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Successful Completion of the JWST OGSE2 Cryogenic Test at JSC Chamber-A while Managing Numerous Challenges

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The JWST Optical Telescope Element (OTE) assembly is the largest optically stable infrared-optimized telescope currently being manufactured and assembled, and scheduled for launch in 2018. The JWST OTE, including the primary mirrors, secondary mirror, and the Aft Optics Subsystems (AOS) are designed to be passively cooled and operate at near 45K. Due to the size of its large sunshield in relation to existing test facilities, JWST cannot be optically or thermally tested as a complete observatory-level system at flight temperatures. As a result, the telescope portion along with its instrument complement will be tested as a single unit very late in the program, and on the program schedule critical path. To mitigate schedule risks, a set of 'pathfinder' cryogenic tests will be performed to reduce program risks by demonstrating the optical testing capabilities of the facility, characterizing telescope thermal performance, and allowing project personnel to learn valuable testing lessons off-line. This paper describes the 'pathfinder' cryogenic test program, focusing on the recently completed second test in the series called the Optical Ground Support Equipment 2 (OGSE2) test. The JWST OGSE2 was successfully completed within the allocated project schedule while faced with numerous conflicting thermal requirements during cool-down to the final cryogenic operational temperatures, and during warm-up after the cryo-stable optical tests. The challenges include developing a pre-test cool-down and warm-up profiles without a reliable method to predict the thermal behaviors in a rarified helium environment, and managing the test article hardware safety driven by the project Limits and Constraints (L&C's). Furthermore, OGSE2 test included the time critical Aft Optics Subsystem (AOS), a part of the flight Optical Telescope Element that would need to be placed back in the overall telescope assembly integrations. The OGSE2 test requirements included the strict adherence of the project contamination controls due to the presence of the contamination sensitive flight optical elements. The test operations required close coordination of numerous personnel while they being exposed and trained for the 'final' combined OTE and instrument cryo-test in 2017. This paper will also encompass the OGSE2 thermal data look-back review.

Nomenclature

AOS	= Aft Optics Subsystems
ASPA	= AOS Source Plate Assembly
BATC	= Ball Aerospace & Technologies Corp
BIA	= Beam Image Analyzer
CMU	= Command Multiplex Unit
CPP	= Cryo-Pump Panels
CS	= Center Section
dT	= Temperature Difference
FMHT	= Free Molecular Heat Transfer
FSM	= Fine Steering Mirror
GHe	= Gaseous Helium
GSE	= Ground Support Equipment

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GSFC	= NASA Goddard Space Flight Center
ISIM	= Integrated Science Instrument Module
JSC	= NASA Johnson Space Center
JWST	= James Webb Space Telescope
K	= Kelvin (unit of Temperature)
L&C	= Limits and Constraints
miniBSF	= mini-Backplane Support Frame
mK	= milli-Kelvin (unit of Temperature)
NASA	= National Aeronautics and Space Administration
NGST	= Northrop Grumman Space Technology
OGSE	= Optical Ground Support Equipment
OTE	= Optical Telescope Element
OTIS	= OTE and ISIM Assembly
PMBSS	= Primary Mirror Backplane Support Structure
PF	= PathFinder
PMSA	= Primary Mirror Segment Assembly
SAO	= Smithsonian Astrophysical Observatory
SMA	= Secondary Mirror Assembly
SMM	= Secondary Mirror Mount
SMSS	= Secondary Mirror Support Structure
TM	= Tertiary Mirror
XRCF	= X-Ray Calibration Facility at NASA Marshall Space Flight Center

I. Introduction

THE primary purpose of the James Webb Space Telescope mission is to observe the early universe at a time when the first stars and galaxies were beginning to form. Outfitted with a light-weighted beryllium cryogenic 18-segment, 6.5 meter primary mirror and a complement of near- and mid-infrared sensing cameras and spectrometers, JWST will allow astronomers to study the universe as it emerged from the dark ages that followed the Big Bang. In addition, the telescope provides the unique capability to study the evolution of galaxies, the history of the Milky Way, and the origin and formation of planetary systems.

As an international collaboration among the space agencies of the US, Europe, and Canada, JWST is scheduled to be launched in 2018 by an Ariane 5 launch vehicle from Korou, French Guiana. After a six-month journey, JWST will enter orbit around the Earth-Sun L2 Lagrange point, about 1.5 million km from the Earth in the anti-Sun direction. In this orbit, the telescope and instruments will be shadowed from Earth and Sun inputs by the large deployable sunshield, allowing passive cooling to cryogenic temperatures (see Figure 1). JWST mission is optimized for infrared wavelengths (0.6 – 28.5 microns) therefore, the telescope elements must be able to achieve the operational temperatures below 54K. This range of wavelengths will enable scientists to peer into dust clouds where stars and planetary systems are, and extend discoveries beyond the current capabilities of Hubble Space Telescope. Due to the size of the sunshield and the cold temperature of the optical system, the deployed JWST cannot be fully thermally or optically tested at the combined 'observatory' level in any facilities which currently exist. Instead, sub-assemblies will be optically and thermally test-verified, and analysis will be used to show compliance with system requirements, including margins.

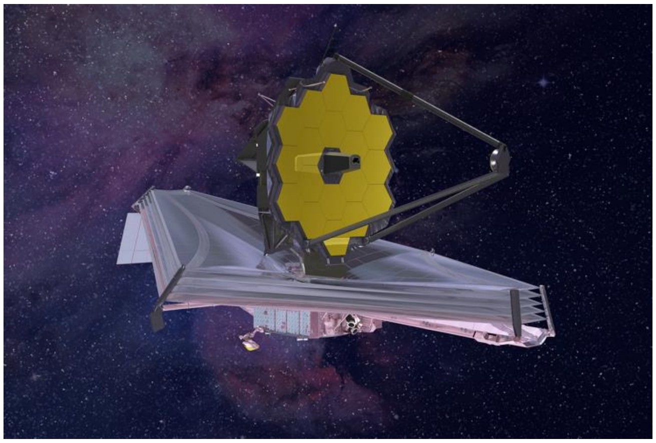

Figure 1. James Webb Space Telescope

II. JWST Cryogenic-Vacuum Test Overview

The JWST Pathfinder tests are planned into 3 major test campaigns prior to the final cryo-vacuum test of the fully assembled flight Optical Telescope Elements (OTE) and the integrated Science Instrument Module (ISIM). The three Pathfinder tests are, OGSE1, OGSE2, and the 'Thermal-Pathfinder'. These tests are incremented to be more complex to fully characterize the test facility including the cryogenic test chamber and the supporting ground system equipment (GSE). Furthermore, the 'flight-like' test articles within the Pathfinder tests are designed to understand the thermal behaviors within the cryogenic environment.

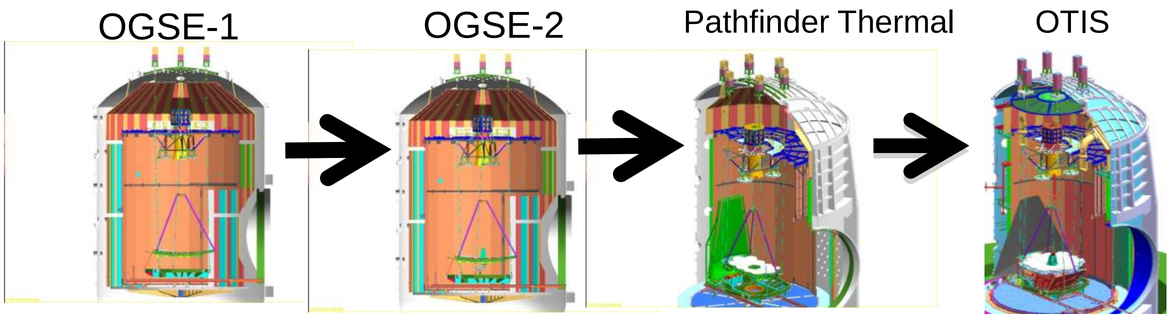

Figure 2. JWST Pathfinder tests are planned into 3 major test campaigns prior to the final cryo-vacuum test of the fully assembled flight Optical Telescope Elements (OTE) and the integrated Science Instrument Module (ISIM).

All of the JWST systems-level cryogenic vacuum tests are performed or will be performed at the NASA Johnson Space Center (JSC) Chamber-A. This chamber was retrofitted with the helium shroud, inboard of the existing liquid-nitrogen shroud and it is now capable of providing an environment of less than 20K. The 30-day OGSE1 test was completed in May 2015 after the JSC Chamber-A was successfully commissioned in 2014 for the JWST use. This paper is focused on the OGSE2 cryo-vacuum test completed in October 2015. The Thermal Pathfinder test is currently scheduled for the summer of 2016. The final test of the fully assembled JWST Optical Telescope Elements and Integrated Science Instrument Module (OTIS) is currently scheduled for early 2017.

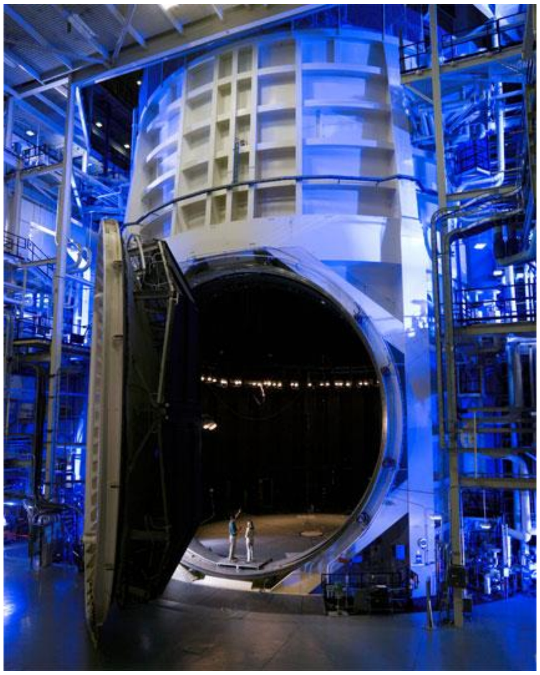

Figure 3. NASA JSC Chamber A with 40-foot door opening.

The successful completion of the OGSE2 marks a major milestone for JWST. This test was the first major cryogenic test with the actual flight telescope optical elements and a specialized fiber-fed optical equipment. It was the first test with the AOS Source Plate Assembly or ASPA, designed to illuminate the telescope's optics through the focal planes. The flight Tertiary Mirror (TM) and the Fine Steering Mirror (FSM) packaged in a bundle called the Aft-Optics-Subsystem (AOS) manufactured by Ball Aerospace and Technologies Corporation (BATC) was optically tested in an integrated configuration in its operational cryogenic environment.

The JWST OGSE2 was primarily an optical test, however, it was thermal team's responsibility and the thermal discipline's primary objective to maintain the hardware safety. This was achieved by staying within the limits and constraints (L&C's), and providing thermal authority to maintain the test articles, specially the flight AOS, within the contamination control requirements. Furthermore, the thermal team was charged with developing a test timeline that was most expeditious and safe during transitions, the cool-down and warm-up phases. The adherence to the timeline was critical in order to maintain the test schedules and keeping the overall project schedule on time. Coincidentally, these thermal objectives conflicted with one another creating the need for a fine balance between meeting all of the hardware safety requirements and maintaining the schedule requirements. This paper mainly covers the OGSE2 thermal performances and it is not intended as a model performance evaluation. The thermal model comparisons will be subjects of future papers.

III. OGSE2 Cryo-Vacuum Cycle Transitions

The OGSE2 test article included the flight hardware Aft-Optics-Subystems (AOS). In addition to the Flight AOS, the test article consisted of the following (see Figure 5):

- Composite backplane that represents the center-section of the flight Primary Mirror Backplane Support Structure (PMBSS).
- A representative of the Backplane Support Frame (mini-BSF).
- 2 primary mirror segments (one of the flight space mirror, and an engineering model of the primary mirror), flight-like secondary mirror.
- Secondary Mirror Mount (SMM).
- Secondary mirror support structure (SMSS)
- Numerous highly complex optical measurement instruments.

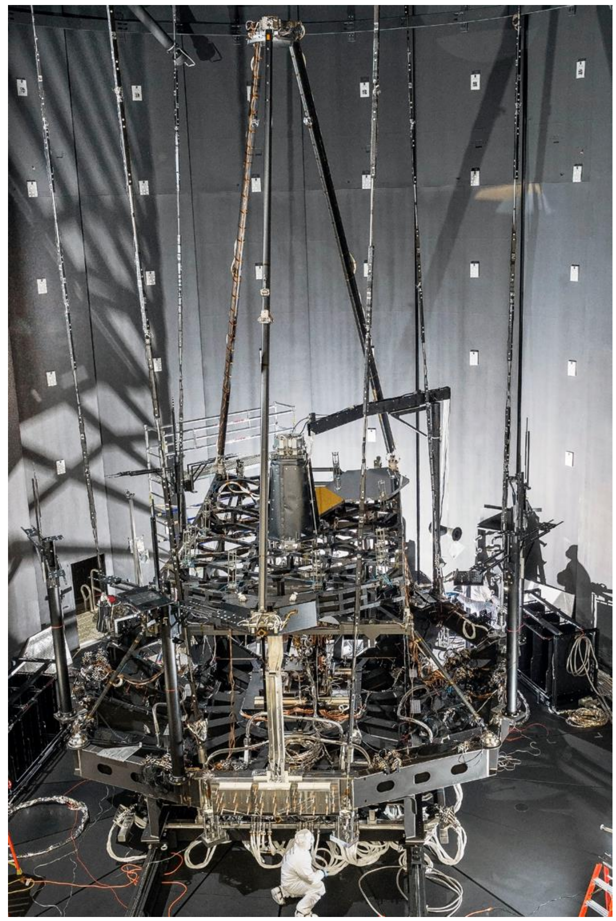

Figure 4. OGSE2 test article configuration inside the Chamber A helium shroud with GSE's.

In order to safeguard the flight hardware and the optical test equipment, it was imperative to manage a long list of limits and constraints which include the contamination control requirements. In addition, it was also important to keep to the planned timeline in order for the flight AOS to be returned to the integration path. During OGSE2, the majority of the hardware was instrumented with temperature sensors (approximately 500 diodes on the test articles). They also contained another 500-plus temperature sensors on GSE's in order to monitor the requirements in real time. However, the AOS fwd-bulkhead and the ASPA bridge dT relied solely on the predictions to keep that dT's within the allowable limits. Furthermore, the average helium shroud rate during the transitions were pre-determined and had to be maintained so as not to exceed the AOS Fwd-bulkhead and the ASPA 'bridge' delta-T requirements. The challenge was to meet the project schedule while maintaining all of the requirements. The faster rates of cool-down and warm-up in real-time would have accelerated the schedule, however, a faster rate would have caused higher temperature differences and thermal gradients among the sub-components.

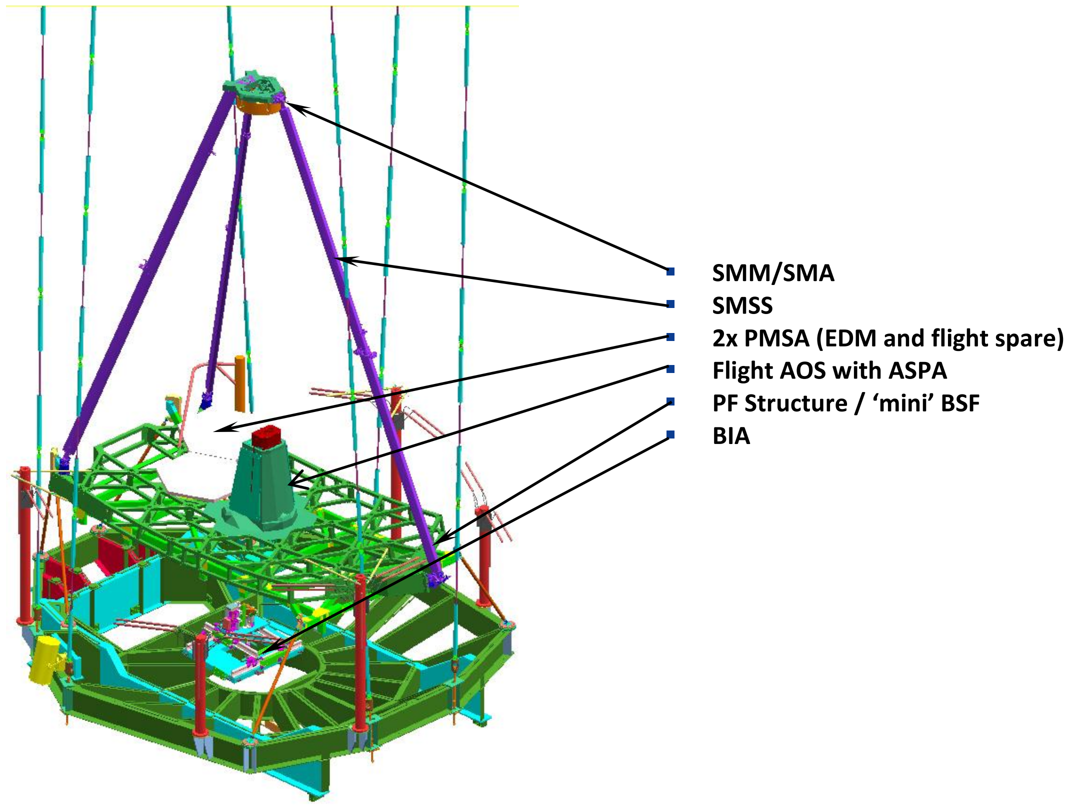

Figure 5. OGSE2 Test Article

A. Cool-Down to the cryo-stable operational temperature

The lower (red colored) solid-line in the Figure 6 depicts the planned average shroud temperature schedule that was developed as a part of the pre-test predictions. This chamber shroud cool-down schedule satisfied all of the L&C's during the pre-test predictions. The upper (blue colored) solid line is the measured average shroud temperatures during the actual cool-down. Note that the chamber helium shroud final average temperature of 32K was reached in 4.8 days compared to the planned 4.6 days. The slight difference in the planned shroud cool-down schedule versus the actual performance was attributed to the real-time management of the L&C and contamination control which will be further discussed in detail.

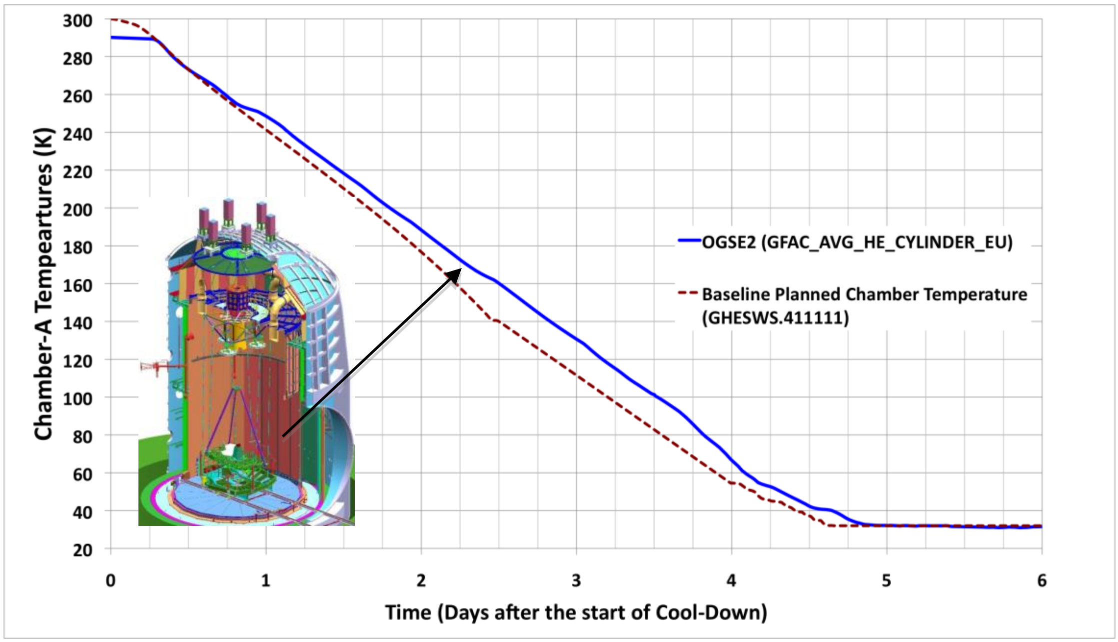

Figure 6. The lower (red colored) solid-line in the graph depicts the planned average shroud temperature schedule that was developed as a part of the pre-test predictions. The upper (blue colored) solid line is the measured average shroud temperatures during the actual cool-down. Note that the chamber helium shroud final average temperature reached 32K for OGSE2.

As the test hardware temperature cools to below 100K, the effectiveness of radiation as a heat transfer becomes less effective and cooling slows. In order to enhance cooling at low temperatures, helium gas was introduced to the test environment. This allowed the chamber environment to continue to cool the test article to the final cryo-stable operational temperatures in a timely manner. As depicted in the Figure 7, the helium gas was introduced in the chamber volume approximately 19 hours after the start of cool-down. The helium gas injection was delayed by approximately 6-7 hours from the original plan as per the pre-test predictions. This ‘delay’ will be discussed further. The chamber pressure was initially increased to 5E-3 Torrr using helium, however after approximately 3 days of cool-down at that 5E-3 Torr pressure, some of the helium gas was evacuated in preparations for the primary mirror electronics unit (Command Multiplex Unit or CMU) operations. A requirement was imposed on this electronics unit where the local regional pressure must be lower than 1E-3 Torr of helium in order for that unit to be able to move the primary mirror motors. The lowering of pressure would, in effect, slow the cool-down at lower temperatures while at the same time the hardware safety must be adhered to during the test. Note that there were two pressure gauge readings, located at different elevations within the chamber volume. Also, note that the two gauge measurements were showing an offset as much as 0.5E-3Torr (approximately 10% differential) at times. Though the lower pressure reading was at the same elevation level where the CMU’s were located, it was decided to use the higher readings in order to err on the side of conservatism. As depicted in the measured pressure profile, there were some attempts to accelerate the cool-down by ‘spiking’ the pressure when there were opportunities to do so while the CMU was sitting idle.

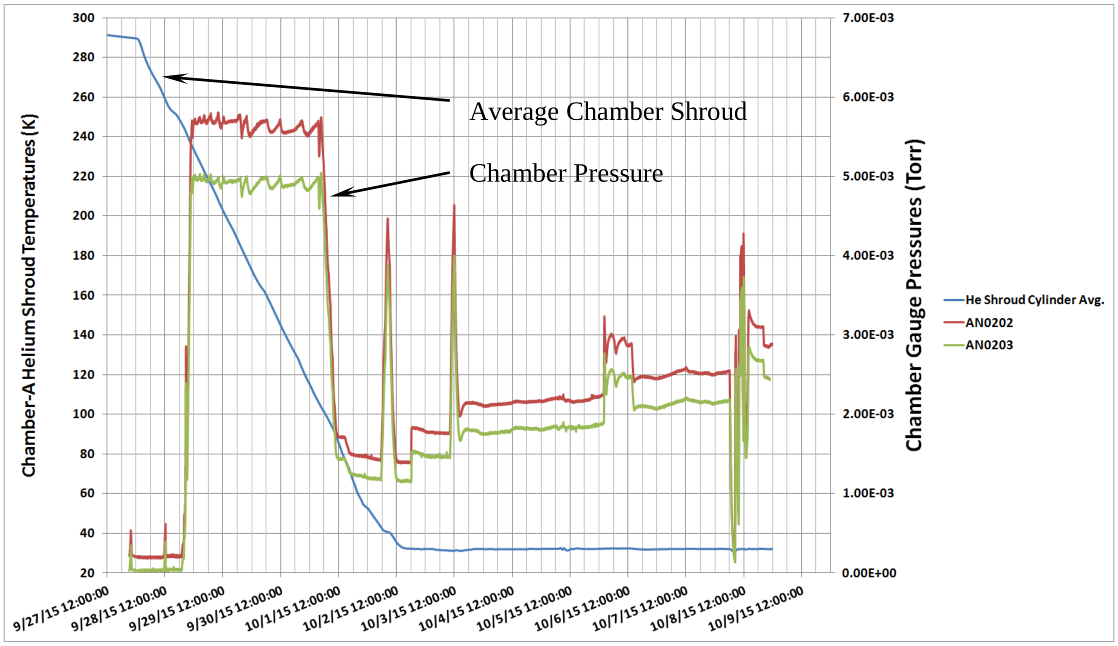

Figure 7. Helium gas was introduced in the chamber volume approximately 19 hours after the start of cool-down. The chamber pressure was initially increased to 5E-3 Torrr using helium, however after approximately 3 days of cool-down at that 5E-3 Torr pressure, some of the helium gas was evacuated in preparations for the primary mirror electronics unit (CMU) operations.

The chamber pressure gauges were mounted at the chamber outer wall where they were kept at the local ambient temperatures. However, the actual pressures local to the CMU were lower as its local temperature were lower while being cooled. Therefore, the local CMU pressure was derived using the pressure/temperature relationships:

P (local) / Sqrt (T-local) = P (Gauge) / Sqrt (T-gauge)

Where:

P(local) = Pressure at CMU (derived)
T(local) = Temperature of CMU (measured)
P(gauge) = Pressures (measured)
T(gauge) = Temperature of the gauge (measured)

As noticed on the pressure plots above (Figure 7), there's a general increasing trend in the gauge pressures, as high as 2.5E-3 Torr, after helium was first evacuated to 1E-3 Torr. Though the measured gauge pressures may have been as high as 2.5E-3 Torr at times, since the CMU local temperature had reached the final cryo-operational temperatures, the local CMU pressure was maintained at less than 1E-3 Torr even while commanded to move the mirror motors.

As stated earlier, helium gas was used inside the chamber volume to enhance heat transfers between the test article and the chamber shroud at cryogenic temperatures where the radiation heat transfer alone was no longer an effective mean when pressed against time. Developing a model to predict the rarified helium gas heat transfer in the Chamber-A configuration proved to be challenging. From the earlier experiences at the OGSE1 test in Chamber-A along with experiences through the cryo-vac tests at NASA Marshall Space Flight Center (MSFC) XRCF chamber, a method was developed to predict the test article's thermal transition behaviors from the perspective of test timeline development. Though the method may not predict accurately the fine details of each of the subcomponents, it was sufficiently accurate to predict the cool-down and warm-up behaviors at a systems-level. This method was also conservative in predicting the local temperature differences (dT's) among those subcomponents that are governed by the L&C's.

The OGSE2 environment may have been in low enough pressure where it was deemed to be in the rarified gas environment but the pressure was too high to be classified as the true Free-Molecular-Heat-Transfer (FMHT) regime. However, using the FMHT conductors equation as shown below, and applying the 21% reduction in its effectiveness (Reference 1), it provided sufficient accuracy in the timeline predictions. The primary objective of the thermal analysis during the pre-test phase was to provide accurate timeline predictions in support of the project schedule, including a consideration for the hardware safety and the contamination control requirements. The FMHT heat transfer value is computed as:

$$FMC = G * p = p * \frac{\gamma + 1}{\gamma - 1}\sqrt{\frac{g_c R_u}{8\pi * MW * T}}$$

Where:

γ	Specific heat ratio (1.667 for He)
g_c	Units conversion constant (1 here with correct unit choice)
R_u	Universal gas constant
MW	Molecular weight
T	Absolute temperature, K
P	Pressure (Pascals)

During OGSE2 test, the completion of cool-down was defined as when the test article and GSE conditions were thermally stable enough and achieved the cryogenic operational temperatures to perform the optical tests. One of the major variables that defined the optical test readiness was when the Pathfinder backplane thermal stability reached less than 150mK/Hr. As depicted in the Figure 8, that 150mK/Hr thermal stability was achieved in 7 days after the start of the cool-down in comparison to the predicted 6.5 days in order for the optical tests to begin.

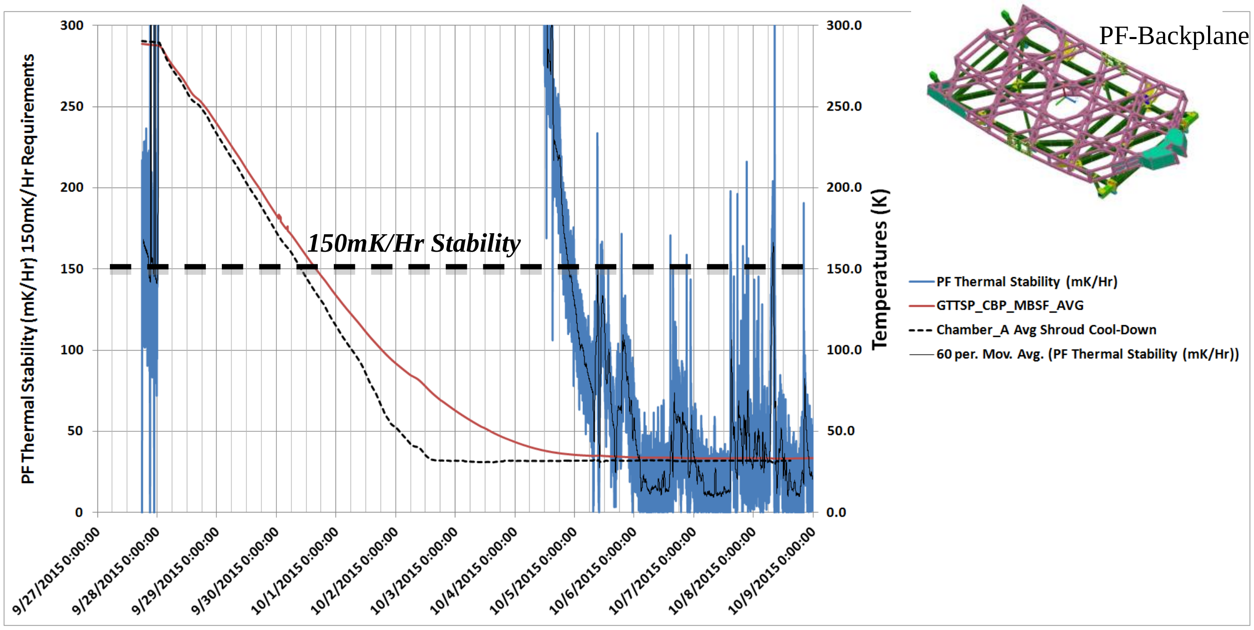

Figure 8. The variable that defines the optical test readiness was the Pathfinder backplane thermal stability being reached 150mK/Hr. As depicted in the graph, that 150mK/Hr thermal stability was achieved in 7 days after the start of the cool-down

The half-day differential between the predicted versus the achieved timeline to the cryo-stable conditions was attributed to the flight hardware safety management at the early phase of the cool-down. As noted in the Figure 9, prior to the helium gas injection, the AOS FSM mirror substrate temperature and the FSM baseplate temperature started to diverge at a rate that would have violated the dT allowable constraint. The first course of mitigating action was to slow the shroud cool-down rate, followed by applying power to the heaters that were located at the baseplate. The FSM baseplate, by design, was conductively coupled to the AOS radiators in order for the FSM to reach its operational temperatures on orbit in a timely manner. This caused the rapid cool-down of the FSM baseplate as an expected behavior. Also the FSM baseplate was equipped with decontamination heaters that were designed to protect the FSM optical surface from condensing molecular contaminants and water released from the near by science instruments during cool-down on orbit. By applying power to the FSM decontamination heaters, the cool-down rate of baseplate was controlled so not to exceed its yellow allowable L&C's. Furthermore, the previous subsystem tests on AOS had demonstrated that the higher pressure in the chamber would increase the gaseous conduction between the FSM substrate and the baseplate thus decreasing the dT's between the two. The helium was then injected in the chamber volume and the original cool-down rate was resumed. The temperature-differential between the FSM mirror substrate and the FSM baseplate was kept below the 80% of their allowable limits at that given temperature. The AOS FSM L&C's were defined specifying the various allowable dT's (from 25K to 100K) at various absolute temperatures (from 323K to 25K). All of these were pre-planned going into the test and were seamlessly executed during the test. The overall cool-down may have taken approximately a half day longer, but this was due to being cautious in order to protect the one-of-kind flight hardware.

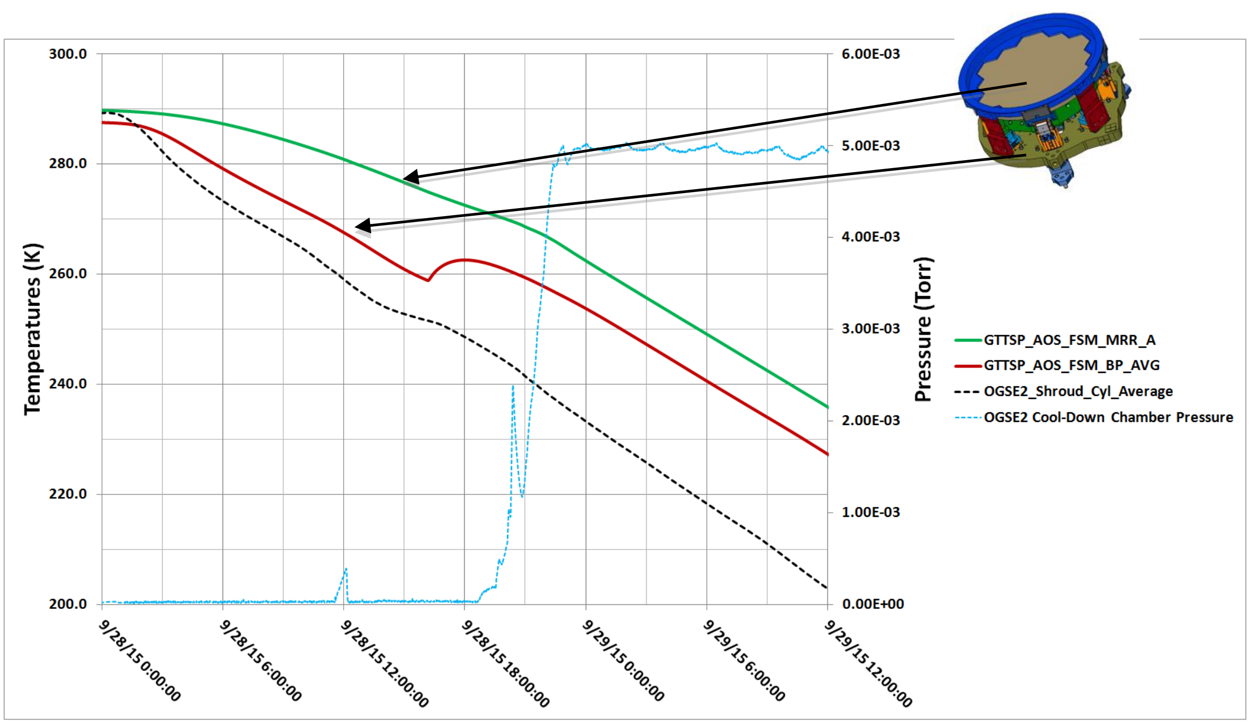

Figure 9. AOS FSM measured temperatures during the FSM L&C's mitigation management: First the shroud cool-down rate reduced, followed by applying power to the heaters that are located at the baseplate. Then helium was injected in the chamber volume to further decrease the dT between the FSM mirror substrate and the baseplate, and then the original cool-down rate was resumed.

During the cool-down phase of OGSE2, the flight AOS FSM and TM turned out to be the 'pacing' items among other parts of the test-articles and including all of the ground-support-equipment that are equally thermally and optically sensitive. The Figure 10 depicts the measured AOS-FSM mirror substrate and baseplate temperatures plotted along with the actual average chamber shroud temperatures, a GSE surface (Beam Image Analyzer or BIA), chamber pressures, and the FSM decontamination heater usage (plotted in percent of total power).

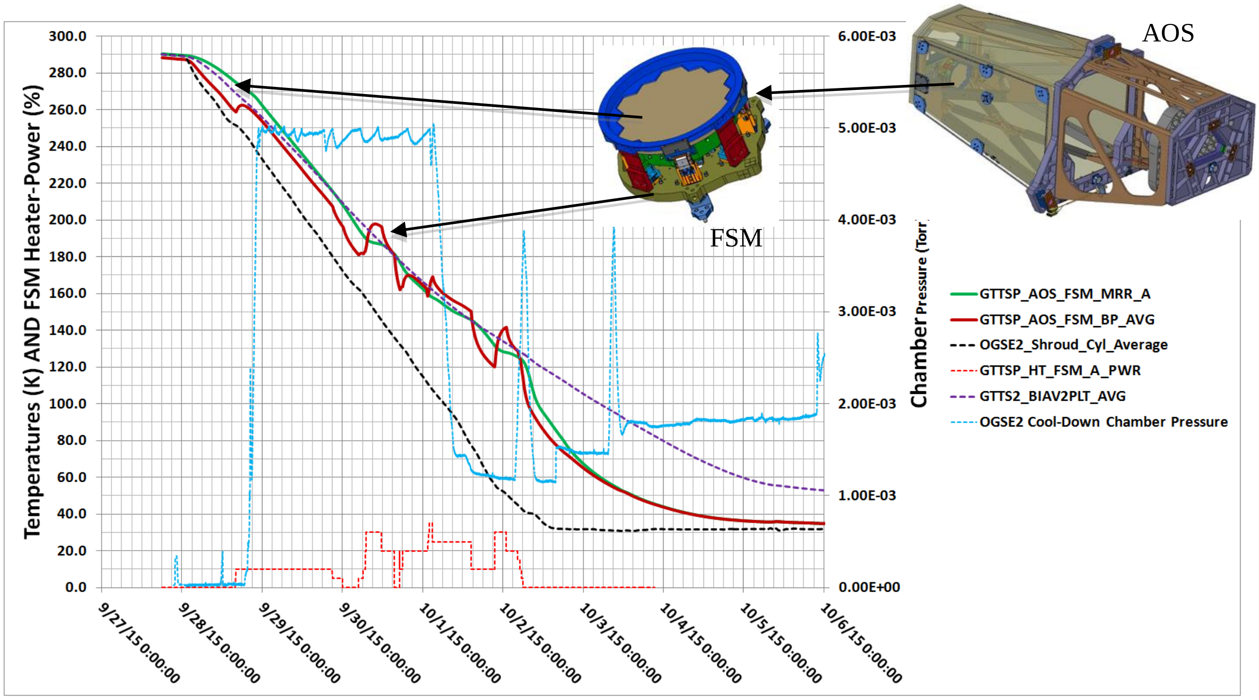

Figure 10. Shown are the AOS-FSM measured data during OGSE2 cool-down; the FSM mirror substrate (Green solid-line) and the baseplate (Red solid-line) are plotted against the Average shroud temperatures (Black dotted-line), BIA baseplate temperatures (Purple dotted-line), and the chamber pressures (Blue dotted-line). Also note the FSM decontamination-heater usage (Red dotted-line). The heaters were used to manage the L&C and the contamination-control requirements during cool-down.

In addition to the temperature dependent allowable dT L&C's for the FSM, the contamination control requirements dictated that the FSM optical surface must be maintained no colder than 10K from the potential contaminant sources between temperatures from the local ambient temperature (ie: 293K) to 220K. The limits were implemented to protect from the potential heavy molecular contaminants such as hydrocarbon and polymer species, and the instrument must be maintained no colder than 20K from the potential water condensation at temperatures between 120K and 170K. The possible contamination source surfaces inside the chamber volume included the Nitrogen and Helium shroud, many of the GSE surfaces, and the Beam Image Analyzer (BIA) that's in the close proximity to the flight AOS. Though the listed contamination control requirements are the 'hard' not-to-exceed limits (deemed as the 'Red' limit), the desirable goal was to maintain the FSM optical surface temperature at equal to or warmer than any of the potential contaminant surfaces. As depicted in the graph below, the temperature differences between the BIA-baseplate and the FSM substrate required close attention during the cool-down which was at the same time that the FSM dT L&C's were being closely monitored to avoid any hardware safety violations. The FSM decontamination heaters were actively and constantly adjusted in order to find an efficient balance among the dT L&C's, the dT between the optical surface to the potential contaminant sources for the contamination control management. The active and constant adjustments also created a desirable rate of cool-down in order to keep to the tight test schedule. As shown in the Figure 11, AOS FSM was able to get through the contamination control regions (ie: between 293K – 220K, and between 170K-120K) and within the desirable temperature ranges, though with a brief excursion in the Yellow limit, without any hardware L&C violations in a timely manner.

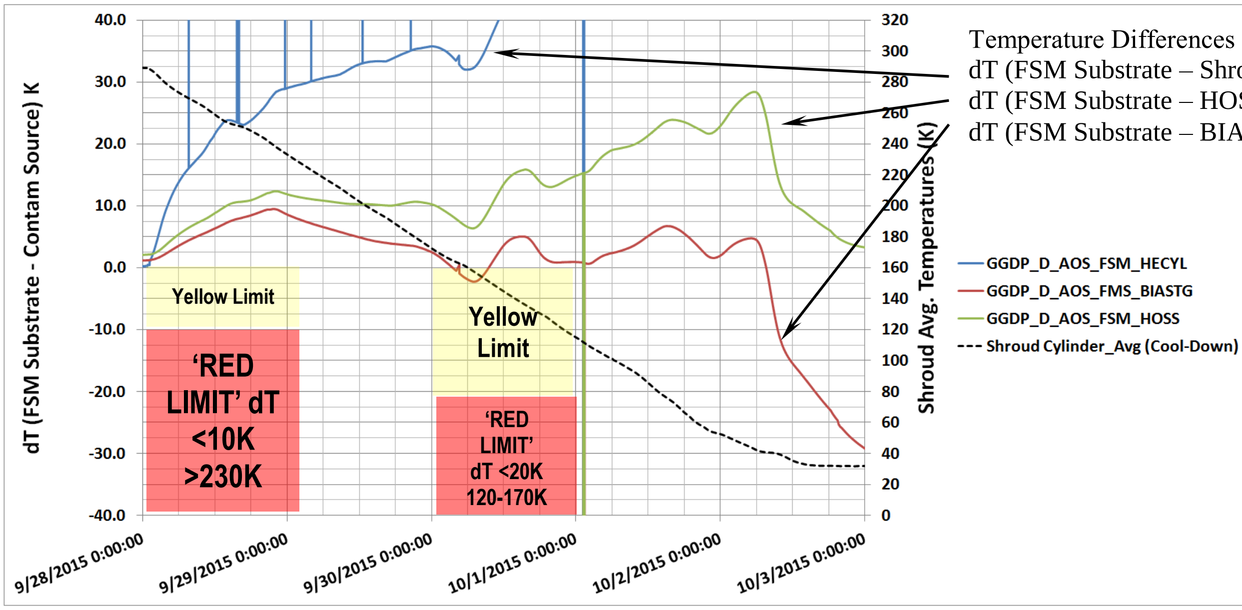

Figure 11. The contamination control requirements dictated that the FSM optical surface must be maintained no colder than 10K from the potential contaminant sources between temperatures from the local ambient temperature (ie: 293K) to 220K to protect from the potential heavy molecular contaminants such as hydrocarbon and polymer species, and must be maintained no colder than 20K from the potential water condensation at temperatures between 120K and 170K.

In a similar manner as the AOS-FSM, the Figure 12 below depicts the measured AOS-TM mirror substrate and sub-bench temperatures plotted along with the actual average chamber shroud temperatures, a GSE surface (BIA), chamber pressures, and the TM 'clip-and-fly' (for ground test only) warm-up heater usage (plotted in percent of total power).

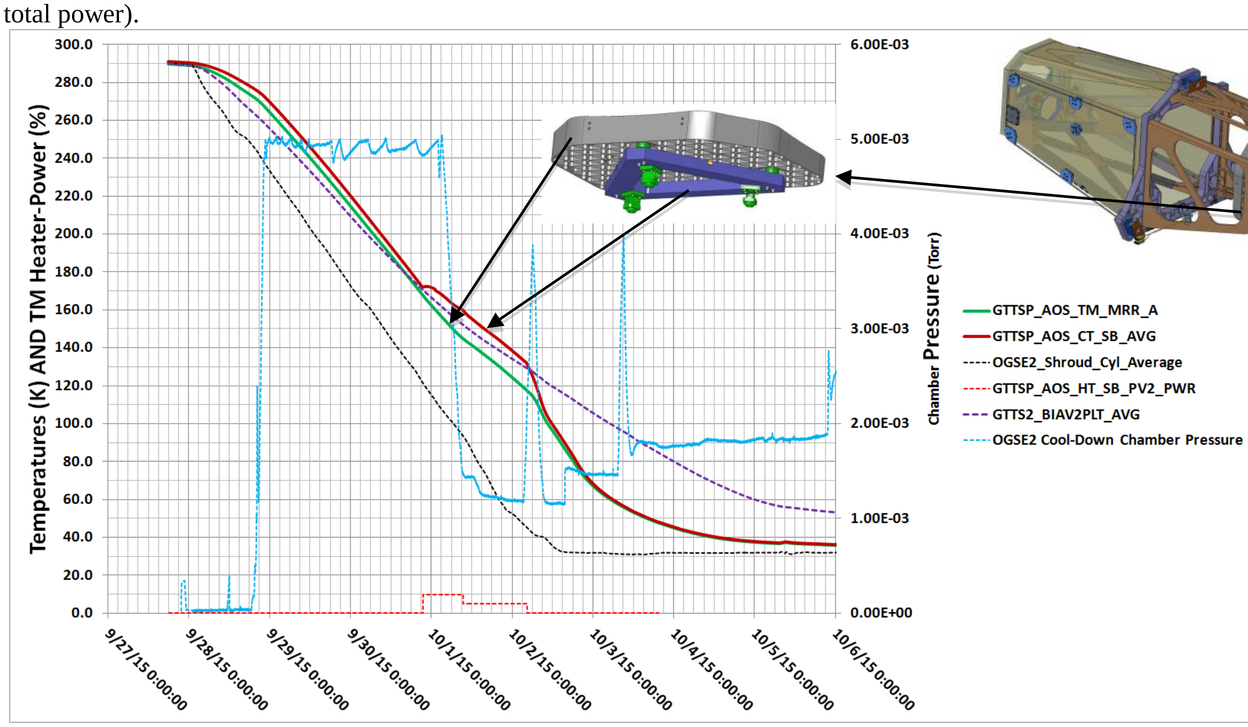

Figure 12. Shown are the AOS-TMA measured data during OGSE2 cool-down; the TMA mirror substrate and the sub-bench are plotted against the Average shroud temperatures and the chamber pressures. Also note the TMA warm-up heater usage, the heaters were used to manage the L&C and the contamination-control requirements during cool-down.

As described in the FSM performances, the contamination control requirements dictated that the TM optical surface must be maintained no colder than 10K from the potential contaminant sources between temperatures from the local ambient temperature (ie: 293K) to 220K and must be maintained no colder than 20K from the potential water condensation at temperatures between 120K and 170K. Again, though the listed contamination control requirements are the ‘Red’ limit, the desirable goal was to maintain the TM optical surface temperature at equal to or warmer than any of the potential contaminant surfaces. As shown in the Figure 13 below, AOS TM was able to get through the contamination control regions (ie: between 293K – 220K, and between 170K-120K) within the desirable temperature ranges in a timely manner without any hardware L&C violations throughout the entire cool-down.

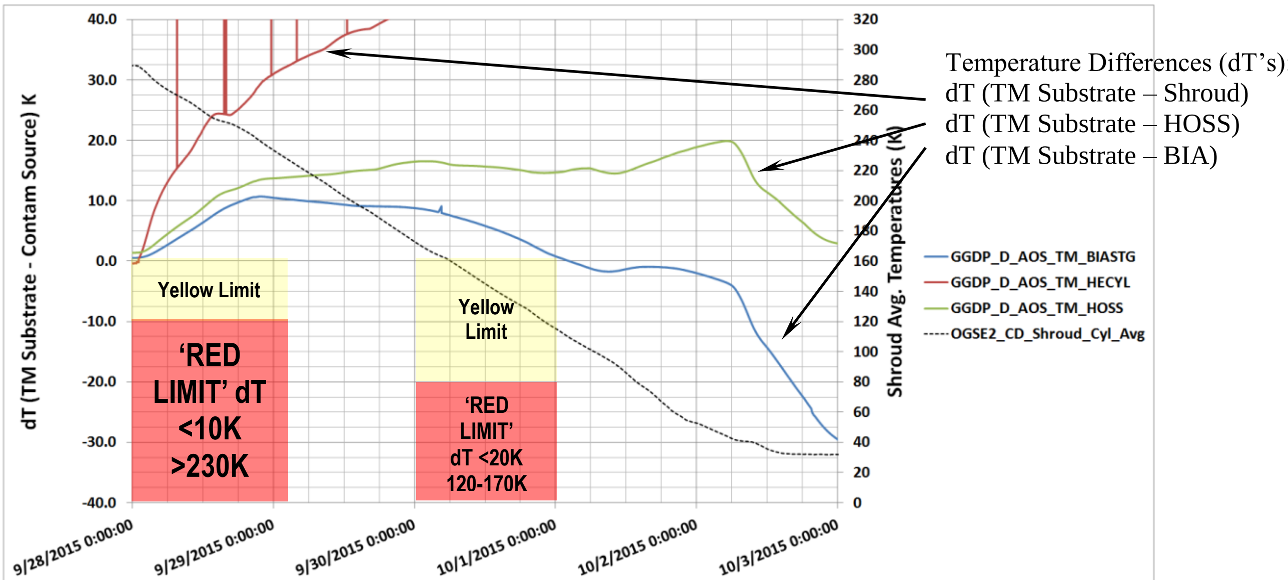

Figure 13. AOS TM was able to get through the contamination control regions (ie: between 293K – 220K, and between 170K-120K) within the desirable temperature ranges in a timely manner without any hardware L&C violations throughout the entire cool-down.

B. Warm-Up: Return to local ambient

In the Figure 14, the planned average shroud temperature schedule (shown in Blue dotted-line) was developed as a part of the pre-test predictions. This chamber shroud warm-up schedule satisfied all of the L&C’s during the pre-test predictions. The solid blue line is the measured average shroud temperatures during the actual warm-up. The average chamber helium shroud final average temperature of 293K was reached in just under 9 days compared to the planned 8.3 days. However, when compared the test article warm-up performances, the warm-up overall was completed in 9.5 days as compared to the predicted 9.5 days. There are several factors that attributed for the lagging in the average shroud temperature rate when compared against the planned rate. There were also several real-time relaxations on some of the desires and expectations while still maintaining the hardware safety and the contamination control requirements during the warm-up. These relaxed expectations were in an effort to complete the test within the allocated project schedule.

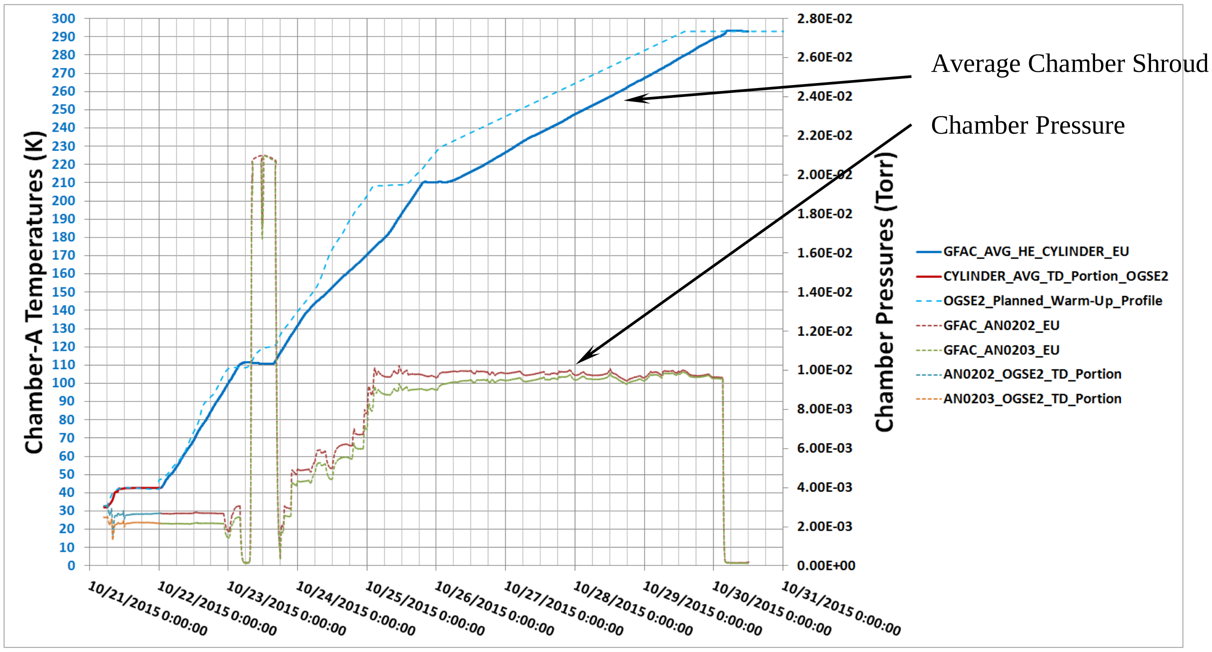

Figure 14. The planned average shroud temperature schedule (shown in Blue dotted-line) versus the measured average shroud temperatures during the actual warm-up (Solid blue line). The average chamber helium shroud final average temperature of 293K was reached in just under 9 days, compared to the planned 8.3 days.

Throughout the 18.5 days of the cryo-stable optical test phase of the OGSE2 test, gaseous helium was kept at a constant pressure of 2.5E-3 Torr. This allowed the test environment to be undisturbed, thus keeping the test article as thermally stable as possible. The chamber was also filled with helium during the warm-up phase of the test. The chamber pressure was kept constant until the shroud temperature reached the 110K plateau where the shroud temperature was held constantly at that temperature. This strategic step served several purposes:

- It provided an opportunity for the dT's among sub-components to merge together as part of the dT L&C's management.
- It created an environment for the AOS optical surface, FSM and TM, temperatures to catch up to the shroud and other potential contaminant source surfaces prior to entering into the contaminant control regimes.
- It was an opportune time to release the gas molecules condensed on the cryo-pump panels (CPP) during the test.

As noted in the Figure 15, prior to releasing the condensed gas molecules by warming up the CPP, helium was fully evacuated from the chamber to provide an added margin in the chamber pressure. The chamber pressure was then allowed to reach as high as 20E-3 Torr while the condensed gas species from the CPP were released and pumped away. The process of eliminating the condensed gas molecules took almost 12 hours. The end of this gas releasing event was marked by the chamber pressure returning back to high-vacuum, as defined by the gauge pressure reading in the ranges of 1E-5Torr and lower. At that time, the gaseous helium was re-injected into the chamber to continue to accelerate the warm-up by the enhanced heat transfer via the added helium gas conductions. The shroud temperature was also resumed warming at a rate of 2.5K per Hour. Following the re-injection of the gaseous helium, the chamber pressure was allowed to gradually increase to 10E-3 Torr to further enhance the heat transfer. At this time, the hardware was monitored closely for any negative impacts. The remainder of warm-up continued with the chamber gauge pressure at 10E-3 Torr until the shroud had reached the local ambient temperature. Once the chamber shroud and the test article temperatures reached the local ambient temperature then helium gas was fully evacuated, creating once again a 'hard-vacuum' environment. This allowed the chamber repress process to return the chamber pressure to the local site atmospheric pressure.

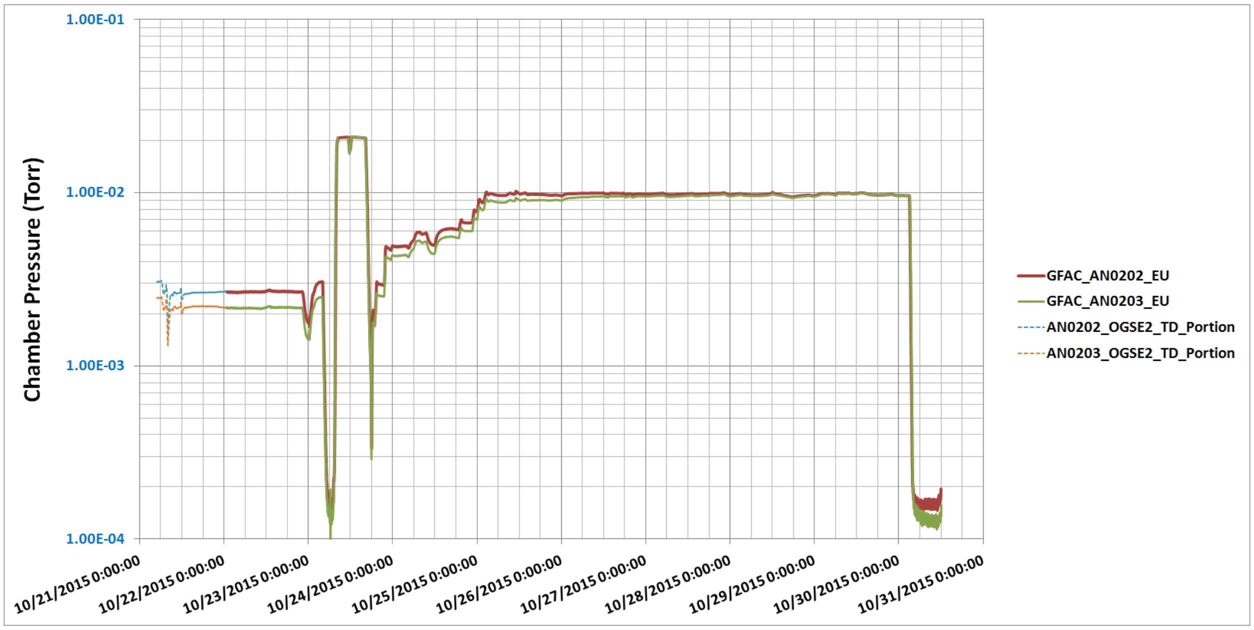

Figure 15. OGSE2 Measured chamber pressure profile shown.

During the warm-up, the gating item that prevented from warming-up at a faster rate was the flight AOS TM. The TM's hardware safety dT L&C's and its contamination control requirements both were in competing situations while attempting to complete the test on time. The Figure 16 below depicts the measured AOS-TM mirror substrate and sub-bench temperatures plotted along with the actual average chamber shroud temperatures, chamber pressures, and the TM 'clip-and-fly' (for ground test only) warm-up heater usage (plotted in percent of total power).

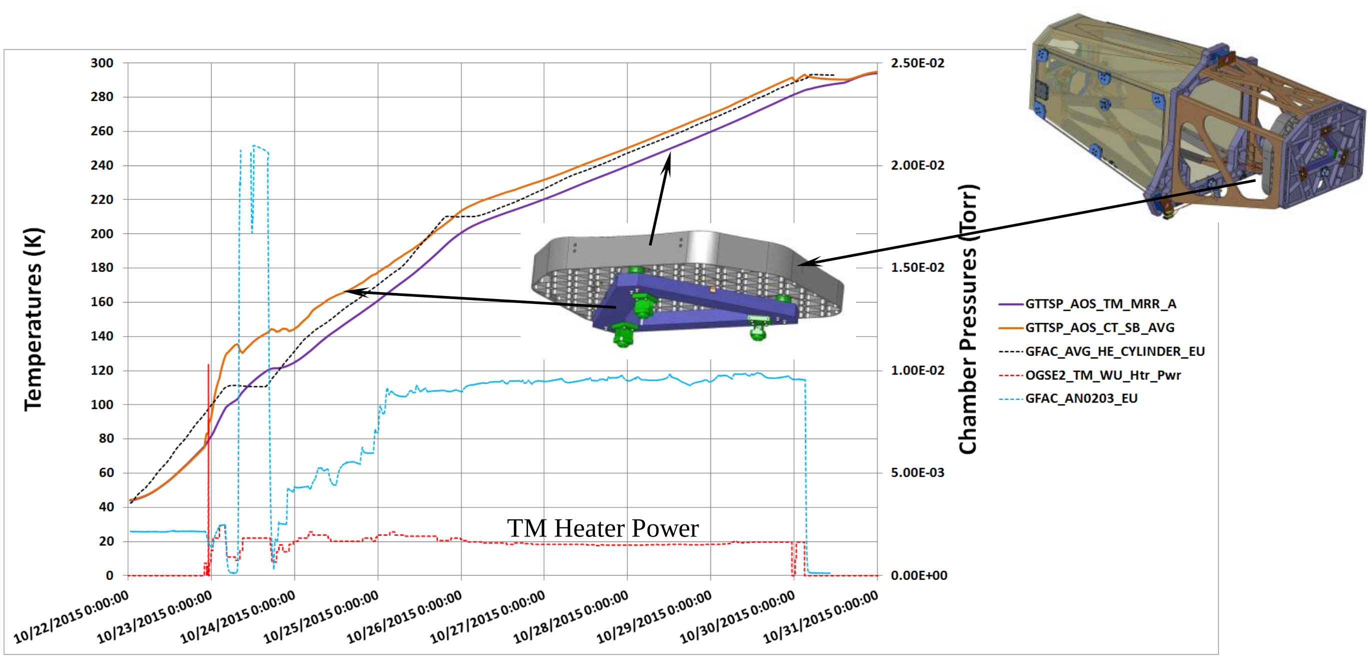

Figure 16. Shown are the AOS-TMA measured data during the OGSE2 warm-up; the TMA mirror substrate and the Sub-Bench are plotted against the Average shroud temperatures and the chamber pressures. Also note the TMA warm-up heater usage, the heaters were used to manage the L&C and the contamination-control requirements during the warm-up.

As stated earlier, the gating item during the warm-up was the thermal performances of the flight AOS TM. The AOS TM thermal behavior is defined as where the rate of changes in its environment would result in a direct increase of the temperature differentials between the mirror substrate and its sub-bench. However the hardware safety L&C's would only allow limited dT's. Therefore the allowable real time shroud warm-up rate was limited by this TM dT L&C's at given temperatures. As shown in the Figure 17 below, the flight AOS TM dT's were allowed to be well in the Yellow-limit with the concurrence from the Test Director and the on-site thermal-subject-matter-expert of the AOS. The allowance to 'live-in-the-yellow' provided an opportunity to continue to warm-up at a pre-planned rate, allowing the overall test to be completed in the allotted period. As noted on the graph, allowing the dT's between the AOS TM mirror substrate and the sub-bench be in 110% of the Yellow limit (or 90% to the Red limit) meant the temperature was only 1K away from the L&C violation. The experiences have shown that the dT could be readily managed by adjusting the heater power therefore the possible risk to the hardware safety was very low and manageable.

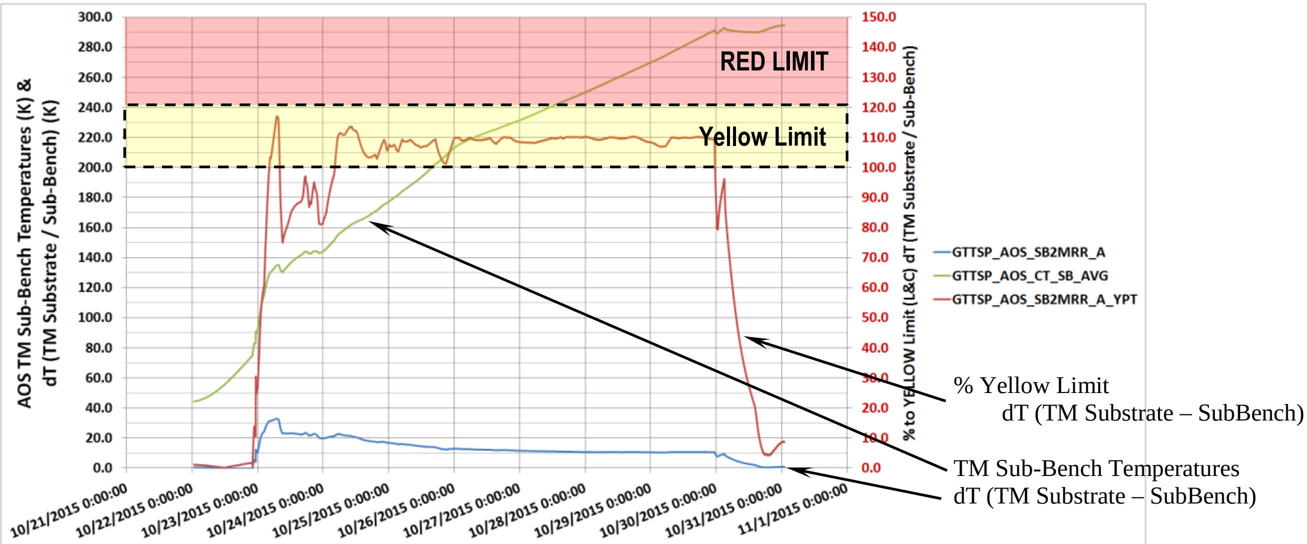

Figure 17. the flight AOS TM dT's were allowed to be well in the Yellow-limit with the concurrences from the Test Director and the on-site thermal-subject-matter-expert of the AOS. Allowing the dT's between the AOS TM mirror substrate and the sub-bench be in 110% of the Yellow limit (or 90% to the Red limit) meant the temperature was only 1K away from the L&C violation.

Compounding the difficulty of warming up at a faster rate was the contamination control management during the warm-up. The contamination control requirements required that the sensitive optical surface (ie: TM optical surface) must be maintained no colder than 10K from the potential contaminant sources between temperatures from the local ambient temperature (ie: 293K) to 220K to in order to protect from the potential heavy molecular contaminants. Also, it must be maintained no colder than 20K from the potential water condensation at temperatures between 120K and 170K. The desirable option was to apply additional power into the TM heaters in order to achieve a warmer optical surface when compared to the potential contaminant sources such as the chamber shroud. However, the TM dT L&C prevented applying any more power into the system as described above. Therefore, in order to warm the TM in a timely manner and be able to stay within the contamination control requirement limits, a decision was made with the concurrences from the Test Director and the contamination control engineers allowing the hardware to proceed in the yellow limit range. As depicted in the Figure 18, the temperature differential between the TM optical surface to the chamber shroud was, again, allowed to 'live-in-the-yellow' of this limit. In the contamination control regions at temperatures above 220K, the margin between the TM optical surface to the shroud was only approximately 2K to the requirement. Though monitoring these values required constant vigilance, the chamber shroud control was very responsive and manageable making the risk to the flight hardware very low.

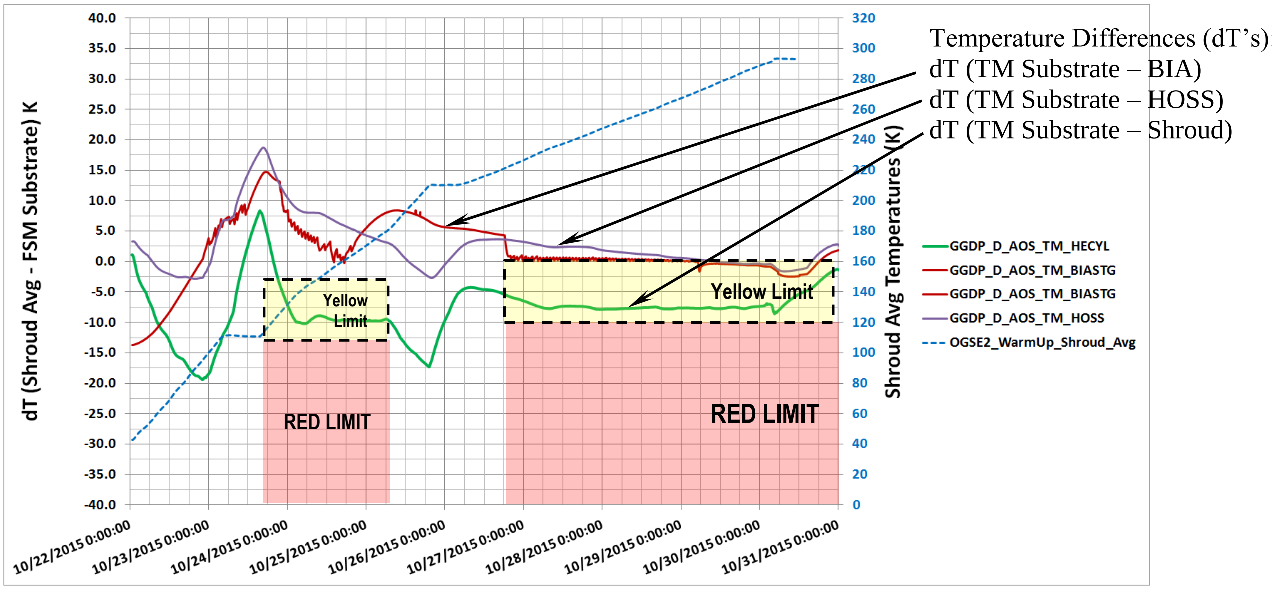

Figure 18. The temperature differential between the TM optical surface to the chamber shroud was allowed to 'live-in-the-yellow' of the limits. In the contamination control regions at temperatures above 230K, the margin between the TM optical surface to the shroud was approximately 2K to the requirement.

IV. Conclusion

The JWST OGSE2 was successfully completed within the allocated project schedule while faced with numerous conflicting thermal requirements during cool-down to the final cryogenic operational temperatures, The challenges include developing a pre-test cool-down and warm-up profiles without a reliable method to predict the thermal behaviors in a rarified helium environment, and finding a fine balance among the test article hardware safety driven by the project Limits and Constraints (L&C's). Furthermore, up against the project schedule, OGSE2 test included the time critical Aft Optics Subsystem (AOS), a part of the flight Optical Telescope Element that would needed to be placed back in the overall telescope assembly integrations. The OGSE2 test required the strict adherence of the project contamination controls due to the presence of the contamination sensitive flight optical elements. Even with these technical challenges associated with the major cryogenic test, the JWST OGSE2 test was completed in 35 days as it was budgeted for.

There were many valuable lessons and knowledge gained during the OGSE2 cryo-test. Some of those lessons learned are listed as follow:

- The thermal model was used as a gauge to track the test progress in real time during the test. This was extremely beneficial in keeping the overall test schedule on track.
- The experiences from the past cryo-tests, such as the OGSE1 and XRCF tests, provided knowledge bases for the rarefied helium environment. Though the absolute accuracy of thermal predictions in the rarefied helium could be improved but the method developed for the timeline prediction was sufficient to support the project test schedule.
- The presence of other discipline's subject matter experts during critical phases of the test was a huge asset. This made possible the real time adjustments in the operational steps when the test schedule may have been at jeopardy due to conflicts among test article hardware safety requirements.
- The OGSE2 test involved the flight optical assembly, namely the AOS. This test provided opportunities for the project test staff the real exposure to the cryogenic test operations which will be a valuable experiences towards the success of the OTIS, the fully integrate flight JWST cryogenic test.

Acknowledgments

A hearty thanks to all those NASA JSC Chamber-A operators, for they are a great bunch of professionals worked tirelessly around the clock to make the JWST OGSE2 test a complete success.

An equally hearty thanks to the test coverage thermal engineers from various agencies and organizations, including NASA-GSFC, Ball Aerospace and Technologies Corp., Harris Corporation, Genesis Engineering Solutions, and Edge Space Systems. Without their long hours and dedicated efforts, this one-of-kind cryogenic test would not have been possible.

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[1] Park, Sang C., Freeman, Mark D., Cohen, Lester M., "JWST PMBSS Deployable Wings Thermal Management during Cryo-Cycle at XRCF", ICES-2014-239 44th International Conference on Environmental Systems 13-17 July 2014, Tucson, Arizona