



Contamination Control for the MSX: An Overview

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The Midcourse Space Experiment is designed to demonstrate the ability to observe and track objects in space. The range of objects is wide, as is the array of onboard sensors, covering the optical spectrum from the near ultraviolet to the far infrared. Also included is an onboard contamination experiment to measure the level of pressure and particulate scattering in the satellite field of view as well as the mass spectra and mass accumulation of contamination on orbit. From the early design stage of the payload, contamination control was a factor in materials selection, design and fabrication requirements, and integration and test procedures. To achieve the required performance levels for this highly contamination-sensitive project, an integrated approach was required, taking into consideration factors such as contamination budgets, venting of thermal blankets, contaminant lines of sight, and flux modeling. The contamination control engineer was directed to design a protocol for maintaining the flight hardware at the defined cleanliness level while keeping the impact of costs and scheduling to a minimum. This article describes the protocol and its implementation prior to integration of the spacecraft with the launch vehicle.

INTRODUCTION

The Midcourse Space Experiment (MSX) onboard sensors are designed to gather data on various objects in space (satellites, sounding rockets, and intercontinental ballistic missiles) and on space backgrounds (auroras, Earth-limb, and celestial spheres). Onboard instrumentation includes the Spatial Infrared Imaging Telescope III (SPIRIT III), the ultraviolet and visible imagers and spectrographic imagers (UVISI) instrument suite, a space-based visible (SBV) instrument, a contamination experiment, and an onboard signal and data processor (OSDP) experiment. Of these components, only the last is not sensitive to contamination.

The nature of an instrument, along with its on-orbit operating temperature, gives a preliminary indication of its potential contamination sensitivity. For example, the UVISI instrument suite includes sensors for the vacuum ultraviolet wavelengths. Such instruments are much more sensitive to hydrocarbon contamination than one operating in the visible portion of the spectrum. In addition, UVISI operates at 233 to 283 K, making condensation of volatile organic species more likely than for an instrument operating at higher temperatures. Although instruments operating in the visible and infrared regions of the spectrum are not as

susceptible as vacuum ultraviolet instruments to films of condensable substances, specific wavelengths will be absorbed by film thicknesses of as little as 100 Å.

Particulate contamination is defined in terms of levels (on surfaces) and classes (for airborne particles). A class M 5.5 (10,000) clean room has an airborne particulate distribution, as described in FED-STD-209, with no more than 1 particle measuring 10,000 μm in the longest dimension per cubic foot of air. Similarly, a level 10,000 surface, as defined by MIL-STD-1246, has no more than 1 particle measuring 10,000 μm in the longest dimension per square foot of surface area. A lower class or level number indicates fewer particles of a smaller overall size range in the total particle population.

A level 100 mirror surface is desirable to achieve a bidirectional reflectance distribution function (BRDF, a measure of light scattering) of 10^{-5} per steradian at 10° off specular at visible wavelengths.¹ Allowing the mirror surface to go to level 300 increases the BRDF by an order of magnitude. Calculations based on particle size distributions per MIL-STD-1246 and typical fallout rates² predict that exposure of a vertical mirror to twenty 8-h days in a class 1000 room will result in a level 370 surface. Thus, to ensure the cleanest possible mirror, optical surfaces should only be exposed to clean-room conditions of class 100 or better. For upper-level assembly operations conducted in less stringently controlled areas, the optics of these visible and ultraviolet sensors must be protected to prevent particulate contamination from the ambient environment.

It therefore follows that the location of hardware in a clean room does not guarantee that it will never get dirty. As illustrated in the previous example, particulate fallout accumulates over time, the rate depending on the efficiency of the air filtration system and, most importantly, the level and types of activity in the clean room. Major activities involving many people or movement of large equipment will cause a much greater redistribution of fallout than will one or two people engaged in small-scale, quiet operations. This is particularly true for spacecraft integration, when some occasions legitimately require 20 or more personnel to be in the clean room at a particular time.

All external surfaces of the spacecraft were maintained at level 300 or cleaner throughout integration and test. Internal instrument surfaces, as described in what follows, are more sensitive and were protected from the external environment to the greatest extent possible. This degree of cleanliness was estimated to allow fallout from the launch fairing, cleaned to level 300, to relocate onto the spacecraft while keeping the on-orbit level to the program goal of 500.

PAYLOAD DESCRIPTION

Figure 1 shows the fully integrated MSX spacecraft during testing at the Goddard Space Flight Center

(GSFC). The payload has essentially three zones. The top portion, the instrument section, houses the sensors and a minimal amount of support electronics, thereby minimizing the heat load to the cryogenic optics. The large structure atop the spacecraft is the beacon receiver bench. The center portion comprises a structural truss section within which the large SPIRIT III solid-hydrogen dewar is mounted. Below this is the electronics section, with all of the housekeeping electronics, antennas, solar panels (shown partially deployed in Fig. 1), tape recorders, and reaction wheels. The spacecraft's structural frame measures about $1.4 \text{ m}^2 \times 4.3 \text{ m}$ tall; the sunshade and SPIRIT III door add about 1 m at the top and the stowed solar panels add 0.6 m on each of two sides of the electronics section. The weight at launch, including cryogenics, is about 6200 lb.

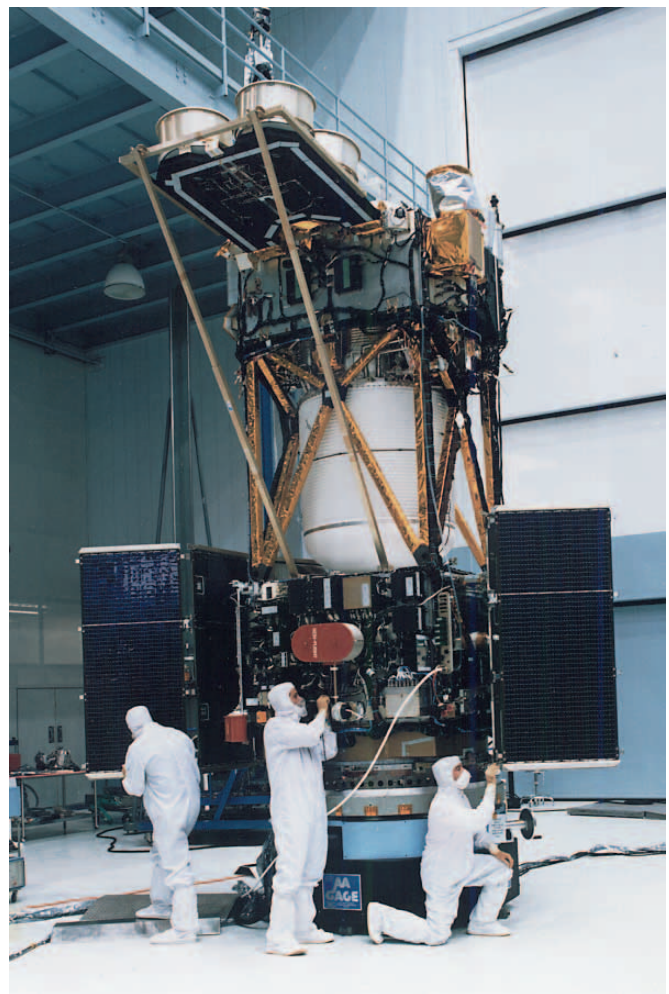


Figure 1. Fully assembled MSX spacecraft on the optical alignment table at Goddard Space Flight Center before acoustic testing. The solar panels are partially deployed, and the beacon receiver antenna bench is deployed and supported by nonflight struts. In the center of this side of the electronics section is the X-band gimbal assembly.

INSTRUMENT DESCRIPTIONS

SPIRIT III is a long-wavelength infrared instrument built by Utah State University's Space Dynamics Laboratory. It consists of a sensor system, including a solid-hydrogen cryostat and telescope, and supporting electronics. The telescope's aperture door includes a small, solid-argon-cooled dewar to prevent hydrocarbon deposition on the primary mirror and provide additional cooling at the instrument aperture. On orbit, the SPIRIT III focal plane temperature is about 10 K. During ground operations, the cryostat was cooled by liquid helium, and the door dewar was cooled with liquid argon. Inside the cryostat, next to the primary mirror, a cryogenic quartz crystal microbalance is thermally coupled to the mirror and floats at the mirror temperature, monitoring accumulation of condensed material adjacent to the primary mirror. SPIRIT III is sensitive to both hydrocarbon and particulate contamination (Table 1).

The UVISI instrument suite houses four imagers and five spectrographic imagers built by APL and Research Support Instruments, Inc., of Cockeysville, Maryland. The instruments cover wavelengths from 100 to 900 nm, and the spectrographic imager focal arrays operate at 233 to 283 K. All of the UVISI instruments are sensitive to both hydrocarbon and particulate contamination and have contamination covers and a continuous nitrogen purge in place for all ground operations. Internal optics were exposed only in class 100 conditions, and all internal components were vacuum-baked before assembly.

The SBV is a visible-wavelength telescope and supporting electronics built by Massachusetts Institute of Technology's Lincoln Laboratory. Its focal plane is cooled to 233 K during operation, is sensitive to both hydrocarbon and particulate contamination, and has an aperture cover and a continuous nitrogen purge in place for all ground operations.

Table 1. MSX contamination requirements for internal surfaces.

Instrument	Wavelength (μm)	Molecular (\AA)	Particulate
SPIRIT III			
Radiometer	6–28	<20	100
Interferometer	4–28	<20	100
Autocollimators	NA	<20	500 (external)
UVISI			
Spectrographs	0.1–0.9	<10	300
Ultraviolet imagers	0.11–0.3	<10	300
Visible imagers	0.3–0.9	<100	300
SBV telescope	0.3–0.9	<50	300
Contamination experiment			
Krypton lamp	NA	<10	300
Neutral mass spectrometer	NA	<100	300
Ion mass spectrometer	NA	<100	300
Reference objects	NA	<100	300
Solar arrays	NA	<100	500 (external)
Star camera	0.45–1.1	<100	500 (external)
Ring laser gyroscopes	NA	<100	500 (external)
Thermal control surfaces	NA	<100	500 (external)
Beacon receiver antenna bench	NA	<100	500 (external)

Note: NA = not applicable.

In addition to the SBV instrument, MIT Lincoln Laboratory provided a set of six reference objects and their launch canisters, which are mounted on the instrument section. These objects are deployed on orbit for SPIRIT III calibration. To prevent changes in the objects' optical properties, the canisters are purged with nitrogen.

The contamination experiment consists of four temperature-controlled quartz crystal microbalances (TQCMs), a cold-cathode pressure gauge, neutral and ion mass spectrometers, and krypton and xenon lamps. These components monitor the on-orbit environment of the spacecraft and are the first instruments activated after launch. They have protective covers for any critical external surfaces (e.g., the crystals of the TQCMs), and the krypton lamp cover is purged with nitrogen to prevent the generation of ozone during flash testing.

Additional components are listed in Table 1 that are not themselves sensitive to contamination degradation. They are, however, in the line of sight of other contamination-sensitive systems and must therefore be kept clean. These items include the star camera, ring laser gyroscopes, and the autocollimators, all located on the optical bench, which extends out over the top of the spacecraft (not visible in Fig. 1). In addition, the beacon receiver bench, mounted atop the instrument section, might be a source of contamination for the instruments (shown deployed in Fig. 1). Because of this geometry, these systems must be maintained at level 500 or less. To range test the antenna assembly, it was bagged using a specific material with known RF absorption properties and was kept under nitrogen purge to minimize dirt penetration into the bagging (Fig. 2).

DESIGN AND OPERATIONS

Contamination reduction must deal with both volatile materials and particulates. Volatiles can be controlled by material selection, purging, and vacuum bakeout of flight hardware. Particulates can be controlled using established clean-room procedures along with bagging, sealing, cleaning, and purging with ultra-clean gas. Contamination may also be reduced by using spare optics during integration, alignment, and system functional tests if necessary. Items used to simulate orbital operations (e.g., sensor stimulators) must be designed like flight hardware because of their long association with the hardware. It is particularly important to design these items for vacuum compatibility for use during thermal-vacuum testing.

For the launch and early flight environment, the direction of depressurization venting away from sensitive instrument apertures is controlled by the careful placement of blankets on the spacecraft. This venting concept allows the flight hardware and the inner layers of the blankets to outgas in a controlled fashion, thus

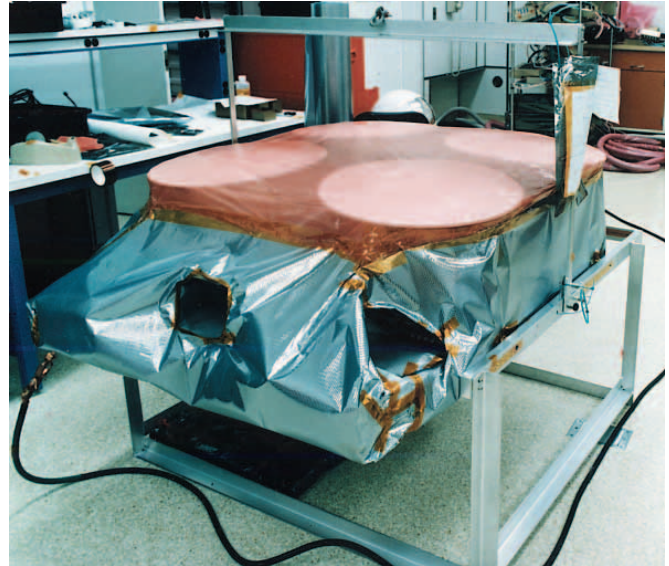


Figure 2. The beacon receiver bench is double-bagged for outdoor range testing. The two holes in the near end of the bagging allow cable connections to be made. The pink bagging on the top, a Teflon film used in composite processing, was found to cause the least interference with the bench signal response. To shield this delicate film, a protective layer of scrim-reinforced film was placed over the top of the bench whenever possible.

minimizing the contaminant flow toward the instrument apertures while minimizing particulate outflow from the blankets.

Contamination Budgets

Contamination-sensitive spacecraft and payload surfaces should have designated allowances for degradation from a pristine condition. These budgets outline the impact of contamination levels expected through launch, whether and how the levels will adversely affect mission goals, and the extent to which the levels must be reduced to attain mission goals. Modeling is then used to estimate whether the budgets will be met with a given design and process regimen. Since particle distributions cited in MIL-STD-1246 are somewhat idealized and vary from facility to facility, data should be gathered in the actual integration facility to determine real size distributions and fallout rates. Another important consideration when designing flight hardware is how to evaluate the critical surfaces after the instrument is assembled and integrated into the larger spacecraft structure.

MSX Contamination Control Specifications

The contamination control plan for the MSX program is contained in four basic documents. At the beginning of the design phase, a document outlining Phase I was released stating a general philosophy of

contamination control as it would be applied to the program.³ Guidelines for minimizing the condensable volatile and particulate contamination of critical surfaces throughout the MSX mission were established. The primary goal included listing the kinds and amounts of materials going into each spacecraft system so that a known potential for contamination could be assessed and modeled. This requirement resulted in the development of an extensive, although still incomplete, materials database. Secondary objectives of the Phase I plan were to provide for the measurement of the outgassed products and quantification of contamination rates before, during, and after the vacuum bakeout of each system so that a baseline cleanliness could be established for individual items of flight hardware and for the overall spacecraft. Finally, by controlling the method of venting from boxes and thermal blankets during liftoff, the plan outlined attempts to minimize the impact of residual contaminants on the instruments and make the modeling effort more realistic with respect to the location and configuration of contamination sources. Consequently, modeling predictions can be verified on orbit.

Phase II of the contamination control plan was designed to provide a minimum guideline for the development of fabrication, cleaning, and handling procedures for building and shipping flight and ground support hardware to APL.⁴ As such, this phase served as the basis for standardizing hardware handling procedures throughout the MSX program. Manufacturers of the various components were expected to develop their own contamination control measures tailored to the specific instrument requirements. Phase II would ensure that other flight hardware would not adversely affect the instruments. It also partially fulfilled a desire by the instrument engineers for full documentation of practices used at APL after equipment had been received for integration. In addition to the contamination control plan, a document⁵ was prepared to specify the cleaning techniques to be used by APL for all MSX flight and ground support equipment.

The requirement for thermal-vacuum bakeout of all items on the instrument section was also elucidated in Phase II. Bakeouts are defined relative to a measured base pressure for the vacuum chamber being used. The base pressure is the minimum pressure of the clean, dry, empty chamber at the bakeout temperature, which for this program was in the low 10^{-6} Torr range. When the hardware bakeout pressure levels off at a similar vacuum pressure, the bakeout is terminated. For critical components located within the line of sight of optics, more detailed instrumentation (e.g., TQCMs, residual gas analyzers) was used to identify the nature and source of outgassing species in real time and to allow the bakeout to continue until only benign species such as water vapor and nitrogen were present.

The purpose of Phase III of the MSX contamination control plan was twofold: (1) to define the processes and procedures necessary to protect the spacecraft during shipment to GSFC and Vandenberg Air Force Base and (2) to measure its cleanliness during operations at GSFC.⁶ Goddard operations included optical alignment checks, acoustic testing, thermal-vacuum testing, and the associated electrical testing required for each phase as well as transportation of MSX within the GSFC physical plant.

The Phase IV document provided the controls needed to keep the flight hardware free of particulate and molecular contaminants during the final stages of prelaunch activities, primarily during cryogen loading at the launch-site payload processing facility and electrical testing and prelaunch activities at Vandenberg.⁷

The MSX integration facility at APL was certified in March 1992, and the first item of flight hardware, the composite truss structure, was cleaned shortly thereafter. From that time until the spacecraft was double-bagged for transport to GSFC, the clean room was maintained as a limited-access controlled environment facility operating at level 10,000. This required use of full "bunny suits" in the clean room, with full-coverage overalls, hat, boots, gloves, and a surgical-type mask to minimize particulate fallout onto the flight hardware. Every item needed in the clean room—including 4 towers of scaffolding, over 100 breakout boxes, and 7 racks of electronics for UVISI system testing—was precision-cleaned before going into the integration area or adjacent test or staging areas.

Cleaning and Inspection Techniques

Each box or subsystem in a hydrocarbon-sensitive payload, including all wire harness and associated hardware, fittings, and structural components, must be subjected to a vacuum bakeout before spacecraft integration, ideally with covers removed and electronics unpowered. Following the bakeout, components must be handled with proper clean-room procedures to minimize recontamination from external sources. (Surface soils, such as fingerprints and skin oils, outgas very slowly for long periods of time and can redeposit on cooler hardware surfaces.) Thorough cleaning of the item immediately before bakeout will reduce the required time for the bakeout.

Particulate redistribution during pump-down and backfilling of the chamber can be monitored using witness plates and can also give an indication of condensation of gross volatile contamination. A scavenger plate (a large liquid-nitrogen-cooled plate in the vacuum chamber) is used to trap volatile materials. The residue on the plate can be collected and analyzed to compare the bakeout composition with that obtained for the chamber background.

If a given component has not been fabricated in a controlled environment up to the time of bakeout, this is the point after which its exposure is usually controlled. Bakeout is a significant investment in both time and dollars, and its benefits should be preserved by careful handling thereafter. Items should be kept bagged, and bags should be opened only in a controlled area (e.g., a clean room or clean bench) and handled with gloves. Bags should be noncontaminating and antistatic to protect electronics from electrostatic discharge (ESD) and should be replaced each time the item is unwrapped. When properly bagged, the parts do not require special storage conditions to maintain cleanliness. Inspection of the bag and the part when the bag is opened will reveal any failure of the seal and allow cleaning as required.

The vast majority of MSX hardware was hand cleaned. This entailed vacuuming and/or tacky mitt cleaning followed by surface wiping with clean-room-grade isopropyl alcohol on low-extractable-polyester clean-room wipers or swabs. Some items were also cleaned with a stream of ionized research-grade nitrogen. Working quantities of solvents were kept in the laminar flow workbench in well-rinsed wash bottles. All flight electronics packages were cleaned at a grounded workstation with appropriate ESD protection. All cleaning personnel were trained in both clean-room protocol and ESD avoidance.

The cleaning station was located in a clean area immediately outside a large roll-up door of the class 10,000 integration area. The area was separated from the outer class 300,000 area by a static-dissipative pink vinyl curtain. With the curtain closed and the ceiling clean air inlet vent and laminar flow clean bench operating, the area normally operated at about class 30,000. This setup allowed large items to be cleaned without excess ambient fallout and to be transferred directly into the integration area; positive air pressure in the high bay prevented any influx of contamination from the cleaning area into the high bay.

For small items (e.g., hand tools, fasteners, washers) or complex surfaces (e.g., cables), a degreaser in an adjacent area was used whenever possible. During the course of MSX integration, the degreaser solvent was changed from Freon TE to Genesolv 2005. Genesolv can be quite aggressive, damaging acrylic parts such as modular phone jacks or stripping paint from lift fixtures. However, most space-grade materials are resistant to Genesolv, and spraying the distilled solvent onto a cable to flush out material trapped under the overbraid is the most efficient cleaning method. All ground support equipment cables needed during thermal-vacuum testing were baked out before use in the clean room and covered with clean plastic tubing to minimize particulate accumulation. These cables were all recleaned at GSFC before installation in the thermal-vacuum chamber.

In addition, all parts of the UVISI were precleaned using a different degreaser charged with Freon TS before the instruments were assembled in a class 100 horizontal-flow clean room.

Spacecraft Cleaning and Ionization

The spacecraft itself was cleaned using clean-room wipers or swabs wet with isopropyl alcohol; a grounded clean-room vacuum cleaner or the built-in facility vacuum system was also used. Because of the risk of hydrocarbon contamination, only small quantities of solvent were kept in the clean room, and only approved materials were taken into the room. Some of the electronics packages on the payload were found to be extremely sensitive to ESD. Thus, extensive grounding measures were instituted to protect the packages, including the use of ionizers to prevent charge buildup on nonconductive surfaces (including the harness). The routine use of ionizers greatly reduced the accumulation of particulate contamination on these surfaces and aided in the release of any accumulated particles when the surface was vacuumed. Detailed, very-small-scale cleaning with custom, small-diameter vacuum accessories was therefore unnecessary, and the time required to clean the complete spacecraft was greatly reduced.

INSPECTION METHODS

The primary inspection method for all hardware entering the integration area was visual. Every item was examined by a trained technician after cleaning using both white light and black light. The goal for each method was lack of any visible particles or contrast in the surface finish such as smears or fingerprints.

In practice, surface anomalies (e.g., smears of potting material, adhesive droplets, or fingerprints etched into bare aluminum panels) were often present that could not be removed with any of the approved cleaning methods. This was particularly true for some of the older items of ground support equipment, which contained obsolete and untraceable materials. The contamination control engineer had to judge the potential impact of having such items in the clean room and determine which method other than routine cleaning to use. Many such items were bagged for use and removed immediately following completion of the required activity.

Visual inspection with the unaided eye will reveal particles larger than about 50 μm , leaving many smaller particles such as skin flakes invisible, regardless of the type of illumination used. Visual inspection must be used only as a qualitative measure of how thoroughly the item has been cleaned and examined. If no large particles are visible and, most importantly, no clusters

of large particles are visible, then the cleaning has covered the entire surface. Visual inspections of this type are not intended to give detailed information on the surface level of particles, but only to validate the cleaning process. When detailed quantitative information is needed, microscopic methods, either direct or by tape lift, are required.

Accuracy and speed are words used infrequently to describe particle counting on critical surfaces. Traditionally, particle counting is done by using an optical microscope at 50 \times , 100 \times , or 200 \times and measuring the longest dimension (length) of each particle.⁸ These particle lengths are tabulated and plotted on a lognormal graph. The slope of the regression of these data is used to determine the percentage of area coverage (PAC) of the inspected surface, assuming a characteristic geometry and orientation for all observed particles.² Data collection is tedious, and data manipulation is circuitous.

Another method is to use an image analyzer. This provides PAC directly; however, image analyzers often cost \$40,000 or more and provide many more features than are needed for determining particulate area coverage. A third method, described here, is to use off-the-shelf hardware and software to build an image analysis system. With this method, experimental samples are used in the selection of an appropriate sample size to accurately reflect the true PAC.

Image analyzers consist of three elements: image acquisition optics, image manipulation hardware, and image manipulation software. An interface card captures a digital image and stores it for the computer. The computer and interface card must, of course, be compatible, but the platform choice is broad. The system used at APL is the EIA-422 standard, which renders black and white digital images at the computer. Cost and computer compatibility restricted our choices to an MS-DOS or Macintosh computer; we chose a Macintosh II since its image manipulation software is a public-domain product and therefore free.

To detect particles between 5 and 250 μm in size, the surface to be examined must be magnified 200 \times . A microscope can magnify the critical surface if the object of interest can fit on the microscope stage. Image analysis is a satisfactory method for small, flat parts such as witness plates or tape samples. Resolution must be sufficiently fine to see the outline of the particle and enough features to distinguish it from the background. Our camera has a field size of 1.8×1.4 mm and a resolution of 1317×1035 pixels, so it can resolve a feature of 1.4×1.4 μm at full intensity and 5 \times magnification. A practical lower limit for the features that can be counted on this system is a major axis "dimension" of about 4 pixels, approximately equal to a 5- μm particle.

The software program employed at APL offers the user easy access to the functions of the frame-grabber

card. It acquires the image, highlights each particle, counts the pixels covered by the particle, calculates the PAC with respect to the frame in which it is found, and allows the data to be exported to a spreadsheet for data reduction. The user can also save the images in a picture file for later use. The software creates a table containing the particle number, in order of measurement, and the corresponding area in pixels. It is a simple matter to normalize the particulate area, which yields the fractional area covered by each particle. The data, expressed as PAC, are cut and pasted to a spreadsheet, where they are tabulated for a certain number of fields. By averaging all fields, an average PAC for the object evaluated is found.

Tape Lift Test Method

With the tape lift test method, about 10 cm of 3M 480 tape is placed onto the surface to be evaluated, making sure that no bubbles or creases form as the tape is applied. The tape is removed from the test surface and placed in the same manner onto a microscope slide, which has just been cleaned with isopropyl alcohol and low-lint, low nonvolatile residue wipers until visibly clean. All sample slides are taken to the laboratory, where they are soaked for about 0.5 h with clean-room-grade acetone to dissolve the tape backing. When all backing has been dissolved, the adhesive side of each slide is coated with an acrylic mounting medium, and a cover slip is bonded over the tape adhesive with its trapped particle population. This procedure provides a transparent, permanent sample for evaluation with a light-transmitting microscope.

The sample is evaluated with a 5 \times objective lens. Final magnification on the computer screen is about 170 \times ; the additional magnification results from the increase in pixel size from the camera to the computer monitor. At least 50 fields, or 100 particles, are analyzed for each tape lift. The image is captured in the computer, and the particles are highlighted. The computer then counts the pixels in each particle chosen by the operator. Dividing the particle size by the field size yields a normalized particle size, expressed as a PAC. A spreadsheet easily sums and averages the results after they are cut and pasted in.

Flight Qualification Cycle

When electrical testing of an electronics package is completed, the standard procedure at APL is to close the package, conduct a vibration test, then perform thermal-vacuum testing without opening the package again. To do so is held to invalidate the vibration test, requiring this step to be repeated. It was therefore not generally possible to use a portion of the thermal-vacuum test for a cover-off bakeout. Most packages

were not precision-cleaned until after the thermal-vacuum test. Although this procedure made package handling much simpler for the test engineers, it left something to be desired in terms of contamination control.

The effects of vibration testing on clean instruments were of great concern. The APL Vibration Test Laboratory is a nominal class 300,000 room, with no additional environmental controls in place. The shake tables are hydraulically driven with large cooling fans, presenting possible hydrocarbon and particulate contamination concerns. Early in the program, these effects were evaluated. Using a hydrocarbon sensor, the background in the Vibration Test Laboratory was evaluated and found to be below the required 15-ppm limit with the tables operating. Since the background did not change from the general background level of 5 ppm, the danger of hydrocarbon contamination from vibration testing was deemed minimal, as long as the base plate to which the package was bolted remained clean.

The particulate contamination potential, however, was significant when the table cooling blower was operating. With samples mounted vertically in a fixture on the vibration table and the sensor head of a particle counter mounted 6 in. from the bottom of the sample, no difference was seen in particle counts between a test thermal blanket and a piece of clean bagging material.⁹ Obviously, contamination-critical assemblies like the UVISI sensors had to be protected from particulate contamination during vibration testing. All UVISI instruments were double-bagged in the class 100 assembly area, leaving only the mounting feet exposed. A purge using research-grade nitrogen was connected, and the instrument was transported from the assembly area to the Vibration Test Laboratory, keeping a relative positive pressure inside the bagging to minimize penetration of contaminants into the bags.¹⁰

DESIGN AND FABRICATION OF SPACECRAFT BAGS

During processing, including transportation to Goddard and Vandenberg, the spacecraft had to be double-bagged six times, including the time of inactivity at Vandenberg. While the spacecraft was bagged, operations such as lifting for installation and removal of the shipping can, instrument purging, and SPIRIT III cryogen venting were ongoing, necessitating accommodations in the bag enclosure. The access requirements for acoustic testing were extensive, demanding unhampered deployment of antennas, covers, payload attach fitting, and the solar panels. Although instrument covers were restrained from actually opening (thus preventing contamination of the optics), a mechanic had to observe the operation of the mechanism to verify its function.

The bag design was sized from a scale drawing of the fully assembled spacecraft, and panels were sized for each of its six faces. With the exception of the acoustic test bag, each bag layer consisted of 10 precut pieces of National Metallizing, Inc., NMD-FR 190 N PA1-NN scrim-reinforced bagging material. All bag seams were taped with 2-in. Kapton (3M 1205 or equivalent). The lifting eyes at the top of the spacecraft, the tube for the purge manifold, and any necessary cables were passed through the bag, and additional bag penetrations (e.g., the cryogen vent) were made as the bag was installed.

For the acoustic test bag, all deployable items were bagged separately from the body of the spacecraft, with the latches left unbagged. Because of the time required to do this detailed, highly tailored bagging, the deployable items were single-bagged only, except for the X-band gimbal antenna. This steerable antenna was sufficiently delicate to cause fears that any hindrance or additional weight from bagging would cause too much interference in the testing. It was therefore covered with a removable flap of bagging material, which was folded back for testing and replaced at the end of each test.

Also, the testing of the spacecraft while in the acoustic test cell required the removal and reinstallation of nine stimulators, mating and demating of cables, removal of the solar panels, installation of two complete sets of pyrotechnic devices for all the deployable items, and servicing of both the telescope and door dewars of the SPIRIT III instrument. These requirements were met by a combination of prefabricated, tailored bag access ports and bag cutting as required to reach specific areas of the spacecraft. Figure 3 shows the bagged spacecraft being moved from the acoustic test cell to the thermal-vacuum test chamber; some of the many retaped areas of the bag can be seen.

THERMAL-VACUUM TESTING AND INSTRUMENTATION

Immediately before the spacecraft was lifted into the thermal-vacuum chamber (Fig. 4), the outer bag was removed and the inner bag checked to ensure that all penetrations were resealed. As soon as the spacecraft was secured in the thermal-vacuum chamber, the inner bag was removed and detailed recleaning was begun in preparation for blanket installation. During this period, all ground support equipment cabling was also being reconnected for testing. A particle counter operated continuously in the chamber; airflow through this area is such that the total particle count never exceeded that characterizing a class 1000 facility after the lid of the chamber was replaced and the clean-room-filtered airflow started. Some spikes were found in the particle counts when large cryogen hoses were being lifted

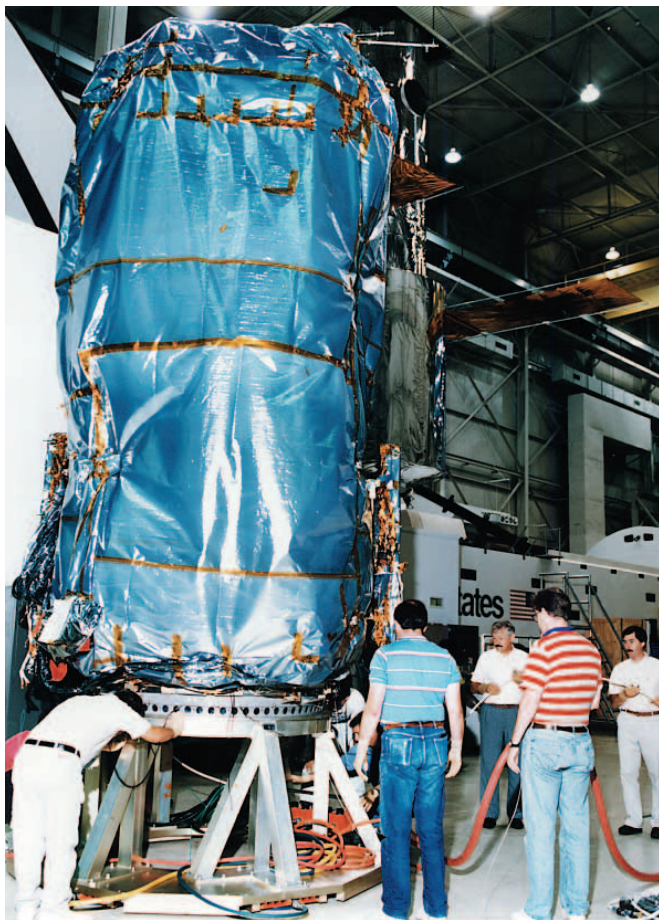


Figure 3. The MSX spacecraft during transport from the acoustic test cell to the thermal-vacuum chamber at GSFC. The straight horizontal lines of yellow tape were used in the initial assembly of the bag on the spacecraft; the L-shaped pieces mark some of the places where the bag was opened to install pyrotechnic charges for deployment testing. The spacecraft is being moved on air bearings, fed by the large orange hose. The smaller white hose (held in the background) is for the instrument purge. The two solar array booms are visible on each side of the spacecraft.

directly over the sensor head, but these quickly returned to counts in the 300 to 500 range.

The vacuum chamber, with all the MSX test shrouds and associated hardware, was baked out before the arrival of MSX to remove any contamination present in the chamber from previous operations and from new materials in the fixtures. The chamber was pumped down to a vacuum of less than 10^{-6} Torr and the test shroud heated to 80°C . TQCMs mounted on the shroud support structure were used to monitor the environment within the shroud during the bakeout. The TQCM sensors were controlled to -50°C to enhance the deposition of material onto the crystals. When the TQCM beat frequency reached 10 kHz the sensor was cleaned *in situ* by performing a thermogravimetric analysis (TGA) by heating the sensor head from -50 to $+80^{\circ}\text{C}$. The 10-kHz limit was applied to keep the TQCM sensors in their linearly sensitive region. As

the collected material increases in mass, the residue can be sticky and multilayers can cause erroneous measurements of mass deposition.

The chamber bakeout lasted 350 h. The first 80 h were spent reaching and stabilizing the temperature of the test shroud in the chamber. Figure 5 shows the TQCM change in mass deposition rate over time (dm/dt in $\text{g}/\text{cm}^2\cdot\text{h}$) for three different sensors for times from 80 to 270 h. Data were only plotted when the TQCM temperature was less than or equal to -50°C and the TQCMs were collecting contamination; the gaps in the plots indicate times when TGAs were performed. During the TGAs the frequency f and df/dt vary rapidly and the data are not useful for measuring the chamber environment. The deposition rates differ for the three TQCMs because of differences in the field of view of each sensor. The lowest rate of accumulation is for sensor #5 (pink), located at the midpoint of one long side of the shroud, looking straight across to another long side. Of the other two sensors, one (#2, black) was located at the center bottom of the shroud, looking straight up the center line, and the other (#3, green) was in the top section of the shroud, approximately 3 ft above and rotated 45° counterclockwise from #5.

A second derivative of frequency verses time was calculated to determine when the bakeout had finished. For all three sensors the d^2f/dt^2 was about -2 Hz/h/h and was approaching 0 Hz/h/h, indicative of a steadily decreasing rate of mass accumulation when the bakeout was stopped. Table 2 shows the final values of the mass deposition rate and the second derivative of frequency for the three TQCMs used for the empty chamber bakeout. Continuing the bakeout past this point will not yield a significant improvement in the environment for the flight hardware. The last 70 h of the bakeout were spent returning the chamber to ambient temperature and backfilling to ambient pressure.

These same sensors were also used during the actual thermal-vacuum test. In addition, a residual gas analyzer was mounted in the chamber wall, with no direct view of the spacecraft, to monitor cryogen gas leaks in the chamber.

The data indicate the utility of the TQCMs for measuring the vapor-phase environment in a vacuum chamber during a bakeout. They can be used as real-time diagnostic tools to determine when the chamber and any items inside the chamber in the line of sight of the sensor have reached their "clean state" and therefore when to terminate the bakeout.

SPACECRAFT TRANSPORTATION

As the program neared launch, the spacecraft had to be moved from APL to GSFC and finally to Vandenberg. A specially designed shipping container was

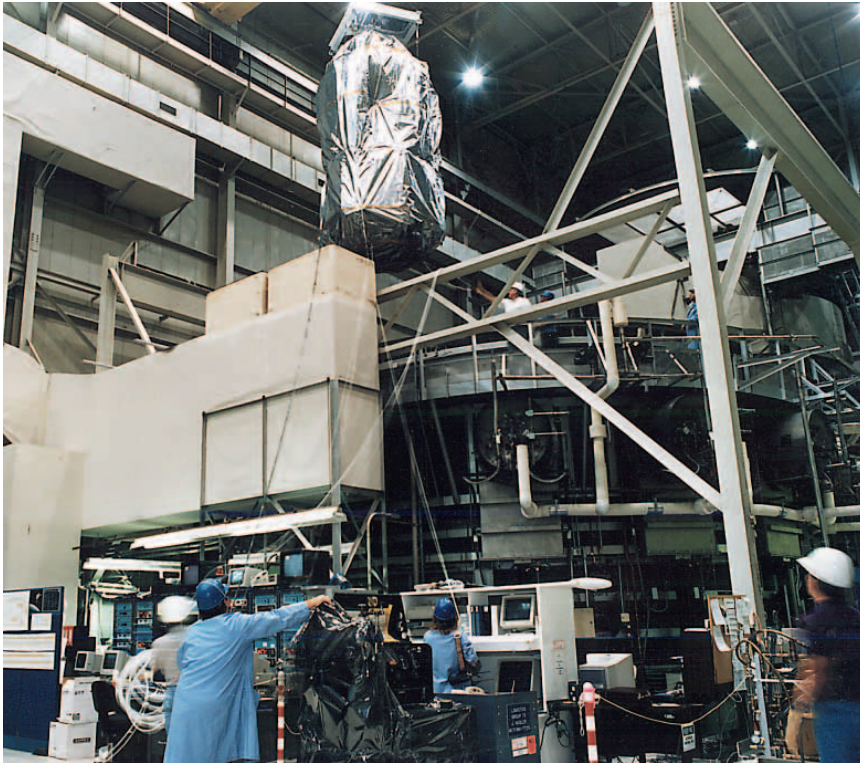


Figure 4. MSX being lifted into the thermal-vacuum chamber. The outer bag has been removed, as have the two solar array booms. Removal of the booms was necessary for clearance through the partially erected thermal test fixture inside the chamber. The large white ducts in the foreground are part of the chamber's clean air handling system.

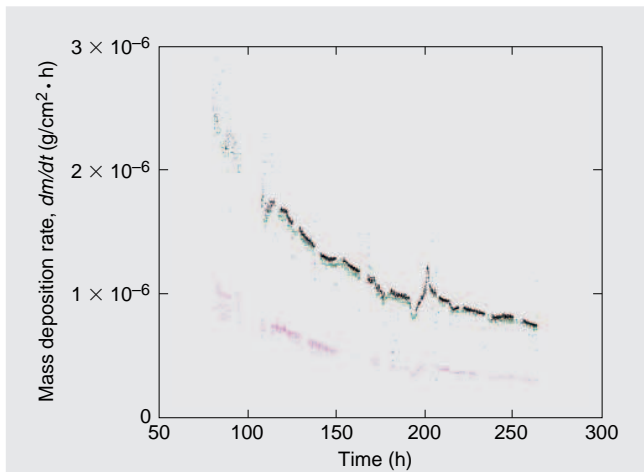


Figure 5. Plot of mass deposition rate over time for three TQCMs (sensor #2, black; sensor #3, green; sensor #5, pink) located inside the NASA Goddard vacuum chamber during chamber bakeout before installation of the MSX spacecraft for test. Each of the three instruments was mounted in the thermal test shroud, with different views of the inside of the chamber and its contents. Gaps in the data correspond to removal of accumulated mass by heating the TQCM crystal to 80°C.

built, providing protection for the spacecraft against mechanical loading, radar exposure, and contamination. Since the first canning of the spacecraft would occur inside the APL class 10,000 facility, clean-room-compatible materials were selected whenever possible. The principal exception was the chainfall mechanism used to rotate the loaded container from vertical to horizontal; this was not used in the clean room until bagging and canning were complete. Feed-throughs in the container were designed to accommodate instrument purging, cryogen outgassing, and instrument cable attachments. The seals on the container were sufficient to prevent penetration of water or road dirt during transport. Figure 6 shows the canned spacecraft being loaded into the cargo hold of the Air Force C-5 for transport to Vandenberg. The nitrogen dewars mounted on the transporter and purge line are visible.

All parts of large items like the shipping container (and the scaffolding) were power-washed with

high-pressure water and either soap or degreasing solution, wiped dry, and then vacuumed and precision-cleaned with isopropyl alcohol and clean wipers. The four sections of the container were precision-cleaned and stored in the clean room about 1 week before final packing to go to GSFC.

Following arrival at GSFC, the double-bagged spacecraft was removed from the container in an uncontrolled area, and the container was draped with

Table 2. End-of-bakeout data for a clean, dry, empty NASA Goddard space simulation chamber.

TQCM #	dm/dt ($g/cm^2 \cdot h$)	d^2f/dt^2 (Hz/h/h)
2	770×10^{-9}	-2.5
3	760×10^{-9}	-1.0
5	340×10^{-9}	-0.5



Figure 6. MSX shipping container, with the spacecraft inside, being loaded into the C-5 for flight to Vandenberg Air Force Base. The dewar at the end of the transporter cart supplies the nitrogen for the instrument purge during transport; the line is visible along the near side of the container. The dewar to the far right supplies the SPIRIT III door dewar with argon if required.

clear polyethylene bagging and stored in an uncontrolled area.

FAIRING CLEANING

The MSX 10-ft trisector fairing was gross-cleaned at Vandenberg in the high bay of NASA building 836. Each sector was moved into Laboratory 2 for final precision cleaning. Laboratory 2 is a horizontal laminar flow soft-wall clean room enclosed in a larger room of building 836. Only one sector was placed in the laboratory at a time. Particle counts inside the laboratory were below 100 particles/ft³ for the entire residence period.

The first sector was used to qualify the cleaning method for all three fairing sectors. The aft end of the sector was placed near the high-efficiency particulate air (HEPA) filter bank, and cleaning proceeded from the aft end toward the nose of the sector. The first cleaning pass was made with halogen lighting to enhance the visibility of metallic particles as well as the organic particles revealed by ultraviolet light. Each fairing sector was considered clean when no particles were visible on the surface when viewed at a distance of 12 to 18 in. A final cleaning under ultraviolet light only was subsequently performed. Cleaning was deemed to be complete when no visible particles or films remained.

The acoustic blankets for the inside of the fairing were cleaned by McDonnell Douglas technicians in

Laboratory 1, another horizontal laminar flow clean room in building 836. The blankets were wiped with isopropyl alcohol and low-linting, low nonvolatile residue wipers and inspected with ultraviolet light. All cleaning and inspection procedures were done with facility lighting turned off to enhance the effect of the ultraviolet lamps. After cleaning, the blankets were double-bagged and placed on the floor just in front of the air filter bank. Six tape lift tests on the blankets averaged 0.010 PAC, with a high reading of 0.023. These values translate to MIL-STD-1246 levels 259 and 312, respectively, well under the 0.22 PAC (level 500) allowed.

Nonvolatile residue test samples were taken from the blankets and returned to APL for evaluation. These results showed over 3 mg/ft² of residue, well above the required 1 mg/ft² maximum allowed. The

residue was analyzed and found to be a vinyl plasticizer, traceable to the polyvinyl chloride gloves used during fairing cleaning. Retesting of the first fairing sector showed less than 1 mg/ft² nonvolatile residue. The high level of residue present in the first test samples may have been due to plasticizer extraction directly from the gloves by the isopropyl alcohol into the wiper, with very little transfer to the acoustic blankets.

Following cleaning of the blankets and fairing sectors, the acoustic blankets were installed in the fairing. The blankets are held in place with Inconel wire tightly strung in a zigzag pattern across the blankets between rails in the fairing. The wiring caused a large increase in particles on the blankets, most likely from Inconel shavings from the wires. These particles were removed by recleaning the fairing. Final tape lifts showed an average of 0.033 PAC (level 336) with a maximum of 0.145 PAC (level 456), all below the desired maximum of 0.22 PAC (level 500). The cleaned fairing sectors were double-bagged and taken to the launch tower white room for storage, where they will remain until the spacecraft can be mated with the launch vehicle.

LAUNCH SITE OPERATIONS

A new payload processing facility was built by Astrotech at Vandenberg and was completed in time for MSX to be the first payload to use the facility. The facility consists of two high bays, an outer air lock, and an inner clean room. Each room is about 18 × 12 m

(2400 ft²) and contains two small low bays with roll-up doors off the clean room, a change room, and a control room. A facility certification of the Astrotech facility was performed on 18 September 1994 in accordance with FED-STD-209E. The goal certification was to a maximum class 10,000 at 5 μm , or 70 particles/ft³ larger than 5 μm . Although several locations in the clean room showed particle counts in excess of the desired maximum, the average for all data was 43 particles/ft³ at 5 μm , in accordance with certification requirements. The highest count, that taken near the air shower door, was 93 particles/ft³. In general, particle counts were highest below the air inlet and outlet registers. The range of particle counts and the location of the high reading were troublesome, resulting in further investigation.

An inspection of the HEPA filter bank showed damage to two filters; one was crushed in a 1-in² area and another in a 13-in² area. The HEPA filter manufacturer's representative inspected the filters on 22 September and discovered ripped filter media in the damaged filters. These areas were filled with room-temperature vulcanizing silicone. After curing, the air outlets into the payload processing facility were rechecked, and particle counts dropped to and remained well under the class 10,000 limits. This finding indicates that even damage to 14 in² in a filter bank of 64 ft² can severely reduce volumetric air cleanliness.

On arrival of the spacecraft at the payload processing facility, the shipping container was moved into the air lock and disassembled. The outer bag was removed and the spacecraft craned into the clean room. All required ground support equipment was partially unwrapped, inspected, and staged through the roll-up door in groups as required.

Cryogen storage dewars were processed through the south low bay, while the north low bay was used for blanket work. Helium and argon dewars were partially cleaned and bagged with reusable skirts of scrim-reinforced material to contain the gross contamination on these large tanks.

During final preparations to move the spacecraft to the launch pad, SPIRIT III experienced a cryogen system failure. The integrity of the vacuum space was lost, and the entire outer surface of the dewar tank was coated with ice. As the ice started to melt, water dripped onto the blankets on the top of the electronics section and threatened to penetrate into the electronics packages, which included tape recorders and other items. An emergency drape was slung under the cryostat to collect the water and drain it through a hose.

When it was deemed safe to resume routine operations, all the blankets were removed, inspected, and cleaned, and the electronics section was inspected for water damage. No indication that the water had penetrated the electronics section was found, and testing

confirmed proper operation of all packages. Standing water on the mounting flange of the SPIRIT III dewar may have penetrated some connectors there, and testing of this instrument was not completed. The wet blankets were dried and returned to APL for bakeout.

To remove the damaged SPIRIT III instrument, the instrument section had to be extensively disassembled. The optical bench, beacon receiver bench, and reference objects (with the top and bottom instrument section panels) were removed, cleaned, and double-bagged. Following removal of SPIRIT III, the remainder of the spacecraft was double-bagged except for the battery radiator. Since the battery was to be on a regular charge cycle during the stand-down, cooling was required on this radiator in excess of what was possible through the bag.

The final stage, i.e., moving MSX to the launch pad, mating it to the launch vehicle, and installing the launch fairing, has not occurred because of the damage to SPIRIT III. When this stage resumes, the first step in moving the spacecraft to the launch pad will be the placement of the double-bagged MSX onto the McDonnell Douglas transporter. After securing the spacecraft, precleaned container sectors are to be placed around it, and a cover will be bolted to the top. The container, covered with bagging material, will be removed from the Astrotech payload processing facility and driven to the base of the mobile service tower. The spacecraft, still inside the bagged container, will be lifted into the white room at the top of the tower and bolted to the second stage of the launch vehicle. At this point, the container will be disassembled, removed from the tower, and lowered to the ground.

Lifting and decanning operations will take place in an uncontrolled environment. Following decanning, the tower white room doors on the west wall and in the ceiling will be closed and clean-room conditions reestablished. All personnel working in the clean room must exit and dress in clean-room garments. Class 100,000 conditions are required before the spacecraft bag can be opened; however, other work, such as cleaning the facility and setting up ground support equipment, may proceed in the clean room as long as penetration of the spacecraft bagging is not required. When facility conditions have settled within the requirements for class 100,000 operation, the bag may be cut and resealed for connection of ground support equipment. The inner and outer bags will remain in place until fairing mating is initiated.

At the start of fairing mating, white room conditions must be class 10,000. Fairing installation begins with the removal of the entire outer bag and the lower portion of the inner bag, leaving a cap of bagging covering the instrument section. As each fairing trisector is unbagged, MSX contamination control personnel will

remove the section of the cap that would be under the incoming fairing sector in order to keep the SPIRIT III sunshade as clean as possible. Fallout from moving the fairing sectors could adversely affect the thermal properties of the sunshade and reduce the life of the SPIRIT III cryogenic sensors. The last cap section removed will uncover the sunshade. After the fairing sectors are in place around the spacecraft, environmental requirements will be relaxed to class 100,000 until SPIRIT III aperture door cooling operations are initiated.

The SPIRIT III aperture door will be cooled by a solid-argon ice mass, which must be recooled every 7 days to avoid cryogen loss. Cooling will occur on the tower twice during prelaunch operations. The nose cap of fairing sector 3 will be removed and replaced with a contamination control shroud made of aluminum wire ribs and bagging material scrim panels. The shroud will be attached to the SPIRIT III door cryogen servicing ports at one end and extended to the edges of the opening of the fairing at the other end. This shroud will protect the instrument section of the spacecraft from fallout from the ambient environment and personnel activities during aperture cryogen servicing until final launch preparations. Insertion and removal of the nose cap shroud will be performed in a class 10,000 environment by the MSX contamination control team.

In the event of launch delays, the mobile service tower must be rolled back over the launch vehicle, and cryogen recooling operations must be initiated. Early operations can be done inside the white room before class 100,000 is achieved by building a clean tent of bagging material around the entry points into the fairing. All personnel entering the fairing will be dressed in class 10,000 clean-room attire. Class 10,000 will be achieved before opening the sector 3 nose cap and reinstalling the nose cap shroud. If the fairing must be removed, the clean room will be class 10,000 before initiating removal.

CONCLUSION

From the space contamination science perspective, MSX is the first space mission to include a demonstration of the effectiveness of the system's contamination control plan.¹¹ Data in support of the plan's effectiveness will be measured by the onboard contamination instruments as well as by the degradation of the three major optical sensors (i.e., SPIRIT III, SBV, and UVISI).

Several unforeseen incidents occurred during the course of the contamination control program. The first was the large amount of particles trapped inside the spacecraft cable bundles, which were fabricated under a tight schedule. After visual inspection verified that the particle contamination could not be removed by vacuuming because the particles were trapped between the strands of cable and the overbraid used to bundle

the cables, a decision was made to leave them in place. Another incident, discussed earlier, was the high level of vinyl plasticizer residue found on the test wipes taken from the acoustic blankets of the spacecraft fairings. This residue was generated during cleaning procedures by the use of vinyl gloves instead of latex, which was called for in the contamination control plan. Fortunately, this contamination was high only on the test wipes, which were in direct contact with the gloves, and not on the fairing blankets when new wipes were taken using the required latex gloves.

Several incidents (e.g., crushed areas of the HEPA filters, which caused inefficient filtering of particles) were attributable to start-up pains, as MSX was the first spacecraft in the new payload processing facility. Finally, the cryogen failure and subsequent ice formation around the dewar could not have been anticipated; however, the quick response of the contamination control team minimized the impact of the incident.

In the final analysis, the effectiveness of the contamination control plan will be measured by the on-orbit sensitivities of the optical sensors while performing their scientific and tactical objectives. Among those objectives is to assess whether the contamination control plan is sufficient to prevent gaseous and particulate contaminants from being generated in quantities exceeding amounts predicted by contamination models.¹² This will be the topic of another article after MSX is launched. Until then, it is sufficient here to show that the MSX contamination control plan has been well thought out and implemented throughout the design, fabrication, testing, and integration of the spacecraft.

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