

Overview of contamination control for the James Webb Space Telescope launch campaign

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ABSTRACT

The James Webb Space Telescope (JWST) is a large, infrared space telescope operating at Lagrange point 2. JWST is a joint effort between NASA, ESA, and CSA and was launched from the Centre Spatial Guyanais (CSG) on an Ariane 5 rocket in December 2021. The three-month launch campaign utilized enhanced contamination controls to meet JWST's strict cleanliness requirements. Prior to launch, JWST was permitted to only be exposed to ISO Class 7 cleanrooms, whereas the processing facilities at CSG are ISO Class 8. NASA, ESA, Arianespace, and CNES implemented temporary upgrades to the nominal contamination control operations for the launch campaign unique to JWST, including the use of vetted, portable High Efficiency Particulate Air (HEPA) filter walls, pre-entrance cleanliness acceptance surveys of each facility and the intra-plant transporter, tightened cleanroom protocols, upgraded garmenting and laundering techniques, cleaning of Self-Contained Atmospheric Protection Ensemble (SCAPE) suits, increased maintenance, staffed pre-cleaning stations, adaptation of the house purge network, and a contamination control enclosure atop the Ariane 5 launcher prior to fairing encapsulation. The Ariane 5 fairing interior and Vehicle Equipment Bay membrane also received multiple cleanings, detailed inspections, and verification sampling to achieve necessary cleanliness levels. The fairing itself was specially sealed to protect the inner environment with just a small, doored porthole accessible via diving board for final closeout of the purge interface. All these enhancements together allowed JWST to meet its contamination requirements for launch, ensuring successful post-separation deployments and mission science.

Keywords: James Webb Space Telescope, launch, contamination, Ariane 5, Centre Spatial Guyanais, clean facility

1. INTRODUCTION

1.1 James Webb Space Telescope

The James Webb Space Telescope (JWST) is a large observatory designed to seek out knowledge of First Light, how galaxies were first assembled, the birth of stars and planetary systems, and the origins of life. JWST's major external optics include a 6.5 m diameter primary mirror (PM) optimized in the infrared (IR) to collect faint light signals from billions of years in the past and a 0.7 m focusing secondary mirror (SM). Both optics were exposed to numerous facilities for over a decade of integration and test (I&T) at various locations in North and South America, ending with the 3-month launch campaign at the Centre Spatial Guyanais (CSG) in French Guiana.

JWST consists of three major components, shown in Figure 1, including the Optical Telescope Element (OTE), the Integrated Science Instrument Module (ISIM), and the Spacecraft Element (SCE). The two most critical items with respect to launch site contamination control were the OTE, given its exposed PM and SM carrying very tight particulate cleanliness requirements for the telescope's high sensitivity and light throughput, and the ISIM, due to the science instruments' vulnerability to fibers. These drivers would define the launch campaign contamination control program. While JWST possessed many other contamination prone aspects, they were inherently covered by the measures taken to protect the OTE and the ISIM.

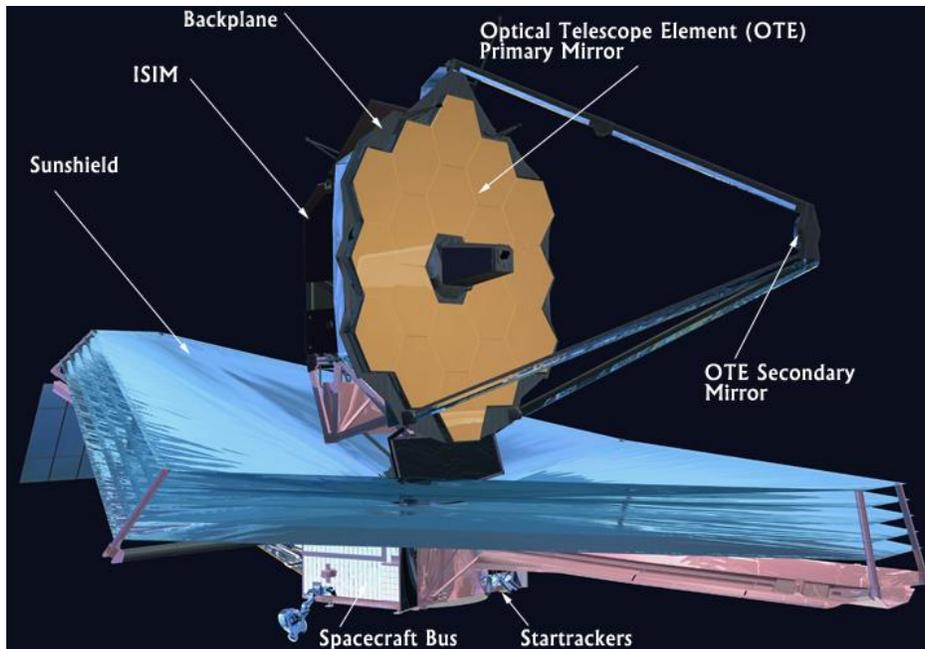


Figure 1. Digital image of JWST showing the locations of the OTE's PM, SM, and Backplane, the ISIM, and the SCE's Sunshield, Spacecraft Bus, and Startrackers. (Credit: NASA)

1.2 Ariane 5

The European Space Agency (ESA) provided JWST's launch services using the Ariane 5 Launch Vehicle (LV) as part of an international collaboration agreement between the National Aeronautics and Space Administration (NASA), ESA, and the Canadian Space Agency. Ariane 5, shown in Figure 2, is the European heavy-lift space LV developed and operated by Arianespace for ESA. It is launched from CSG in French Guiana and provides a variety of mission opportunities, ranging from the typical 10-ton payload in Geostationary Transfer Orbit to 20 tons in Low Earth Orbit, and is also capable of custom trajectories such as those required for Rosetta, Herschel, Plank, and JWST.



Figure 2. Ariane 5 LV at CSG awaiting the JWST launch. (Credit: ESA/S. Corvaja)

The unique nature of the JWST mission led to various adaptations of the Ariane 5 launch system to fulfill stringent technical and cleanliness requirements along the launch preparation. Ariane 5 performed a specially developed rolling maneuver to avoid exposure of any fixed position of the telescope relative to the Sun. The fairing was fabricated with modified vents to prevent the risk of depressurization that could damage the payload during fairing jettison¹ and custom

seals to protect the inner environment, ensuring the equivalent of International Organization for Standardization (ISO) Class 7 air cleanliness. The fairing received multiple cleanings and inspections throughout its development. During the JWST launch campaign, VA256, the Final Assembly Building Encapsulation Hall (BAF HE) was deeply cleaned and equipped with dedicated portable High Efficiency Particulate Air (HEPA) filter walls.² The BAF Composite Hall (BAF HC) was upgraded with a removable clean containment, dubbed the "Air Shower Curtain" (AShC), between its mobile platforms surrounding JWST, and the dedicated air supply system was equipped with HEPA and Airborne Molecular Contamination (AMC) filters installed in the umbilical mast.

JWST was integrated with the Ariane 5 and then launched in December 2021. Figure 3 shows digital renderings of JWST inside the fairing.



Figure 3. Digital images of the stowed JWST inside the Ariane 5 LV. (Credit: NASA/ESA/Arianespace)

2. JWST LAUNCH CAMPAIGN CONTAMINATION REQUIREMENTS AND IMPLEMENTATION

2.1 Requirements

Contamination requirements for the launch campaign were defined as particulate and molecular allocations for the PM and the SM and derived from overall mission systems and science objectives and the current cleanliness of the hardware nearing the campaign. The allocations encompassed the entire period from arrival at CSG until launch and were budgeted by time spent in each facility. The particulate allocations, presented in Percent Area Coverage (PAC), were the main concern given the hardware's sensitivities, cleanliness levels approaching shipment to the launch site, and knowledge of the CSG environments. Molecular allocations were presented as deposition thickness in angstroms (Å). The overall launch campaign allocations are shown in Table 1 relative to their End-of-Life (EOL) requirements.³

Table 1. PM and SM particulate and molecular contamination allocations for the launch campaign against their EOL requirements.

Phase	PM		SM	
	Particulate (PAC)	Molecular (Å)	Particulate (PAC)	Molecular (Å)
Launch Campaign Allocation	0.60	15	0.42	15
Mission EOL Requirement	1.50	300	0.50	300

An additional requirement to prevent water deposition on JWST through temperature and relative humidity controls was also levied on the project.⁴ Compatible temperature and relative humidity ranges and change rates were specified for all launch campaign environments to avoid hardware crossing any dew point and collecting water.

2.2 Implementation for integration and test

JWST's contamination control program prior to the launch campaign focused on maintaining flight hardware as clean as possible throughout I&T. Special precautions were implemented for surfaces that were inaccessible or risky to clean, such as the PM, SM, and science instrument pick-off mirrors, though certain cleaning procedures were designed and executed for the exterior optics.⁵ The science instruments, for example, were continuously purged with dry, clean, manufactured air.

I&T operations were conducted in ISO Class 7 or better clean areas, often utilizing ISO Class 6 protocols. The facility cleanliness class requirement applied to all locations leading up to the launch campaign, and operations that were conducted outside of ISO Class 7 or better facilities required present JWST components to be sufficiently isolated from the surrounding environment. Consequently, upgrades were necessary for processing JWST in CSG's ISO Class 8 facilities.

Continuous monitoring of I&T facilities and hardware surfaces verified compliance and triggered corrective actions throughout. Flight hardware inspections were embedded in the I&T workflow, and routine work area inspections were conducted with white and ultraviolet (UV) flashlights and the facility lights dimmed or turned completely off. Facilities were cleaned daily, and all Ground Support Equipment (GSE) was required to be at least as clean as nearby flight hardware. The contamination control team maintained a crew of engineers and technicians present in I&T facilities during all operations to provide in-situ support and prevent schedule delays or protocol disobedience.⁶ Material restrictions in the clean areas were also strictly enforced.

These practices produced a successful I&T program and were brought to CSG to maintain that success during the launch campaign.

2.3 Training sessions

A series of contamination control training sessions were conducted at CSG, Northrop Grumman's Space Park Facility, and virtually to familiarize all personnel requiring access to any of the cleanrooms at CSG during the launch campaign. The training sessions included a brief overview of JWST's sensitive surfaces, the necessity for contamination control measures throughout I&T, the facilities planned for use, contamination control implementations, personnel garmenting procedures, hardware ingress and egress procedures, material restrictions, and general best practices. The training package customized sections already used at the Goddard Space Flight Center (GSFC) and the Johnson Space Center (JSC) for JWST for the CSG facilities, incorporating cleanroom layouts, gowning nuances, and the unique equipment developed for the launch campaign. In-person sessions included live demonstrations of the gowning procedure, performed either by the instructor or a student volunteer, and virtual sessions relied on videos of the procedure recorded at CSG. Participation was mandatory for access to any CSG cleanroom having already passed a Pre-Entrance Acceptance Survey, and cards were issued to each participant indicating their approval for entrance. An example card is shown in Figure 4.

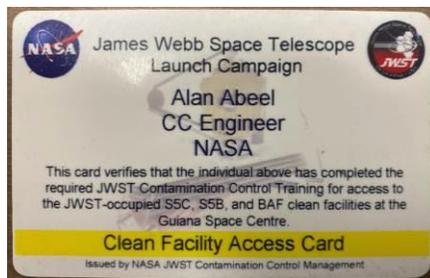


Figure 4. Example Clean Facility Access Card granted to contamination control training session participants for deposit and retrieval at cleanroom entrances.

Cards were deposited in racks when entering the gowning rooms and retrieved upon exit. This allowed the contamination control team to monitor the personnel count inside of the cleanroom and ensure all individuals inside were approved for entrance at any given time.

2.4 Observatory Space Telescope Transporter for Air, Road, and Sea

JWST was shipped to CSG in a custom transporter capable of supporting multiple travel methods. At 33.5 m long, 5.5 m tall, and 4.5 m wide, the Observatory Space Telescope Transporter for Air, Road, and Sea (OSTTARS) is a massive, mobile cleanroom capable of keeping its sensitive cargo protected from outside, contaminating environments. OSTTARS is an upgrade of JWST's original STTARS, retrofitted to accommodate the full Observatory. It is equipped with robust air conditioning and filtration, cleanable components, an inner hard-shell chamber, and built-in purge line provisions. The interior surfaces of OSTTARS were thoroughly cleaned and inspected with white and UV flashlights by the CC team prior to loading flight hardware.

JWST utilized STTARS for its large subassemblies and test article, including the Optical Telescope Element + Integrated Science Instrument Module, backplane, and Pathfinder to safely traverse the United States via road and air. The transporter was movable by truck and airplane. However, for the full Observatory journey to French Guiana, OSTTARS traveled via ship from Los Angeles, CA to Kourou through the Panama Canal.⁷ Figure 5 shows the loaded OSTTARS arriving at CSG and then being opened inside of the S5C Payload Preparation Facility (PPF) airlock.



Figure 5. JWST inside OSTTARS arrives at CSG in French Guiana on October 12, 2021 (left) and is opened inside the S5C PPF airlock (right). (Credit: NASA and ESA/CNES/Arianespace/Optique vidéo du CSG - P. Piron)

3. CSG FACILITIES

3.1 Introduction

CSG is located between the two cities of Kourou and Sinnamary, as shown in Figure 6, and has been operational since 1968. The Center covers an area as large as the city of Paris and provides state-of-the-art Spacecraft Preparation Facilities (SPF) operated by Arianespace and Centre National d'Etudes Spatiales (CNES) equipped to process several spacecraft from different customers simultaneously.⁸ VA256 operated in parallel with three other campaigns on three different launchers involving five spacecraft.

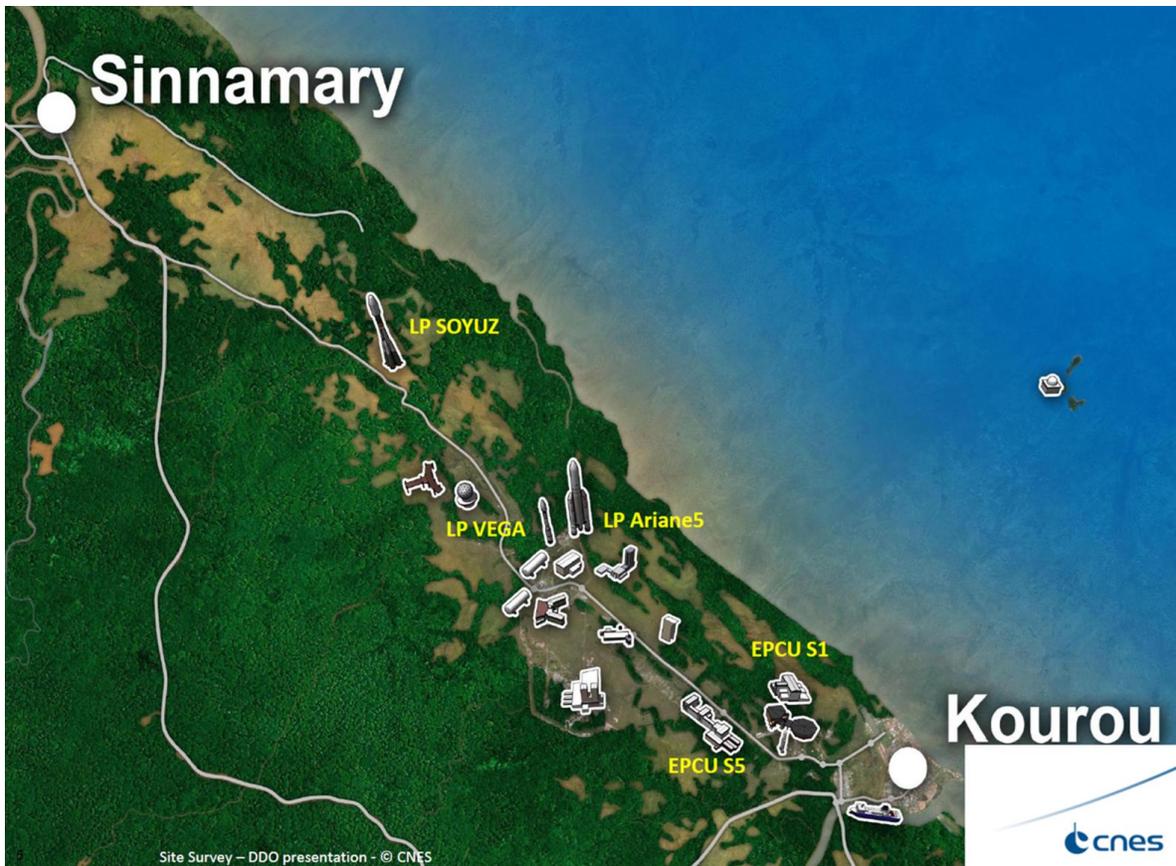


Figure 6. The front gate and Technical Center at CSG. (Credit: CNES)

For a standard launch campaign, the spacecraft arrives in French Guiana at the Port de Pariacabo in Kourou or Félix Eboué Airport in Cayenne and is brought to the Ensemble de Préparation des Charges Utile (EPCU). Campaigns begin in the PPF with fuel-free operations such as functional, electrical, mechanical, and fluidic checks. Once the payload is fully prepared, it is fueled in a dedicated Hazardous Processing Facility (HPF) and then moved to the BAF to be integrated and encapsulated on top of the launcher leading up to liftoff. Each payload is moved within CSG inside a dedicated transporter, Conteneur Charge Utile (CCU).⁸ JWST used the CCU3.

All CSG facilities used for housing spacecraft, including cleanrooms, airlocks, and CCUs, nominally comply with ISO Class 8 parameters and maximum hydrocarbons deposition of $0.5 \text{ mg/m}^2/\text{week}$.⁸ Monitoring, controls, and analysis of contamination and cleanliness are regularly performed, allowing for continuous verification of the environments that every spacecraft experiences from arrival at CSG until liftoff. Specific adaptations of the baseline operational plan were introduced for VA256, and the facilities selected were S5C as the PPF, S5B as the HPF, and both the BAF HE and BAF HC for final integration with the LV.

3.2 EPCU S5

The S5 complex of the EPCU is located close to Route de l'Espace, approximately 3 km northwest of the CSG main entrance. S5 is a safe 10 km southeast of the Ariane Launch Sites (ELA), allowing spacecraft teams to remain in place during launch countdowns. The complex is approximately 7000 m² large and is primarily comprised of three main areas, S5A, S5B, and S5C, interlinked by two access corridors. It also includes two disconnected buildings for decontamination, S5D, and Self-Contained Atmospheric Protection Ensemble (SCAPE) preparation, S5E. The complex's layout is shown in Figure 7.⁸



Figure 7. JWST arriving in OSTTARS at the EPCU S5 complex. (Credit: ESA/CNES/Arianespace/Optique vidéo du CSG – P. Baudon and E. Prigent)

3.3 S5C PPF

The EPCU S5C PPF, shown in Figure 8, is located at the far west of the S5 complex and is linked by clean corridors to S5A and S5B. S5C includes two identical ISO Class 8 cleanrooms separated by a removable curtain with a shared airlock capable of hosting two satellites during parallel launch campaigns, office areas, meeting rooms, and electrical checkout rooms equipped with direct feeds into the cleanrooms.⁸ The two cleanrooms were combined for the JWST campaign.



Figure 8. S5C outside view (left) and JWST inside the S5C PPF cleanroom (right). (Credit: Arianespace and ESA/CNES/Arianespace/Optique vidéo du CSG – P. Piron)

Major JWST operations that occurred in the S5C PPF included unloading from OSTTARS in the airlock, tilting, mechanical preparation, electrical checkouts, functional acceptance testing, mating with the LV adapter, and arming of the pyrotechnic separation system in the combined cleanrooms, and installation of JWST into the CCU3 for transport to the S5B HPF. Preparation of the facility to house JWST required extensive cleaning, detailed inspections, protection of potential contamination sources, erection of portable HEPA filter walls, and configuration of a dedicated purge network.

3.4 S5B HPF

The EPCU S5B HPF, shown in Figure 9, is located at the far east of the S5 complex and is linked by clean corridors to S5A and S5C. S5B includes an ISO Class 8 cleanroom and airlock, a fuel tank transfer room, and a fueling preparation anteroom.⁸ The clean corridors were not usable for JWST's transfer due to an unsafe height margin.



Figure 9. S5B outside view (left) and JWST inside the S5B HPF cleanroom (right). (Credit: Arianespace and ESA/CNES/Arianespace/Optique vidéo du CSG – P. Piron)

The S5B HPF cleanroom was used to inject JWST's liquid propellant and pressurize its fuel tanks. The airlock was used to receive JWST from the CCU3 and reinstall into the CCU3 for transport to the BAF. Preparation of the facility to house JWST required a repeat of the activities used to prepare the S5C PPF and coordination of a SCAPE suit cleaning process unique to VA256.

3.5 BAF

The BAF is located approximately 2.6 km south of the ELA with a railroad connecting the facility with the ZL3 launchpad. The building is approximately 4500 m² large with a total air-conditioned volume of 280,000 m³ and is primarily comprised of two main areas, the BAF HE and BAF HC. The facility is fit for final preparation of the LV on the Ariane 5 Launch Table, integration of spacecraft onto the LV, and fairing encapsulation before transport to the ZL3. The exterior and path to the ZL3 are shown in Figure 10.⁸



Figure 10. BAF exterior and Ariane 5 transfer from the BAF to the ZL3. (Credit: Arianespace)

3.6 BAF HE

The BAF HE, shown in Figure 11, includes the horizontal segment of the building and is comprised of a 900 m² cleanroom and 570 m² airlock. It is linked to the BAF HC by a transfer chimney in the airlock for hoisting spacecraft and fairings to the LVs.⁸



Figure 11. BAF HE cleanroom housing JWST and the Ariane 5 and Ariane 6 fairings (left), BAF HE airlock during JWST's hoist to the LV (center), and Ariane 5 fairing passing through the chimney (right). (Credit: ESA/CNES/Arianespace/Optique vidéo du CSG)

The BAF HE was used to prepare the Ariane 5 fairing and receive JWST inside the CCU3 before mating with the LV. Operations on the fairing, among electrical, mechanical, and cosmetic activities, included final cleanings and cleanliness inspections of the interior and exterior. Preparation of the facility to house JWST required a repeat of the activities used to prepare the S5C PPF and wrapping of additional potential contamination sources on the Ariane 6 fairing scaffold, which was in a work-in-progress configuration.

3.7 BAF HC

The BAF HC, shown in Figure 12, includes the vertical segment of the building and houses the Launch Table and LVs. It includes mobile ISO Class 8 work platforms, the lower Plate-Forme Elévatrice Inferieure (PFEI) and upper Plate-Forme Elévatrice Superieure (PFES), that move vertically for access to various heights of spacecraft, fairings, and LVs.⁸



Figure 12. JWST inside the BAF HC before encapsulation. (Credit: ESA/CNES/Arianespace/Optique vidéo du CSG)

The BAF HC was used for JWST's integration with the LV, final electrical checkouts, final mechanical closeouts, and fairing encapsulation. Preparation of the facility to house JWST required extensive cleaning, detailed inspections, protection of potential contamination sources, and configuration of a dedicated purge network. However, the HEPA filter walls could not be installed on the platforms due to their size and mass, so the AShC, shown previously in Figure 12, was installed around the top of the LV prior to fairing encapsulation to protect the environment. The local air supply system was equipped with AMC and HEPA filters in the umbilical mast, which was used for flooding both the AShC and fairing with clean air.

3.8 CCU3

The CCU3, shown in Figure 13, is used to transfer spacecraft between various integration buildings across CSG. The transporter is designed to protect spacecraft from shock and vibration and provide an environment compatible with

predefined cleanliness, conditioning, and overpressure requirements. Inflatable seals ensure the structure is airtight and combined with the pressurization system, prevent outside air from entering the interior.⁸

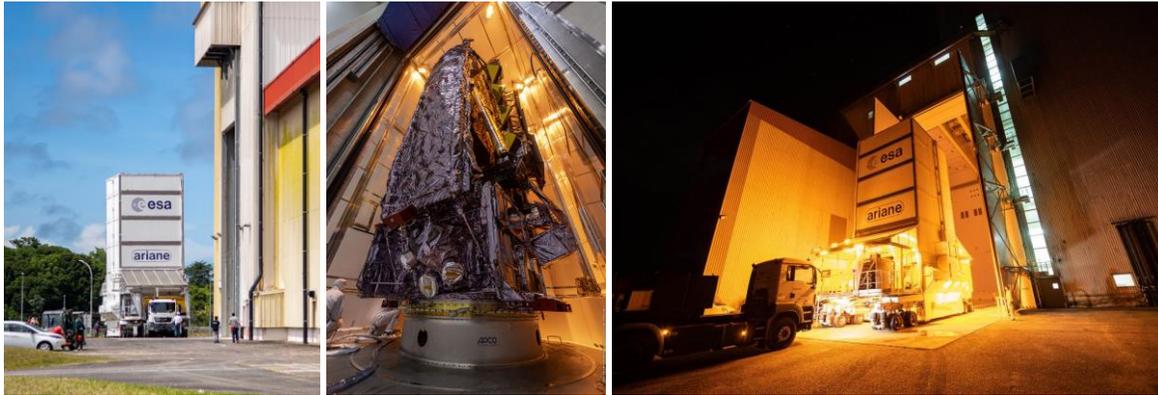


Figure 13. CCU3 transport from S5C to S5B (left), JWST inside the CCU3 (center), and CCU3 arrival at BAF HE. (Credit: ESA/CNES/Arianespace/Optique vidéo du CSG)

JWST moved twice in the CCU3, from S5C to S5B and from S5B to the BAF, utilizing its cable pass-through port to connect its purge system. Key internal environmental parameters were recorded and transmitted in real time via wireless connection to a radio receiver following the convoy. Several shock recorders were also utilized and immediately analyzed after the transports. The CCU3 was thoroughly cleaned and inspected prior to each transport, and no contamination events occurred.

4. OPERATIONAL AND FACILITY UPGRADES

4.1 Portable HEPA walls

To temporarily upgrade the CSG facilities' ISO Class 8 architecture to meet ISO Class 7 air particle counts, the JWST project procured a series of 12 portable HEPA modules that were assembled as walls in configurations customized to each facility. The HEPA modules included carbon pre-filters and full coverage HEPA filters. HEPA wall stacks were comprised of two modules, stacked one on top of the other, on rolling dollies that allowed for easy movement inside the cleanrooms. Each wall included one to three stacks depending on the floorspace of the facility. Prior to procurement, the project collaborated with Jacobs Engineering to perform a series of Computational Fluid Dynamics (CFD) analyses to determine what compatible set-ups would maximize air cleanliness. Jacobs ran simulations using the existing S5C PPF and S5B HPF layout and various arrangements of HEPA walls with a JWST avatar. The CFD analyses ultimately demonstrated that push-push configurations in each facility allowed filtered air to reach the most of JWST's critical surfaces. The use of a return wall was ineffective as JWST's sheer size prevented airflow from sufficiently traversing the area inside the HEPA envelope. Figure 14 below shows the push-push configuration of three HEPA stacks per wall with the JWST avatar inside the S5C PPF from horizontal and top-down perspectives.⁹

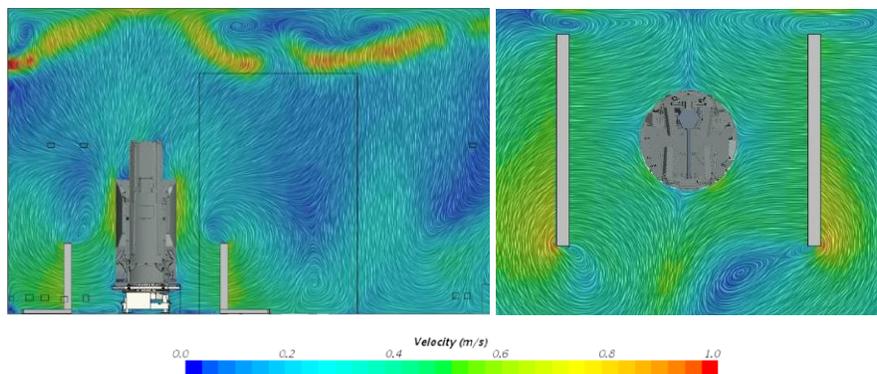


Figure 14. Horizontal (left) and top-down (right) views of the CFD simulation of push-push HEPA configuration with vertically oriented JWST inside the PPF. (Credit: Jacobs Engineering/A. Khazari, A. Flynt, and P. Agarwal)

The HEPA modules were purchased from Atmos-Tech Industries and initially delivered to GSFC for verification check-outs and facility simulation testing. Upon arrival, each module was assembled and thoroughly cleaned inside an ISO Class 8 cleanroom. The modules underwent a suite of verification measurements to confirm their compliance with specifications developed by the contamination control team, including hydrocarbon output, airflow velocity, filter leakage, and heat gain. The first two modules also underwent a 48-hour air particle and particle fallout test prior to the authorization for Atmos-Tech to manufacture the remaining 10 units. Once the entire set passed verification measurements, the HEPA stacks were relocated to an uncontrolled, non-cleanroom high bay for testing. 3 tests were run representing the three facilities JWST would use at CSG. The S5C PPF layout included three HEPA stacks per wall, the S5B HPF layout inside one stack per wall, and the BAF HE layout included two stacks per wall. Each test also included a mock-up of the WFIRST satellite as JWST surrogate since the CFD analyses demonstrated that a large obstruction would significantly affect airflow but no JWST mock-up was available. The test floor arrangements aligned with planned campaign layouts. Each test ran for 2 weeks and included continuous air particle counts, particle fallout wafers, and non-volatile residue (NVR) foils both in between and outside of the HEPA walls. The results exhibited improvements in air particle counts from 83-99%, particle fallout improvements of 79-91%, and molecular improvements of 50-90%.² Figure 15 shows the test layout of the S5C PPF simulation.



Figure 15. S5C PPF simulation testing inside the GSFC uncontrolled Building 29 high bay with HEPA walls of 3 stacks each and the JWST surrogate. (Credit: NASA/Z. Huang)

Once testing was complete, the HEPA modules were moved back to the ISO Class 8 cleanroom, disassembled, cleaned, and packaged for transportation to CSG. The HEPA filters were each double-bagged and carbon filters double-bagged in groups of three using polyethylene. The modules were also wrapped in polyethylene.²

At CSG, the HEPA modules were assembled in their planned arrangements and demonstrated the same ability to reduce contamination shown during validation testing at GSFC. The HEPA modules ran continuously in the S5C PPF and BAF HE but were shut off during Explosive Atmosphere (ATEX) restricted activities in the S5B HPF. Figure 16 shows the HEPA walls in each of the three CSG facilities.



Figure 16. Portable HEPA stacks in the S5C PPF (left), S5B HPF (center), and BAF HE (right) fostering a clean environment for critical JWST operations at CSG. (Credit: NASA/C. Gunn, ESA/CNES/Arianespace/Optique vidéo du CSG, and ESA/M. Pedoussaut)

4.2 Pre-entrance acceptance surveys

Before JWST’s entrance into each facility, the NASA, ESA, Arianespace, and CNES teams performed initial walkthroughs to identify and mitigate contamination threats. This included removing or bagging extra equipment unnecessary for JWST activities, bagging needed items that were potential contamination sources and did not conform to JWST materials restrictions, cleaning all surfaces, and collecting baseline air particle counts, as shown in Figure 17. Required equipment that included lubricated surfaces, motors, chipping paint, sand, or unapproved insulation jacketing were wrapped or sleeved with either static-dissipative, polyethylene, or polyvinyl fluoride (PVF) bagging. PVF was the only approved bagging material for use in ATEX-restricted areas.



Figure 17. Bagging and sleeving of potential contamination sources in the S5C PPF and BAF HE cleanroom. (Credit: ESA/CNES/Arianespace/Optique vidéo du CSG)

After full scale cleanings and corrective and preventive actions were completed, the teams performed facility lights-out inspections using white and UV flashlights to further identify and then mitigate unobvious contamination accumulation areas, such as coiled cables and hoses, as shown in Figure 18 and Figure 19.



Figure 18. Pre-entrance lights-out inspection in the S5C PPF. (Credit: ESA/CNES/Arianespace/Optique vidéo du CSG)



Figure 19. Coiled cable under UV light (left) and then bagged for protection (right) in the S5C PPF.
(Credit: ESA/CNES/Arianespace/Optique vidéo du CSG)

Daily maintenance of each facility commenced after all findings were addressed and the teams together issued and signed pre-entrance acceptance reports.

4.3 Laundry facility

Typical garment laundering during JWST's assembly, integration, and testing at GSFC, JSC, and Northrop Grumman occurred in regular cycling of soiled cleanroom coveralls, boots, and hoods to and from a third-party launderer. Used garments would be shipped off site on a regular basis as clean garments were returned to ensure a constant supply and avoid disruptions. This format was practical in the United States because the third-party launderer operated several facilities across the country and could streamline the shipping and receiving process. The launderer also adhered to strict laundry techniques, including the use of fragrance-free detergents, verified clean machines, controlled facilities, and double-bagging and vacuum sealing cleaned garments. The launderer also performed drum testing to verify cleanliness of garments before returning them to JWST.

However, shipping garments for laundering from CSG to the United States was a challenging and long process. The estimated turnaround time was not compatible with the up-tempo launch campaign, and dependence on laundry cycling would have presented schedule and costs risks. While the JWST project did ship two loads of garments back to the United States for laundering during the launch campaign, the baseline plan included bringing a large sum of NASA garment sets initially and transforming CSG's on-site laundry facility in S5E to clean CSG garments in a way to meet the project's needs. Because drum testing for cleanliness verification of garments was unavailable, the CC team mandated that garments cleaned on site only be used for non-flight-but-clean operations, such as facility preparation, advanced training, and pre-entrance acceptance surveys. Making these garments available to the launch campaign allowed the project to reserve the verified clean NASA garments for flight and critical operations. In collaboration and led by Cole Horton and Ismael Rodriguez, the teams made the following upgrades to the on-site laundry process:

1. Lined rooms used for processing cleaned garments with polyethylene and covered contamination sources,
2. Obtained air particle counts from the air conditioner,
3. Donned coveralls, hair nets, and shoe covers for processing cleaned garments,
4. Inspected cleaned garments with white and UV flashlights,
5. Double-bagged cleaned garments after inspections,
6. Cleaned and performed daily inspections of the interiors of washing and dry machines with white and UV flashlights,
7. Reviewed and approved chemical compositions of detergents.¹⁰

Figure 20 includes photographs of the CSG S5E facility preparations.



Figure 20. The contamination control team lays polyethylene throughout the S5E folding and packaging room and obtains air particle counts from the air conditioner. (Credit: NASA)

4.4 SCAPE suits cleaning

The traditional satellite fueling process at CSG begins with technicians donning SCAPE suits in the S5E facility and transferring via shuttle to the S5B HPF. However, boarding and exiting the shuttle included exposure of the SCAPE suits to the outside environment, which rendered the process a contamination risk for JWST. Led by Kimberly Morales and Florent Delamare, the teams explored several options for mitigation and ultimately crafted a procedure that included dressing the fueling technicians in a pre-cleaned S5B HPF anteroom, shown in Figure 21, and a touch-up cleaning of the SCAPE suits after their donning. The team prepared the S5B HPF anteroom by removing contamination sources, covering sources that could not be removed, vacuuming and wiping or mopping all surfaces with high-purity isopropyl alcohol (IPA), and inspecting each surface with white and UV lights. The team maintained the anteroom's cleanliness with daily cleaning and inspection throughout the entire fueling phase.¹⁰



Figure 21. Technicians prepare for fueling inside the prepared S5B HPF anteroom. (Credit: ESA/CNES/Arianespace/Optique vidéo du CSG – P. Piron)

Cleaning of the SCAPE suits was three-fold: the suits continued to be cleaned per CSG's nominal laundering procedure in the S5E facility but were then vacuumed upon delivery to the S5B HPF anteroom and precision cleaned on the technicians just prior to entering the cleanroom and interfacing with JWST. The precision cleaning process included re-vacuuming of the suits, helmets, gloves, and boots and then wiping each component with sealed-edge cleanroom wipers and either IPA or demineralized water since the rubber components were not IPA-compatible. The SCAPE suits were then inspected with white and UV lights to verify cleanliness and logged for traceability. Figure 22 below shows CC technicians vacuuming and inspecting SCAPE suits being worn by fueling technicians just prior to JWST fueling operations.¹⁰



Figure 22. Contamination control technicians vacuum (left) and UV flashlight inspect (right) SCAPE suits donned by fueling technicians in the S5B HPF anteroom. (Credit: ESA/CNES/Arianespace/Optique vidéo du CSG – P. Piron)

4.5 Purge adaptations

Certain scientific instruments aboard JWST were subject to irreversible stiction if the relative humidity exceeded 60% during ground processing. Of the environments JWST experienced at CSG, only the pre-launch fairing interior that was continuously flushed with ultra-dry manufactured air provided a reliable control system compatible with this requirement. Therefore, dry purging was necessary to maintain conforming humidity levels and provide a safety margin during all operations prior to liftoff.

The introduction of a continuous purge system required several adjustments to CSG facilities and processes, including the installation of stationary purge networks in S5 and the BAF, mobile networks for the CCU3 and transfer from the BAF to ZL3, and provisions for purge disconnections during JWST integration with the LV and fairing encapsulation. It also required that the temperature of the air injected into the fairing during the transfer between the BAF and ZL3 be increased by 3°C to keep the relative humidity within the acceptable limit.

The purge system consisted of a dry air supply, a control, filtration, and monitoring unit, and a distribution network leading to the sensitive science instrument interfaces. The air supply consisted of portable racks of pressurized dry air bottles kept outside of the cleanrooms, and the distribution network included flexible hoses that fed through pre-installed pass-through ports and accommodated transports between facilities. The BAF alone required routing approximately 250 m of hoses to accommodate the various altitudes JWST experienced during integration with the LV. The control, filtration, and monitoring unit was also kept outside the cleanrooms to eliminate sources of contamination and provide easy access for check-ups and adjustments. CCU3 transports utilized a smaller iteration of the purge system to simplify the two trips.

Other than quick and negligible purge outages for transitioning back and forth from the stationary to mobile purge networks, two longer outages were planned for and managed during the campaign. These occurred during the lift of JWST to the LV and fairing encapsulation. The outage durations were within allowable limits, and disconnections only occurred after the teams verified that the relative humidity of the respective environments had consistently remained under 60%. In addition, an aerial work platform was installed on the PFEI to disconnect the purge at the last possible and safe moment just before fairing encapsulation. The platform and timing both prevented any operator activity underneath the suspended fairing and minimized the total time of the outage. The purge line was reconnected as soon as the fairing was lowered onto dedicated supports. The final purge disconnection after encapsulation occurred only once the required ventilation condition inside the fairing was verified. For this operation, an extendable diving board platform was introduced on the PFEI and cranked into the fairing through a special access door uniquely added for JWST.

4.6 Pre-cleaning stations and regular maintenance

Throughout the JWST integration and test phases at GSFC, JSC, and Northrop Grumman's Space Park facility, the contamination control team performed regular maintenance of the cleanrooms and operated cleaning stations to prepare flight hardware, tools, and any equipment needed inside of the cleanrooms. The team continued these practices in each of the CSG facilities used for the JWST launch campaign to ensure facility and resource cleanliness and screen items

needed by every team. The cleaning stations operated in both a built-in equipment airlock attached to the S5C PPF and portable, HEPA-filtered clean tents erected in the airlocks of the S5C PPF and BAF HE. The cleaning stations were equipped with wipers, vacuums, white and UV lights, stainless steel tables and chairs, and an array of approved solvents, tapes, and bagging materials. They offered a simple approach for teams to drop off items, fill out a form, and retrieve their cleaned, inspected, and bagged (if necessary) items for use in the JWST-occupied cleanrooms. Operators were ensured their items coming out of the cleaning stations were approved for use by JWST contamination control in accordance with their purpose as described in the form. The cleaning stations employed consistent operating hours, aligning with flight hardware and facility preparation activities. This provided a hassle-free system for meeting contamination control impositions while minimizing schedule risk. Figure 23 shows the portable cleaning station in the S5C PPF airlock.



Figure 23. Cleaning station in the S5C PPF airlock during JWST transfer into the CCU3.
(Credit: ESA/CNES/Arianespace/Optique vidéo du CSG – P. Baudon)

Regular maintenance of the cleanrooms was critical for keeping JWST clean during all operations. After the pre-entrance acceptance surveys of each facility were complete, the contamination control team initiated daily cleaning activities to maintain the cleanliness achieved ahead of JWST's arrival throughout its residency. The contamination control maintenance program was governed by a log that listed each maintenance task with its necessary frequency. Technicians initiated the task under the given shift and day. The log was designed as a monthly schedule, allowing the team to confirm task frequencies were being met. Many tasks were required daily, while some were deemed necessary to be performed each shift (twice/day), and some only needed to be performed weekly. Daily maintenance included vacuuming and wet-mopping of all floors, solvent-wiping of horizontal surfaces, cleaning the gowning rooms, removing trash, pulling tacky mats, and cleaning the JWST mounting fixture. Because the man lifts were used often and for long durations, the contamination control team cleaned each of them every shift. Weekly tasks revolved around changing out cleanroom garments and replenishing gowning room supplies, though certain project activities occasionally necessitated an increase in that frequency.

4.7 AShC

Starting from JWST integration with the LV through fairing encapsulation in the BAF HC, the work environment needed to remain compatible with JWST cleanliness constraints while maintaining the ability to work in its vicinity without electrostatic discharge (ESD) concerns. Therefore, supplemental protection from the nominal ISO Class 8 BAF HC environment was needed in addition to provisions on the bottom of the JWST-LV interface by the PFEI being in contact with the LV structure and on the top by the PFES with the Manhole Cover. A contamination control enclosure, called the AShC and shown in Figure 24, was built to isolate the work area around JWST after integration with the LV.¹¹ The AShC was supplied with the same upgraded air supply system used to pressurize the fairing after encapsulation.



Figure 24. AShC deployed around JWST in the BAF HC during fairing encapsulation.
(Credit: ESA/CNES/Arianespace/Optique vidéo du CSG – S. Martin)

Two other constraints were levied on the AShC to be compatible with the launch campaign flow. The AShC had to be removable to prevent its own contamination when the BAF was opened to receive the LV prior to JWST integration, and it had to be flexible to allow for up-and-down movement of the PFES with respect to the PFEI. While the AShC ideally would have only been installed after the LV arrived, the tremendous effort needed to clean it and verify its cleanliness necessitated two formal cleaning events. However, the schedule could not manage two cleanings between LV arrival and JWST arrival. So, the first cleaning occurred prior to LV arrival, and the second prior to JWST arrival. The initial cleaning reduced the amount of time needed for the second cleaning. Several previous cleanings had also been held ahead of the launch campaign by ArianeSpace with NASA personnel participating in one to train personnel, rehearse the flow, and validate the process.

The AShC was built in accordance with contamination control best practices by completely sealing to pre-existing structures and avoiding uncleanable boxed volumes where dust could accumulate. The transparent, urethane curtain material was selected in consideration of minimizing particulate and molecular contamination and the need to provide

visibility for security and safety cameras installed in the BAF HC. Prior to opening the BAF door for LV ingress, the curtains were stowed in an accordion-like fashion inside a closable, metal basin around the AShC perimeter. This folding pattern also allowed it to remain in place during PFES moves. As the PFES raised, the AShC unfolded with it, and as the PFES lowered, the AShC stowed. A portable, HEPA-filtered gowning room provided access inside the AShC where personnel changed from CSG garments to NASA garments prior to entrance.

The Ariane 5 ventilation system provides six different flow lines for various LV configurations, and only the two allocated to the fairing can be used simultaneously. However, the introduction of the AShC necessitated a third line and therefore required a unique transition from the phase with AShC to the phase with just the two fairing lines. The system also underwent upgrades with respect to air quality. To monitor cleanliness, air particle counters and Volatile Organic Compound (VOC) analyzers were installed in the launch table mast just downstream of the filters and continuously monitored during both ventilation phases. Additional VOC analyzers were installed upstream of the AMC filters to verify their effective use and remaining lifetime. Furthermore, since the nominal ventilation system uses dry air manufactured in a dedicated plant, its relative humidity levels are typically below 5%. However, ESD-safe working conditions require at least 25% relative humidity, so the LV rollout control system was used instead to supply air inside the AShC. This required specific adaptations of its power supply system to avoid using the internal diesel generator, which would have presented contamination and reliability concerns.

4.8 Manhole Cover

Atop the PFES, the teams installed a soft cover to protect the cleanliness of the working area where JWST was installed onto the Ariane 5 interface. The Manhole Cover consisted of a large, PVF tarp and four heavy duty sawhorses used to stabilize and tighten the tarp. The sawhorses were padded with PVF to prevent tears in the tarp and were equipped with hooks to secure the corners of the tarp using cut and reinforced holes. PVF was selected due to its electrostatic discharge and hypergolic compatibilities. Guardrails positioned around the PFES opening remained in place, as the Manhole Cover was designed to safely rest on top. The Manhole Cover was installed just after the AShC and working area was cleaned, temporarily removed for the installation of JWST, and ultimately removed for encapsulation with the Ariane 5 fairing. Figure 25 shows the installed Manhole Cover just prior to JWST integration and removal of the Manhole Cover as JWST is translated above the PFES.



Figure 25. Manhole Cover protecting the inside of the AShC (left) and being removed for JWST integration to the Ariane 5 (right). (Credit: ESA/CNES/Arianespace/Optique vidéo du CSG)

5. ARIANE 5 UPGRADES

5.1 Fairing modifications

The Ariane 5 payload fairing, manufactured by the Swiss company Rüstungs Unternehmen Aktiengesellschaft (RUAG) Space (now Beyond Gravity), is a nosecone used to protect a payload from the impact of dynamic pressure and aerodynamic heating during atmospheric ascent. Once outside Earth's atmosphere, the shroud is jettisoned in two pieces, exposing the payload to outer space and readying the payload to be separated from the LV. The fairing is nearly 17 m tall and measures 5.4 m in diameter, containing room for multiple satellites or a single large observatory like JWST. Because of its size, JWST was folded to fit under the payload shroud of the Ariane 5 rocket for launch. After separation, its solar array, antennas, Sunshield, PM, SM, and radiators deployed to form its final configuration on its way to L2.¹²

ESA, Arianespace, and RUAG modified the design of vents on the Ariane 5's payload shroud to address the concern that a depressurization event could damage JWST when the fairing jettisons after liftoff by residual air trapped in JWST's folded sunshield membranes causing an over-stress condition at the time of fairing separation.¹ Pistons were placed near the purge vents in the fairing to force their opening and maximally reduce any pressure differential between the inside of the fairing where JWST was located and the vacuum of space. This system had been successfully tested on previous launches, including VA252, VA253, and VA254, and was flawlessly utilized for JWST.¹²

Special attention was paid to the fairing's cleanliness, and as in the Herschel/Planck mission case, the clean fairing halves and extension module were protected with clean, polyethylene-aluminum-polyester blankets sealed with high temperature and high tensile strength polyester tape. In addition, a small aluminum cover was installed on each handling point used during assembly and encapsulation. These covers housed filters to facilitate vacuuming and were bonded or screwed to the internal structure of the fairing to prevent particles generated by the installation of lifting brackets or caps from entering the volume.¹¹

5.2 Fairing cleaning

Cleaning of the JWST fairing was primarily performed at the RUAG Space manufacturing facility in Emmen, Switzerland. The facility, scaffolding, and fairing all underwent an initial cleaning prior to a NASA contamination engineer arriving for an inspection and a final cleaning responding to findings. Figure 26 includes images from the cleaning session.



Figure 26. Cleaning and inspection of the JWST fairing at RUAG Space. (Credit: RUAG Space)

Under UV, most of the Fairing Acoustic Protection (FAP) panels showed very few particles and fibers, as each of them had been thoroughly cleaned with a wide-mouthed, HEPA-filtered vacuum. However, there were a few holding a high density of particles and fibers that did not come clean with just vacuuming. RUAG Space personnel began removing the particles and fibers with tape, but the process became time consuming. The RUAG Space quality inspector then devised a simple solution using approved tape rollers that had already been acquired for the cleaning. The process effectively removed the remaining particles and fibers, and all FAP panels passed their UV inspections. Afterward, molecular contamination samples were collected and sent for analysis. Once passing results were obtained, each fairing half was transferred to its shipping container, bagged, and encased for transport to CSG, as shown in Figure 27.



Figure 27. Fairing halves at RUAG Space being packaged for shipment to CSG. (Credit: RUAG Space)

Upon arrival at CSG, each fairing half was removed from its shipping container and unbagged in the BAF HE airlock. The halves were then transported to the adjacent cleanroom and assembled on scaffolding that had already been cleaned in preparation. A post-shipment inspection inside the fairing was then performed with white and UV flashlights. The dark fairing interior provided a perfect inspection background. Fortunately, the fairing had mostly maintained its cleanliness during shipment, and only a post-shipment touch-up cleaning was necessary.

5.3 Fairing inspections and monitoring

Once the fairing was assembled, a detailed cleanliness inspection of the inner surfaces, including the FAP panels, was performed with white and UV flashlights. The dark fairing interior provided a perfect inspection background. Fortunately, the fairing had mostly maintained its cleanliness during shipment and assembly, and only a post-assembly touch-up by tape-lift, shown in Figure 28, was necessary.



Figure 28. Tape-lift cleaning and inspection of the interior of the fairing with a UV flashlight. (Credit: ESA)

After compliance was declared, the fairing was hoisted from the scaffolding and placed on a temporary storage stand for approximately 3 weeks prior to encapsulation. All openings on the stand were sealed with static-dissipative bagging material to avoid ingress of insects or particles stirred up by the facility's airflow, as shown at the bottom of Figure 29.



Figure 29. Fairing on storage stand with sealed stand openings in the BAF HE high bay. (Credit: ESA)

During storage, particulate and molecular contamination sensors were installed inside to monitor the inner environment and provide notification of contamination build-up in the static state that would necessitate another cleaning. No significant levels were detected. To then monitor the inner environment around JWST after encapsulation, one of the fairing flight doors was temporarily replaced by a tooling door equipped with a set of contamination sensors, including particle fallout plates, a metallic molecular witness plate, and a calcium fluoride optical crystal, as shown in Figure 30.



Figure 30. Fairing tooling door equipped with particle fallout plates (red), metallic molecular plate (purple), and optical crystal (green) temporarily installed to monitor contamination from encapsulation through rollout to the ZL3 (left). The tooling door can be seen inside (center) and outside (right) the fairing before and after encapsulation. (Credit: ESA)

Again, all measurements complied with allocations. The tooling door was removed and replaced with the flight door just prior to rollout to the ZL3.

After encapsulation, the fairing was ventilated with the same dry, HEPA and AMC-filtered air from the umbilical mast used to fill the AShC. Airflow was set to 1 m³/s to sufficiently pressurize the fairing, and cleanliness was continuously monitored with an internal photoionization detector at the injection point and external airborne particle counter at a vent along with the VOC analyzers and airborne particle counters already in use. Temperature and relative humidity were also monitored at same vent. These parameters were verified with handheld devices just prior to installation of the duct to the fairing, and they had previously been verified to minimize any schedule or technical risk resulting from a noncompliant reading.

5.4 Vehicle Equipment Bay cleaning and inspection

The Vehicle Equipment Bay (VEB) membranes, LV cone, and LV interface surface were cleaned and inspected with white and UV flashlights multiple times in collaboration with RUAG leading up to JWST's installation to the LV and fairing encapsulation. The LV interface surface and cone were spot cleaned by delicate vacuuming, and the cone was protected from damage with pads wrapped in PVF that were also cleaned and inspected with white and UV flashlights. The VEB membranes were cleaned by delicate, dry wiping and were protected with hard covers that allowed personnel to safely crawl on to access critical LV and JWST locations. The hard covers were cleaned in place daily by vacuuming and solvent wiping. Figure 31 shows the LV interface surface, cone with wrapped pads, and hard covers protecting the VEB membranes just prior to JWST installation.



Figure 31. LV interface surface, cone, and covered VEB inside the AShC just prior to JWST installation. (Credit: ESA/CNES/Arianespace/Optique vidéo du CSG)

Keeping these areas clean was vital for JWST’s success. Contamination could have migrated by airflow or contact transfer to sensitive JWST areas that were not cleanable on the LV, especially with personnel crawling on the VEB covers to access JWST. Furthermore, iterative cleanings reduced the risk of schedule-halting findings and the amount of time needed for the final cleanings and inspections occurring during the long and critical installation and encapsulation operations.

6. DISCUSSION

6.1 Effectiveness against requirements

Years before the start of the JWST launch campaign, efforts began to estimate the amount of contamination JWST would accumulate during its time at the launch site. The JWST contamination control team scrutinized data from the few available sources, including reports from the Herschel-Plank and Automated Transfer Vehicle missions and facility monitoring history provided by CSG. Based on this data, the team predicted that JWST was at risk of not meeting its EOL particulate cleanliness requirements. Additional data was needed to refine the predictions, so on-site particle fallout tests were conducted during Ground Operations Working Group visits to better characterize the environments to which JWST would be exposed. The predictions were enhanced with these results, and by incorporating coefficients capturing the protection afforded by the portable HEPA modules², surface orientation knockdown factors¹³, deposition rate uncertainty, and cleanroom activity levels, they indicated JWST would likely meet its EOL requirements.³

As JWST progressed through the launch campaign, the data collected showed that the processes, procedures, and special GSE implemented by the NASA, Arianespace, and ESA teams were effective. Particle fallout results in the S5C PPF, S5B HPF, and BAF HE facilities showed 85% less accumulation than predicted. The largest improvement was achieved in S5B. The HPF was anticipated to contribute the highest fallout rate during the campaign, but even though the predicted net accumulation for S5B was 0.18 PAC, the measured particle fallout during operations was only 0.01 PAC.³ Originally, the HEPA modules were expected to be powered off during all fueling operations, but provisions were made to power them on during periods of inactivity. This, coupled with extraordinary maintenance efforts put forth by the contamination control technician team, certainly influenced the result.⁶

Efforts at the launch site resulted in the PM particulate cleanliness being approximately 50% better and the SM approximately 70% better than their EOL requirements. Molecular measurements indicated an even greater achievement. Table 2 compares the launch campaign allocations and EOL requirements with actual measurements obtained at CSG and EOL values.³

Table 2. JWST PM and SM contamination measurements against allocations and EOL requirements.

Phase	PM		SM	
	Particulate (PAC)	Molecular (Å)	Particulate (PAC)	Molecular (Å)
Launch Campaign Allocation	0.60	15	0.42	15
Launch Campaign Measurement	0.16	1	0.17	1
Mission EOL Requirement	1.50	300	0.50	300
Mission EOL Measurement	0.75	45	0.15	59

The contamination data collected during the launch campaign showed that employing reasonable mitigations significantly decreased contamination levels in all facilities compared to the data collected during previous missions. The processes and procedures that the contamination control team developed over years of I&T in various facilities proved very effective, even in some of the most challenging conditions.⁶

6.2 Use of upgrades for future CSG campaigns

The Ariane 5 launcher will soon be replaced by its successor, Ariane 6, and consequently, the BAF HC will no longer be used for future launch campaigns at CSG. Nevertheless, the campaign to launch the Jupiter Icy Moons Explorer on an Ariane 5 will impose similar operational constraints as JWST and leverage some of the upgrades, particularly the use of sealed-edge wipers and cleanroom garment specifications. In addition, many of the environmental management systems and contamination control methodologies developed during the VA256 campaign are now part of the CSG standard

operating procedures, contributing to the provision of excellent service and continuous improvement for satellite processing.

6.3 Lessons learned for future space telescopes

Lessons learned during the JWST launch campaign are drawn from experiences that were both successful and unsuccessful. They include technical achievements, such as the benefit of the portable HEPA modules, facility nuances, and strengthening of team morale.

An experienced technician team made a hectic launch campaign with long hours of I&T run smoothly and provided the engineers flexibility to work other responsibilities. Seasoned technicians were authorized to enforce cleanroom rules, approve or reject GSE for cleanroom ingress, support laboratory processing, and perform critical GSE cleanliness inspections without oversight. Given the volume of work required with a limited engineering staff, training technicians to both perform and take ownership of advanced tasks catered to their individual strengths and empowered them, creating a sense of pride that resulted in high quality work. A technician with previous laboratory experience was trained to process particle fallout wafers through Image Analysis and ellipsometry, a high energy technician spearheaded the laundry facility upgrades in collaboration with CNES, and another technician demonstrating leadership potential built a positive working relationship with CNES in development and execution of the SCAPE suit cleaning procedure. While these duties would have normally fallen on the engineers' lists, a limited staff necessitated creative use of available resources. The empowerment of technicians allowed the team to execute a strong contamination control program.

Providing sufficient support to I&T also proved crucial. Scheduling shifts in accordance with the rest of the I&T teams initially resulted in midday lulls. An additional, small mid-shift team moved the overlaps to different parts of the day than the rest of I&T, allowing the contamination control team to provide seamless support without burnout. This particularly avoided interference between contamination control maintenance and other operations, providing a safety net for ensuring consumables were properly stocked and readily available. Coverage like this helped foster and maintain good working relationships with management since the contamination control team was able to successfully operate in the background. Providing reliable service also influenced management to keep the contamination control team abreast of general issues, schedule updates, and technical challenges.

The JWST launch campaign occurred in facilities foreign to the NASA team. When a space telescope or other contamination-sensitive program plans to use a new or unfamiliar facility, pre-characterizing that facility in advance with data can allow for proper planning. Historical data may be limited, and given the nature of space telescopes, unique sensitivities may be new to any given facility. Quantifying the risk levied by environments in advance can allow for the development of custom protective GSE, corrective actions, and facility upgrades and justify consequential costs.

The CSG facilities also bore supply chain challenges, particularly due to the COVID-19 pandemic. For remote locations where obtaining supplies may be difficult or subject to delays, good practice entails stocking extra supplies and consumables. Launch campaigns can be dynamic and running out of items due to an extended schedule in a remote area could be costly. This may require purchasing supplies a year or more in advance and identifying long term storage options. Long lead items may need even longer. As plans develop and necessary quantities are determined, budgeting for a surplus is worthwhile. Cleanroom consumables can quickly be used up by unexpected work. While short term costs may increase, this practice hedges against risks arising as a program approaches its launch date.

Throughout JWST I&T, the use of sealed-edge cleanroom wipers became a necessity. The development of the Near Infrared Spectrograph (NIRSpec) revealed the shedding nature of typical cleanroom wipers during darkened room UV inspections. Fibers were liberated during nominal use and were appearing throughout cleanrooms. Wiper fibers were even found inside of NIRSpec.⁶ The switch to sealed-edge wipers alleviated the issue and, along with regular darkened room UV inspections, should become standard procedure for any fiber-sensitive mission.

The portable HEPA modules allowed for creating and maintaining cleaner work areas inside of cleanrooms, but they became attractive supports for individuals to lean on. Future missions utilizing free-standing filters should stanchion off areas in front of the filter faces to prevent personnel from blocking airflow by standing too close or leaning on modules.

In geographic areas supporting large hardware ingress and egress that have issues with insects, such as at CSG, operation of bug zappers in cleanrooms and airlocks during off-hours can be mission-saving. When rollup doors to the outside are opened, positive pressure can be quickly lost, and insects will be attracted to light coming from inside. Time will be needed after rollup door closure with the facility lights darkened for intruding bugs to be captured or eliminated. This should be added to the written work orders and procedures to ensure its occurrence.

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Some of the JWST Contamination Control delegation at CSG, including (left to right): Daniel DaCosta (PST), Jason Durner (KBR), Genevieve Dede (Arianespace), Marie-Helene Ferreira (CNES), Azuka Harbor (Peraton), Elaine Stewart (NASA), Marco Calcabrini (Arianespace), Eve Wooldridge (NASA), Craig Jones (KBR), Alan Abeel (NASA), Asanka Jayawardena (PST), Kimberly Morales (PST), Amelia Simon (Arianespace), Wafaa Tabibi (Arianespace), Luca Santoro (CNES), Colette Lepage (Peraton), Remi Le Douarin (CNES), Cole Horton (PST), Leonardo Perez (PST), and Leslie McClare (ASRC).
(Credit: Russell Wooldridge)

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