Precious Cargo: Transporting contamination-sensitive instruments & optics

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ABSTRACT

The James Webb Space Telescope (JWST) is a multi-national program with Instruments and hardware supplied by companies all over the world and numerous states in the United States. In order to transport larger assemblies, like the Optical Telescope Element / Integrated Science Instrument Module (OTIS), and ultimately JWST, the Space Telescope Transporter for Air, Road and Sea (STTARS) was designed and constructed. STTARS is a massive mobile cleanroom (longer than 2 semi-trailers) that provides an ISO class 7 payload environment while being transported by road, airborne and marine vehicles. Temperature, humidity and particle counts are controlled and continuously tracked, with fallout and NVR witness samples for confirmation. Instruments or sensitive hardware may be purged continuously during transport. STTARS has 5 main components: the upper tent frame, lower tent frame, pallet, strong back and lid. After transporting OTIS to Northrup Grumman (NG), STTARS was modified to increase its height to house the JWST Observatory on its voyage to French Guiana. This new configuration was designated Observatory STTARS (OSTTARS). OSTTARS was too tall to travel by C5 aircraft, so the trip to the launch site was made by ship. Through JWST's land, air and sea transports, STTARS and OSTTARS kept JWST hardware exceptionally clean and safe.

Keywords: James Webb Space Telescope, contamination control of transport, particulate contamination, particulate fallout, air cleanliness

1. INTRODUCTION

At 33.5 meters long, 5.2 meters and 4.6 meters wide (110'x17'x15') the Space Telescope Transporter for Air, Road and Sea or more affectionately known as STTARS, is massive. STTARS is a 165,000-pound shipping container designed to move Webb and its components around the world safely. This custom container was designed specifically to provide all of the necessary mechanical and environmental needs of Webb during transport. The primary method of travel for STTARS was by air on a specially modified Air Force C-5C, of which there are only two of these aircraft in existence[1] (Figure 1). The STTARS transporter is literally a mobile cleanroom that keeps its precious cargo safe from the contamination filled outside world.

To safely move around the country, the James Webb Space Telescope (JWST) program utilized STTARS for all of its larger hardware moves. STTARS was used to transport hardware such as the flight backplane, pathfinder and the Optical Telescope Element / Integrated Science instrument module (OTIS). STTARS transported the OTIS from Goddard Space Flight Center (GSFC) in Greenbelt, Maryland to Johnson Space Center (JSC) in Houston, Texas for thermal vacuum testing[3]. After the successful completion of the thermal vacuum test, OTIS was then transported from JSC to Northrup Grumman (NG) in Redondo Beach, California. Following the delivery of OTIS to NG, STTARS was transported to Nelson Manufacturing (the STTARS manufacturer) located in Ottawa, Ohio to undergo modifications.

The STTARS modifications were necessary to accommodate the complete Webb telescope. These modifications included a new strongback, upper tent frame, lower tent frame, filter box, end gate and extensions (see Figure 2). When equipped with the new hardware, the height of STTARS increased by 0.3 meters (1foot) to a towering 5.5 meters (18 feet) and in this configuration it was then referred to as the Observatory Space Telescope Transporter for Air, Road and Sea or OSTTARS. At 5.5 meters (18 feet) high, OSTTARS was too tall to fit in the Air Force C-5C and was already too heavy to cross the many bridges between the airport in Cayenne, French Guiana and the launch site in Kourou, French Guiana. To get to the launch site, the remaining option for Webb was to travel by ship from Seal Beach, CA to the port in Kourou. The voyage to the launch site lasted approximately 18 days.

Figure 1. STTARS preparing to load onto the C-5C space cargo modified (SCM) in November 2012 at Wright-Patterson Air Force Base. *(Credit: USAF Photo/John Andersen)*

2. OSTTARS OVERVIEW

There are many components that go into the makeup of OSTTARS. The two primary components are the running gear and the container (Figure 3). The running gear is what connects to the container and allows it to move down the road and provides all of the electrical and environmental equipment necessary to keep critical hardware safe. The container which holds the flight hardware can be further broken down into six subcomponents.

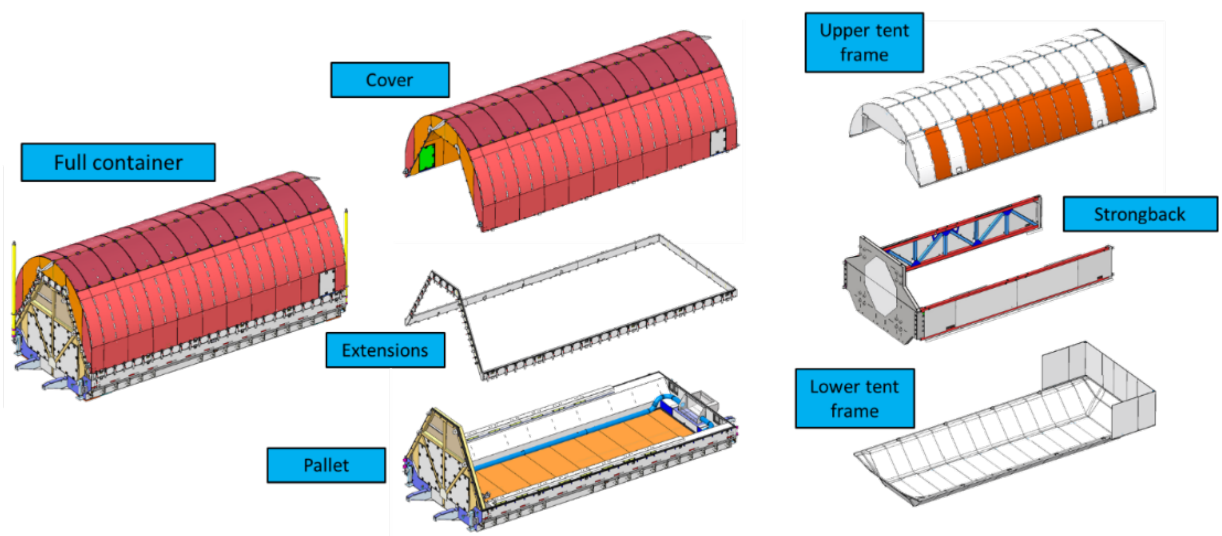

Figure 2. OSTTARS container components. *(Credit: NASA/GSFC)*

The subcomponents (Figure 2) of the container are the cover, pallet, extensions, upper tent frame, lower tent frame and the strongback. The extensions are what increases the height of STTARS to 5.5 meters (18 feet). The OSTTARS configuration was only used to transport the JWST to the launch site. All of the previous transports were completed using the STTARS configuration. The contamination control requirements did not change from STTARS to OSTTARS, the requirements are summarized in Table 1. To monitor contamination generated during transports and verify requirements, particle counters, fallout wafers and non-volatile residue (NVR) foils were deployed.

In preparation for transport, OSTTARS underwent a series of checkouts and cleanings to ensure that Webb would be safe during transport to the launch site. The cleanings included a rough cleaning that was performed after the final modifications were complete at Nelson Manufacturing. Following the rough cleaning several of the OSTTARS components, including the extensions, were bagged and shipped to NG separately from the container. This was necessary to allow the container in the shorter STTARS configuration to be loaded into the C-5C for transport to Southern Claifornia. Once at NG the container and all of the components for OSTTARS were moved into the M4 cleanroom where a detailed cleaning was performed over several weeks. After the final cleaning was complete, OSTTARS was assembled and put on standby in a warehouse until Webb was ready. OSTTARS was draped withUline poly bagging material while in the warehouse, this helped to significantly reduce the cleaning time of the container prior to moving into the Webb cleanroom.

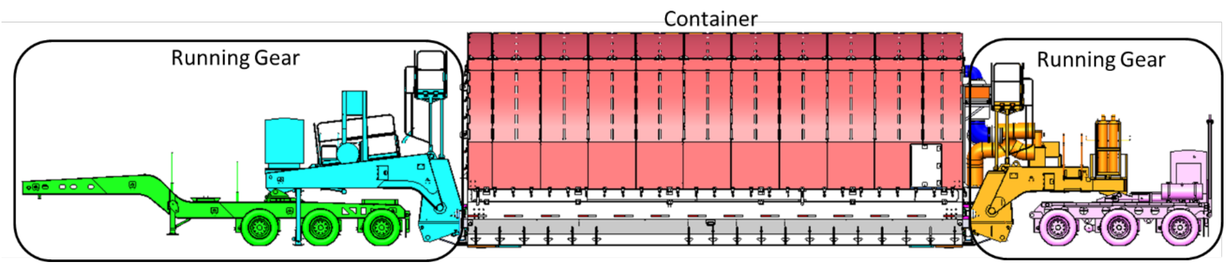

Figure 3. STTARS main components. *(Credit: NASA/GSFC)*

3. ENVIRONMENTAL CONTROL

OSTTARS traveled with a primary and a secondary Environmental Control Unit (ECU), along with an onboard generator to provide power to all of the onboard electrical equipment. The secondary ECU was only to be utilized if the primary failed. A few weeks prior to Webb transport the primary ECU system underwent a complete checkout. For the checkout the ECU was connected up as it would be during transport of flight hardware. There are two duct input locations on the filter box that allow the backup ECU to be attached, if necessary, without deconfiguring the primary ECU ducting. The return air plenum box, located on the pallet, also has two return duct ports. One port feeds the primary ECU and the second is available for the backup ECU. The checkout included testing for particulate and hydrocarbon contamination. On the downstream side of the filter box are two bulkhead 3/8” fittings which are used as sampling ports. The bulkhead fittings have tube extensions on the inside, extending from the bulkhead fitting to the HEPA filter face. Both particle counts and hydrocarbon measurements are made at the HEPA filter face. As part of the preparations for the Webb transport to the launch site, the OSTTARS HEPA filters and carbon pre-filters were replaced while the transporter was in the M4 cleanroom at NG for detailed cleaning and inspection. The HEPA filters used are Camfil F2000 24”x24”x11.5” aluminum housing, silicone free, non-DOP tested. During discussions with Camfil it was discovered that the filters are constructed silicone free but if there are leaks found during testing, the leak is sealed using a silicone material.

Table 1. OSTTARS contamination control requirements and fallout allocation.

OSTTARS Requirements								Allocation
Descriptions	Air Cleanliness			Surface Cleaniness		Temperature	Humidity	Fallout (PAC)
	Inside the tent frame	At the HEPA filter face	Hydrocarbons inside & outside the tent frame	OSTTARS exterior surfaces	Inside OSTTARS			
Requirement	ISO Class 7	ISO Class 5	15 ppm	VC	VC-2 UV	12°C - 27°C (53.6°F - 80.6°F)	0% - 55%	0.003

The OSTTARS filter box located on the cover (Figure 4) has two sides: a left and right side. Each side contains two carbon pre-filters and a HEPA filter. A single large plenum feeds both the right and left side filters. The filter box plenum is fed by the ducting coming from the Primary and Backup ECUs. At the time of the checkout the ECUs had not been operated in many months, and the filter box with new filters had not been tested. It was necessary to let the ECU operate (blow down) prior to the "run for record" that measured particle counts and hydrocarbons. After approximately an hour blow down time and some trouble shooting, the makeup air and return air required some adjusting. The particle count results (Figure 5) showed that the air entering the OSTTARS container met the ISO Class 5 requirement for particulate. Following the particle count test, hydrocarbons were measured using a handheld RAE volatile organic compound (VOC) monitor capable of measuring 0 – 5000 ppm. The results of the hydrocarbon test showed no hydrocarbons present in the air stream.

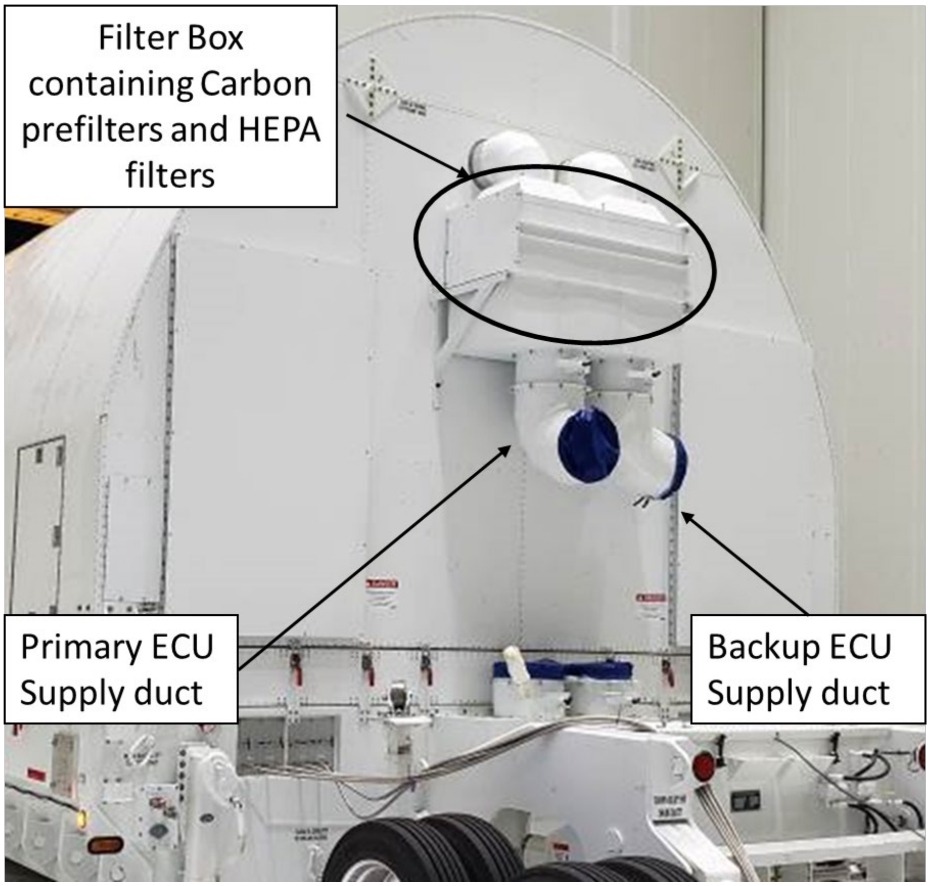

Figure 4. OSTTARS filter box located on the cover. *(Credit: NASA/GSFC)*

There are two volumes inside OSTTARS that required monitoring and control. The volume between the cover and the tent frame is controlled by the ECU and the volume inside the tent frame, where the flight hardware lives, has no air flow but has purge gas going to the flight hardware and a separate purge feeding the tent frame volume itself. During transports, the ECU is typically operated only to maintain the temperature within the cover volume. The temperature inside the tent frame volume lags behind the cover volume because there is no flow into the enclosure supported by the tent frame. This lag results in a more thermally stable environment for the hardware. Due to the high temperatures experienced during the transport to the launch site, it was necessary to run the ECU the entire time. During previous transports the ECU was run intermittently. The ECU is not equipped with a dedicated dehumidifier.Because of this, humidity reduction of the supply air to the cover volume came from air conditioning and balancing the ratio of makeup and return air. The tent frame volume humidity is primarily maintained by the dry purge gas feeding the instruments and the tent frame. Extensive efforts were made to seal the tent frame volume to keep its humidity as low as possible inside. After Webb was loaded into OSTTARS, the tent frames were closed out and the cover installed, the container sat in the NG cleanroom for several days allowing the relative humidity inside the tent frame time to dry out. Inside the tent frame a relative humidity (RH) of 20% or less was the goal for the transport, which was achieved.

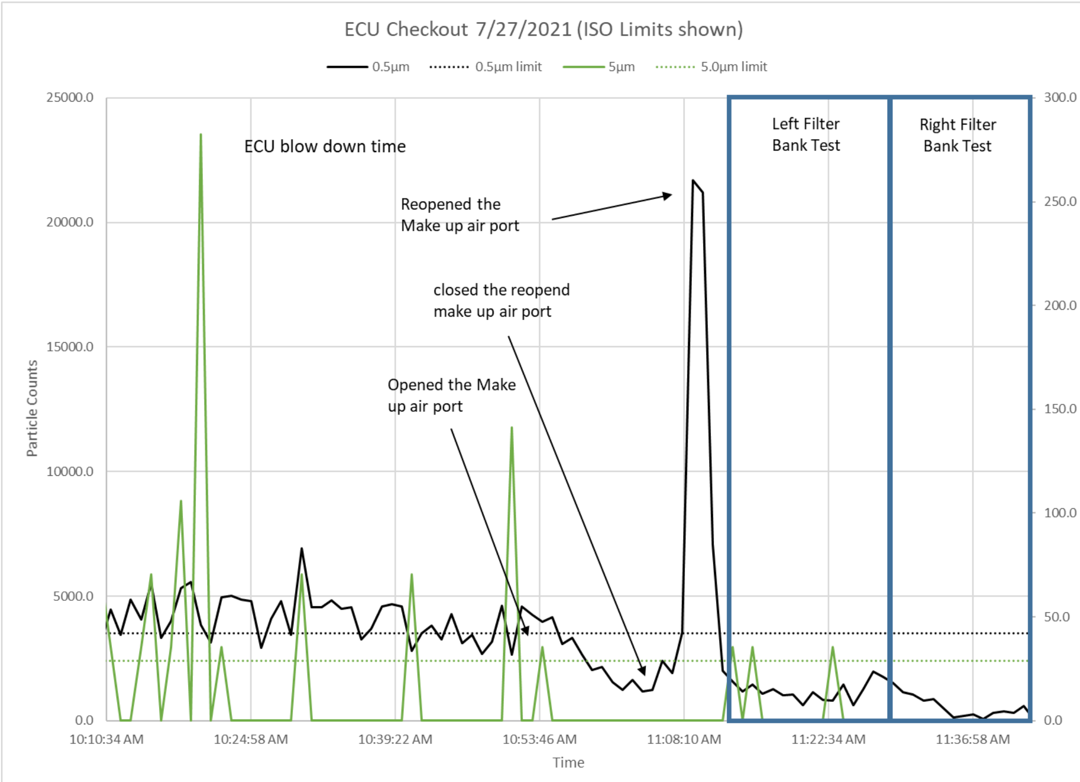

Figure 5. 7/27/2021 ECU checkout particle count results *(Credit: NASA/GSFC)*

4. CLEANING OSTTARS

The cleaning of OSTTARS was a daunting task due to its massive size and the level of contamination that had built up during the modifications at the manufacturer. To prepare OSTTARS for Webb, the cleaning took place in stages and consumed more than 100 L of isopropyl alcohol (IPA), 15 cases of sealed border cleanroom wipes, 24 L of deionized Water, 10 cases of mop heads, 6 rolls of 10’ C-Fold low outgassing polyethylene film and 3 rolls of 20’x 100’ Uline polyethylene film. The crew sizes varied from 7 during the rough cleaning stage to a high of 12 for parts of the final cleaning.

The sheer size of the transporter often vexed the contamination control team. Despite being made of highly cleanable surfaces, every transport brought unique challenges to preparing it for entry into each cleanroom facility. For example, while cleaning the container for entry into the Johnson Space Center (JSC) a large amount of contamination from striking small oak tree limbs along the transport route required removal. The small limbs would flex and drag along the lid while underway, leaving streaks of plant material which required multiple passes with cleanroom wipes and de-ionized water to clean.

4.1 Rough cleaning OSTTARS

Modifications to the OSTTARS shipping container were carried out in a typical manufacturing environment without the benefit of a cleanroom or clean work space environment that the container eventually resides in. The necessary changes to the container which provided additional height to safely house the completed observatory produced significant challenges. Extensive cleaning was required to remove contamination generated by cutting, grinding, welding and fallout from the facility. In concert with the cleaning effort, a method to close out seams and gaps from the newly redesigned upper and lower tent frames was needed.

Figure 6. Rough cleaning of the inside of the OSTTARS cover at Nelson Manufacturing *(Credit: NASA/GSFC)*

The newly designed upper and lower tent frames have direct line-of-sight exposure to the observatory and required extensive cleaning and verification prior to loading of the JWST. The rough clean was performed at Nelson, the manufacturing facility in Ottawa, Ohio (Figure 6) during the week of February 22nd 2021. A team of seven engineers and technicians spent five days performing the rough cleaning. To start, the tent frames were lifted by crane and placed on cribbing. The upper tent frame interior and exterior surfaces were fully accessible for cleaning, but the lower tent frame was not designed to allow personnel to walk on it, so a crane and rigging crew were required to flip the lower frame upside down to allow access to its interior surfaces (see Figure 7).

While JWST cleaning procedures typically utilized wiping with high purity IPA, this proved to be ineffective for the initial cleaning pass due to the severity and composition of fallout on the tent frame surfaces. The tent frame surfaces were coated in a film containing dirt, dust, and various fallout from the manufacturing process, all of which tended to smear and leave a residue behind when only IPA-wiping was utilized. Contamination control engineers directed a change to de-ionized water for the initial cleaning pass, followed by IPA, which proved effective in removing the stubborn substance.

Removing old tape and adhesive residue left behind from other transport operations is always time consuming. To remove the adhesive, contamination control technicians and engineers used IPA-soaked wipes held on the adhesive for a few seconds before wiping. This method allowed the adhesive to soften prior to wiping which, in turn, allowed the residue to be removed without smearing, which is typically an issue when mitigating adhesive residue. Adhesive residue was present in such a volume that a member of the team working to remove it suffered from delaminated fingernails from the hours of work wiping and picking at the stubborn mess with gloved fingers.

Figure 7. Rotating the lower tent frame for cleaning access *(Credit: NASA/GSFC)*

The OSTTARS pallet, arms and tombstone were somehow spared the fallout found on the tent frames; however, the sheer size of these parts and extensive adhesive residue present required significant effort.

Scissor lifts were needed to enable the team to reach the apex of the arched cover, which held significant particulate fallout. With OSTTARS rising roughly 5.5 meters (18 feet) in height, the scissor lifts were required to extend roughly 7.6 meters (25 feet)into the air to enable a downward angle that would allow sufficient access and downward pressure to clean the area. . Despite the access afforded by using scissor lifts, the team on lifts still needed cleanroom mops on long telescoping handles to reach all surfaces and remove the contamination. One manlift would be positioned on each side of the container, stocked with multiple packs of dry cleanroom mop heads and poly bags containing mop heads pre-soaked with IPA. Contamination present at the top of the lid was heavy enough to require multiple passes with dry mop heads to minimize streams of dirty IPA cascading down the sides of the container. Upon completing a few passes with dry mop heads a transition to pre-soaked IPA mop heads was made.

Riveted, overlapping metal panels were used to form the lid and each seam exhibited an increased amount of contamination due to the mechanics of the removal process. The seam interfaces and associated rivets caused pooling of IPA which, in turn, could redistribute the contamination and form a film once the IPA evaporated. To combat this, the team would alter the amount of IPA used for the presoaked mop heads when spot cleaning around the panel interface seams. Essentially a mop head with a greater amount of IPA would be used for the initial post dry wipe cleaning and be followed by another pass with lightly dampened mop heads with emphasis on the seamed interfaces (Figure 8). The process required hours of awkward reaching, extending, and performing of exaggerated mopping motions which required honest self-assessment of fatigue by all in the team to avoid injury, all while maneuvering scissor lifts within inches of the OSTTARS shipping container at roughly 7.6 meters (25 feet) in the air.

Figure 8. Exterior cleaning of OSTTARS. *(Credit: NASA/GSFC)*

Cleaning inside the pallet allowed a return to the typical CC cleaning process. Vacuums were utilized for the preliminary cleaning and the most effective way to reach various tight corners and hidden areas harboring contamination. As portions of the inner pallet were vacuumed, another member of the team would follow behind and wipe down the area with IPA. All work was performed from the top down to allow any escaping contamination to land in the lower pallet where cleaning was performed as a last step in the process. Once all cleaning above the lower pallet was completed, the lower pallet was vacuumed and mopped with IPA. Each component of OSTTARS was covered or wrapped with poly after cleaning and inspection. Where possible, the poly was secured in place and was not removed until the detailed cleaning started in the M4 NG facility.

4.2 Detailed cleaning of OSTTARS

The detailed cleaning of OSTTARS occurred during the month of May 2021 in the NG M4 ISO 8 cleanroom. Although the rough cleaning that occurred at the manufacturer's facility was very successful, hundreds of more man hours of cleaning was necessary before the container was ready for Webb. To prepare for OSTTARS, the M4 facility was cleaned and anything not related to OSTTARS was moved out because of the vast footprint of the transporter and its associated hardware. To further improve the air cleanliness of the cleanroom, two HEPA-filtered fan unit stacks were setup and operated for some time in advance of OSTTARS' arrival. Testing of the HEPA walls at GSFC had shown a 80% reduction in fallout when two HEPA stacks were utilized together.[2] Due to security restrictions, the gown room normally used for changing into cleanroom garments before entering the cleanroom was not available for use. A side entrance was subsequently used but required setting up one of the mobile gownrooms which would later be used at the launch site.

Upon arrival in the M4 cleanroom the mechanical team completely disassembled OSTTARS into its main components to allow for this final, detailed cleaning and inspection. All inspections were done to Visibly Clean Level 2 with Ultraviolet illumination (VC2+UV). Additionally, all of the hardware and equipment needed for lifting Webb into the transporter required detailed cleaning and inspection. The detailed cleaning began with the support equipment that arrived stored in multiple large pelican cases. Each case was emptied, cleaned and inspected. The equipment from each case was cleaned and inspected, then wrapped in poly film, when needed, and placed back into the clean case. Shackles had been nickel plated to reduce contamination generated during lifting activities. All blackoxide coated, zinc plated or galvanized hardware was replaced with nickel plated hardware. Cables that are part of the lifting sling were wiped with a dry wipe and covered with electrostatic static discharge (ESD)-safe bagging material. Any required turnbuckles were taped or bagged with cutouts to allow access. After completing cleaning of the pelican cases, the larger lifting hardware was cleaned, inspected and bagged. The sheer size and quantity of the different large lifting slings slowed progress. The slings often had chips and scrapes that needed to be evaluated to determine if any coating would come off during operations. The use of tape to cover chips and scratches was minimized to prevent future issues that old tape delamination could cause.

The cleaning of the OSTTARS container and its components was overwhelming when taken all together. The CC team focused on each piece at a time and methodically worked from top to bottom, and from one end to another. The team often worked in pairs, all the while communicating with the rest of the group to prevent duplicating work. Communication was vital to prevent loss of time due to repeat work or missing areas that team members thought had been cleaned. The upper and lower tent frames were covered with poly after cleaning and inspection. The opening in the container cover was also covered to prevent individuals from walking inside the cover to "check it out".

After weeks of cleaning and inspections (nearly the entire month of May), the container was ready for entry into the Webb cleanroom. The transporter had arrived at NG in the STTARS configuration. After the CC team was finished, the mechanical team assembled the transporter in the OSTTARS configuration and moved it to a standby building where it waited for Webb to be ready. The CC team placed contamination witness samples in OSTTARS when the cleaning was finished. The samples were retrieved after OSTTARS moved into the Webb cleanroom.

4.3 Final Cleaning Preparations for Webb

At the end of August 2021, OSTTARS was moved from the holding facility to M8 (the Webb cleanroom). The interior of OSTTARS had been cleaning to VC2+UV. All of the support hardware underwent another inspection and cleaning as it was brought into the airlock, and then into the cleanroom. The cover of OSTTARS had been draped with poly before it left the M4 facility and the drape had remained in place during the holding period, only being removed as it entered the M8 airlock. This helped reduce the fallout on the lid and speed the time needed to clean the exterior of OSTTARS. At this point the process of moving the container into the Webb cleanroom was the same as the previous moves.

The M8 airlock had been prepped for OSTTARS the night before the move. The floors were cleared, vacuumed and mopped. Two sheets of poly, large enough to cover the entire underside of the pallet, were placed on the floor. The top sheet was a sacrificial layer that would be removed after OSTTARS moved over the top of it into the airlock. The lower sheet was used to diaper the underside of OSTTARS and up the side of the pallet to the red and white reflector strip. This can be seen in Figure 8. The jacks had seen a fair amount of use and abuse, so they required extensive bagging with clean poly sheeting due to leaking oil and severely flaking paint. Care was taken to ensure the rotating handles needed to raise and lower the jacks were left exposed and the surrounding bag encapsulating the jack housings did not interfere with the rotation. The tangs, which connect the pallet to the running gear, also suffered from extensive chipping and required bagging. It was far faster and cleaner to cover them than to try to only clean them.

After the poly was in place, the exterior cleaning began. Two scissor lifts, one on each side of the container cover, started the cleaning process. Each scissor lift had two techs and started the cleaning by going top-down, beginning at one end and moving to the other. Normally two complete passes were required before the work from the lifts was complete. The remaining crew worked from the floor and on ladders to ensure the ends of the cover were prepared for entry. As the lifts moved down the cover, the techs on the floor would follow. The techs on the lifts were responsible for cleaning from the top of the cover to where the curve of the cover stopped. The straight section of the cover and below were the responsibility of the floor crew. A crew of experienced technicians and engineers took approximately 6 hours to prep and clean OSTTARS for entry into a cleanroom. After completing the preparations and cleaning, the container would be inspected and only given the approval to move into the cleanroom with Webb once the CC Engineers approved the cleanliness.

4.4 Final Inspection

Once in the cleanroom with Webb the cover, upper tent frame and strong backs were removed and placed in a staging area of the cleanroom. The contamination witness samples (fallout wafers and NVR foils) placed in OSTTARS after the completion of cleaning in M4 were retrieved. Earlier STTARS transports had been completed using a smaller tent frame, a different stongback and no spacer. At this time there was no fallout or NVR data with the new OSTTARS configuration. The wafers and foils were place on 5/19/2021 and collected on 9/1/2021, a total of 105 days of exposure. The PAC per day fallout rate was calculated to be 0.000038 and the total NVR collected was 0.035mg/sqft. These results confirmed that OSTTARS with no payload has very low particulate and NVR fallout rates.

While Webb was being prepared for the lift into OSTTARS, the final VC2+UV inspections were completed. Special attention was taken with the upper tent frame and the stongback. With the upper tent frame directly over the telescope and the tombstone and arms in very close proximity, any sign of contamination had to be removed or risk cross contamination onto the telescope. The inspections were, again, a team effort often with 4 to 6 engineers and technicians participating in the inspections. The UV light preferred for these inspections was the Crime-lite 82S, used in a darkened room. This Crime-lite illumination allowed for inspection of a larger area at once and provided an even illumination across a surface with no hotspot. Once satisfied with the final cleanliness, the hardware would be covered with poly until needed.

5. CLOSE OUTS

The newly manufactured arms, tent frames, and end gate joined together differently from the previous designs, necessitating a fresh approach to sealing seams and gaps at component interfaces. The final transport of JWST would see the OSTTARS container with the fully assembled JWST payload transported via an ocean-faring ship to the launch site. With an over water transport and delivery to a launch site a mere 6 degrees from the equator, effective sealing and close outs became critical due to the strict humidity requirements of the onboard science instruments and exposed optical surfaces. Upon completion of OSTTARS modifications, temperature/humidity stability tests were run to validate the environmental control unit's ability to properly maintain the conditions within the tent frames. This testing allowed contamination control engineers a chance to evaluate the effectiveness of planned closeout techniques. The tent frames were closed out as if the telescope was inside. To test the close outs, the tent frame volume had a blower connected to it and turned on (Figure 9). This provided a high positive pressure and allowed the team to search for leaks and make adjustments to the close outs as necessary. This proved very effective in finding leak paths that were not easily identifiable.

Figure 9. Leak testing the closeouts at Nelson Manufacturing. *(Credit: Joseph Ward)*

Running along the length of the lower pallet and at the interface of the tombstone is a series of isolators to which the arms and tombstone would mount and provide vibrational dampening and shock load mitigation. The design of the isolators created an open path for potential humidity ingress and to a lesser degree, contamination. While OSTTARS had its own integrated climate control system and purge for the science instruments, it was still critical to seal any potential leakage points to provide a stable temperature and relative humidity environment within the container.

Figure 10. OSTTARS final closeouts around the upper and lower tent frames. *(Credit: NASA/GSFC)*

The isolator design utilized a lower mount attached to the lower pallet, a series of steel cable coils and top plate which interfaces with the arms while the center section containing the coils and each end remained open. To close out the open areas of the isolators the contamination control team utilized ESD-safe 12” tube stock and polyethylene tape. One side of the 12-inch ESD tube stock was securely taped to the pallet near the lower isolator mounts along its entire length. The opposing side of the ESD tube stock was secured with tape along the edge of the isolator top plate. This process was utilized for the inboard and outboard side of the isolators. Closing out each end of the isolator was accomplished by cutting smaller pieces of 12-inch ESD-safe tube stock to wrap around the ends and overlap with the tube stock already secured to the inboard/outboard side of the isolators. The tube stock on all sides of the isolators was installed with slack to avoid tearing or popped seams under the weight of the arms and observatory.

A similar technique was used to close out areas at the interface of the tombstone and the lower tent frame. This interface required larger sheets of ESD compliant material to be patched together from both the interior and exterior to ensure proper sealing. A contamination control engineer would climb into the lower tent frame through an access panel in the arms and begin sealing openings in the interface. On the exterior of the container another contamination control engineer would provide additional sealing of seams in the closeouts and guidance for any areas which could not be seen from the interior.

Additional team members worked to seal out seams and gaps at the end gate opposite the tombstone. By design a large gap was present vertically along each side of the end gate/arm interface. This gap was sealed with 12-inch ESD compliant tube stock with care given to allow enough slack for potential movement and any pressurization present from the purge system and environmental control unit. A smaller gap was present along the upper edge of the interface of the end gate and upper tent frame which received the same mitigation efforts utilizing ESD compliant tube stock taped in place with allowances for independent movement of each structure. (Figure 10)

6. MONITORING

For all of the JWST transportations, contamination monitoring for NVR, fallout, hydrocarbons and airborne particle was performed. In general, NVR and fallout witness samples were deployed in a volume just prior to losing access. Typically, the samples within the tent frame volume were place first, just before the flight hardware was installed. The samples outside the tent frame, but within the cover volume were placed just prior to the cover installation. It is very important to frequently communicate with the I&T team on sample placement and timing. This prevents any delays or accidental contamination of the witness samples while I&T performs their work.

OSTTARS transport of Webb followed the same monitoring processes as the previous transports. The particle counters were set to automatically start counting when power was supplied to the units. The counters were handheld units with a 0.1 cfm pump. The counter inside the tent frame volume was mounted on an arm using a bracket made for the counter. The counter outside the tent frame measuring the cover volume, was taped in place. Both counters were set to sample for 10 minutes with no hold or delay between samples. This allowed for complete monitoring of the transport. Prior to the cover installation power was connected to OSTTARS and all instrumentation was checked to verify fuctionallity. Figure 11 shows the approximate locations of the fallout wafers, NVR foils and the particle counters placed inside OSTTARS. Each location was photographed (Figure 12) after deployment of the samples.

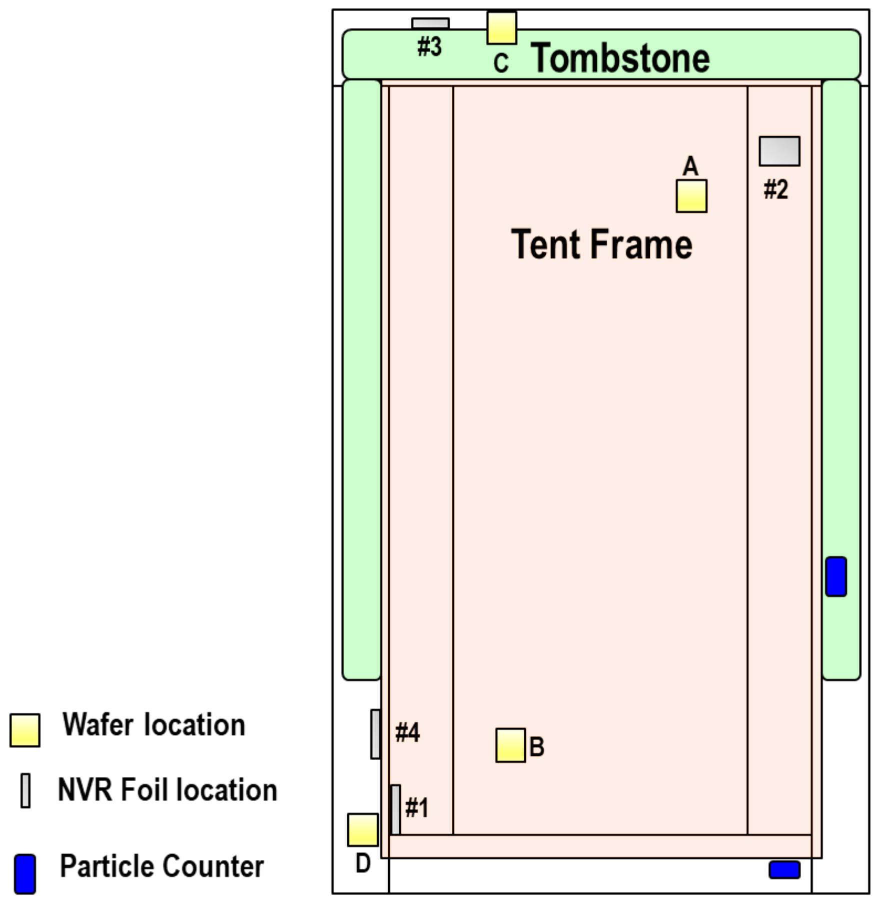

Figure 11. Layout of the contamination monitoring locations for transport to the launch site. *(Credit: NASA/GSFC)*

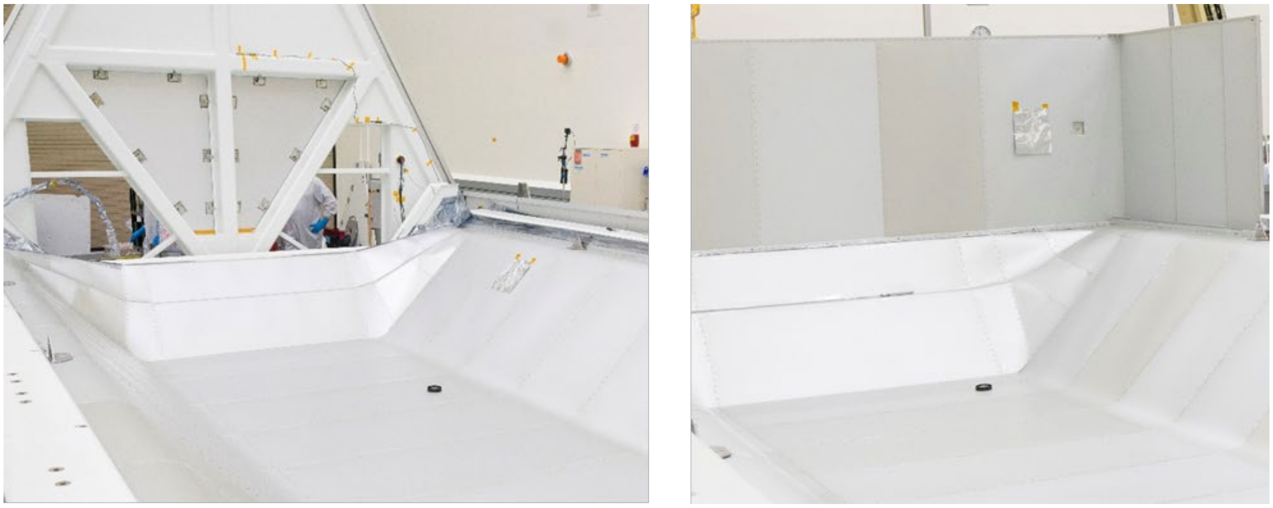

Figure 12. Contamination samples NVE 2 and Wafer A on the left and NVR 1 and Wafer B on the right inside OSTTARS. *(Photo credits: Chris Gunn)*

7. RESULTS

Figure 13. October 12, 2021 Webb arrives at CSG in French Guiana. *(Credit: Joseph Ward)*

With the safe arrival of OSTTARS at the launch site in French Guiana, the precious cargo was unloaded and continued its amazing journey, while the job of OSTTARS came to an end (Figure 13). Following the removal of the container cover, the external fallout wafers and NVR foils were collected. Total exposure time of the contamination samples outside the tent frame was 22 days (9/21/2021 to 10/13/2021). Following collection of the external contamination samples, the closeout material was removed to allow the lift of Webb out of the container. With the closeout bagging material removed, the first look at Webb was possible (Figure 14). The secondary mirror was just visible through openings between the tent frames. A couple of days later, once Webb was lifted out of OSTTARS, the samples inside the tent frame were collected. Total exposure time for those samples was 24 days (9/20/20211 to 10/14/2021).

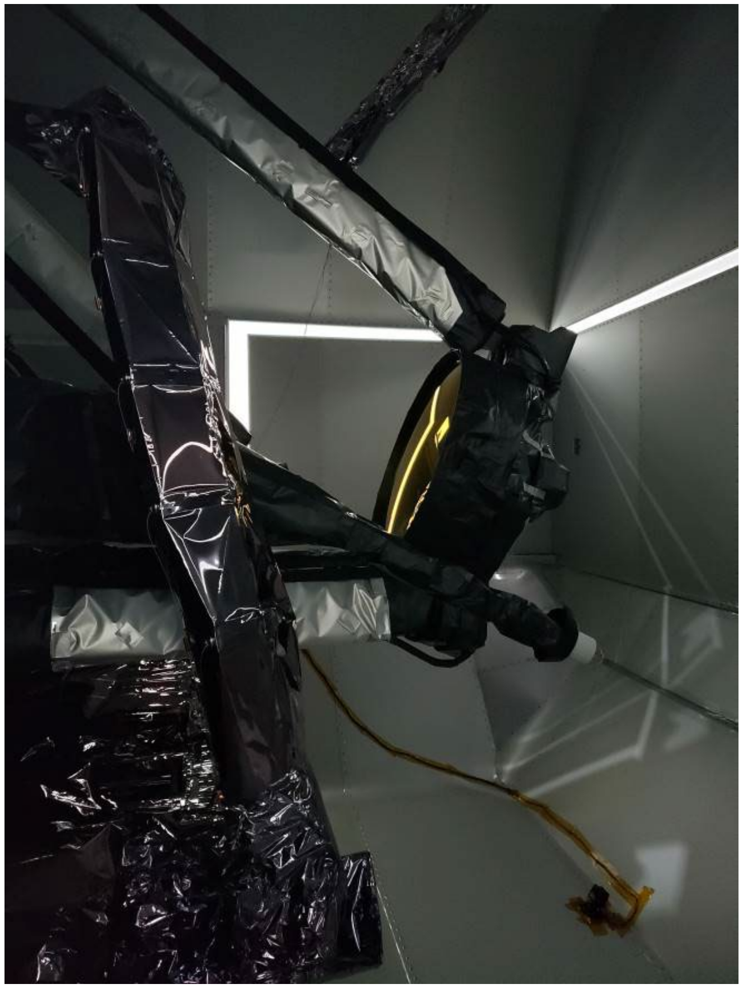

Figure 14. The secondary mirror was the first view of Webb inside OSTTARS at the launch site. *(Credit: Joseph Ward)*

Though the wafers were able to be analyzed at the launch site, the NVR samples were sent back to Goddard Space Flight Center for analysis. The total PAC inside the tent frame during the transportation of Webb to the launch site was 0.003 and the NVR was 0.02 mg/sqft, both exceeding their requirements and allocation. The particle count data inside the tent frame easily met the ISO Class 7 requirement (Figure 15). It is unknown what caused the unidentified 0.5 micron spike around 10/6/2021. Even so, the counts were well below requirement. When OSTTARS left California it was headed to an environment that it had never experienced before, with high temperatures and oppressive humidity. The CC team was confident with the closeouts and the plan for the ECU and purge. The temperature and relative humidity was monitored during the entire journey. In the end, the relative humidity inside the tent frame (Figure 16) maintained an average of just under 20% and the temperature inside the tent frame (Figure 17) averaged just over 70º F for the journey.

The transportation of Webb to the launch site was just one success of many that can be attributed to the planning, dedication and hard work of those involved.

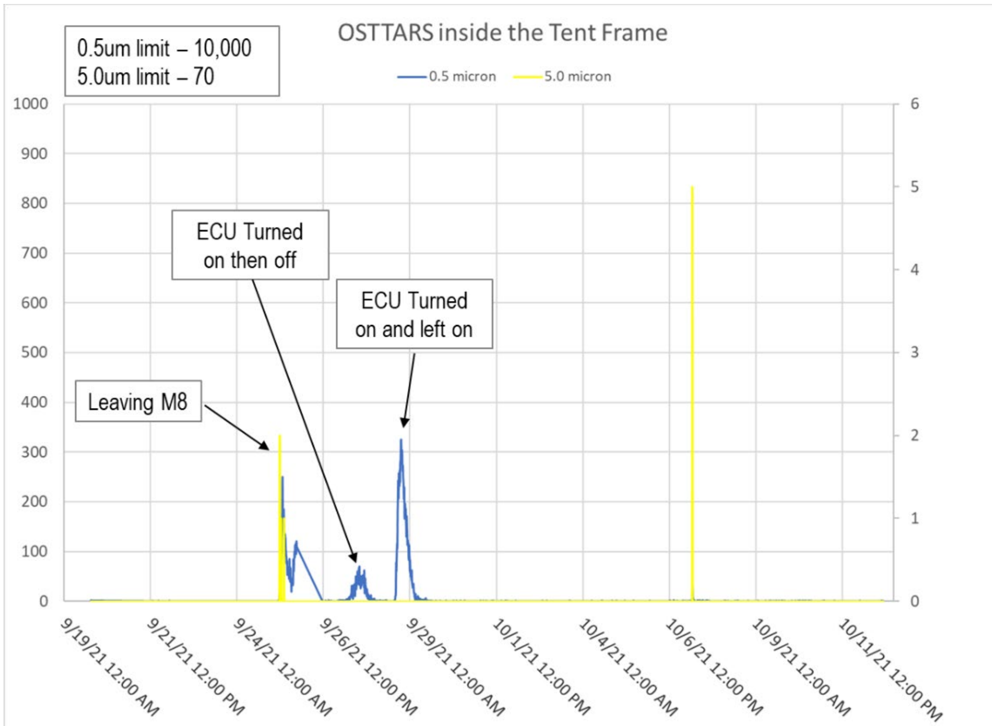

Figure 15. Particle count data inside the tent frame during the JWST transport to CSG. *(Credit: NASA/GSFC)*

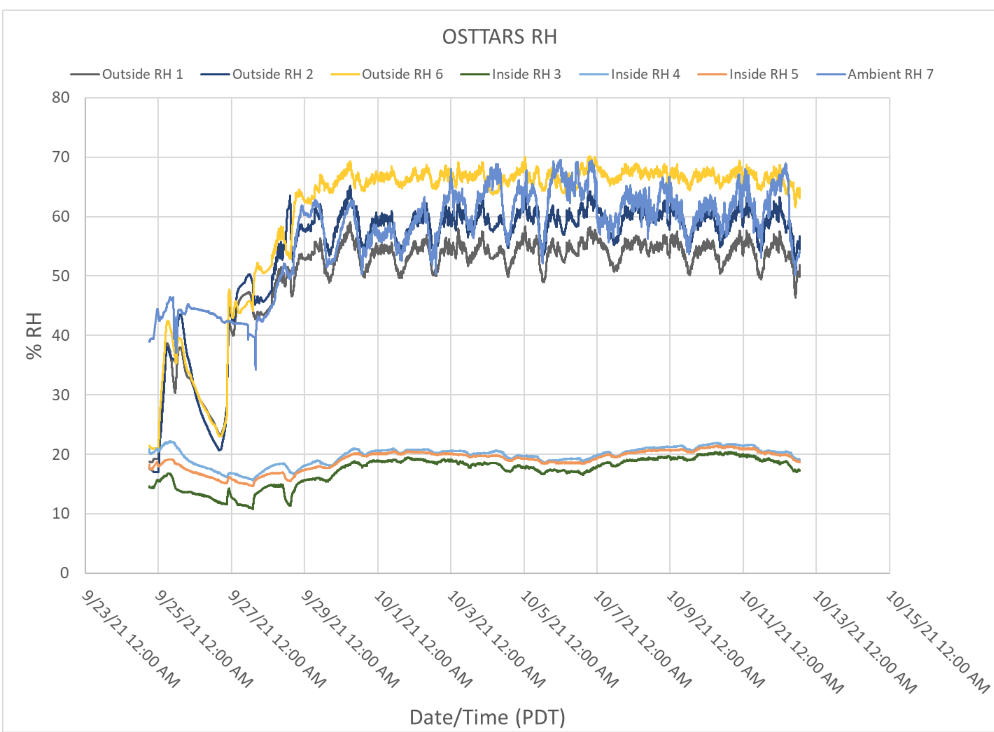

Figure 16. OSTTARS relative humidity data for the JWST transport to CSG. TF in the legend refers to the tent frame. *(Credit: NASA/GSFC)*

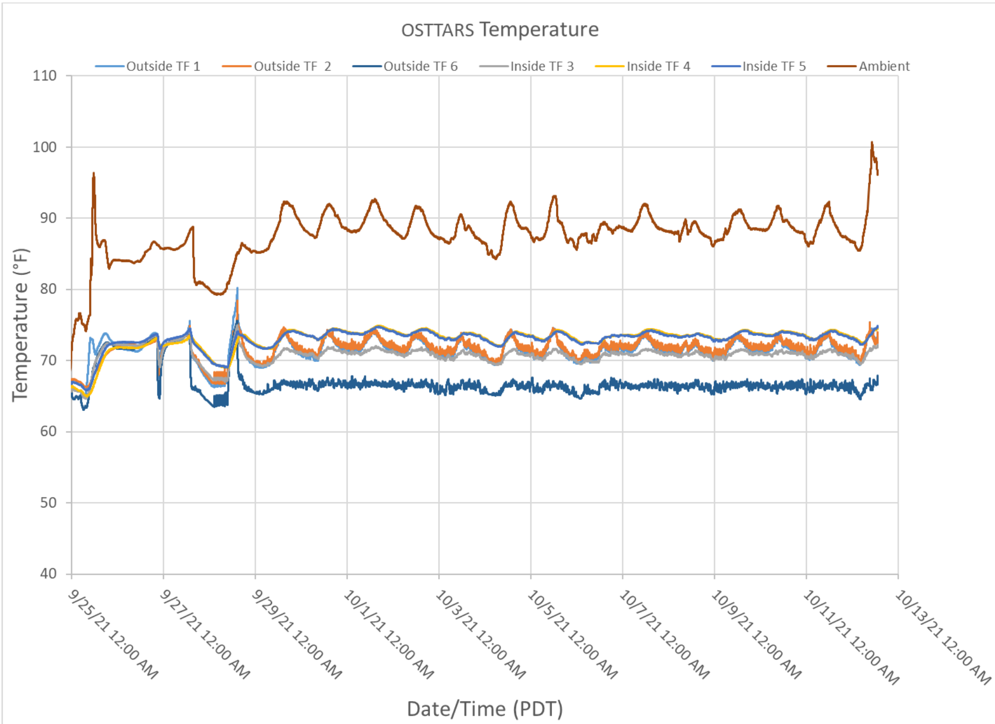

Figure 17. OSTTARS temperature data for the JWST transport to CSG. TF in the legend refers to the tent frame. *(Credit: NASA/GSFC)*

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