

MMS OBSERVATORY TV RESULTS CONTAMINATION SUMMARY

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ABSTRACT

The Magnetospheric Multiscale (MMS) mission is a constellation of 4 observatories designed to investigate the fundamental plasma physics of reconnection in the Earth's magnetosphere. The various instrument suites measure electric and magnetic fields, energetic particles, and plasma composition. Each spacecraft has undergone extensive environmental testing to prepare it for its minimum 2 year mission. In this paper, we report on the extensive thermal vacuum testing campaign. The testing was performed at the Naval Research Laboratory utilizing the "Big Blue" vacuum chamber. A total of ten thermal vacuum tests were performed, including two chamber certifications, three dry runs, and five tests of the individual MMS observatories. During the test, the observatories were enclosed in a thermal enclosure known as the "hamster cage". The enclosure allowed for a detailed thermal control of various observatory zone, but at the same time, imposed additional contamination and system performance requirements. The environment inside the enclosure and the vacuum chamber was actively monitored by several QCMs, RGA, and up to 18 ion gauges. Each spacecraft underwent a bakeout phase, which was followed by 4 thermal cycles. Unique aspects of the TV campaign included slow pump downs with a partial represses, thruster firings, Helium identification, and monitoring pressure spikes with ion gauges. Selected data from these TV tests is presented along with lessons learned.

INTRODUCTION

The Magnetospheric Multiscale (MMS) mission is a constellation of four satellites that will use Earth's magnetosphere as a laboratory for studying fundamental plasma processes of magnetic reconnection, energetic particle acceleration, and plasma turbulence. These processes play an important role in space weather. Each of the four identical observatories was built and integrated at the NASA Goddard Space Flight Center. In order to prepare for the minimum 2 years long mission, each observatory (OBS) has undergone an extensive environmental testing campaign. This testing included thermal vacuum testing, which is the subject of this paper. As will be discussed in more detail later, the observatories were tested individually in a large vacuum chamber at the Naval Research Laboratory in Washington, D.C. Pressure and cleanliness requirements imposed by the instrument suite as well as a suite of special tests, such as thruster firings, imposed a number of contamination control (CC) challenges. The mitigation strategies as well as lessons learned are the subject of this paper.

[Figure 1](#) shows the observatory in a NASA/GSFC clean room. This picture was taken during preparation for an acoustic testing, in which the instruments were covered with soft covers, and a Llumalloy drape (not on yet) is to be suspended around the sides of the observatory. The crossed fishing lines in front of the solar array were in place to prevent the drape from contacting the observatory. From this picture, we can see the configuration of the MMS observatories. Each observatory consists of an octagonal bus divided into two sections. The bottom section (spacecraft deck) contains the solar arrays, while the upper section is the instrument deck. A small subset of instruments was also located below the spacecraft deck. The observatories also contains several deployable magnetometer and electric field booms as well as antennas.

Instrument Suite

The instrument suites (IS) on each observatory consists of 27 instruments for measuring plasma composition, fluxes of energetic particles, and electric fields. Majority of instruments utilize some combination of micro-channel plates (MCP) and solid state detectors (SSD) to magnify and collect the incoming signal. The presence of these two technologies makes the detectors and the charged particle focusing “optics” sensitive to particulate and molecular contamination. Instruments utilizing micro-channel plates (MCP) are sensitive to molecular contamination, moisture, and conductive particles. Instruments with solid state detectors (SSD) are sensitive to moisture. See Figure 2 for IS locations on MMS Observatory. The MMS contamination control team came up with various mitigations to protect the IS during TV testing that would also afford opportunities to collect pertinent test data to validate the molecular cleanliness of each observatory.



Figure 1. MMS Observatory in NASA/GSFC cleanroom

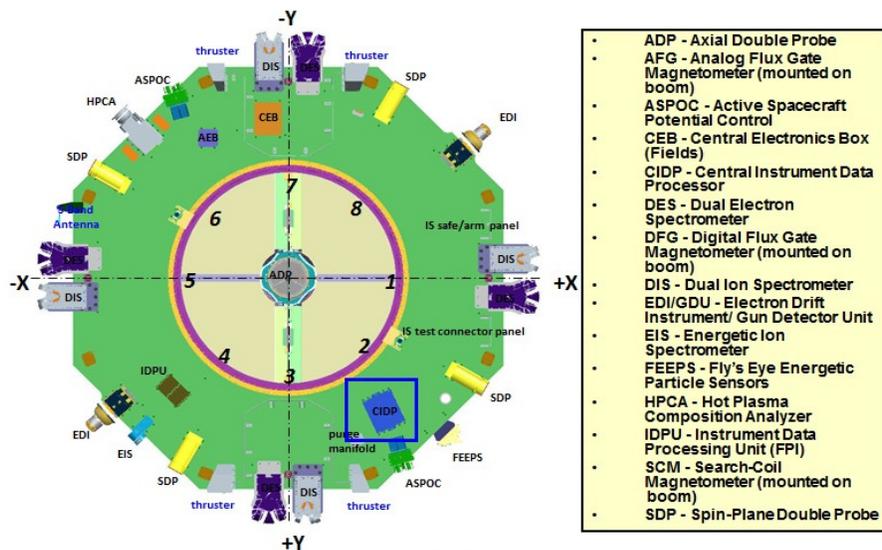


Figure 2. IS layout on IS deck, seen from underneath

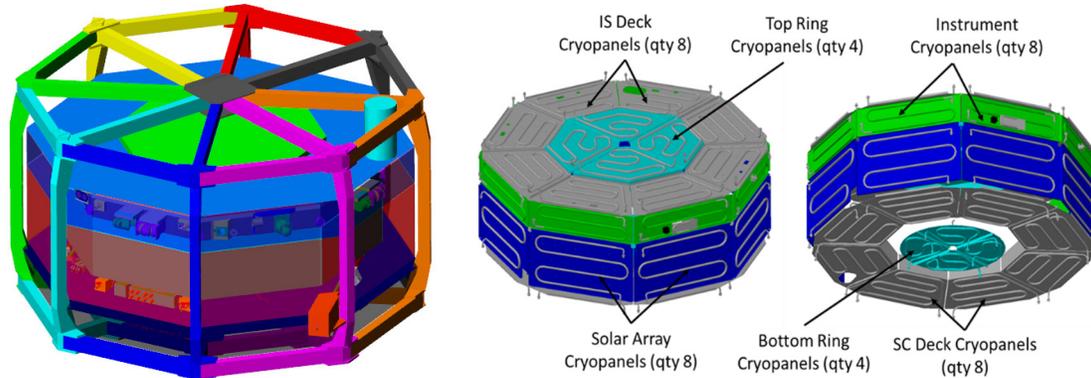


Figure 4. a) Hamster cage structure and b) cryopanel designations

CHAMBER READINESS

There were 2 clean dry empty bakeouts or precerts of the chamber before any Hamster cage bakeout proceeded. We (project personnel) wanted to verify that the shrouds did not leak when going hot or cold and check the pumping performance of the 3 of the cryopumps. The cryopumps have a 35" diameter and an advertised capability of each pumping 30,000 liters/sec of gaseous nitrogen (N_2). The cryopumps are typically cooled to $<15^\circ K$, which is cold enough for rapid pumping of water vapor, N_2 , and oxygen (O_2), but not necessarily Helium (He). In addition the chamber shrouds was freshly painted with a low outgassing flat black top coat and though said to have been pre-cured, it was strongly desired to verify that with a high temperature bakeout with minimal test support hardware in the chamber.

Cryopump pumping performance was also derived from this precert testing. There was a 33% loss in pumping capability going from 2 to 1 cryopumps and only a 15% gain going from 2 to 3 cryopumps. The shrouds were exercised hot, to $100^\circ C$, and cold, flooded with liquid nitrogen (LN_2), to verify no leaks. TQCM data yielded a low outgassing rate for the Big Blue chamber with respect to condensable on a TQCM set to $-20^\circ C$, while pressure levels obtained a low and steady $2E-7$ torr at $50^\circ C$. Chemical analysis from rinsate of the facility scavenger plate, termed the Contam plate, yielded low levels of hydrocarbons and various plasticizers. Thus the chamber was deemed ready to precede with MMS hardware pretesting.

Subsequent hamster cage bakeouts were termed Dry Runs and would be limited to $60^\circ C$ mainly due to the gold iridized finish on the aluminum framing. The hamster cage cryopanel were coated with an easy-to-clean, non-outgassing black anodization on both sides. Cryogenic rated D-shaped tubing was stitched welded to the outer surface for fluid transfers. Strip heaters, along with heat dispersing silver plated copper braid, were affixed about every foot in between the tubing. These higher watt density heaters were used to trim the temperatures of the cryopanel during most test phases by adjustments to the power supplies. All parts and fasteners of the hamster cage were ultrasonically precleaned by the contamination control staff. Cryopanel and framing just received IPA wetted wipe offs. Assembly of both cages was completed at NRL in clean tents (holding Class 100K conditions). A low outgassing Braycote was used on the *million* fasteners used to hold the cages together.

To complete the thermal hookup from the hamster cage to the 4 new thermal conditioning units (TCUs) required hundreds of feet of cryogenic-rated flexible stainless steel all metal hoses. All lines and 2" diameter headers were ultrasonically bathed and prebaked out to $100^\circ C$ before being used in the Big Blue chamber. A completed hamster cage, with cryogenic flex line jumpers attached, weighed almost 5000 pounds. A MMS Observatory ready for testing weighed 2100 pounds. TV test readiness involved lifting the OBS (by overhead crane) and placing it onto the Hamster cage base. The spider shaped hamster cage framing, minus side cryopanel, was then lifted over the top of the spacecraft. Solar Array panel covers and IS Melinex (clear poly) covers and all red tag covers were removed as the side cryopanel were installed around the spacecraft. The vapor deposited

aluminum (VDA) Mylar contamination (contam) barriers were installed during the cryopanel installation. They were requested by contamination control to reduce possible silicone transmission from the solar arrays back to the IS “optics”. The barriers provided a thermal break as well, since the IS were to operate at different temperatures than the solar arrays.

Once fully assembled the same overhead crane was used to lift the entire assembly up and placed onto a chamber sled that was on an air barge. This barge was then able to be positioned in front of the vacuum chamber. The assembly was then staged here, just outside the chamber while electrical and thermal hookups took place and all the remaining cryo-flex lines were attached to fittings to cryopanel on the Hamster cage. Once the spacecraft was hooked up and put through an abbreviated aliveness verification and thermal completed their checkout, the chamber was cleaned back to front to remove accumulated particulates during the buildup. The sled with Hamster cage and OBS was then winched into the chamber. After a few more quick checkouts, then the chamber door was closed, the IS purge was stopped, and pump down would begin.

MONITORING EQUIPMENT

The IS micro-channel plates and solid state detectors are contamination sensitive to molecular and particulate contamination. To assist with monitoring contamination real-time events happening inside the chamber, there were several devices used. Each Hamster cage thermal enclosure was outfitted to hold four (4) thermoelectric-controlled Quartz Crystal Microbalances (TQCMs), which was essentially the maximum available due to conflate limitations. The number of QCMs was adequate to track outgassing from within the hamster cage and from the OBS. Fifteen (15) Ion gauges (IG) were attached to the enclosure to monitor pressure levels and to provide ions to IS. Another IG was attached to a chamber conflate that allowed for pressure comparison with 2 different facility pressure gauges. The facility pressure gauges included a low pressure gauge which was especially helpful for tracking real-time pressure during pump downs and ventbacks. A residual gas analyzer (RGA) was affixed to the chamber shroud that allowed for monitoring individual gases up to an atomic mass unit (amu) of 200 being released inside the chamber.

There were also scavenger plates that helped control outgassed molecules inside the chamber. There was a 6” by 18” scavenger Plate affixed to IS cryopanel Bay 2, thermally isolated from the Hamster cage with 2” long Delrin standoffs, to collect outgassed material from the OBS bus vent in Bay 2. There was a special duct affixed to the cryopanel and extended over the OBS vent, to assist with passage of outgassed molecular mass to the SP. The very large facility Contam plate was hung in the back of the chamber. The backside of the plate facing the chamber shroud was blanketed. There were also 2 to 4 “witness” aluminum foils placed inside the Hamster cage on the bottom deck cryopanel just prior door closure to collect outgassed non-volatile residue (NVR) throughout TV testing. These foils were collected post-test and chemically analyzed along with rinsate from the scavenger plates.

The TQCMs were attached to the Hamster cage, facing inwards to view outgassed molecules through 2” diameter holes. Each were mounted on copper heat sinks and were able to be individually thermally controlled. Table 1 notes the QCM locations.

Table 1: QCM locations

TQCM #	Location	Purpose
1	Bay 2 IS cryopanel, off centered	Monitor outgassing around vent area and IS in Bay 2
2	Bay 3 IS cryopanel, centered	Monitor outgassing from DIS2/DES2 in Bay 3
3	Bay 6 IS cryopanel, centered	Monitor outgassing from HPCA in Bay 6
4	Bay 6 SA cryopanel, centered	Monitor outgassing from Solar Array in Bay 6

The IS team had requirements to test the functionality of their instruments in vacuum and they needed an ion source. Therefore each instrument had a dedicated ion gauge on the Hamster cage enclosure. These micro ion gauges were offset from the respective IS and mounted to the top deck cryopanel. Table 2 notes the Ion Gauge locations. Note, these IG had similar specifications as commonly used by the Fast Plasma Investigation (FPI) DES and DIS instruments during their assembly and test at the instrument level. Small rectangular holes in the cryopanel allowed for ion throughput to IS. This gauges had dual functionality in that they could be ion source and also monitor pressure levels. Pretesting of several ion gauges provided confirmation to thermal operating ranges and functionality of heaters that were attached to the housings.

Table 2: Ion Gauge Locations

Ion Gauge #	Location	Purpose
1	Outside HC, IS cryopanel Bay 3	External HC pressure
2	Outside HC, IS cryopanel Bay 7	External HC pressure
3	Inside HC, between IS cryopanel Bays 1 & 2	Internal HC pressure for IS
4	Inside HC, between IS cryopanel Bays 3 & 4	Internal HC pressure for IS
5	Inside HC, between IS cryopanel Bay 5 & 6	Internal HC pressure for IS
6	Inside HC, between IS cryopanel Bay 7 & 8	Internal HC pressure for IS
7	Outside HC, Top cryopanel Bay 1	Ion Source for DIS1 + External HC pressure
8	Outside HC, Top cryopanel Bay 3	Ion Source for DIS2 + External HC pressure
9	Outside HC, Top cryopanel Bay 5	Ion Source for DIS3 + External HC pressure
10	Outside HC, Top cryopanel Bay 7	Ion Source for DIS4 + External HC pressure
11	Outside HC, Top cryopanel Bay 1	Ion Source for DES1 + External HC pressure
12	Outside HC, Top cryopanel Bay 3	Ion Source for DES2 + External HC pressure
13	Outside HC, Top cryopanel Bay 5	Ion Source for DES3 + External HC pressure
14	Outside HC, Top cryopanel Bay 7	Ion Source for DES4 + External HC pressure
15	Outside HC, Top cryopanel Bay 6	Ion Source for HPCA + External HC pressure
16	On Chamber Shroud, right side	Chamber pressure comparison

TEST PLAN PROFILE

The test plan had CC inputs embedded to protect the OBS during all phases of vacuum exposure. After the IS purge was stopped and manually capped at chamber conflate, the pump down of the chamber could begin. A slow pump down was requested to reduce disturbing small particles inside the chamber and to lessen vibrations over instruments with MCPs. Several slow represses were conducted to help remove water vapor. After a couple cycles the chamber cryopumps were enabled and the test proceeded to high vacuum. Additional vacuum pumping time transgressed to continue evacuating water vapor before thermal transitioning to bakeout settings would occur.

Once the TCU checkouts were completed, the facility and HC scavenger plate were flooded. The QCMs and RGA were activated as well. When the pressure was low enough, several Ion Gauges were also turned on. Once chamber pressure levels lowered adequately, the hamster cage and thermal shrouds were stair-stepped up to bakeout settings. The bakeout settings were in force until QCM readings had achieved the goals with margin and vacuum pressure (mainly driven by water vapor) had sufficiently dropped. Thermal had to reduce the bottom cryopanel during the bakeout in order to keep larger internal OBS subsystems below maximum temperatures. For example, the battery had a red limit of 35°C. Internal OBS and IS operation heaters helped also transition and maintain payload temperatures at bakeout settings. The cooling of this bottom cryopanel created a molecular collection surface that required additional bakeout time before proceeding to the next phase. Thruster firings and catalytic bed warmup also provided another reason to continue bakeout settings for several hours.

Thereafter the OBS was to begin the majority of the comprehensive performance tests (CPT); refer back to Figure 3. There were 4 hot and cold cycles to complete. High voltage testing of the IS during hot and cold plateaus was completed when internal hamster cage pressures were <1E-6 torr. The A and B side of electronic boxes had to

be powered on and complete similar CPTs during these plateaus as well. After another Magnetic Boom partial deployment and another thruster firing in the last cold plateau, the OBS was to be warmed back up to ambient temperature. As in the bakeout, the return to ambient the OBS was warmed up in a stair-stepped method in a way to keep the spacecraft always warming than the surroundings. The entire test profile was around 25 days, from pump down to vent back. OBS2 was the first spacecraft to be TV tested and it had a slightly different thermal testing profile. It underwent thermal balance testing first and then was vented back. After a few reconfigurations were made it was then back under vacuum to complete 3 additional thermal cycles.

DATA ACQUISITION

Thermal vacuum operations at NRL were overseen by a small GSFC support team that included a contamination control engineer, 2 thermal engineers, a quality assurance, an electrical ground support person, and a project management representative. There were at least 2 NRL thermal vacuum chamber operators at all times, in addition to NRL management support during the day. The main OBS and IS support teams remained back at GSFC. Verbal communications between the centers were enabled by voice loops. Test data from the chamber that included 300 thermal couples, ion gauge pressures, TQCMs were collected by a NRL-developed program called CDACS (Computerized Data Acquisition and Control System). The Python-based GUI control system allowed for creating real-time plots of all areas of interest. To see the data back at GSFC required a secure Thin Client internet connection between the centers. GSFC utilized their ASIST (Advanced Spacecraft Integration and System Test) program to acquire IS and OBS telemetry. System telemetry data from the OBS could then be set up in tabular displays and options in the program made it possible to create instantaneous plots of real-time telemetry.

The RGA screen, the Contamination Control console screen, and the Systems console screen at NRL were mirrored and those images and chamber raw data were accessible by internet connection. CDACS data and ASIST telemetry were updated every minute. This then afforded all test personnel to see console data from anywhere they had internet access. Figure 5 shows a picture of the typical console data. Camera/screen options are noted in the left side. Having all the data streamed in the same data acquisition system greatly simplified anomaly investigations, which seemed to occur during every TV test. CDACS data plots could be set to as short as 15 minutes and at times they were set to 24 hours.

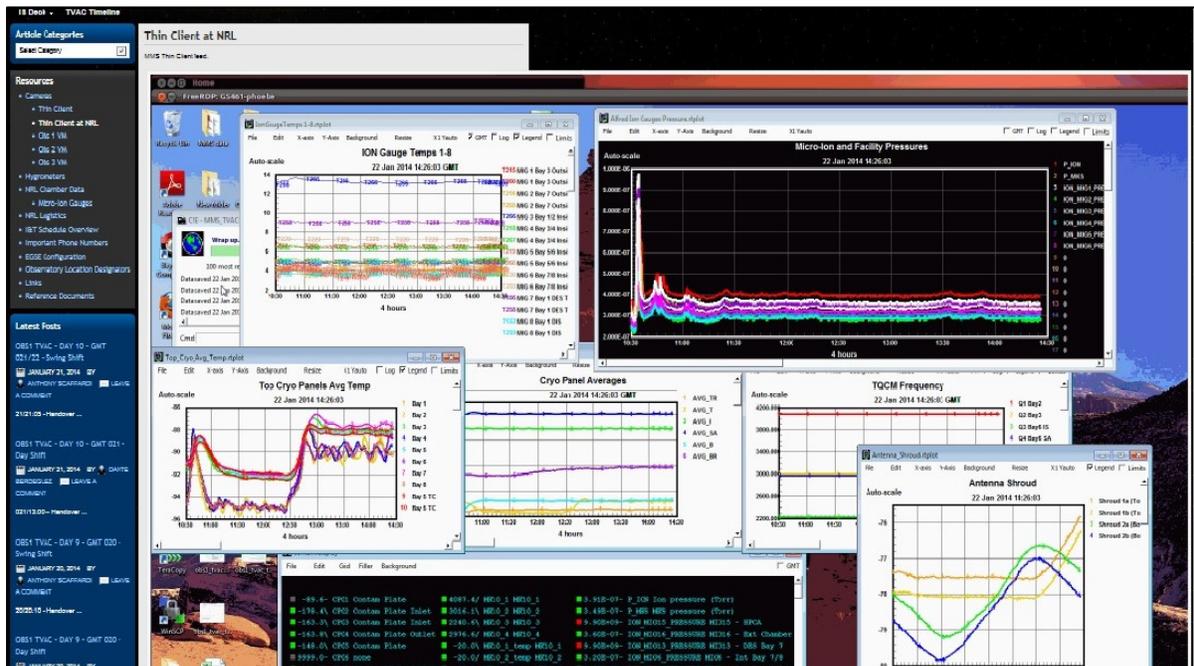


Figure 5. CDACS data plots seen in Thin Client feed from NRL

TEST RESULTS

Multiple pump downs and represses were requested to be as slow as possible to reduce particulate stir up and to reduce vibrations to MCPs. These multiple cycles helped remove water vapor, thus lessening the work the cryopumps would have to do later. The chamber utilized rough pumping with a small blower until a pressure of <8 torr was reached and then larger blowers were used to obtain pressure levels <0.05 torr (termed 50 microns). Once pressure levels were <0.05 torr, valves were closed and a ball valve was adjusted to back fill the chamber with GN₂ at slow rates to 500 torr. The rough pump valves were then closed and the chamber was then backfilled with GN₂ at slow rates of 50 torr/hr to 200 torr and then 100 torr/hr to 500 torr. Another couple cycles were performed. Each cycle took about 9 hours. Typically after the 3rd pump down, the chamber was “crossed over”, which involved opening the cryopumps and proceeding to high vacuum and conducting thermal TCU checkouts. See Figure 6 for a typical multiple pump down and repress as monitored with the low pressure gauge.

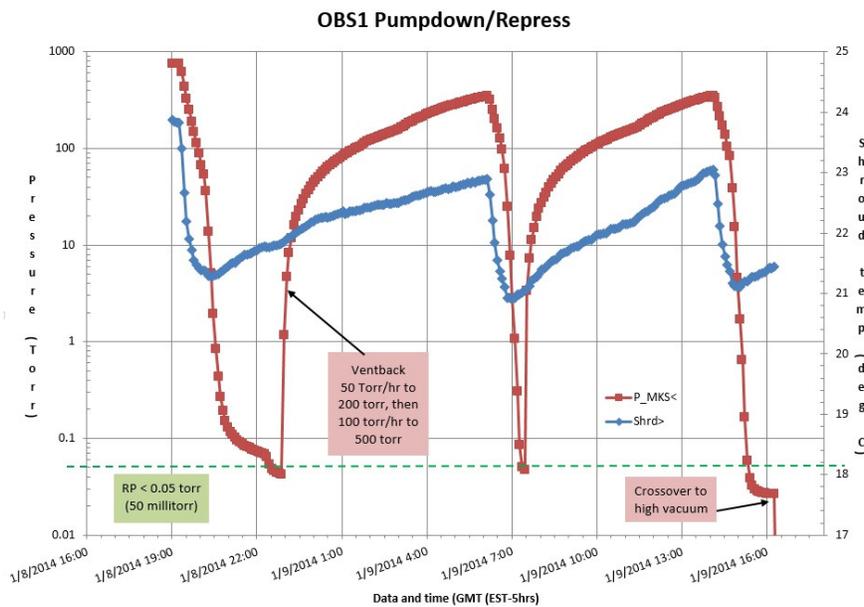


Figure 6. Typical OBS cycle purge

The Bakeout phase was important for removing additional water vapor and polymeric material from the OBS and from the surrounding GSE. Water vapor outgassing was known to suppress obtainment of low vacuum pressures and the high temperature bakeout of the OBS to 50°C enabled reducing water vapor from the environment at a much quicker rate. The ultimate goal of driving off the water vapor was for obtaining internal Hamster cage pressures of < 1E-6 torr so the IS could conduct high voltage operations. Since the empty Big Blue chamber could easily get to the low E-7 torr range by normal pumping with 2 cryopumps, the OBS test setup required a decent bakeout to achieve desired pressure levels later on. CC monitored ion gauges and the RGA (see Figures 7 & 9) for decreasing pressures mainly due from water vapor and light molecular weight polymeric material. QCMs were set to -20°C during this phase and the delta frequency data were desired to meet pre-test goals of around 200 Hz/hr (see Figure 8) which were computed based on obtaining values an order of magnitude lower than required. Almost all MMS flight subsystems and IS were individually thermal vacuumed baked out to temperatures of 50°C or higher before integration onto the spacecraft and their respective certification outgassing rates were always much lower than required. So the fully assembled OBS was expected to exhibit low outgassing rates and come closer to the respective QCM delta frequency goals.

OBS1 TVAC Bakeout Phase

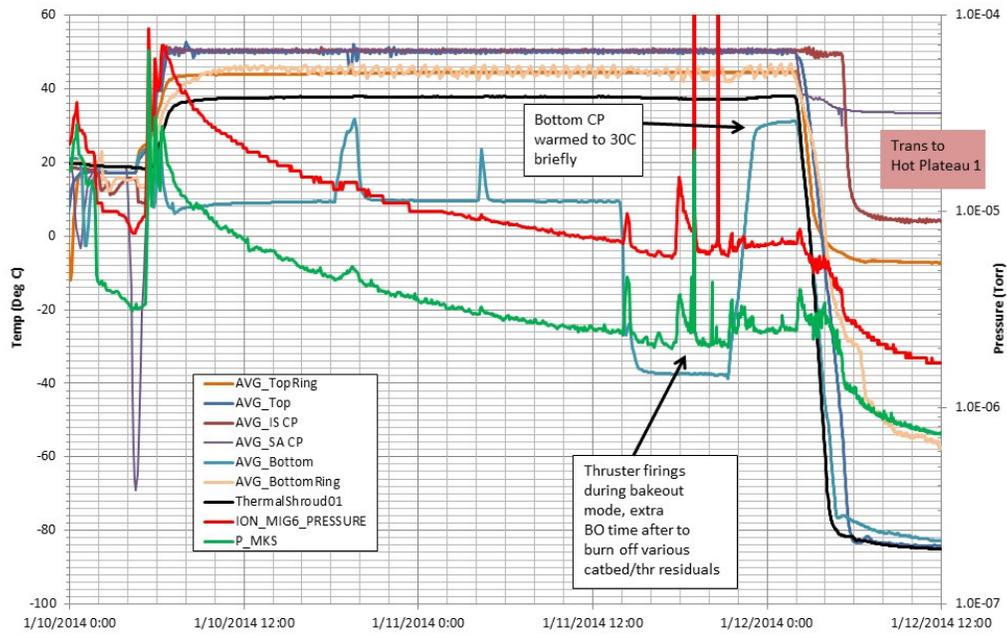


Figure 7. Pressure decay inside and outside of Hamster cage during bakeout

Delta Frequency response

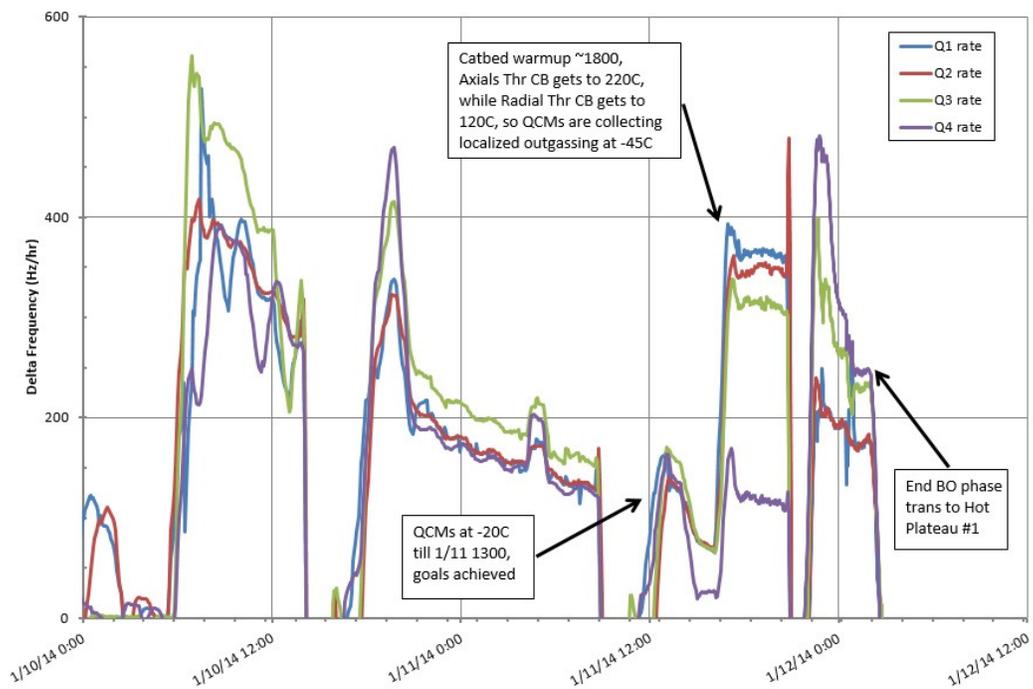


Figure 8. QCM Delta Frequency decay during bakeout mode

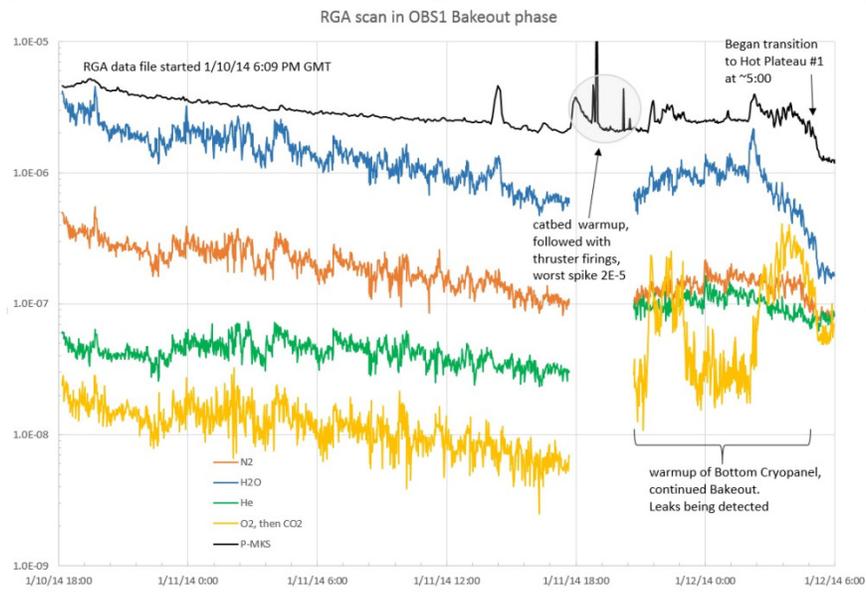


Figure 9. RGA partial pressures during bakeout mode

The thruster firings was an exciting time to validate the MMS thruster performance in vacuum. Each of the 12 thrusters were to be individually fired for 50 milliseconds. The propulsion tanks were pre-filled GN₂ (28 amu) with an Argon tracer (40 amu). Propulsion agreed to use GN₂, instead of Helium, because the Big Blue chamber did not have a turbo pump and GN₂ (w/Argon) could still be traced (by an RGA) and could be pumped from the chamber with the cryopumps. Helium would not have been pumped out effectively with the chamber's cryopumps. If Helium had been used the project would have had to procure a pricey turbo pump for the chamber or add support time at NRL in all TV exposures because the chamber would have had backfilled to ambient atmosphere to remove the Helium buildup. Therefore using GN₂ (with tracer) made the most sense.

Prior to thruster firing the catalytic (cat) beds were activated to test their response. Polymeric material nearby outgassed briefly as the 4 axial thruster catbeds approached 220°C and the 8 radial housings approached 120°C. The outgassing “bumps” are seen in Figures 7-9 as well. QCMs were set to -45°C during this phase which was to emulate the coldest operating range of the IS. Figure 7 shows that the outgassing load is roughly 2.5X the rate at -20°C. Most of this gain was from the entire OBS outgassing, not just from materials around the thruster catbeds. For RGA monitoring of the thruster firings, the on-shift CC person switched the scan mode to pressure versus time and shortened the scan time to 3 seconds. Once prop initiated a firing, it only took a few seconds to verify the on-screen RGA response. Other atmospheric gases were continued to be tracked for any buildup during the process, which included Helium (4 amu), water vapor (18 amu), and Carbon dioxide (44 amu).

The thruster firings were conducted in the same order every time, starting with the axial thrusters 9, 10, 11, and 12 and then going 1 through 8 of the radial thrusters. Internal IGs were also used to track the internal Hamster cage pressures. The instrument suite were always placed in safe mode prior to thruster firings, so there was no voltage issues to worry about during this activity. The internal IGs pressure levels exceeded 1E-5 torr and sometimes shut off when several upper radial thrusters were fired and required resetting (turning them back on before next firing). Figure 10 shows a typical Ion Gauge response during thruster firings. As one can see, vacuum pressure levels inside the chamber, but outside the Hamster cage (refer to IG #1, 2, & 16) increased a little bit, but not to the point of flooding the cryopumps. As a safety precaution, thruster firings were always done with 2 cryopumps open and the 3rd pump was idle, but ready, just in case pressure levels caused a significant pressure increase to trigger their gate valves to close.

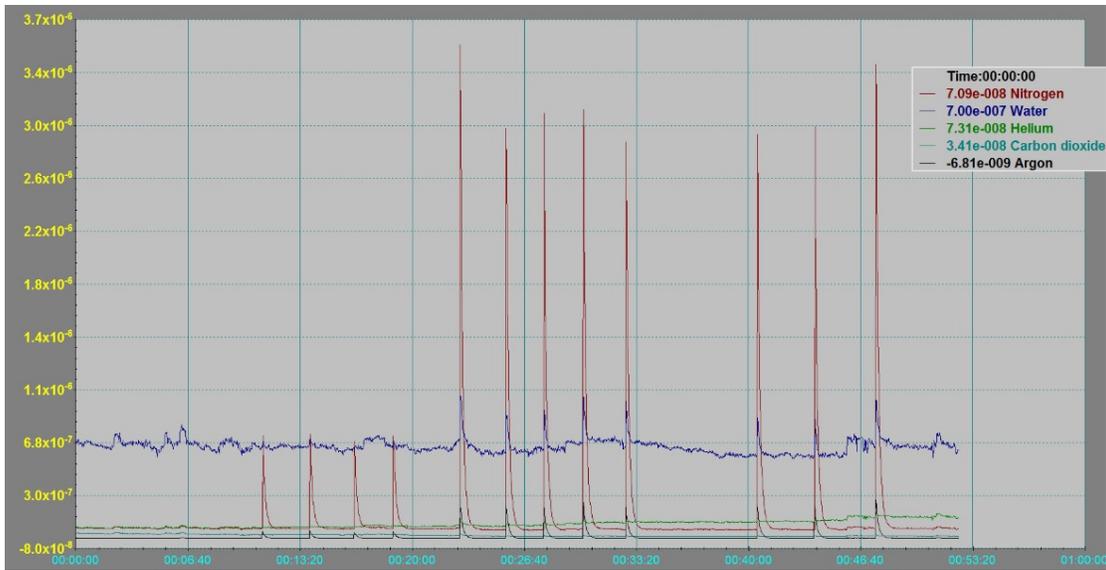


Figure 10. Typical RGA screen during thruster firing

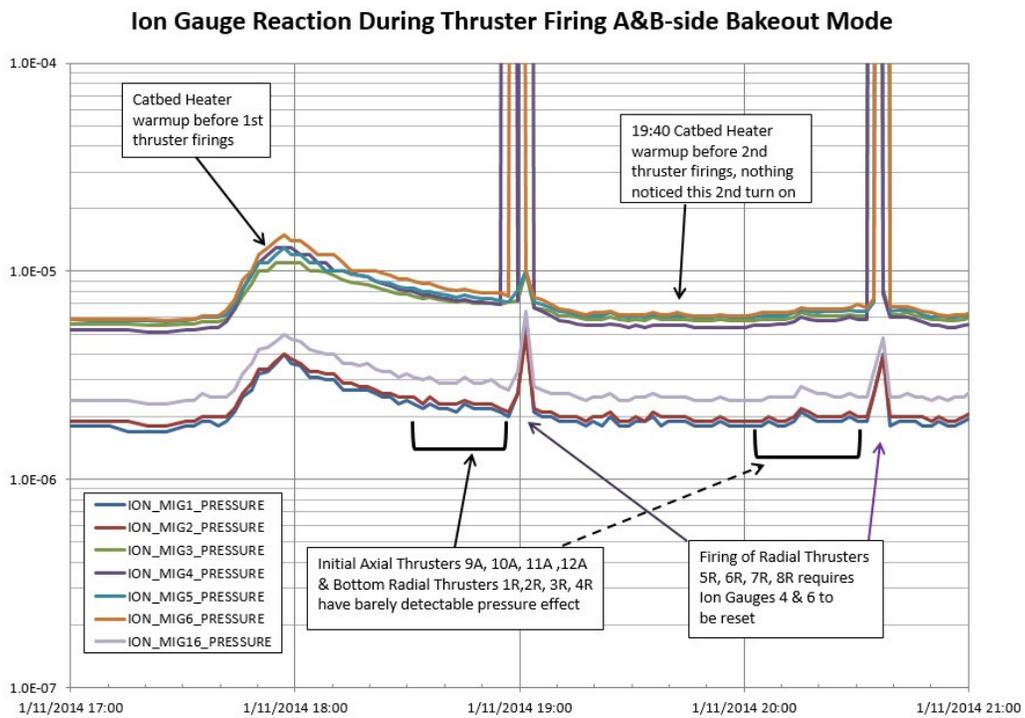


Figure 11. OBS1 ion gauge response during thruster firing

Transitions between hot and cold plateaus typically resulted in the discovery of GN_2 leaks or water vapor outgassing, which resulted in pressure spikes. The IS team typically placed the IS *trans* safe mode when thermal transitions occurred. The most occurrences pressure spikes happened early in TV. After the transitions had occurred a few times, the spikes seemed to reduce. Sometimes the reduction in spikes were because the TCUs were controlled better during the transitions and it also appeared at times that the leaks sealed themselves! The actual

source of the GN₂ leaks varied as well, since the flex lines had to be disconnected between TV tests and 2 different Hamster cages were used. During TV operations leak checking with Helium and later with Argon helped in few instances but not in all. Monitoring TCU trends helped in several other instances, and then other instances we could not identify the source of the leaks. We identified that TCU #3, supplying GN₂ to solar array cryopanel did exhibit trends that earmarked it as a source of leaks, especially during OBS #3 TV. The leak could have been anywhere along the GN₂ supply or return circuit. Early on in OBS TV testing pressure spikes were associated with water vapor being released from cold spots on cryopanel or from cryo-flex lines that may have warmed up to greater than -110°C. Therefore, thermal was requested to minimize the coldest inlet temperature to cryopanel at -90°C, and the set point for scavenger plates was to < -150°C therefore leaving some buffer to keep the supply lines and panels away from the magical -110°C temperature. These pressure spikes kept the support team glued to the console screens, especially when the IS were powered on and they were not in *trans* safe mode. Hot to cold transitions took almost 20 hours, while cold to hot went in half the time. Figure 12 shows an especially spikey time on 01/15/2014 when OBS1 was in transition from hot plateau #1 to cold plateau #1.

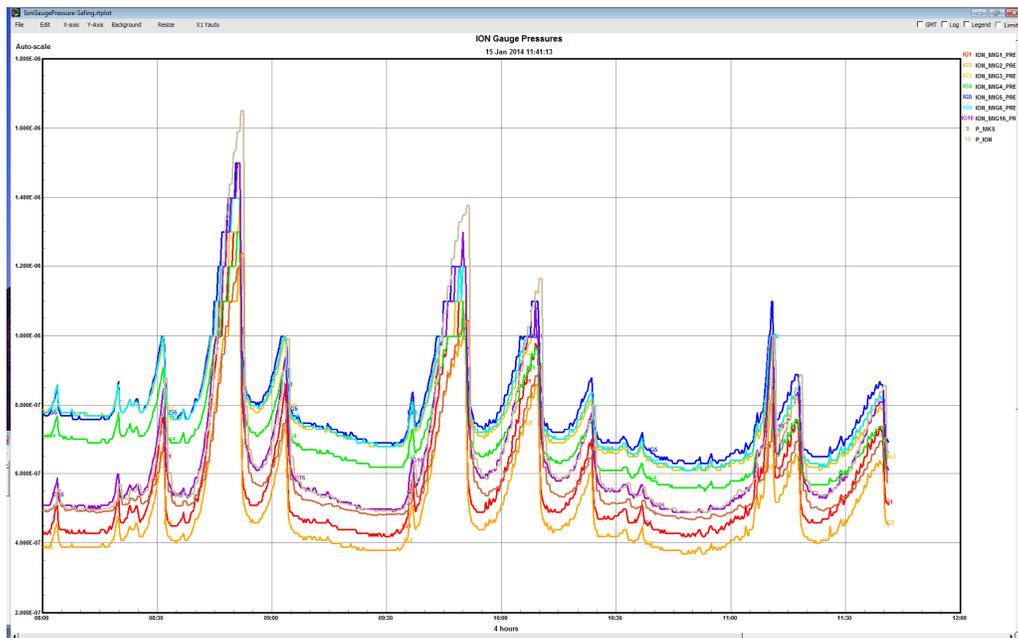


Figure 12. Pressure spikes during OBS1 transition

Subsequent transitions were less eventful and OBS1 was able to conduct HV operations later in testing as the chamber was able to hold < 1E-6 torr for majority of the remainder of TV operations. See Figure 13 for the entire vacuum pressure profile. Really only during thruster firings, conducted at the end of Cold plateau #4, did the internal HC pressure levels exceed 1E-6 torr, which was anticipated.

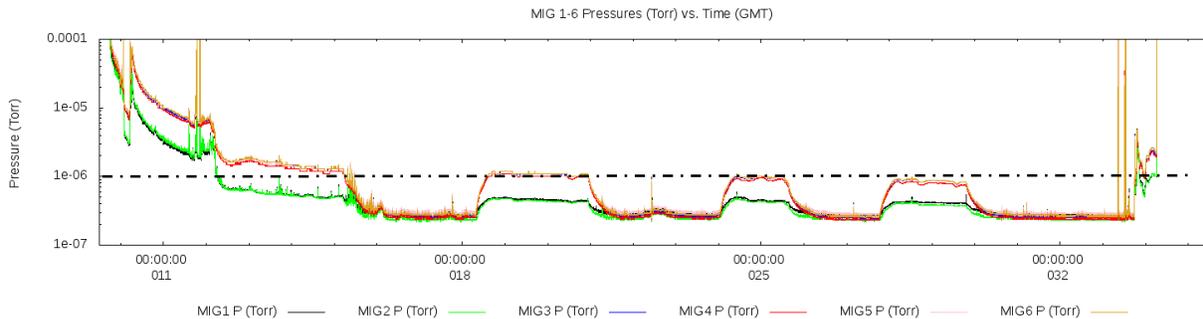


Figure 13. OBS1 TV pressure profile

At the end of Cold Plateau #4, TV testing on the IS and most subsystems was completed and thus the OBS and GSE were stair-stepped up back to ambient temperature. The OBS and IS surfaces were actually stepped up prior to the respective cryopanel. OBS and IS operational heaters were activated and prewarming occurred before cryopanel. The thermal shrouds (TS) lagged every other surface in the chamber (except SP) and they were typically only warmed to 20°C. So the thermal shrouds were typically a source of outgassing for the next OBS test and as such precautions were taken then, as mentioned, it was warmed up to lag the OBS and IS as well when going hot. Figure 14 shows a typical cryopanel warmup along with pressure response by a facility gauge and an Ion gauge (#2). Because of the slow backfill, it became apparent to keep the Cryopanel and shrouds on, maintained at +20°C to minimize future condensation during ventback.

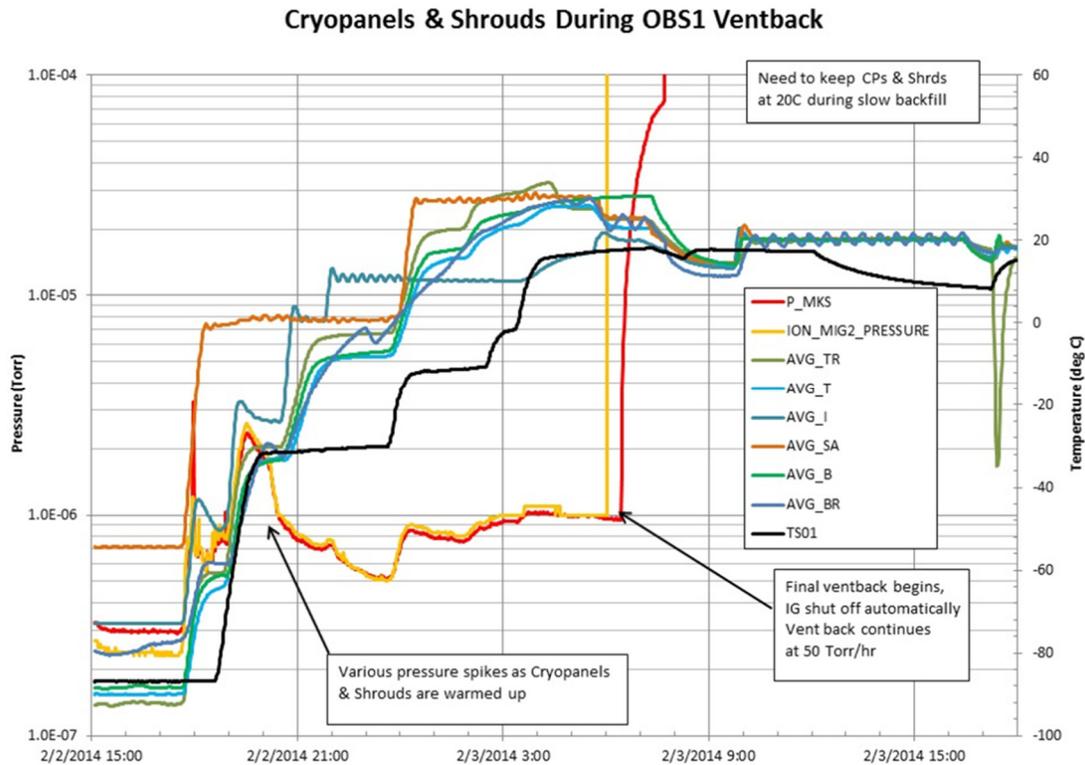


Figure 14. Cryopanel stair-stepped warmup and pressure response

OBS3 TV ISSUES

OBS3 TV provided the most entertainment for the project support staff. This testing was delayed from following OBS4 by almost 3 months. During that dwell timeframe, the project desired to conduct vibration on the stacked observatories. So in the meantime, an eventful third Dry Run was performed on the hamster cage to be used for OBS3. The belts on the main rough pump blowers broke during pump down. The Contam plate thermocouple leads were not connected inside the chamber. And lastly the cryo-flex lines inside the chamber were not hooked up, so the TCUs were not checked out during the bakeout, therefore there was no cold cycle phase in this dry run. Work-arounds enabled completion of a satisfactory 2 day bakeout. Another in-line blower was used to rough pump the chamber, while new belts were ordered. A spare thermocouple was attached to the Contam plate supply line, external to the chamber, which essentially kept the Contam plate flooded with LN₂ during vacuum. The TCU checkout was always a part of the OBS TV plan, so that formal checkout would have to wait until OBS3 TV.

OBS3 wanted to get underway before the July 4th weekend and there was a flurry of activity the week before the Friday's pump down. All internal cryo-flex lines were again leaked checked (with Helium) after they were connected. Leak checking the TCUs circuits from outside the chamber before TV was actually requested and

completed. No leaks were noted from these checkouts. The belts on the rough pumps were replaced and the pumps were activated for a few hours to validate operation. The Contam plate internal TC harness was checked to have been connected. All other checkouts proceeded nominally.

While the pump down and represses proceeded the TCUs were activated. TCU#3 trips a circuit break when the blower was activated setting off NRL console alarms. It was discovered a manual valve on the TCU from a purge line was left open, during the pre-TV leak checking. This was foreshadowing for TCU#3 issues! The test proceeded to high vacuum. Initial activation of the RGA created some issues and after the external controller was swapped out, the RGA resumes working nominally, but we (CC) did lose several days of early data gathering of gas load inside the chamber. TCU and omega checkouts on cryopanel, once under vacuum, also provided more excitement. A solenoid valve for Omega 10, which controls the Bottom Ring, was stuck open and these cryopanel got to -180°C for short period (1 hour). It became another scavenger plate during this short duration. The only viable solution, at the time, was to stop all LN_2 flow, which was to affect the Contam Plate and HC scav plate as well. The scav plates warmed up briefly, which created a large water vapor induced pressure spike to 1E-4 torr. The solenoid was fixed and bottom ring cryopanel was warmed back up to $>30^{\circ}\text{C}$. The QCM and RGA computer were discovered to be miswired, as they had been reversed for another TV test in another chamber recently brought on-line. This delayed QCM data tracking for the initial 12 hours of bakeout. Fortunately internal HC pressure data was able to be monitored by several ion gauges. Once the RGA was brought back on-line, the support staff noted elevated partial pressure levels of Helium in the chamber, which were higher than water vapor! At this point, it was agreed upon to regenerate the cryopumps to reduce Helium levels, this had worked in the past with some success. All 3 cryopumps were cycled through for regeneration and no change in Helium levels were noted. Thruster firings commenced and no increase in Helium levels was detected. The bottom cryopanel were then warmed for several hours, as had been conducted for all previous TV tests. Once the QCM delta frequency data had reduced to an acceptable level, transition to Hot Plateau commenced.

Thermal set points on the TCU #3 were inadvertently set to a temperature rate of $5^{\circ}\text{C}/\text{min}$ and this created a pressure issue inside the TCU. LN_2 was being sent into the internal cryo-flex lines into a warm chamber (Shrouds still at 40°C), which caused the LN_2 to flash to a gas inside the lines. The gas expanded so quickly that it burst the pressure relief disk on the external TCU. The TCU settings were reset to change at rate of $1^{\circ}\text{C}/\text{min}$ and the burst disk was replaced, issue resolved. The RGA noted large amounts of water vapor and carbon dioxide spikes during the vent. Helium and Nitrogen levels were still at elevated levels and exhibited no changes as the cryopumps were regen'd one more time each. Overall chamber pressure levels were high, around 6E-6 torr. OBS CPTs continues, but some IS related CPTs were bypassed (for later completion) due to the elevated pressures. The TCUs were thought to be part of the pressure spikes so their temperature set points were incrementally warmed from a low of -90°C to -85°C , to alleviate cold spots on the cryopanel. The project decided to open all 3 cryopumps. This did little to reduce overall Helium levels, so it was reluctantly decided to vent chamber back to 100 torr, in a hopeful exercise to try and rid the chamber of this "excess" Helium! The return to ambient procedure was followed, the chamber was backfilled to 100 torr and then pumped back down to high vacuum. Back under high vacuum at ambient temperature and the best the chamber can get is 4E-6 torr. Helium is still the highest partial pressure and close to pre-backfill levels!

Belief that leaks in the systems still are there, leak checking with Argon was requested. Other than a spotty, small leak on TCU#3, nothing else was clearly identified. The project decides to put the cryopumps through a lengthy regeneration process that involves cycle purging the cryopump volume with GN_2 10 times. Each cycle purge is about an hour and it took about 18-20 hours to complete a cryopump regeneration. There was no noticeable decrease in Helium levels after this exercise. Based on discussions with GSFC and APL vacuum personnel, the Project decides to ventback the chamber to atmospheric pressure and install a turbo pump on the one remaining conflate on the Big Blue chamber. The turbo pump was a cobbled together setup that was to assist with pumping Helium out from the chamber, if it should still be predominately present. During the non-vacuum time, the TCUs were again pressurized, but there was no noted pressure losses in the circuits. The Turbo pump was installed,

checked out on for on/off operation and pumped to the manual gate valve. Once deemed safe, the chamber underwent 1 pumpdown/repress cycle and went to high vacuum.

The RGA was reactivated and now finally Helium levels were low, like in previous TV tests, and were 2-3 orders of magnitude lower than water vapor. Now the chamber is exhibiting elevated partial pressures from N₂ and water vapor. The turbo pump was turned on for a short duration to see if it made any difference in Helium or any other gas. No noticeable change after several hours, so it was turned off. It was suspected that TCU#3 was the source of the GN₂ leaks, so it was taken off-line and a small rough pump was hooked up to the gas supply line. This was continually rough pumped for about a week. The solar array cryopanel this TCU was controlling was allowed to drift a little bit more, but was still reasonably maintained within temperature range by strip heaters on the cryopanel. It was then decided to open all 3 cryopumps, since there is essentially no Helium. Pressure levels could hold ~1.0E06 torr during Cold Plateau #3. The project then sides with flooding the shrouds to further create a large cryo trap to collect all water vapor and nitrogen on the shrouds walls! This now keeps the pressure steadily below 1E-6 torr and High voltage testing commences anxiously. While checking and demelting ice buildup by the solenoids, the staff noticed that the vent valves were closed (probably from previous leak checking) and were manually reopened to relieve LN₂/GN₂ flow through the cryo-flex lines. Pressure levels subsided a little more and pressure spikes disappear. HPCA conducts High voltage testing and completes ranging to an operational level of 10,000 volts!

It was looking good to continue with HV testing, but pressure levels gradually inch up and it was discovered that Omega #10 solenoid valve stuck open again and several other supply lines were sent cold as an ice ball enveloped several control systems near this solenoid. At this point of the test the option of stopping LN₂ again to these circuits, including the scav plates, was not considered, therefore the ice ball had to be melted to gain access to that individual solenoid. A software fix for controlling the solenoids was to be implemented, so the CDACS was taken off-line briefly while the new fix was implemented. Nominal HV testing resumed and completed thereafter.

The next phase was to place the OBS into an eclipse mode. This had not been since the first OBS2 TV test. This involved putting TCU#3 back on-line, preheating the OBS (and IS) and then flooding all the cryopanel. The shrouds were already flooded from the previous decision a few days earlier. As the cryopanel were flooded, a large pressure spike of GN₂ was noted. Chamber pressure increased to 1.2E-5 torr, project personnel got nervous, and fortunately the pressure levels subside and then magically decreases sharply and reaches ~4E-7 torr within minutes! Overall chamber and ion gauge pressure levels reach even lower, to ~1E-7 torr during the eclipse mode. Figure 15 shows the dramatic pressure changes during implementation of eclipse settings.

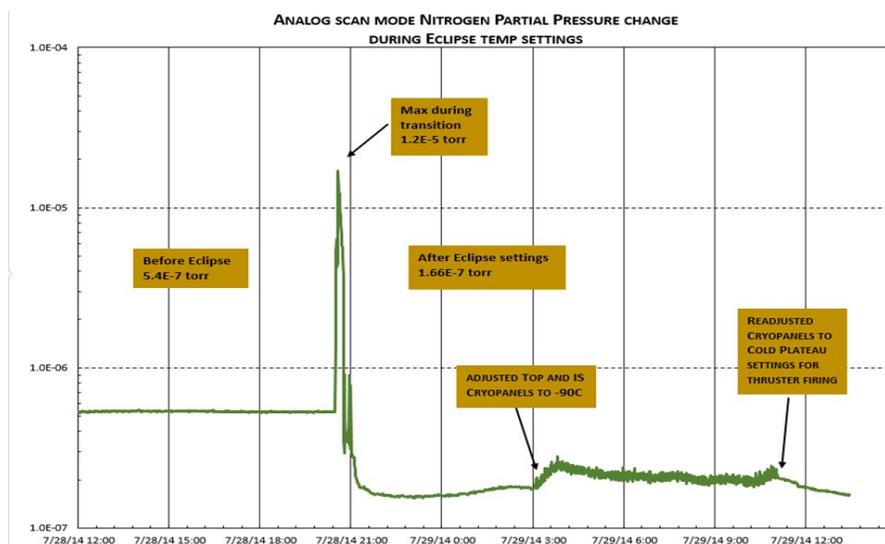


Figure 15: Chamber pressure changes going to Eclipse set points

The main pressure drop was suspected to be from the chamber's burst disk reseating after the pressure spike. This disk is located at the top of the chamber and was not easy to detect if the gasket in it is probably seated. It had been a noted leak source in previous tests. Anyways the eclipse mode lasted about 6 hours and then the cryopanel were adjusted to conduct the last set of thruster firings. These firings went off nominally, with RGA data being tracked and collected, as requested. Ion gauges recorded similar pressure spikes as in previous tests. The project polled the OBS and IS team members whether any additional testing was requested now that the pressure levels have been corrected. No further testing was requested and the return to ambient was completed without any further issues. Figure 16 shows the entire TV profile of OBS3. The chamber pressures were certainly more elevated and there are noticeably more pressure spikes in this TV test, when compared to OBS1 data (Figure 13).

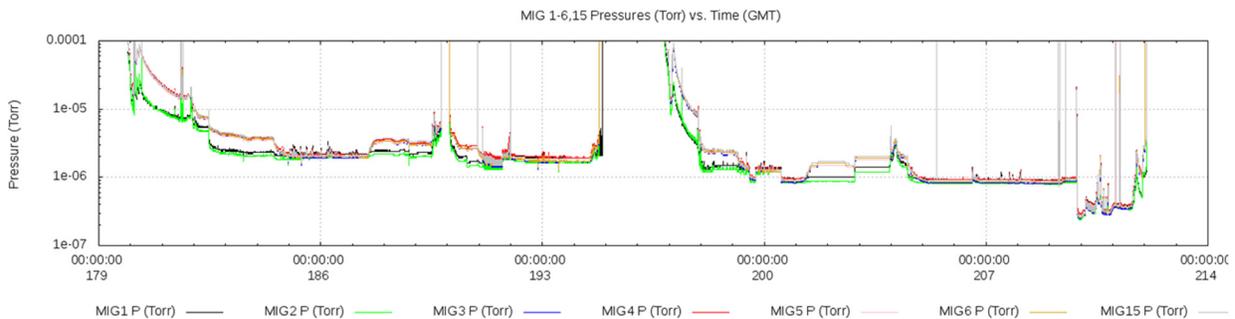


Figure 16: OBS3 Thermal Vacuum pressure profile

LESSONS LEARNED

- Complex tests are difficult to capture 100% of every step or procedure needed to complete an uneventful test.
- Expect problems, consider workarounds and have back plans before testing begins.
- Consider leak checking with inert gases, like argon, instead of Helium. Perhaps reserve Helium use to confirm a leak first detected through use of argon.
- Pressure leak test TCU circuits before vacuum. Reserve adequate time to complete leak checking of enclosed circuits.
- Conduct precerts and/or dry runs to shake out the entire system. Conduct a mini-cycle to validate operation of thermal control systems as they will be conducted with spacecraft testing. Exercise all monitoring equipment to validate their functionality beforehand.
- Utilize multiple ion gauges whenever pressure issues are concerns.
- Maintain spacecraft operational heaters on until shrouds and other test support panels have been adequately warmed up >10C.
- Check and re-check the known problems or nuances of the vacuum chamber. Replace with more reliable apparatus whenever possible.
- In complex TV tests, have real-time monitoring, even if it conducted remotely, which allows for catching issues in almost real time. This allows for corrective actions to be completed in a timely fashion.