Space Environmental and Contamination Effects on Cryogenic and Warm Optical Surfaces – A Review*

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ABSTRACT

This review paper focuses on measurement techniques and facilities for the study of the contamination and space environment effects on optical and thermal radiative surfaces. Laboratory measurements are reviewed and illustrate how cryogenic and relatively warm surfaces can be affected by contaminants, vacuum, and UV. The laboratory data are used to illustrate the important parameters that require consideration when trying to determine these types of effects on future satellite missions. Optical properties of thin contaminant films, BRDF measurements on cryogenic films, quartz crystal microbalance (QCM) measurements, and UV effects on silicone/hydrocarbon films are presented and discussed relative to their applications to satellite systems. The laboratory data are complemented with flight data from the Midcourse Space Experiment (MSX) satellite. Laboratory results were used to interpret MSX spacecraft flight data. The MSX demonstration and validation satellite program was funded by the Ballistic Missile Defense Organization (BMDO). MSX had UV, visible, and infrared instruments including the Spirit 3 cryogenic telescope and had several contamination instruments for measuring pressure, gas species, water and particulate concentrations, and condensable gas species. Some of the data collected from the flight QCMs are presented.

Keywords: cryogenics, spacecraft, quartz crystal microbalance, QCM, TQCM, CQCM, infrared, MSX, satellite, cryofilm, infrared, telescope, contaminant, BRDF, transmittance, reflectance, germanium.

INTRODUCTION

This paper is intended to be a review paper, a history of sorts, to describe optical property measurement systems and optical properties of materials measurements that have been obtained over the years at the Arnold Engineering Development Center (AEDC), Arnold Air Force Base, TN. These measurements, using unique measurement facilities, eventually led to participation in the BMDO-sponsored Midcourse Space Experiment (MSX) satellite program. Measurements of contamination and the space environment will be addressed in relation to effects on cryogenic and warm optical surfaces. Facilities developed to meet the *in situ* measurement requirements for vacuum cryogenic testing will be described. Finally, some of the flight data from the MSX satellite program will be presented to show the usefulness of the laboratory data obtained prior to the flight.

CRYOGENIC OPTICAL PROPERTY FACILITIES AND MEASUREMENT TECHNIQUES

At the AEDC, optical property measurements of cryofilms began in the mid 1960s to support thermal balance testing in local, large thermal vacuum simulation chambers. The vacuum space simulation chamber walls were painted black and were cooled with liquid nitrogen to simulate the cold, black conditions of outer space. Due to materials outgassing and chamber atmospheric leaks, a small amount of cryofrost would form on the cold, black surfaces, thereby altering, and in most cases, increasing the reflectance of the chamber surroundings. This increase in solar reflectivity had to be accounted for in the ther-

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mal balance equations. No previous reflectance measurements for these conditions had been made, so this requirement initiated programs for measuring the change in reflectance due to these cryofilms.

Vacuum-rated reflectometers were developed to provide *in situ* reflectance of cryofilms. The instruments developed included vacuum-rated magnesium oxide and barium sulfate-coated integrating spheres for the solar wavelength range.[1-4] Water vapor was of most concern since it was most prevalent and would condense on a 77K surface. Since carbon dioxide was another gas that could condense at 77K under vacuum and was relatively abundant due to materials outgassing, it was decided to investigate the reflective properties of these two most common condensates. The scattering properties of these frosts were also investigated by measuring *in situ* the bidirectional reflectance distribution function (BRDF) of the condensed gases on black paint and polished stainless steel surfaces.[5-7]

Initially, the primary focus was on measuring the change in hemispherical reflectance for the solar wavelengths, but as the requirements began to change, it became necessary to extend these measurements further into the infrared. A powdered sodium chloride-coated vacuum integrating sphere was developed to operate in the infrared range out to wavelengths of 14.0 μm.[8-10] Later, an ellpsoidal mirror reflectometer was developed for hemispherical reflectance measurements of cryosamples in vacuum at temperatures as low as 20K, and for wavelengths extending out to 34 μm.[11-12]

During these early studies, the thin-film interference phenomenon for cryofilms was first observed and found to be both very interesting and extremely useful. Thin-film interference patterns were first observed at AEDC during reflectance measurements on a liquid nitrogen cooled black paint surface.[2] Later, it was found that higher quality patterns could be obtained for thin condensate films and for greater film thicknesses using a helium-neon laser. This led to techniques being developed for determining cryofilm refractive index and thickness. Using two lasers at two incidence angles allowed the determination of the film refractive index at 0.6328 μm. Once the refractive index was known at that single wavelength, film thicknesses were easily calculated. Thin-film interference maxima and minima, "or fringe counting," provided a very accurate technique for determining film thicknesses that were on the order of 0.1 to ~ 20 μm.[2, 5,6] Having a technique for accurately determining film thickness led to techniques for determining cryofilm density,[13-14] which was another cryofilm physical property of interest.

Optical properties of condensed gases on cryogenic optics became the next area of interest. The thin-film interference technique provided a means for determining the refractive (n) and absorptive (k) indices over a broad range of wavelengths (or wavenumbers) for a variety of condensed gases at temperatures varying from 20 K(gaseous helium cooling) to 77 K (LN_2 cooling). An analytical code, based on thin-film interference, was developed to determine the cryofilm optical properties from infrared transmittance measurements made using an interferometer spectrometer. Use of this code also required the use of the thin-film interference thickness measuring technique using a laser. This code, TRNLIN (**TR**ansmittance - **N**on**LIN**ear) was an analytical code based on Fresnel's transmittance equations for a thin film formed on an optically thick substrate and used a nonlinear least-squares convergence routine. Using TRNLIN, the refractive and absorptive indices of cryofilms of H_2O, CO_2, NH_3, CO, CH_4, N_2O, NO, HCl, O_2, N_2, Ar, N_2O_4 (nitrogen tetroxide), NH_2NHCH_3 (monomethyl hydrazine or MMH), N_2H_4 (hydrazine), and mixtures were determined.[15-18] A Kramers-Kronig technique for determining optical constants was also used for certain situations.[19]

Optical property (n,k) measurements were also made on contaminants condensed on a cold optical element during firings from a bipropellant (monomethyl hydrazine – nitrogen tetroxide) thruster engine.[20-21] Transmittance measurements were made *in situ* on a cryogenically cooled germanium window located in the backflow region behind the nozzle exit plane. A Fourier transform interferometer (FTIR) was used for obtaining the transmittance measurements at specific film thicknesses which were measured using the previously discussed laser thin film interference technique.

After acquiring a database of cryogenic refractive and absorptive indices that were obtained for films condensed from pure gases and bipropellant exhaust products, researchers developed a new analytical code that allowed the calculation of reflectance and transmittance of optical elements for any film thickness and angle of incidence for wavenumbers in the 700 to 3700 cm^{-1} range. This program, CALCRT, (**CALC**ulation of **R**eflectance and **T**ransmittance) has been very useful for determining effects of contaminants on optical elements.

Having had success at measuring the optical properties of pure gases at cryogenic temperatures, the next step was to perform similar measurements and analysis of cryofilms condensed from the outgassing products of satellite materials. This was accomplished through the cooperative efforts with the Air Force Wright-Patterson Materials Laboratory. The chamber used for making the cryogenic transmittance measurements is shown in Fig. 1. A 4-mm-thick germanium window was located in the center of the chamber and was cryogenically cooled to either 77 K or 20 K. Using the same optical techniques as discussed previously, outgassing products from individual materials were condensed on the cold germanium window. and the transmittance was measured for several thicknesses. The materials were heated to 125°C for comparison with the ASTM E-595 outgassing standard. A database of the n's and k's now exists for about 35 commonly used satellite materials, including various paints, potting compounds, adhesives, films, and insulation.[22-25]

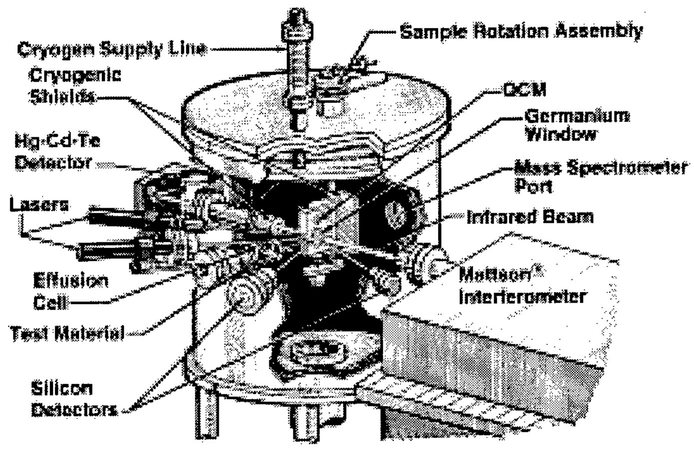


Fig. 1. Schematic of AEDC's 2– by 3–ft Cryogenic Optics Degradation Chamber.

The issue of ultraviolet radiation effects on paints and contaminants has been an ongoing concern. A chamber was developed (Fig. 2) for assessing such concerns and has been named the Solar Absorptance Measurements (SAM) Chamber.[26,27] The UV issue is an important one with regard to the development of thermal control coatings, as some white paints degrade with UV exposure time. Similarly, the UV accelerates the deposition of silicone and organic outgassing products on satellite surfaces and hardens the condensed film through a process called "solarization." To study the effects of the shorter UV wavelengths, another system was developed for operation in the vacuum UV (VUV) range (wavelengths less than 2000 Å).[28] An example of the transmittance data obtained with this system is shown in Fig. 3 for two satellite materials – Solithane and RTV-142. In this system, the film thickness is measured using a QCM.

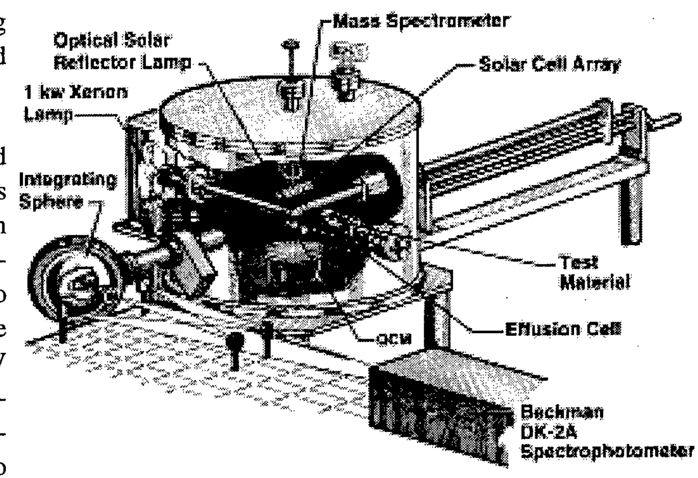
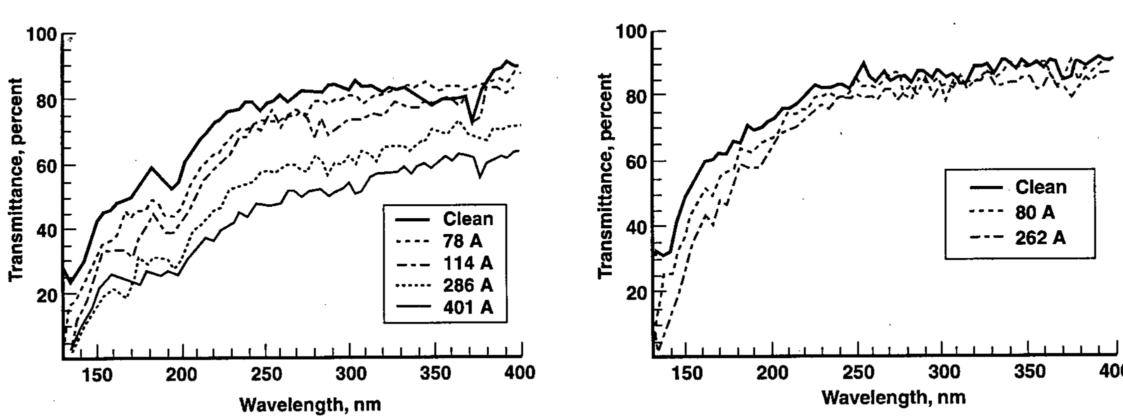


Fig. 2. Solar Absorptance Measurements (SAM) Facility.



a. Solithane b. RTV-142

Fig. 3. VUV transmittance as a function of film thickness.

The use of cryogenically cooled optics produces concerns other than just changes in the reflectance. Deposited films of gases can also reduce the signal level by scattering the beam's energy. This is similar to trying to see through a frosty windshield on a cold morning. Working with the Air Force Rome Laboratory, a facility was developed at AEDC for the measurement of the bidirectional reflectance distribution function (BRDF) for condensed gas films on cryogenically cooled optics. Using this facility (Fig. 4), BRDF measurements were made *in-situ* for films of gases condensed on a superpolished mirror cryocooled to temperatures between 20 and 77K. The condensed gases included air, oxygen, nitrogen, H_2O, CO_2, argon, and CO. The measurements were made at both visible and infrared wavelengths.[29-30] The facility has been used for studying the effects on mirrors using satellite material outgassing products as sources of the contaminant films. The laboratory BRDF measurements were also used to determine the status of the MSX Spirit 3 primary mirror during its mission, and will be discussed in the next section.

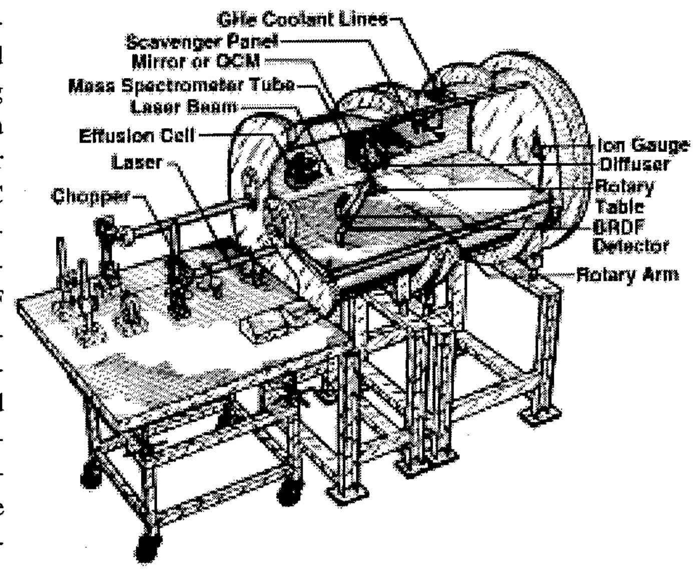


Fig. 4. Schematic of AEDC's Cryo-BRDF Measurement Facility.

One of Rome Laboratory's objectives in the late 80's was to fund the development of an improved and miniaturized version of the quartz crystal microbalance. A prototype was fabricated by the vendor (Mark 16 by QCM Research) and tested in one of the AEDC cryo-vacuum chambers. Based on the findings of that study,[31] several improvements were added to the units. Later, this model of QCM became commercially available. During the BRDF measurements previously discussed, the QCM was used to monitor deposition levels for thicknesses that were less than could be measured using the thin film interference technique. As a part of the AEDC/Rome Laboratory program, a QCM was developed (SPQCM),[29] which had a superpolished sensing crystal as the mass deposition surface. With this arrangement, BRDF measurements could be made using the external QCM as the test substrate. Coupled with the thin-film interference technique for measuring thickness, the SPQCM made possible the determination of the refractive index, film thickness, mass deposited, film density, and finally, the BRDF scattering properties of the condensed film.

Based on the past experience with the QCM development programs and cryogenic testing, AEDC was asked to participate in the cryogenic calibration and characterization of the flight QCMs for the MSX satellite program. Both cryogenic QCMs (CQCMs) and temperature controlled QCMs (TQCMs) were tested extensively[32-33] in a cryogenic pump chamber that provided an ultraclean environment that could be used in calibration of the units. These tests required maintaining the CQCMs at a temperature of 15K for periods up to 2 months. This chamber (Fig. 5) was a modified version of a commercially available cryogenic pumping system that was one section of the overall vacuum system. The flight QCMs and the associated flight electronics box were tested, and several improvements were made based on the test results.

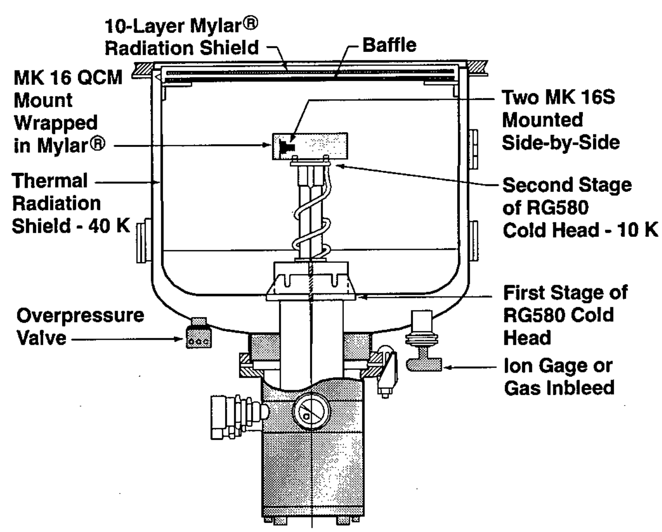


Fig. 5. Cryogenic Small Component Test Facility.

MIDCOURSE SPACE EXPERIMENT (MSX) SATELLITE PROGRAM

Development of the aforementioned systems for measuring the contamination optical effects on cryogenic systems and familiarity with quartz crystal microbalance calibration techniques made possible AEDC's participation in the Midcourse

Space Experiment (MSX) satellite program. MSX (Fig. 6) was funded by the Ballistic Missile Defense Organization (BMDO) and was part of a demonstration/validation program which had both defense and civilian applications.[34-37] With telescopes and imagers operating in the wavelength range from the UV through the infrared spectrum, data from spacecraft instruments were used in the identification and tracking of ballistic missiles during midcourse flight. Data were also collected for test targets and space background phenomena. It was also used to monitor in-flight contamination and for investigating the composition and dynamics of the Earth's atmosphere.

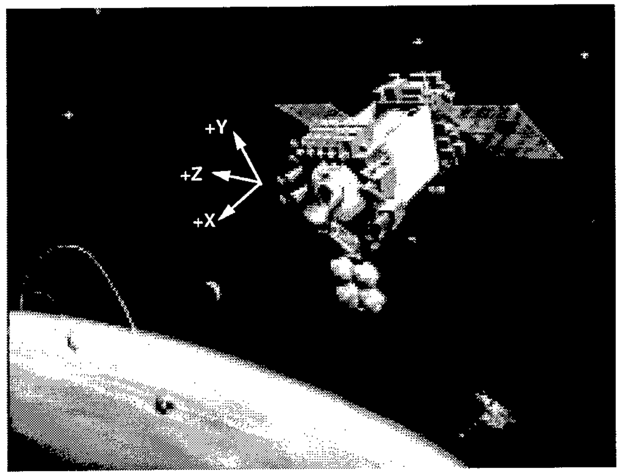


Fig. 6. Artist's drawing of Midcourse Space Experiment in orbit and showing reference axes.

The MSX satellite was launched into a 903-km, 99.4-deg orbit from Vandenberg Air Force Base on April 24, 1996 (Day 115). The UV-Visible data were collected by a suite of four imagers and five spectrographic imagers (UVISI) which were operating in wavelength segments from 110 – 900 nm. Visible and Near-IR data were collected by the Space-Based Visible (SBV) sensor system comprised of a CCD camera operating in the 400- to 1,000-nm wavelength range. Both of these sensor systems operated over the –20°C to +30°C temperature range. The final sensor system was the Spatial Infrared Imaging Telescope (SPIRIT 3), a cryogenic telescope cooled from an onboard dewar of solid hydrogen with component temperatures ranging from 8.5 K up to 65 K, depending on their location and spacecraft orientation. A gold-coated sun shield was placed near the entrance of SPIRIT 3 to protect against unwanted solar radiation getting into the telescope. All of the science instruments were located on the +X face of the spacecraft (see Fig. 7) with the electronics placed near the –X face at the other end of the spacecraft. This was designed to minimize contaminants outgassing from warm electronic boxes and condensing on science instrument surfaces.

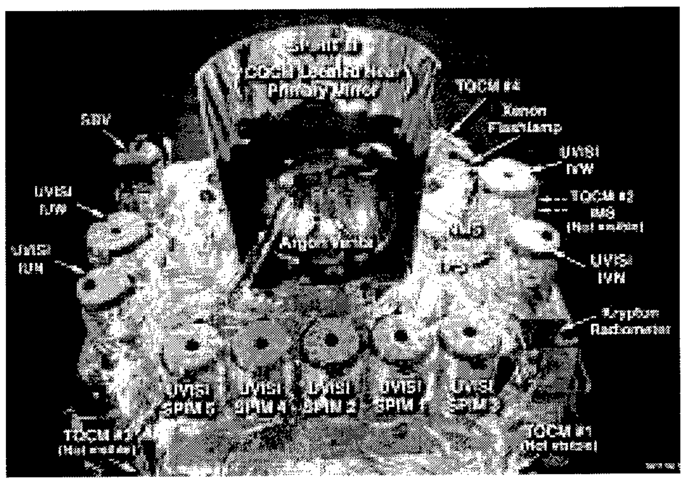


Fig. 7. Photograph of instrument section of MSX (+X direction).

MSX stayed in its parked mode orientation for most of the time. In this mode, the –Y face of MSX (see axes locations in Fig. 6) was facing towards the sun for maximum power generation by the solar panels. The +Z face was into ram, and the –X face was always facing earth. The +X direction was always perpendicular to the sun vector looking out and away from earth to minimize thermal loading on the Spirit 3 telescope. With these precautions, the lifetime of the dewar of solid hydrogen was extended to 10 months. Generally, the spacecraft remained in the parked mode prior to spacecraft maneuvers for dedicated experiments that required other orientations. Upon completion of the data collection event, the spacecraft was returned to the parked mode.

One of the major objectives of the MSX program was to characterize the contamination levels within the cryogenic telescope during its entire mission, and to monitor the molecular and particulate levels around the exterior of the spacecraft. The data would be used for future satellite programs for assessing contamination potential during a mission. This was accomplished through the establishment of a Contamination Experiment team. The Contamination Experiment team utilized the following instruments: (1) a total pressure sensor, (2) a neutral mass spectrometer, (3) an ion mass spectrometer, (4) krypton and xenon flash lamps for measuring water molecular density and particulates, respectively, and (5) four temperature-controlled QCMs (TQCMs) and one cryogenic QCM (CQCM) that was located inside the SPIRIT 3 cryogenic telescope. With these instruments it was possible to characterize the time-varying health of the spacecraft throughout its mission. The results described in this paper are those collected by the five QCMs.

CRYOGENIC QUARTZ CRYSTAL MICROBALANCE (CQCM)

The CQCM is a Mark 16 model from QCM Research, Laguna Beach, CA. The CQCM uses two quartz crystals (to minimize temperature effects) which oscillate at 10 MHz and are positioned such that the sense crystal is exposed to the environment external to the sensor, whereas the reference crystal is protected from any deposition. The difference frequency is directly proportional to the mass condensed on the sense crystal. The CQCM on MSX was located adjacent to, and was thermally coupled to, the cryogenically cooled primary mirror of the SPIRIT III telescope. It was used to monitor deposition of contaminants on the interior optics and, with associated laboratory optical data, was used to determine mirror performance degradation. The CQCMs were calibrated and characterized at temperatures as low as 15 K in a cryogenic calibration facility at the Air Force Arnold Engineering Development Center (AEDC), TN.[32] Following its installation in the SPIRIT III telescope, the CQCM was a valuable tool for monitoring the mirror status during cryogenic testing of SPIRIT III at Utah State University Space Dynamics Laboratory (USU/SDL), thermo-vacuum testing at the NASA Goddard Space Flight Center (GSFC), and pre-flight measurements at the launch site.

The CQCM's sensitivity to mass deposition (for 10-MHz crystals) is given by

$$\Delta m/A\ (\mathrm{gm/cm^2}) = 4.42 \times 10^{-9}\ (\mathrm{gm/cm^2 \bullet Hz})\ \Delta F\ (\mathrm{Hz})$$

where Δm = condensed mass, gm,
ΔF = change in CQCM frequency, Hz, and
A = active crystal surface area = 0.317 $\mathrm{cm^2}$.

The contaminant film thickness, t, can be calculated if the film density is known. Typically, the film density is unknown, but it is usually assumed to be 1.0 $\mathrm{gm/cm^3}$ to facilitate film thickness calculations. For unity density, the film thickness in angstroms is given by

$$t(\text{Å}) = 0.442\ (\text{Å/Hz})\ \Delta F\ (\mathrm{Hz})$$
$$= 0.442\ \text{Å for a frequency change of 1 Hz.}$$

TEMPERATURE CONTROLLED QUARTZ CRYSTAL MICROBALANCES (TQCM)

The TQCMs were also built by QCM Research and were designed 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.[33] The temperatures were controlled by a Peltier cooler/heater unit which was built into these Mark 10 TQCM units. The crystals oscillated at a frequency of 15 MHz.

The mass sensitivity for the TQCMs is given by

$$\Delta m/A\ (\mathrm{gm/cm^2}) = 1.96 \times 10^{-9}\ (\mathrm{gm/cm^2 \bullet Hz})\ \Delta F\ (\mathrm{Hz})$$

Using similar expressions to those derived for the CQCM results in the frequency vs. thickness relationship (where again the density is assumed to be 1.0 $\mathrm{gm/cm^3}$),

$$t(\text{Å}) = 0.196\ (\text{Å/Hz})\ \Delta F\ (\mathrm{Hz})$$

$$= 0.196\ \text{Å for a frequency change of 1 Hz.}$$

The satellite axes are indicated in Fig. 6. Thus, TQCM 1 was pointed with components in the (−X, Y, Z) directions, TQCM 2 pointed in the +Z direction, TQCM 3 had (Y, −Z) components, and TQCM 4 had (X, −Y, Z) components. The TQCM covers limited their fields of view (FOV) to a right cone with an approximate 64-deg half angle. TQCMs 1 and 2 both had view factors which contained 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.

The TQCMs were mounted on individual radiators which were isolated from the main frame of the spacecraft to allow better thermal control. The heat generated by each Peltier thermoelectric device was radiated to space by the radiators. TQCMs 2-4 maintained an operating temperature of –50°C, whereas TQCM #1 operated at a slightly warmer temperature, –43°C, because it was mounted on a smaller radiator. As the satellite was rotated to achieve a commanded attitude, the projected area of the solar panel within the TQCMs' fields of view (FOVs) varied. In addition to the solar panel, the TQCM 1 field of view included some of the spacecraft electronics module, which is to the left of the +Z solar panels in Fig. 6. 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° to –50°C was calculated to be cooler than all external contamination sources such as the multilayer insulation, electronic boxes, and other noncryogenically cooled surfaces of the spacecraft. At this temperature, the TQCMs were cold enough to condense many silicones and hydrocarbons outgassing from MSX materials. 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.

MSX SATELLITE FLIGHT RESULTS

MSX Cryogenic Quartz Crystal Microbalance

The changes in CQCM temperature and frequency with time are shown in Figs. 8-9, respectively, for the time from launch (Day 115, April 24, 1996) until Day 235 (August 23, 1997).[43] This timeframe includes the time from launch through the end of the Cryo period and through the end of the two SPIRIT 3 warmup sequences. The warmup periods are referred to as SECOT (for SPIRIT 3 End of Cryogenic Testing) which were tests performed using solar heating.

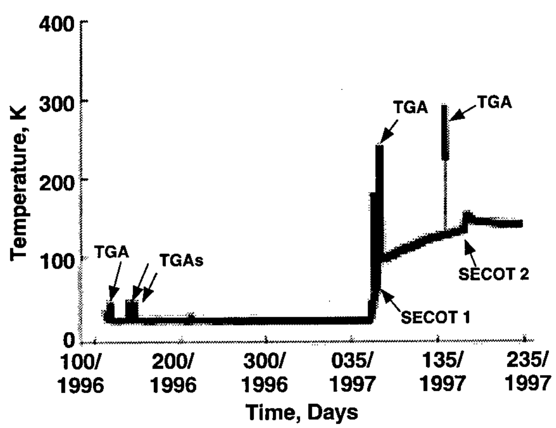


Fig. 8. CQCM temperature versus time since launch.

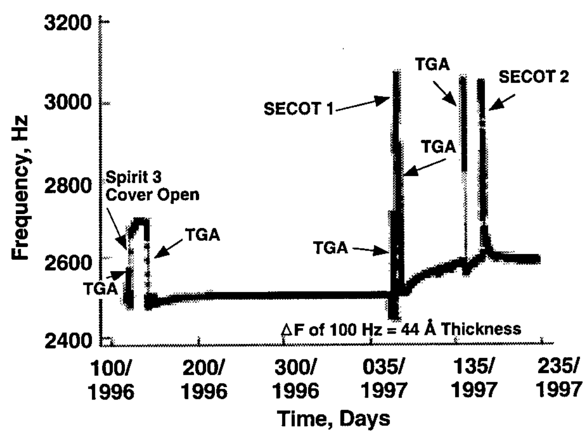


Fig. 9. CQCM frequency versus time since launch.

At launch time the CQCM frequency was approximately 2,492 Hz which was 12 Hz (~ 5 Å) higher than the frequency for the completely clean CQCM at 2,480 Hz. During the first 7 days in orbit and prior to the SPIRIT 3 cover opening, the CQCM sensing crystal temperature dropped from an initial value of 28K down to 21K. During these 7 days, there was a gradual buildup of contaminant film on the CQCM, even though the cryogenically cooled SPIRIT 3 protective cover was still in place. Thermogravimetric analyses (TGAs) of the CQCM contaminants provided a means for determining the species and amount of contaminant condensed during this time. From 2 TGAs performed during the first 7 days on orbit and prior to the cover release, it was determined that the contaminant deposited inside was primarily oxygen[38] caused by redistribution of previously condensed gaseous oxygen on the baffle within the telescope.

When the SPIRIT 3 cover was released on Day 122, 7 days after launch, there was a rise in CQCM frequency of about 163 Hz (72 Å), most of which occurred within 1 minute after cover release. Nineteen days after the cover release, another TGA was performed to determine the mass and species of the 72-Å-thick film. The results of this TGA are shown in Ref. 38. Most of the condensate evaporated between 28-30K and was determined to be argon, which came from the solid argon used as the cover coolant. This evaporation temperature is consistent with that seen from the argon vapor pressure vs. temperature curve. A small amount of deposit evaporated between 30 and 32 K and is believed to be oxygen, which was deposited by redistribution prior to the cover release. The maximum evaporation rates were modeled using vapor pressure curves by treating the CQCM cryofilm at a pressure in equilibrium with the CQCM temperature. The results were a good fit for the two expected species, argon and oxygen.

Figure 9 shows that very little film accumulation occurred on the CQCM after the cover release. Most of the small, incremental increases occurred when the spacecraft was maneuvered into positions in which radiation from the earth irradiated portions of the telescope baffles. The baffle surfaces after warmup caused some of the previously adsorbed gases on the baffle to be redistributed within the telescope. Since the last TGA was performed on Day 149, 1996, there was a CQCM frequency change of only 30 Hz (13 Å) for the remainder of the Cryo period. The total deposition on the CQCM, and presumably the primary mirror, was 155 Å for the period from the telescope cooldown prior to launch, until the SPIRIT 3 end of life.

The TGAs indicated that the condensed cryofilm on the primary mirror was composed of argon and oxygen, neither of which absorb in the infrared, and hence had no effect on mirror reflectance. Even if it were assumed that the condensed species were H_2O, CO_2, or CO (the infrared absorbing species most likely to be present) the change in mirror reflectance would be negligible.[38-39] Therefore, the film thickness of 155 Å had a negligible effect on MSX mirror reflectance and BRDF.

MSX Temperature Controlled Quartz Crystal Microbalances

Only data for one TQCM are presented, and TQCM #2 was chosen since it exhibited the largest change in frequency during the mission time reported here.[43] For TQCM #2, the temperature vs. time is shown in Fig. 10, and the frequency vs. time plot is shown in Fig. 11. The time periods for Figs. 10-11 are the same as those previously shown for the CQCM in Figs. 8-9. The TQCMs were sensitive to incident solar flux. Negative shifts in frequencies (ΔF) from 300-450 Hz were seen for the TQCMs when the spacecraft orientation went from no sun to full sun. According to the QCM Research personnel, this frequency decrease with solar radiation is caused by the thermal stress generated in the quartz crystal by solar exposure. Since this frequency change is greater than the expected change due to contaminant buildup, this phenomenon made analysis of the data more difficult.

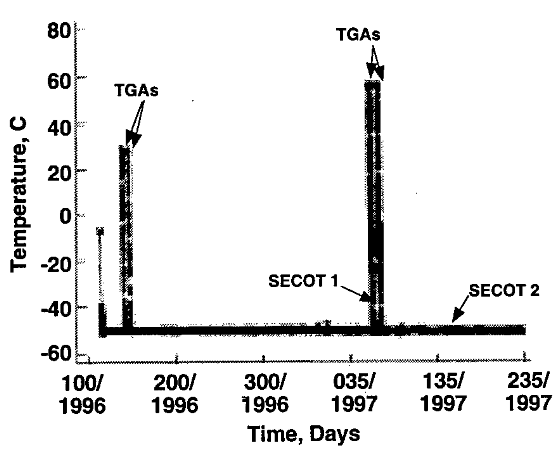


Fig. 10. Temperature versus time for TQCMs 2 since launch.

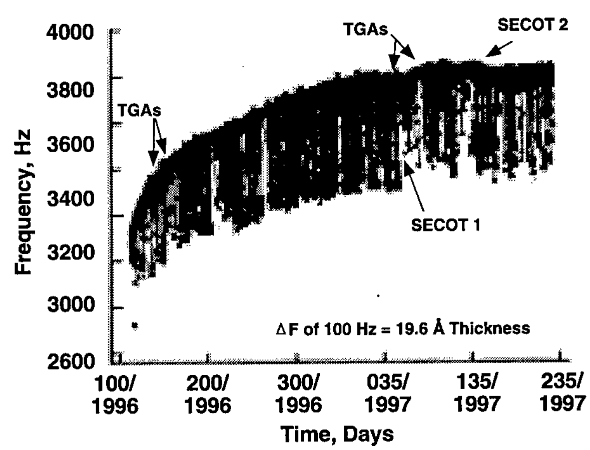


Fig. 11. TQCM #2 plot showing increase in frequency due to accreted mass at (+Z) location.

The many spikes in the data of Fig. 11 are indicative of times when the spacecraft was maneuvered out of park mode to other attitudes that caused direct solar irradiance on TQCM #2. These solar effects complicated the data analysis on a shortterm basis, but the data corresponding to TQCM darkness times can be used to determine the long-term deposition thickness and rates. A thickness trend was developed using the data points at the top of the curves,[38] which correspond to times when the TQCMs were in darkness.

Total contaminant deposition rates since launch as measured by TQCMs 1 - 4 were 134, 144, 13, and 63 Å, respectively. This deposition has occurred during the first 486 days in space. TQCMs 1 and 2 both had view factors of the solar panels which apparently are the predominant sources of contaminants on MSX. The deposition rate has varied considerably during the 16 months in orbit. The deposition rate on the TQCMs increased after the SPIRIT 3 telescope and dewar warmed up at the end of the Cryo period. TQCM 3, as expected, has shown the least amount of deposition since it had very little surface area in its field of view.

In contrast to TGA data observed for the CQCM, the TQCM TGA's data sets were of minimal value due to the "solarizing" of the contaminants on the external sensing crystals. This feature has been seen previously in laboratory measurements, as well as in previously flown QCMs in space where the outer crystal is exposed to the sun's UV wavelengths. TGAs on each of the four TQCMs showed very little, if any, change in frequency due to the crystal warmup to 60°C. The contaminant, presumably comprised of organics and silicones from material outgassing, was essentially "baked on."

The times that TGAs were performed are noted in Figs. 10-11. The TGAs were performed in pairs in order to get a frequency vs. temperature plot for each TQCM while contaminated, followed by another with the supposedly cleaned crystal. However, the TGAs were unsuccessful in reducing any appreciable mass from the contaminated surface. The first TGAs were performed between days 140-150 (1996), and the temperature was raised from –50°C up to +30°C. The second set was performed between days 55 and 75 (1997), and the temperature was raised from –50°C to +60°C. Each TGA data set required the use of the tape recorder, which sometimes reduced the time available, due to higher priority experiments. As seen in Fig. 10, the TQCM Peltier heating/cooling units have been very dependable in maintaining the commanded temperatures over the entire mission.

SUMMARY AND CONCLUSIONS

The AEDC has an extensive role in the history of the development of cryogenic vacuum facilities for measurement of contaminant optical properties. The thin-film interference phenomenon using lasers has led to techniques being developed for the measurement of cryogenic film refractive index, film thickness, film density, and the complex refractive and absorptive indices. Contaminant optical property measurements have included transmittance, reflectance, and BRDF, as well as the refractive and absorptive indices. These optical property measurements and test experience with various QCMs led to AEDC's involvement with the MSX satellite.

From the MSX satellite results, QCMs have been proven to be quite useful for monitoring the on-orbit contaminant mass buildup on the primary mirror of the SPIRIT 3 cryogenic telescope, and also on the satellite external surfaces. After ~10 months in orbit, the CQCM (and primary mirror) accumulated 155 Å of condensate on the 20 K surfaces. Almost 50 percent of this condensate was due to the argon condensed during the SPIRIT 3 cover release. Essentially all of the condensate during the Cryo period was argon and oxygen. There was no indication of any water or carbon dioxide deposited which was determined from the thermogravimetric analyses data obtained before and after the cover release. Ground tests on the optical effects of condensed films on cryogenic mirrors at 20K indicate that this 155-Å film had a negligible effect on the mirror scatter and reflectance.

The four TQCMs mounted on satellite external surfaces were operated at temperatures of –40°C to 50°C (depending on location), and have shown accumulations between 13 and 144 Å, depending on the TQCM view factors on the spacecraft. The TQCMs having the solar panels in their field of view (TQCMs #1 and #2) have shown the largest deposition rates. The solar radiation incident on the crystals has shown two separate effects: (1) a quick response negative shift in output frequency between 300 and 400 Hz when solar radiation is incident normal to the crystal and (2) the solar UV component solarizes the contaminant such that during TGAs, only a small portion, if any, of the condensed mass is evaporated. The TQCMs are continuing to accumulate mass, and the long-term trends established for MSX will be extremely valuable for future satellite systems.

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