



Satellite Contamination and Materials Outgassing Knowledgebase— An Interactive Database Reference

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Prepared for Marshall Space Flight Center
under Contract NAS8-98215
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The Space Environments and Effects Program
managed at the Marshall Space Flight Center

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Space Administration

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1. INTRODUCTION

The goal of this program is to collect at one site much of the knowledge accumulated about the outgassing properties of aerospace materials based on ground testing, the effects of this outgassing observed on spacecraft in flight, and the broader contamination environment measured by instruments on-orbit. We believe that this website will help move contamination a step forward, away from anecdotal folklore toward engineering discipline. Our hope is that once Operational, this site will form a nucleus for information exchange, that users will not only take information from our knowledgebase, but also provide new information from ground testing and space missions - expanding and increasing the value of this site to all. We urge government and industry users to endorse this approach that will reduce redundant testing, reduce unnecessary delays, permit uniform comparisons, and permit informed decisions.

The Internet revolution has enabled this approach to information exchange. This site will allow the user to learn about contamination sources and concerns through reading articles prepared by experts, linking to other websites, observing graphs created to illustrate specific processes, and interactive analysis of the actual ground test and flight data. The papers, graphs, and even the entire datasets (in spreadsheet form) can be downloaded to the users home computer location. While not meant to be a tutorial on contamination, the interested spacecraft engineer will find this combination of expert knowledge and massive data sets to be an extremely valuable resource for space mission design and implementation. We have used the term "knowledgebase" to capture the unique nature and value of this site.

We have reviewed the current database to remove obvious flaws, but cannot guarantee the complete accuracy of all the data. The papers, text and figures represent a clear illustrative summary of the effects observed and conclusions reached through analysis by the responsible researchers. It is our intent that the NASA SEE Program will manage the introduction of new material to maintain that philosophy.

This website and the databases were created for and are managed by the NASA's Space Environments and Effects (SEE) Program Office located at the Marshall Space Flight Center in Huntsville, Alabama. We hope that you will find these databases useful. The databases contain information on materials outgassing, obtained using the ASTM E1559 standard, and also space flight observations of mass accumulations obtained using Quartz Crystal Microbalances (QCMs) on satellites or spacecraft. This effort began by consolidating data from QCMs that will enable one to rapidly locate previous measurements on specific materials and data from past space flight experiments. Hopefully, these databases will provide a valuable source of material outgassing information, and should be useful to those working in the Contamination area for mission design and materials specification.

Data are being accumulated from both national and international sources. To date, data using the ASTM E1559 standard have been received from OSI, Inc., NASA/GSFC, ESTEC of the European Space Agency and NASA/JSC. Data from other sources will be added as they arrive.

The space flight database includes data from past NASA missions as well as DOD (including the BMDO sponsored Midcourse Space Experiment (MSX) program), Canadian Space Agency, European Space Agency, Russian MIR space station, and eventually will include QCM data from the International Space Station.

1.1 Background

The origin of this program began during a NASA Space Environments and Effects (SEE) roadmap workshop on Neutral Contamination that was held at the Marshall Space Flight Center in Huntsville, Alabama on April 29-30, 1997. The attendees, from various locations from around the country, discussed the future subject areas that they thought would be most beneficial to the contamination community that could be funded as part of the then upcoming NASA Research Announcement NRA8-20.

At the end of the workshop, the ideas were prioritized. Two of the top three items agreed upon were to 1) establish a material outgassing database based on the ASTM E1559 test method 1 ("E 1559-93 Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials") and 2) establish a database consolidating quartz crystal microbalance (QCM) data from previous missions in space. There was general agreement by the attendees that the QCM has become the primary instrument for providing materials outgassing property data as well as for characterizing the on-orbit real time satellite environments.

A proposal combining both databases using QCMs was submitted and was accepted for funding through NASA NRA8-20. Physical Sciences, Inc. of Andover, MA was the prime contractor for this program with Sverdrup Technology, Inc., Arnold Air Force Base, TN and Johns Hopkins University/Applied Physics Laboratory, Laurel, MD being subcontractors. Personnel at these organizations have worked with the NASA/SEE Program Office to establish the two QCM databases as a resource for the aerospace community. The databases will enable one to rapidly locate previous measurements on specific materials and from past space flight experiments.

1.2 Approach

Because the goal of the functional knowledgebase was to allow researchers around the world remote access to its complete contents, having this program performed by researchers distributed around the U.S. provided a motivation for electronic communication and transfer from the start of the effort. While Physical Sciences Inc. was the prime contractor, Mr. Wood at Sverdrup Technology, Inc. was to collect and review the materials outgassing data from ground and flight, and the Applied Physics Laboratory was to create the website structure, develop the software, search engine, and populate the site. We participated in teleconferences every two weeks to review progress and assign actions throughout the program duration. Data formats and test data were transferred electronically over the Internet allowing free communication of ideas and permitting effective parallel efforts at the various locations. Relevant papers were identified, release permission obtained and formatted into .PDF format to permit accurate transfer to the development site and to ultimate users locations. Keywords were assigned to permit access by the powerful search engine.

1.3 Website Development

The Satellite Contamination and Materials Outgassing Knowledgebase was developed using the Microsoft InterDev platform to permit smooth incorporation into the SEE website. The structure was designed to: minimize processing time to the user; provide quick search and download capability; and provide easy incorporation of new datasets. The separate ground, flight datasets and bibliographic publication references are searchable by keywords that link to the actual files. The plot routines allow the user to select specific data, manipulate the plot axes and print the results at their location. All plots and files are contained in MS Excel spreadsheets and .jpg or .gif files that have compressed versions (in "zip" format) that permit rapid download. Navigation through the website is compatible with both Internet Explorer and Netscape Communicator. The user follows a menu driven response to find data within the site as described in the next section of the report. A more complete description of the development is given in Appendix A.

1.4 NASA/SEE Website Users Manual

Here are some tips that hopefully will help in navigating through the database. We have found that for best performance use either Internet Explorer 5.0 or Netscape 4.7 Internet browsers (or later versions). For full performance, access to the programs Adobe Acrobat, Excel, and WinZip (or other unzip program) is required. A part of this database is a collection of approximately 100 references that provide papers or reports that are accessed for keywords during data searches.

When the homepage for the NASA/SEE Website/Database is accessed, the 3 main options listed on the left side of the page are **E1559 Data**, **Flight Data**, and **MSX**. There are three other options listed that are the **Global Search**, **Glossary**, and **Help**. The QCM data are all found in the **E1559 Data**, **Flight Data**, and **MSX** directories.

The **E1559 Data** directory contains the data acquired using the ASTM E1559 Standard that uses QCMs to measure material outgassing parameters. Deposition measurements provide data that have been acquired during the time that the sample material inside the effusion cell is heated (usually 24 to 48 hours) and the outgassing products condense on the QCM external crystal. The thermogravimetric (or TGA) data are obtained after the deposition measurements have been completed and are acquired by warming the QCM surface to a specified temperature and recording the QCM frequencies during the time of warm-up. By plotting frequency vs. warm-up temperature, an indication of the condensed species can be ascertained from the temperatures at which the masses evaporate.

In order to get to the ASTM E1559 type data you must first select "**E1559 Data**." Clicking on **E1559 Data** brings up the subdirectories **Search** and **Contributors of Data**. For information regarding those who have provided data (and have facilities available for making these types of measurements) you should select "**Contributors of Data**." If you want to access the E1559 material outgassing data you should choose the "**Search**" option. After choosing the "**Search**" option, a list of the materials available is displayed. By scrolling down, a complete list of the materials can be seen. To choose a material or materials, click on the name(s) and then hit

the "Search" button down at the bottom of the page. The search is then executed with the results displayed below. You must scroll down the page in order to see the results. The information is organized under two columns, that are labeled "Information" and "Data". All of the listings for the material selected will be displayed. Under the "Information" column, you should see the following:

- Material
- Temperature
- Sponsor
- Specification
- Key Words

All of these words are highlighted and clicking on any of these highlighted options can access a .pdf (Portable Document Format) file. (This information is brought up using Adobe/Acrobat.) The format of information available in this .pdf file will depend on the sponsor of the data as various data formats have been used.

Under the "Data" column (right side of the listing) there are 3 or 4 options on how the data can be accessed:

- Plot
- Download
- Compress

The fourth option, in some cases, provides .gif (Graphics Interchange Format (GIF)) or .jpg (Joint Photographic Experts Group format (JPEG)) file options (highlighted in blue) that will provide data plots with different possibilities, again depending on who provided the data. For some of the data, the options may be either "Outgassing Rate vs Time" or "TML vs Time." These plots show data obtained during deposition with data from all of the QCMs operating shown. For the QCM warm-up (or TGA) data, the .gif or .jpg files are labeled "Evaporation Rate vs Time" or "Percent remaining vs Time."

If you desire other online plot options, click on "PLOT" which will enable a JAVA plot routine. A dialog box appears "Click here to graph the data" and "This button brings up a graphing utility." To graph the data, under the window menu, select the file name. After selecting to graph the data, the Grapher comes into view. You must click on the "Window" button on the toolbar. A dropdown window appears with the name of the data file that you have just selected. You must again click on the filename in the dropdown window. At this point the data is loaded into the Grapher and a "Temperature vs Time" default plot is shown for QCM number 1 in the listing. T1 and Q1 are the temperature and frequency respectively for QCM #1, etc. for QCMs 2-4. The temperatures and frequencies can be plotted as desired on both the X and Y axes.

The "Download" option allows you to download a stripped down version of the data to the screen or to disk. This data contains only time, Frequency 1, Temperature 1, Frequency 2, Temperature 2 - etc. for QCMs 1-4. Note in some cases the QCMs may be numbered 5-8. The

QCM frequency options may be labeled as either Q1 or F1, again depending on the supplier of the data.

The "Compress" option allows you to download a zipped Excel file that contains all of the data provided by that sponsor for that set of data and includes plots in the worksheets. This option provides the most information and is highly recommended. In some instances, the TGA data are contained inside this file and can be stored in individual worksheets.

The E1559 data have been accumulated since around 1993. The procedures, instrumentation, facilities, and formats of data presentation have changed during these years. Therefore, there is some variance in the way the data are presented - even from the same data provider.

Many of the materials listed in the database are from ESTEC/ESA who provided the data in a different format than that proposed in the ASTM E1559 standard but they did use QCMs in obtaining the outgassing data. By clicking on the "Material" or any of the other options under the Information Heading, you get a copy of a report authored by P. Brault and Marc van Eesbeek. It describes the system, how the data were taken, and how the data can be used to project outgassing rates at various time intervals.

In order to see the data, the "Compressed" option must be selected. The file can be downloaded either to your disk or to the screen (depending on the browser used). If the "Screen" option is selected, the Winzip Program is opened and the name of the file is displayed. By clicking on the file name, Excel is opened up and tabulated data are displayed. At the bottom of the page, various worksheets are available. Go to the worksheet at the farthest left, labeled "6.1 Name and Reference" and you will see a listing of all of the materials that have been tested using this format. Each material will have a "reference number" which can then be traced through the other worksheets to view the data. Worksheet "6.2 Test and Sample Descriptions" describes the samples and test temperatures. Worksheets 6.3 - 6.7 are labeled TML model, CVCM 1 model, CVCM 2 model, CVCM 3 model, and General result, respectively.

Flight Data

The flight QCM data have been subdivided into **Shuttle** and **Satellite** subsets. The "**Shuttle**" option provides information for NASA shuttle experiments in which QCMs were used (and data available) beginning with the use of the Induced Environment Contamination Monitor (IECM) on STS 2-4. Descriptions of these experiments are contained in the .pdf files with datasets.

The **Satellite** option includes data from several missions having longer flight times (months or years) and includes some QCM data from the Mir space station. A directory is also provided for QCM data that will eventually be available from the International Space Station (ISS). Again, the data available from each mission varies. For some missions only reports or papers are available whereas for others datasets are available for replotting if desired.

MSX

The Midcourse Space Experiment (MSX) was a BMDO sponsored satellite mission that had multiple objectives. One of those was the measurement of the contamination environment surrounding the spacecraft and also within the SPIRIT 3 cryogenic telescope. Data from the first 21 mission months in space are provided for the 5 QCM instruments on board as well as data and discussions of the other contamination measurement instruments on board such as the total pressure sensor, neutral and ion mass spectrometers, and the xenon and krypton flash lamps. As of November 1, 2000, MSX will have been in space for ~ 4.5 years. Papers summarizing the QCM, TPS, and particle measurements for the first 4 years in space are available (Refs. Wood, Boies, Galica, and Green).

The MSX information has been subdivided into the following subheadings:

- Instruments
- Films
- Gases
- Particles
- Legacy
- Executive Summary

The Instruments section provides discussions for each of the contamination instruments included on the spacecraft and includes the ion mass spectrometer (IMS), the krypton flash lamp (KRE), the neutral mass spectrometer (NMS), the QCMs, the total pressure sensor (TPS) and the xenon flash lamp (XFL). Also described is the SPIRIT 3 cryogenic telescope.

The Films section provides information on the deposited films as measured using the 5 QCMs onboard. MSX ground tests include the thermal vacuum tests performed at GSFC. The MSX Flight Data sub-directory includes discussions about the Early Operations, TQCMs, CQCMs, and the specialized set of measurements labeled SECOT that were performed at the end of the cryo-phase of Spirit 3. When accessing the Films section, the QCM data for the 21 mission months is available by scrolling down to the very bottom of the listings. The data is given individually for each mission month and can be accessed similarly to that discussed previously for the E1559 data.

The Gases section describes the composition, trends, and data observed using the TPS, NMS, IMS, and KRF instruments.

The Particle section has sub-sections describing particle distributions, occurrence, size and velocity. Data obtained using optical sensor systems are provided for spacecraft slewing, cover and door openings, and meteorite events.

The Legacy and Executive Summary section provide summaries of the accomplishments of the mission and how they can be applied to future missions.

Global Search

This provides a capability for executing a search using the keywords listed in the sections provided for the Flight data and MSX directories. The search can provide publications and data if available that meet the criteria provided for the search routine. Selections can be made from the listings for Gases, Films, Particles, Environments, Contamination, Spacecrafts, Sponsors, and Conferences in any combination desired. After requesting the search, one has to scroll down the page to see the results. Typically, only references are provided but in some cases, data sets will be referenced.

Glossary

The Glossary provides definitions and acronym interpretations.

Help

This section provides additional information on the construction of the website and requirements.

1.5 Community Involvement

Information on materials outgassing is widely distributed throughout the spacecraft community. Missions will often test materials of specific interest to their program, but not disseminate the results widely. Our major challenge was to locate and encourage members of the spacecraft contamination and test community to share these ground test and flight observational data. We created and distributed a letter (and e-mail) under NASA SEE aegis to over 200 members of the scientific community. Several significant repositories of E1559 materials outgassing information volunteered to provide data including Outgassing Services International and Lockheed (80 materials), Goddard Space Flight Center (90 materials), the European Space Agency/ESTEC (100 materials). A complete list of the contributors is given in the appropriate section of this report and in the knowledgebase site. We are very appreciative of the generosity and efforts of these researchers in sharing their data. We created a flyer for distribution at meetings to increase community awareness of this program. (This flyer is reproduced as Appendix B).

In addition, we realized that this Satellite Contamination and Materials Outgassing Knowledgebase would have value only if the community made use of its capabilities. Throughout the program, we presented descriptions of its design and capability both to increase awareness and obtain comments. Presentations were targeted to access the broad spectrum of civilian, military and international satellite community, and included:

- The International Space Station Attached Payloads External Contamination TIM in May 1999
- The SPIE Optical System Contamination: Effects, Measurements, and Control VII Workshop in July 1999
- The AIAA Space Technology Conference in September 1999 (see Appendix A)

- The AIAA 37th Aerospace Sciences Meeting in January 2000 (see Appendix C)
- The Space and Missiles Materials Symposium in March 2000
- The 8th International Symposium on Materials in a Space Environment(see Appendix D).

These presentations created a significant interest in the US and International community for access to the operational Knowledgebase. NASA SEE has established a procedure for obtaining access (login account and password) by making a request to:

Ms. Donna Hardage
 SEE Program Office
 Marshall Space Flight Center, Huntsville AL
 Telephone: 256-544-2342
 email: donna.hardage@msfc.nasa.gov

or the 2 forms can be downloaded directly from the Internet at the address:

<http://see.msfc.nasa.gov/see/databases/databases.html>

by clicking on the 1) ***SEE Server Access Form***

and ***SEE Databases Software Release Agreement Forms***

2) **Satellite Contamination and Materials Outgassing Knowledgebase** .

After we finished initial testing of the website including the complete Midcourse Space eXperiment (MSX) data set and text descriptions and a subset of the E1559 materials outgassing data in October 1999, we opened the website to review by staff at the MSX Program, NASA SEE Program, and 15 volunteer "beta testers" within the aerospace industry. We incorporated many of their comments to significantly improve the website clarity, accessibility and content.

1.6 **Transfer of the Satellite Contamination and Materials Outgassing Knowledgebase website to the NASA SEE Program Office**

To permit an early test of the website access and permit additional datasets to be incorporated into the website in its final configuration, we transferred the final test version of the knowledgebase site on CD to the NASA SEE Program Office in May 2000. This enabled us to evaluate the site from the users point of view. Bobby Wood acted as liaison during this process. NASA's SEE Program Office, Russ Cain and Manny Uy at APL and Jason Thorpe (a student formerly at APL who played a significant role in the website structure development) provided support during this process. We gratefully acknowledge the extensive assistance of Sopo Yung and Billy Kauffman of the SEE Program Office in supporting this activity and making it a success.

1.7 **Structure of this Report**

To facilitate use of the Satellite Contamination and Materials Outgassing Knowledgebase, this report follows the general structure of the website. The website format creates

self-contained units of text, figures, and data. This report can only present a tiny fraction of the materials data and plots. We can only list the reference papers available from the website. The intent is to help the user get started exploring the extensive information available. The Website Users Manual and the Help feature are also valuable aides. Finally we hope the Knowledgebase will not be a static entity. As new information is added this report will become outdated. We have endeavored to create a structure that will permit this growth to occur in a logical fashion so that the user will notice new materials and new information folders within the structure as they revisit the site many times in the future.

2. ASTM E1559 DATA

The ASTM E1559 database is being established for consolidating data obtained using the ASTM E1559 standard test method for contamination outgassing characteristics of spacecraft materials. This test method is based on a technique for characterizing the outgassing kinetics of materials used in space and space simulation laboratories. The test method is defined by the American Society for Testing and Materials (ASTM) under the jurisdiction of Committee E-21 on Space Simulation and Applications of Space Technology. The ASTM E1559 standard was developed to supplement data obtained using the ASTM E595-77/84/90 Standard - "Total Mass Loss (TML) and Collected Volatile Condensable Materials (CVCM) from Outgassing in a Vacuum Environment." The apparatus required for acquiring data using the E1559 standard is considerably more elaborate as it requires the use of multiple QCMs within a vacuum cryogenic environment. With this apparatus, temporal outgassing trends are established and the total mass outgassed is also quantified. In addition, thermogravimetric analyses (TGAs) can be performed with the QCMs to enable the identification of the individual condensed species.

This section forms the core of the database. After material is selected, by following the directions, the user can access representative plots of the temporal appearance of mass loss, download data files and even access the actual "raw" experimental data spreadsheets from a window dropdown menu.

2.1 Materials for the E1559

| | |
|--|--|
| 3m 9469 | Bisco BF 1000 sep12 |
| 47mm CFRP-CASA-PPF-Honeycomb | Black kapton |
| Ablative Mat AQ 60I | Black paint MAP S2 |
| Ablebond 7526U Epoxy | Black paint MAP S2 + phosmap 11 |
| Ablebond 83-4J feb19 | Black Russian Tissue Fabric |
| Ablebond 967-3 MAR03 | Braycote 600 |
| ABLEfilm 5020K | Braycote 601 |
| Ablefilm 5020K @100#1 jan28 | Braycote 815Z |
| Ablefilm 5020K @100#2 jan31 | Butyl Benzyl Phthalate |
| Aeroglaze-306_Black_Paint | Cetyl Alcohol |
| Alodine 1200S | Cetyl Alcohol - verification |
| Aluminium foil with black kapton bonded on both sides using FM 96U | CFC T300 |
| Aluminized Kapton mar18 | CFRP fiberite HYE 3454-2AJ |
| American Cyanamid FM24 adhesive | CFRP for XMM |
| Anodised aluminum | CFRP goldised-2000A-XMM |
| Apiezon C Oil - Degassed | CFRP HYE 3454-3H unidirectional |
| Apiezon C Oil - Not Degassed | CFRP HYE 3454-3J M55J-fiber |
| AppliTec epoxy | CFRP M60-L20-SL |
| ARALDITE HYL 5052 | CFRP M60-L20-SL + T300 |
| Aremco | CFRP M60J/L20-SL |
| AS43501-6A | CFRP with aluminised kapton on both side |
| AS43501-6B | CFRP with aluminium foil on both side |
| AS4PEEK | CFRP with aluminium foil on one side |
| AS4PPS | Chemglaze Z306 |
| Au-Kap-Acrylic-Kap-Au Laminate Film | Chemglaze Z306 Paint - flashed jul02 |
| Bacon LCA 4 | Chemglaze Z306/P123 |
| Bacon SA 1 | Cis-polyisoprene bulk material |
| Basotect | Cis-polyisoprene on glass slides |
| Basotect "pretreated" | Cohrlastic Foam |
| | Cohrlastic ope 1 |

Cohrlastic ope 2
 Cohrlastic ope 3 (125C)
 Cohrlastic ope 3 (53C)
 Cohrlastic ope 4
 Colinal 3100
 Colinal 3100
 Composite, COI K1100/954-3 #1 feb 17
 Composite, COI K1100/954-3 #2 feb25
 Composite, COI K1100/954-3 w/A276 paint feb02
 Composite, COI M55J / cyanate ester #1 jan 13
 Composite, COI M55J / cyanate ester #2 jan 20
 Composite, COI M55J / w A276 paint jan 26
 Connectors withSilicone Boot -- for accelerometer may19
 CTL 15
 Cycom 92/M40/099 GSM
 Cycom 92/M40B/108 GSM
 DC 6-1104
 DC 93-500
 DC Q9-6313
 DC704 Pump Oil jun25
 DCW assembly
 Dunmore EOR 5444
 Eccobond 285
 Electrodag 501
 Epibond 1210-A9815-10
 Epibond 1210-A9861
 Epibond 1210A dec05
 Epotek 377
 Epotek H 74
 ERIKS O-ring 714177
 FEP Teflon
 Fiberite HYE1534
 Fiberite HYE9182
 Fileca FA3901
 FM 73 U
 Foam, #WF-110, polymethacrylimide jun05
 FRSI
 FRSS FM frontshield
 FS 1265-300 CS
 Gamma Al
 Gamma Al Equil
 GORE wire GO SP 2065 SPL-10-22
 Gore-Constantan
 Goretex S4
 Graphite Epoxy
 Harness for PPF
 Heat shrink (white)
 Herberts 1002E
 Herberts 1356 H.01
 Honeycomb (alclad 2024 T81)
 Hysol Cat-L-Ink
 Hysol EA934
 Hysol EA9394
 IC 7373-12 white paint
 K1100X
 Kapton
 Kapton - metallized, with SiC coating
 Kapton - Tape - black, with acrylic adhesive
 Kapton - Tape - black, with acrylic adhesive #2 jun22
 Kapton sheet .005 in. thick
 Kapton sheet .005 in. thick, rinsed with alcohol
 Kapton Tape - black, with acrylie adhesive @30 jul01

Kapton, uncoated
 Kapton, with SiC coating
 Kapton-Acrylic
 Kapton-Constantan
 Krytox
 Laminate HYE 3454-3H, Al foil, FM 96U and black kapton
 Laminate HYE 3454-3H, Al foil, secondary bonding FM 96U
 and black kapton
 Lekutherm X227/T3 (40%)
 LMSC 1170
 Loctite 290
 MAP Aero static b
 McGhan Nusil CV1144-0
 MLI - 25 Layers apr07
 MLI - 25 layers mar24
 MLI - 5 layers nov024
 Mylar
 Mylar double aluminized
 Nusil CV-2568
 Nusil CV2943
 Nusil CV2946
 Optical Fiber Connectors
 Optical fibers (Toray)
 OSR panel using NUSIL CV-2566
 OSR panel using RTV 566
 Parylene C on Acrylic-Kapton
 Parylene C on Constantan
 Peltier for ERS2
 PLASMOCER - ceramic coating
 Polyethylene beads
 Polyimide Label
 Polyurethane Grommets
 PU 1
 Pyralux
 QCM Verification DC704
 QCM Verification TPP
 R-2560
 RAYCHEM 55/9952-24-2
 Resistor Pack, ITT - GOES feb 10
 RF Absorber
 ROHACELL 31 foam
 RSE 13329A Silicone wire insulation
 RT 555 - Shrink tubing
 RTV 566
 RTV S691
 RTV566
 RTV566 - 2
 Russian cable
 Russian MLI ####-Z#-20
 Russian Tape LT-19
 S13GLO
 S13GP LO1
 Scotch Y966 Hi-temperature acrilic
 Scotchweld, 1838 B A jun18
 Scotchweld, 1838 B A jun24
 Scotchweld, 1838 B A jun29
 Seal 34700-214 BAE 14
 Seal 34700-214-P1
 Seal S80050-7021
 Shrink Tubing, RT555
 Silicone Paint NSB 6982 on Al foil, Baked mar17
 Silicone Paint NSB 6982 on Al foil, prebaked #1 may18

Silicone Paint NSB 6982 on Al foil, prebaked #2 may21
 Silicone Paint NSB 6982 on Al foil, prebaked #3 may24
 Silicone Paint NSB 6982 on Al foil, unbaked mar 25
 Siltex Disk
 Silver Teflon #1 may03
 Silver Teflon #2 nov09
 Silver Teflon #3 nov15
 Silver Teflon #4 oct20
 Sodium Silicate
 Solithane
 Solithane 113/300
 Spark anodisation CARL ZEISS JENA
 Stearyl Alcohol nov20
 Stycast 1090
 STYCAST 1090/9
 Stycast 1266
 T700-ERL2258 Composite
 T700-EX1515 Fiber & Resin
 T700-GY6010_Hy5200 Resin
 TETKO poly.cloth
 Thermal Interfaces w/adhesives - Qpad 3 - HST #2 jul09
 Thermal Interfaces w/adhesives - Qpad 3 - HST #3 jul15
 Thermal Interfaces w/adhesives - Qpad 3 - HST aug7
 Thermal Isolator for HST
 Thermal Isolator for HST 30, 60, 80
 Tri Phenyl Phosphate #1 jun11

Tri Phenyl Phosphate #2 may12
 Tri Phenyl Phosphate #3 oct9
 UD/914
 Uralane 5750 conformal coating
 Uralane 5753 Staking Material
 Uralene 5753LV
 Urelane 5753LV
 VacKote
 Variseal static (PTFE+metal)
 Variseal-H (PTFE+metal)
 Verification w TPP
 VICOTEX SXM 18
 Visco Elastic Material
 Viton O Rings
 VK-9
 White Russian Tissue Fabric
 Wire Insulation, silicone - RSE 13329A
 Wire Insulation, silicone - RSE 13329A apr17
 Wire Insulation, silicone - RSE 13329A apr26
 Wire Insulation, silicone - RSE 13329A mar25
 WZ 3301 black paint #1
 WZ 3301 black paint #2
 X2-7725
 XMM/TT barrier
 XMM/TT barrier with bond line
 Y996 on Ag_Telfon

2.2 Example

Searching under Chemglaze Z306 the user can view several JPEG images and can see frequency and temperature versus runtime; an example is given in Figure 1. Several plots illustrating important features have been created for each material. Data from multiple sources

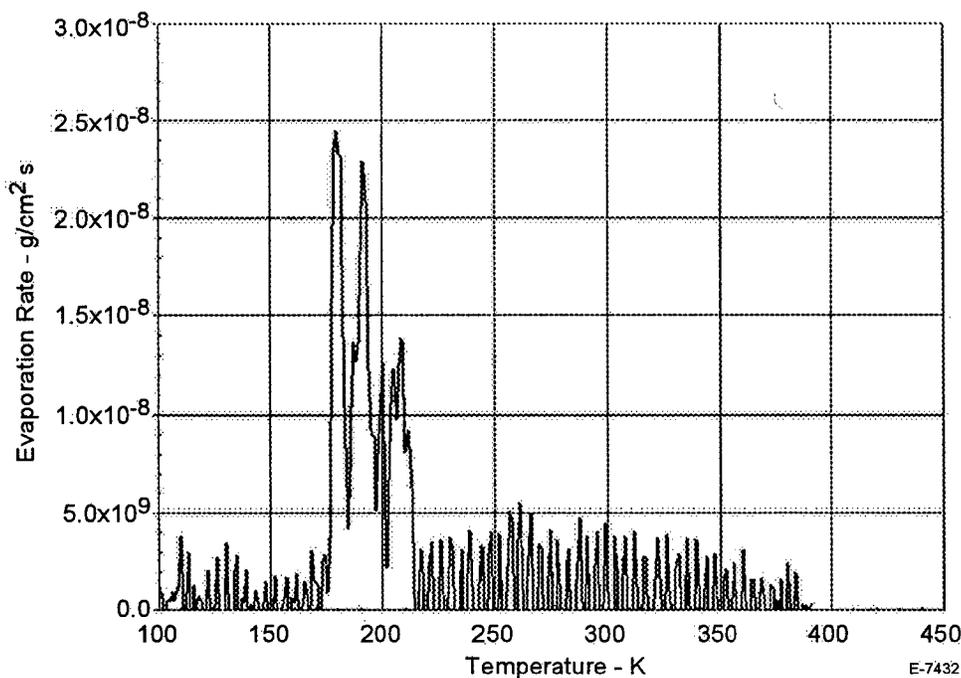


Figure 1. Chemglaze Z306 Example Evaporation Rate Plot at 125°C.

are presented as available. Site users can plot the data for themselves or within the plot select the dropdown menu under Window to interactively plot the data. Selecting the materials name brings up the test report results form for that material. Users may also download the raw uncompressed data spreadsheet to their own computer to permit detailed inspection, analysis and interpretation. After the file is unzipped, the website user will have available plots of QCM equilibration, reemission as a function of experiment time, and full spreadsheets in excess of 10,000 lines containing experiment time, temperature and frequencies. Typical spreadsheets are 5 MBytes of information once decompressed. This makes the full knowledge base on this test material available to users.

2.3 Sources for E1559 Data

The databases are the result of generous cooperation with those companies and agencies who were willing to provide us with the data that they had generated. These databases would not have been possible without the efforts of the following and we owe them a great debt of gratitude for the success of this effort:

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A Word of Caution

Please be advised that these data files were obtained from those listed above and all efforts have been made to insure that the transfer of these files to the website have been made correctly and that the data included are correct. However, there are always some experimental anomalies that can take place during testing especially in tests that run several days. These include QCM frequency shifts, temperature effects caused by LN2 fills, etc. Therefore, the data contained here undoubtedly contain some of these anomalies and so the user should be advised to scrutinize the data before use. In this manner, the data should be looked upon as providing added value for the user.

3. SEE FLIGHT DATA

3.1 Short Duration Missions

There are several data sets of measured accretion during orbital missions of ~ 1 week duration. Although outgassing has the highest magnitude upon initial exposure to the near-vacuum on-orbit, offgassing is also largest then and dominates the pressure environment around the spacecraft affecting backscatter redistribution. In addition, for manned, maneuvering missions, cabin leakage and thruster firings complicate analyses. QCMs have been flown on many spacecraft for the purpose of measuring the contamination levels at various locations on or about the spacecraft or to measure atomic oxygen levels. The objective of this effort was to locate those flight experiments that had QCMs on board and to make available the data collected during those flights. In some instances, processed or raw QCM data have been included whereas in other instances only papers or reports describing the results were available. The flight data have been subdivided into Shuttle and Satellite subsets.

3.1.1 Shuttle

The NASA shuttle program has had several missions on which quartz crystal microbalances (QCMs) were flown. NASA shuttle flights containing QCM experiments have been researched to provide summaries of the data that were collected as part of each mission in which QCM data was available. The QCMs were used for either monitoring contamination deposition or the measurement of environmental effects - such as atomic oxygen. In the early days of the shuttle, the Induced Environment Contamination Monitor (IECM) was developed by NASA and flown on flights STS 2,3,4, and 9, with QCMs being part of the instrument package. Another monitoring package, the Contamination Monitoring Package (CMP) was a smaller version and was flown on flights STS 3,8, and 11. An Environment Monitoring Package (EMP) containing QCMs for measuring atomic oxygen was flown on STS-46 as part of EOIM 3. A Contamination Environment Package (CEP) was flown on STS-82 for measuring contamination in the vicinity of the Hubble Telescope during the second servicing mission.

NASA Shuttle programs which had missions on which QCMs were flown.

| | | |
|-----|----|---|
| STS | 2 | IECM - Zwiener, Miller |
| | 3 | IECM - CMP, Zwiener, Miller, Triolo |
| | 4 | IECM - Zwiener, Miller |
| | 8 | CMP, EOIM (1?) - |
| | 32 | IOCM - Maag |
| | 46 | EOIM 3 - Straka |
| | 52 | SPIE QCMs on the arm - Canadian - Albyn, Soares |
| | 56 | Inside SSBUV - Maag |
| | 62 | SSBUV - Maag |
| | 66 | SSBUV - Maag |
| | 72 | REFLEX - Benner |
| | 74 | PIC - Albyn, Soares |
| | 82 | HST Second Servicing Mission - Patti Hansen |

IOCM - Interim Operational Contamination Monitor
CMP - Contamination Monitor Package
CEP - Contamination Environment Package (HST #2)
PIC - Plume Impingement - Steve Kuntz, Keith Albyn
EOIM - Evaluation of Oxygen Interaction with Materials
IECM - Induced Environment Contamination Monitor
REFLEX - Return Flux Experiment

3.1.2 EOIM-3

The Evaluation of Oxygen Interaction with Materials Experiment (EOIM-3) was flown on STS Mission 46 which was launched July 31, 1992. This was the third of such missions flown to investigate the materials degradation phenomena. The environment monitoring package (EMP) was flown as a part of the instrumentation to measure materials interaction and degradation rates due to atomic oxygen. Included in the EMP were 5 TQCMs (15 MHz) that were to be used to monitor the erosion rates of the materials that were used to coat the external TQCM crystals. The coatings applied were polyurethane, Kapton, carbon, and Teflon. The 5th TQCM was left uncoated and was used as a control sample. The results of this mission are contained in a technical paper.

This information on EOIM-3 was provided by:

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Reference

Banks, B. A., Gebauer, L., and Hill, C. M., Atomic Oxygen Interactions with FEP Teflon and Silicones on LDEF. LDEF Post-Retrieval Symposium, Kissimmee, Florida, June, 1991.

3.1.3 IECM

In the early days of the shuttle, the Induced Environment Contamination Monitor (IECM) was developed by NASA and flown on flights STS 2, 3, 4, and 9, to monitor the environment and changes associated with space flight. This monitor consisted of 10 instruments, among which were 5 TQCMs and 2 CQCMs, and was contained in a package having dimensions 121 x 82 x 79 cm. The design of the IECM and results of flights STS 2, 3, 4, and 9 (Spacelab 1) are discussed.

The information on the IECM was provided by:

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edm@aztechnology.com

and

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FAX: (256) 837-1155
jimz@aztechnology.com

3.1.4 Reflex

On January 11, 1996, the space shuttle Endeavor was launched from Kennedy Space Center on mission STS-72. In the payload bay was the OAST Flyer, a free-flyer Spartan carrier (Sp206) which contained the REFLEX experiment. The primary objective of REFLEX was to investigate an important contamination mechanism, referred to as Molecular Backscattering or "return flux", associated with on-orbit molecular contaminant transport. This phenomenon occurs when contaminants released into the local spacecraft environment collide with molecules comprising the Earth's residual atmosphere and reflect back onto the spacecraft surface. This "return flux" is believed to be one of the major sources of uncertainty in the analytical models used to predict the on-orbit contamination environment surrounding an instrument or spacecraft. A secondary objective was to study the erosion of coatings as a result of reaction with atomic oxygen (AO) (See REFLEX - SPIE Paper).

After launch the OAST Flyer was lifted from the bay, and released into a 165 n.mi. (306 km), 28 deg inclination orbit. After the payload release was completed, the Endeavor began its movement away from the now free flying carrier. The Flyer was later returned to the shuttle bay by the RMS after 46 hours of free flight.

REFLEX consisted of several instruments - three of which were temperature-controlled quartz crystal microbalances (TQCMs). One TQCM was coated with graphite. During the flight duration the graphite reacted with the atomic oxygen (AO) in the environment and was eroded away. One of the other TQCMs was coated with Kapton and the remaining TQCM was uncoated. The results are contained in Ref. (REFLEX-SPIE Paper).

The data and information for this experiment was provided by Steve M. Benner of NASA/GSFC. An example of the Mission data is presented in Figure 2.

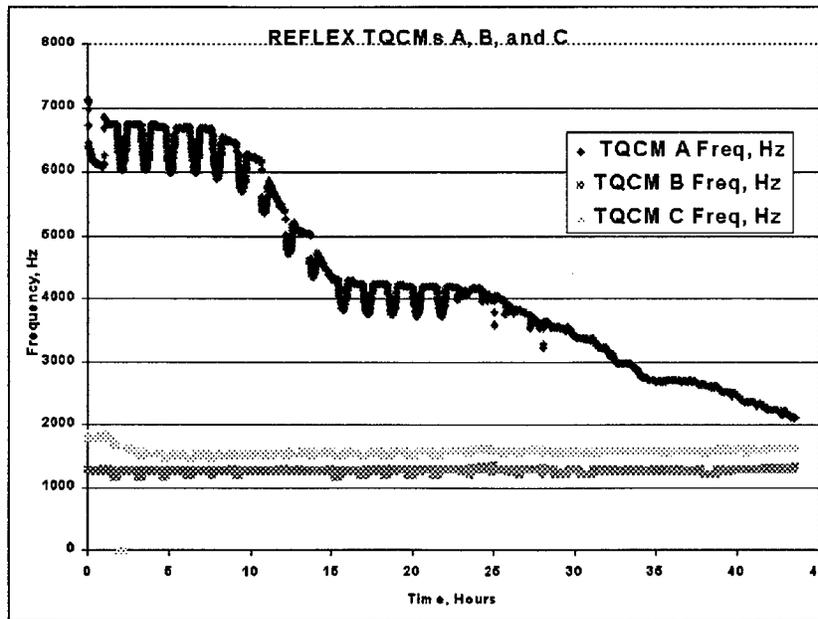


Figure 2. REFLEX Mission TQCM Data

References

- Coulter, D.R., Liang, R.H., Chung, S.H., Smith, K. O., and Gupta, A.; "O-Atom Degradation Mechanisms of Materials," proceedings of NASA Workshop on Atomic Oxygen Effects: June 1, 1987, P. 42.
- S. Benner, C. Lorentson, P. Chen, S. Thomson "Atomic Oxygen Erosion of a Graphic Coating on a TQCM Aboard the Return Flux Experiment" *Proc. SPIE*, Vol. 3427, "Optical Systems Contamination and Degradation," pp. 168-177, July 20-23, 1998 (1655KB)

3.2 Satellites

Longer term satellite missions provide the ability to measure long-term material outgassing contributions and obtain long term trends at times dramatically longer than possible in laboratory experiments. In addition, the effects of the orbital environment's interaction with the accreted material can be determined. With this knowledge, the effects of these depositions on material performance, power generation, thermal control can be estimated.

These datasets from QCMs are for missions that required much longer times in space than for the typical NASA shuttle experiments. Typically, exposure times for these missions were measured in months or years. Included in this section are results from the Russian Mir Space Station (<http://www.maximov.com/Mir/mircurrent.asp>) and eventually the International Space Station (<http://www.boeing.com/defense-space/space/spacestation/index.html>).

3.2.1 MSX Midcourse Space Experiment

The Midcourse Space Experiment (MSX) spacecraft was designed to precisely measure the optical signatures from a broad range of natural phenomena (the earth, its upper atmosphere, and celestial objects) as well as man-made targets. These scenes are observed with a suite of fully characterized, carefully calibrated, very sensitive optical instruments with broad spectral imaging capability. Optical measurements spanning from the far ultraviolet (110 nm) to the very long wavelength infrared (28 μm) spectral region are performed in a series of systematic measurement sequences or data collection events (DCEs). The designed mission lifetime is 4 years.

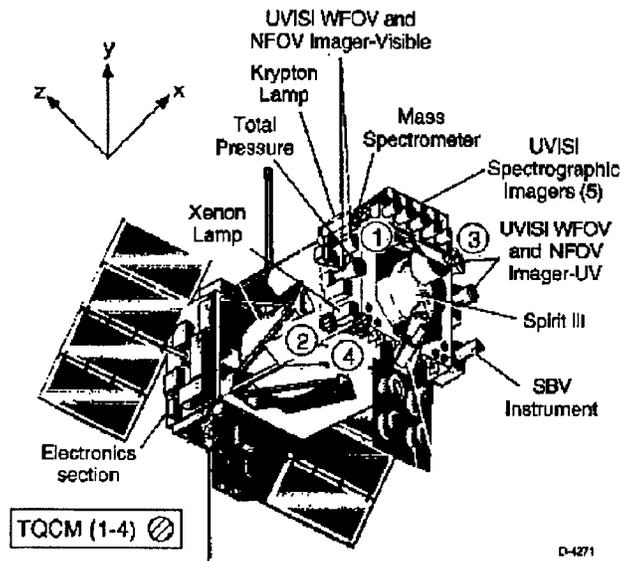


Figure 3. Midcourse Space Experiment Satellite

The primary optical sensors and contamination instruments were assembled, tested and integrated under carefully controlled conditions. Contamination control was an integral part of the MSX program. Design, materials selection, multiple instrumented bakeouts, ground assembly, handling, and bagging all addressed contamination concerns. Visual and tape lift inspections were performed frequently, and cleaning (vacuum and alcohol wipe) was performed as required. In spite of the multiple year assembly process, the spacecraft external surfaces were measured to be about Level 300 for particles with no measurable molecular films at 1 month before launch. On the pad, several adverse conditions rose during servicing and close out. Due to the necessity of frequent cryogenic servicing, activity induced particulate redistribution was a concern. Procedures were developed and levels monitored frequently.

3.2.1.1 TQCM

Five quartz crystal microbalances (QCMs) were a part of the contamination instrumentation flown on MSX. One cryogenic QCM (CQCM) was installed adjacent to the primary mirror inside the SPIRIT III cryogenic telescope and operated at ~ 20 K. The 4

temperature controlled QCMs (TQCMs) were installed at strategic locations on the exterior of the spacecraft and were controlled to temperatures of $\sim -50^{\circ}\text{C}$.

The CQCM was installed early in the assembly phase and hence was available for contamination monitoring throughout the SPIRIT III assembly, performance testing, integration and prelaunch activities in addition to providing continuous health status of the primary mirror throughout the cryogen lifetime after launch. The QCMs monitor the mass deposited on the sense crystal. Assuming a density of 1 g/cc allows the condensed mass to be converted into thickness values. During early operations the CQCM provided near real time data for determining the contaminant deposition rate inside SPIRIT III prior to the cover opening. It provided, for the first time ever, a definitive assessment of the contaminant level deposited during a pyro-actuated cover opening. A contaminant molecular film thickness of $\sim 72 \text{ \AA}$ was observed during the cover opening sequence. Using a thermogravimetric analysis (TGA) technique the CQCM TGA data also showed that the deposited gas during the cover release was made up of argon which was boiled off from the supply used to provide cooling for the cover. For the entire 10 months of the mission the CQCM accretion level was 155 \AA .

The 4 TQCMs provided data that were used to determine long-term outgassing rates from the satellite. Operating at -50°C , the TQCMs condense primarily organics and silicones which are outgassing products from various satellite materials such as paints, adhesives, potting compounds etc. The -50°C temperature is not cold enough to condense water due to the hard vacuum of space. The TQCM locations were chosen as follows:

- Facing in the (+Y, -X) direction and viewing the solar panels
- Facing into Ram (+Z) and also having the solar panel in its FOV
- Located in the wake (-Z, +Y) with only a very small FOV of one solar panel
- Facing in the same direction as the science instruments (+X)

Eighteen months after launch, TQCMs 1-4 had accumulated contaminant film thicknesses of 144, 155, 11, and 50 \AA , respectively. The TQCMs (#1 and #2) having a direct view of the solar panels experienced the largest deposition rates. The deposited films were found to have been polymerized by the solar exposure. Therefore performing TGAs on the crystals had very little effect on removing mass.

All 5 QCMs are still operating as designed and continue to provide outgassing rate data that will be beneficial to present and future satellite programs.

3.2.2 MIR

The Russian space station has been in operation for over a decade, with frequent resupply and new component/new module additions. Thus it provides a unique opportunity to observe the effects of materials outgassing from a complex manned operational structure.

3.2.2.1 Optical Properties Monitor (OPM)

The Optical Properties Monitor (OPM) was developed by AZ Technology and was derived from the Thermal Control Surfaces Experiment that was previously flown on the Long Duration Exposure Facility (LDEF). The OPM is a multifunctional, reusable in-flight laboratory for the in-situ study of the surface optical properties of materials. Optical and thermal properties were measured by the OPM utilizing 3 *in-situ* measurement subsystems, 1) spectral total hemispherical reflectance, 2) total integrated scatter, and 3) vacuum ultraviolet reflectance/transmittance.

The OPM was flown on the Russian MIR station to study the long term effects of the natural and induced space environment on materials and also monitored selected components of the environment including the molecular contamination. The OPM was exposed on the exterior of the MIR docking module for approximately 8-1/2 months. The OPM was transported to the MIR space station in January 1997 on STS-81. It was deployed on the exterior of the docking module on April 29, 1997. The OPM remained activated except during several MIR power outages. Power was off from June 25, 1997 to approximately September 9, 1997 due to the Progress accident. The OPM was retrieved from the docking module on January 9, 1998 and returned to ground on STS-89 later that month.

Molecular contamination deposition was monitored real-time on OPM using two temperature controlled QCMs (15 MHz) manufactured by Faraday Laboratories. One was held at -30°C while the other was maintained at -10°C. The sensitivities of the OPM TQCMs were both $1.6 \times 10^{-9} \text{ g/cm}^2\text{-Hz}$.

The OPM results on MIR are discussed in references SPIEvol3784_pp72-83..pdf.

Examples of the TQCM data before and after the collision/power loss event are shown in Figures 4 and 5. A significant contamination accretion event occurred on 12/16/97. Figure 6 shows the QCM data (sensor at -10°C) during the rapid accretion and subsequent slower evolution of accreted material at the time of an unknown contamination event.

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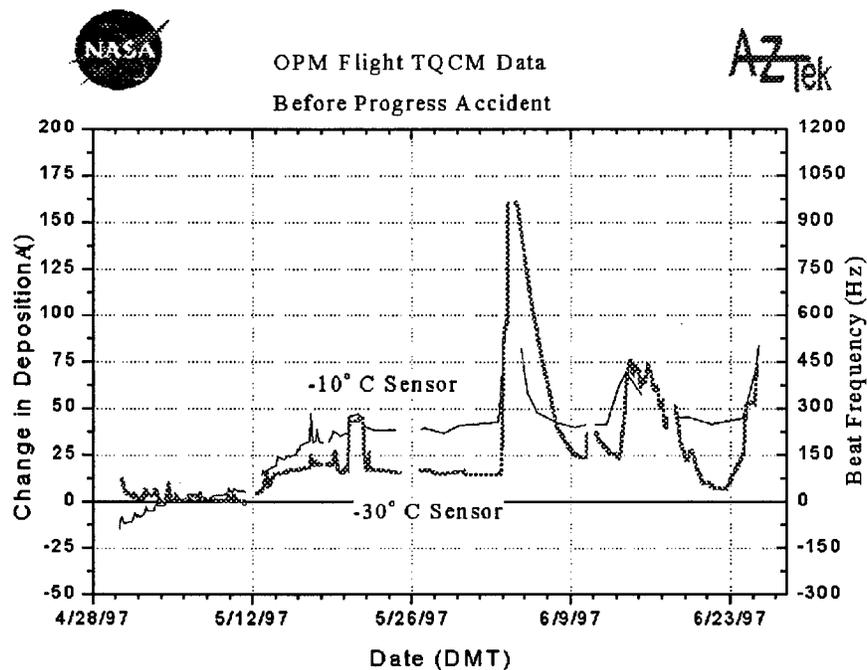


Figure 4. OPM on MIR, TQCM data before power loss

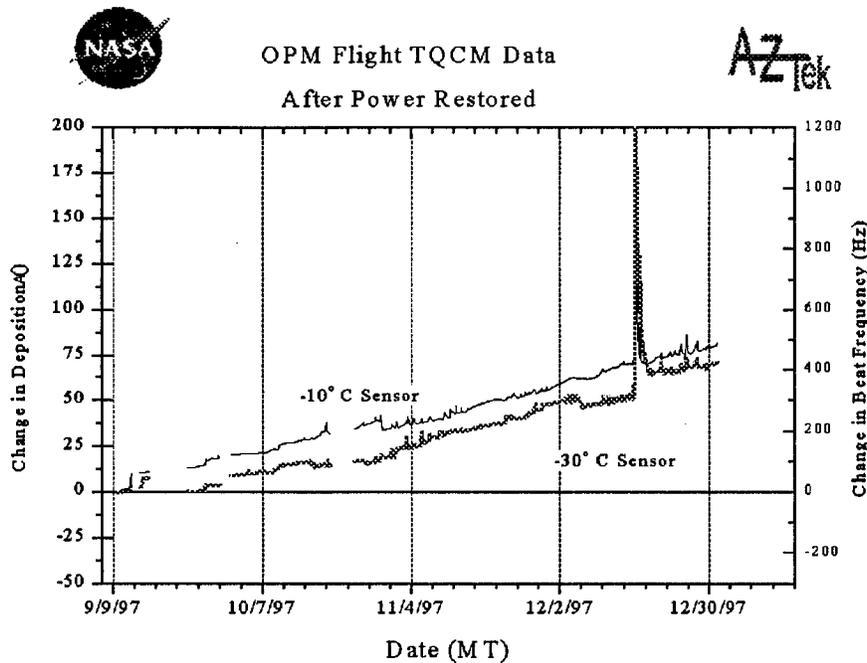


Figure 5. OPM on MIR, TQCM data after power restoration



OPM TQCM Flight Data on Mir

AZtek

-10° C Sensor

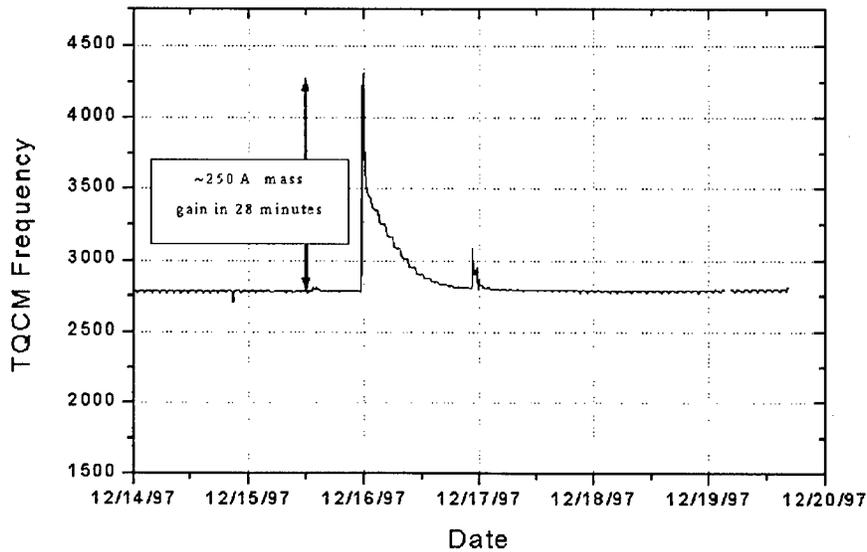


Figure 6. OPM on MIR, time dependence of accretion during an event

3.2.3 Measurement of Surface Erosion From Discoverer 26

The first known use of a quartz crystal microbalance during spaceflight was on the Discoverer 26 and was launched on July 27, 1961 in support of the Atlas Missile program. The intent of this flight was to measure the erosion rate of gold films in space (in particular the Atlas nose cone) - therefore the QCM crystals were coated with gold. A paper, describing these results, was authored by Daniel McKeown, Marvin G. Fox and James J. Schmidt (see Discoverer Ref.). After this initial flight there were 3 additional Discoverer flights.

This information was provided by:

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FAX. 619-454-7581
Email: dm@faradaylabs.com

Reference

1. McKeown, D., "New method for measuring sputtering in the region near threshold," *Rev. Sci. Instr.* **32**, 133 (1961).
2. Minsper, R. A., Champion, K. S. W., and Pond, H. L., "The ARDC model atmosphere, 1959" Air Force Cambridge Research Center, Bedford, Mass. (August 1959).

3.2.4 Hubble Space Telescope

Servicing Mission 2 on the Hubble Space Telescope (HST) was performed in February 1997 during the STS-82 shuttle mission. During this mission the Contamination Environment Package (CEP) was flown to monitor the contamination environment in the vicinity of the HST during the servicing procedures. The CEP was composed of four quartz crystal microbalances (QCMs) and a pressure gauge. Two of the QCMs were maintained at a temperature of -20C whereas the other 3 were maintained at 0C. A description of the instruments, locations, and results can be found in the reference by Hansen and Maag. QCM and pressure sensor data are included in the data sets. An example of the QCM data from HST Servicing Mission 2 is shown in Figure 7 as compared with the total pressure measured.

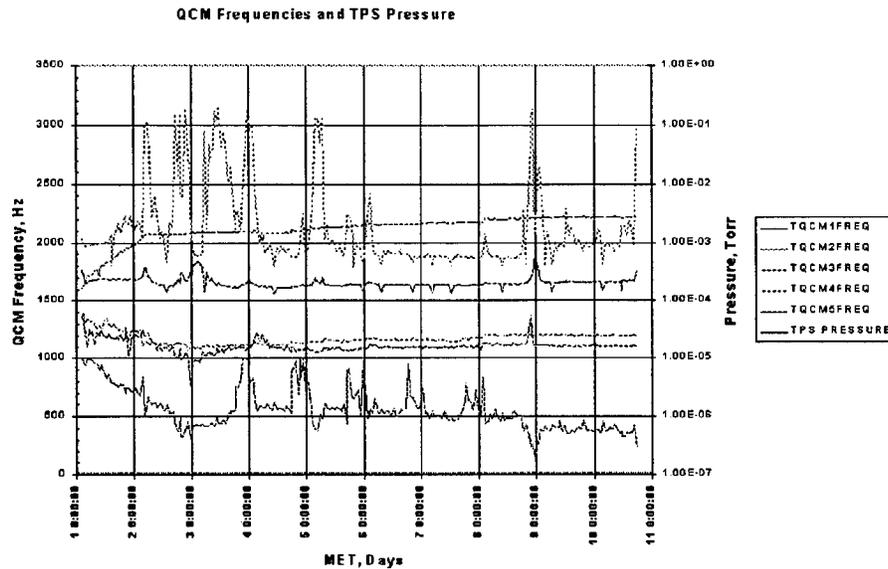


Figure 7. QCM accretion as compared to total pressure during the Hubble Servicing Mission

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Reference

R.J. Hedgeland, P.A. Hansen, and D.W. Hughes, "An Integrated Approach for Contamination Control and Verification for the Hubble Space Telescope First Servicing Mission", SPIE Optical systems Contamination: Effects, Measurement, Control IV, 2261:10-21, July 1994.

3.2.5 International Space Station (ISS)

Placeholder for future information.

3.2.6 LDEF M0003-14 Experiment

This data was provided by Don and Scott Wallace of QCM Research, in Laguna Beach, CA. The data were recorded during the first 424 days of the Long Duration Exposure Facility (LDEF) mission and ended when the tape recorder batteries reached the end of their lifetime. One of the two QCMs was located on Row 9 of the leading edge of LDEF and the second QCM was located on Row 3 of the trailing edge. This effort, M0003-14, was one part of the 19 part M0003 Experiment. The QCM crystals were each coated with a 9000 Å thick layer of aluminum and aluminum oxide and an overcoat of 150 Å of indium oxide (In_2O_3). Flight data for the two QCM frequencies, temperatures, and flight times are shown in Figure 8 and Figure 9. Analyses of these QCM crystals (and other sets of crystals) made after they were retrieved from space are presented in (Ref. LDEF - QCMs). The data were obtained during 111.7-minute bursts which was roughly the equivalent of one LDEF orbit. During this interval, each data channel was scanned approximately 32 times. Between each burst of data, there was a quiescent period of approximately 93 hours. The QCM temperature was not controlled but was allowed to "float" with the spacecraft. These changes in thermal conditions caused a subsequent change in QCM output frequency on the order of 300 to 500 Hz. The trailing edge QCM indicated a slight increase in frequency (mass) during its lifetime while the leading edge QCM showed a decrease in frequency (mass loss).

Reference

W.K. Stuckey, G. Radhakrishnan (Aerospace Corporation), and Don Wallace (QCM Research), Post-Flight Analyses of the Crystals from the M0003-14 Quartz Crystal Microbalance Experiment, LDEF - 69 Months in Space, Second Post-Retrieval Symposium (June 1-5, 1992 in San Diego, CA) NASA Conference Publication 3194, Part 4, 1993, pp. 1269 - 1283.

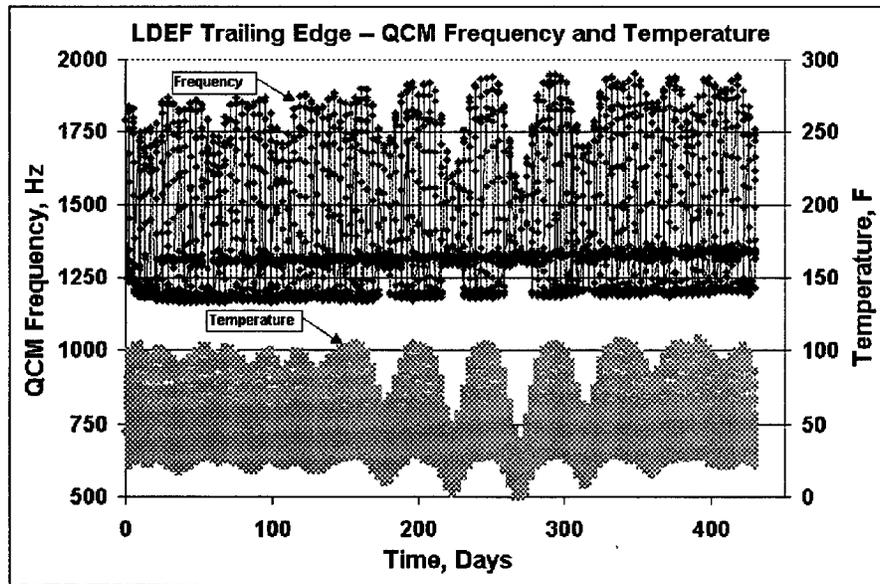


Figure 8. QCM “wake” measurements observed during the first 1.15 years

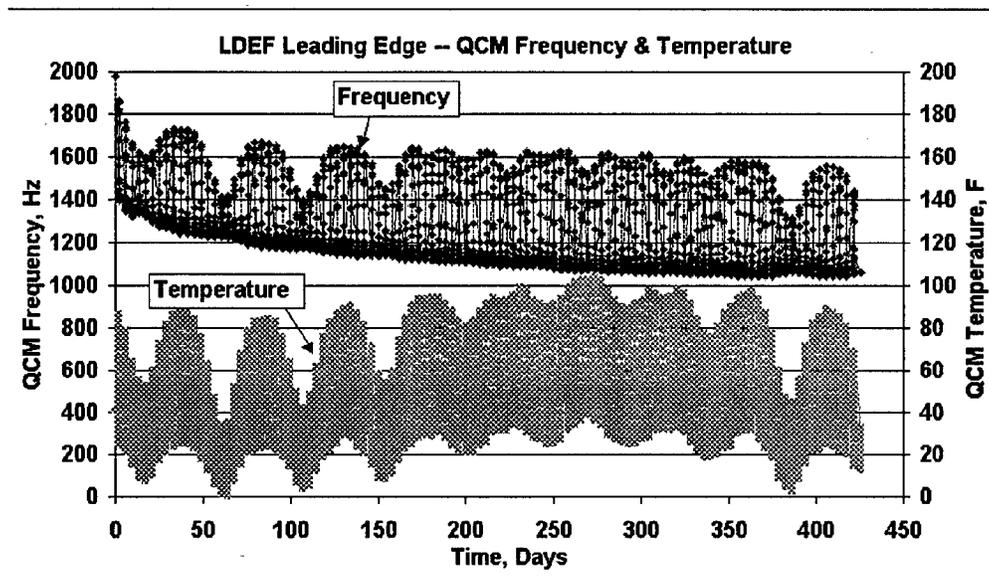


Figure 9. QCM “ram” measurements observed during the first 1.15 years

3.2.7 Gas-Surface Energy Transfer Experiment for OGO-F

The Orbiting Geophysical Observatory (OGO) Mission F satellite, was launched June 5, 1969. The objective was to measure gas-surface energy transfer by upper atmospheric atomic and molecular impacts to determine how satellite drag is effected by various surface materials. The experiment was flown on OGO-6 and was launched into a polar orbit having a perigee of 397 km and an apogee of 1,098 km. There were 4 GCMs onboard for measuring erosion rates,

sputtering rates, contamination deposition rates, and surface clean-up rates. This paper was authored by Daniel McKeown and Richard S. Dummer.

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R. Schamberg, "Analytic representation of surface interaction for free molecular flow with application to drag of various bodies," in "Aerodynamics of the Upper Atmosphere," RAND Corp., Santa Monica, Calif., Rept. R-339, 1959, sec. 12, pp. 1-41.

3.2.8 Analysis of TOCM Surface Contamination Absorbed During the Spacelab 1 Mission

The temperature-controlled quartz crystal microbalance (TQCM) system with five sensors was flown on the Spacelab 1 mission as part of the MSFC Induced Environment Contamination Monitor (IECM) to monitor surface contamination in the payload bay. The TQCM system was constructed at Faraday Laboratories and the QCMs were returned after the flight for analysis of the contamination that had been condensed during the STS-9 flight. The amounts of contamination adsorbed ranged from 1.4 $\mu\text{g}/\text{cm}^2$ for the -Z direction to 39.0 $\mu\text{g}/\text{cm}^2$ for the +X QCM. The contaminants were analyzed to determine the chemical composition using infrared spectroscopy, scanning electron microscopy, and energy dispersive x-ray fluorescence. The molecular contamination showed strong CH_2 , CH_3 and carbonyl absorption bands indicative of ester and polyester compounds found in adhesives, plasticizers and tape. Most of the particulate contamination ranged in size between 1 and 20 μm and was composed mainly of Mg, Al, Al_2O_3 and Si. The probable source of these particles was solid rocket firings. This paper was authored by Daniel McKeown, Faraday Labs, La Jolla, CA; J.A. Fountain and V.H. Cox.

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A Word of Caution

Please be advised that these data files were obtained from those listed above and all efforts have been made to insure that the transfer of these files to the website have been made correctly and that the data included are correct.

4. MIDCOURSE SPACE EXPERIMENT (MSX)

4.1 Instruments

The Midcourse Space Experiment (MSX) spacecraft was designed to precisely measure the optical signatures from a broad range of natural phenomena (the earth, its upper atmosphere, and celestial objects) as well as man-made targets. These scenes are observed with a suite of fully characterized, carefully calibrated, very sensitive optical instruments with broad spectral imaging capability. Optical measurements spanning from the far ultraviolet (110 nm) to the very long wavelength infrared (28 μm) spectral region are performed in a series of systematic measurement sequences or data collection events (DCEs). The designed mission lifetime is 4 years.

This sophisticated spacecraft is 5.1 m in length, 1.5 m² and weighs ~2700 kg. A schematic representation of spacecraft and its reference axis system are shown in Figure 10. Most of the external surfaces of MSX are covered with multi-layer insulation (MLI) comprising 20 layers of aluminized Mylar separated by Dacron netting with the innermost surface and exterior layers being silver/ ITO coated Teflon or beta cloth. Attitude maneuvering is achieved via reaction wheels to eliminate thrust exhaust contamination effects. To help ensure the desired operational performance, a thorough contamination control plan for material selection and handling was implemented. Furthermore, a suite of contamination instruments were included in the manifest to monitor performance during the ground processing and integration, and on-orbit. The MSX spacecraft was launched from Vandenberg Air Force Base into a circular 99 deg near sun-synchronous 904 km altitude orbit by a Delta II booster on 24 April 1996.

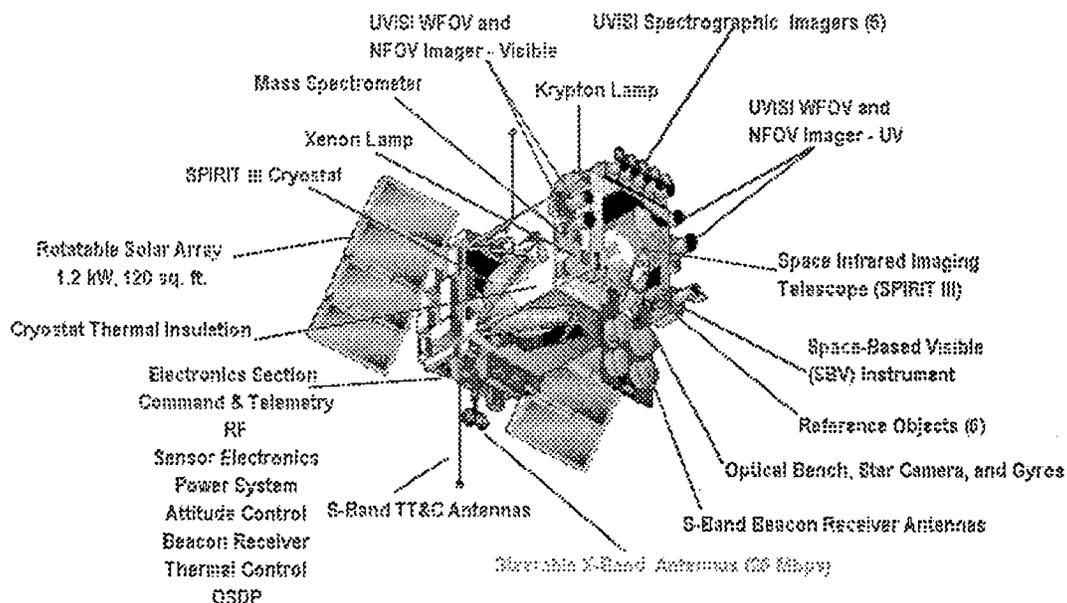


Figure 10. The Midcourse Space Experiment spacecraft with instrument positions indicated

Molecular species concentrations, deposited film thicknesses, particle occurrence above surfaces, and spacecraft charging are all monitored. The contamination instruments include:

1. A TPS covering the 10^{-5} to $<10^{-10}$ Torr range, and pointing into the same direction as the primary optical sensors (+X)
2. A closed-source quadrupole mass spectrometer for neutral molecules (NMS) with electron impact detection, covering masses 1 to 150 with 1 amu resolution, and sensitivity of $\sim 10^5/\text{cm}^3$, also pointing into +X
3. A KRF to specifically monitor water densities above $10^7/\text{cm}^3$ at meter distances above surfaces on the +X instrument deck
4. A Bennett RF IMS measuring masses 1 to 64 with sensitivity of ~ 10 ions/ cm^3 , pointing in the +Z direction
5. Four TQCMs operated at -43 to -50°C (to sense deposited molecular films with sensitivities to detect 0.01 nm film thick-nesses) located at different positions around the instrument section of MSX facing largely -X, +X, +Z, and -Z
6. Another QCM operated at near 20 K (CQCM) located near the IR sensor primary mirror to monitor all species frozen onto cryogenic optical surfaces with 0.02 nm sensitivity
7. A XFL to illuminate particles in a volume 2 m above the +X face of the instrument deck surfaces operating in concert with a visible 10×13 deg imager (IVW) to enable μm diameter particle detection. In addition, the primary sensors: the UVISI imagers with wide (10×13 deg) and narrow (1.32×1.6 deg) fields of view in the UV and visible, as well as the SPIRIT III radiometers sweeping across at 1×3 deg field of regard, will also be very sensitive detectors of spacecraft-produced particles as small as 0.1 and $10 \mu\text{m}$ respectively.

These instruments can operate individually, but by acting in concert during planned data collection events, their data can provide insight into the entire local environment. Experiment plans include brief periodic surveys of the environment, experiments to identify trends, to discriminate the effects of discrete events, and to measure the earth's upper-atmospheric composition and variability. Because the instruments observe both spacecraft surfaces and space, they are able to observe the ambient atmosphere, direct outgassing flux from surfaces, and molecules scattered by collisions with contaminant and ambient molecules (return flux).

The early-time spacecraft environment will be dominated by release of material from ground and ascent operations (materials outgassing and venting, particle release). These effects are expected to decay with time on orbit. At later times, orbital production processes (abrasion from operations and thermal stresses and erosion) will dominate the near-spacecraft environment.

4.1.1 Ion Mass Spectrometer

The IMS is a Bennett 5-3 cycle radio frequency mass spectrometer which records the flux of thermal ions in the mass range from 1 to 56 amu. The instrument mass resolution is a function of the instrument efficiency which can be controlled by varying the instrument stopping potential voltage (Vs). The instrument is generally operated in a Vs range such that $M/Dm \sim 20$ to 30, which allows mass peaks associated with O^+ , H_2O^+ , and H_3O^+ to be resolved. The instrument

sensitivity is $\sim 9 \times 10^5$ ions/cm²s which corresponds to ambient ion densities ~ 10 ions/cm³. The instrument has been used in the past to provide an absolute determination of the detected ion mass, a feature to be used in this study to search for contaminant ions associated with the early-time contamination environment of MSX. It is also noted that similar instruments have flown on the STS as well as other satellites.

4.1.2 Krypton Radiometer and Flashlamp (KRF)

The Krypton Radiometer operation is based on photodissociation of water vapor in the near field with VUV radiation and the subsequent measurement of the emission from the electronically excited products. The intensity of the resulting radiation is directly related to the density of water vapor. The Krypton Radiometer includes a VUV source that dissociates the H₂O molecules. The chemiluminescence is detected with a filtered photometer (part of the Krypton Radiometer) and by one of the MSX UVISI Spectrographic Imagers (UVISI SPIM3). The Krypton Flash Lamps, having a strong emission line at 123.6 nm, provide a convenient source for the photolysis radiation. The absorption coefficient for water at 123.6 nm is 2×10^{-17} cm² molecule⁻¹, and the quantum yield for production of the excited state OH radical is 0.07 for excitation at that wavelength. The instrument comprises an array of 16 RF-excited krypton line source lamps, VUV flux monitors, and a filtered photometer. The filter spectral bandpass is 305-325 nm and encompasses the OH emission band.

4.1.3 Neutral Mass Spectrometer

The NMS was originally manufactured by the Space Physics Research Laboratory at the University of Michigan, and had flown as part of the Space Transportation System (STS) induced environment contamination monitor (IECM). Similar mass spectrometers were also flown on Atmospheric Explorers C, D, and E and on Dynamics Explorer. A detailed description of the IECM NMS instrument, extensively refurbished for MSX, has been published by Miller and Decker. The NMS is a closed-source quadrupole instrument with an electron-bombardment ion source. Chemical species enter the mass spectrometer antechamber through a knife-edged orifice. Once in the antechamber, the species come into thermal equilibrium through multiple collisions with the walls before being ionized using conventional electron-impact techniques (150 eV; selectable emission current: 30 μ A or 90 μ A). The ionized species are then collimated into the quadrupole analyzer which uses both a DC and RF voltage across four rods to select a specific mass-to-charge ratio (m/z). The instrument can operate over the range of 1 to 150 m/z. Ions with the selected mass-to-charge ratio then pass through the quadrupole analyzer and are detected using an electron multiplier. The spectrometer can be operated in either a scanning mode with 1 or 1/16 m/z steps or a single ion monitoring mode in which selected peaks are monitored continuously for increased sensitivity. The NMS is located on the instrument section with its line of sight parallel to the optical axis of the satellite.

4.1.4 Quartz Crystal Microbalance (QCM)

See Subsection 3.2.1.1.

4.1.5 Spatial Infrared Imaging Telescope (SPIRIT III)

The primary infrared sensor on MSX is a Spatial Infrared Imaging Telescope (SPIRIT III) was built by the Space Dynamics Laboratory of Utah State University in Logan, Utah. The optics were cooled to about 20 K to achieve sensitive detection of passive upper atmospheric and celestial radiances (see Figure 11). This sensor was equipped with a vacuum tight door covering the sensor aperture to permit cryogenic loading during ground processing. To minimize the radiant load, the door was also cooled to well below 100 K using solid argon. The SPIRIT III radiometers form an array 192 elements high (subtending a one deg angle) by only a few detectors wide in each of six color bands. These bands span different segments of the 4.2 to 26 μm spectral region. A mirror repeatedly scans the instantaneous narrow field of regard across a 3 deg angle during a seven second period. Noise Equivalent Spectral Radiances of the radiometer arrays are in the 10 to 13 $\text{W}/\text{cm}^2\text{-sr-}\mu\text{m}$ range, permitting detection of 20 to 50 μm particles. The SPIRIT III interferometer will permit spectral signatures of radiometrically detected particles to be measured. The observed spectral radiances may permit the particle's composition to be determined from its signature as shown by previous modeling.

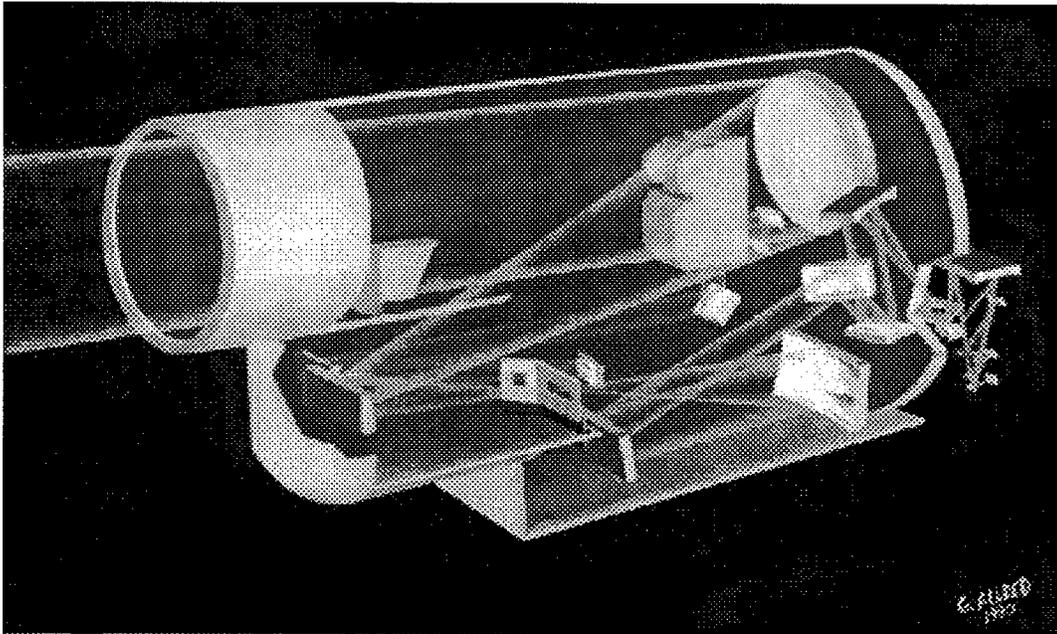


Figure 11. Optical layout of SPIRIT III telescope CQCM is located adjacent to the primary mirror at right.

4.1.6 Total Pressure Sensor (TPS)

The Total Pressure Sensor (TPS) on-board the Midcourse Space Experiment (MSX) spacecraft has continuously measured the ambient local pressure since its launch on April 24, 1996. The primary goals of the sensor are:

1. To monitor the ambient pressure surrounding the spacecraft's optical telescopes and to indicate when environmental conditions were acceptable for opening the protective covers
2. To monitor the long- term decay of the species (predominantly water from the thermal blankets) outgassed from the spacecraft.

The water-induced environment was expected to rapidly decay over the first few months to levels more closely approaching the natural environment. The data generally shows decay toward this level, however, the pressure is quite variable with time and can be influenced by discrete illumination and spacecraft orbital events. Several experiments conducted approximately 1 year into the mission indicate that the thermal blankets retain significant quantities of water. The local pressure, due to water vapor, is shown to increase by a factor of 100 from direct solar illumination. Moreover, the multi-layer construction of the blankets causes them to form a deep reservoir which continues to be a source of water vapor several tens of months into the mission. The MSX TPS is an inverted-magnetron cold cathode gauge that operates on the Penning discharge principle. The sensor was calibrated to NIST standards and cross-characterized to other spacecraft sensors. The instrument is mounted on the -Z face of the spacecraft between the IVW and IVN sensors (the wide [IVW] and narrow [IVN] field of view, visible imagers) and in front of the SPIRIT III sunshade. The boresight of the instrument is along the +X axis in the same direction as all of the optical sensors. The instrument aperture is slight above (< 1 in.) the pallet that defines the +X instrument deck and has three sunshades within its field of view: IVN, IVW, and SPIRIT III. The exterior surfaces of these sunshade baffles are covered with 20 layer MLI blankets.

4.1.7 Xenon Flashlamp (XFL)

The Xenon flashlamp produces an intense beam of visible light for detection of back-scattered radiation by the UVISI wide FOV visible imager. Particles as small as 1 μ m with velocities up to 1 m/s will be detected. The Xenon Flashlamp incorporates an ILC Technologies LX150F Xenon illuminator and the associated control electronics. The illuminator itself has an integral prefocused reflector which provides a beam divergence of roughly 4.5 deg (fwhm). The Xenon Flashlamp instantaneous intensity is $\sim 1 \times 10^{20}$ photons s^{-1} over the visible wavelength region (400 to 900 nm). The intensity of each flash is measured by an optical flux monitor. The flashlamp is operated in a burst mode, where each 0.5 second burst consists of nine 11-ms flashes of the lamp. The bursts repeat at a 1 Hz rate. This flash pattern provides a modulation in the particle signature within a single image, thereby allowing one to determine the angular velocity of the particles.

4.2 Films

Probably the most prevalent form of contamination on spacecraft surfaces is that of condensed molecular films. These can be films condensed on cryogenic optics or can be films condensed on much warmer surfaces. Surfaces exposed to the solar ultraviolet are subjected to the additional threat of polymerization of organic/silicone films into a hardened film that for the most part can not be removed by surface heating alone. For MSX, there was a major concern of

contamination of the cryogenic primary mirror in the SPIRIT III telescope. A CQCM was mounted inside the telescope to monitor the deposition of contaminants during the lifetime of the telescope. This CQCM provided an opportunity to monitor contaminant deposition during the very important telescope cover removal. This was accomplished by a pyrotechnic firing. The CQCM not only provided a means of measuring the film thickness deposited during this process but in addition through the use of the thermogravimetric analysis (TGA) the species of condensed contaminant were determined.

The four temperature-controlled QCMs (TQCMs) were located on the exterior of the spacecraft for monitoring the levels of contaminant condensed on the exterior surfaces. Three QCMs were operated at $\sim 50^{\circ}\text{C}$ whereas the other one operated at $\sim 43^{\circ}\text{C}$ due to it having a smaller radiator. One of the TQCMs was mounted looking in the same direction as the science instruments (+X) and provided a good indication of the contaminant deposition rates experienced by optical surfaces in the science instruments. The effect of the solar UV on the TQCMs was to "solarize" or polymerize the organics/silicones that had been deposited. TGAs had little effect on these films and therefore could not be used for specie identification. Total film thicknesses varied from about 10 \AA up to as much as 150 \AA depending on the surfaces in the direct field of view of the TQCMs.

4.2.1 MSX Ground Preparation

Cryofilm deposition will severely affect mirror optical performance. During the initial cooldown of the cryogenic IR sensor, the abundance of condensable water vapor is more than 1000 times higher than any other condensable species. Water condensation on the optics is avoided by using the deployable aperture door as a scavenger trap, i.e., it is cooled to liquid nitrogen temperatures before the telescope optics drop below 200 K. The SPIRIT III CQCM has verified that this procedure can restrict water condensation to less than 10 \AA on the primary mirror during cooldown.

Once the telescope is cooled to less than 50 K, the vapor pressure of water, carbon dioxide, and organic species is extremely low (< 10 to 13 Torr) and redistribution of these species onto the optics during normal operations is not expected or observed. It can be seen that temperature fluctuations of a few degrees in the 20 to 30 K range can cause significant pressure bursts that may result in redistribution of air cryofilms onto sensitive optics.

Figure 12 shows the CQCM temperature and frequency trend during integration and testing with the MSX spacecraft. This testing was performed by Utah State University personnel. It can be seen that anomalous CQCM depositions of 300 to 400 MHz magnitude were observed during liquid helium refills after the telescope had reached its base temperature of approximately 20K. These depositions can be understood by examining the response of the baffle temperature during a cryogen refill operation.

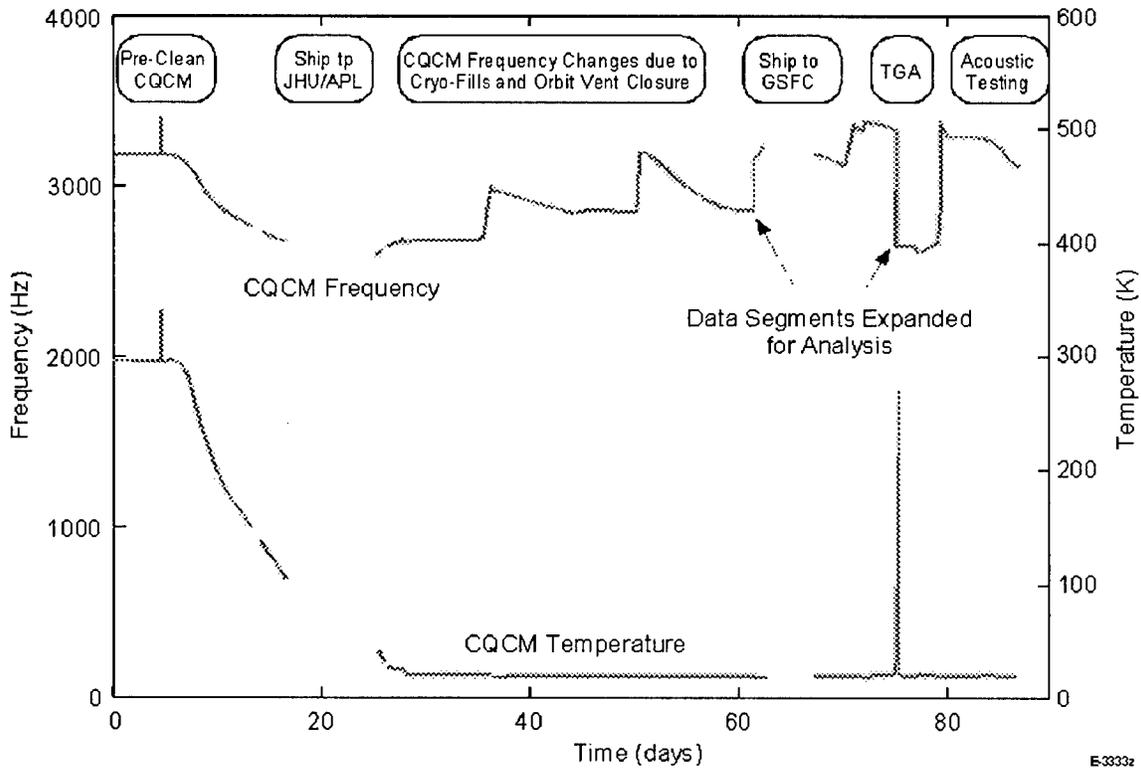


Figure 12. CQCM Frequency and temperature during cryosensor integration and testing.

The SPIRIT III baffle is vapor- and radiation-cooled; it is not cooled directly by the cryogen in the tank.

The cryodeposition anomaly that occurred at approximately $t = 62$ days in the figure began when the orbit vent valve was closed and the baffle began to warm. The deposition ended when the orbit vent valve was reopened and the high cryogen flow caused the baffle to become colder than the CQCM. After the refill operations the CQCM began to slowly lose mass at a rate of $5.4 \times 10^{-13} \text{ g cm}^{-2} \text{ s}^{-1}$. This is consistent with the slow migration of nitrogen from the CQCM back to the colder baffle.

N_2 vapor pressure data was used to estimate the effective sublimation temperature necessary to produce a mass loss of $5.4 \times 10^{-13} \text{ g cm}^{-2} \text{ s}^{-1}$. This derived temperature is 19.9 K, which is in excellent agreement with the measured CQCM temperature of 20.5 K.

The local N_2 vapor pressure was estimated by assuming it to be in equilibrium with the temperature of the baffle region nearest the CQCM and primary mirror. The predicted N_2 mass flux at the CQCM is found to be in good agreement with the measured mass deposition rate.

The actual composition of the cryofilm deposited on the CQCM and primary mirror can be derived by thermal-gravimetric analysis (TGA). A TGA experiment was performed on day 75 of the figure after significant warming of the baffle ($>30 \text{ K}$) during the shipment of the spacecraft to Goddard Space Flight Center. The TGA was performed using the ground support

equipment and a nominal 1 K/min heating rate. The rate of frequency change versus temperature clearly demonstrated the onset of evaporation of nitrogen and oxygen at 23 K and 29 K respectively. The relative abundance of oxygen and nitrogen approximates that of air. The magnitude of each cryodeposition is consistent with expected O-ring permeation gas loads. Apparently, the air that permeates through the O-ring seals in the forward sections of the telescope housing and aperture door is cryo-pumped by the cold baffle, and then released when the baffle warms during a cryogen refill operation.

Thermal Vacuum Testing of MSX

Acoustic and thermal vacuum testing was done at GSFC. Except for during the thermal-vacuum test, extensive use was made of bagging and purging to keep the spacecraft and payloads as clean as possible. These bags were made of precut NMD-FR 190 N PA1-NN scrim-reinforced material, manufactured by National Metallizing, Inc. Seams were closed with 2 in., 3M 1205 Kapton tape.

For the acoustic test, all deployable items were bagged separately from the body of the spacecraft, with latches left unbagged. The X-band gimballed antenna was considered sufficiently delicate to make bagging inadvisable. Therefore, the antenna was covered with a removable flap of bagging material that could be folded back for testing and replaced at the end of each test. In addition, the solar arrays and GSE, such as simulators and cables, were removed for the acoustic testing after a solar panel deployment test.

The GSFC thermal-vacuum chamber, and all the MSX shrouds and associated hardware, were vacuum baked before testing MSX in order to remove any contamination present from previous chamber operations and from new fixtures. This was one of the most important steps in minimizing molecular contamination before launch. The chamber was pumped below 1.3×10^{-4} Pa (10^{-6} Torr), and the test shroud heated to 80°C for 350 hr. Three 15 MHz GSE TQCMs viewed a shroud inner surface, the top of the chamber, and the bottom of the chamber, respectively. These TQCMs, held at -50°C (-58°F), were used to monitor the bake-out progress. From time to time, it was necessary to clean the TQCM crystals by heating them to 80°C (176°F) so that they would not saturate. The TQCM heating was done linearly, and the output monitored so that the temperature at which various species evaporated from the crystal could be determined. After about 280 hr, the deposition rate on the TQCM with the highest rate had decreased from more than 3×10^{-6} to 7.7×10^{-7} g/cm²-hr (7.1 to 1.7×10^{-7} oz/in²-hr), and the rate of change of the deposition rate had fallen to -2.5 Hz/hr/hr. This was considered to be the point of diminishing returns, and the next 70 hr were used to return the chamber to ambient temperature and pressure.

In addition to the real-time monitoring by the TQCMs, two diagnostic plates, each with two polished gold-plated mirrors and two ATR crystals, were used to evaluate the risk of potential changes in emissivity of the SPIRIT III sunshade or contamination of other surfaces in the instrument section. One test plate was allowed to thermally float while the other plate was maintained warmer than the shrouds throughout the bake-out phase, then dropped to -40°C during the chamber certification phase. Subsequent FT-IR analysis indicated insignificant

changes in the spectral reflectance of the samples. Auger analysis indicated a slight molecular film with carbon and oxygen present.

Immediately before the spacecraft was lifted into the thermal-vacuum chamber, 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 thermal blanket installation. A particle counter operated continuously in the chamber. Air flow throughout this area was such that the total particle count never exceeded that characterizing a Class M 4.5 (Class 1000) facility after the chamber lid was replaced and the filtered air flow started.

The three GSE TQCMs, the four flight TQCMs, and a GSE residual gas analyzer were used to monitor the chamber during the thermal-vacuum test. These instruments provided valuable data. However, the approximately 3-week-long test was not staffed full time by MSX contamination control or contamination team personnel. This resulted in inadequate records being kept of important events.

4.2.2 MSX Flight Data

The QCM data consisted of normal and diagnostic telemetry frames. Normal frames contained science data while the diagnostic frames also contained instrument operational status information. The QCM telemetry output is 1 byte/second into the MSX spacecraft housekeeping data stream in all spacecraft modes. The housekeeping data can be telemetered to the ground in any of three ways - real-time at 16 Kbps, tape-recorded at 25 Mbps and downlinked, or tape recorded at 5 Mbps and downlinked. All three types of QCM satellite data were downlinked to the Mission Control Center at JHU/APL. During early Ops the Air Force Satellite Control Network was also used to collect MSX housekeeping data.

The 16 Kbps and 25 Mbps data streams provided a normal frame of QCM data every 40 seconds and, when commanded, a diagnostic frame every 52 seconds. The 5 Mbps data provided a QCM normal data frame every 200 seconds and, when commanded, a diagnostic frame every 260 seconds. All three types of data were downlinked to the Mission Processing Center (MPC) as so-called Level 0 data. It was then processed and sent to the Contamination Experiment Data Processing Center (CEDPC) as Level 1 data, and finally, after further processing, sent to the Contamination Experiment Data Analysis Center (CEDAC) as Level 2 data. During early Operations (first week of flight and before SPIRIT III cover ejection), all of the data analysis by the principal investigators took place on location at the CEDAC. The 16 Kbps data provided an additional advantage in that they could be monitored real time during each ground station contact. This was especially important during early Ops since expedited processing to Level 2 took about 12 hr, and SPIRIT III, UVISI, and SBV wanted reports more current than that. The real-time data were monitored by extracting the single byte per second of Level 0 data in the MPC data flow and sending them to a Mac Plus computer. The Mac recorded all the data and searched for the QCM frame synchronization bytes. It then determined the type of each frame telemetered, and converted the data to engineering units. The data were transferred to another computer and analyzed using Excel. This nearly real-time data analysis capability was nominally for engineering assessment. Since all program certified data flow

through the MPC-CEDPC-CEDAC pipeline, certified data were processed in the CEDAC using an Interactive Data Language (IDL) routine that was created specifically for displaying the Level 2 data.

4.2.2.1 Early Operations

The CQCM has played a major role in determining the contamination environment in space for the MSX SPIRIT III telescope. The CQCM is mounted adjacent to the telescope primary mirror and is maintained at the same temperature as the mirror (~20 K). The contaminant mass deposition rate measured by the CQCM is assumed to be the same as that on the primary mirror. By monitoring the deposited contaminant mass (or film thick-ness), a realistic estimate can be made of the health of the mirror. When launch occurred on Day 115 (April 24), the CQCM frequency was approximately 2492 Hz which was 12 Hz (~ 5 Å) higher than the frequency for the completely clean CQCM – 2480 Hz. During the first 7 days after launch (Early Operations), there was a gradual buildup of contaminant film on the CQCM even though the cryogenically cooled SPIRIT III protective cover was still in place. Thermogravimetric analysis (TGA) of the CQCM contaminants provided a means for determining the species and amount of contaminant condensed at specified times.

From TGAs performed prior to the cover release, it was determined that the contaminant deposited inside was primarily oxygen. When the cover was released 7 days after launch, there was a rise in CQCM frequency of about 163 Hz (72 Å). Nineteen days after the cover release another TGA was performed to determine the mass and species of the 72 Å thick film. Most of the condensate evaporated between 28 to 30 K and is believed to be argon, which came from the solid argon used as the cover coolant. This evaporation temperature was consistent with that seen from the argon vapor pressure versus temperature curve. A small amount of deposit evaporated between 30 and 32 K and is believed to be oxygen which was deposited prior to the cover release. The maximum evaporation rates were modeled using vapor pressure curves by treating the CQCM cryofilm as an effusive source at an effective pressure in equilibrium with the CQCM temperature. The results were a good fit for the two expected species argon and oxygen.

The 4 TQCMs were cooled enough to condensed organic species 3.5 hours after launch. During the Early Operations period, all TQCMs observed some amount of contaminant accretion with TQCM #2 showing a film deposition of approximately 15 Å. TQCM #2 had a significant view factor of the solar panels and was also oriented such that it was looking in the ram direction. The other TQCMs showed film deposition levels varying between 7 and 14 Å during this period.

4.2.2.2 TQCMs

The TQCMs were also designed and built by QCM Research to operate at temperatures as low as -70°C and as high as 70°C. Preflight calibration and operational characteristics of the TQCMs were determined in ground testing 9. The temperatures are controlled by a Peltier cooler/heater unit which is built into these Mark 10 TQCM units. As in the case of CQCM, one of the two crystals is exposed to the environment while the other crystal is the reference crystal

and is protected. The crystals operate at a frequency of 15 MHz. That makes the TQCM 2.25 times more sensitive than the CQCM. The mass sensitivity for the TQCMs is given by

$$Dm/A = 1.96 \times 10^{-9} \text{ (g/cm}^2 \cdot \text{Hz) DF (Hz)}$$

Using similar expressions to those derived for the CQCM results in the frequency vs thickness relationships (where again the density is assumed to be 1.0 g/cm³),

$$t(\text{\AA}) = 0.196 \text{ (\AA/Hz) DF (Hz)}$$

= 0.196 for a frequency change of 1 Hz.

Similarly, DF (Hz) = 5.102 for a film thickness of 1 \AA.

The four TQCMs are mounted on the exterior of MSX with the direction cosines indicated in Table 1.

Table 1. TQCM Direction Cosines

| TQCM No. | X | Y | Z |
|----------|--------|--------|--------|
| 1 | -0.865 | 0.251 | 0.433 |
| 2 | 0.000 | 0.000 | 1.000 |
| 3 | 0.000 | 0.500 | -0.865 |
| 4 | 0.896 | -0.213 | 0.388 |

Thus, TQCM 1 is pointed with components in the (-X,Y,Z) directions, TQCM 3 has (Y,-Z) components, and TQCM 4 has (X,-Y,Z) components. TQCM 2 points in the +Z direction. The TQCM covers limit their fields of view (FOV) to a right cone with approximately 64-deg half angle. TQCMs 1 and 2 both have view factors which contain considerable area of the solar panels. TQCM #3 was positioned to look in a direction where minimal contamination would be seen. TQCM #4 was mounted on the +X face of the spacecraft and thus provided the deposition rate on the surfaces where all of the science instruments were located. The +X face of the spacecraft was predicted to cool to temperatures on the order of -20°C. Therefore, the deposition levels measured by the TQCMs at -50°C represent a "worst case" condition for the UV-visible instruments of UVISI and SBV.

The TQCMs are mounted on individual radiators which are isolated from the main frame of the spacecraft to allow better thermal control. The heat from each Peltier thermoelectric device is radiated to space by the radiators. TQCMs 2-4 have maintained an operating temperature of -50°C whereas TQCM #1 has operated at a slightly warmer temperature, -43°C, due to being mounted on a smaller radiator. As the satellite rotates on the solar panel axis to achieve a commanded attitude, the projected area of solar panel within their fields of view (FOVs) varies. In addition to the solar panel, TQCM 1 views some of the spacecraft electronics module. The degree to which the TQCMs can receive line-of-sight outgassed molecules from these surfaces has been calculated from spacecraft drawings. The planned TQCM operational temperature range of -40°C to -50°C was calculated to be cooler than all external contamination

sources, such as the multilayer insulation, electronic boxes, and other non-cryogenically cooled surfaces of the spacecraft, and should be cold enough to condense many silicones and hydrocarbons outgassing from MSX materials.

4.2.2.3 CQCMs

The CQCM is a Mark 16 model which was designed and fabricated by QCM Research of Laguna Beach, CA. It is a mass sensor and can detect masses condensed on the order of 10^{-9} grams and was designed to operate at temperatures as low as 4 K. The mass sensitivity is proportional to $1/F^2$ where F is the oscillation frequency of the crystals. The CQCM uses two quartz crystals (to minimize temperature effects) which oscillate at 10 Mhz and are positioned such that one crystal is exposed to the external environment whereas the reference crystal is protected from any deposition. The difference frequency is directly proportional to the mass condensed on the external crystal. The quartz crystals were previously exposed to 100 KRad (Si) in a Cobalt-60 source at JHU/APL in order to minimize radiation-induced frequency degradation during the time in orbit. On MSX, the CQCM is located adjacent to and thermally coupled to the cryogenically cooled primary mirror of the SPIRIT III telescope. It is used to monitor the deposition of contaminants on the interior optics, as a predictor of the degradation in performance of the mirror. The CQCMs were calibrated/characterized at temperatures as low as 10 K in a cryogenic calibration facility at the Arnold Engineering Development Center (AEDC) in Tullahoma, TN. After installation in the SPIRIT III telescope the CQCM has been a valuable tool in monitoring the mirror status in cryogenic testing of SPIRIT III at Utah State University (USU), thermo-vac testing at the Goddard Space Flight Center (GSFC) and pre-flight measurements at Vandenberg AFB.

The sensitivity of the CQCM to mass (for 10 MHz crystals) is given by

$$D_m/A = 4.42 \times 10^{-9} \text{ (g/cm}^2 \cdot \text{Hz) DF (Hz)}$$

where D_m = condensed mass, g
 DF = change in CQCM frequency, Hz
 A = crystal surface area, 0.3167 cm^2

The contaminant film thickness, t, can be calculated from the equation

$$\begin{aligned} t \text{ (cm)} &= (D_m/A) / r \\ &= 4.42 \times 10^{-9} \text{ (g/cm}^2 \cdot \text{Hz)DF (Hz) / r (g/cm}^3) \end{aligned}$$

where r = density, g/cm^3 .

Typically, the film density is unknown but is usually assumed to be 1.0 g/cm^3 to facilitate film thickness calculations. The actual density range is thought to be between 0.8 and 1.5, depending on the species. For unity density the film thickness in Å is given by

$$\begin{aligned} t \text{ (Å)} &= 0.442 \text{ (Å/Hz) DF (Hz)} \\ &= 0.442 \text{ for a frequency change of 1 Hz.} \end{aligned}$$

Similarly,

$$D(\text{Hz}) = 2.262 \text{ Hz for a film thickness of } 1 \text{ \AA}$$

4.2.2.4 SECOT

At the end of the cryogenic operations period on-orbit, which occurred approximately February 27, 1997, the surfaces inside SPIRIT III began to warm up. One of the objectives of the Contamination Experiment was to determine how much, if any, H₂O had been deposited on the baffle near the entrance aperture and also within the surfaces surrounding the primary mirror and CQCM. An experiment was planned to warm the cryogenic telescope during two experimental phases which were designated SECOT 1 and SECOT 2 .

During SECOT 1, the objective was to warm only the baffle up to 160 K to evaporate any water previously condensed. Approximately 3 months later, the SECOT 2 experimental plan was executed and the remaining surfaces inside the telescope were warmed to about 160 K to drive off the remainder of any water condensed. The CQCM provided condensation/evaporation data for determining levels of water vapor present during these times. During the SECOT, experiments warm-up of the telescope was accomplished by positioning the spacecraft at an attitude which allowed the solar flux to enter just inside the telescope baffle. For SECOT 1, the desired baffle temperatures were achieved using 14 solar pulses of 25 minute duration.

During this time the CQCM warmed from 51 to 99 K but remained cold enough to condense any H₂O that evaporated from the baffles and was incident on the CQCM. During the heating pulses the CQCM frequency increased approximately 450 Hz due to the deposition of H₂O. This corresponds to a film thickness of approximately 200 Å. At the conclusion of the heating pulses another TGA was performed on the CQCM to determine the species of condensed mass. The warm-up rate was 2.5 K/minute. The film thickness, originally 200 Å, began decreasing at approximately 150 K and essentially all had been removed by ~ 165 K. This is a typical observation for H₂O films that are surrounded by vacuums on the order of 10⁻⁹ to 10⁻¹⁰ Torr. The CQCM heating continued until a temperature of 240 K had been reached. It is also seen that essentially all of the deposited film was removed by the time the 165 K temperature was reached indicating that the entire film was H₂O. The source of the H₂O is the multilayer insulation (MLI) which had some edges located near the entrance aperture. It is almost impossible to outgas the MLI so this being a source of H₂O was not unexpected. It did show that the baffles were extremely efficient in eliminating the possibility of H₂O depositing on the primary mirror during the Cryo period.

Another TGA was performed on the CQCM near Day 140 ('97) in order to warm the CQCM up to near 300 K. This was done to complete the CQCM frequency vs temperature calibration curve for the additional temperature range prior to the beginning of SECOT 2. Between the times of SECOT 1 and SECOT 2 the temperature of the CQCM (and SPIRIT III) continued to increase. At the beginning of SECOT 2 on Day 167 the CQCM temperature had risen to about 140 K. This was nearing the borderline temperature where H₂O will condense/evaporate. During the second set of heating pulses the CQCM temperature increased from 140 K up to ~ 160 K. During this time the CQCM frequency increased from about 2600 Hz up to

3060 Hz - which was slightly higher than the deposition seen during the first series of heating pulses. This time no additional heating was required from within the CQCM as the mass first increased and then slowly came back off as the CQCM temperature passed through the evaporation temperature region. By Day 175 (of 1997) essentially all of the previously condensed film had been removed.

4.2.3 Materials Degradation

In space, materials are subjected to various conditions which can lead to degradation of physical properties. Atomic oxygen, ionizing radiation such as electrons and protons, vacuum environment, and solar exposure including UV are the effects of most concern. An optical element or thermal control surface can deteriorate due to the outgassing from surrounding materials with the subsequent polymerization due to solar UV. The TQCMs on MSX monitored the deposition of these material outgassing products on the spacecraft external surfaces.

4.3 Gases

The gases around the spacecraft during flight were measured by the neutral mass spectrometer, the total pressure sensor, the ion mass spectrometer and the krypton flashlamp. The gases which condensed on surfaces maintained at either cryogenic or ambient (-50°C) temperatures were measured by the CQCM and TQCMs respectively. The gases observed were classified either as contamination, i.e. induced from local sources or as atmospheric, i.e. found as the natural gases at the 900 km altitude of the spacecraft. With the exception of the krypton flashlamp and radiometer (KFR), all the above mentioned instruments detected gases whose trajectory intercepted the sampling port or sampling surfaces, i.e. backscattered. Care was made to minimize that these instruments' field-of-view did not include any spacecraft surfaces, but this proved to be impractical during the spacecraft design because of the large volume of the SPIRIT III sunshade which hovered over most of the other instruments. In the case of the TQCMs, one was specifically oriented so that it can monitor the outgassing from the solar arrays and the "dirty" electronic end of the spacecraft. The ion mass spectrometer was oriented generally into the ram direction during Parked Mode, therefore the amount of ions measured from the ambient atmosphere were maximized with respect to its velocity vector.

4.3.1 Composition-Neutral

The major neutral contamination measured during flight was water vapor, which was observed in the near-field environment of the spacecraft and on the cryogenic quartz crystal microbalance (CQCM) located inside the cryogenically-cooled IR telescope (SPIRIT III). Before the SPIRIT III door was ejected, argon gas was the dominant major neutral "contaminant." The major ambient neutral gas observed was helium. Atomic oxygen, if any, was masked by the background effect of water vapor in the neutral mass spectrometer.

4.3.1.1 Contamination

As expected from modeling studies, the major induced contamination neutral gas measured by the TPS, NMS and KRE was water vapor. The water vapor was shown to rapidly

sublime from the solar exposed surfaces of multilayer insulation. The sources of water appear to regenerate during eclipse since water vapor "bursts" continue to be measured three years after launched. Argon gas was the dominant early "contamination" until its source, the argon-cooled cover of the SPIRIT III, was ejected. There was some small organic contamination observed during the first day, mostly CF₃, which was probably due to residual Freon used to clean some part of the spacecraft before launch.

4.3.1.2 Atmosphere

The major ambient atmospheric composition observed was helium. Even though our atmospheric model predicted a small concentration of atomic oxygen, none was measured because of high background from water vapor fragments.

4.3.2 Composition-Ion

The only instrument originally selected to measure ionic species, either from contamination or from the ambient atmosphere, was the Bennett ion mass spectrometer. It was also equipped with an external retarding grid for measurement of spacecraft potential up to -32 V because the MSX Contamination Model predicted that the spacecraft will charge up to about -30 V during the nighttime portion of the orbit. Results however, did not support this since spacecraft charging stayed mostly constant at around -10 V throughout its orbit.

4.3.2.1 Contamination

The only ionic "contamination" observed was H₂O⁺, and only during the early portion of the mission. This ion was thought to be the product of the ion-molecule exchange reaction between neutral H₂O and H⁺.

4.3.2.2 Atmosphere

The major ionic species observed were O⁺, He⁺ and H⁺. However, 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 spheres. Similarly, the TPS, NMS, and IMS were able to measure spatial variabilities during auroral events over the poles.

4.4 Trends

Because future systems will require long lifetimes in orbit, MSX contamination instruments will continue to monitor the long-term trends of the generation of water vapor from MLI and of particles as a result of thermal cycling during terminator crossings, UV exposure, or materials erosion. Continuing measurements on temperature data from thermal radiators of the TQCMs, coupled with film deposition measurements, 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 aurora events.

4.4.1 Early Operations

During early operations, the pressures measured by the TPS, NMS and KRE followed an exponential decay in time. The major gas composition was argon from the SPIRIT III cryo-cooled door. The flight data for gases were measured by the total pressure sensor, the neutral mass spectrometer, the ion mass spectrometer and krypton flashlamp and radiometer. Even though gases were measured by the QCMs as the mass of their condensates, these data are reported here in the CQCM and TQCM sections. As mentioned previously, of these instruments, only the krypton flashlamp and radiometer measured gases (water vapor) even though the gaseous species were not being backscattered into the sampling port of the instrument. The mass spectrometer is a quadrupole-type mass spectrometer with an electron impact ionization source, while the ion mass spectrometer is a Bennett type instrument. The total pressure sensor is an inverted Redhead cold cathode gauge and measured the total gas pressures inside its ionization chamber as a total current. Because of this, the TPS can also measure electrons generated by the ambient during auroral events. The krypton flashlamp and radiometer utilizes the UV photons generated by the krypton flashlamp to photo-ionize the near-field water molecules in its field of view regardless of direction of travel while its integral radiometer measures the fluorescence of the excited OH* molecule and converts it into water vapor concentrations.

4.4.1.1 Total Pressure Sensor (TPS)

During the first several hours in orbit, the TPS showed argon cryogen subliming via its vent port. The total pressure was above the Go/No-Go criterion for water vapor, but since the NMS identified the environment as mostly argon, no change in plans was recommended to the program. After the SPIRIT III argon-cooled cover was deployed, the pressure measured by the TPS was mostly water vapor. The TPS measurements showed excellent reproducibility with respect to solar heating of surfaces on the +X face of MSX.

4.4.1.2 Neutral Mass Spectrometer (NMS)

During the first days in orbit, argon was the major gas species, as verified by the mass spectrum obtained from the NMS which showed a very large mass 40 argon peak and the "normal" gases as a result of water vapor and residual gases. The volatile organic molecules (defined as the sum total of molecules with AMU >45) also showed negligible organic contamination beyond 24 hr MET, and the amount detected during the first day of orbit was not of concern to the UV and VIS optical instruments.

4.4.1.3 Ion Mass Spectrometer (IMS)

The IMS measured several positive ions such as O⁺, He⁺ and H⁺ during the cryogen phase, but its major contribution was the measurement of spacecraft charging of between 5 to 10 V irrespective of solar illumination.

4.4.1.4 Krypton Radiometer Flash Lamp (KRF)

The KRF measured a much larger time variation for water vapor, which is also correlated to a different area being solar-illuminated during spacecraft maneuvers and a different volume being observed. The effect of solar illumination on the data from the KRF showed that the higher water vapor measurements significantly clustered around observations as the spacecraft exited the umbra.

4.4.2 Specific Events

There were many specific events during the first three years in orbit. However, three are the most noteworthy so far. These are the many terminator crossings data measurements on the variation of gases and particles observed by the instruments, the results of rapid slewing or maneuvers of the spacecraft and the effect of solar illumination during these maneuvers and during the end of solid hydrogen (cryogen) in the SPIRIT III Dewar. There were other specific events such as the initial outgassing events during the first few days in orbit (the "barbecue" mode) and the release of the UVISI, SBV and SPIRIT III doors. The release of the doors resulted in large amounts of particles being generated, as described elsewhere in Section 4.5.

4.4.2.1 Terminator Crossings

Terminator crossings, especially the portion when the spacecraft goes from dark to solar illumination, has been observed to generate most of the water vapor and has been positively correlated with particle generation, possibly due to a mechanical "deflection" effect due to thermal shock (see particles section).

4.4.2.2 Maneuvers

Rapid slewing has been shown to generate more particles than during quiescent operations (see particles section). As discussed above, solar illumination rapidly increases the near-field concentration of water vapor, followed by an exponential decay due to the depletion of surface water.

4.4.2.3 SECOT

SPIRIT III End-of-Cryogen Operations Tests (SECOT) Measurements on the local environment during the warm-up of a large cryogenic telescope have been made during a series of tests called SECOT (SPIRIT III End-of-Cryogen Operations Tests. See the SECOT description in the Film Section, 4.2.2.4). These data have shown that water sublimating at around 150 K could condense on colder surfaces with a direct line-of-sight from the source. It also showed that a large primary mirror with condensed ice on its surface may be "cleaned" by the careful use of solar illumination to sublime the surface ice.

4.4.3 Long Term

The particle generation due to thermal cycling and exposure to solar UV flux is being monitored for long-term trends. The behavior of water vapor sublimation, especially inside IR optics which hover around 150 K, would be of interest to optical systems which is expected to have a lifetime of more than 5 years.

4.4.4 Model Comparison

The MSX Contamination Model has been fairly successful in predicting the general trends of argon and water vapor concentrations from early operations during the first six months. The MSX Contamination Model is described in Section 4.6.2.

4.5 Particles

Particles can reduce optical sensor performance by depositing on sensitive surfaces, increasing scattering and by obscuring/distorting farfield optical scenes. Particles originating from the spacecraft can be detected across the UV-IR spectrum by their thermal emission, scattered sunlight and earthshine. The Xenon flashlamp (XEF) operating in conjunction with a 10.5 x 13.1 deg visible imager (IVW) permits quantitative particle measurement in a volume centered 2 m above the spacecraft under conditions independent of external illumination levels. Particles are illuminated with 400 to 900 nm light in a series of nine 11-ms pulses sequenced to permit velocity determination within a single image. During the first week in orbit, the particulates observed are likely residual from ground operations as brought to orbit with the spacecraft.

Although particles were clearly observed associated with discrete operational events, particles were observed even during spacecraft passive periods. At the 904 km altitude of MSX, atmospheric drag effects are small and particles can remain in the fields of view of the optical instruments for long periods. Particles were observed to remain in the IVW field of view for over 200 seconds. Several data-collection events were scheduled at different positions around the orbit to isolate production processes.

4.5.1 Occurrence

The quiescent particulate environment became more benign with time over the course of the first year on orbit. The graph shown in Figure 13 represents a monthly average of this particle occurrence rate for the first year of the mission. The particle occurrence rate is highly variable, with anywhere from half the images containing particles to essentially no frames containing particles (<0.001). Each data collection event (DCE) comprises 3 to 12 min of observation time. Each image frame is 0.5 seconds in duration. Particles are present in 3% of all UVISI image frames. The occurrence rate has declined slowly with mission duration. (Ten percent of the frames had at least one particle during the first mission month, 1% had at least one particle during the twelfth mission month.) This long time trend data shows that while there is great variability even in the monthly averages, the clear trend to a reduced release of particles is

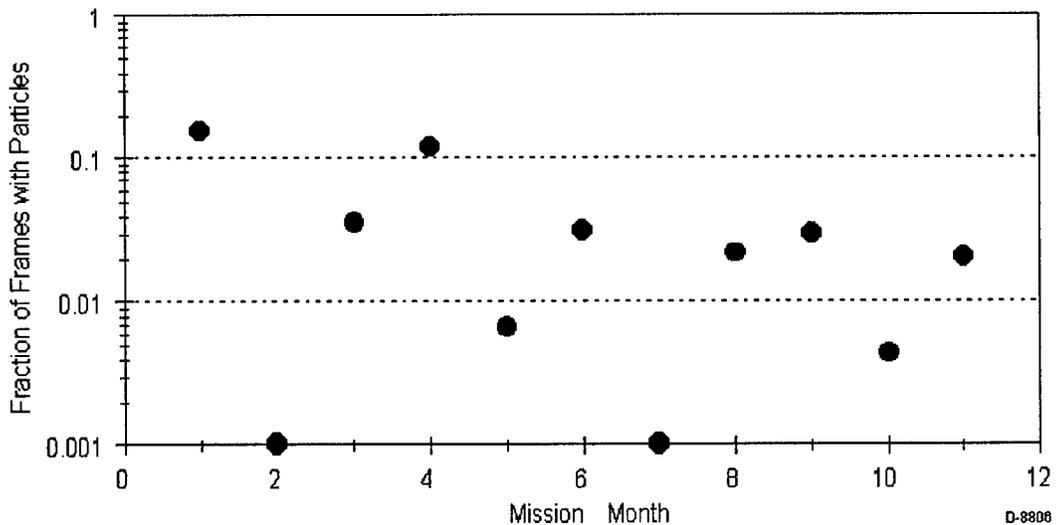


Figure 13. Fraction of UVISI visible wide field of view sensor frames containing a detectable particle as a function of mission month.

observed. Based on total spacecraft surface particle loading at launch and the observed particulate history, we estimate that even after 1 year on orbit, we are still observing residual particles from ground operations and not particles produced by orbital processes such as abrasion.

4.5.2 Size

The particles are 10 to 20 μm in size with a distribution shown in Figure 15. Solar illumination (umbra exit) reproducibly stimulates particle release, and thus represents the least favorable viewing time for performing remote observations.

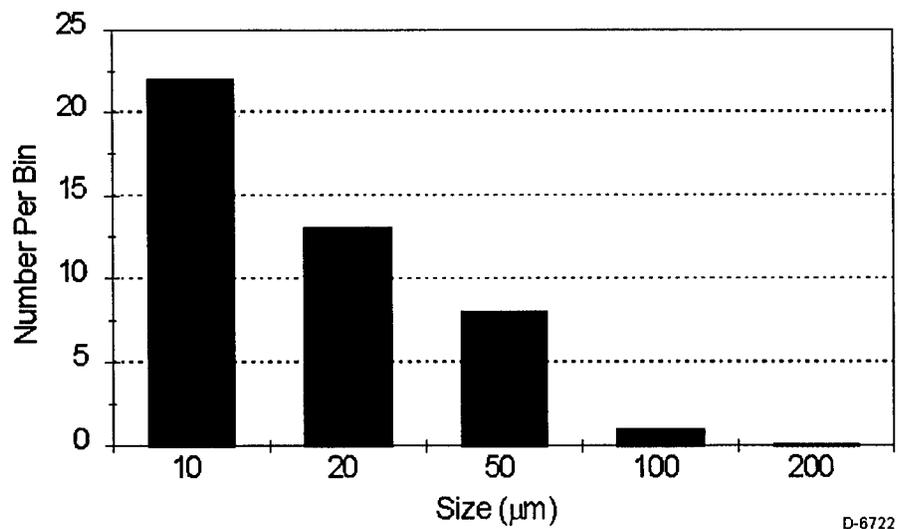


Figure 14. Deduced particle size distributions.

4.5.3 Velocity

The particles reside in the sensor field of view 2 to 20 seconds typically. The particles have a 5 cm/s most probable velocity with a distribution spanning 0.1 to 50 cm/s as shown in Figure 15.

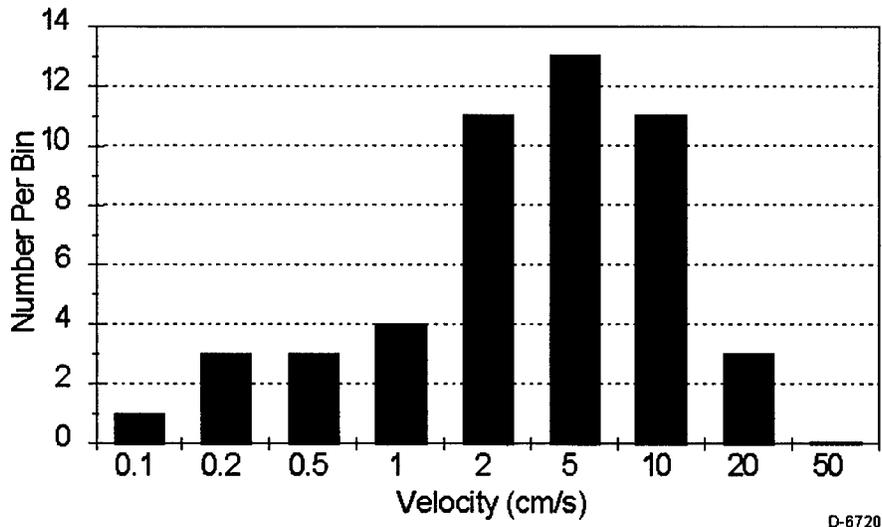


Figure 15. The deduced particle velocity distribution based on quiescent time UVISI data.

Figure 16 shows the average distribution of residence times for particles in the UVISI IVW. The UVISI IVW has a 10.5 x 13.1 field of view. Since the particles represented in this distribution were observed in the near-field of the spacecraft (distances < 4 m), the residence times are long, but finite. Particles in the far field, with comparable cross-field velocities will have proportionately longer residence times. It is perfectly conceivable that a single particle could remain in the field of view of a sensor for an entire DCE.

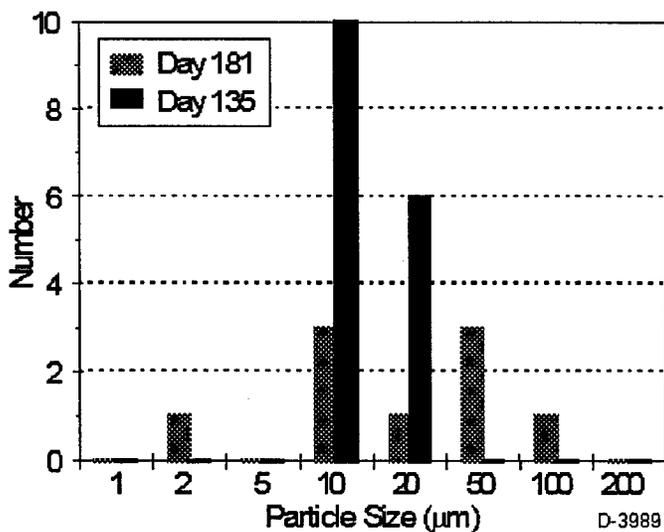


Figure 16. Size distributions for particles observed during umbra exits on days 139 and 181.

4.5.4 Particle Effects on Optical Sensors

Solar illumination determines the observed signature and detection limits in the ultra-violet and visible, while self emission and scattered earthshine radiances will produce the infrared signature. Visible light film camera-based observations of the environment surrounding the Shuttle have provided an extensive particle observational data set. Size distributions peak to smaller radius particles. Particle velocities relative to the spacecraft of m/s were observed. Activities such as maneuvers, mechanical operations, and even terminator crossings induced the release of particles from surfaces. Infrared emission from particles was observed by the CIRRIS1A radiometers and interferometer during STS-39. Particles over the cm to 100 μm range were detected in the field of view for several seconds.

Short duration missions will be dominated by the release of particles brought to orbit from the ground and ascent environments. On extended duration missions, after these ground-origin particles have evolved from surfaces, additional particles will be created by erosion, abrasion, impacts, and thermal stresses. A long duration orbital database on the magnitudes of these processes does not exist. The Midcourse Space Experiment will be the first mission to provide quantitative information from on-board environmental monitors that will permit an assessment of the thorough Contamination Control Plan that guided its design, assembly, and handling. Previous space missions have lacked either a detailed plan, sufficient instruments for verification, or were of too short duration to provide guidance for future space-based-assets designers. Because particles can arise from both ground and orbital sources, both a Contamination Control Plan and monitoring instruments are required.

The primary sensors on MSX are the telescoped optical instruments covering the 0.1 to 26 μm spectral region. All these sensors are aligned along the spacecraft +X axis. The UVISI instrument contains four imagers (both UV and visible wide and narrow fields of view) and five imaging spectrographs covering the 110 to 900 nm spectral range. Sensitivities are in the single photon/cm²-s range, permitting detection of particles down to 0.2 to 10 μm via scattered sunlight. The Space Based Visible instrument consists of five sets of CCD array (420 x 357) detectors each having a 1.65 x 1.4 deg fixed FOV. There are a range of gains and integration times for both UVISI and SBV. The SPIRIT III radiometers form an array 192 elements high (subtending a one deg angle) by only a few detectors wide in each of six color bands. These bands span different segments of the 4.2 to 26 μm spectral region. A mirror repeatedly scans the instantaneous narrow field of regard across a 3 deg angle during a seven second period. Noise Equivalent Spectral Radiances of the radiometer arrays are in the 10 to 13 W/cm²-sr- μm range, permitting detection of 20 to 50 μm particles. The SPIRIT III interferometer will permit spectral signatures of radiometrically detected particles to be measured. The observed spectral radiances may permit the particle's composition to be determined from its signature as shown by previous modeling.

The particles are expected to leave the surface with only a small velocity relative to the spacecraft. The molecules of the tenuous upper atmosphere collide with the particle at 8 km/s velocity and exert drag, forcing the particle to slow relative to the atmosphere (but accelerate away from the spacecraft). The particle acceleration in the spacecraft frame depends on the atmospheric density and composition (these quantities will be measured by the neutral mass

spectrometer and pressure sensor aboard MSX). Particles will be observed in the optical field of views either by having a trajectory passing directly through the nearfield observed volume, or a trajectory initially to the windward of the optical axis that is swept by drag back into the observation volume. Particles remain in the vicinity of the spacecraft and are accelerated only slowly over a 100 to 10,000 second period. Thus particles have been observed to be resident in the field of view for times ranging from seconds to the duration of an entire data collection event.

4.5.5 Particle Generation During Early Mission Slew Events

In addition to the umbra exits, slewing of the spacecraft also releases particles. At the conclusion of a DCE with a fixed attitude (for example a particular ram angle or sun angle), the spacecraft slews back to its nominal "parked" attitude. Often during these slews, particles are released. Figure 17 shows a series of images that illustrate the trajectory of a particulate released during a spacecraft slew. These particles are typically moving with angular velocities very close to that of the spacecraft. In the images, the spacecraft angular velocity is approximately 1 deg/s, whereas the particles angular velocity is approximately 1.4 deg/s. The linear velocity of the particle is very close to the linear velocity of the outer spacecraft surfaces at an angular velocity of 1 deg/s. This seems to indicate that during slewing, particulate release with very low relative velocities.

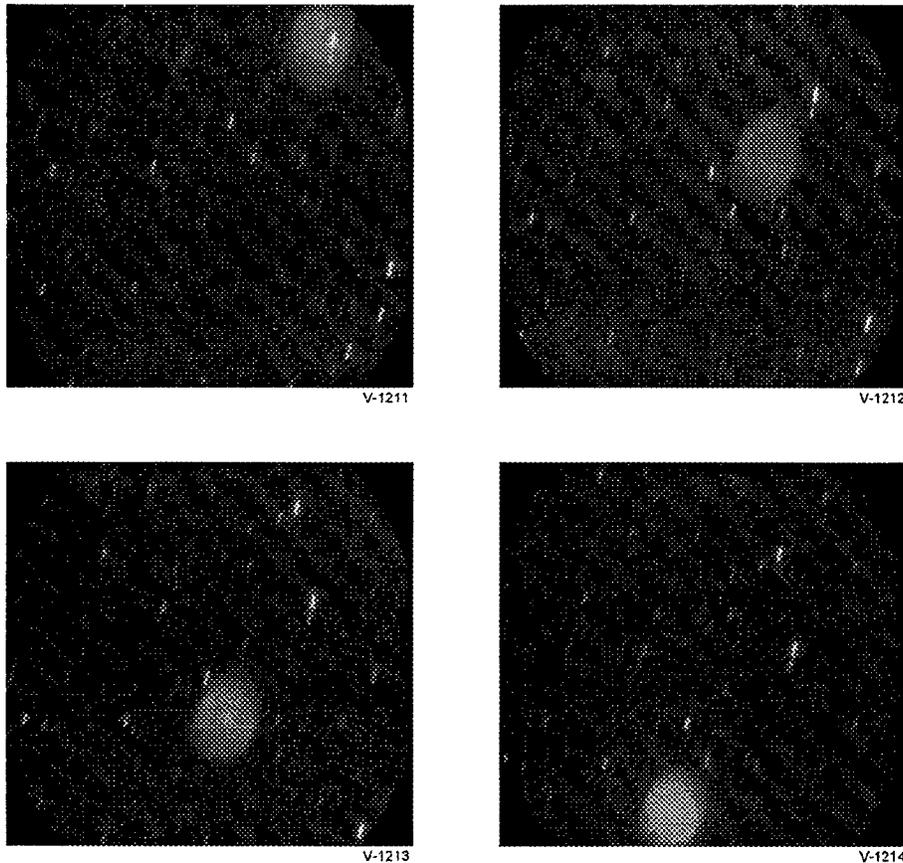


Figure 17. Time sequence of images of a particle released during a spacecraft slew. Stars are in focus and are moving at approximately 0.7 deg/s. The particle is defocused and is moving at 1.4 deg/s at a range of 170 cm.

Particles are released during umbra exits. Every observation during the early time on orbit performed during an umbra exit has yielded particle data. An example of a particle observed after terminator crossing is shown in Figure 18. This result confirms the shuttle observations of previous investigators. There is a latency of approximately 2 min between umbra exit and the appearance of the first particles. This latency is longer than the particle's transit time through to the sensor field of view. This latency implies that the release mechanism relies on the heating of some spacecraft component (or particle) with a fair thermal mass (or low absorptivity). In addition to umbra exits, spacecraft slewing results in particle release. During many spacecraft slews a small number of particles is released with very slow relative velocities.

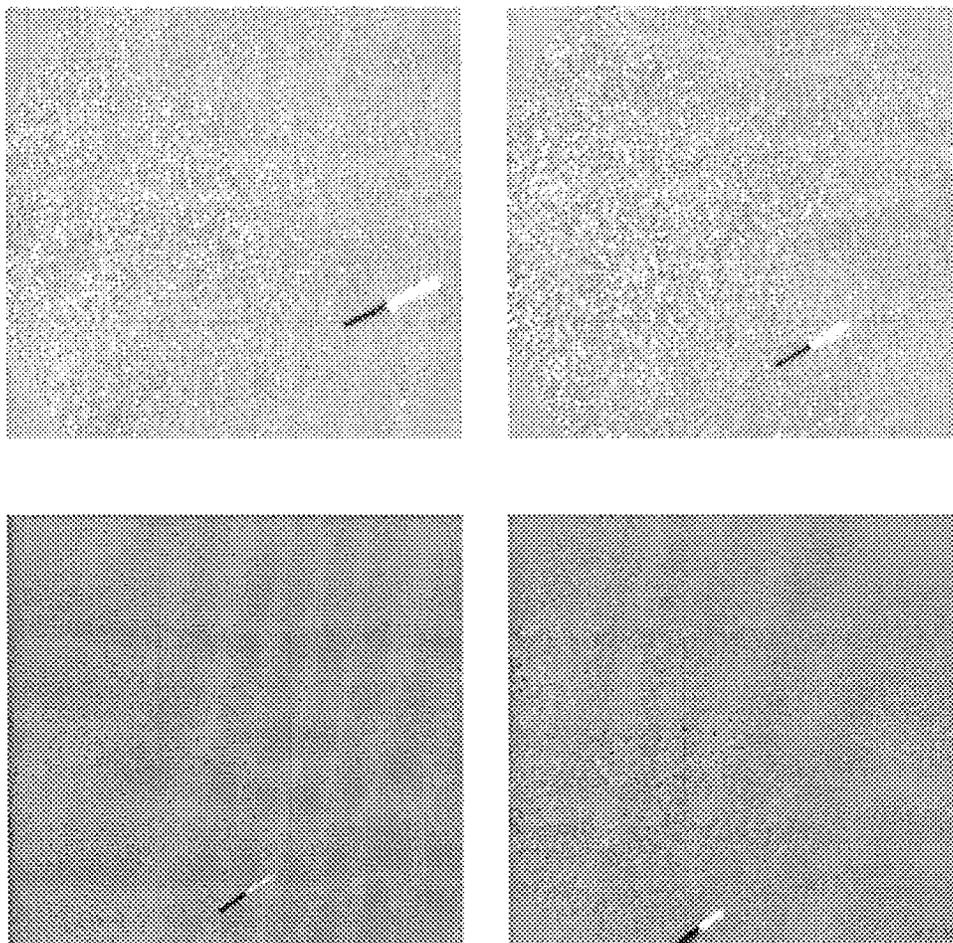


Figure 18. Sequential images of a single particle observed after a termination crossing at 123 hours MET.

We have determined X, Y, Z velocity components for many particles observed. Since drag is unimportant over short distances at MSX altitudes, one can get insight into the particle sources by propagating the straight-line trajectory backwards in time until it inter-sects the spacecraft. In practice, the limited precision of the velocity determinations results in a rather

large uncertainty circle at the intersection with the spacecraft. However, taken in total, the particle trajectories do provide insight into source regions.

4.5.6 Particle Generation Upon Early Mission Door Opening

The XEF was operated during periods of mechanical operations such as all sensor door openings and cover release events. In spite of the careful ground operations procedures to minimize particulate levels, particles associated with every one of these events were detected. An image acquired by the wide field visible imager 20 sec after its hinged cover opening contained approximately 20 particles. The particles were observed via scattered sunlight (125 deg to +X). To protect the image intensifier, the gain was relatively low for this image. The particles have similar trajectories: away from the spacecraft with a large velocity component along the direction of cover motion and a smaller perpendicular velocity. Similar particle densities and trajectories were observed associated with every sensor door opening. Although the optical environment was severe during door openings, the particles cleared quickly.

4.5.7 Particle Generation Upon SPIRIT III Cover Ejection

The primary infrared sensor on MSX is a telescoped radiometer/interferometer sensor (SPIRIT III) whose optics are cooled to about 20 K to achieve sensitive detection of passive upper atmospheric and celestial radiances. This sensor was equipped with a vacuum tight door covering the sensor aperture to permit cryogenic loading during ground processing. To minimize the radiant load, the door was also cooled to well below 100 K using solid argon. After launch the door remained in place during the period of spacecraft systems initial checkout ("Early Operations"). The outgassing and local contamination environment were carefully monitored during this Early Operations checkout period. Because the environment surrounding the MSX spacecraft as measured by the suite of Contamination Instruments was determined to be sufficiently benign, the SPIRIT III door cover was released as planned seven days after launch.

The IR sensor system is required to perform observations with high off-axis rejection. The level of scattered radiation is an extremely sensitive function of particulate contamination levels on the cryogenic primary mirror. Because significant particle generation was expected and observed with all mechanical cover openings on MSX, we planned to open the SPIRIT III cover after all other systems had been operated in orbit. This delay also permitted molecular outgassing to decay to lower levels.

The release of the SPIRIT III cover marked the end of the early operations period and the start of cryogenic operations period. Based on modeled cover opening safety criteria, the contamination team advised operations that it was safe to remove the SPIRIT III cover by 108 hours MET. Because the temperatures of the argon cryogen cooled cover were still in the acceptable range, the release was performed as planned slightly less than seven days after launch.

The shock from the pyrotechnic actuators imparted momentum to the spacecraft and resulted in the release of many particles from spacecraft surfaces. These dislodged particles are probably from ground operations, brought to orbit on MSX surfaces. The dislodged particles are observed with the primary optical sensors by UVISI and by SPIRIT III itself. Three sequential

frames for the UVISI IVW imager are shown below in Figure 19. They are taken just after the time of the SPIRIT III cover release and are separated by 0.5 seconds. The optical environment is very severe at this time, with an optical transmission to the far field near zero. Particle velocities extracted from the pulsed illumination are on the order of meters per second.

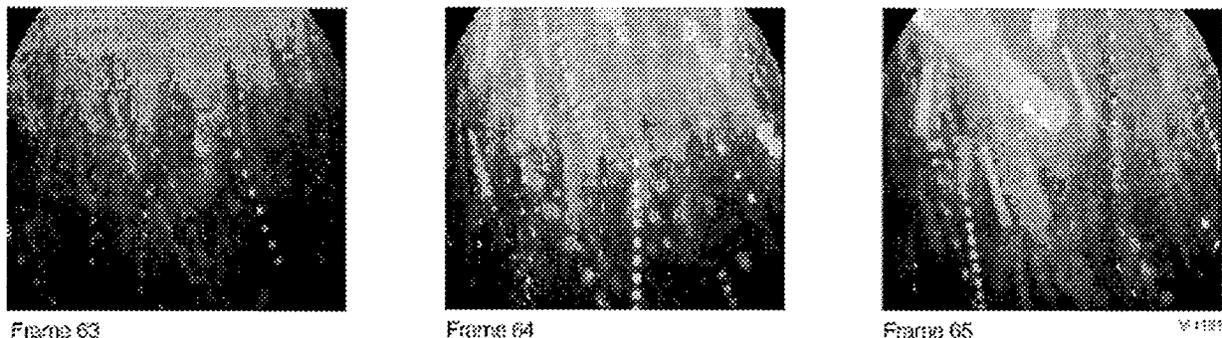


Figure 19. IVW imager data frames 0.5 second apart from time of SPIRIT III cover ejection. Particles in the meter/s range are observed moving at approximately 0.7 deg/s. The particle is defocused and is moving at 1.4 deg/s at a range of 170 cm.

A pseudo-image of the radiance detected by the SPIRIT III radiometers in the 6.0 to 10.9 μm (Band A) spectral bandpass is shown in Figure 20. This image was acquired in the first few minutes after the door release. The pseudo-image is created by a mirror scanning the 192 pixel radiometer column across a 3 deg field of regard. The sweep moves from right to left in the image and takes about seven seconds. The optical axis of the sensor is the +X axis of the spacecraft. The attached image is about 1 deg high (the spacecraft Y axis) and 3 deg wide (Z axis). cursory examination of the pseudo-image reveals nine particle tracks that are labeled on the figure. The tracks display a wide range of optical characteristics: from nearly single pixel point sources to ellipses extending beyond the edge of the pseudo-image. We observed several particle tracks within a single pseudo-image. These tracks were analyzed to extract particle positions and velocities relative to the spacecraft and velocities relative to the spacecraft optical axis. Particles out to several kilometers from the sensor were potentially detectable.

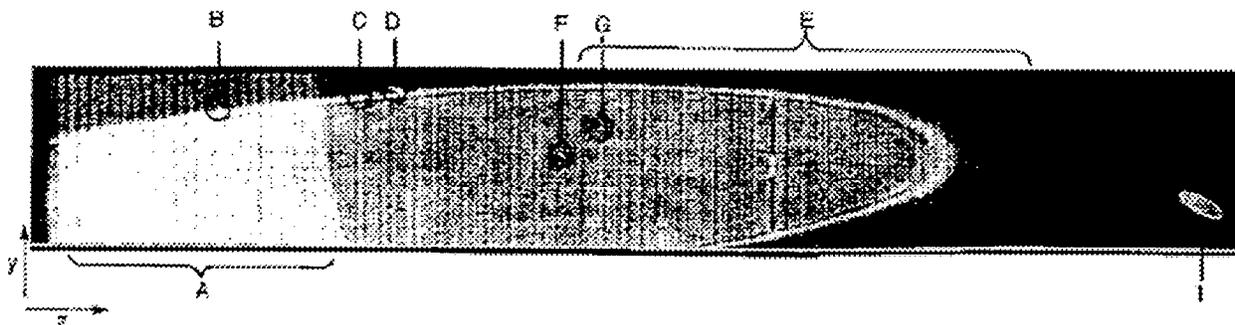


Figure 20. Radiometer data after door opening..

The SPIRIT III door is a 102 kg, meter diameter-scale object released with a separation velocity on the order of 1 m/s. This event imparts sufficient momentum change/shock to the spacecraft to dislodge particles loosely adhered to external surfaces. At this time based on the preliminary data, we are unable to determine the particle sizes or likely source(s) during this event. We will investigate the origin of particles observed during all the sensor cover openings once certified data becomes available. The SPIRIT III data from the period 11.5 minutes to 18 min after door opening was also inspected for particles. No particles were observable by the SPIRIT III radiometers during this period only ~10 min after the data shown in the figure. These wide spectral bands would be sensitive to particle radiance in the thermal emission region. No particles were detected down to the average radiance levels in the pseudo-image. We conclude that the particle environment surrounding the MSX spacecraft cleared quickly after the door release, and that by 10 minutes after the release, no particles were visually detectable. This conclusion is in agreement with the MSX contamination experiment near-field observations using the Xenon Flashlamp. The particle clearing times of the region two meters above the spacecraft surface following optical sensor door openings is on the order of 2 min.

Shortly after the SPIRIT III cover release, MSX maneuvered its optical axis away from the receding cover. Within 2.5 min, particles were no longer observable in the UVISI IVW images. The cover-induced particles rapidly move away from MSX and out of the field of view.

4.5.8 Particle Generation Upon Meteorite Impact

On 11 November 1996, after nearly 7 months on orbit, we observed a discrete particle event that was not associated with any known spacecraft activities. The size and velocity distributions from that event are in distinct contrast to the quiescent distributions. While the spacecraft does perform some discrete mechanical maneuvers and deployments, these activities are planned long in advance and are not interjected into routine spacecraft operations. That is, their schedule is well known in advance. The spacecraft is solar illuminated for the entire DCE. The sun is ~90 deg to the X axis for the entire DCE, and the DCE begins near the equator and continues through 33 deg N latitude. The Xenon flashlamp was turned off at the time of the particle release event; therefore all the particle imagery is with solar illumination only.

Before the particle event, there were no particulates observed during this DCE. Figure 21 shows a sequence of image frames from around the time of the event. Figure 21a shows the IVW image approximately 2 seconds before the event. In-focus stars are clearly visible. Figures 21b-e show a time sequence of images beginning 3 seconds after the event and the out-of-focus particles are seen moving through the sensor field of view. As the particles move away from the spacecraft, their angular velocity decreases and they become more focused (Figure 21e). The numerous particles released are clearly visible in the later images. The particles' velocity is directed mainly away from the spacecraft.

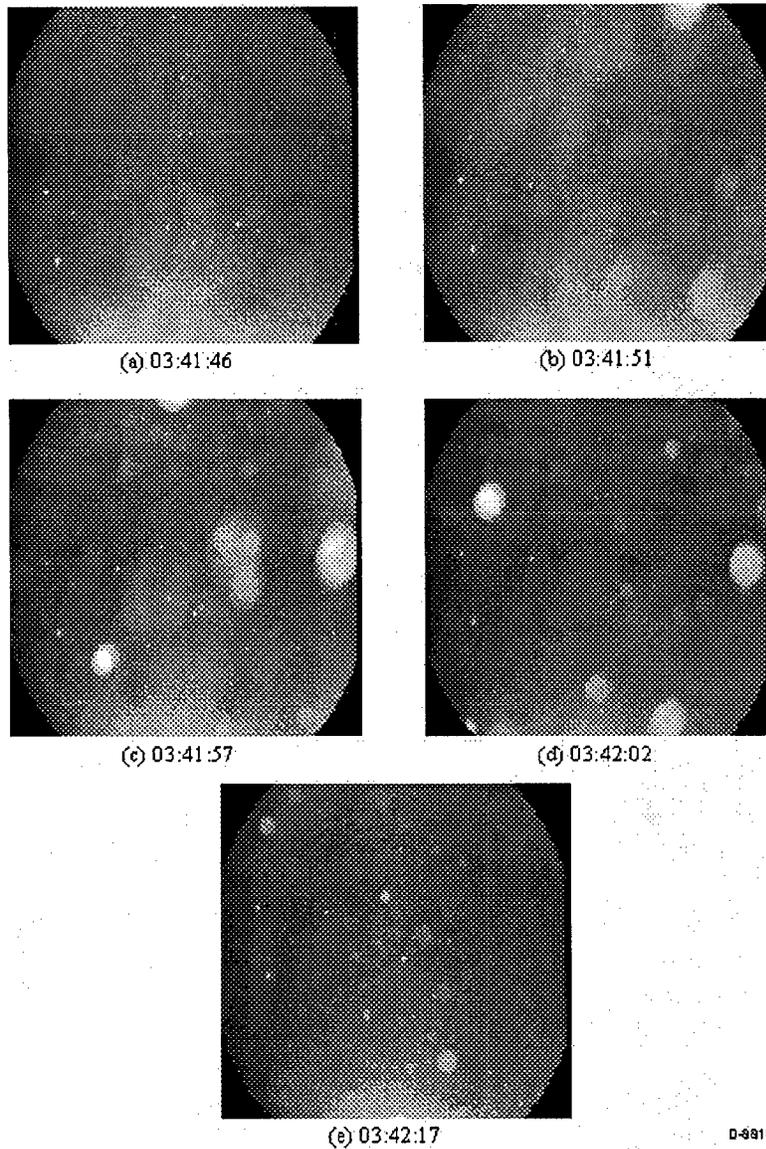


Figure 21. Sequence of visible images (UVISI IVW) from time of particle event.

The particle scattering cross-section is determined directly from the calibrated imagery and the illumination conditions. The cross-section can be determined with uncertainty of about 50%. In order to estimate particle sizes, however, one must assume an albedo for the particle. For these data we have assumed an albedo of 0.1. A particle's range and line-of-sight velocity are determined from the blur circle and its temporal behavior. The cross-field velocities are determined by tracking particles from image frame to image frame. Uncertainties in the range are typically 25% and uncertainties in the velocity are typically 40%.

The particle size distribution from this event is shown in Figure 22. The minimum detectable particle size for this experiment is 20 μm . The size distribution peaks at 50 μm and contains many larger particles. This distribution is in contrast to the quiescent size distribution shown in Figure 23. The average particle size distribution for the first year on orbit follows an

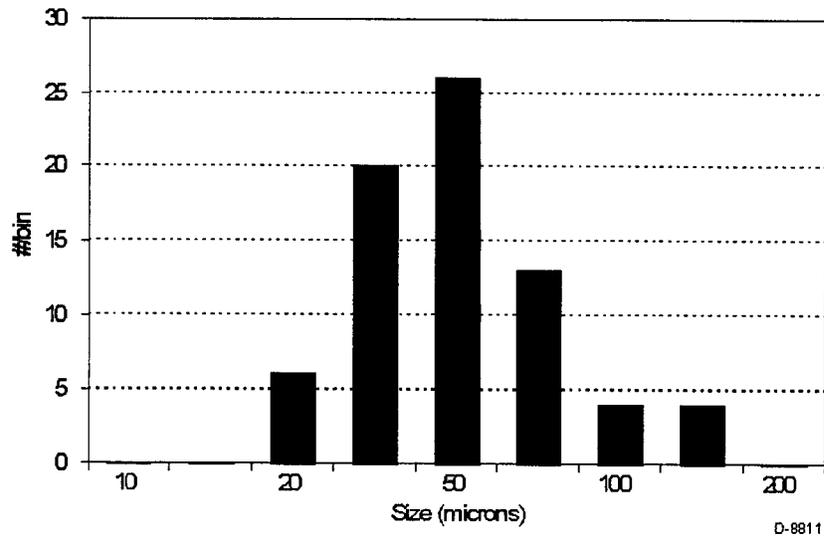


Figure 22. Particle size distribution from CE0101000148.

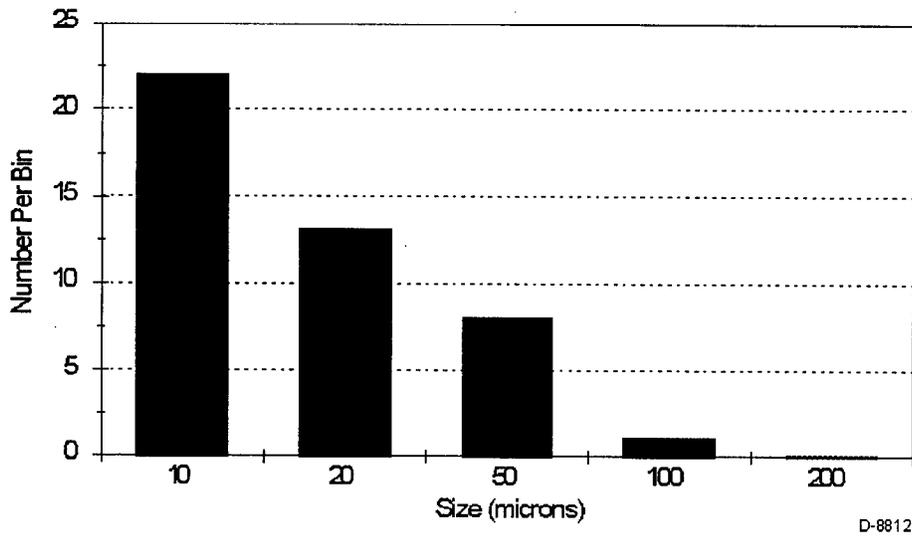


Figure 23. Average particle size distribution from first year on orbit.

$r^{-1.5}$ law and has very few particles over 50 μm in size. The minimum detectable particle size for that quiescent distribution is 10 μm and the quiescent distribution is in agreement with previous orbital measurements. The particle event velocity distribution also differs from the quiescent velocity distribution. The event velocity distribution peaks at 0.2 m/s to 0.5 m/s, while the quiescent distribution peaks at 0.05 m/s, with very few particles moving faster than 0.2 m/s. The quiescent distribution is consistent with particles being released with very slow initial velocities. The mechanism for most particle releases is likely solar illumination.

The size and velocity distributions have been modeled previously. The distribution from the present event is in fair agreement with the distribution expected from spallation of material from a crater after an impact. Further evidence that this event results from a discrete impact is

the spatial and temporal origin of the event. We analyze the particle imagery to determine the three dimensional velocity vector of each particle. From those instantaneous velocity vectors, we have propagated the trajectories back to the spacecraft, ignoring the effect of drag, to determine the spatial and temporal origin of the particles. The uncertainties in the velocity and position determinations limit the accuracy of any given determination; however, with many tens of individual particles, the standard deviations of the mean become reasonable. The origin (intersection with the +X plane of the spacecraft) is $Y = -0.89 \pm 0.18$ m, $Z = 0.42 \pm 0.16$ m, and $t = 03:41:48.3$ UT ± 2.1 seconds. The approximate origin position is near the beacon receiver.

The MSX Contamination Experiment has observed a discrete particle release of several hundred particles not associated with any spacecraft activity. We have hypothesized that this event is due to debris particle or micrometeoroid impact. The particle size and velocity distributions are consistent with previous predictions of pre-existent particles released as a result of a micro-meteoroid impact. We have also propagated the particle trajectories backwards to determine the spatial and temporal origin of the particle release. The origin of these trajectories within the uncertainties indicate a spatially and temporally discrete event. While more modeling is needed, we can state with reasonable certainty that the particle release was due to an impact. Further modeling may shed light on the size and velocity of the impacting particle.

4.6 Legacy

The Midcourse Space Experiment (MSX) is the first mission to provide quantitative information from on-board environmental monitors that enable assessment of the orbital environment surrounding spacecraft after years in orbit and assessment of the effectiveness of the thorough contamination control plan that guided its design, assembly, and handling. Previous space missions have lacked either a detailed plan or sufficient instruments for verification, or were of short duration. They have not provided the guidance required by future, space-based-assets system designers. Because particulate contamination can be carried up from the ground or created by mechanical stresses/wear, erosion, or impacts while in-orbit, both a control plan and monitoring instruments are required. The measured contaminants and levels at the monitors are traced back to the sources using an external transport model. The MSX contamination experiment will provide a legacy by:

- Identifying and quantifying sources in orbit,
- Measuring the time dependence of contamination and its effects from the second day of in- orbit operations,
- Validating the spacecraft external transport model,
- Validating the effectiveness of the contamination control plan and recommending improvements,
- Relating contamination levels to the effects they produce,
- Measuring the occurrence and magnitude of particle-induced false tracks during realistic viewing scenarios,
- Providing increased knowledge of the natural atmosphere, its variability at these altitudes, and its effect on space-based systems.

4.6.1 Calibration

Quartz Crystal Microbalances (QCM)

The QCMs were calibrated and characterized at temperatures as low as 10 K in a cryogenic calibration facility at the Air Force Arnold Engineering Development Center (AEDC) in Tullahoma, TN.

Total Pressure Sensor (TPS)

The MSX Total Pressure Sensor (TPS) is a cold cathode gauge designed to measure the ambient pressure. The cold cathode ionization gauge operates on the Penning discharge principle of crossed electric and magnetic fields, whereby electrons in the discharge region become trapped. These electrons collide with incident neutral particles, resulting in ionization. These ions are collected at the cathode and the magnitude of the cathode current is proportional to the pressure. The calibration of the TPS consisted of measuring instrument response to known pressure changes of various calibration gases. To minimize calibration uncertainty, the majority of testing consisted of measuring TPS output at increasing values of calibration gas pressure. This method of "increasing gas pressure" was used to avoid the error generated by slow desorption of gas from the walls of the calibration chamber which occurs when pressure is decreased. The selection of calibration gases was based on the expected on-orbit constituents. Additionally, nitrogen was used so that the results for the two MSX pressure sensors (one of which is flown) may have their performance compared to other pressure sensors. The gases chosen for use in the calibration were helium, nitrogen, argon, and water. The calibration was performed by specialists at NIST in Gaithersburg, MD and was conducted against their primary standard. The calibration curves for each of the gases for the MSX flight TPS are shown in the Figure 24.

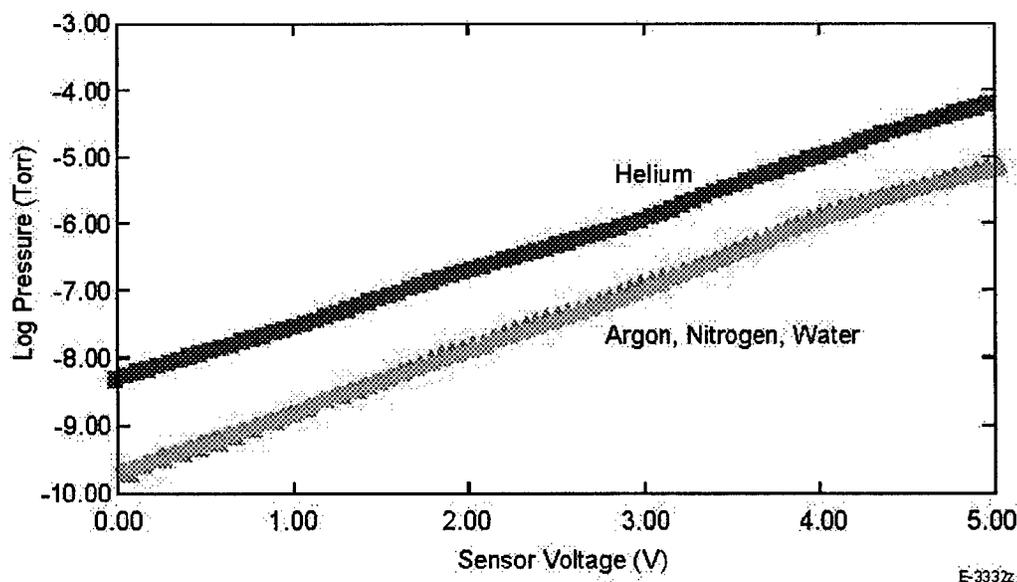


Figure 24. Calibration curves for MSX gases.

Neutral Mass Spectrometer (NMS)

NMS calibration was performed in an all-metal turbo-pumped vacuum chamber with a typical base pressure of approximately 5×10^{-9} Torr. A quadrupole partial pressure analyzer and two Bayard-Alpert ionization gauges, previously calibrated in the NIST calibration chamber, were used to provide transfer standards. The ion gauges, previously calibrated in the NIST calibration chamber, were used to provide transfer standards. Calibration gases were introduced into the chamber via a precision leak valve, which was connected to a ballast tank. The partial pressure of the calibration gas in the vacuum chamber was controlled by varying the ballast tank pressure. By this technique, the partial pressure was varied from the base pressure up to 1×10^{-6} Torr (limited to 1×10^{-7} Torr for reactive gases) by a factor of 3 at each step. To provide a reproducible baseline, the NMS was repeatedly calibrated with helium. Helium, the predominant naturally occurring species on orbit, is not reactive, and therefore does not produce chemical changes in the source region or the filaments. (The two filaments had slightly different sensitivities.) The NMS sensitivity is reproducible within 20%, even after exposure to a highly reactive gas such as oxygen or water vapor.

The characterization of the NMS in water is extremely important to the MSX program because water vapor is expected to be the primary contaminant in the spacecraft environment. The spacecraft itself is the primary source of the water vapor, having been adsorbed onto the blankets and exposed surfaces of all elements of the spacecraft. Calibration of the NMS for water vapor was accomplished using a NIST prototype water vapor source connected to the vacuum chamber through a precision leak valve. The NMS response to water vapor was essentially linear, although it should be noted that CO, H₂, CO₂, and CH₄ were observed, presumably due to chemical reactions occurring on the filaments since the concentration of these species increased at a similar rate to water vapor during the initial measurements at low pressure.

In addition to helium and water vapor, the NMS was also calibrated with argon, hydrogen, oxygen, and nitrogen; the latter was used in instrument testing as the standard by which the NMS could be compared with other mass spectrometers. Argon was expected to be the dominant gas present during the early operations phase of the mission since it was vented from the solid argon cryogen in the SPIRIT III aperture door which is located near the NMS. Although solid hydrogen is the primary cryogen used for SPIRIT III, its vent is located at the opposite end of the spacecraft and is not expected to be detected. However, hydrogen and oxygen atoms, along with helium, are the major atmospheric species present at 900 km and will react on surfaces and remain adsorbed or recombine to form molecular hydrogen and oxygen. Providing that the instrument background for hydrogen and oxygen is relatively low and that the equilibration time for the surface reactions is not too long, it was hoped that ambient hydrogen and oxygen atoms could be indirectly detected. The sensitivities of the calibration gases are listed in Table I for low emission (30 μ A) and high emission (90 μ A). The NMS sensitivity for other gases is assumed to be similar to argon and nitrogen; these values are 7×10^{11} counts/Torr (low emission) and 2.1×10^{12} counts/Torr (high emission).

Xenon Flashlamp (XF), UVISI IVW and SPIM3

The Xenon Flashlamp and the UVISI IVW are calibrated independently. The primary standard used for the Xenon Flashlamp is an Eppley Laboratories 1000 W tungsten irradiance standard with a NIST traceable calibration against which the spectral irradiance of the Xenon Flashlamp is compared. In addition, properties including pulse-to-pulse intensity variation, temporal pulse shape variation, and temperature and voltage effects are characterized. After the completion of the individual instrument calibrations, an end-to-end performance test was carried out with the two instruments in joint operation. The test was performed in a cleanroom that is certified for Class 10000, but that typically approaches Class 1000 in cleanliness. The Xenon Flashlamp and the UVISI IVW were bolted to a mock spacecraft instrument pallet that ensured the instruments would be in their relative flight geometry. For contamination control reasons, the IVW aperture cover remained in place during the testing. That cover is equipped with a window through which the sensor viewed the illuminated volume with a reduced field of view (~5.5 deg circular). The particle measurements made during the early phase of the mission will also be performed with the IVW observing through its aperture cover window. The window allows particle measurements to be made very early in the mission, without risking contamination of the UVISI IVW. During ground testing, the Xenon Flashlamp was operated both in its normal configuration (with a 4.5 deg fwhm beam) and with the beam externally baffled to an ~1 deg fwhm. The room was sealed off from external light sources and all internal light sources (monitors, LEDs, etc.) were covered or blocked. The background for the IVW field of view was provided by a set of black plates. Although the baffling and light blocking measures were quite effective, some reflected stray light is present in the images. Three sizes of latex spheres (50 μm , 14 μm , and 5 μm radius) were introduced into the measurement volume. The spheres are provided as a suspension in a solvent. The 5 μm spheres were introduced with a nebulizer that evaporates the solvent and essentially dispenses particles on a current of air. The larger spheres could not be used in the nebulizer, but were introduced with a pipet after evaporation of the solvent in ambient air. Measurements were performed over a period of two days. Because of the limited data rate and storage capacity of the ground support equipment (GSE), only a few images could be saved at a time. Each image was visually inspected in real time on the GSE monitor, and a decision was made as to whether it was saved or not. Only those images with visibly obvious particle tracks could be saved. A total of 23 images were recorded. A variety of image processing tools, including background subtraction and Fourier filling, were used in the analysis. Figure 25 shows an image and the corresponding surface plot of two 50 μm particles traversing the field of view. These images were collected with the full Xenon Flashlamp beam. The individual signatures correspond to the burst pattern of the Xenon Flashlamp - each pulse is 11 ms in duration and the pulses occur 55 ms apart. By measuring the pixel separation of the particle signatures, one can determine the cross-image component of the velocity. The variation in the intensities of the individual signatures is the result of the experiment configuration. The lamp beam is approximately 16 cm in diameter at this point; therefore, if the particle is moving across the beam, the irradiance on that particle (and hence the resultant scattered radiation) will change along the track. In addition, when the IVW must make observations through its aperture cover window, the field of view is vignetted and reduced to ~5.5 deg. As a particle approaches the edge of the reduced field of view, it is vignetted; therefore, the effective sensitivity to that particle is reduced.

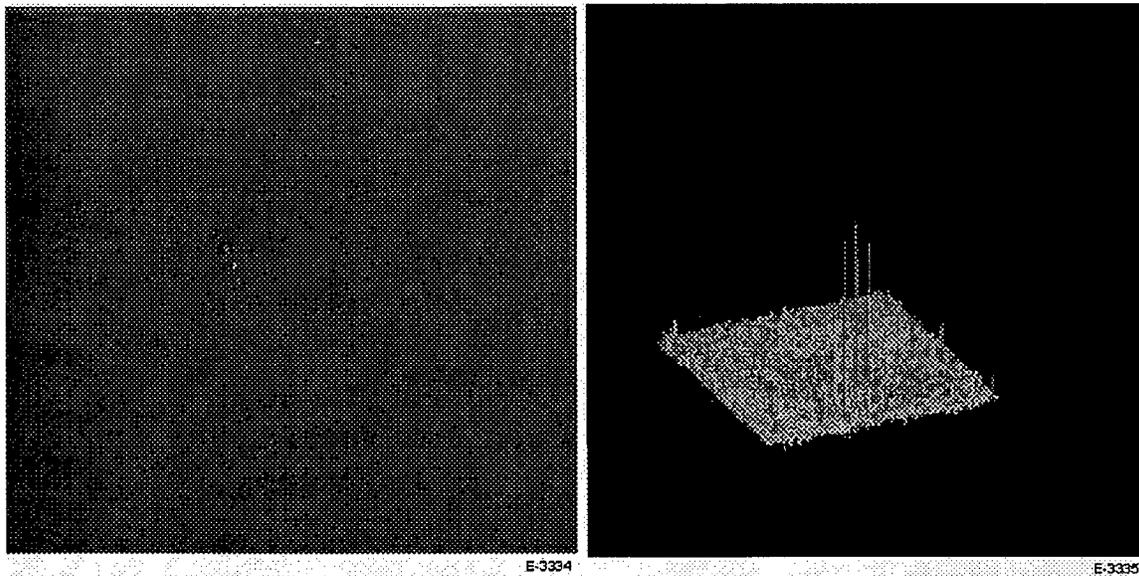


Figure 25. An image and surface plot of a 50 μm particle traversing the field of view from data acquired during joint ground testing of the Xenon Flashlamp and UVISI IVW.

Krypton Flashlamp and Radiometer (KR)

The Krypton Radiometer was calibrated as a unit in an ultraclean thermal vacuum facility chamber. The chamber was evacuated, and measurements were taken as the pressure slowly decreased. After the initial evacuation of the chamber, the primary constituent species is water vapor. The absolute pressure is measured with a Bayard-Alpert gauge, calibrated by NIST for response to H_2O . A residual gas analyzer provides a measurement of the mole fraction of H_2O in the chamber. The dynamic range of the Krypton Radiometer spans approximately six decades. However, the full calibration could be performed only over approximately two decades in the center of the dynamic range because of the limitations of the chamber measurement. The calibration is extrapolated over the entire dynamic range based upon the independent calibrations and characterizations of the krypton lamps and OH Radiometer.

4.6.2 Spacecraft Model

Molecular contamination effects for molecular outgassing and return flux, and interactions of the MSX spacecraft with the expected ambient flight environment were modeled. Outgassing source terms, which include volatile condensable material, water, argon, hydrogen and other miscellaneous molecules, were included. Return flux of contaminant molecules back to the MSX and return flux ratio for collisional return were developed. Using these source terms and return flux ratios, the predictions of mass flux return were compared with flight data from the MSX contamination experiment instruments, showing reasonable agreement. The design, fabrication and handling of the MSX spacecraft have been aimed at mitigation of contamination effects. Consequently, the predicted levels of molecular outgassing contamination are low enough to be within the tolerable limits imposed by the needs of the optical instruments.

Laboratory and previous in-flight measurements provide a basis for contamination modeling. The application of theoretical models and tools allows predictions of the dispositions of molecules that leave a spacecraft during orbital flight. Molecular outgassing is a temperature, pressure and species dependent diffusion, venting and evaporation process. Once molecules have escaped from their encapsulation within the spacecraft and its materials, their molecular trajectories can be direct line-of-sight, involve ricochet off intervening surfaces, or involve collisions between outgassing, venting or ambient molecules. The interaction of an outgassed molecule at an incident surface will depend on the temperature, incident flux density, species properties, surface properties and solar insolation. The specific geometric detail of the spacecraft and the materials, placement and fastening of thermal blanketing on the outer surface of the spacecraft play an essential role in the modeling of molecular contamination. The combination of all these aspects comprises the MSX Contamination Model and procedures. Comparison of the pre-launch calculations with flight data during early operations shows excellent agreement.

4.7 MSX Flight Contamination Data Executive Summary

MSX satellite provides a unique data set for assisting future spacecraft designers. MSX developed a careful ground contamination control plan controlling all facets of pre-orbit environment, monitored ground state, developed a contamination budget, developed an external transport model and included the instruments for measuring the on orbit initial level and temporal decay of molecules, particles, film accretion on sensitive surfaces, and charging. Moreover these instruments have been operating for the first 18 mission months and will permit specific events and the onset of aging processes to be detected.

Lessons Learned for Planning

- Identify contamination sources early (materials selection, abrasion, vent location)
- Develop a plan with budget for entire satellite and model (through launch)
- Select instruments for on-orbit verification at critical locations (mirror accretion, pressure)

The MSX Contamination Control Plan (CCP) guided materials selection, control, handling, assembly and bakeout. The sensor's performance requirements were used to set contamination level budgets for all stages of the pre-orbit environment. A phased CCP approach was developed for each stage. Very critically, we applied materials selection guidelines based on ASTM E595 to as many MSX satellite systems as possible. Including (and linking) ASTM E595 and E1559 databases in our deliverable (as Task 2) will provide a great value at this critical step of the process. These procedures establish instrumented bakeout guidelines and provide the sound basis that permits clean, yet economical, satellite assembly and orbital performance.

Other insights we gained during the MSX development program included: requiring charcoal/HEPA filters; use of air ionizers to significantly reduce particle accumulation; careful cleaning of cables before assembly eliminates a major source of particulates; periodic monitoring and cleaning (as opposed to final) is required to achieve the desired surface cleanliness; bagging can successfully provide a controlled environment during transport; contamination control can be accommodated unobtrusively into integration schedule; electrostatic discharge and cleanroom

training for all assembly personnel are an essential step in meeting contamination level goals as is getting all spacecraft engineers to sign up to contamination plan benefits. We will also present launch area and launch vehicle preparation, monitoring plans, and lessons.

MSX developed a complementary suite of instruments to assess the effectiveness of these procedures and to provide an accurate measure of the local environment surrounding the spacecraft. The early time spacecraft environment was dominated by release of material from ground and ascent operations (materials outgassing and venting, particle release). These effects decayed as expected with time on orbit. At later times, orbital production processes (abrasion from operations and thermal stresses and erosion) may dominate the near-spacecraft environment.

Molecular species concentrations, deposited film thicknesses, particle occurrence above surfaces, and spacecraft charging are all monitored. The contamination instruments include: a total pressure sensor (TPS) covering the 10^{-5} to $<10^{-10}$ Torr range, pointing into the same direction as the primary optical sensors (+X); a closed source quadrupole mass spectrometer for neutral molecules (NMS) with electron impact detection, covering masses 2 to 150 with 1 amu resolution, and sensitivity of ~ 104 per cm^3 , also pointing into +X; a krypton flashlamp and radiometer (KRF) to specifically monitor water densities above $10^7/\text{cm}^3$ at meter distances above surfaces on the +X instrument deck; a Bennett RF ion mass spectrometer (IMS) measuring masses 1 to 64 with sensitivity of ~ 10 ions per cm^3 , pointing in the +Z direction (ram); four temperature-controlled quartz crystal microbalances (TQCMs) operated at -43 to -50°C to sense deposited molecular films at sensitivities down to 0.01 nm film thicknesses) located at different positions around the instrument section of MSX facing largely -X, +X, +Z, and -Z; another QCM operated at near 20 K (CQCM) located near the IR sensor primary mirror to monitor all species frozen onto cryogenic optical surfaces at 0.01 nm sensitivities; a xenon flashlamp (XEF) to illuminate particles in a volume two meters above the +X face of the instrument deck surfaces operating in concert with a visible wide field imager (IVW) to enable μm diameter particle detection.

These instruments can operate individually, but acting in concert during planned data collection events provided insight into the entire local environment. Experiment plans included brief periodic surveys of the environment, experiments to identify trends, to discriminate the effects of discrete events, and to measure the earth's upper atmospheric composition and variability. Because the instruments observe both spacecraft surfaces and space, they are able to observe the ambient atmosphere, direct outgassing flux from surfaces, and molecules scattered by collisions with contaminant and ambient molecules (return flux).

The MSX spacecraft was launched from Vandenberg Air Force Base into a circular 99 deg near sun-synchronous 904 km altitude orbit by a Delta II booster on 24 April 1996. Following launch, the TPS and QCMs were among the first science instruments provided power and began sending data at only 87 min after launch.

Data from the early operations periods provided much valuable insight. Data from multiple MSX instruments were consistent and agreed with model predictions. Solar illumination induced outgassing produced the most significant variability. The observed general

temporal trend = $1/\text{time}$ to $1/\text{time}^{0.5}$. Negligible film depositions above pre-launch level were observed on both the CQCM and TQCMs. For the MSX scientific sensors, 1 week was sufficient time for MLI surface outgassing to fall to acceptable levels - after first week it was safe to initiate the mission measurements program. Contamination did not impair operations but rather was at the occasional nuisance level. The information provided by our instruments permitted the primary sensors to become operational as soon as possible without compromising their performance. Moreover, the contamination instruments permitted informed decisions, and minimized contingency planning. The QCMs were of particular value during this period. The CQCM sensed the total integrated film thickness deposited near a location of critical concern - the infrared sensor primary mirror. The composition of the sensed film thickness was determined. The QCMs also provided continuity from ground operations, and accurately measured that little molecular film deposition had occurred during final launch preparations, launch ascent, and initial operations in orbit.

A 10-month cryogenic operations period followed the early operations period. Solar illumination and satellite operations produce local pressure increases by factors of 10 to 100, with water dominating. The local environment improved slowly with time, but persisted longer than expected. Pressures are measurable even after one year after launch. We attribute this to outgassing of the multilayer insulation. Careful design and venting of the multilayer insulation are critical issues, as MLI represents a long-term internal reservoir with slow transport to external /internal surfaces. During cryo operations, QCMs accreted films and deduced that film accretion greatest when viewing "dirtier" spacecraft sections (surfaces with lines-of-sight to the electronics suffered greater accretion than those facing the orbital velocity direction (ram)). Surfaces facing in the direction of the primary sensors optical axis and wake incurred successively decreasing accretion. Solar polymerization effects were observed resulting in reduced thermal performance for radiators. Particles were intermittently observed throughout the mission, at levels that were significant during discrete events.

Contamination modeling proved to be a valuable tool in hardware design and operational planning. Prelaunch predictions of early operations environment accurately matched trends and magnitudes of gaseous contamination effects. Model predictions of charging, gaseous, and particle environment during the cryogenic operations period were a valuable aid in data interpretation.

The MSX particulate environment was found to be fairly benign overall. At ranges within hyperfocal distance (km for telescoped radiometers, 50 m for imagers) particles added radiance to signals on pixels. Particles of diameters $1 - >100 \mu\text{m}$ were detectable within this distance, and were observed during mechanical cover openings and maneuvers and during umbra exits (not entry). The particles remained in the sensor field-of-view for minutes because there is negligible drag at MSX altitudes. About 3% imager frames (during the first year of operation) contain a detectable particle. Particles were found to have an average velocity of 5 cm/s (0.1 to 20 cm/s range), with residence times in field of view between 2 to 100 seconds. Particle sizes were in the 0.5 to 100 μm radius with a 10 μm mean. Although particles were clearly observed to be directly associated with discrete operational events, particles were even observed during spacecraft passive periods.

After over 10 months on orbit, the solid hydrogen cryogen reservoir was depleted and the infrared Dewar, sensor optics and telescope began to warm. This represented an invaluable database - the contamination produced and measured upon warming of surfaces after nearly a year in space. MSX successfully performed controlled heating of the cryogenic mirror and telescope using solar illumination pulses. The sensor warm up was not a violent event. Water vapor was observed above MSX (outside the telescope) by the flashlamp, in synchronicity with the solar heating of the baffles. However, only minor collisional redistribution of contamination to spacecraft exterior surfaces was observed. Small accretion was observed on QCMs with a line-of-sight to Dewar surfaces. The heating pulses created a temperature gradient down the telescope leading to serial desorption from aperture baffles to primary mirror. A total of 50 nm of ice was deposited on CQCM during the two-stage heating process, temporally correlated with total sensor heat input. During the first stage, the telescope baffles were heated above 160 K to successfully desorb water (as monitored by the CQCM). During the second stage (after 3 months of slow sensor warming), the water which had remained immobilized for months (year) at temperatures below 133 K) was driven out of the cryogenic sensor MLI using solar heating pulses. Once the MLI was heated above 155 K, the water on the MLI became very mobile and migrated to redistribute within the telescope. In addition, rarely illuminated spacecraft external blanket surfaces produce 10^{-8} Torr bursts when sunlit after 1 year on-orbit.

As a result of these observations we have gained significant insight into the contamination environment surrounding complex spacecraft. Upon warming, MSX saw significant mass redistribution between mirror and baffles. Careful vent path location is essential to prevent contamination migration to sensitive surfaces. A small gap at the aperture permitted 50 nm of deposition on the primary mirror during the warmup period. Sensor systems with surfaces in the 133 to 155 K temperature range require accurate internal thermal profile measurements to permit contamination migration assessment. We recommend thermal simulations and ground testing to evaluate magnitudes and remedial/minimization procedures.

The success of the orbital operations was soundly based on a careful ground operations plan. It is important to educate and enlist entire spacecraft engineering staff onto the contamination team, and apply the contamination control plan as widely as possible. Lack of attention to a single major subsystem can result in significant contamination. Board and box level bakeouts were extremely successful in reducing organic contamination (VOCs). Simple diagnostics on orbit are of great value - scatter monitors for optical sensors, pressure gauges, QCMs. They can provide traceability, permit informed decisions, and validate spacecraft models currently under development.

5. GLOBAL SEARCH BY KEYWORDS

We have created a powerful search engine to permit data and paper retrievals. The philosophy and implementation are described in greater detail in Appendix A. Each retrievable has up to 8 keywords that are used by the search engine. Data sets can be searched by spacecraft, instrument, sponsor or time. Examples of these two searches are shown below.

| Information | Data |
|--|---|
| Spacecraft Keywords: MSX Instrument Keywords: TQCM, CQCM, QCM Mission Month: 1 Sponsor Keywords: BMDO | 369K 74K Images: http://see3.msfc.nasa.gov/qcldb/data/Converted/ |
| Spacecraft Keywords: MSX Instrument Keywords: TQCM, CQCM, QCM Mission Month: 2 Sponsor Keywords: BMDO | 364K 73K Images: http://see3.msfc.nasa.gov/qcldb/data/Converted/ |
| Spacecraft Keywords: MSX Instrument Keywords: TQCM, CQCM, QCM Mission Month: 3 Sponsor Keywords: BMDO | 425K 84K Images: http://see3.msfc.nasa.gov/qcldb/data/Converted/ |
| Spacecraft Keywords: MSX Instrument Keywords: TQCM, CQCM, QCM Mission Month: 4 Sponsor Keywords: BMDO | 376K 73K Images: http://see3.msfc.nasa.gov/qcldb/data/Converted/ |
| Spacecraft Keywords: MSX Instrument Keywords: TQCM, CQCM, QCM Mission Month: 5 Sponsor Keywords: BMDO | 439K 80K Images: http://see3.msfc.nasa.gov/qcldb/data/Converted/ |
| Spacecraft Keywords: MSX Instrument Keywords: TQCM, CQCM, QCM Mission Month: 6 Sponsor Keywords: BMDO | 372K 67K Images: http://see3.msfc.nasa.gov/qcldb/data/Converted/ |
| Spacecraft Keywords: MSX Instrument Keywords: TQCM, CQCM, QCM Mission Month: 7 Sponsor Keywords: BMDO | 423K 75K Images: http://see3.msfc.nasa.gov/qcldb/data/Converted/ |
| Spacecraft Keywords: MSX Instrument Keywords: TQCM, CQCM, QCM Mission Month: 8 Sponsor Keywords: BMDO | 435K 75K Images: http://see3.msfc.nasa.gov/qcldb/data/Converted/ |
| Spacecraft Keywords: MSX Instrument Keywords: TQCM, CQCM, QCM Mission Month: 9 Sponsor Keywords: BMDO | 431K 74K Images: http://see3.msfc.nasa.gov/qcldb/data/Converted/ |

| Information | Data |
|---|---|
| Spacecraft Keywords: MSX Instrument Keywords: TQCM, CQCM, QCM Mission Month: 10 Sponsor Keywords: BMDO | 423K 74K Images: http://see3.msfc.nasa.gov/qcmdb/data/Converted/ |
| Spacecraft Keywords: LDEF Instrument Keywords: QCM Mission Month: Sponsor Keywords: NASA | 85K 390K Images: LDEF Trailing Edge Data(25K).gif |
| Spacecraft Keywords: LDEF Instrument Keywords: QCM Mission Month: Sponsor Keywords: NASA | 83K 581K Images: LDEF Leading Edge Data(25K).gif |
| Spacecraft Keywords: REFLEX Instrument Keywords: TQCM Mission Month: Sponsor Keywords: NASA | 387K 3749K Images: REFLEX_QCM_Frequencies.gif TQCM A graphite coated.gif |
| Spacecraft Keywords: Discoverer Instrument Keywords: QCM Mission Month: Sponsor Keywords: AF SD | Images: http://see3.msfc.nasa.gov/qcmdb/data/Converted/ |
| Spacecraft Keywords: OGO-F Instrument Keywords: QCM Mission Month: Sponsor Keywords: NASA | Images: http://see3.msfc.nasa.gov/qcmdb/data/Converted/ |
| Spacecraft Keywords: Spacelab1 Instrument Keywords: TQCM Mission Month: Sponsor Keywords: NASA | Images: http://see3.msfc.nasa.gov/qcmdb/data/Converted/ |
| Spacecraft Keywords: STS-46 Instrument Keywords: TQCM Mission Month: Sponsor Keywords: NASA | Images: EMPdata.gif |
| Spacecraft Keywords: Mir Instrument Keywords: TQCM Mission Month: Sponsor Keywords: NASA | 103K Images: OPMBeforeAccident.gif OPMAfterAccident.gif OPMJun26Event.gif OPMDec16Event-10C.gif OPMDec16Event-30C.gif |
| Spacecraft Keywords: HST Instrument Keywords: TQCM Mission Month: Sponsor Keywords: NASA | 33K 1005K Images: HST_QCM_Frequencies.gif HST_QCM Frquencies TPS Pressure.gif |

6. SEE GLOSSARY

absorptance, a , n - ratio of the absorbed radiant or luminous flux to the incident flux.

activity coefficient of crystal, Q , n - energy stored during a cycle / energy lost during the cycle or the quality factor of the crystals.

AT cut crystal, n - a quartz crystal orientation that minimizes the temperature coefficient (frequency change versus temperature) over a wide range of temperature.

BRDF, n - Bi-directional Reflectance Distribution Function is an optical property of a surface that describes the optical scattering features of that surface.

BMDO, n - Ballistic Missile Defense Organization.

CQCM, n - Cryogenic QCMs, have the ability to operate successfully below the temperature of liquid Nitrogen (-200 °C). They have an internal heater which can be used to boil off surface films from the sensor crystals. Usually smaller in size, CQCMs use less power than other QCMs and are readily adaptable to space environments.

CVCM, n - (from Test Method E 595) Collected Volatile Condensable Material is the quantity of outgassed matter from a test specimen that condenses on a collector maintained at a specific constant temperature for a specified time and measured before and after the test outside the chamber. CVCM is specific to Test Method E 595 and is calculated from the condensate mass determined from the difference in mass of the collector plate before and after the test in a controlled laboratory environment. CVCM is expressed as a percentage of the initial specimen mass. The view factor is not considered; so all the VCM outgassing from the sample may not be collected. Care should be used in comparing the CVCM from Test Method E 595 with VCM from this test method,

crystallographic cut, F , n - rotation angle between the optical axis and the plane of the crystal at which the quartz is cut; typically 35 deg 18 min AT cut for ambient temperature use or 39 deg 40 min cut for cryogenic temperature use.

density of quartz, n - at $T = 25$ °C, $r_q = 2.6485$ g/cm³ (1); at $T = -195.63$ °C, $r_q = 2.664$ g/cm³ (2)

DSC, n - Differential Scanning Calorimetry is a technique in which the difference in energy inputs into a substance and a reference material is measured as a function of temperature while the substance and reference material are subjected to a controlled-temperature program.

DoD, n - Department of Defense.

effusion cell, n - a container, placed in a vacuum, in which a sample of material can be placed and heated to some specified temperature. The container has a cylindrical orifice at one end so that evolving gases exit the cell in a controlled manner. The effusion cell dimensions and orifice size are specified such that there is free molecular flow of the evolving gasses and a predictable molecular flux from the orifice.

EML, n - Equivalent Monomolecular Layer is a single layer of molecules, each 3×10^{-8} cm in diameter, placed with centers on a square pattern. This results in an EML of approximately 1×10^{15} molecules/cm².

ex-situ TML, n - total mass of material outgassed from a test specimen that is maintained at a specified constant temperature and operating pressure for a specified time and measured outside the test chamber. *Ex-situ* TML is calculated from the mass of the specimen as measured before and after the test in a controlled laboratory environment and is expressed as a percentage of the initial specimen mass. (From Test Method E 595.)

IMS, n - Ion Mass Spectrometer.

in - situ TML, n - calculated from the mass deposited on a cryogenically cooled QCM and the view factor from the effusion cell orifice to the QCM. In - situ TML is a function of the outgassing test time and is expressed as a percentage of the initial specimen mass. This is not necessarily the same as the TML determined by Test Method E 595.

irradiance at a point on a surface, E_e , n - ratio of the radiant flux incident on an element of the surface containing the point, to the area of that element. $E_e = dI_e / dA$, (watt per square meter, Wm^{-2}),

KFR, n - Krypton Flashlamp and Radiometer.

mass sensitivity, S, n - relationship between the frequency shift and the arriving or departing mass on the sensing crystal of a QCM. As defined by theory,

$$Dm/A = - (r_q c / 2f^2) Df$$

where:

Dm = mass change, g

A = area on which the deposit occurs, cm^2

f = fundamental frequency of the QCM, Hz

r_q = density of quartz, g/cm^3 , and

c = shear wave velocity of quartz, cm/s.

mass flux ($g \cdot cm^{-2} \cdot s^{-1}$), n - the mass of molecular flux.

molecular contamination, n - molecules that remain on a surface with sufficiently long residence times to affect the surface properties to a sensible degree.

molecular flux ($molecules \cdot cm^{-2} \cdot s^{-1}$), n - the number of gas molecules crossing a specified plane in unit time per unit area.

MLI, n - multilayer insulation.

MSX, n - Midcourse Space Experiment funded by BMDO.

NASA, n - National Aeronautics and Space Administration.

NMS, n - Neutral Mass Spectrometer.

NVR, n - Nonvolatile Residue is the quantity of residual molecular and particulate matter remaining following the filtration of a solvent containing contaminants and evaporation of the solvent at a specified temperature.

optical polish, n - the topology of the quartz crystal surface as it affects its light reflective properties, e.g. specular (sometimes called "clear polish") or diffuse polish.

optical solar reflector, OSR, n - a term used to designate thermal control surfaces on a spacecraft incorporating second surface mirrors.

outgassing, n - the evolution of gas from a material, usually in a vacuum. Outgassing also occurs in a higher pressure environment.

QTGA, n - QCM Thermogravimetric Analysis is a technique in which a QCM is heated at a constant rate to remove a collected deposit. This is performed to determine the evaporation characteristics of the species in the deposit. The mass of the deposit on the QCM is recorded as a function of time or temperature to do an elemental analysis on the mass. At increasing temperatures the contaminants tend to evaporate, and from the frequency change as a function of time the mass change and the relevant vapor pressures can be calculated for the

actual temperature. If the vapor pressure versus temperature of the candidate molecules is known, identification of one or more molecular species can be made.

QCM, n - Quartz Crystal Microbalance, a device for measuring small quantities of mass using the properties of a quartz crystal oscillator. The resonant frequency of a quartz crystal oscillator is inversely proportional to the thickness of the crystal. When the mass of a uniform deposit is small relative to the mass of the crystal, the change in frequency is proportional to the mass of the deposit.

reflectance, r, n - ratio of the reflected radiant or luminous flux to the incident flux.

RGA, n - Residual Gas Analyzer is a mass spectrometer mounted inside or attached to a vacuum chamber. RGA can be used for identifying gases in the vacuum chamber.

SBIRS, n - Spaced Based Infrared Systems.

SBV, n - Spaced-Based Visible Sensor.

SPIRIT III, n - Spatial Infrared Imaging Telescope III .

SECOT, n - SPIRIT III End-of-Cryogen Operations Tests.

super-polish, n - polish of a quartz crystal that produces less than 10Å root mean square (rms) roughness on the surface.

surface of interest, n - any immediate surface on which contamination can be formed.

Space Transportation System, STS, n - The overall NASA shuttle program.

total mass flux ($g \cdot cm^{-2} \cdot s^{-1}$), n - the summation of the mass from all molecule species crossing a specified plane in unit time per unit area.

total mass loss, TML, n - total mass of material outgassed from a test specimen that is maintained at a specified constant temperature and operating pressure for a specified time and measured within the test chamber. TML is expressed as a percentage of the initial specimen mass.

total outgassing rate ($g \cdot s \cdot cm^{-2}$), n - the net rate of mass loss from a material sample due to outgassing per unit sample surface area.

TPS, n - Total Pressure Sensor.

TQCM, n - Thermally controlled QCMs. TQCMs have an internal Peltier heat exchanger which can either heat or cool the QCM to aid in both collecting condensables and then boiling them off later.

UV, n - Ultra-Violet.

UVISI, n - Ultraviolet and Visible Imagers and Spectrographic Imagers.

volatile condensable material, VCM, n - the matter that outgasses from a material and condenses on a collector surface that is at a specified temperature. This is the quantity of outgassed matter from a test specimen that condenses on surfaces maintained at QT2 or QT3. The VCM is calculated from the mass deposited on QCM2 or QCM3 and the view factor from the effusion cell orifice to the QCMs. VCM is a function of the outgassing test time and is expressed as a percentage of the initial specimen mass. This is not the same as CVCM as determined by Test Method E 595.

XFL, n - Xenon Flash Lamp.

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8. HELP FILE

8.1 Version Compatibility

The SEE website was developed using Microsoft® Visual Interdev® 6.0 and Java™ Software Development Kit (SDK) Version 1.1. The Java™ SDK includes the Abstract Window Toolkit AWT as part of the Java Foundation Classes (JFC) -- the standard API for providing graphical user interfaces (GUIs) for Java programs. This software exclusively supports the data plotting utility and creates some version issues which are addressed below (if you are not interested in on-line plotting, there should be no problems with incompatibility):

- Microsoft® WinNT/Win95: Netscape 4.0.6 and above and Microsoft® Internet Explorer 4.x and above.
- Unix: Netscape 4.06 or above
- Apple Macintosh OS: Netscape 4.0.x does not support Java 1.1. However, Microsoft® Internet Explorer 4.x will work with the installation of Apple's Mac OS Runtime for Java (MRJ).
- Both JAVA and JAVAScript must be enabled for the SEE website to search correctly.

Since several formulae are used in text of the website, it is advantageous to enable the website fonts on the user's browser:

- In Netscape Communicator: Edit > Preferences (Appearance > Fonts) and check either of the "Use document-specified fonts..." boxes.
- In Microsoft Internet Explorer: View > Internet Options (General > Accessibility) and uncheck all the "Ignore..." boxes.

8.2 Use and Instructions

Plotting: Comma Separated Volumes (*.csv) files may be plotted using an embedded Java script. Several plots can run simultaneously to allow data comparison. All the files variables may be printed against one variable. The features provided include:

File: Add Series: Add additional y variables to the plot or change the x variable.
Print: Prints the plot window.
Quit: Closes the plot window.

View: Zoom In: Zooms in 2x to the location selected.
Zoom Out: Zooms out 2x from the location selected.
Fit to Window: Fits the data to the window ($\pm 5\%$).
Show Grid: Presents a grid on the plot window.

Options: x, y axis label: Allows labeling of the x and y axes.

Window: List the data file to be loaded. This must be selected before data is downloaded.

Download: Compressed versions of the original data files can be downloaded. Note that several are very large and download time will be dependent on Internet connection speed. Some typical download times are listed below. The estimates assume the worst case and 100% throughput. Your mileage may vary, realistically by 50% and limited by Ethernet at 10Mbps. Note that speed is in bits, while file size is in Bytes (8 bits/Byte).

| Connection/File Size | Actual Speed (bits/s) | Download Time (seconds) | | | |
|----------------------|--------------------------|-------------------------|-------|-------|--------|
| | | 10KB | 100KB | 1MB | 10MB |
| | | 2.7 | 27.8 | 277.8 | 2777.8 |
| 33.3KB Analog Modem | 33.3 K | 2.4 | 24.0 | 240.2 | 2402.4 |
| 56.6KB Analog Modem | 56.6 K | 1.4 | 14.1 | 141.3 | 1413.4 |
| ISDN | 125 K | 0.6 | 6.4 | 64.0 | 640.0 |
| T1/DS1 | 1.5 M | 0.1 | .5 | 5.3 | 53.3 |
| ADSL | 1.5 M | 0.1 | .5 | 5.3 | 53.3 |
| Cable Modem | 1.5-30 M | 0.1 | .5 | 5.3 | 53.3 |
| T3 | 45 M | 0.0 | 0.0 | 0.2 | 1.8 |

8.3 Software Support

| Activity | Software Package | Description |
|------------------|------------------|--|
| File compression | MacZIP | Free. Macintosh. MacZip is a cross-platform compatible tool with zip (for compression) and unzip (for extraction) capabilities. MacZip can compress files for the following systems: Unix, VMS, MSDOS, OS/2, Windows NT, Minix, Atari, Macintosh, Amiga, and Acorn RISC OS. MacZip can also work with archives produced by PKZip, and PKZip and PKUNZip can work with archives produced by MacZip. This port supports Apple events, so you can install it in your Web browser as a helper app. Or try Zipit. Shareware. |
| | WinZIP | Shareware. Windows. WinZip makes it easy for Windows and Windows 95 users to work with file archives. WinZip features an intuitive point-and-click drag-and-drop interface for viewing, running, extracting, adding, deleting, and testing files in archives with a standard Windows interface. WinZip can handle ZIP, TAR, gzip, and UNIX compress format files by itself. External programs are required for the less frequently used ARJ, ARC, and LZH formats. |
| | Info-Zip | Free. All platforms. Info-ZIP supports hardware from microcomputers all the way up to Cray supercomputers, running on almost all versions of Unix, VMS, OS/2, Windows NT/9x (a.k.a. Win32), Windows 3.x, Windows CE, MS-DOS, AmigaDOS, Atari TOS, Acorn RISC OS, BeOS, Mac OS (Zip port underway), SMS/QDOS, MVS and OS/390 OE, VM/CMS, FlexOS, Tandem NSK and Human68K (Japanese). There is also some support for LynxOS, TOPS-20, AOS/VS and Novell NLMs. Shared libraries (DLLs) are available for Unix, OS/2, Win32 and Win16, and graphical interfaces are available for Win32, Win16, WinCE and Macintosh. |

| | | |
|-----------------------------------|------------------------------|---|
| Web Browsing | Netscape | Free. All platforms |
| | Microsoft® Internet Explorer | Free. All platforms. |
| .pdf Viewer | Adobe Acrobat | Free. All platforms. Acrobat .pdf files are compact files which have all the information necessary to present and print documents in their original fonts and layout, unencumbered by the layout limitations of HTML files. .pdf files are an excellent choice for use on the Internet as they are compact, independent of the software used to layout the original, and can be read, presented to screen and printed by Adobe Acrobat Reader software running on Windows, Mac or UNIX platforms. The Beta versions of Acrobat Reader 3.0 automatically install a plug-in which allows it to work with Netscape Navigator 2.0 or better, and an ActiveX control which allows it to work with Microsoft Internet Explorer 3.0. |
| Software and Database Development | Microsoft® Visual InterDev | First born. PC Platforms. Microsoft Visual InterDev 6.0 is a powerful development environment for rapidly creating database-driven Web applications. Integrated visual design tools, debugging support, and database features enable you to build interactive, cross-platform Web sites quickly and easily. |
| Office Suite Software | Microsoft® Office 97 | Second born. Macintosh and PC Platforms. The SEE database uses Word and Excel format files. |

APPENDIX A

Satellite Contamination and Materials Outgassing Effects Databases

Physical Sciences Inc. Paper No. SR-989 for AIAA Space Technology Conference



AIAA STC211
Satellite Contamination and Materials
Outgassing Effects Databases

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AIAA Space Technology Conference
30 September 1999

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SATELLITE CONTAMINATION AND MATERIALS OUTGASSING EFFECTS DATABASES*

B.D. Green[†], B.E. Wood[‡], O. M. Uy[§], and R. P. Cain[§]

ABSTRACT

This paper describes an on-going effort for consolidating contamination data from previous space missions and specifically from quartz crystal microbalances (QCMs) that will enable one to rapidly locate previous measurements on specific materials and data from past space flight experiments. When complete, the databases will contain information on materials outgassing obtained using the ASTM-E-1559 standard, and flight observations of mass accumulations. Once established, these databases will be available to the entire community and will provide a valuable source of material outgassing information. The data should be useful to those working in the Contamination area for mission design and materials specification. Data are being accumulated from both national and international sources. The space flight database will include data from past NASA missions, as well as DOD (including the BMDO-sponsored Mid-course Space Experiment (MSX) program), Canadian Space Agency, European Space Agency, Russian MIR space station, and eventually, the International Space

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Station. The carefully instrumented MSX satellite mission will be used as a case study of the contamination environment encountered by a payload developed with a contamination control plan. A website is being generated which will be the vehicle for storing the data that are accumulated. Once completed, the databases will be managed by the NASA/Space and Environmental Effects (SEE) Program Office at the Marshall Space Flight Center in Huntsville, Alabama.

INTRODUCTION

This program was conceived during a NASA Space and Environmental Effects (SEE) roadmap workshop on Neutral Contamination held at the Marshall Space Flight Center in Huntsville, Alabama, on April 29-30, 1997. The attendees identified high priority activities beneficial to the contamination area.

The ideas were prioritized at the end of the workshop. Two of the top three items agreed upon were to (1) establish a material outgassing database based on the ASTM-1559 test method¹ ("E 1559-93 Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials"), and (2) establish a database consolidating quartz crystal microbalance (QCM) data from previous missions in space. The attendees generally agreed that the QCM has become the primary instrument for providing materials outgassing property data, and for characterizing the on-orbit real-time surface film accretions.

The QCM is an instrument that has been developed for measuring the deposition of mass on a surface at specific temperatures. The mass sensitivity depends on the oscillation frequency of the quartz crystals being used, which range from 5 MHz up to as high as 50 MHz. For 10-MHz crystals, the mass sensitivity is given as

$$S = 4.43 \times 10^{-9} \text{ gm/cm}^2 \cdot \text{Hz.}$$

With this sensitivity, film thicknesses on the order of 0.1 nm can be detected. A schematic of one version of the QCM is shown in Fig. 1.

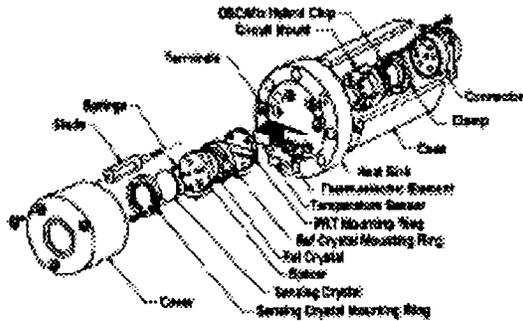


Fig. 1. Temperature-controlled QCM (TQCM) assembly diagram.

A proposal to combine both databases that use QCMs was submitted and was accepted for funding through NRA8-20. Work on the program began in October 1998, and the project is scheduled for completion in August 2000. The databases will be organized as shown in Fig. 2.

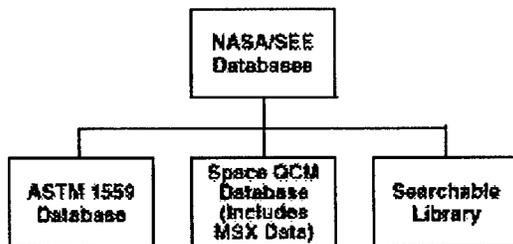


Fig. 2. Structure of NASA/SEE databases.

The QCM data consolidation program is underway with Physical Sciences Inc. (PSI), as the prime contractor, and with Sverdrup Technology and Johns Hopkins University/Applied Physics Laboratory (JHU/APL) as subcontractors. Personnel at these organizations are currently working with the NASA/SEE Program Office to establish the two QCM databases as a resource for the aerospace community. The databases being developed will enable one to rapidly locate previous measurements on specific materials and from past space flight experiments. Sverdrup Technology personnel are responsible for acquiring the needed data and transferring

it to JHU/APL for the databases. JHU/APL is developing the website and establishing the database structures. At the end of the program, JHU/APL will transfer the databases to the NASA/SEE Program Office at the Marshall Space Flight Center in Huntsville, Alabama.

The databases will contain information on materials outgassing and flight observations of mass accumulations. Specifically:

1. An ASTM 1559 Database, and
2. A Space Flight QCM Database.

Both of these databases will include QCM data. The ASTM-E-1559 Database will include the outgassing data obtained using this relatively new standard. The intent of this database is to complement the data archived by NASA Goddard Space Flight Center using the ASTM-E-595 standard (NASA Reference Publication 1124).² ASTM Standard E-1559 provides the time-dependent material outgassing properties for three collector temperatures. Data are being requested from facilities having data generated by chambers such as the Vacuum Outgassing Deposition/Kinetics Apparatus (VODKA) that is being marketed by QCM Research of Laguna Beach, CA or chambers with similar capabilities. Once established, this database will be available to the entire community, and will provide a valuable source of material outgassing information for mission design and materials specification to those working in the Contamination area. Plans also include links to publications relating to the data included in the database.

Similarly, the Space Flight QCM Database will include QCM data that have been collected on satellites operating in space. Among others, this will include data from NASA programs including the Shuttle, DOD (including the BMDO-sponsored Midcourse Space Experiment (MSX) satellite program), Canadian Space Agency, European Space Agency, Russian MIR space station, and eventually, the International Space Station.

The website being generated at JHU/APL will be the vehicle for storing and accessing the accumulated data. In addition to the other two databases, an excerpted MSX database will be established. The MSX program has been the source of on-going contamination measurements and

experiments from a suite of instruments. The website will be generated and tested at JHU/APL, after which it will be delivered to the NASA SEE Program Office for its implementation.

The benefits of the databases are that better procedures can be established for materials selection for space flight. The associated cost savings will be attributable to successful missions (risk mitigation). Other benefits will be a better understanding of what to expect in space, based on mission requirements and the ability to design systems with appropriate end-of-life performance margins. Having all of the necessary data in one location will allow a user/designer to have all of the available data at his fingertips.

APPROACH

Preparatory to building the databases, a survey was prepared and distributed to those working in the "Contamination" technical area in November 1998. The responses were assembled, and agencies where known sets of data were in existence were contacted. During the data collection, the database platform and website were constructed at JHU/APL. Publications associated with either ASTM-E-1559 QCM data or space related QCM data are also being collected and will be available at the website. Initially, data from several materials will be included in the database, and will serve as test cases. Since the format and approach of measurement is somewhat varied between the data sources, the data from each source will require individual attention.

The contamination data obtained during the MSX satellite program (see Fig. 3) is also being assembled for inclusion in the Space Flight QCM database. The data from the five QCMs on board will be available, as well as data from other instruments such as the total pressure sensor (TPS) used in characterizing the space environment around the spacecraft (Fig. 4).

MSX FLIGHT CONTAMINATION DATA EXECUTIVE SUMMARY

MSX satellite provides a unique data set for assisting future spacecraft designers. MSX developed a careful ground contamination control plan (CCP) controlling all facets of pre-orbit environment, monitored ground state,

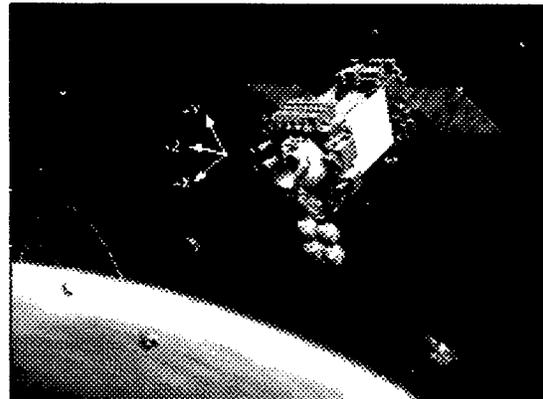


Fig. 3. Midcourse space experiment satellite in orbit.

developed a contamination budget, developed an external

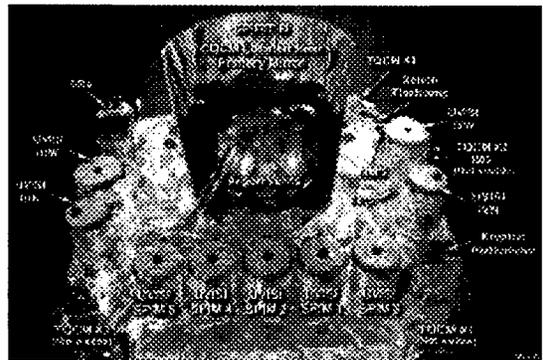


Fig. 4. Instrument section of MSX.

transport model and included the instruments for measuring the on orbit initial level and temporal decay of molecules, particles, film accretion on sensitive surfaces, and charging. Moreover these instruments have been operating for the first 18 mission months and will permit specific events and the onset of aging processes to be detected.

Lessons Learned for Planning

- identify contamination sources early (materials selection, abrasion, vent location)
- develop a plan with budget for entire satellite and model (through launch)
- select instruments for on-orbit verification at critical locations (mirror accretion, pressure)

The MSX Contamination Control Plan guided materials selection, control, handling, assembly and bake-out. The sensor's performance requirements were used to set contamination level budgets for all stages of the pre-orbit environment. A phased CCP approach was developed for each stage. Very critically, we applied materials selection guidelines based on ASTM E595 to as many MSX satellite systems as possible. Including (and linking) ASTM E595 and 1559 databases in our deliverable (as Task 2) will provide a great value at this critical step of the process. These procedures establish instrumented bakeout guidelines and provide the sound basis that permits clean, yet economical, satellite assembly and orbital performance.

Other insights we gained during the MSX development program included: requiring charcoal/HEPA filters; use of air ionizers to significantly reduce particle accumulation; careful cleaning of cables before assembly eliminates a major source of particulates; periodic monitoring and cleaning (as opposed to final) is required to achieve the desired surface cleanliness; bagging can successfully provide a controlled environment during transport; contamination control can be accommodated unobtrusively into integration schedule; electrostatic discharge and cleanroom training for all assembly personnel are an essential step in meeting contamination level goals as is getting all spacecraft engineers to sign up to contamination plan benefits. We will also present launch area and launch vehicle preparation, monitoring plans, and lessons.

MSX developed a complementary suite of instruments to assess the effectiveness of these procedures and to provide an accurate measure of the local environment surrounding the spacecraft. The early time spacecraft environment was dominated by release of material from ground and ascent operations (materials outgassing and venting, particle release). These effects decayed as expected with time on orbit. At later times, orbital production processes (abrasion from operations and thermal stresses and erosion) may dominate the near-spacecraft environment.

Molecular species concentrations, deposited film thicknesses, particle occurrence above surfaces, and spacecraft charging are all monitored. The contamination instruments include: a total pressure sensor covering the

10^{-5} to $<10^{-10}$ Torr range, pointing into the same direction as the primary optical sensors (+X); a closed source quadrupole mass spectrometer for neutral molecules (NMS) with electron impact detection, covering masses 2-150 with 1 amu resolution, and sensitivity of $\approx 10^4$ per cm^3 , also pointing into +X; a krypton flashlamp and radiometer (KRF) to specifically monitor water densities above $10^7/\text{cm}^3$ at meter distances above surfaces on the +X instrument deck; a Bennett RF ion mass spectrometer (IMS) measuring masses 1-64 with sensitivity of ≈ 10 ions per cm^3 , pointing in the +Z direction (ram); four temperature-controlled quartz crystal microbalances (TQCMs) operated at -43 to -50C to sense deposited molecular films at sensitivities down to 0.01 nm film thicknesses) located at different positions around the instrument section of MSX facing largely -X, +X, +Z, and -Z; another QCM operated at near 20 K (CQCM) located near the IR sensor primary mirror to monitor all species frozen onto cryogenic optical surfaces at 0.01 nm sensitivities; a xenon flashlamp (XEF) to illuminate particles in a volume two meters above the +X face of the instrument deck surfaces operating in concert with a visible wide field imager (IVW) to enable μm diameter particle detection.

These instruments can operate individually, but acting in concert during planned data collection events provided insight into the entire local environment. Experiment plans included brief periodic surveys of the environment, experiments to identify trends, to discriminate the effects of discrete events, and to measure the earth's upper atmospheric composition and variability. Because the instruments observe both spacecraft surfaces and space, they are able to observe the ambient atmosphere, direct outgassing flux from surfaces, and molecules scattered by collisions with contaminant and ambient molecules (return flux).

The MSX spacecraft was launched from Vandenberg Air Force Base into a circular 99 degree near sun-synchronous 904 km altitude orbit by a Delta II booster on 24 April 1996. Following launch, the TPS and QCMs were among the first science instruments provided power and began sending data at only 87 minutes after launch.

Data from the early operations periods provided much valuable insight. Data from multiple MSX instruments was consistent and agreed with model predictions.

Solar illumination induced outgassing produced the most significant variability. The observed general temporal trend = $1/\text{time}$ to $1/\text{time}^{0.5}$. Negligible film depositions above pre-launch level were observed on both the CQCM and TQCMs. For the MSX scientific sensors, 1 week was sufficient time for MLI surface outgassing to fall to acceptable levels - after first week it was safe to initiate the mission measurements program. Contamination did not impair operations but rather was at the occasional nuisance level. The information provided by our instruments permitted the primary sensors to become operational as soon as possible without compromising their performance. Moreover, the contamination instruments permitted informed decisions, and minimized contingency planning. The QCMs were of particular value during this period. The CQCM sensed the total integrated film thickness deposited near a location of critical concern - the infrared sensor primary mirror. The composition of the sensed film thickness was determined. The QCMs also provided continuity from ground operations, and accurately measured that little molecular film deposition had occurred during final launch preparations, launch ascent, and initial operations in orbit.

An 11-month cryogenic operations period followed the early operations period. Solar illumination and satellite operations produce local pressure increases by factors of 10 to 100, with water dominating. The local environment improves slowly with time, but persists longer than expected. Pressures are measurable even after one year after launch. Careful design and venting of the multilayer insulation are critical. MLI represents a long term internal reservoir with slow transport to external /internal surfaces. During cryo operations, QCMs accreted films and deduced that film accretion greatest when viewing "dirtier" spacecraft sections (surfaces with lines-of-sight to the electronics suffered greater accretion than those facing the orbital velocity direction (ram)). Surfaces facing in the direction of the primary sensors optical axis and wake incurred successively decreasing accretion. Solar polymerization effects were observed resulting in reduced thermal performance for radiators. Particles were intermittently observed throughout the mission, at levels that were significant during discrete events.

Lessons Learned for Modeling

The MSX external contamination environment model demonstrated that:

- Modeling is a valuable tool in hardware design and operational planning;
- Prelaunch predictions of early ops environment matched trends and magnitudes accurately;
- Cryo period model predictions of charging, gaseous, and particle environment valuable aid in data interpretation.

The MSX particulate environment was found to be fairly benign overall. At ranges within hyperfocal distance (km for telescoped radiometers, 50 m for imagers) particles added radiance to signals on pixels. Particles of diameters $1 - >100 \mu\text{m}$ were detectable within this distance. Particles were observed during mechanical cover openings and maneuvers and during umbra exits (not entry). The particles remained in the sensor field-of-view for minutes because there is negligible drag at MSX altitudes. About 3% imager frames (during the first year of operation) contain a detectable particle. Particles were found to have an average velocity of 5 cm/s (0.1 to 20 cm/s range), with residence times in field of view between 2 to 100 seconds. Sizes were in the 0.5 to 100 μm radius with a 10 μm mean. Although particles were clearly observed associated with discrete operational events, particles were even observed during spacecraft passive periods.

After over 11 months on orbit, the solid hydrogen cryogen reservoir was depleted and the infrared dewar, sensor optics and telescope began to warm. This represented an invaluable database - the contamination produced and measured upon warming of surfaces after nearly a year in space. MSX successfully performed controlled heating of the cryogenic mirror and telescope using solar illumination pulses. The sensor warm up was not a violent event. Water vapor observed above MSX (outside the telescope) by the flashlamp, in synchronicity with the solar heating of the baffles. However only minor collisional redistribution of contamination to spacecraft exterior surfaces was not observed. Small accretion was

observed on QCMs with a line-of-sight to dewar surfaces. The heating pulses created temperature gradient down telescope leading to serial desorption from aperture baffles to primary mirror. A total of 50 nm of ice was deposited on CQCM during the two-stage heating process, temporally correlated with total sensor heat input. During the first stage, the telescope baffles were heated above 160 K to successfully desorb water (as monitored by the CQCM). During the second stage (after 3 months of slow sensor warming), the water which had remained immobilized for months (year) at temperatures below 133 K) was driven out of the cryogenic sensor MLI using solar heating pulses. Once the MLI was heated above 155 K, the water on the MLI became very mobile and migrated to redistribute within the telescope. In addition, rarely illuminated spacecraft external blanket surfaces produce 10^{-8} Torr bursts when sunlit after 1 year on-orbit.

As a result of these observations we have gained significant insight into the contamination environment surrounding complex spacecraft. Upon warming MSX saw significant mass redistribution between mirror and baffles inside warming telescope. Careful vent path location is essential to prevent contamination migration to sensitive surfaces. A small gap at the aperture permitted 50 nm of deposition on the primary mirror during the warmup period. Sensor systems with surfaces in the 133 to 155 K temperature range require accurate internal thermal profile measurements to permit contamination migration assessment. We recommend thermal simulations and ground testing to evaluate magnitudes and remedial/minimization procedures.

The success of the orbital operations was soundly based on a careful ground operations plan. It is important to educate and enlist entire spacecraft engineering staff onto the contamination team. Apply the contamination control plan as widely as possible. Lack of attention to a single major subsystem can result in significant contamination. Board and box level bakeouts were extremely successful in reducing organic contamination (CVCMS). Simple diagnostics on orbit are of great value - scatter monitors for optical sensors, pressure gauges, QCMs. They can provide traceability, permit informed decisions, and validate spacecraft models currently under development.

ASTM E-1559 DATABASE

The ASTM E-1559 database is being established to consolidate data obtained using the ASTM-E-1559 standard test method for contamination outgassing characteristics of spacecraft materials. This test method is based on a technique for characterizing the outgassing kinetics of materials used in space and space simulation laboratories. A schematic of a suggested design for the apparatus needed in making these measurements is shown in Fig. 5. The test method is under the jurisdiction of the American Society for Testing and Materials (ASTM) Committee E-21 on Space Simulation and Applications of Space Technology. It is the direct responsibility of Subcommittee E21.05 on Contamination. The ASTM-E-1559 standard was developed to supplement data obtained using the ASTM-E-595-77/84/90 Standard — "Total Mass Loss (TML) and Collected Volatile Condensable Materials (CVCMS) from Outgassing in a Vacuum Environment."² An online database of data taken using the ASTM-E-595 standard has been established at the NASA Goddard Space Flight Center and is useful in the materials screening process. It can be accessed at: <http://misspiggy.gsfc.nasa.gov/og/>. The hardcopy version for some of this data can be obtained as presented in Ref. 3.

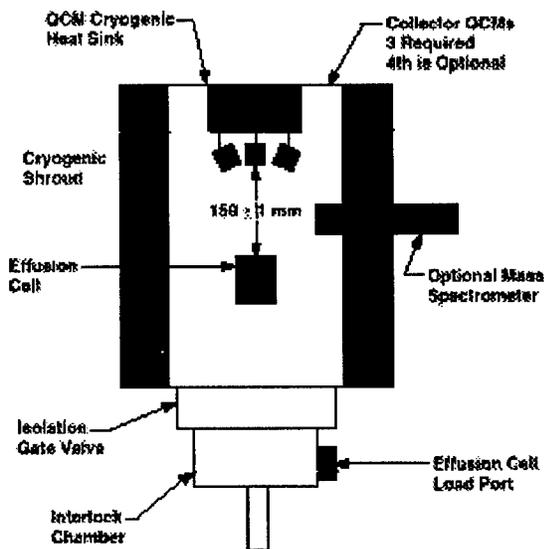


Fig. 5. Schematic of a typical test chamber used for ASTM-E-1559 standard testing.

The apparatus required for acquiring data using the ASTM-E-1559 Standard is considerably more elaborate because it requires the use of multiple QCMs within a vacuum cryogenic environment (Fig. 5). This apparatus establishes temporal outgassing trends and quantifies total mass outgassed. Additionally, thermogravimetric analyses (TGAs) can be performed with the QCMs to identify the individual condensed species. An example of a typical data set showing the volatile condensable material (VCM) mass loss as a function of time for a 48-hr test is shown in Fig. 6. An example of the thermogravimetric data is shown in Fig. 7.

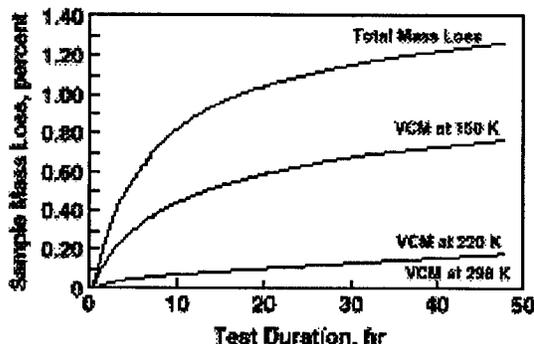


Fig. 6. Typical material outgassing dataset using ASTM-E-1559 Standard.

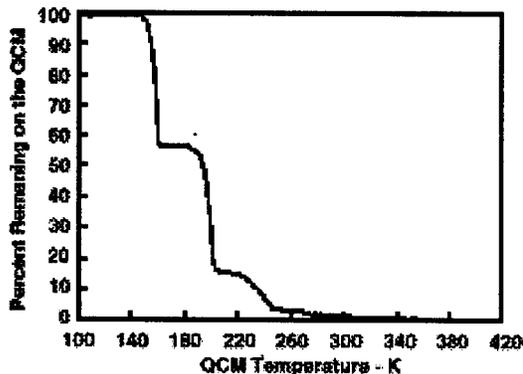


Fig. 7. Typical dataset showing results of thermogravimetric procedure.

ASTM-E-1559 has two test methods: Test Method A requires standard temperatures for the specimen and collectors, whereas Test Method B allows some

flexibility in the temperatures required, number of QCMs, and material and test geometries. Details of the requirements for each test method are given in Ref. 1.

SPACE FLIGHT QCM DATABASE

The data covered in the Space Flight Database are those measurements made in space using QCMs. Flight programs such as those sponsored by NASA, Department of Defense, and international agencies will provide the sources of most of this data. Examples of some of the sources identified already include:

1. NASA shuttle flights and those made prior to the shuttle
2. Russian MIR spacelab (Optical Properties Monitor)⁴
3. Canadian Space Agency
4. NASA Mars Pathfinder
5. DOD flights such as MSX, SCATHA, and DIP

The MSX QCM data for the first 21 mission months will be included in this database. The five QCMs on board the satellite provided data that were invaluable in characterizing contamination levels around the spacecraft and inside the SPIRIT 3 cryogenic telescope. One of the QCMs, the CQCM, was located internal to the SPIRIT 3 cryogenic telescope and was mounted adjacent to the primary mirror. Real-time monitoring of contaminant mass deposition on the primary mirror was provided by the CQCM, which was cooled to the same temperature as the mirror — ~20 K. Thermogravimetric analyses (TGAs) on the CQCM provided insight into the amount and species of contaminants condensed on the SPIRIT 3 primary mirror. The four TQCMs were mounted on the outside of the spacecraft for monitoring contaminant deposition on the external surfaces. The TQCMs operated at ~ -50°C, and were strategically positioned to monitor the silicone and organic contaminant flux arriving at specific locations. These TQCMs were located near the UV instruments or positioned to monitor mass coming from specific contaminant sources such as the solar panels. Updated time histories of contaminant thickness deposition for each of the QCMs will be presented. In addition, on-orbit data taken with some of the other contamination monitoring instruments will be included.⁵⁻⁷

Plans are for future QCM contamination measurements made on the ISS to be included in this database. Hopefully, QCMs will be included in the Environmental Monitoring Package (EMP) and will provide a continuing source of data.

SEE WEBSITE DEVELOPMENT

The SEE Website is being built on Microsoft's InterDev™ platform to conform with the existing NASA SEE system. The structure was designed to meet several criteria, particularly:

- Minimize processing time on the NASA website,
- Provide quick database searching,
- Provide quick downloading to the user, and
- Provide ease of updating data.

The website consists of two separate databases and an on-line bibliography which contain keywords in specific categories that link to the actual files. The keyword lists are automatically generated from the entries in the database so that added files do not require modification to the HTML and Java code. When requested, data and a Java Applet are transferred to the user to plot the comma-separated variable (csv) data on the user's machine. The plot routine allows the user to select specific data categories, zoom, and print the results. The Java Applet will run on PC, Mac, or UNIX machines. All files have compressed versions (in standard zip format) for download; the file sizes are listed with the files. The on-line bibliography is a collection of over 75 papers in .pdf format written on spacecraft contamination and totaling nearly 80 MB. The papers can be searched on several categories:

- Conference
- Contamination Control
- Date
- Environment
- Films
- Gases
- Instrument
- Particles
- Spacecraft

- Sponsor
- Miscellaneous

The results are displayed papers listed in a bibliographic format. Links (with file sizes) are provided to retrieve the documents in .pdf format.

The ASTM-E-1559 database eventually will contain data for a few hundred materials totaling over one-fourth of a gigabyte. To date, data have been obtained from NASA/GFSC, OSI, and the European Space Agency. Data from other participants are expected in the future. The data may be searched on Material or Test Temperature. The data are displayed with the original query and listed under eight categories:

- Material
- Test Temperature
- Sponsor
- Author
- Test Information File (and length) in MS Word per ASTM-E-1559
- Compressed Data File (and length) in zipped MS Excel
- Converted Data File (and length) in .csv format
- Associated Image Files (and length) in .jpg format.

Plots are contained in the zipped MS Excel documents, but to make the system easier to use, some plots have been saved as small .jpg (<200 Kb) and can be viewed directly through the web browser. The Java Applet is provided for plotting the .csv data.

The last database is QCM data for over 21 months of flight data from the MSX totaling 13 MB. The database will list temperature-controlled QCM, cryogenic QCM (CQCM), and total pressure sensor data. The final flight database allows searching on ten categories:

- Contamination Control
- Date (Mission Month)
- Environment
- Films
- Gases
- Instrument
- Particles

- Spacecraft
- Sponsor
- Miscellaneous

The Flight QCM database may be searched simultaneously with the paper bibliography. The paper results are displayed as in the above paper database, while the data are presented with the following information:

- Spacecraft,
- Mission Month,
- Sponsor,
- Compressed Data File (and length) in zipped .csv format,
- Converted Data File (and length) in .csv format, and
- Associated Image Files (and length) in .jpg format.

Plots have been saved as small .jpg (< 200 KB) and can be viewed directly through the web browser; the Java Applet is provided for plotting the .csv data.

Navigation through the website is provided by a Windows Explorer™-type interface. The structure is based on searching E1559, Flight Data, or MSX, and outlines specific topics of interest to the Space Contamination community. As the user opens folders, topical descriptions are provided in an adjacent window. These descriptions include:

- A textual description authored by an expert in the field
- Images of data plots or descriptive drawings
- Movies
- Associated papers from the SEE paper database
- Associated data from the SEE flight database
- Links to associated websites
- Contacts within the industry.

Help files are also provided with information on using the search engine, plotting data, and overall usage of the NASA SEE databases. A glossary and a user monitoring system will also be provided.

SUMMARY

The NASA/SEE Program Office is funding the

establishment of a website and databases for QCM data. Individual databases are being established for materials outgassing data obtained using the ASTM E 1559

Standard, and also for QCM data obtained from satellites/spacecraft operating in space. A subset of the space data will be contamination data accumulated during the BMDO-sponsored Midcourse Space Experiment (MSX) satellite flight.

The prime contractor for this program is Physical Sciences Inc. Data from various sources are being acquired by personnel from Sverdrup Technology, Inc., and the website and databases are being established by personnel at Johns Hopkins University/Applied Physics Laboratory. The website is being built on Microsoft's InterDev™ platform to conform with the existing NASA SEE system. This system will allow online viewing of the individual databases that are currently being generated. The structure was designed to meet several criteria, including minimal processing time, quick database searching, quick downloading to the user, and ease of updating data. The website will consist of two separate databases and an on-line bibliography that contains keywords in specific categories that link to the actual files. The on-line bibliography is a collection of over 75 papers in .pdf format written on spacecraft contamination. The plot routine will allow the user to select specific data categories, zoom, and print the results. The Java Applet will run on PC, Mac, or UNIX machines. All files have compressed versions (in standard zip format) for download, and the file sizes are listed with the files.

Plans are to complete populating the databases by August 2000, at which time the databases will be transferred from JHU/APL to the NASA/SEE Program Office. It is hoped that any future QCM data obtained from the International Space Station will be included in the Space Database.

ACKNOWLEDGEMENTS

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Keith Albyn of NASA/JSC for data they have provided. We would also like to acknowledge the support from the NASA/SEE program office with special thanks to Steve Pearson, Dewitt Burns, Stu Clifton, and Carolyn Goodloe.

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APPENDIX B

Satellite Contamination and Materials Outgassing Effects Database:
An Interactive Data and Resource Website
Flyer

Satellite Contamination and Materials Outgassing Effects Databases

An Interactive Data and Resource Website

Contamination from materials and ground processing leads to degraded spacecraft system performance:

Thermal control

Power generation

Optical sensor throughput/off axis rejection

Databases' benefits to spacecraft engineers:

- Assist in materials selection
- Appropriate materials location and utilization
- Assess spacecraft environmental and operations impact
- Review previous spacecraft experiences and observations
- Location to upload your data and findings for others

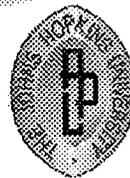
Database features

- Temperature dependent materials outgassing from
 - ASTM E1559 standard test and others
- Spacecraft surface accretion rates on Quartz Crystal Microbalances
 - Flight data from many missions
- Case study: Midcourse Space Experiment Satellite
 - Successfully Implemented Contamination Control Plan
 - Materials selection, assembly procedures, ground handling, and launch operations
 - Gaseous, Particulate, and Accreted Films observed by orbital sensor suite on MSX during multi-year mission



ISI

PHYSICAL SCIENCES INC.



Satellite Contamination and Materials Outgassing Effects Databases

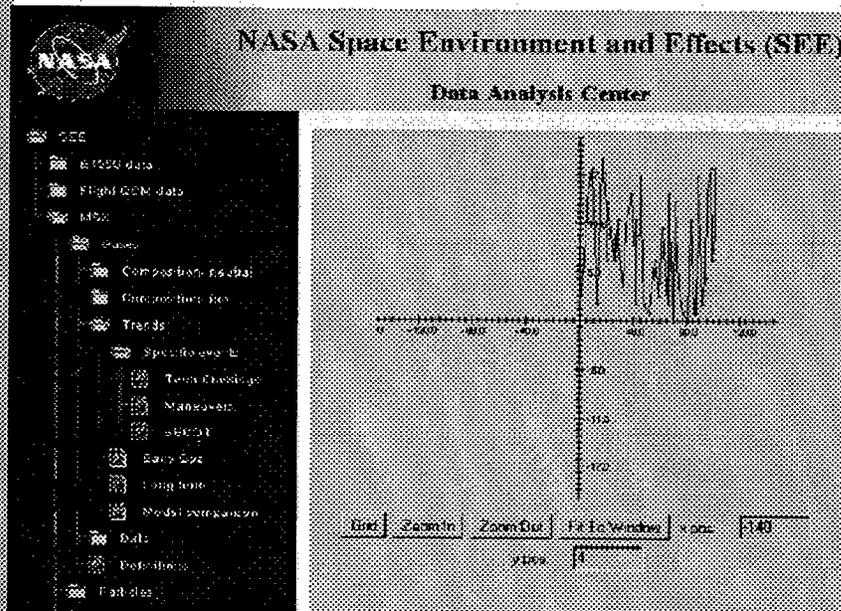
An Interactive Data and Resource Website

Features

- Available for download from the internet to your location
- Complete text of reports and publications available for download in .pdf
- Outgassing data collected for wide range spacecraft materials and missions
 - ▬ ASTM E1559 Standard and E-595
 - ▬ Space effects data from MSX, many other missions
- Universal platform interface
 - ▬ Available world wide through Internet Explorer or Netscape Navigator
- Maintained at NASA MSFC (available Sept 1999)

Tools

- Powerful search engine for cross referencing data and papers
- Display in graphic form, interactive replot/zoom capability
- Help/how-to-use information available with examples



MSX Contamination Experiment

The Midcourse Space Experiment is a multipurpose satellite developed by BMDO. In addition to the many optical sensors, the instrument package included a suite of contamination sensors for measuring gases, particles and films induced by orbital operations. A contamination control plan guided materials selection, spacecraft assembly and testing and launch readiness checks. Dr. U. was Principal Investigator for the Contamination Instruments and Instruments teams. Dr. Green was his deputy for data analysis. Mr. Wood was co-investigator for GCMs. They led the analysis of the gaseous, particulates and films environments induced by orbital operations from launch to 7 years in orbit. These individuals are teamed with Russ Cain of APL and other JPL/JSC staff in this current effort to create the databases and link them to ground and flight observations of the neutral contamination environment encountered/produced by spacecraft under NASA SEE program. This effort began in August 1998.

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NASA Space Environment and Effects (SEE) Program

NASA's SEE program administered at the Marshall Space Flight Center actively works with industry, academia, and government space activities to disseminate information to enable the design and manufacture of economical spacecraft by the U.S. space community. SEE sponsors development activities in critical technologies including flight demonstrations. Technical working groups in electromagnetic effects, ionizing radiation, materials and processes, meteoroid and orbiting debris, plasma and thermosphere, and neutral external contamination (this effort), are composed of experts in these disciplines. SEE acts as a partner and advocate for advancing our knowledge and capabilities to ameliorate spacecraft environmental interactions.

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APPENDIX C

Materials Outgassing Effects and Satellite Contamination Database

AIAA 2000-0241, 38th Aerospace Sciences Meeting and Exhibit, Reno, NV, 10-13 Jan 2000



AIAA 2000-0241

**Materials Outgassing Effects and
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**38th Aerospace Sciences
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Materials Outgassing Effects and Satellite Contamination Database*

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Abstract

Quartz crystal microbalances (QCMs) have been used extensively in the past for measuring contaminant mass deposition on surfaces, either in ground test facilities or on satellites for space experiments. An American Standard Test Method (ASTM E1559) has been developed that uses QCMs for detailed evaluations of satellite materials outgassing properties. A database has now been assembled which consolidates much of these types of data that have been previously generated. This effort is being funded by the NASA Research Announcement (NRA820), of the NASA Space and Environments Effects (SEE) Program Office. This paper describes the program that will enable one to rapidly locate previous measurements on specific satellite materials. Data from past space flight experiments are also being collected and will be a part of the database. The database will contain information on materials outgassing obtained using the ASTM E1559 standard, and on flight observations of mass accumulations. When completed, this database, will provide a valuable source of material outgassing information. The data should be useful to those working in the contamination technical area for mission design and materials specification. Data are being accumulated from both national and international sources with contributions from NASA/GSFC, NASA/JSC, OSI, and ESTEC/ESA. The space flight database will include data from past NASA missions, as well as DoD (including the BMDO-sponsored Midcourse Space Experiment (MSX) program), Canadian Space Agency, European Space Agency, Russian

MIR space station, and eventually, the International Space Station. A website has been established as the vehicle for storing and accessing the data that have been accumulated. A beta version of the website/database is now being evaluated by approximately 15 scientists at various locations. The website/database will be managed by the NASA/SEE Program Office at the Marshall Space Flight Center in Huntsville, AL. It is expected to become operational by September 2000.

Introduction

The satellite materials outgassing database program was initiated during a NASA Space and Environmental Effects (SEE) roadmap workshop on Neutral Contamination at the Marshall Space Flight Center in Huntsville, AL, on April 29-30, 1997. The attendees from various locations around the country discussed the future subject areas they thought would be most beneficial to the contamination area that could be funded as part of the then upcoming NASA Research Announcement NRA8-20.

ideas were prioritized at the end of the workshop. Two of the top three items agreed upon were to (1) establish a material outgassing database based on the ASTM E1559 test method¹ ("E 1559-93 Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials"), and (2) establish a database consolidating quartz crystal microbalance (QCM) data from previous missions in space. A general agreement among the attendees was that the QCM had become the

* The research reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Materiel Command. Work and analysis for this research were performed by personnel of Sverdrup Technology, Inc., AEDC Group, technical services contractor for AEDC. Further reproduction is authorized to satisfy needs of the U. S. Government.

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primary instrument for providing materials outgassing property data as well as for characterizing the on-orbit real-time satellite environments.

The QCM is an instrument that has been developed for measuring the deposition of mass on a surface at specific temperatures. The mass sensitivity depends on the oscillation frequency of the quartz crystals being used, which range from 5 MHz up to as high as 50 MHz. For 10-MHz crystals, the mass sensitivity is given as

$$S = 4.43 \times 10^{-9} \text{ gm/cm}^2 \cdot \text{Hz}$$

With this sensitivity, film thicknesses on the order of angstroms can be detected. A schematic of one version of QCM is shown in Fig. 1.

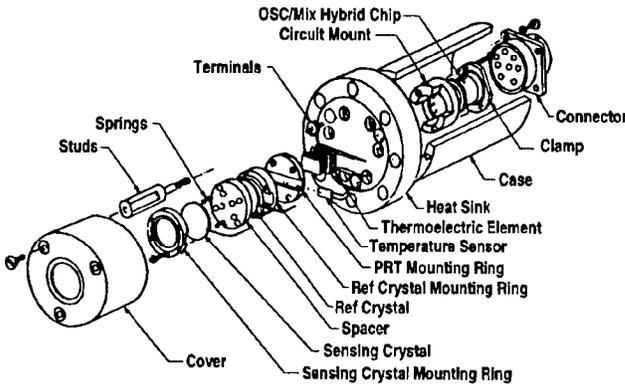


Fig. 1. Temperature-controlled QCM (TQCM) assembly diagram.

A proposal to combine both databases using QCMs was submitted and accepted for funding through NRA8-20. Work on the program began in October 1998, and the project is scheduled to be completed in August 2000. The database will be organized as shown in Fig. 2.

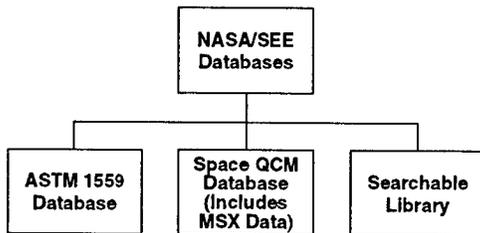


Fig. 2. Structure of NASA/SEE databases.

The program for consolidating data from QCMs is well underway with Physical Sciences, Inc. as the prime contractor for the program, and Sverdrup Technology and Johns Hopkins University/Applied Physics Laboratory as subcontractors. Personnel at these organizations are currently working with the NASA/SEE Program Office to establish the database as a resource for the aerospace community. The database being developed will enable one to rapidly locate previous measurements on specific materials and from past space flight experiments. Sverdrup Technology personnel are responsible for acquiring the needed data and transferring it to JHU/APL for the database. JHU/APL is developing the website and establishing the database structures. At the program's conclusion, the database will be transferred by JHU/APL to the NASA/SEE Program Office at the Marshall Space Flight Center in Huntsville, AL.

The database contains information on materials outgassing and flight observations of mass accumulations. Specifically:

- (1.) An ASTM E1559 Database, and (2.) A Space Flight QCM Database

Both portions of the database will include QCM data. The ASTM E1559 Database will include the outgassing data obtained using this relatively new standard. The intent of this database is to complement the data archived by NASA Goddard Space Flight Center using the ASTM E595 standard (NASA Reference Publication 1124).² ASTM Standard E1559 provides the time-dependent material outgassing properties for specified QCM crystal temperatures.

Data were requested from facilities having data generated by chambers such as the Vacuum Outgassing Deposition/Kinetics Apparatus (VODKA) that is being marketed by QCM Research of Laguna Beach, CA, or chambers with similar capabilities. When it is completed, this database will provide a valuable source of material outgassing information for mission design and materials specification to those working in the contamination area.

Similarly, the Space Flight QCM Database will

include QCM data that have been collected on satellites operating in space. This will include data from, among others, NASA programs including the Shuttle, DoD (including the BMDO-sponsored Mid-course Space Experiment (MSX) satellite program), Canadian Space Agency, European Space Agency, Russian MIR space station, and eventually the International Space Station.

The website constructed at JHU/APL is the vehicle for storing and accessing the data that have been accumulated. A part of the database is an excerpted collection of data from the BMDO-sponsored MSX satellite program. The MSX program has been the source of ongoing contamination measurements and experiments from a suite of instruments since April 1996. The website will be generated and tested at JHU/APL, after which it will be delivered to the NASA SEE Program Office for implementation.

The benefits of the database are that better procedures can be established for materials selection for space flight. The associated cost savings will be due to missions which are successful (risk mitigation). Other benefits will be the better understanding of what to expect in space, based on the mission requirements and the ability to design systems with appropriate end-of-life performance margins. Having all of the necessary data in one location will allow a user/designer to have all of the available data at his fingertips.

Approach

The first step in building the database was to prepare and distribute a survey to those working in the "contamination technical area." This step was accomplished during November 1998. The responses were assembled and the appropriate steps were taken to contact those agencies where known sets of data were in existence. While the data were being collected, the database platform and website were constructed at JHU/APL. Publications associated with either ASTM E1559 QCM data or space-related QCM data are also being collected and will be available at the website. Initially, data from several materials have been included in the database and will serve as test cases. Since the format and approach of measure-

ment is somewhat varied between the data sources, the data from each source have required individual attention.

The contamination data obtained during the MSX satellite program is also being assembled for inclusion in the Space Flight QCM database. The data from the five QCMs on board will be available, as well as data from some of the other instruments used in characterizing the space environment around the spacecraft.

Plans are to complete the population of the database by August 2000, when the database will be transferred from JHU/APL to the NASA/SEE Program Office. It is hoped that any future QCM data obtained from the International Space Station will eventually be included in the Space Database.

ASTM E1559 Database

This database was established to consolidate data obtained using the ASTM E1559 standard test method for spacecraft materials. This test method is based on a technique for characterizing the outgassing kinetics of materials used in space and space simulation laboratories. A schematic of a suggested design for the apparatus that can be used in making these measurements is shown in Fig. 3. The test method is under the jurisdiction of the American Society for

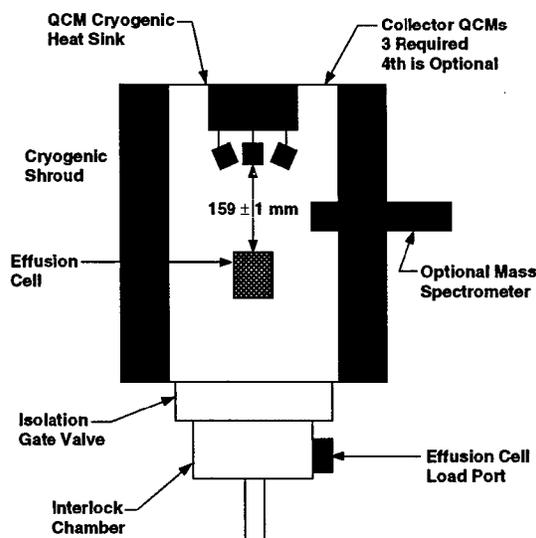


Fig. 3. Schematic of a typical test chamber used for ASTM E1559 Standard testing.

Testing and Materials (ASTM) Committee E-21 on Space Simulation and Applications of Space Technology. It is the direct responsibility of Subcommittee E21.05 on Contamination. The ASTM E1559 standard was developed to supplement data obtained using the ASTM E 595-77/84/90 Standard -- "Total Mass Loss (TML) and Collected Volatile Condensable Materials (CVCM) from Outgassing in a Vacuum Environment".² An online database of data taken using the ASTM E 595 standard were previously established at the NASA Goddard Space Flight Center, and has been useful in the materials screening process. It can be accessed at <http://misspiggy.gsfc.nasa.gov/og/>. The hardcopy version for some of this data can be obtained as presented in Ref. 3.

The apparatus required for acquiring data using the E 1559 standard is considerably more elaborate than that required for ASTM E595 tests, because it requires the use of multiple QCMs within a vacuum cryogenic environment (Fig. 3). With this apparatus, temporal outgassing trends are established, and the total mass outgassed is also quantified. In addition, thermogravimetric analyses (TGAs) can be performed with the QCMs to enable the identification of the individual condensed species. An example of a typical data set showing the volatile condensable material (VCM) as a function of time for a 48-hr test is shown in Fig. 4. An example of the thermogravimetric data is shown in Fig. 5.

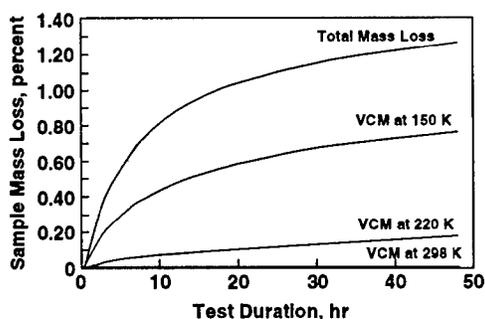


Fig. 4. Typical material outgassing dataset using ASTM E1559 Standard.

Standard E1559 has two test methods, A and B. The details of the requirements for each Test Method are given in Ref. 1.

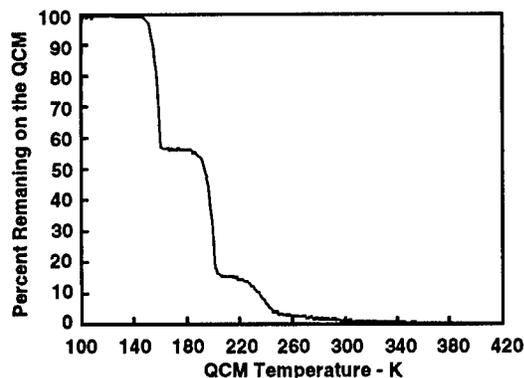


Fig. 5. Typical dataset showing results of the thermogravimetric (TGA) procedure.

Test Method A requires standard temperatures for the specimen and collectors.

Test Method B allows some flexibility in the temperatures required, number of QCMs, and material and test geometries.

Space Flight QCM Database

The data covered in this database are those measurements made in space using QCMs. Flight programs such as those sponsored by NASA, Department of Defense, and international agencies will provide the sources of most of this data. Examples of some of the sources identified already include:

1. NASA shuttle flights and those made prior to the shuttle
2. Russian MIR spacelab (Optical Properties Monitor)⁴
3. Canadian Space Agency
4. NASA Mars Pathfinder
5. DOD flights such as MSX, SCATHA, and DIP

The MSX QCM data for the first 21 mission months are included in this database. The five QCMs on board the satellite provided data that were invaluable in characterizing contamination levels around the spacecraft and inside the SPIRIT 3 cryogenic telescope. One of the QCMs, the CQCM, was located internal to the SPIRIT 3 cryogenic telescope and was mounted adjacent to the primary mirror. Real-time monitoring of contaminant mass deposition on the primary mirror was

provided by the CQCM, which was cooled to the same temperature as the mirror -- ~20K. Thermogravimetric analyses (TGAs) on the CQCM provided insight into the amount and species of contaminants condensed on the SPIRIT 3 primary mirror. The four TQCMs were mounted on the outside of the spacecraft for monitoring contaminant deposition on the external surfaces. The TQCMs operated at ~ -50 C and were strategically positioned to monitor the silicone and organic contaminant flux arriving at specific locations. These TQCMs were located near the UV instruments or positioned to monitor mass coming from specific contaminant sources such as the solar panels. Updated time histories of contaminant thickness deposition for each of the QCMs will be presented. In addition, on-orbit data taken with some of the other contamination monitoring instruments will be included.⁵⁻⁷

Plans are for future QCM contamination measurements made on the ISS to be included in this database. Hopefully, QCMs will be included in the Environmental Monitoring Package (EMP) and will provide a continuing source of data.

SEE Website Development

The SEE Website was built on Microsoft's Inter-Dev[®] platform to conform with the existing NASA SEE system. The structure was designed to meet several criteria, particularly:

- Minimize processing time on the NASA website,
- Provide quick database searching,
- Provide quick downloading to the user, and
- Provide ease of updating data.

It consists of two separate portions of the database and an on-line bibliography that contain keywords in specific categories that link to the actual files. The keyword lists are automatically generated from the entries in the database, so added files do require modification to the HTML and Java code. When requested, data and a Java Applet are transferred to the user to plot the comma-separated variable (csv) data on the user's machine. The plot routine allows the user to select specific data categories, zoom, and print the results. The Java Applet will run on PC, Mac, or UNIX

machines. All files have compressed versions (in standard zip format) for download, and the file sizes are listed with the files.

The on-line bibliography is an 80-MB collection of over 75 papers in .pdf format written on spacecraft contamination. The papers can be searched on several categories, including conference, date, environment, films, gases, instruments, particles, and spacecraft.

The results are displayed papers listed in a bibliographic format. Links (with file sizes) are provided to retrieve the documents in .pdf format.

The ASTM E1559 database contains data for about 200 materials totaling over 1/4 of a gigabyte. The data may be searched on Material or Test Temperature. The data are displayed with the original query and listed with:

- Material,
- Test Temperature,
- Sponsor,
- Author,
- Test Information File (and length) in MS Word per ASTM E1559,
- Compressed Data File (and length) in zipped MS Excel,
- Converted Data File (and length) in csv format, and
- Associated Image Files (and length) in jpg format.

Plots are contained in the zipped MS Excel documents, but to make the system easier to use, some plots have been saved as small .jpg (< 200KB) and can be viewed directly though the Web browser. The Java Applet is provided for plotting the csv data.

The last database is 13 MB of MSX, QCM data for over 21 months of flight data. The database will list temperature-controlled QCM (TQCM), cryogenic QCM (CQCM), and total pressure sensor (TPS) data. The final flight database allows searching on: Contamination Control, Date (Mission Month), Environment, Films, Gases, Instrument, Particles, Spacecraft, Sponsor, and Miscellaneous, headings.

The Flight QCM database may be searched simultaneously with the paper bibliography. The papers results are displayed as in the above paper database while the data are presented with the following information:

- Spacecraft
- Mission Month
- Sponsor
- Compressed Data File (and length) in zipped csv format
- Converted Data File (and length) in csv format, and
- Associated Image Files (and length) in .jpg format.

Plots have been saved as small .jpg (< 200KB) and can be viewed directly through the Web browser, and the Java Applet is provided for plotting the csv data.

Navigation through the website is provided by a Windows Explorer[®]- type interface. The structure is based on searching E1559, Flight Data, or MSX, and outlines specific topics of interest to the Space Contamination community. As the user opens folders, topical descriptions are provided in an adjacent window. These descriptions include a textual description authored by an expert in the field, images of data plots or descriptive drawings, movies, and associated papers from the SEE paper database, associated data from the SEE flight database; links to associated websites, and contacts within the industry.

Help files are also provided with information on using the search engine, plotting data, and overall usage of the NASA SEE database. A glossary and a user monitoring system is also provided.

Summary

The NASA/SEE Program Office is funding the establishment of a website and database for quartz crystal microbalance data. Individual portions of the database are being established for materials outgassing data obtained using the ASTM E1559 Standard, and for QCM data obtained from satellites/spacecraft operating in space. A subset of the space data will be contamination data accumulated

during the BMDO-sponsored Midcourse Space Experiment (MSX) satellite flight.

The prime contractor for this program is PSI, Inc. Data from various sources are being acquired by personnel from Sverdrup Technology, Inc., and the website and database are being established by personnel at Johns Hopkins University / Applied Physics Laboratory. The website is being built on Microsoft's InterDev[®] platform to conform with the existing NASA SEE system. This system will allow on-line viewing of the data that are included. The structure was designed to meet several criteria, including minimizing the processing time, providing quick database searching, providing quick downloading to the user, and providing ease of updating data. The website will consist of the database and an on-line bibliography that contains keywords in specific categories that link to the actual files. The on-line bibliography is a collection of over 75 papers on spacecraft contamination in .pdf format. The plot routine will allow the user to select specific data categories, zoom, and print the results. The Java Applet will run on PC, Mac, or UNIX machines. All files have compressed versions (in standard zip format) for download, and the file sizes are listed with the files.

Acknowledgements

The authors would like to thank Jeff Garrett and Peter Glassford from OSI for the use of some of their data in this paper. Thanks also to George Meadows of NASA/GSFC, Marc van Eesbeek of ESA/ESTEC, and Keith Albyn of NASA/JSC for data they have provided. We would also like to acknowledge the support from the NASA/SEE Program Office, with special thanks to Steve Pearson, Dewitt Burns, Billy Kauffman, Stu Clifton, and Carolyn Goodloe.

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APPENDIX D

Satellite Contamination and Materials Outgassing Effects Databases

SATELLITE CONTAMINATION AND MATERIALS OUTGASSING EFFECTS DATABASES*

B. E. WOOD,[†] B. D. GREEN,[‡] O. M. UY,^{**} R. P. CAIN,^{**} and Sopo K. YUNG^{††}

ABSTRACT - This paper describes a program for consolidating data from quartz crystal microbalances (QCMs) that will enable one to rapidly locate previous measurements on specific materials and data from past space flight experiments. When complete, the databases will contain information on materials outgassing obtained using the ASTM-E-1559 standard, and flight observations of mass accumulations. Once established, these databases will be available to the entire community and will provide a valuable source of material outgassing information. The data should be useful to those working in the Contamination area for mission design and materials specification. Data are being accumulated from both national and international sources. The space flight database will include data from past NASA missions, as well as DOD (including the BMDO-sponsored Midcourse Space Experiment (MSX) program), Canadian Space Agency, European Space Agency, Russian MIR space station, and eventually, the International Space Station. A website is being generated which will be the vehicle for storing the data that are accumulated. Once completed, the databases will be managed by the NASA/Space and Environmental Effects (SEE) Program Office at the Marshall Space Flight Center in Huntsville, Alabama.

1 - INTRODUCTION

The origin of this program began during a NASA Space and Environmental Effects (SEE) roadmap workshop on Neutral Contamination held at the Marshall Space Flight Center in Huntsville, Alabama, on April 29-30, 1997. The attendees from various locations around the country discussed future subject areas they thought would be most beneficial to the contamination area that could be funded as part of the then-upcoming NASA Research Announcement NRA8-20.

The ideas were prioritized at the end of the workshop. Two of the top three items agreed upon were to (1) establish a material outgassing database based on the ASTM-1559 test method [E1559 93], and (2) establish a database consolidating quartz crystal microbalance (QCM) data from previous missions in space. The attendees generally agreed that the QCM has become the primary instrument for providing materials outgassing property data, and for characterizing the on-orbit real-time surface film accretions.

The QCM is an instrument that has been developed for measuring the deposition of mass on a surface at specific temperatures. The mass sensitivity depends on the oscillation frequency of the quartz crystals being used, which range from 5 MHz up to as high as 50 MHz. For 10-MHz crystals, the mass sensitivity is given as

$$S = 4.43 \times 10^{-9} \text{ gm/cm}^2 \cdot \text{Hz}$$

*The research reported herein was funded by the NASA Space Environmental Effects (SEE) Program Office. Work and analysis for this research were performed by personnel of Sverdrup Technology, Inc., AEDC Group, technical services contractor for AEDC, by personnel of Johns Hopkins University/Applied Physics Laboratory, and by personnel of Physical Sciences, Inc. Further reproduction is authorized to satisfy needs of the U. S. Government.

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^{††}NASA Marshall Space Flight Center, Huntsville, AL 35816 USA.

With this sensitivity, film thicknesses on the order of angstroms can be detected. A schematic of one version of the QCM is shown in Fig. 1.

A proposal to combine both databases that use QCMs was submitted and was accepted for funding through NRA8-20. Work on the program began in October 1998, and the project is scheduled for completion in August 2000. The databases will be organized as shown in Fig. 2.

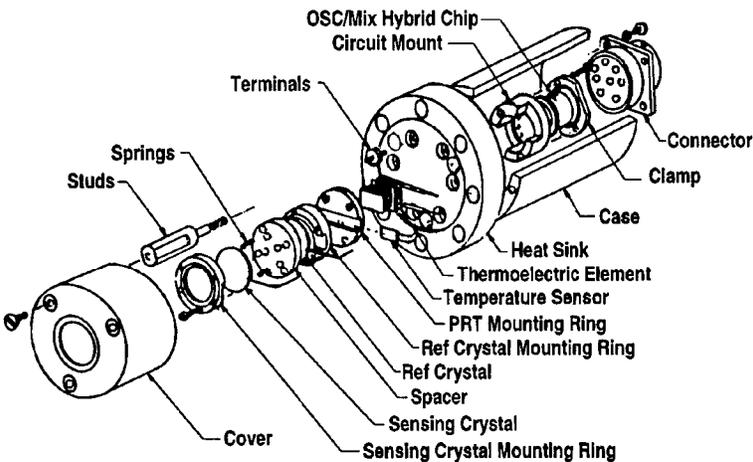


Fig. 1: Temperature-controlled QCM (TQCM) assembly diagram.

The QCM data consolidation program is underway with PSI, Inc., as the prime contractor, and with Sverdrup Technology and Johns Hopkins University/Applied Physics Laboratory as subcontractors. Personnel at these organizations are currently working with the NASA/SEE Program Office to establish the two QCM databases as a resource for the aerospace community. The databases being developed will enable one to rapidly locate previous measurements on specific materials and from past space flight experiments. Sverdrup Technology personnel are responsible for acquiring the needed data and transferring it to JHU/APL for the databases. JHU/APL is developing the website and establishing the database structures. At the end of the program, JHU/APL will transfer the databases to the NASA/SEE Program Office at the Marshall Space Flight Center in Huntsville, Alabama.

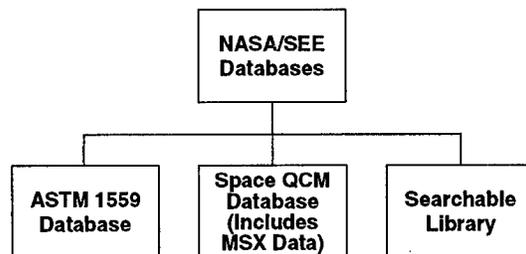


Fig. 2: Structure of NASA/SEE databases.

The databases will contain information on materials outgassing and flight observations of mass accumulations. Specifically:

1. An ASTM 1559 Database, and
2. A Space Flight QCM Database.

Both of these databases will include QCM data. The ASTM-E-1559 Database will include the outgassing data obtained using this relatively new standard. The intent of this database is to complement the data archived by NASA Goddard Space Flight Center using the ASTM-E-595 standard (NASA Reference Publication 1124) [E595 90]. ASTM Standard E-1559 provides the time-dependent material outgassing properties for three collector temperatures.

Data are being requested from facilities having data generated by chambers such as the Vacuum Outgassing Deposition/Kinetics Apparatus (VODKA) that is being marketed by QCM Research of Laguna Beach, CA or chambers with similar capabilities. Once established, this database will be available to the entire community, and will provide a valuable source of material outgassing information for mission design and materials specification to those working in the Contamination area. Plans also include links to publications relating to the data included in the database.

Similarly, the Space Flight QCM Database will include QCM data that have been collected on satellites operating in space. Among others, this will include data from NASA programs including

3 - ASTM E-1559 DATABASE

The ASTM E-1559 database is being established to consolidate data obtained using the ASTM-E-1559 standard test method for contamination outgassing characteristics of spacecraft materials. This test method is based on a technique for characterizing the outgassing kinetics of materials used in space and space simulation laboratories. A schematic of a suggested design for the apparatus needed in making these measurements is shown in Fig. 5. The test method is under the jurisdiction of the American Society for Testing and Materials (ASTM) Committee E-21 on Space Simulation and Applications of Space Technology. It is the direct responsibility of Subcommittee E21.05 on Contamination. The ASTM-E-1559 standard was developed to supplement data obtained using the ASTM-E-595-77/84/90 Standard — "Total Mass Loss (TML) and Collected Volatile Condensable Materials (CVCM) from Outgassing in a Vacuum Environment" [E595 90]. An online database of data taken using the ASTM-E-595 standard has been established at the NASA Goddard Space Flight Center and is useful in the materials screening process. It can be accessed at: <http://misspiggy.gsfc.nasa.gov/og/>. The hard-copy version for some of this data can be obtained as presented in the Campbell paper [CAMP 93].

The apparatus required for acquiring data using the ASTM-E-1559 Standard is considerably more elaborate because it requires the use of multiple QCMs within a vacuum cryogenic environment (Fig. 5). This apparatus establishes temporal outgassing trends and quantifies total mass outgassed. Additionally, thermogravimetric analyses (TGAs) can be performed with the QCMs to identify the individual condensed species. An example of a typical data set showing the volatile condensable material (VCM) mass loss as a function of time for a 48-hr test is shown in Fig. 6. An example of the thermogravimetric data is shown in Fig. 7.

ASTM-E-1559 has two test methods: Test Method A requires standard temperatures for the specimen and collectors, whereas Test Method B allows some flexibility in the temperatures required, number of QCMs, and material and test geometries. Details of the requirements for each test method are given in the Annual Book of ASTM Standards [E1559 93].

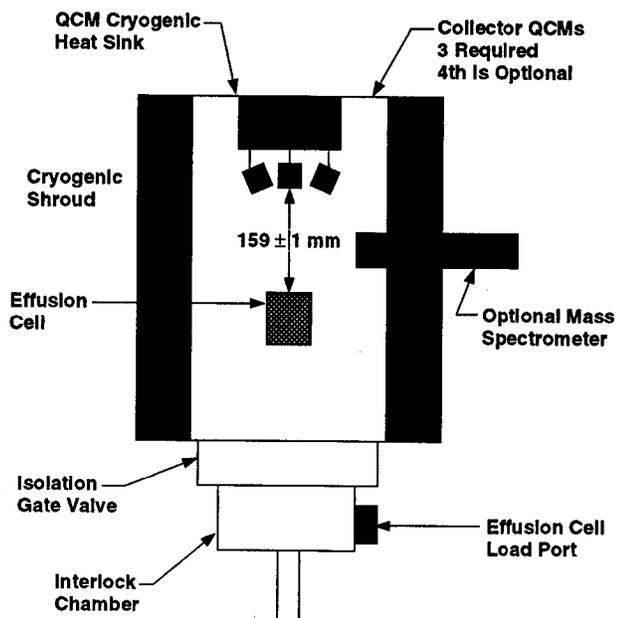


Fig. 5: Schematic of a typical test chamber used for ASTM-E-1559 standard testing.

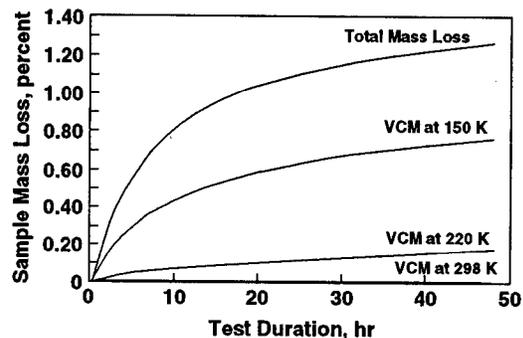


Fig. 6: Typical material outgassing dataset using ASTM-E-1559 Standard.

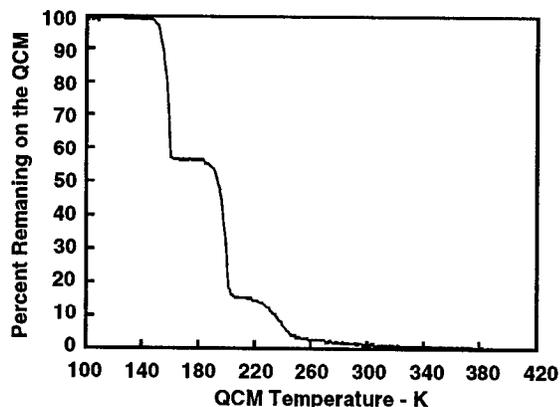


Fig. 7: Typical dataset showing results of thermogravimetric procedure.

4 - SPACE FLIGHT QCM DATABASE

The data covered in the Space Flight Database are those measurements made in space using QCMs. Flight programs such as those sponsored by NASA, Department of Defense, and international agencies will provide the sources of most of this data. Examples of some of the sources identified already include:

1. NASA shuttle flights and those made prior to the shuttle
2. Russian MIR spacelab (Optical Properties Monitor) [WILK 98]
3. Canadian Space Agency
4. NASA Mars Pathfinder
5. DOD flights such as MSX, SCATHA, and DIP

The MSX QCM data for the first 21 mission months will be included in this database. The five QCMs on board the satellite provided data that were invaluable in characterizing contamination levels around the spacecraft and inside the SPIRIT 3 cryogenic telescope. One of the QCMs, the CQCM, was located internal to the SPIRIT 3 cryogenic telescope and was mounted adjacent to the primary mirror. Real-time monitoring of contaminant mass deposition on the primary mirror was provided by the CQCM, which was cooled to the same temperature as the mirror — ~20K. Thermogravimetric analyses (TGAs) on the CQCM provided insight into the amount and species of contaminants condensed on the SPIRIT 3 primary mirror. The four TQCMs were mounted on the outside of the spacecraft for monitoring contaminant deposition on the external surfaces. The TQCMs operated at ~ -50°C, and were strategically positioned to monitor the silicone and organic contaminant flux arriving at specific locations. These TQCMs were located near the UV instruments or positioned to monitor mass coming from specific contaminant sources such as the solar panels. Updated time histories of contaminant thickness deposition for each of the QCMs will be presented. In addition, on-orbit data taken with some of the other contamination monitoring instruments will be included [UY 97, WOOD 97, GREE 99]

Plans are for future QCM contamination measurements made on the ISS to be included in this database. Hopefully, QCMs will be included in the Environmental Monitoring Package (EMP) and will provide a continuing source of data.

5 - SEE WEBSITE DEVELOPMENT

The SEE Website is being built on a Microsoft® InterDev® platform to conform with the existing NASA SEE system. The structure was designed to meet several criteria, particularly:

- Minimize processing time on the NASA website,
- Provide quick database searching,
- Provide quick downloading to the user, and
- Provide ease of updating data.

The website consists of two separate databases and an on-line bibliography which contain keywords in specific categories that link to the actual files. The keyword lists are automatically generated from the entries in the database so that added files do not require modification to the HTML and Java code. When requested, data and a Java Applet are transferred to the user to plot the comma-separated variable (csv) data on the user's machine. The plot routine allows the user to select spe-

cific data categories, zoom, and print the results. The Java Applet will run on PC, Mac, or UNIX machines. All files have compressed versions (in standard zip format) for download; the file sizes are listed with the files.

The on-line bibliography is a collection of over 75 papers in .pdf format written on spacecraft contamination and totaling nearly 80 MB. The papers can be searched on several categories:

| | |
|-----------------------|------------|
| Conference | Gases |
| Contamination Control | Instrument |
| Date | Particles |
| Environment | Spacecraft |
| Films | Sponsor |
| Miscellaneous | |

The results are displayed papers listed in a bibliographic format. Links (with file sizes) are provided to retrieve the documents in .pdf format.

The ASTM-E-1559 database eventually will contain data for a few hundred materials totaling over one-fourth of a gigabyte. To date, data have been obtained from NASA/GFSC, OSI, and the European Space Agency. Data from other participants are expected in the future. The data may be searched on Material or Test Temperature. The data are displayed with the original query and listed under eight categories:

- | | |
|---------------------|--|
| 1. Material | 5. Test Information File (and length) in MS Word per ASTM-E-1559 |
| 2. Test Temperature | 6. Compressed Data File (and length) in zipped MS Excel |
| 3. Sponsor | 7. Converted Data File (and length) in .csv format |
| 4. Author | 8. Associated Image Files (and length) in .jpg format |

Plots are contained in the zipped MS Excel documents, but to make the system easier to use, some plots have been saved as small .jpg (< 200 Kb) and can be viewed directly through the web browser. The Java Applet is provided for plotting the .csv data.

The last database is QCM data for over 21 months of flight data from the MSX totaling 13 MB. The database will list temperature-controlled QCM (TQCM), cryogenic QCM (CQCM), and total pressure sensor (TPS) data. The final flight database allows searching on ten categories:

| | |
|-----------------------|---------------|
| Contamination Control | Instrument |
| Date (Mission Month) | Particles |
| Environment | Spacecraft |
| Films | Sponsor |
| Gases | Miscellaneous |

The Flight QCM database may be searched simultaneously with the paper bibliography. The paper results are displayed as in the above paper database, while the data are presented with the following information:

| | |
|---------------|---|
| Spacecraft | Compressed Data File (and length) in zipped .csv format |
| Mission Month | Converted Data File (and length) in .csv format |
| Sponsor | Associated Image Files (and length) in .jpg format |

Plots have been saved as small .jpg (< 200 KB) and can be viewed directly through the web browser; the Java Applet is provided for plotting the .csv data.

Navigation through the website is provided by a Microsoft® Windows® Explorer®-type interface. The structure is based on searching E1559, Flight Data, or MSX, and outlines specific topics of interest to the Space Contamination community. As the user opens folders, topical descriptions are provided in an adjacent window. These descriptions include:

A textual description authored by an expert in the field

Images of data plots or descriptive drawings

Movies

Associated papers from the SEE paper database

Associated data from the SEE flight database

Links to associated websites

Contacts within the industry.

Help files are also provided with information on using the search engine, plotting data, and overall usage of the NASA SEE databases. A glossary and a user monitoring system will also be provided.

6 - SUMMARY

The NASA/SEE Program Office is funding the establishment of a website and databases for QCM data. Individual databases are being established for materials outgassing data obtained using the ASTM E 1559 Standard, and also for QCM data obtained from satellites/spacecraft operating in space. A subset of the space data will be contamination data accumulated during the BMDO-sponsored Midcourse Space Experiment (MSX) satellite flight.

The prime contractor for this program is PSI, Inc. Data from various sources are being acquired by personnel from Sverdrup Technology, Inc., and the website and databases are being established by personnel at Johns Hopkins University/Applied Physics Laboratory. The website is being built on Microsoft's InterDev® platform to conform with the existing NASA SEE system. This system will allow online viewing of the individual databases that are currently being generated. The structure was designed to meet several criteria, including minimal processing time, quick database searching, quick downloading to the user, and ease of updating data. The website will consist of two separate databases and an on-line bibliography that contains keywords in specific categories that link to the actual files. The on-line bibliography is a collection of over 75 papers in .pdf format written on spacecraft contamination. The plot routine will allow the user to select specific data categories, zoom, and print the results. The Java Applet will run on PC, Mac, or UNIX machines. All files have compressed versions (in standard zip format) for download, and the file sizes are listed with the files.

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