Operating and Maintaining the JWST Cleanroom attached to JSC's Chamber A during preparations for the OTIS Cryogenic Thermal Vacuum Test

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ABSTRACT

In order to maintain cleanliness during preparations for JWST's OTIS (Optical Telescope Element-Integrated Science Instrument Module) Cryogenic Thermal Vacuum Test, a cleanroom was built that attached directly to the 60-year-old Chamber A. The cleanroom and chamber were outfitted with independent environmental control systems each providing ISO Class 7[1] air cleanliness. To maintain balanced, positive pressure in both the cleanroom and chamber volumes, a special control protocol was developed and successfully implemented. Dual back-up environmental control units (one each for the chamber and cleanroom) were installed just outside the building to provide environmental control redundancy due to a single source chilled water supply and weather threats. In addition, lack of a dedicated cleanroom airlock facilitating clean ingress and egress made it necessary to perform additional cleaning and packaging, as well as augment the uncontrolled truck lock space with small clean tents for pre-cleaning. Special procedures were developed to allow ingress of extra-large support equipment required for load testing of the cleanroom crane, installation of optical equipment in Chamber A and accommodation of the OTIS shipping container. A thorough bake-out and cleaning of Chamber A was also necessary to reduce volatiles from the shroud's black thermal paint and to reduce particle fallout. Acrylic adhesive fracture discovered during early cryo-testing represented a significant challenge that was successfully mitigated prior to OTIS testing. A dedicated team of Contamination Control (CC) Technicians was specifically trained to clean support equipment and screen materials entering the cleanroom and chamber to ensure cleanliness and vacuum compatibility.

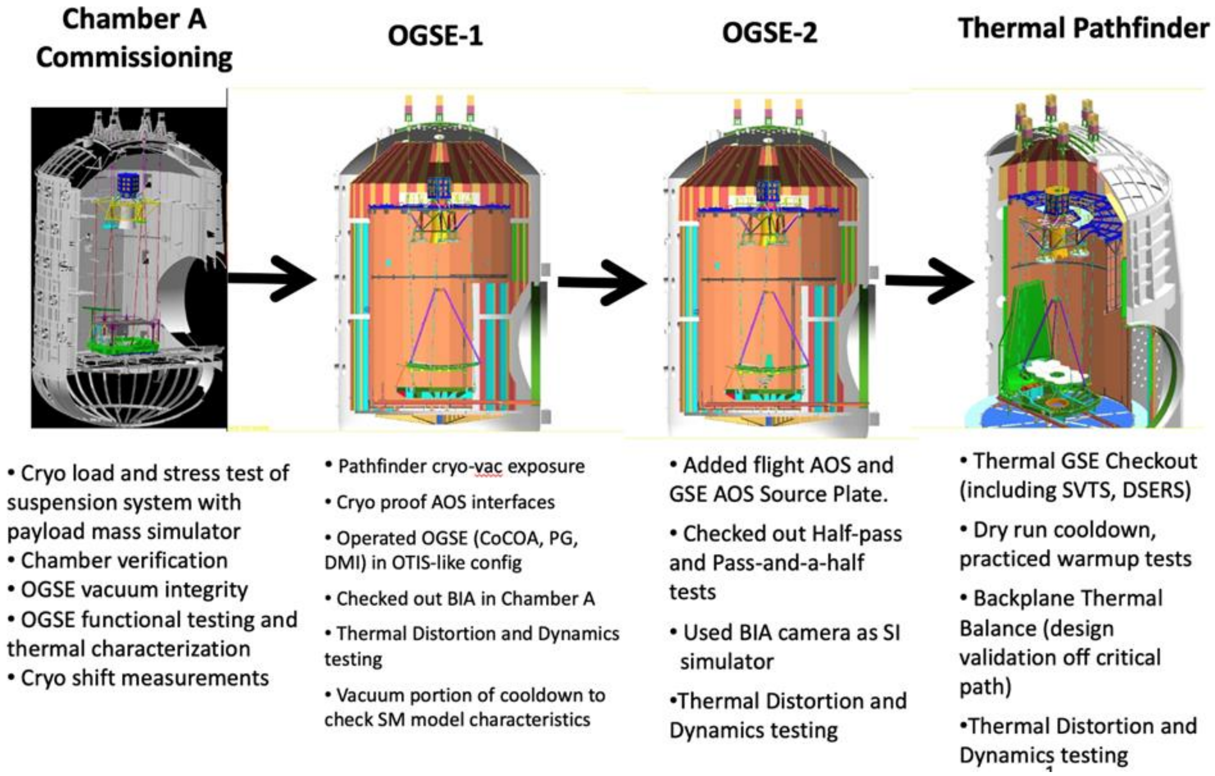
Keywords: JWST, JSC, OTIS, cleanroom, Chamber A, air cleanliness, cryogenic thermal vacuum test

1. INTRODUCTION

Robust, reliable design and operation of the cleanroom and Chamber A vacuum test facilities at Johnson Space Center (JSC) were critical to the OTIS (Optical Telescope Element-Integrated Science Instrument Module) system performance during cryogenic testing and later on-orbit activities. Optical system throughput and stray light performance is directly tied to particulate and molecular cleanliness levels, and the NIRSpec Instrument Microshutter Array (MSA) could be permanently damaged if exposed to a relative humidity (RH) environment >60%. As a result, the cleanroom design was driven by the need to adhere to strict cleanliness and environmental control requirements while allowing the extremely challenging OTIS test program to proceed without compromising system performance. To allow for a seamless, and clean transition of OTIS from pre-test operations into the chamber for cryogenic test operations, the cleanroom was built such that it directly attached to Chamber A. Both the new cleanroom and the upgraded chamber systems provided clean ISO 7[1], conditioned air and redundant environmental control from two independent make-up air and filtration systems. As a result, customized cleanroom and chamber operational protocols were developed to facilitate and maintain balanced positive pressure when the chamber door was open to the cleanroom, and when the cleanroom roll up door was opened to bring in the massive support equipment necessary to accommodate OTIS Integration and Test (I&T). Protocols also addressed support equipment cleaning and cleanliness inspections during hardware ingress from an uncontrolled truck lock into the cleanroom. And, Contamination Control Technicians (CCT) were trained to screen all incoming hardware, for not only cleanliness, but vacuum compatibility because most of what was brought into the cleanroom would ultimately end up in Chamber A. In addition to cleanroom protocols, specific protocols were implemented for Chamber A itself, including a thermal vacuum bake-out to reduce volatiles from the previous missions and from the new helium shroud black thermal paint, as well as a top to bottom inspection and cleaning to reduce particle fallout and support mitigation of acrylic adhesive sources.

The cleanroom construction and chamber modifications were complete in early 2014. The risk reduction program, also known as the Pathfinder (PF) test program, commenced just after the Chamber A thermal vacuum bake-out in 2014. It consisted of 4 major tests: Commissioning, Optical Ground Support Equipment (OGSE)-1, OGSE-2 and Thermal Pathfinder (TPF) (Figure 1). There were two short vacuum function tests also, known as the mini-pumpdown and the Pre-OTIS Cryo-Vacuum (CV) vacuum functional test or mini-pumpdown #2 just before the OGSE-1 and OTIS CV tests respectively. The lessons learned about the facility during this period preceding the OTIS CV test would prove to be invaluable to the contamination control (CC) efforts for JWST at JSC.

The purpose of this manuscript is to show how the challenges of this test program were overcome, by describing the processes and protocols put in place. These sufficiently mitigated contamination sources and enabled environmental control systems to consistently meet tight temperature (T) and RH requirements.



- Cryo load and stress test of suspension system with payload mass simulator
- Chamber verification
- OGSE vacuum integrity
- OGSE functional testing and thermal characterization
- Cryo shift measurements

- Pathfinder cryo-vac exposure
- Cryo proof AOS interfaces
- Operated OGSE (CoCOA, PG, DMI) in OTIS-like config
- Checked out BIA in Chamber A
- Thermal Distortion and Dynamics testing
- Vacuum portion of cooldown to check SM model characteristics

- Added flight AOS and GSE AOS Source Plate.
- Checked out Half-pass and Pass-and-a-half tests
- Used BIA camera as SI simulator
- Thermal Distortion and Dynamics testing

- Thermal GSE Checkout (including SVTS, DSERS)
- Dry run cooldown, practiced warmup tests
- Backplane Thermal Balance (design validation off critical path)
- Thermal Distortion and Dynamics testing

Figure 1. PF Test Program (*Drawing credit: NASA*)

2. CLEANROOM

2.1 Cleanroom Description

Cleanroom Floorplan/Hardware and Personnel Ingress & Egress - Despite being built within a pre-existing building, the JWST cleanroom contained 539 m^2 (5800 ft^2) of controlled workspace with roughly 465 m^2 (5000 ft^2) in the main high bay and approximately 74 m^2 (800 ft^2) in equipment room (Figure 2). Big equipment was brought into the high bay by means of a large roll up door while the equipment room utilized a pass through for smaller items and tools. Personnel entered through a gowning room of approximately 37 m^2 (400 ft^2). Once gowned, personnel stepped into an air shower before passing into the cleanroom. Personnel exiting the facility utilized a transfer hallway with double doors leading back into the gowning room.

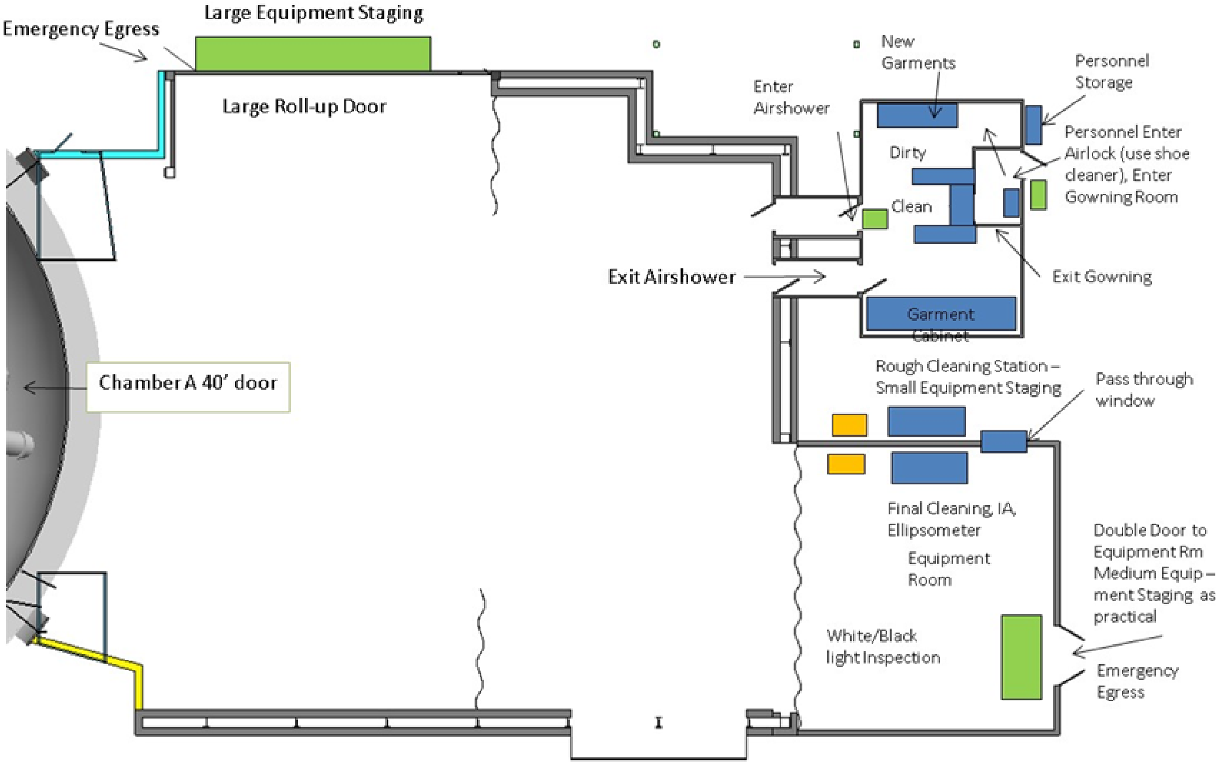


Figure 2. Floorplan of JWST cleanroom attached to Chamber A.[2] (*Drawing credit: NASA*)

Airflow - A top-down, laminar flow design consisting of 179 HEPA filter equipped fan filter units (FFU's) were utilized to fine tune the airflow and provide final stage particle filtration. Together with the FFU's, the make-up air unit (MAU) provided a cleanroom airflow rate of 4.53 million liters per minute (lpm) (160,000 cubic feet per minute (cfm)) and 40 air exchanges an hour, resulting in facility performance which was consistently cleaner than the ISO 7[1] requirement. Figure 3 shows the MAU ducting fed the FFUs in the plenum above the cleanroom. The gowning room is serviced by a small branch duct from the MAU and 9 FFU's to ensure cleanliness and T control on par with the facility. The main return ducts for the cleanroom were located in the North and South walls. The make-up air supply was typically a 60-40 split between plant air and recirculated or return air.

Structural - The cleanroom built to support integration and testing of JWST in building 32 at JSC was designed to provide a constant ISO 7[1] cleanliness standard (Figure 3). Working within the available space in building 32 the cleanroom was constructed using a framework of steel beams welded and bolted to the existing building support columns. An additional steel beam section extended into the cleanroom to support a bridge crane, which was installed to perform the necessary lifts during integration activities. The exterior ceiling was assembled using corrugated metal, and the walls were aluminum honeycomb panels. A series of utility trenches traversed the floor of building 32, and due to space limitations, some of the cleanroom support columns rested on the trench covers requiring additional structural support. To support both integration of JWST hardware and the necessary CV testing, the cleanroom directly attached to JSC's historic Chamber A and accommodated the swing of its 12 m (40 ft) diameter door.

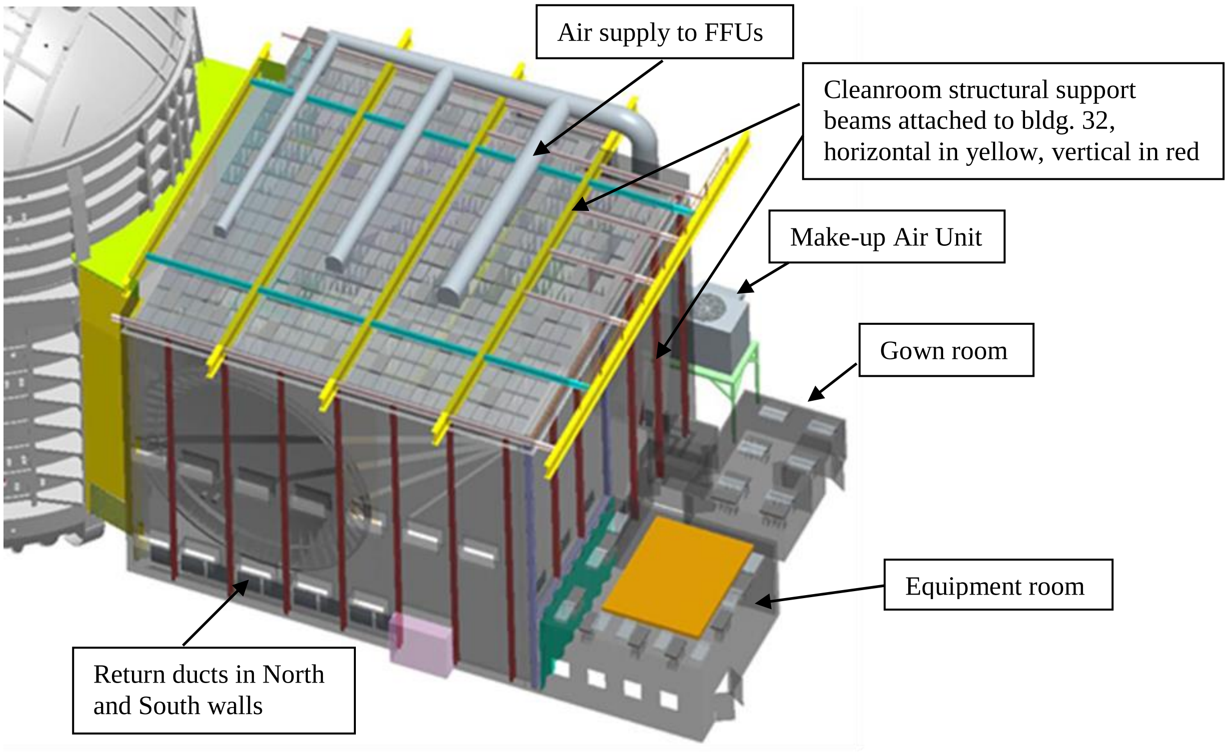
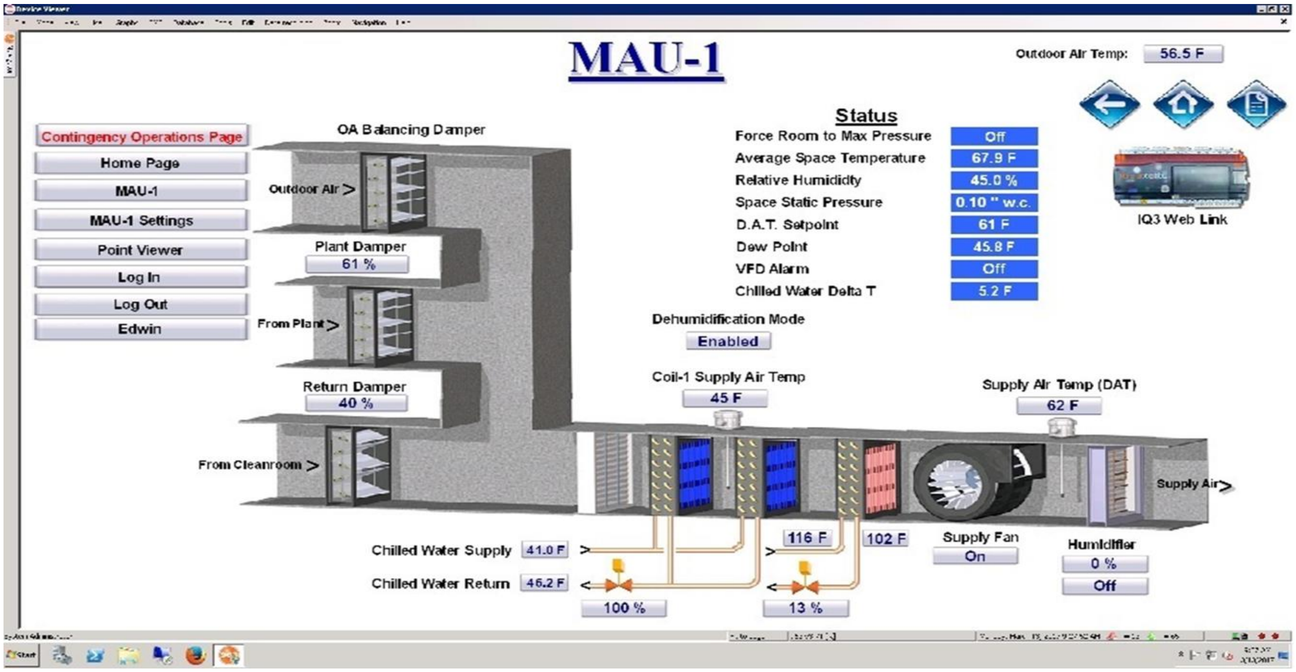


Figure 3. Exterior of cleanroom attached to Chamber A.[3] (*Diagram credit: NASA*)

2.2 Cleanroom Environmental Control

Cleanroom requirements called for T and RH control between 20-32 Celsius (C) (68-73 degrees Fahrenheit (F)) and 40-60% RH. To meet these specifications the cleanroom airflow management system (AFMS) consisted of a single MAU within the building 32 high bay with two chilled water coils requiring 719 lpm (190 gallons per minute (gpm)) flowrate, single hot water reheat coil requiring 76 lpm (20gpm), and a humidifier which utilized electric coils to convert deionized water into steam. To maintain a positive pressure differential of 0.12 mbar (0.05 inches of water column), two modulating dampers constantly adjusted to vary the amount of plant air from the high bay being introduced into the cleanroom. A centralized building automation system (BAS) for the cleanroom modulated chilled and hot water valves, plant air dampers, and the cleanroom humidifier to maintain system set points during changing conditions (Figure 4). When opening the roll up door to pass large hardware into the cleanroom the BAS had a user selectable mode to force the room to maximum pressure to minimize ingress of outside air and particulate. This mode would force both plant air dampers of the MAU to the fully open position without waiting for the system to respond to the pressure drop as the door opens.



Outdoor Air Temp: 56.5 F

Status
Force Room to Max Pressure Off
Average Space Temperature 67.9 F
Relative Humidity 45.0 %
Space Static Pressure 0.10 " w.c.
D.A.T. Setpoint 61 F
Dew Point 45.8 F
VFD Alarm Off
Chilled Water Delta T 5.2 F

Plant Damper 61 %
Return Damper 40 %
Dehumidification Mode Enabled
Coil-1 Supply Air Temp 45 F
Supply Air Temp (DAT) 62 F
Chilled Water Supply 41.0 F
Chilled Water Return 46.2 F
100 %
116 F
102 F
13 %
Supply Fan On
Humidifier 0 %
Off

Figure 4. Control software schematic of cleanroom MAU (*Diagram credit: Performance Controls Group, Houston, TX*)

2.3 Cleanroom Cleanliness Protocols and Monitoring

A comprehensive process was implemented to support control of contamination levels within the JWST cleanroom at JSC. The need for a robust set of cleanroom protocols was driven by the fact that cleanroom footprint was considered to be extremely small for the planned level of activity involving extremely large support equipment (Figure 5). Protocols were developed to specifically address these challenges as well as the stringent OTIS cleanliness requirements. These protocols included continuous airborne particle counting and monitoring, particle and non-volatile residue (NVR) fallout monitoring, daily monitoring of positive pressure, daily cleaning of floors and equipment as well as monthly (or as needed) white and black light inspections. Prior to each major test, airborne hydrocarbons were measured and there was a requirement to measure sulfur dioxide and hydrogen sulfide prior to the arrival of flight hardware due to the significant number of chemical processing plants in Houston.

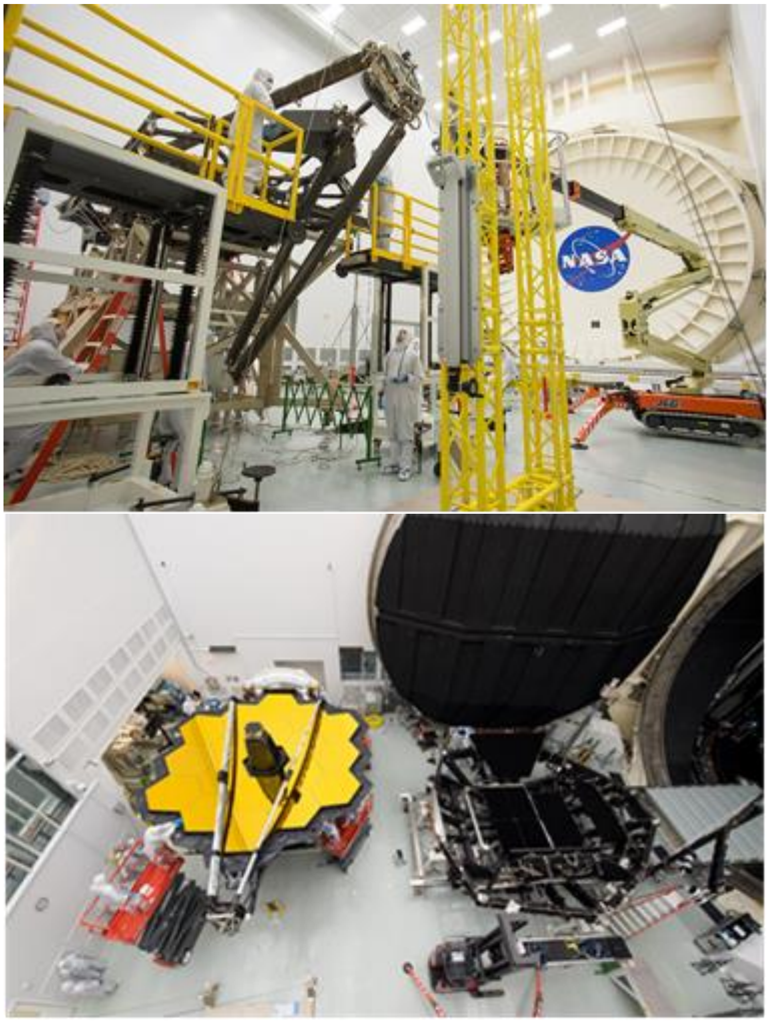


Figure 5. Very crowded JWST cleanroom at JSC during PF and OTIS Testing (*Photo credit: NASA/Chris Gunn*)

Continuous Particle Count Monitoring/Software – Initial airborne particle count monitoring was conducted with a pair of Lighthouse Solair 3100 units which soon proved to be a less than ideal system due to difficulties and expense to enable distributed alarms and remote downloads via NASA network requirements. A new system consisting of 3 Particle Measuring Systems Solair 310P remote counters and accompanying software was deployed. The Solair system proved easier to configure for network use, alarm distribution, and provided a means to capture the minute-by-minute particle count data on hard drives capable of storing the almost 200,000 data points per month. The data feed from the networked counters displayed on monitors at the cleanroom facility manager's desk; this data included information regarding alarm status, counter status, and graphs of particle count data which continuously updated allowing immediate visual feedback of real-time particle counts. A total of 4 Solair 310P units were deployed, 3 of which were located along the north, south, and east walls of the cleanroom with a 4th on level 7 of the building where the AFMS supply duct connects to the chamber, just upstream of the COV-1535 vacuum isolation valve.

Particle and NVR fallout monitoring – Particles and NVR were monitored continuously throughout the PF and OTIS CV test campaigns at JSC. Particle and NVR foil samples were place throughout the cleanroom in locations varying from high to low activity (Figure 6). Silicon wafers used to capture particles were measured by Image Analysis (IA) for percent area coverage (PAC) and NVR foils were used for gravimetric analysis of NVR.

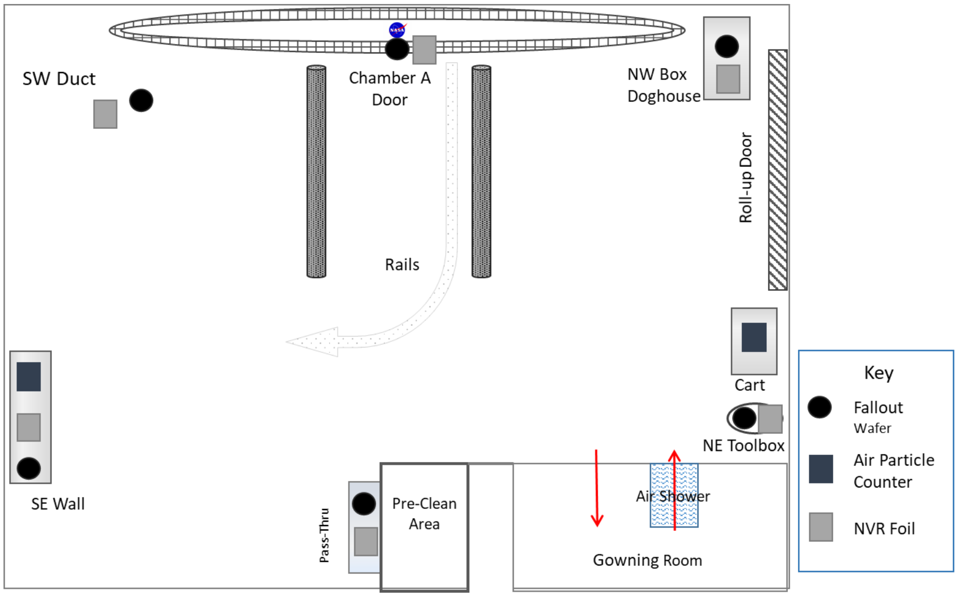


Figure 6. JSC JWST cleanroom layout and sample map (*Drawing credit: NASA/Alan Abeel*)

Monitoring of Positive Pressure – See Section 4.0

Cleanroom Garments – Full cleanroom garments were required to enter the cleanroom and/or the chamber. Initially, garments were changed out once per week. Increasing activity caused an escalation particle fallout rates, so the frequency of garment replacement was changed to twice per week. Face masks and gloves were required. Gloves were taped to sleeves using an approved cuff sealing tape to minimize contamination from exposed skin.

Cleanroom Cleaning Processes and Schedule – Throughout the PF and OTIS test programs, the cleanroom was cleaned and inspected on a regular basis. The entire room was cleaned (crane, walls, floors, support equipment, the exterior of Chamber A exposed to the cleanroom, etc.) just prior to the beginning of PF testing. Before OTIS arrived, the room was cleaned again from top to bottom. For maintenance cleaning, the floors, horizontal surfaces (work surfaces, cabinets, etc.) and support equipment were cleaned on a daily basis prior to the first shift. HEPA filtered vacuums, cleanroom approved mops (hydrophilic polyester) and sealed edge polyester wipers were used to perform this cleaning, along with a 50/50 blend of isopropyl alcohol (IPA) and deionized water. The floors were inspected on a daily basis for acrylic adhesive (from aluminum tape used to secure cables), and if found, it was removed immediately with acetone. Prior to air-bearing operations, floors and equipment were re-cleaned. Prior to all lift operations, lift hardware and hardware to be hoisted were inspected with white and black light and cleaned as necessary before the operation commenced. Any type of operation that involved generation of particles was either contained in a custom made “tent” and/or performed with a HEPA filtered vacuum held nearby to capture the contamination.

2.4 Cleanroom environmental control reliability and cleanliness

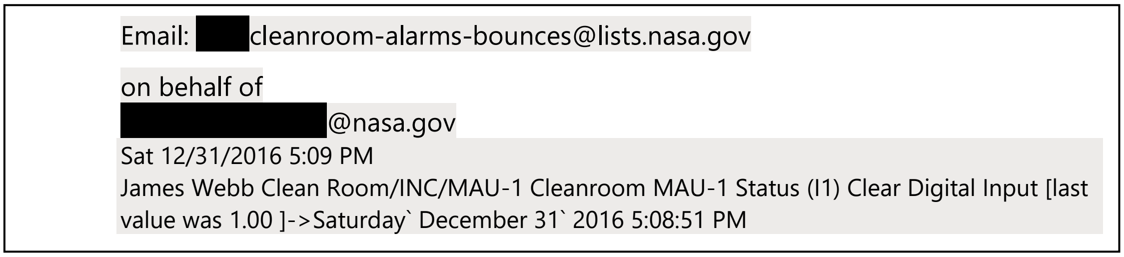
Lesson learned from 2015 weather event – Just after the OGSE-1 test was complete, a major thunderstorm hit Houston. Unfortunately, the variable fan drive (VFD) fuses were blown during a lightning event that affected several load centers that distributed power throughout building 32. The cleanroom back-up power was initiated prior to that of the chamber, which resulted in a lower pressure in the cleanroom. That resulted in the need for 100% make-up air from the cleanroom MAU. At 100% make-up air, the cleanroom struggled to maintain control of RH. As a result of this condition, special protocols were developed that required chamber man lock doors to be closed and access through the large cleanroom roll up door was not allowed until the chamber AFMS system was restored to nominal operation. In addition, a backup VFD unit and replacement fuses were procured for the MAU to avoid down time in the event of another power outage caused by weather.

Chilled Water Supply - The chilled water supply provided to building 32 and the new cleanroom was a single source supply. Due to Center-wide chilled water demand at JSC in the humid conditions of Houston, the chilled water flow rate and T would often fluctuate. To reduce the probability of an out of spec humidity issue, a specialized controls program was written within the BAS software to monitor the chilled water T for excursions above 7.2 C (45 F). When the chilled water supply T exceeded 7.2 C, a 5-minute software timer was triggered. If, at the expiration of the timer the chilled water had not fallen below 7.2 C, the control program sent a shutdown command to the MAU. With the MAU shut down, there is typically a 2-hour window that enabled troubleshooting before humidity exceeded specifications. Fortunately, most short-term chilled water supply T increases caused by plant chillers falling offline were rectified in 5 – 30 minutes after backup units were activated. When the air handler controlled by automation software is shutdown, all motorized valves would default to the closed position. The needs of the cleanroom dictated a modification to that standard so the chilled water valve would remain open and allow flow past the T sensor enabling feedback to the BAS software, and an automated restart of the MAU as chilled water temperatures fell below 7.2 C. The result was a fully automated safe mode that would decrease the RH rate of rise while self-monitoring for a safe restart and transmitting alarms to a call tree of people who could stand ready to safe hardware and respond to root cause of increased chilled water supply T.

Cleanroom Environmental Control Redundancy – Instability in the critical utility delivery to cleanroom air handlers due to severe weather, necessitated the development of a stand-alone redundant system that could provide conditioned air in the event of equipment failure, utility disruption, or other system failure. To back up the cleanroom AFMS a large system (Figure 7) was acquired consisting of 4 direct expansion cooling units coupled with two mechanical dehumidifiers and a 65kw electric heater. Power was provided by a trailer mounted diesel generator with external fuel tank enabling approximately 12 hours of run time before refueling. The units were arranged in a serial configuration with the cooling unit feeding into the dehumidifier before entering the heater. From the heater, approximately 283,169 lpm (10,000 cfm) of airflow was ducted into a manifold which could be attached directly to the cleanroom MAU. When operating on the backup system the plant dampers were de-coupled from their motors and locked in the fully open position. The chilled and hot water valves were closed via the BAS software and the MAU fans remained active.

Figure 7. Cleanroom backup AFMS (*Photo credit: NASA/Edwin Goldman*)

Cleanroom Alarms – Given the sensitivity of Webb’s science instruments, optics, and composite structures it was necessary to establish a robust alarm scheme for T, RH, particle counts, and critical utility supply status. The cleanroom facility manager identified critical utility supply parameters, yellow/red limits for particle counts, and worked with JWST information technology (IT) staff to gain the required network infrastructure that would allow for a system of broadcast alarms via email and text messaging. Utilizing existing NASA systems for creating targeted email lists, a specific account was established to allow key members of the Webb team (including Safety, OTIS, Quality Assurance, and Facility Managers) to receive system alarms from the cleanroom 24 hours a day, 7 days a week. This ensured a rapid response to any facility issues. Using cell phone numbers from the newly established alarm distribution list, the cleanroom facility manager programmed the BAS to generate outbound system alarms for T, RH, system on/off status, chilled water supply T, VFD status, and send them via email and text to the group. The data stream distributed via the BAS could cause significant confusion as parameters such as fan state were expressed in binary code. The archived alarm captured in (Figure 8) is signifying a restart of the MAU stating the previous digital state has cleared and the value of 1 represents a restart of the cleanroom MAU main fans.



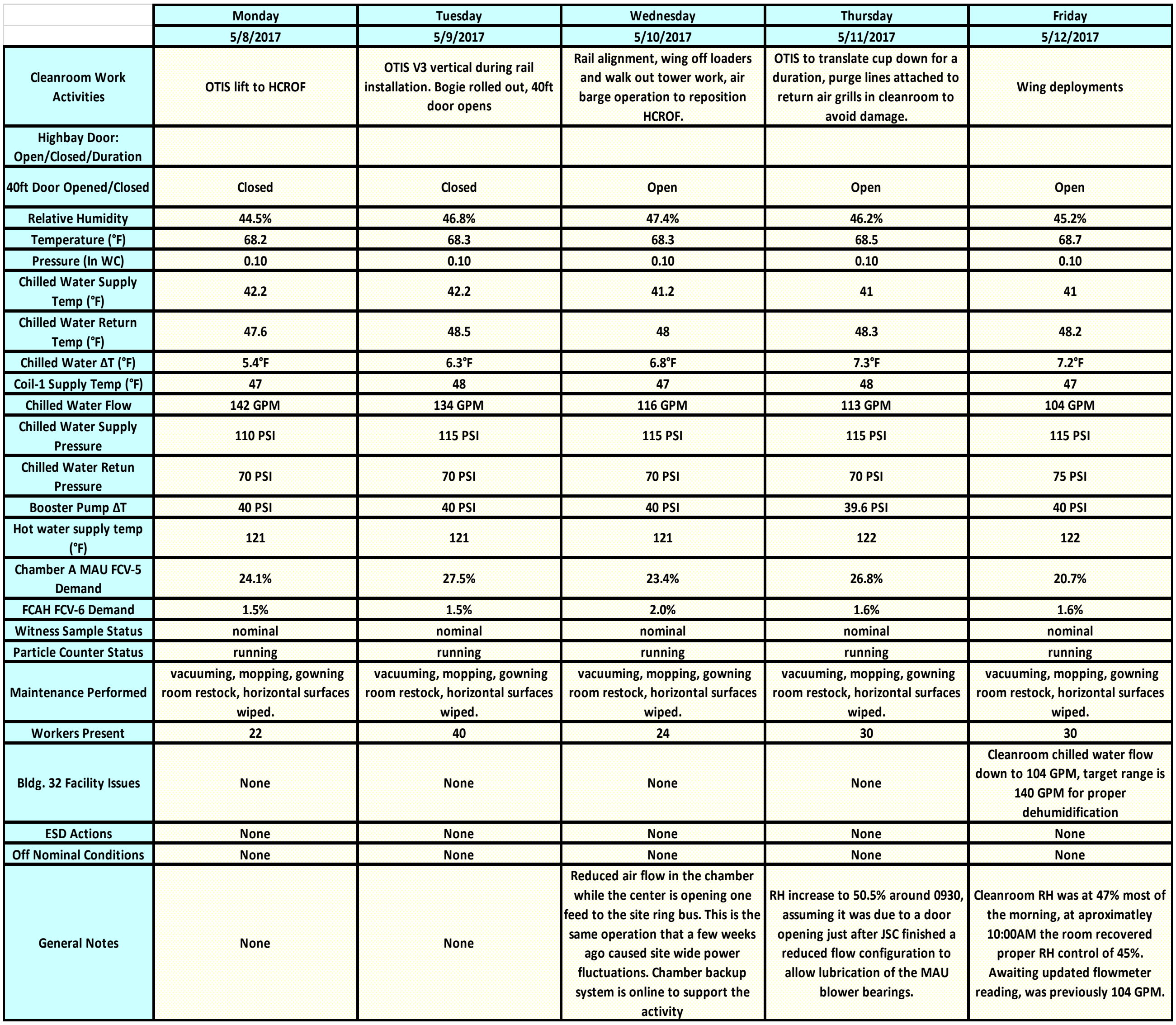
Email: [redacted]cleanroom-alarms-bounces@lists.nasa.gov

on behalf of
[redacted]@nasa.gov
Sat 12/31/2016 5:09 PM
James Webb Clean Room/INC/MAU-1 Cleanroom MAU-1 Status (I1) Clear Digital Input [last value was 1.00]->Saturday` December 31` 2016 5:08:51 PM

Figure 8. Example of alarm email sent to program distribution list

Particle count alarms were distributed in a similar manner but to a smaller distribution list consisting mainly of Contamination Control Engineers (CCE’s) and generated by the Particle Measuring Systems software. Yellow alarm particle count limits were defined as meeting or exceeding 75% of the ISO 7[1] maximum allowable for 0.5µ particles in 5 consecutive samples, while the red alarm would trigger upon reaching 100% of the ISO 7[1] maximum allowable for 0.5µ particles in a period of 3 samples. The particle count system consisted of 3 Particle Measuring Systems ISOAIR 310P units which continually sampled without a hold time; this enabled the contamination control team to monitor the particle counts real-time and correlate specific activities to spikes in particle counts. The impact of extended door openings, crane rigging, and other I&T tasks could be examined immediately and if needed the activity could be placed on stand down before risking a major impact to the integrity of the cleanroom environment.

Weekly logs – Weekly logs (Figure 9) were implemented to document activities and ensure T, RH, pressure, and particle counts remained within specification. The parameters that were tracked were based on operations and facility infrastructure performance that could trigger alarms for these conditions. The chilled water T and flow rate had the most significant effect on the T and RH and in the cleanroom. I&T operations, number of personnel, frequency of cleanliness maintenance, as well as the open/close configuration of the 40’ chamber door and roll up door affected particle counts.



	Monday	Tuesday	Wednesday	Thursday	Friday
	5/8/2017	5/9/2017	5/10/2017	5/11/2017	5/12/2017
Cleanroom Work Activities	OTIS lift to HCROF	OTIS V3 vertical during rail installation. Bogie rolled out, 40ft door opens	Rail alignment, wing off loaders and walk out tower work, air barge operation to reposition HCROF.	OTIS to translate cup down for a duration, purge lines attached to return air grills in cleanroom to avoid damage.	Wing deployments
Highbay Door: Open/Closed/Duration					
40ft Door Opened/Closed	Closed	Closed	Open	Open	Open
Relative Humidity	44.5%	46.8%	47.4%	46.2%	45.2%
Temperature (°F)	68.2	68.3	68.3	68.5	68.7
Pressure (In WC)	0.10	0.10	0.10	0.10	0.10
Chilled Water Supply Temp (°F)	42.2	42.2	41.2	41	41
Chilled Water Return Temp (°F)	47.6	48.5	48	48.3	48.2
Chilled Water ΔT (°F)	5.4°F	6.3°F	6.8°F	7.3°F	7.2°F
Coil-1 Supply Temp (°F)	47	48	47	48	47
Chilled Water Flow	142 GPM	134 GPM	116 GPM	113 GPM	104 GPM
Chilled Water Supply Pressure	110 PSI	115 PSI	115 PSI	115 PSI	115 PSI
Chilled Water Retun Pressure	70 PSI	70 PSI	70 PSI	70 PSI	75 PSI
Booster Pump ΔT	40 PSI	40 PSI	40 PSI	39.6 PSI	40 PSI
Hot water supply temp (°F)	121	121	121	122	122
Chamber A MAU FCV-5 Demand	24.1%	27.5%	23.4%	26.8%	20.7%
FCAH FCV-6 Demand	1.5%	1.5%	2.0%	1.6%	1.6%
Witness Sample Status	nominal	nominal	nominal	nominal	nominal
Particle Counter Status	running	running	running	running	running
Maintenance Performed	vacuuming, mopping, gowning room restock, horizontal surfaces wiped.	vacuuming, mopping, gowning room restock, horizontal surfaces wiped.	vacuuming, mopping, gowning room restock, horizontal surfaces wiped.	vacuuming, mopping, gowning room restock, horizontal surfaces wiped.	vacuuming, mopping, gowning room restock, horizontal surfaces wiped.
Workers Present	22	40	24	30	30
Bldg. 32 Facility Issues	None	None	None	None	Cleanroom chilled water flow down to 104 GPM, target range is 140 GPM for proper dehumidification
ESD Actions	None	None	None	None	None
Off Nominal Conditions	None	None	None	None	None
General Notes	None	None	Reduced air flow in the chamber while the center is opening one feed to the site ring bus. This is the same operation that a few weeks ago caused site wide power fluctuations. Chamber backup system is online to support the activity	RH increase to 50.5% around 0930, assuming it was due to a door opening just after JSC finished a reduced flow configuration to allow lubrication of the MAU blower bearings.	Cleanroom RH was at 47% most of the morning, at aproximatley 10:00AM the room recovered proper RH control of 45%. Awaiting updated flowmeter reading, was previously 104 GPM.

Figure 9. Example of weekly cleanroom status and activity log

3. CHAMBER A

3.1 Chamber A Description

Chamber A towers almost 7 stories above the flat prairie land which JSC sits atop. Chamber A is a veteran of the space race and is deemed a National Historic Landmark for its contributions to some of the most important NASA programs from Apollo to Space Station. The OTIS CV test required significant upgrades to Chamber A to maintain the stringent cleanliness, T, and pressure requirements needed to successfully simulate the deep space environment in which JWST operates.

The transition to high vacuum was handled by an array of oil diffusion pumps which, due to their risk of back streaming required replacement; back streaming of oil could have a disastrous effect on the exposed optics and critical systems of JWST. A combination of turbo molecular and cryogenic pumps were installed to reach high vacuum in a safe and efficient manner.

The existing liquid nitrogen shrouds would remain, but a massive new helium shroud measuring 14 m (45 ft) in diameter and 24 m (80 ft) tall was installed to control temperatures within its volume to 40 Kelvin. Openings atop the helium shroud were created for the Center of Curvature Optical Array (COCOA) and ISO 7[1] clean airflow supply ducting.

As shown in Figure 10, Level 1 is where the test hardware resided and just below it is the plenum. Above Level 1 is Level 3, which consists of a catwalk exterior to the helium shroud. Level 5 is on top of the helium shroud, where the COCOA is located. Above Level 5 is the space above the nitrogen shroud known as the “circus tent.”

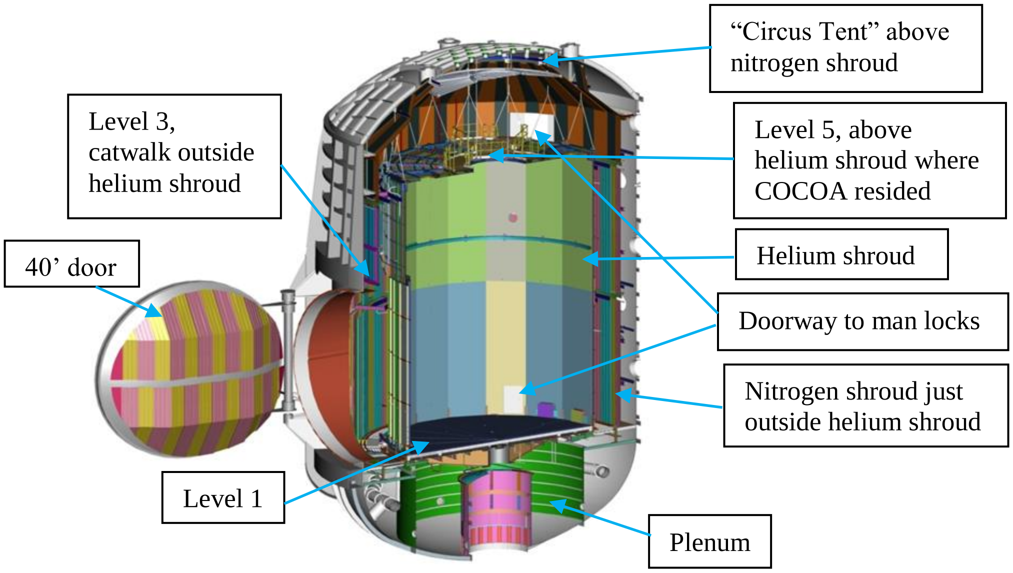


Figure 10. Diagram of Chamber A (*Diagram credit: NASA*)

3.2 Chamber A Environmental Control

Like the Cleanroom, Chamber A requirements called for T and RH control in the ranges of 20-23 C (68-73 F) and 40-60% RH. To meet these requirements, Chamber A was outfitted with a Heating, Ventilation and Air Conditioning (HVAC) system, called the AFMS, independent of the building 32 and Cleanroom systems. The AFMS circulates a large amount of temperature controlled, humidity controlled, and HEPA filtered air through the chamber whenever it is at ambient pressure. A MAU is also included to thermally condition, dehumidify and filter particulate and hydrocarbons from outside air before it is allowed to enter the AFMS. The MAU is instrumental in retaining a positive internal pressure on the chamber volume and for filtering fresh air during chamber purges following a dry nitrogen repress. The result is a chamber that is controlled to better than Class 10,000 (ISO Class 7[1]) clean room conditions.[4]

The MAU is located on the roof of the 3rd floor of building 32. This unit consisted of pre-filters, chilled water coils, reheat coils, HEPA filter banks, and a humidifier. This unit provided conditioning of outside air and ducted the air to the 2nd floor where a second unit known as the Filter Coil Air Handler (FCAH) was installed.

The FCAH was designed to provide additional conditioning and HEPA filtration of air prior to traveling to the 1st floor where a large blower produced the necessary movement of conditioned air to the 7th floor prior to entry into the chamber by way of a motorized gate valve which would be closed to isolate the chamber while under vacuum (Figures 11 and 12). During ambient operations the airflow would pass the open gate valve and enter the chamber through multiple penetrations through the ceiling of the helium shroud. At each penetration point in the helium shroud, a diffuser was installed to minimize eddy currents and achieve laminar flow. The return ducts were in the lower plenum.

The AFMS was monitoring continuously for T and RH as well as particle counts during ambient operations. T and RH probes are located in supply and return ducting. Particle counters were installed in the supply ducting downstream of the blower on the first floor, another in the return duct on the first floor, and two were located inside the chamber helium shroud on the North and South sides.

3.3 Chamber A environmental control reliability and cleanliness

Lesson learned after OGSE-1 – Due to leaks in the recirculation segment of the AFMS ducting, high particle counts were observed after the OGSE-1 test while purging the chamber to remove nitrogen. To correct this issue, only the MAU (with no recirculation) in “purge mode” (Figure 11) was used to purge the chamber after re-pressurization in following tests. In addition, when the MAU shut down during a power outage caused by the 2015 thunderstorm, there was a slight negative pressure within the AFMS. It was discovered that when the MAU shuts down, the MAU intake louvers close immediately, while the blower fan downstream continues to rotate to a slow stop. This caused the negative pressure and a spike in the AFMS system particle counts.

Chamber AFMS inspections - In order to ensure particle count fallout goals would consistently be met during PF and OTIS CV tests, a “due diligence” inspection of the entire Chamber A AFMS was conducted. The MAU was the first item to be inspected. A few leaks were discovered in the housing, which were subsequently repaired. The filters in the chamber MAU were checked with a particle counter and found to be in good condition with the exception of a few leaks where the HEPA filters were damaged, which were later replaced. Next, an inspection of the FCAH and its plenum was conducted. The FCAH filters were also found to be acceptable, but there was some contamination found in the FCAH plenum that had built up in a system recirculation mode that was no longer used. The area was cleaned and returned to visibly clean criteria. Finally, accessible areas of the supply ducting downstream of the FCAH were inspected through available duct ports. Figure 12 shows the ducting on the 7th floor that leads to the chamber air inlet gate valve. The cleanroom facility manager is inspecting the interior of the ducting with a borescope.

Gaseous Nitrogen Re-pressurization Filter - To further reduce the potential for particle build up, a 0.5 micron filter was added to the gaseous nitrogen re-pressurization system of the chamber.

Environmental control redundancy - A standalone backup AFMS system was placed on the 3rd floor roof and connected to the Chamber A air handler. The system provided conditioned air via a modular system of direct expansion air conditioners and separate dehumidifiers in series which would force air through the chamber AFMS system. A custom-made plenum was manufactured and placed over the main air intake of the Chamber A air handler that served as a point of connection for the backup systems duct work while allowing nominal airflow to the main air handler when not relying on the backup system.

Chamber AFMS Alarms – Chamber A’s AFMS had set-points and alarms to maintain the aforementioned T and RH requirements of the PF hardware and OTIS flight hardware. Particle count and pressure differential alarms were also added to the system after the initial negative pressure event.

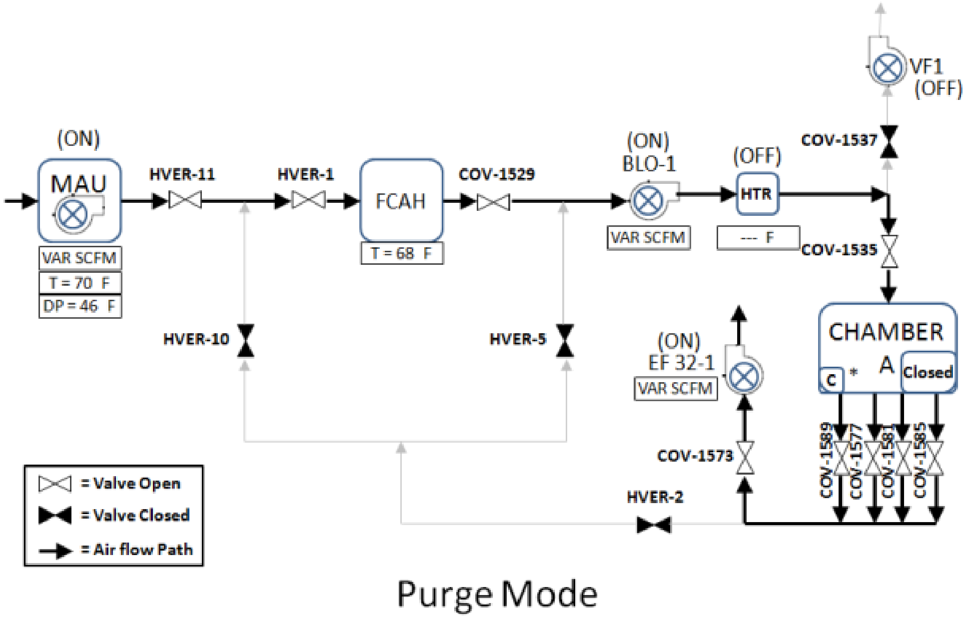


Figure 11. Schematic of Chamber A AFMS in purge mode, and MAU, FCAH, blower, and gate valve locations.[5] (*Diagram credit: NASA*)

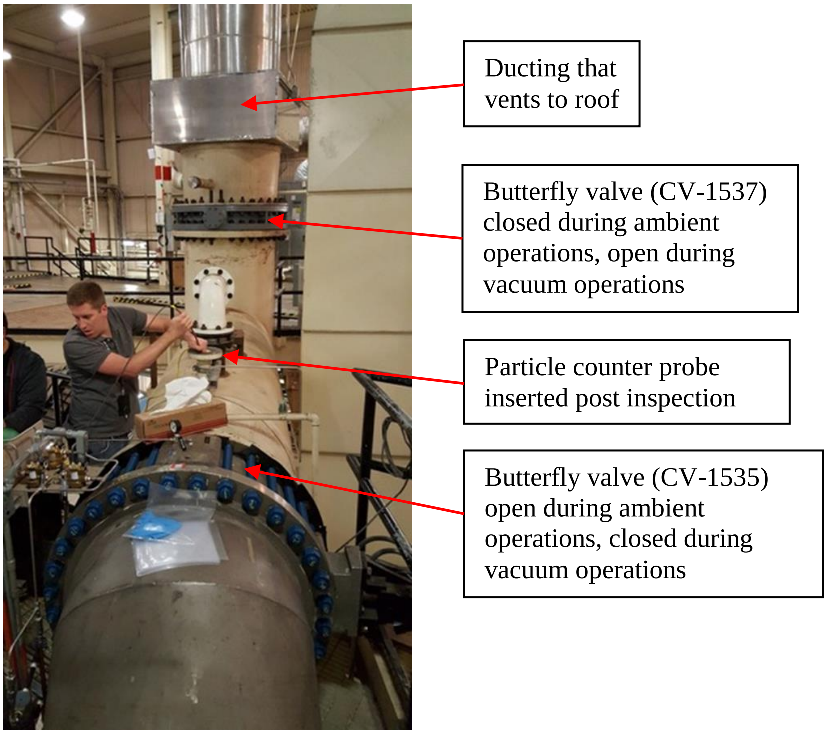


Figure 12. Photograph of technician inspecting interior of chamber AFMS ducting with borescope (*Photo credit: NASA/Joe Ward*)

Chamber inspection and cleaning – Particulate and debris contamination was discovered during initial CC inspections of the chamber. Some was attributed to previous tests conducted in Chamber A, but most was created during modifications made to accommodate OTIS testing. Metal shavings were generated during helium shroud and support equipment installation, nitrogen shroud modifications (conducted prior to PF and OTIS tests), and temporary scaffolding installation. There were black thermal paint flakes from surfaces inside the helium shroud that had not been prepared properly prior to painting or were affected by coefficient of thermal expansion (CTE) differences between the paint and the substrate during cryogenic testing. Dust was also found in areas that were typically hidden, or difficult to access. The main sources of metal debris contamination however appeared to be from work conducted in the upper levels of the chamber, descending to the lower levels. As a result, most of this debris was localized, and was found on horizontal surfaces directly below the location where the work was performed. Unfortunately, there were many surfaces in the chamber that could not be accessed, so the cleaning and removal of debris was a "best effort" endeavor.

Major chamber cleaning was conducted two times, just before the first "mini-pumpdown," and before the pre-OTIS CV vacuum functional test or "mini-pumpdown 2." There were approximately 20 CC technicians that supported the effort each time. From the very top of the nitrogen shroud in the "circus tent," to the bottom of the chamber in the plenum, technicians cleaned all of the interior chamber shell, as well as interior and exterior nitrogen and helium shroud surfaces. This included walls, floors, support structures, ledges, cable trays, and supply tubing. Steel plate floors and catwalk gratings were removed so surfaces underneath could be thoroughly cleaned (Figure 13). Technicians crawled into small and confined spaces (which required special training) while wearing full bunny suits and carrying cleaning equipment. During the cleaning process on all levels, CC technicians were responsible for repairing, sealing or removing, and cleaning peeling tape and damaged multi-layered insulation on support equipment and chamber supply tubing. They also inspected for peeling paint or any other potential source of contamination and reported it to the lead Contamination Control Engineer for resolution. During the cleaning, extra caution was exercised near installed optical alignment support equipment.

Cleaning tools included cleanroom mops, HEPA filtered vacuums, wipes and the 50/50 IPA and deionized water blend discussed in Section 1.3. Extension poles were designed and fabricated to bridge the gap between personnel catwalk platforms so that most of the interior and exterior of the nitrogen and helium shrouds could be reached. Surfaces were vacuumed first, followed by solvent wiping or mopping. After cleaning, surfaces were inspected with both white and ultraviolet flashlights. Maintenance cleaning of floors and accessible equipment continued to be performed on a daily basis on level 1, level 5, and in high traffic areas as was done for the cleanroom described in Section 1.3. Also, before each test, technicians were hoisted up inside the helium shroud on a man lift to inspect for and remove contamination and any indication of peeling paint, tape, or acrylic adhesive.

Figure 13. CC technicians cleaning areas under floor grating on level 5 (*Photo credit: NASA/Joe Ward*)

3.4 Chamber thermal vacuum bake-out and black thermal paint

In order to ensure that the prototype hardware and ultimately the OTIS flight hardware, met their cleanliness requirements during cryogenic thermal vacuum testing in Chamber A, a high T bake-out of the Chamber and support equipment was required. Most of the structural support equipment, and all internal surfaces of the helium shroud were painted with a black thermal paint. Early on, after sampling a painted GSE surface and the helium shroud, examination of test data and material safety data sheets revealed that the coating contained tri-phenyl phosphate (TPP). Tri-phenyl phosphate is a high outgassing plasticizer commonly used as a flame retardant. Further investigation revealed that the source of the TPP was the two-part primer used on the substrate under the black thermal paint, which would later seep into the pores of the thermal paint after coating the primed surface. With a vapor pressure of 1e-06 Torr at 25^{o}C, there was a concern that the TPP would be a significant source of volatile material under the expected vacuum test conditions. In addition, early sampling indicated that there was residual methyl silicone in the plenum of Chamber A from previous testing. For this reason, and to reduce volatile from other sources (e.g., cabling, lubricated hardware, residual cutting fluids, etc.), the bake-out was conducted at 60^{o}C and 5e-05 Torr for approximately 25 days.

3.5 Acrylic Adhesive Fracture and Mitigation

During inspection of support equipment after one of the initial cryogenic risk reduction tests that preceded the OTIS CV test, acrylic adhesive was discovered on various surfaces. With a glass transition T of -40^{o}C, 966 became brittle at cryogenic temperatures, fractured, and generated particles (Figure 14). In some cases, tape would peel (Figures 15), or delaminate and completely lose its backing (Figure 16). Independent testing directed by the program[6] revealed that the fracturing phenomenon occurs with tape, film adhesive, and tape residues and becomes more severe with each cryo-cycle. The cleanliness of the substrate and how well the tape was burnished to the surface played a role in the adhesion failure. Both the independent study and Chamber A post-test inspections showed that the film adhesive and regular Kapton tape exhibit brittle fracture and minor delamination, but did not exhibit particle shedding as readily as the black Kapton tape. As the adhesive passes through its glass transition T during cycling or cool down, it fractures into extremely small particle sized adhesive (Figure 17) or a geometrically shaped larger feature ranging in size from approximately 50 to 3000 microns (Figure 14).

Mitigation techniques implemented included switching from black Kapton to uncoated Kapton where possible, thoroughly cleaning and burnishing the tape to the surface, and using tie wraps to secure tape around cylindrical structures. Aluminum tape also appeared to perform better than black Kapton tape, so in some cases black Kapton was replaced with aluminum tape. All of these mitigations were implemented for the TPF test, the last cryogenic test performed prior to the OTIS CV test. Post-test TPF inspections on surrogate samples revealed significantly reduced adhesive acrylic contamination levels compared to previous tests. In fact, any remaining acrylic adhesive particles were treated as dust particles in order to assess the potential impact of this contamination if it were to occur during the OTIS CV test. The estimated percent area coverage from it was 0.0055, significantly less than the requirement for OTIS CV testing at 0.10 PAC.

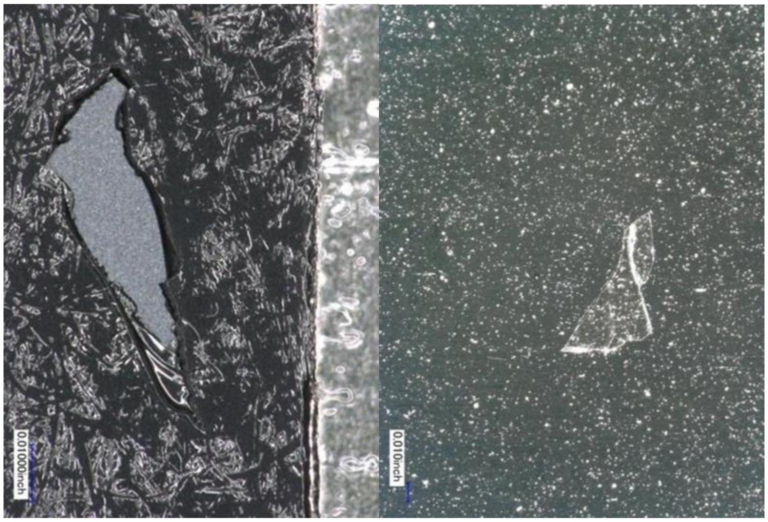


Figure 14. Black Kapton tape adhesive missing/fractured after exposure to cryogenic temperatures in vacuum. (*Photo credit: NASA)*

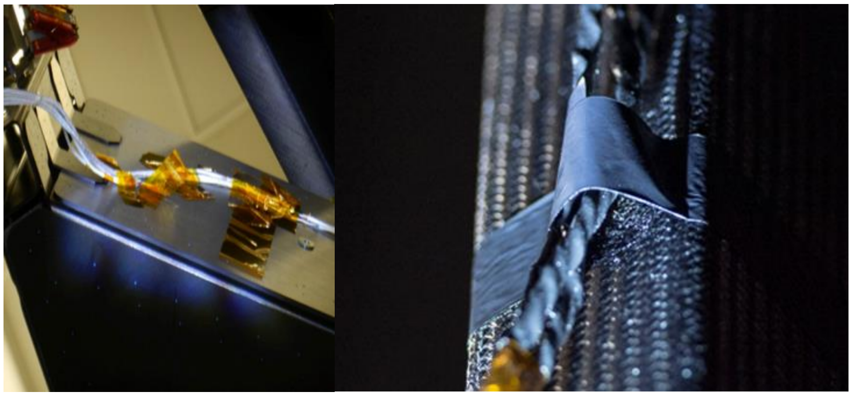


Figure 15. Tape peeling from GSE after exposure to cryogenic T in vacuum. (*Photo credit NASA/Chris Gunn*)

Figure 16. Tape backing completely delaminated from adhesive after exposure to cryogenic T in vacuum. (*Photo credit: NASA/Joe Ward*)

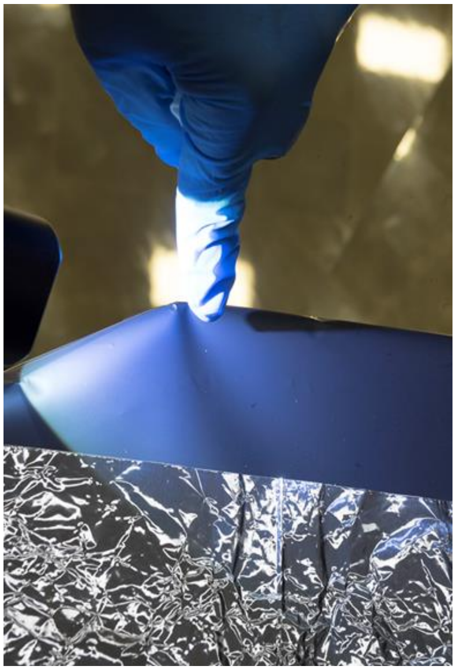


Figure 17. Extremely small acrylic adhesive particle found on support equipment after cryogenic testing (*Photo credit: NASA/Chris Gunn*)

4. BALANCING THE CLEANROOM AND CHAMBER A AIRFLOW SYSTEMS TO MAINTAIN POSITIVE PRESSURE

Maintaining the necessary 0.05 inches w.c. positive pressure differential in the cleanroom while the 40’ door of Chamber A was open was a delicate balance. Despite the airflow supplied by the chamber AFMS and the cleanroom MAU, the cleanroom could suffer positive pressure issues. The chamber had 3 separate man locks for entry into the chamber on level 1, 3 and 5. All 3 doors were equipped with seals and latches which maintained vacuum integrity, but were not closed during ambient operations due to the presence of temporary power cords. It was soon determined that when the 40’ chamber door was open to the cleanroom, dramatic swings in cleanroom positive pressure would coincide with how far the exterior man lock doors were opened. Based on testing conducted early in the program, a protocol was implemented requiring the man lock doors to be placed within 6 inches of the closed position. The testing also indicated that if the man lock doors were completely closed while the 40’ door was open, the two volumes would over pressurize causing the cleanroom roll up door to bulge outward more than usual. Given the volume of work constantly occurring in the chamber and the multiple working groups involved, it was common practice to check the open/close status of each door to ensure the pressure remained within the required range of 0.05 to 1.0 inches of water as shown on the cleanroom systems pressure panel (Figure 18). Before the large cleanroom roll up door was allowed to be opened, technicians checked to ensure the pressure was at or above the minimum pressure level to avoid a drastic decrease in positive pressure or a negative pressure issue in the cleanroom, and also, the man lock doors had to remain open to the 6 inch position until the 40’ chamber door was closed for testing to avoid over pressurizing the cleanroom. Figure 18 shows the pressure panel used to monitor cleanroom pressures.

Upon delivery of the flight hardware ahead of the OTIS CV test another protocol was implemented to further protect cleanroom pressure during roll up door operations. The cleanroom BAS was programmed with a software button to force the room to maximum pressure by overriding the modulation of the motorized plant air intake dampers and commanding them to their 100% open position. The resulting increase in positive pressure differential prior to opening the door was intricately timed with one member of the contamination control team standing by at the roll up door controls on a radio awaiting a call to open the door from the cleanroom facility engineer at the BAS user station. Precise timing and communication were required due to the risk of over pressurization that could result in blowing the roll up door off its tracks. This method was preferred in the presence of flight hardware rather than relying on the cleanroom pressure sensor to signal the pressure drop from a door opening and command the plant dampers to open. This way, the cleanroom maintained a slight outflow of air to the ambient environment which minimized the ingress of contamination and humidity in the space.

Additional procedural controls to maintain the positive pressure differential during hardware ingress/egress were to pre-stage hardware, plan door operations to minimize the number of openings per day, allow the roll up door to only be opened to the minimum safe height needed to transfer hardware, and allow only a member of the contamination control team to have access to the locked door controls. The contamination control team favored fewer roll up door operations with slightly longer open times and coordinated hardware moves rather than opening the door multiple times a day. This reduced the time required for the recovery of the cleanroom particle counts which could have impacted the work schedule.

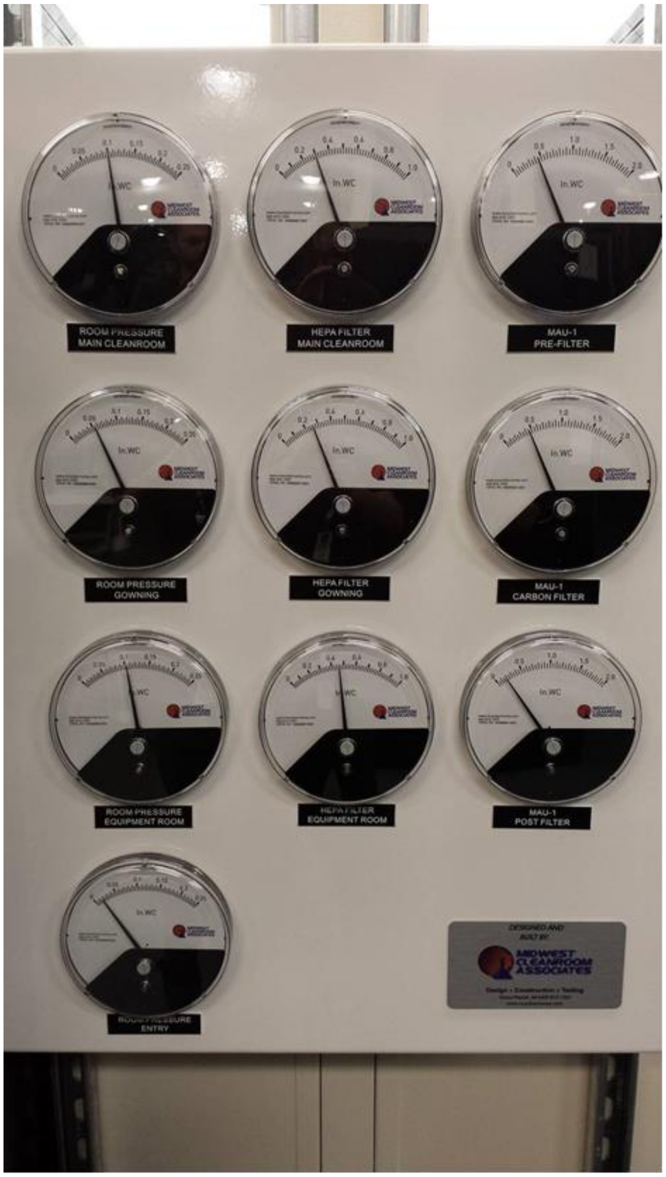


Figure 18. Cleanroom systems pressure panel (*photo credit: NASA/Joe Ward*)

5. INGRESS OF HARDWARE AND EQUIPMENT

5.1 General requirements and ingress procedures

All hardware and equipment had a minimum requirement of visibly clean highly sensitive (VC-HS) prior to entering the JWST cleanroom attached to Chamber A. The requirement for flight hardware and GSE was that it be delivered to the cleanroom meeting the cleanliness levels called out in the OTIS Contamination Control Plan (CCP)[7], and double bagged in an approved plastic material. GSE that was near or in intimate contact with flight hardware had more stringent requirements, from a VC-HS + ultraviolet (UV) cleanliness level, to verification of PAC and NVR levels equivalent to that of the OTIS flight hardware. And, because a significant portion of the hardware entering this cleanroom would also be exposed to a vacuum environment during testing in Chamber A, it also had to meet material vacuum compatibility and outgassing requirements dictated by the CCP. Hardware or equipment entering the chamber was required to be delivered with documentation showing evidence of the required cleanliness level and outgassing certification. If this information was not provided, then the hardware supplier was contacted for resolution. In many cases, the lead CCE would work with the hardware provider to develop cleaning instructions and plans for thermal vacuum bake-out of the hardware. Most of the vacuum test support equipment was included in the chamber bake-out.

Hardware and equipment to be brought into the cleanroom was staged in the space known as the truck lock (Fig 19), typically used for transition of hardware and equipment delivered to the building 32 into the vacuum test high bay. Because the truck lock was an uncontrolled area, special protocols were developed that included twice daily vacuuming of the floors and equipment. For hardware transitioning to the cleanroom, initial cleanliness inspections conducted in the truck lock included looking for evidence of dust, chipping paint, debris, uncured coatings, and disallowed materials. Once the initial inspection was complete, the hardware was rough cleaned following hardware provider instructions. Any hardware that was rough cleaned and not immediately brought into the cleanroom was covered and sealed. Final cleaning (also conducted per hardware provider procedures), VC-HS + UV inspections, and/or contamination sampling for quantitative measurements occurred after the hardware was moved into the cleanroom. Hardware delivered double bagged and pre-certified followed the standard protocol for exterior bagging to be removed in the truck lock and final bagging removed inside the cleanroom. Even hardware that was delivered with a cleanliness certification was inspected once inside the cleanroom due to random issues with bagging integrity, actual hardware cleanliness, and material usage.

Cleanroom entry points for hardware are shown in Figure 2. The large roll-up door was used for large GSE and flight hardware, while medium and small pieces of hardware and equipment were sent into the cleanroom through the equipment room and pass through door respectively. There were two ISO 7[1] cleaning stations equipped with the necessary cleaning supplies for small piece parts and hardware: one cleaning station was located next to the pass through window and another was located in the truck lock. Any hardware cleaned within the cleaning stations was double bagged and hand carried to the pass through window for ingress into the cleanroom.

Figure 19. Scaffolding staged in truck lock before ingress into cleanroom and cleaning station on left. (*Photo credit: NASA/Joe Ward*)

5.2 Small hardware and piece parts

Small hardware and piece parts were cleaned in one of the two ISO 7[1] clean tents located in the truck lock and just outside the pass through window. The cleaning was typically performed by wiping with polyester sealed edge cleanroom wipers and a 50/50 blend of IPA and deionized water. Ultrasonic baths containing the same solution were used for fasteners and small metallic parts. Any on-site cleanliness verification would be performed just after the cleaning by rinsing with 100 % IPA, followed by drying with filtered nitrogen. NVR rinsate samples were evaporated down in an ISO 7[1] exhaust fume hood and sent to the lab for analysis. Post cleaning visual inspections were conducted using white and ultraviolet flash lights.

5.3 Critical Support Equipment and flight hardware

Critical support equipment and flight hardware shipping containers or packaging were staged in the truck lock and initially inspected for shipping and/or packaging damage. Any damage was immediately reported to the hardware owner or responsible engineer (RE) for resolution. If the container and/or packaging appeared to be intact and there were no signs of contamination, the CCE and RE reviewed the requisite cleanliness certification paperwork, removed the outer bag or container lid and immediately transitioned the hardware into the cleanroom. Once in the cleanroom, inner packaging material was removed in the presence of the RE. After final packaging was removed, the hardware was inspected for damage, anomalies, and visual contamination. Typically, a white light visual inspection was conducted in partial room lighting, and if allowed by the RE, an ultraviolet light inspection was also performed. Any findings were photographed and reported by the RE and lead CCE to management for determination of a path forward. If cleaning or direct cleanliness verification sampling was necessary, again, it was performed per RE direction or by the RE, with management approval.

5.4 Large support equipment

Large support equipment was a necessary part of the PF and OTIS I&T program at JSC but because of its size, suppliers typically had a difficult time fabricating and maintaining it to the required cleanliness standards. Most of the equipment was painted, either with the black thermal paint for the pending thermal vacuum test, or a cleanroom approved epoxy paint. It was common to find a significant amount of chipped paint during inspections. Some support equipment was delivered to JSC (building 9) where additional cutting and/or drilling was performed to finalize the fabrication process. Unfortunately, in a number of cases, an inordinate amount of cutting fluid was used to drill holes into blind cavities. There was also dye penetrant found oozing from welds, on support equipment that would ultimately be installed in the upper portion of the helium shroud! And in some black anodized GSE, black dye particulate was found in its cavities.

Mitigating these sources included extensive solvent flush and wipe cleaning, and vacuuming. GSE that would not be used during vacuum testing in Chamber A would have blind holes sealed to contain the cutting fluid and debris. GSE that was to be used during vacuum testing could not have all openings sealed due to venting requirements, therefore, it was included in the Chamber A bake-out covered in Section 3.4. Chipping paint would be removed and or encapsulated with an approved tape. If the sources could not be sufficiently mitigated by the CC technicians, the hardware would be rejected and returned to the supplier for resolution. Below are some examples of large support equipment that represented significant challenges to the CC team at JSC.

Aluminum scaffolding – There was a significant amount of aluminum scaffolding used during I&T operations at JSC. Some was erected on Level 5 around the COCOA, in the cleanroom, and a significant amount around the PF installed on Level 1. Figure 19 shows a stack of scaffolding struts in the truck lock awaiting rough cleaning. Internal strut surfaces were cleaned by flushing or swabbing (using a large custom fabricated swab) with a solution of 80/20 deionized water and IPA, and all exterior surfaces were cleaned by vacuuming and wiping with the same 80/20 solution. Open ended struts that could not be cleaned in this manner were sealed with an approved plastic. Final cleaning and inspection occurred in the cleanroom. CC technicians stood by with a vacuum in order to remove any aluminum shavings generated during assembly and disassembly of the scaffolding. Due to limited space, scaffolding could not be stored in the cleanroom, and as a result, there were multiple iterations of this process.

Pentalift – A 40ft scissor lift with a 12’x12’ platform was custom fabricated to support installation of auto-collimating flat (ACF) mirrors to the helium shroud ceiling. Unfortunately the manufacturer did not have experience building cleanroom compatible equipment. It was delivered to JSC with paint chipping from all joints, mechanisms and recesses, along with metal debris, and hydraulic fluid contamination. Post-delivery adjustments to the structure required additional grinding and drilling. Insufficient ceiling height in the truck lock and cleanroom required it to be cleaned outdoors, so that it could be fully deployed for the cleaning (Figure 20). Once in the cleanroom, it was extended as high as possible and re-cleaned. Additional post fit test findings caused the Pentalift to be removed from the cleanroom, and re-cleaned again after additional modifications. Hydraulic leaks continued to be a challenge, but were closely monitored and well contained by CC technicians using approved plastic and special “diapering” techniques.

Figure 20. Pentalift inspection just outside the JSC building 32 truck lock (*Photo credit: NASA/John Byard*)

Crane load testing – Load testing of the cleanroom crane was conducted prior to the arrival of OTIS. In order to perform this test, steel weights were delivered to building 32 from an outdoor storage facility on a flatbed truck. While there is a crane in the truck lock and in the cleanroom, neither could be used to transition heavy equipment through the truck lock into the cleanroom. This made it necessary to use the flatbed to move the weights inside the cleanroom. Initially, outside the truck lock, the weights were lifted off the flatbed trailer with a heavy duty forklift, then the trailer was washed with a high-pressure sprayer. Approved bagging material was placed on the flatbed and then weights were placed back on the flatbed, on top of the plastic. Each weight was then completely covered and sealed to the flatbed plastic. Once this was complete, the trailer was backed into the truck lock (Figure 21) and all packaging material installed outside was solvent wiped. In addition, all sides of the flatbed were wrapped with plastic from the top of the flatbed to the floor. Next, ducting was connected to the truck's exhaust pipe and sealed so that engine fumes could be vented outside via a building exhaust fan port. In parallel, the inside of the cleanroom was prepared for the flatbed: all critical hardware was covered, a particle counter and a hydrocarbon monitor were placed within 5 feet of critical hardware, and contamination samples were deployed. Also, approved plastic corrugated sheeting was placed on the floor where the truck wheels were to be rolled over the cleanroom floor. A final, full inspection was conducted to ensure the weights and trailer were visibly clean and sealed well, and then particle counters and hydrocarbon monitors were started. Floors were mopped outside and inside the cleanroom, and just before the roll up door was opened, the cleanroom MAU plant air supply dampers were opened 100% as described in Section 4. After the roll up door was opened, the Chamber A AFMS (with 40' door open) was also ramped up. A technician was stationed at the pressure panel to monitor pressure, while in communication with the AFMS operator to ensure the pressure did not exceed 0.2 inches w.c. during this process. At this point, the trailer was backed into the cleanroom, and the roll up door was lowered as much as possible over the top of the trailer. The truck engine remained running during the load test to avoid a brake pressure release that could potentially push dirty air back into the cleanroom. Particle counts inside spiked temporarily when the roll up door was opened but quickly settled down to below ISO 7[1] level during the load test. Typically, the load testing took 20-30 minutes to complete before the truck rolled back out of the cleanroom.

Crane hook inspection - Crane hook inspection used a magnetic particle technique that was conducted inside the cleanroom. To contain the extreme contamination generated by this technique, CC technicians built a polyethylene tent around the hook, large enough for the test technician to perform the inspection. Before the technician entered the tent, he donned a Tyvek cleanroom suit over his polyester cleanroom garment. During the application of the magnetic particles, a HEPA filtered vacuum was held within a few inches of the operation. Once the test was complete, the technician removed his Tyvek suit while still inside the tent, then exited the tent. CC technicians carefully wrapped the contaminated Tyvek suit inside the tent, then removed it and the tent from the cleanroom.

Figure 21. Truck trailer being prepared in truck lock then backed into cleanroom with crane load test weights (*Photo credit: NASA/Joe Ward, Chris Gunn*)

STTARS - The Space Telescope Transporter for Air Road and Sea (STTARS) shipping container was used for transport of OTIS from GSFC to JSC and JSC to Northrop Grumman in a C5A aircraft. The shipping container is 4.6 m (15 ft) wide, 5.2 m (17 ft) tall, by 33.5 m (110 ft) long, and it weighs almost 75,000 kg (165,000 lbs). It is comprised of the pallet, tent frame and the exterior lid. It was designed, fabricated, and built to be cleanroom and space flight hardware compatible, with the interior capable of maintaining ISO 7[1] or better air cleanliness.

The sequence of cleaning STTARS began outside with an inspection for and removal of gross contamination. The size of the container forced technicians to remove all other equipment, including the cleaning station from the truck lock before it could be moved in. Once the truck lock was cleared, and the entire floor was covered with stainless steel sheeting, and STTARS was air-barged into the area. Then, the container was vacuumed and cleaned by wiping and mopping with a 50/50 solution of IPA and deionized water. Man lifts were utilized to maximize access to upper surfaces of the container lid. Once in the cleanroom (Figure 22), the container exterior was wipe cleaned once more, and inspected with white and black lighting. After approval was given by the CCE, the container lid was removed, revealing the tent frame that surrounded OTIS. There was not enough floor space in the cleanroom for all three container segments to remain there at once, so once the lid was removed, it was immediately returned to the truck lock. From there, the tent frame was removed revealing the very beautiful OTIS. OTIS was lifted onto a roll-over fixture and the tent frame was replaced onto the pallet structure. Finally, the container lid was re-cleaned, brought back into the cleanroom, and hoisted back up over the tent frame onto the pallet structure so the entire container could be removed from the cleanroom.

Because the inside of the STTARS container was maintained to ISO 7[1] cleanliness conditions, the interior remained very clean during shipments. Airborne particle counts during transport operations were < ISO 6[1]. Witness samples installed outside and inside the tent frame for the transport from GSFC to JSC and JSC to GSFC indicated a ≤ 0.002 PAC or less and < 5 angstroms NVR.

Figure 22. OTIS within the STTARS shipping container as it was delivered to JSC (*Photo credit Chris Gunn, NASA*)

5.5 CC personnel and technician team training

Highly trained CC technicians and mechanical personnel working in the cleanroom were imperative to the success of the JWST CC program at JSC. All technicians and engineers were required to undergo a CC training program that covered general cleanroom protocols, the impact of contamination on JWST's mission success, potential sources and types of contamination, and how to mitigate contamination while performing their work. Mechanical technicians were instructed to "clean as you go," and contain contamination generated during normal I&T operations with the support of the CC technicians. Any indication of foreign objects (FO), debris (FOD), or contamination on flight hardware, in the cleanroom, or chamber was to be immediately reported by the mechanical technicians to the lead CCE.

The CC technicians required more intense training that covered hardware cleanliness inspections, verification sampling, cleaning processes, material-solvent compatibility, as well as cleanliness maintenance of the environment around critical GSE and flight hardware. And, because they would be working near flight hardware, hardware sensitivity training was required. Since CC technicians played an important role in materials screening of incoming hardware, the comprehensive CC technician training program also included instruction on vacuum compatibility of materials, surface treatments, forbidden lubricants and greases, and recognizing disallowed high outgassing materials and coatings such as zinc, cadmium, tin and black oxide. And, they were trained on how to discern black oxide from dry film lubed parts. Technicians also had to be extremely proficient at triaging non-compliant support equipment! Finally, the CC technicians were responsible for ensuring that the integrity of the positive pressure in the cleanroom was not compromised during roll up door openings: the training included information on how to monitor the pressure and avoid negative pressure conditions as discussed in Section 4.

6. RESULTS/DISCUSSION

The OTIS test campaign required the use of an extremely large vacuum cryogenic vacuum chamber and an ISO 7[1] cleanroom that could be used just outside the chamber for test preparation activities. JSC's Chamber A was one of only 2 in the nation that could accommodate OTIS and its test equipment. However, a cleanroom suitable for JWST's cleanliness requirements needed to be built, and the chamber required a helium shroud and a significant amount test equipment to be installed. In addition, JWST CC required that the airflow system, originally built in the 60's, be upgraded to provide ISO 7[1] clean air to the chamber. The lead project CCE was involved during the design and build phases of the cleanroom which enabled a more efficient, clean, build process and timely certification. Improvements made to the Chamber A AFMS however, were performed using existing chamber infrastructure, which represented a challenge. It took time to understand how the upgraded AFMS systems worked under varying conditions and how the nuances of the original portions affected its performance. There was also an important balance between the cleanroom and chamber AFMS to consider when building and maintaining both environmental control systems. Then, there was the hot, humid weather, typical of Houston that brought additional challenges requiring attention to ensure robust systems that consistently remained within specification. And in order to guarantee the success of the contamination program at JSC, a dedicated team of CC technicians and engineers was necessary to certify and maintain these facilities full time. Fortunately, the PF test program provided a unique opportunity over an extended period of time to learn about and get these facilities up and running smoothly before the OTIS arrived for its cryogenic test. Both the cleanroom and Chamber A were clean and ready to go by the time OTIS arrived from GSFC in 2017.

6.1 Cleanroom

Cleanliness - Once the cleanroom construction was complete, the certification process went quickly and easily. The cleanroom was capable of 40 air changes/per hour. In addition, cleanroom protocols called for daily cleaning of floors and surfaces, as well as cleaning performed just before critical lift operations and air-barging. This resulted in low particle fallout rates, even under the pressure of a considerable amount of activity in a small space. Table 1 shows that the typical fallout measurements for particles and NVR were lower than the program goals by a significant margin.

Environmental Control - The biggest challenge for this cleanroom was the weather. The demand for chilled water onsite at JSC was highest during hot humid weather, and the cleanroom was one of many facilities onsite that required it. Updates to the control software provided warnings if chilled water T and/or flow parameters became unstable, and even shut down the MAU in the event that chilled water could not be quickly returned to nominal operation. Logs were kept of conditions that would impact chilled water performance, providing additional insight to impending issues. In addition, after the weather event experienced in 2015, spare parts were procured for any component that was vulnerable to an electrical storm. The back-up environmental control system provided the necessary redundancy to keep cleanroom T and RH levels within specification under any circumstance. Monitoring data from the tracking and alarm system enabled informed management teams of JSC and GSFC to ensure out-of-spec conditions were minimized. Figure 23 includes T and RH plots for June 2017, while OTIS was being prepared for its cryogenic test. In summary, by the time OTIS had arrived at JSC for its cryogenic thermal vacuum test, the environmental control system, its alarms, and back-up systems were reliable and fully operational.

Table 1. Airborne particle count and particle and NVR fallout

Test Method	**Limit or Goal**	**Data Collection Frequency**	**Typical Results**
Airborne Particles	ISO 7[1]	continuous	ISO 6[1] or better
Airborne Hydrocarbons	15 ppm	prior to test	≤ 5 ppm
Silicon wafer fallout	< 0.001 PAC/day	monthly	≤ 0.0002 PAC/day
NVR foil	< 15 angstroms/month	monthly	≤ 6 angstroms/month

Figure 23. T and RH plots for the JSC Cleanroom June 2017[8]

6.2 Chamber A

Preparing the chamber for the PF and OTIS CV test was a significant effort. The chamber's size, access limitations, and intricacies of the AFMS made cleaning and modifications to upgrade the system difficult. For example, the upgraded AFMS included some new supply ducting, but also used existing supply ducting installed back in the 1960's when the chamber was built. The challenge to upgrading the existing supply ducting was that it was only 36 inches in diameter, had one access point on the first floor, and it traversed 7 stories up to the chamber air inlet. To inspect, clean and re-coat the interior of the ducting a small single person lift was used to lower personnel down the ducting from Level 7 to Level 1. In addition, cleaning and coating equipment and supplies were supported and manipulated by the technician on the lift during the process. While detailed inspections were conducted inside the existing ducting before and after the upgrade, it was not possible to inspect the duct joints for minor leaks, due to visibility and access limitations.

AFMS Inspections, Mitigations- Thorough inspection of the AFMS from top to bottom and working together with the JSC AFMS engineers to correct negative pressure issues, mitigation techniques were developed to improve air supply particle counts. Two damaged filters were replaced in the MAU and contaminated filter downstream of the butterfly valve on the 7th level was replace and sealed (Figure 12). Operational modes were modified to reduce valve configuration changes, use the MAU to maintain positive pressure, and minimize the use of the blower. In addition, a pressure transducer was added to the AFMS system with an alarm to warn the operator of negative pressure conditions. All chamber particle counters were alarmed and tracked in the Data Acquisition Records and Controls (DARAC) system. An AFMS re-start procedure was developed that required particle count verification (utilizing a particle count probe installed in the location shown in Figure 12) prior to opening the gate valve to chamber, and a slow ramp up of the ventilation flow rate to minimize turbulence in the system. A plan was also put in place to run the AFMS throughout the OTIS CV test to reduce the risk of a negative pressure event and build-up of particle contamination in the ducting. Figures 24 and 25 show the particle counts before the improvements were made during nominal operations and chamber ventilation, respectively. Figure 26 shows the particle counts after these mitigations were implemented for all operations.

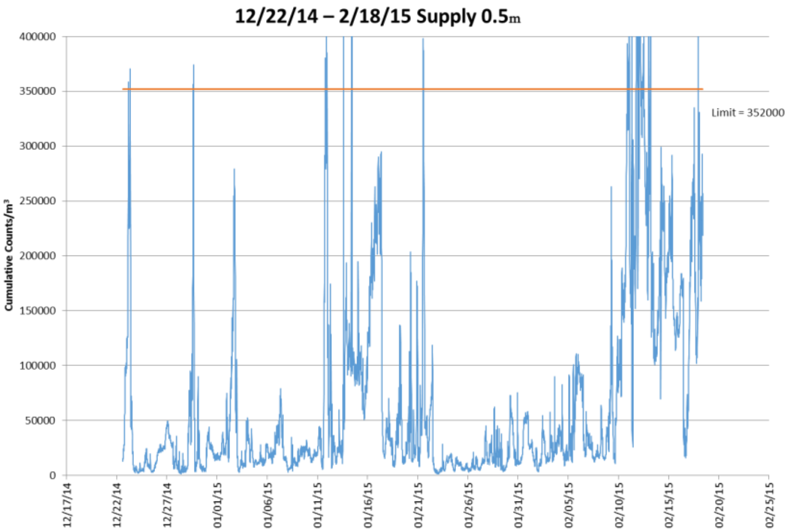


Figure 24. Chamber supply particle counts before OGSE-1 December 2014 - February 2015

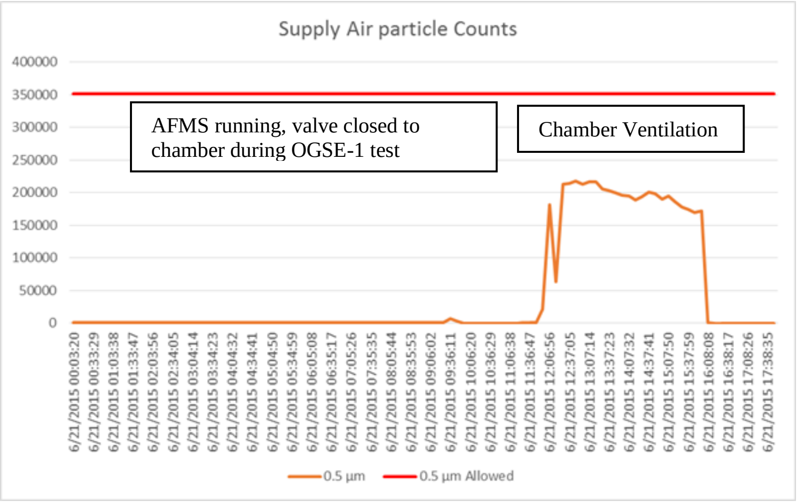


Figure 25. Chamber supply particle counts (0.5 micron) post-test ventilation OGSE-1 June 2015[9]

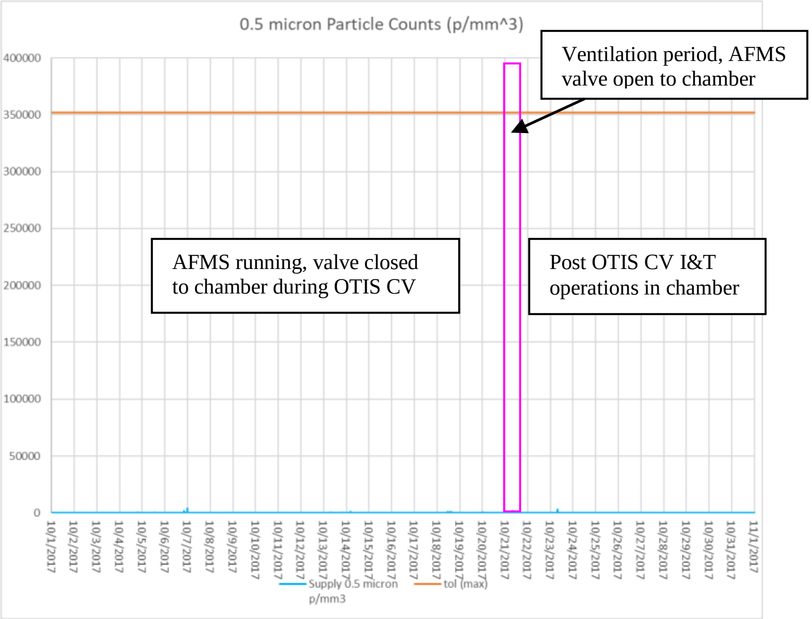


Figure 26. Chamber supply particle counts (0.5 micron) post-test ventilation and ambient OTIS CV operations[10]

Chamber Cleanings – Access limitations and the sheer size of the chamber made cleaning it a significant challenge. Cleanings that were conducted likely improved the particle fallout experienced during post-test ventilation operations. Unfortunately, there were other conditions that affected the particle fallout: shut down of the chamber AFMS during the test, and the level of activity conducted in the chamber while samples were exposed. Table 2 below shows the PAC during the PF test campaign, before and after the chamber cleaning.

Table 2. Average PAC for PF tests before and after cleaning

Chamber A Test	**Average PAC**	**Comments**
Commissioning	0.0189	AFMS shut down
	Chamber Cleaning	
Mini-pumpdown 1	0.0020	AFMS operational
OGSE-1	0.0104	AFMS shut down
OGSE-2	0.0102	AFMS shut down
TPF	0.0077	AFMS shut down
	Chamber Cleaning	
Pre-OTIS Functional (mini-pumpdown 2)	0.0035	AFMS operational

Chamber Bake-out – The bake-out was successful as it reduced the measured outgassing rate from 2450 Hz/hr to 20 Hz/hr or from 1.7e-04 g/s to 1.4e-06 g/s. The primary molecular contaminants collected on the scavengers included TPP, glycol ether, dibutylphthalate, and silicones. The most abundant material, TPP, was likely from the black thermal paint used on almost all GSE and chamber surfaces interior to the helium shroud. Molecular contamination levels measured on the samples exposed during subsequent PF and OTIS testing in Chamber A met requirements with margin. This is discussed in Reference 11, which covers PF and OTIS molecular contamination test results in greater detail.

Environmental Control - The chamber environmental control system appeared to perform better overall than the cleanroom even under extreme weather conditions. This is believed to be due to the fact that the chamber consistently received chilled water flow rates at or above design specifications. As with the cleanroom, the chamber was provided with a full redundant back-up AFMS system, but it was only used during a planned chilled water outage. Below in

Figure 27 shows the plots for T and RH for the Chamber in June 2017 during OTIS CV test preparation operations. The plots show that T and RH levels in Chamber A were well controlled.

Figure 27. T and RH plots for Chamber A June 2017[8]

6.3 Balancing the Cleanroom and Chamber A

The importance of balancing the pressures of the cleanroom and Chamber A cannot be overstated. While the chamber's 40' door was open, the flow rate of the chamber's AFMS had to be maintained at a certain pre-established level and adjusted real time during cleanroom roll up door openings. If not, the consequences included over-pressurization of the cleanroom with potential damage to the roll up door, or diminished positive pressure in the cleanroom and chamber risking ingress of contamination. In addition, both the cleanroom and chamber air supply systems needed to be operating simultaneously at all times while the 40' door was open. If the chamber system was temporarily shut down, the cleanroom system still in operation then required up to 100% make-up air to maintain positive pressure. And, with a higher percentage of make-up air, warm humid air was pulled in from the external environment, making control of RH inside the two volumes difficult. Gaining familiarity through use of these systems throughout the PF test program led to the development of facility procedures for safe operation and coordination of the two systems, enabling them to consistently meet their cleanliness and environmental control requirements during the OTIS CV test.

6.4 The importance of hardware design, fabrication, ingress, and CC support in general

Typically, cleanroom construction companies will only certify a completed facility in "at rest" conditions. This is because the operations and personnel activities that occur in the cleanroom have a very significant effect on its "operational" performance. Support equipment that was not designed and fabricated with cleanroom requirements in mind, and improperly trained personnel can lead to frequent out-of-spec conditions, costly cleaning operations, and even put flight hardware at risk.

At JSC, most of the support equipment was delivered to building 32 needing a considerable amount of work from the CC technicians and engineers to make it acceptable for use in the cleanroom and/or the chamber. This was usually due to a poor design, and/or poor fabrication process. At times, hardware was delivered so highly contaminated, that it was brought to another building for extensive pre-cleaning. As discussed in section 5.4, it was typically fibers, cutting fluid, dye penetrant, and machining debris found on and in the hardware that forced the need for extra cleaning. And, hardware to be used in the vacuum chamber contaminated by cutting fluid or dye penetrant, was heavily scrutinized and either included in the chamber thermal vacuum bake-out, or baked-out separately at another facility.

This work required a full time CC team dedicated to the effort. The team included 7 technicians, 4 on first shift and 3 on second. There were also 6 CCEs assigned to this task that rotated in and out, with a minimum of 3 onsite to cover both shifts and handle testing planning activities. For the most part, the technicians stationed in the truck lock handled the screening of incoming hardware and were provided documented instructions for cleaning if methods other than the standard cleaning process was required by the hardware owner. If there were any issues with the standard or RE recommended cleaning process or regarding the suitability of the hardware for the cleanroom in general, the CCEs were consulted. Nothing was brought into the cleanroom and chamber without going through this process. In some cases, where hardware was delivered with paperwork stating it was certified clean to a specified level, technicians and/or CCEs still examined the hardware through the bagging to ensure there was no gross contamination. There were many instances where this screening process paid off, avoiding ingress of contaminated hardware into the cleanroom and chamber.

Inside the cleanroom, besides facility and cleaning operations described in Section 2.3, CC technicians were assigned to support I&T operations. CCEs also covered floor operations both inside and outside the cleanroom during each shift. Their duties included cleaning hardware just before lift operations, supporting I&T operations that required rework (sanding, drilling, etc.), containing or covering potential sources of contamination, and watching for non-compliance to cleanroom and chamber protocols. To avoid issues with FOD, and disallowed or non-vacuum compatible materials entering the chamber, CC technicians worked with Quality Assurance to maintain a tool log to ensure everything that was not a part of the vacuum test was removed before the test began. Technicians and CCEs were also responsible for maintaining the cleanliness inside the chamber during ambient operations per Section 3.3. This included using man lifts to inspect upper regions of the chamber for particle build up peeling tape adhesives, residues, and chipping paint. Thanks to the efforts of the CCEs and CC technicians, FOD, peeling paint, tape adhesive, particles, and residues were sufficiently mitigated such that there was no risk to OTIS during its cryogenic thermal vacuum test.

7. CONCLUSION

As discussed in this manuscript, there were many challenges to overcome in order to prepare and maintain cleanliness in the JSC cleanroom and Chamber A used for OTIS CV testing. Each challenge faced during the PF program gave the CC and JSC facility teams the opportunity to improve measures used to control cleanliness in the facilities and to make their environmental control systems cleaner and more robust. As a result, the processes implemented and discussed herein were successful in producing a facility that met its cleanliness requirements, and in mitigating processing, paint, and acrylic adhesive contamination from the chamber and GSE. The key to the success of this contamination control program was vigilance in inspections, monitoring, daily maintenance cleaning, and having a well-trained CC technician team that operated as the front line defense against contamination ingress with hardware, and contamination created in the cleanroom or chamber. Witness samples exposed with the OTIS in the cleanroom and chamber indicate that the OTIS Primary Mirror met its allocation requirements with margin: the average PAC was of 0.04 vs an allocation requirement of 0.20 PAC and the NVR was <2 angstroms against an allocation requirement of 55 angstroms for operations at JSC.[12]

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