

Predicting contamination accumulation in facilities with limited data

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ABSTRACT

In preparation for the James Webb Space Telescope (JWST) launch at the Centre Spatial Guyanais (CSG) in French Guiana, particulate contamination accumulation predictions were necessary for each facility in which the hardware would be exposed because the Telescope would be uncovered in each of the facilities and had strict particulate requirements. These included facilities for final integration and testing, fueling, transportation and encapsulation. Minimal heritage data existed from CSG and previous launch campaigns to use as a basis for contamination predictions. Data from the Automatic Transfer Vehicle and Herschel-Planck launch campaigns were used in conjunction with facility monitoring data provided by the European Space Agency (ESA) and data collected during a JWST working group visit to CSG. These campaigns were conducted at varying cleanliness levels that were typically less stringent than JWST requirements. Each facility was evaluated using the data provided and likely performance improvement with the addition of High Efficiency Particulate Air filter (HEPA) banks operating when possible. Once the launch campaign was completed, the predicted fallout was compared with actual data collected throughout the campaign. Based on the actual measurements, JWST's primary and secondary mirrors turned out to be much cleaner than what was predicted.

Keywords: launch site processing, James Webb Space Telescope, accumulation, HEPA, fallout, prediction

1. INTRODUCTION

The James Webb Space Telescope (JWST) launch campaign at the Centre Spatial Guyanais (CSG) was approximately 3 months in duration. Integration and testing (I&T) occurred in the S5-C facility prior to transport to S5-B. Fueling operations were completed in S5-B. The final operations and integration to the Ariane 5 launch vehicle (LV) occurred in the Bâtiment Assemblage Final (BAF) and BAF encapsulation hall (BAF-HE). Transportation in the Conteneur Charge Utile 3 (CCU-3) container was required from S5-C to S5-B and S5-B to BAF¹. During the entire launch processing period in these facilities, the Observatory had to remain uncovered due to mechanical constraints and access limitations. In addition, the CSG launch processing facilities were certified to International Organization for Standardization (ISO) Class 8 rather than the ISO Class 7 level required for JWST. This made it necessary to develop a plan to protect JWST's optical surfaces and perform an analysis to predict contamination levels during launch site processing. Our challenge in doing this analysis was that there was little available data for similar optical satellite missions and site visits were limited due to COVID-19. JWST had strict cleanliness requirements, was especially sensitive to fibers, and could not be covered. For this reason, an analysis was performed to predict contamination levels in all the facilities to which the Observatory would be exposed.

In the prediction analysis described in this manuscript, we focused on particle cleanliness requirements for the primary mirror (PM) and secondary mirror (SM) because they were the most exposed optical surfaces during the launch campaign. The predictions were compared against the End-of-Life (EOL) requirements shown in Table 1^{2,3}. High Efficiency Particulate Air (HEPA) filter enhancements made to improve the facility cleanliness were also considered in the analysis⁴. Particle fallout data used for the JWST predictions included that from Automatic Transfer Vehicle (ATV), which used the same facilities, and Herschel-Planck (HP), which both used the same facilities and was an optical mission^{5,6,7}. We also applied data from a site visit to CSG prior to the arrival of flight hardware, where NASA deployed particle fallout samples⁸. Model uncertainty factors (MUF) were applied, as well as orientation factors for vertical vs. horizontal surfaces⁹. Molecular requirements are noted, but accumulation was insignificant compared to particulate contamination throughout the JWST mission. Predictions and actual data will focus on particulate accumulation.

Table 1. EOL Cleanliness Requirements for OTE Exposed Mirrors.^{2,3}

	Particulate (PAC) (Percent Area Coverage)	Molecular (Å) (Angstroms)
Primary Mirror	1.50	350 <i>allows for 50Å carbon</i>
Secondary Mirror	0.50	350 <i>allows for 50Å carbon</i>

Facility performance was monitored throughout the launch campaign. The predictions for fallout metrics in comparison with the actual particulate contamination accumulated show that our Contamination Control (CC) efforts were successful in greatly improving expected performance, enabling JWST cleanliness requirements to be met with margin.

2. LAUNCH SITE FACILITY PREDICTIONS

The facility fallout rate in PAC/Day for the PM and SM was identified for each environment. Days of exposure for active or inactive conditions were determined based on personnel work operations in each facility during pre-established shifts and limited access due to safety or facility restraints. HEPA walls were utilized as much as possible without interfering with launch I&T operations. HEPA modules could not be operated during certain operations, such as fueling, due to safety concerns. Additionally, HEPA modules could not be lifted onto the Plate-Forme Elévatrice Supérieure (PFES) or Plate-Forme Elévatrice Inférieure (PFEI) in the BAF because of space and weight restrictions. A particle fallout MUF of 50% was applied due to limited data and assumptions that were made as a result of this unfamiliar environment. The same orientation knockdown factor was applied to both the SM and PM optics since the effect of the inverted SM orientation was unknown due to non-laminar turbulent flow in each facility. The proceeding sections will describe the assumptions and calculations made to determine the factors applied in each facility shown in Table 2.

Table 2. Predictions in PAC/Day and accumulation for each launch facility phase with contributing factors.

I&T Phase PM PAC Accumulation	Facility PM PAC/Day	Days exposure			Rate Uncertainty	HEPA Wall	Orientation Knockdown	Effective PM	PM/SM Accumulation
		Active	Inactive	Total Days					
S5-C	0.005	20.868	4.174	25.042	50%	93%	50%	0.001	0.018
CCU-3 Transport to S5-B	0.060	NA	NA	0.250	50%	NA	5%	0.086	0.021
S5-B:	0.010	2.000	11.729	13.729	50%	80%	10%	0.013	0.182
CCU-3 Transport to BAF-HE	0.060	NA	NA	0.542	50%	NA	5%	0.086	0.046
BAF-HE:	0.003	2.691	0.538	3.229	50%	91%	50%	0.001	0.002
BAF-Airlock	0.062	0.168	0.034	0.201	50%	91%	50%	0.013	0.002
Lift	0.062	NA	NA	0.042	50%	NA	10%	0.084	0.003
PFES Fence ops	0.010	NA	NA	0.278	50%	NA	5%	0.014	0.004
AShC ops	0.010	NA	NA	1.500	50%	NA	10%	0.014	0.020

*Air shower curtain (AShC) ops involved an enclosure specifically designed for JWST to provide protection and environmental control on PFEI/PFES platforms

2.1 Previous missions and facility data

Many missions from CSG that processed through these facilities were communication satellites without exposed optics that needed extensive protection. Data was used from the ATV and HP missions in addition to data from the JWST working

group visits to CSG prior to the arrival of flight hardware. Monitoring data from HP CCU-3 transports was combined with provided data from other European Space Agency (ESA) records.

For HP, ESA and Arianespace (AE) performed additional, non-standard cleanings since it was a scientific optical mission. ATV was an unpiloted cargo carrier designed to supply the International Space Station with liquid and dry cargo as well as gases⁵. HP was an informative science project and was used as a baseline and guidance for JWST launch site operations^{6,7}. While ATV cleanliness requirements were not as strict as JWST, the same facilities were used in preparation for a launch on an Ariane 5 rocket.

2.2 Orientation knockdown factors

Short term and long term duration studies were performed to analyze the variation between vertical vs. horizontal surface fallout. These studies showed that surface orientation with respect to air flow had a greater effect on fallout than orientation with respect to gravity.⁹ S5-C and S5-B have similar air flow configurations which cause turbulent air flow within the cleanroom. Orientation knockdown should be considered on a case by case basis for each facility.

2.3 HEPA wall knockdown factors

Portable HEPA filter banks, designed and built by NASA for the JWST launch campaign, were used to mitigate against molecular and particulate contamination in each facility for certain active durations. Performance testing was done at the Goddard Space Flight Center (GSFC) to give a representative improvement factor for inclusion in the estimates⁴. A MUF was applied to the facility rates due to limited data. Orientation factors were used based on computational fluid dynamics (CFD) analysis performed for each of the environments at the launch site. Figure 1 depicts the test set up that used a Roman Space Telescope (RST) mock-up where JWST would be located. To test the different configurations that would be used in CSG facilities, the number of HEPA modules was changed to reflect planned floor layouts. Table 3 shows the configuration of HEPA modules used in each facility. Table 4 demonstrates the fallout rate reduction achieved for overall, horizontal, and vertical orientations for samples utilized during the conducted HEPA testing. The horizontal rate was ultimately used for all facilities since orientation knockdown factors had already been embedded in the model.



Figure 1. Photograph (right) of S5-C Payload Preparation Facility (PPF) layout simulation showing locations of Air Particle Counters (APCs), wafers, and foils. (Photo Credit: NASA/Zao Huang).

Table 3. HEPA wall module configuration in each facility.⁴

Represented Facility	Stacks per Wall	Modules per Wall	Total Modules
S5-C	3	6	12
S5-B	1	2	4
BAF HE	2	4	8

Table 4. HEPA testing performed at GSFC in each module configuration for all facilities with horizontal and vertical orientation samples.⁴

Facility	Orientation	Fallout Rate Reduction	Adjusted Fallout Rate Reduction
S5-B	Overall	79%	*
	Horizontal	80%	*
	Vertical	69%	*
S5-C	Overall	91%	*
	Horizontal	93%	*
	Vertical	0%	35%
BAF HE	Overall	88%	*
	Horizontal	91%	*
	Vertical	0%	47%

3. PREDICTION FOR THE S5-C CLEANROOM

3.1 Facility fallout rate

An overall rate of **0.005 PAC/day** was assumed for operations in S5-C. I&T operations in S5-C required around 25 days with high levels of activities and two shifts of work. Data from the ATV Launch campaign showed an average of 0.007 PAC/Day from three particulate fallout (PFO) plates for 139 days of exposure. It is unknown the level of activity or frequency that occurred during this collection period. Silicon monitoring wafers used by NASA have a larger accumulation area than PFO plates. ESA provided fallout data which an average rate of 0.0056 PAC/Day since 2015 in S5-C. Since the JWST launch campaign required tighter protocols and more frequent cleaning than ATV, CC Engineers (CCEs) considered a rate of 0.005 PAC/Day reasonable.

3.2 Orientation knockdown factor

Figure 2 below shows the CFD analysis results performed with 12 HEPA modules. This configuration does overcome facility airflow but also shows turbulence and dead zones. **50% knockdown** was selected for the 12 module configuration in S5-C^{4,9}. This is a conservative estimate over the industry standard of 90% vertical knockdown to include the unknowns of operations in this facility.

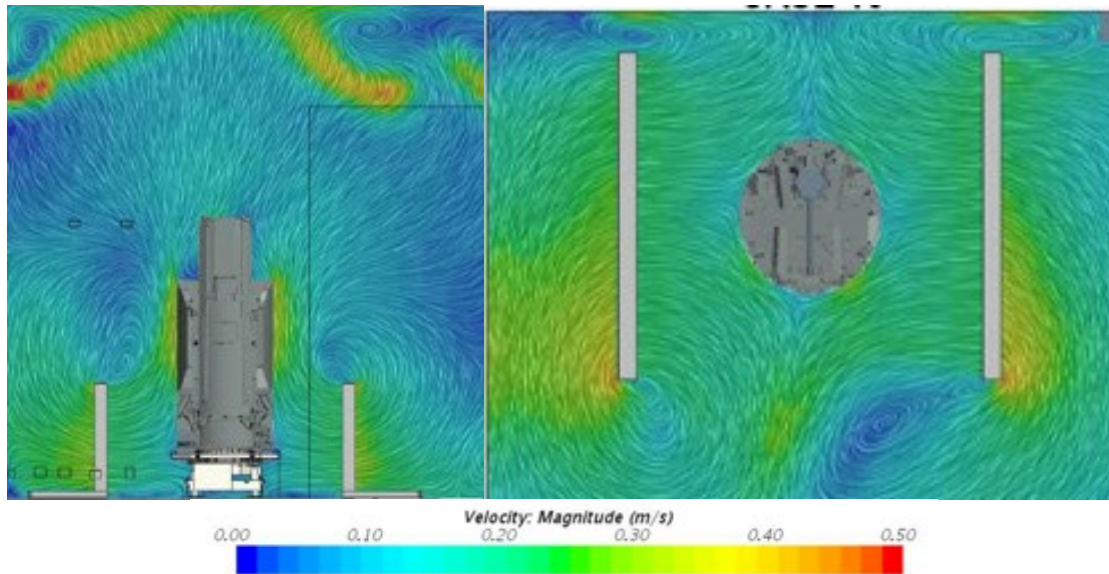


Figure 2. CFD analysis utilizing 12 HEPA modules for S5-C configuration. (Credit: Jacobs Engineering/P. Agarwal, A. Flynt, and A. Kharazi).

3.3 HEPA wall reduction

93% HEPA wall reduction rate utilized in S5-C based off GSFC testing as shown in Table 4.

4. PREDICTION FOR THE CCU-3 TRANSPORTS

4.1 Facility Fallout Rate

An overall rate of **0.060 PAC/Day** was assumed for CCU-3 transports. The duration was estimated to be 12 hours total based off of HP and ATV transports, with 9 hours in the airlocks and 3 hours for the transport time in CCU-3. JWST would have to pass through S5-C, S5-B and BAF airlocks for the two transports. This rate was assumed for both transports from S5-C to S5-B and S5-B to BAF. The 0.060 PAC/Day rate is the weighted average between the airlock rate of 0.008 PAC/Day and a CCU-3 transport rate 0.216 PAC/Day from HP. The 0.0081 PAC/Day is an average rate from HP data for S5-B airlock of 0.0068 PAC/Day and ESA provided data for S5-C airlock of 0.0093 PAC/Day.

4.2 Orientation Knockdown Factor

CCU-3 transports are short term with the telescope in a vertical orientation. There was HEPA filtration within the CCU-3, but the airflow would be turbulent since JWST occupies most of the interior. **5% knockdown** was selected for the transport phases since the duration and air flow presents minimal confidence in the orientation benefit. The transportation from cleanroom through airlock and into CCU3 was expected to take only a few hours, but the airlocks did not have HEPA filtration. HEPA modules were also unable to be used during transportation phases, so no HEPA knockdown factors were applied.

5. PREDICTION FOR THE S5-B CLEANROOM

5.1 Facility Fallout Rate

HP was fueled in S5-B with an average rate of **0.0104 PAC/Day**. Planned S5-B operations included only fueling, which inhibited the use of HEPA walls due to safety concerns. S5-B facility was smaller and required less personnel to complete fueling but also had less facility provided airflow.

5.2 Orientation Knockdown Rate

Due to CSG safety requirements during fueling, the HEPA modules were only able to operate on the first and last days while no hydrazine was detectable in the air. Because of this, the only clean airflow around the mirrors during fueling was from facility. **10% knockdown** was selected because the benefit was only during first and last days in comparison to 50% knockdown in S5-C, where HEPA filters would be running continuously.

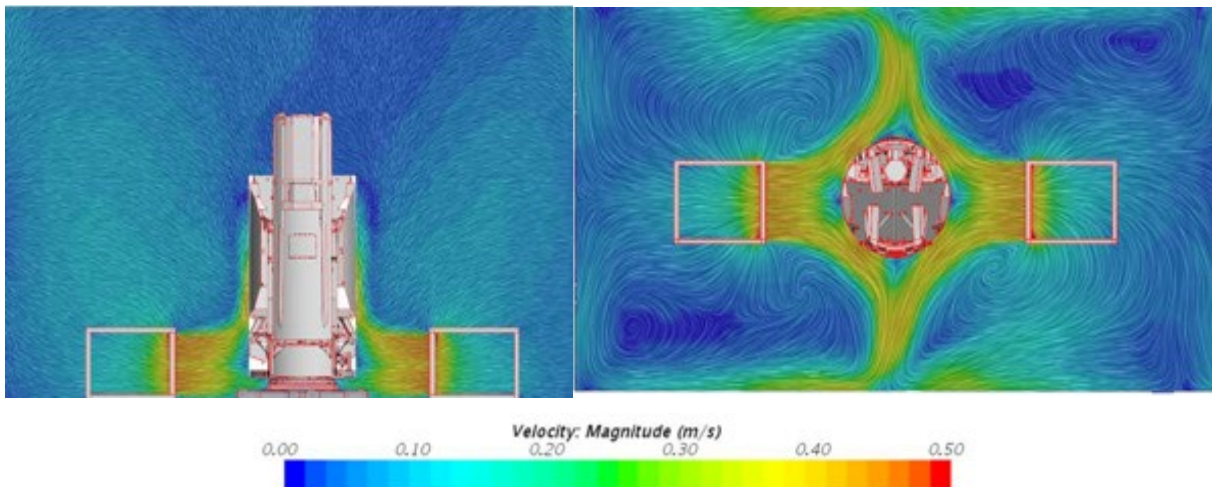


Figure 3. CFD analysis utilizing 4 HEPA modules for S5-B configuration. (Credit: Jacobs Engineering/P. Agarwal, A. Flynt, and A. Kharazi).

6. PREDICTION BAF-HE CLEANROOM

6.1 Facility Fallout Rate

An average rate of **0.003 PAC/Day** was utilized based on HP and ATV fairing processing data. The ATV launch campaign had 3 samples with an average PAC/Day of 0.0034 and the HP launch campaign had an average of 0.0029 PAC/Day for exposure in the BAF-HE.

6.2 Orientation Knockdown Rate

CFD analysis was not performed in this location due to the short duration exposure of ~4 days utilizing 8 total HEPA modules. **50% knockdown** was selected since the PM was in a vertical orientation for a short duration exposure.

7. PREDICTION FOR THE BAF AIRLOCK

7.1 Facility Fallout Rate

An average rate of **0.062 PAC/Day** was utilized based on testing performed by NASA during a site visit prior to launch on 4/10/2019. 0.062 PAC/Day was the fallout rate from 10 general environmental wafers placed outside of the shutter envelope and exposure during a 3 hour test period where 5 wafers were exposed during crane movements and another 5 exposed during the shutter openings.

7.2 Orientation Knockdown Rate

CFD analysis was not performed in this location due to the short duration exposure of ~5 hours utilizing 8 total HEPA modules. **50% knockdown** was selected since the PM was in a vertical orientation for a short duration exposure. The airflow would also be turbulent due to the open shutter that allowed crane access for lifting JWST from the BAF airlock to PFEI/PFES platforms.

8. PREDICTIONS FOR LIFT AND THE PFEI/PFES PLATFORMS

8.1 Facility Fallout Rate

An average rate of **0.062 PAC/Day for the lift** was utilized based on testing performed by NASA during a site visit prior to launch on 4/10/2019. 0.062 PAC/Day was the fallout from 10 general environmental wafers placed outside of the shutter envelope and exposure during a 3 hour test period where 5 wafers were exposed during crane movements and another 5 exposed during the shutter openings. A rate of **0.010 PAC/Day was assumed for PFES and PFEI operations** with ASHC operations based on HP and ESA provided facility data¹. ASHC enclosure provided further contamination and environmental control on PFEI/PFES levels as compared to previous missions.

8.2 Orientation Knockdown Rate

CFD analysis was not performed in this location due to the short duration exposure of ~5 hours utilizing 8 total HEPA modules. **50% knockdown** was selected since the PM was in a vertical orientation for a short duration exposure. The airflow will also be turbulent due to the open shutter to allow crane access for lifting from BAF airlock to PFEI/PFES.

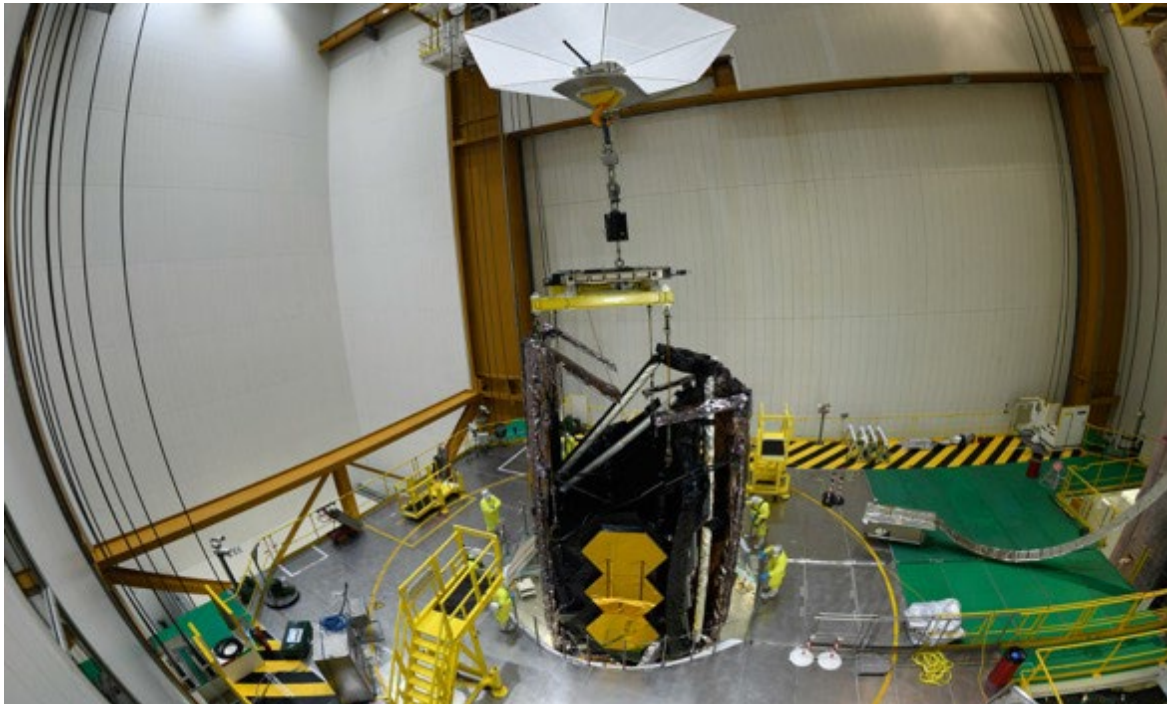


Figure 4. Observatory lifted through PFES onto Ariane 5 launcher. (Photo Credit: ESA/M. Pedoussaut).

9. ACTUAL DATA COLLECTION RESULTS

PM Segment Assembly witness samples (PMSA), silicon wafers that had been tracking with the mirrors since the original arrival of the mirrors from Ball Aerospace to GSFC, were utilized for the S5-C, S5-B and BAF-HE exposure of the Observatory. Table 5 below shows the total accumulation for the PM and SM mirror PAC. The PMSA wafers were read at the start of the campaign with the Observatory arrival, after S5-C activities completion during the move to S5-B, and after the final operations completed in the BAF-HE.

Additional JWST exposures were tracked with surrogate wafers for the CCU-3 transports from S5-C to S5-B and S5-B to the BAF and BAF-airlock, PFES & PFEI operations. SM was separated from PM accumulation for fairing encapsulation, as shown in Table 6, due to the lowering of the PFES for fairing operations. SM was exposed above the PFES floor, while PMSA remained within ASHC. A surrogate wafer was exposed during fairing encapsulation operations with a resulting 0.006 PAC.

Table 5. PM summary for prediction PAC accumulation vs actuals at each phase of the launch campaign for final cleanliness.

PM Summary			
I&T Phase PM PAC Accumulation	Predicted PAC Accumulation	Actuals	Deltas
Completion of I&T at NG	0.280	0.271	-0.009
STARRS Transport	0.001	0.003	0.002
S5C Airlock	0.000	0.002	0.002
S5-C	0.018	0.031	-0.170
S5-B:	0.182		
BAF-HE:	0.002		
CCU-3 Transport to S5-B	0.021	0.004	-0.017
CCU-3 Transport to BAF-HE	0.046	0.009	-0.037
BAF-Airlock	0.002	0.009	0.007
Lift	0.003	0.023	-0.005
PFES Fence ops	0.004		
AShC ops	0.020		
Launch with Reserve	0.025		-0.025
Fairing ops	0.082	0.082	0.000
Launch & CCAM	0.440	0.320	-0.120
PM Prediction	1.126	0.754	-0.372

*CCAM includes the depressurization and redistribution of particulate during launch

Table 6. SM summary for prediction PAC accumulation vs actuals at each phase of the launch campaign for final cleanliness.

SM Summary			
I&T Phase PM PAC Accumulation	Predicted PAC Accumulation	Actuals	Deltas
Completion of I&T at NG	0.046	0.012	-0.034
STARRS Transport	0.001	0.003	0.002
S5C Airlock	0.000	0.002	0.002
S5-C	0.018	0.040	-0.161
S5-B:	0.182		
BAF-HE:	0.002		
CCU-3 Transport to S5-B	0.021	0.004	-0.017
CCU-3 Transport to BAF-HE	0.046	0.009	-0.037
BAF-Airlock	0.002	0.009	0.007
Lift	0.003	0.027	0.000
PFES Fence ops	0.004		
AShC ops	0.020		
Launch with Reserve	0.025		-0.025
Fairing ops	0.082	0.082	0.000
Launch & CCAM	-0.040	-0.040	0.000
SM Prediction	0.412	0.149	-0.264

*CCAM includes the depressurization and redistribution of particulate during launch

Due to limited data and many unknowns, a conservative approach was used for the contamination predictions in each facility. The protocols implemented for JWST were more strict than past missions and regular operations for the launch facilities. NASA CC team had difficulty gathering data due to cancelled trips with the COVID-19 pandemic. Additionally, other customers utilizing varying protocols in each facility resulted in data that was not directly applicable to the JWST campaign but could be used with engineering judgement and assumptions.

During the launch campaign, there were variations in the durations and configurations from plans in each facility due to I&T schedule adjustments. 10 days of schedule margin were incorporated in the “Launch with Reserve” parameter in Tables 5 and 6. The actual vs predicted for S5-B fallout shows significant improvement due to daily cleanings and processing of fueling suits with new protocols to maintain a clean environment without HEPA modules on¹¹. Additionally, the BAF-HE was cleaned and monitored to ensure particulate counts were understood with the presence of the Ariane 6 fairing and scaffolding contributing to airflow.

Changes in budgeting assumptions and schedule in addition to the unknowns and uncertainties of the CSG launch site were monitored in order to strengthen the launch team’s ability to maintain cleanliness levels within mission requirements. JWST was launched cleaner than expected due to significant efforts to understand and mitigate against contamination throughout the launch campaign.

10. DISCUSSION

With the calculated predictions, and with awareness that launch campaign delays resulting in longer exposure times would always be possible, stringent cleanliness measures were implemented for the JWST launch campaign. The excellent cleanliness results, shown in Table 7, demonstrate the effectiveness of this CC strategy. The contamination predictions convinced JWST program management how important it would be to implement a stringent CC program for the campaign. The ultimate measure for the success of the launch campaign CC program was evident shortly after launch with the release of an on-orbit calibration photo, shown in Figure 5, demonstrating excellent PM and SM sensitivity thanks, in large part, to the mirrors' cleanliness.

Table 7. JWST PM and SM cleanliness requirements for allocation compared to actual PAC

	Particulate, PAC		Molecular, Å	
	Allocation	Measured	Allocation	Measured
PM	0.60	0.16	55	1.0
SM	0.42	0.17	55	1.0

Table 8. JWST PM and SM cleanliness requirements and achieved levels

	Particulate, PAC		Molecular, Å	
	EOL Reqt	Measured	EOL Reqt	Measured
PM	1.5	0.75	300	45
SM	0.50	0.15	300	59

On March 11, 2022, JWST's on-orbit fine phasing calibration was complete. The image released on March 16, with the story of successful fine phasing, is shown in Figure 5. The caption in the article included a statement on JWST's sensitivity:

“While the purpose of this image was to focus on the bright star at the center for alignment evaluation, JWST's optics and NIRCam are so sensitive that the galaxies and stars seen in the background show up.”
– *Pinol, N., Fisher, A., and Betz, L.*¹²



Figure 5. NIRCam telescope alignment evaluation image ¹². (Photo credit – NASA/STSci).

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