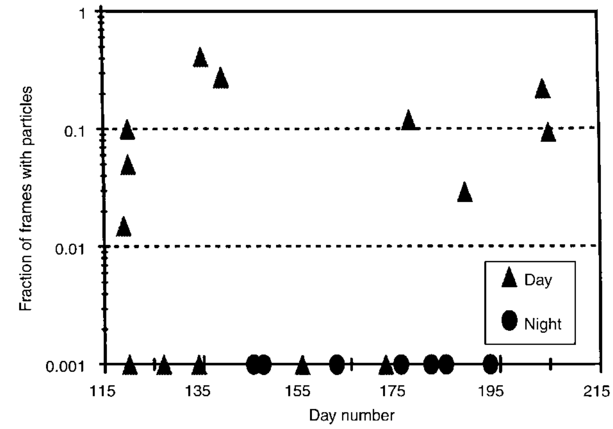

Fig. 17 Particles measured by XFE during quiescent times; each frame is a 0.5-s image from the UVISI imager.

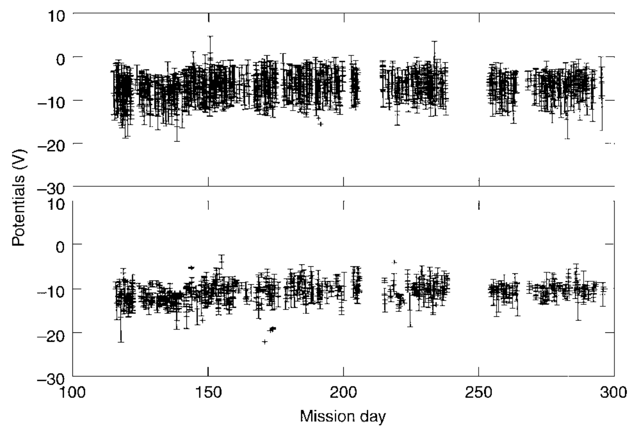

Fig. 18 Spacecraft potentials (charging + kinetic energy) measured by the IMS for H^+ (top panel) and O^+ (bottom panel).

water deposition to have a measurable effect on BRDF.[16,19] Because QCMs cannot measure mass due to particles, the optical scatter due to any particles on the SPIRIT III mirror can only be deduced from off-axis measurements in orbit. Note that most of the mass deposition on the CQCM was due to argon deposition from the argon gas vent of the SPIRIT III door when it was released.[19]

Particle measurements by the xenon flashlamp started from day 2 and have continued to the present. Particles were observed during discrete events such as door releases,[14,21] as well as during quiescent times when the spacecraft was not maneuvering. Figure 17 shows the fraction of frames of the UVISI IVW in which particles were observed during quiet times in orbit. When they are plotted with respect to whether the spacecraft was entering day from umbra (triangles) or entering umbra from day (circles), one can see that quiescent particle generation significantly favors the daylight entry from umbra. These data appear to support the hypothesis that particles are released when the spacecraft surfaces are rapidly heated by solar illumination, possibly indicating that these particles are released from weak binding forces due to thermally induced motion or even solar-induced charge neutralization. During the 10-month cryogen phase, the particle occurrence rate has been constant. Particle velocities are slow (0.1–20 cm/s), and their size distribution ranges from 0.5 to 200 μm in diameter with most of them between 10 and 20 μm (Ref. 21).

In addition to measuring the number densities of ions in orbit, the IMS also collects the spacecraft potential data by measuring the potential of the various ions entering its sampling orifice and subtracting the kinetic energy of the ions due to spacecraft velocity. The spacecraft potentials for H^+ and O^+ are shown in Fig. 18, which, when corrected for their respective kinetic energy, resulted in spacecraft charging of -6.6 ± 3.0 and -6.4 ± 1.1 V, respectively.[22] Continuous measurements of potential were between -5 and -20 V, which are consistent with the MSX contamination model.[6,20]

Comparison with Prelaunch Model Predictions

The measured on-orbit pressures and gas densities were in very good agreement with our MSX prelaunch predictions, especially the steady-state water vapor and argon pressures during early operations. The transition period of about one week from early outgassing of surface water to that expected from the slower diffusion or permeation processes was earlier than expected but is consistent with a relatively clean spacecraft. The water vapor bursts were unexpected because the model did not take into account the short-term effects of spacecraft maneuvers and the consequential solar heating. The water vapor pressures, when averaged over longer periods of time, however, agreed with the model. The film deposition on the QCMs are consistent with the model, adequately predicting the order of deposition on the TQCMs. Even though it was not possible to predict the amount of deposition in orbit on the CQCM, the rate of deposition was consistent with a very clean telescope and, in fact, was quite a diagnostic tool for the cryogenic sensor on the ground. It also aided in the interpretation of off-axis rejection data for the SPIRIT III performance assessment team.

Atmospheric Measurements

Atmospheric measurements at the 900-km altitude were also made possible by the contamination instruments. The neutral and ion density data from the ion and neutral mass spectrometers have been used to explain the discrepancy between the NASA atmospheric density model at this altitude and earlier drag measurement inferred from balloons.[23] Similarly, the TPS, NMS, and IMS were able to measure spatial variabilities of gases and ions during auroral events over the poles.[24]

Postcryogen Measurements and the Aging Spacecraft

Measurements on the local environment during the warm-up of a large cryogenic telescope have been made and will be reported in a future paper. These data will contribute to our knowledge of the contamination behavior of future cooled infrared optical systems during temperature cycles. Because future systems will require long lifetimes in orbit, MSX contamination instruments will continue to monitor the long-term generation of particles because it has been postulated that continued degradation of multilayer insulation as a result of thermal cycling during terminator crossings, uv exposure, or materials erosion will create more particles as the spacecraft ages. Continuing measurements on film deposition, coupled with temperature data from thermal radiators of the TQCMs, will allow the validation of models for passive thermal control and performance of solar arrays. Ambient pressure measurements will be correlated with the solar cycle and the exospheric variations due to seasons and auroral events.

Lessons Learned

Many lessons have been learned on MSX. First and foremost is the great advantage of including the contamination team to interact with spacecraft engineers very early in the program. The integrated team consisting of the contamination engineers with spacecraft designers and thermal engineers allowed numerous alternatives for the minimization of contamination, such as the vent locations away from the optical instruments, the separation of optical instruments from the moderately dirty electronic boxes and solar arrays, the use of nonperforated silver/Teflon® on the $+X$ side, and the approved materials procedures instituted for all hardware suppliers. The materials-list database generated from this integrated team was also used as an input into the prelaunch contamination model, which has proven to be a very good tool to explain the resulting measurements. The inclusion of contamination monitors that also doubled as quality control monitors enabled timely technical decisions to be made during integration and tests about whether to tear down and clean as well as prevent damage to optical systems because of air leaks in the vacuum systems. In this connection, the TPS and the CQCM were the two most useful instruments. The inclusion of instruments to monitor the local environment of the spacecraft also supported the program manager and system engineer during the various mission planning decisions, such as whether the hydrogen vent opened, whether it was safe enough (in the area of contamination) to open the optical sensors' doors, and, in one instance, whether a specific anomaly occurred during a reference sphere release. The clearing times of particles due to door openings have been determined to be on the order of several minutes, a period that must be factored into any rapid deployment of sensors during the terminal phase. Finally, these instruments are continuing to provide data for the long-term understanding of the contamination problems likely to be encountered for space sensors that are required to operate for several years or more. It is hoped that more lessons learned for long-term trending will be the subject of subsequent reports.

Conclusions

The MSX contamination instruments have provided valuable results to improve our understanding of how molecular and particulate contamination is generated in space sensors. They have also validated our contamination model, based on the excellent agreement between prelaunch predictions and in-orbit measurements. The validated model and its companion will help determine the level of effort for contamination control of future spacecraft and sensors. They also point to several minimum monitors necessary for diagnostics during the design, fabrication, and testing phases of the program. Finally, they have shown that they can greatly help in resolution of anomalies in orbit.

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References

[1]Mill, J. D., O'Neil, R. R., Price, S., Romick, G. J., Uy, O. M., Gaposchkin, E. M., Light, G. C., Moore, W. W., Jr., Murdock, T. L., and Stair, A. T., Jr., "Midcourse Space Experiment: Introduction to the Spacecraft, Instruments, and Scientific Objectives," *Journal of Spacecraft and Rockets*, Vol. 31, No. 5, 1994, pp. 900–907.

[2]Cranmer, J. H., Sanders, J. T., Jr., Lesho, J. C., and Uy, O. M., "Contamination Control for the Midcourse Space Experiment: An Overview," *Johns Hopkins University APL Technical Digest*, Vol. 17, No. 1, 1995, pp. 88–101.

[3]Uy, O. M., Benson, R. C., Erlandson, R. E., Boies, M. T., Lesho, J. C., Galica, G. E., Green, B. D., Wood, B. E., and Hall, D. F., "Contamination Experiments in the Midcourse Space Experiment," *Journal of Spacecraft and Rockets*, Vol. 34, No. 2, 1997, pp. 218–225.

[4]Wood, B. E., Seiber, B. L., Bertrand, W. T., and Uy, O. M., "Effects of Thin Cryo-Contaminant Films on Midcourse Space Experiment (MSX) Satellite Cryo-Optics," AIAA Paper 96-0221, Jan. 1996.

[5]Uy, O. M., "Contamination Experiments in the Midcourse Space Experiment (MSX) Satellite," *Proceedings of the SPIE*, Vol. 1754, July 1992, pp. 170–176.

[6]Silver, D. M., "Midcourse Space Experiment Early Flight Molecular Contamination Modeling Predictions," AIAA Paper 97-0839, Jan. 1997.

[7]Uy, O. M., Benson, R. C., Boies, M. T., Kinnison, J. D., Morgan, J. S., Tison, S. A., Fillipilli, A. R., and Tilford, C. R., "Use of the NIST-Developed Water Calibrator for the Midcourse Space Experiment (MSX) Mass Spectrometer," *Proceedings of the SPIE*, Vol. 2227, April 1994, pp. 316–324.

[8]Benson, R. C., Phillips, T. E., Boies, M. T., and Uy, O. M., "Neutral Mass Spectrometer Results from MSX Early Operations Phase," *Proceedings of the SPIE*, Vol. 2864, Aug. 1996, pp. 157–168.

[9]Boies, M. T., Phillips, T. E., Silver, D. M., El-Dinary, A. S., Uy, O. M., Dyer, J. S., and Mill, J. D., "Total Pressure Sensor Results from the Early Operations Phase of the MSX Mission," *Proceedings of the SPIE*, Vol. 2864, Aug. 1996, pp. 138–156.

[10]Erlandson, R. E., Boies, M. T., Uy, O. M., and Grebowsky, J. M., "The MSX Ion Mass Spectrometer: Measurement of Contaminant and Ambient Ions," *Proceedings of the SPIE*, Vol. 2261, July 1994, pp. 181–187.

[11]Bilitza, D., "International Reference Ionosphere—1990," National Space Science Data Center, NSSDC 90-22, Greenbelt, MD, Nov. 1990.

[12]Wallace, D. A., and Wallace, S. A., *Operating Manual—Mark 16*, QCM Research, Laguna Beach, CA, 1996, pp. 1–40.

[13]Bryson, R. J., Bailey, A. B., Seiber, B. L., Bertrand, W. T., Jones, J. H., and Wood, B. E., "Cryogenic Quartz Crystal Microbalance: Characterization and Calibration for Midcourse Space Experiment," *Proceedings of the SPIE*, Vol. 1754, July 1992, pp. 205–214.

[14]Galica, G. E., Green, B. D., Atkinson, J. J., Aurilio, G., Shepherd, O., Lesho, J. C., and Uy, O. M., "Flashlamp Measurement of the MSX Particulate Environment," *Proceedings of the SPIE*, Vol. 2864, Aug. 1996, pp. 169–180.

[15]Galica, G. E., Atkinson, J. J., Aurilio, G., Shepherd, O., Lesho, J. C., and Uy, O. M., "Optical Measurement of the MSX Local H_2O Density," *Proceedings of the SPIE*, Vol. 2864, Aug. 1996, pp. 181–186.

[16]Uy, O. M., Benson, R. C., Erlandson, R. E., Boies, M. T., Silver, D. M., Lesho, J. C., Galica, G. E., Green, B. D., Wood, B. E., and Hall, D. F., "MSX Contamination Instruments: Results of Gaseous and Particulate Environment versus Predictions," AIAA Paper 97-0315, Jan. 1997.

[17]Benson, R. C., Phillips, T. E., Silver, D. M., Uy, O. M., Boies, M. T., and Galica, G. E., "The MSX Local Water Vapor Environment," AIAA Paper 97-0843, Jan. 1997.

[18]Green, B. D., Galica, G. E., Mulhall, P. A., Uy, O. M., Lesho, J. C., Boies, M. T., Benson, R. C., Phillips, T. E., Silver, D. M., Erlandson, R. E., Wood, B. E., Hall, D. F., and Mill, J. D., "Local Environment Surrounding the MSX Satellite During the First Week After Launch," AIAA Paper 97-0840, Jan. 1997.

[19]Wood, B. E., Hall, D. F., Lesho, J. C., Dyer, J. S., Uy, O. M., and Bertrand, W. T., "Quartz Crystal Microbalance (QCM) Flight Measurement of Contamination on the MSX Satellite," *Proceedings of the SPIE*, Vol. 2864, Aug. 1996, pp. 187–194.

[20]Silver, D. M., Benson, R. C., Boies, M. T., Dyer, J. S., Erlandson, R. E., Galica, G. E., Green, B. D., Hall, D. F., Lesho, J. C., Phillips, T. E., Uy, O. M., and Wood, B. E., "Midcourse Space Experiment Molecular Contamination Modeling Predictions for Early Orbital Operations," *Proceedings of the 19th Space Simulations Conference*, NASA CP 3341, 1996, pp. 67–78.

[21]Galica, G. E., Green, B. D., Mulhall, P. A., Uy, O. M., Silver, D. M., and Dyer, J., "Particle Detection by Optical Systems on MSX," AIAA Paper 97-0842, Jan. 1997.

[22]Erlandson, R. E., Boies, M., Uy, O. M., Taylor, J. C., Grebowsky, J., and Coulson, J. T., "MSX Contamination Experiment Ion Mass Spectrometer Observations During Early Operations," AIAA Paper 97-0837, Jan. 1997.

[23]Keating, G. M., Leary, J. C., Uy, O. M., Benson, R. C., and Erlandson, R. E., "Atmospheric Composition Near 900 km from MSX and Drag Measurements," *EOS, Proceedings of the American Geophysical Union*, Vol. 78, No. 17, 1997 (Paper SA41B-05).

[24]Lesho, J. C., Boies, M. T., Uy, O. M., Benson, R. C., Erlandson, R. E., Silver, D. M., Green, B. D., Galica, G. E., Wood, B. E., and Hall, D. F., "Temporal Variations in the Local Pressure Environment Around the MSX Satellite," *EOS, Proceedings of the American Geophysical Union*, Vol. 78, No. 17, 1997 (Paper SA51A-14).

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