

INDUCED CONTAMINATION PREDICTIONS FOR JAXA’S MICRO-PARTICLES CAPTURER AND SPACE ENVIRONMENT EXPOSURE DEVICES

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A comparison of induced contamination predictions and measurements is presented for JAXA’s Micro-Particles Capturer and Space Environment Exposure Device (MPAC&SEED), which was attached to the exterior of the Russian Service Module on the International Space Station (ISS). Material outgassing and thruster plume induced contamination was calculated using analytical and semi-empirical models developed by the Boeing Space Environments Team in Houston. Contamination depth predictions show good agreement (within a factor of 3) compared to measured contamination levels on the flight hardware. Induced contamination predictions are also presented for the next MPAC&SEED experiment to be deployed on the Japanese Experiment Module.

Keywords: MPAC&SEED, International Space Station, External Payloads, Induced Environment, Contamination

1. Introduction

The International Space Station (ISS) induced environment includes contributions from ISS elements and visiting vehicles (i.e., Space Shuttle Orbiter, Soyuz, and Progress). This induced environment is characterized by the Boeing Space Environments Team in Houston. Of key interest are induced contamination sources such as materials outgassing and thruster plumes.

The induced contamination environment is of great interest for externally mounted ISS payloads, such as JAXA’s Micro-Particles Capturer and Space Environment Exposure Device (MPAC&SEED). The contribution of the induced environment must be understood to ensure successful on-orbit performance. In addition, the return of ISS external experiments provides a rare opportunity to compare induced contamination predictions with measurements from flight hardware.

The first MPAC&SEED experiment was mounted outside the Russian Service Module (SM) on October 15, 2001. The SM/MPAC&SEED consisted of 3 identical units which were exposed for periods ranging from 10 months to almost 4 years. Fig. 1 shows a view of the fully deployed experiment. This is a view of the ram-facing side (i.e., the side which pointed into the ISS velocity vector for the majority of the experiment). Fig. 2 shows a view of the experiment from the wake-facing side.[1]

All of the SM/MPAC&SEED units have been returned from ISS for ground-based testing. In addition to characterizing captured particles and materials degradation, JAXA conducted a thorough investigation of contamination deposited on the units.[2]

JAXA is currently preparing another MPAC&SEED experiment to be deployed on the Japanese Experiment Module (or JEM/MPAC&SEED). JEM/MPAC&SEED is expected to launch on ISS Flight 2J/A (tentatively scheduled for March 2009) and has a planned exposure duration of 3 years. Unlike SM/MPAC&SEED, this experiment will have samples on the ram-facing surface only.[3] Fig. 3 shows the approximate JEM/MPAC&SEED location on ISS.

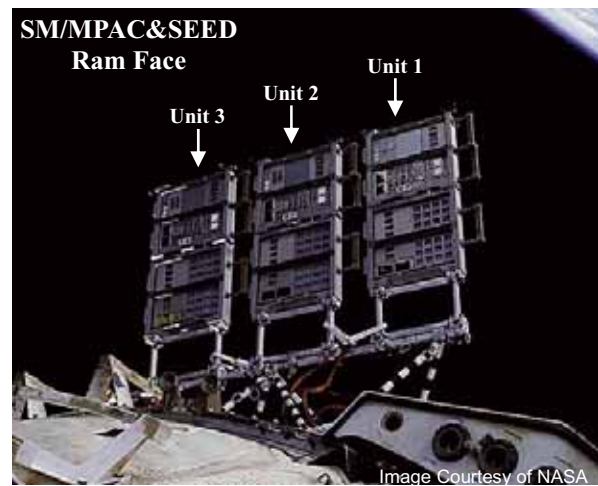


Fig. 1 SM/MPAC&SEED On-Orbit, Ram-Facing Side



Fig. 2 SM/MPAC&SEED On-Orbit, Wake-Facing Side

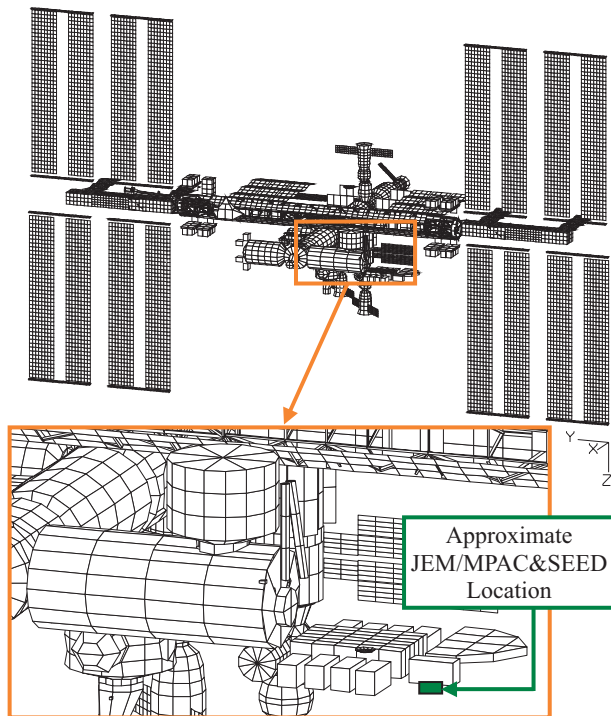


Fig. 3 Approximate JEM/MPAC&SEED Location in ISS Geometric Model

The Boeing Space Environments Team performed induced contamination analyses for SM/MPAC&SEED to compare predictions with measured contamination levels on the flight hardware. Induced contamination was also analyzed for JEM/MPAC&SEED.

2. ISS Contamination Sources

There are several ISS contamination sources which could affect the MPAC&SEED experiments. Given the significant size of ISS and number of elements, the MPAC&SEED experiment location and orientation must be considered when evaluating contamination sources. To identify these sources, views to and from MPAC&SEED were created using an ISS geometric model. These views were inspected to identify potential ISS contamination sources with a line-of-sight to the experiment. The primary contamination sources of concern include material outgassing from ISS hardware elements and thruster plume contamination.

Beyond material outgassing and thruster plume impingement, other potential contamination sources are present on ISS. For instance, there are several propellant purge ports on the Russian Segment which periodically vent fuel or oxidizer. The highest flux region for propellant purges is near the centerline. The MPAC&SEED experiment locations are both far from the centerlines of the purge ports, so this contamination source was neglected. There are also water vents on the Orbiter and US Segment, but these did not have a line-of-sight to either experiment location. Self-contamination from direct or return flux may also contribute to deposition. For the MPAC&SEED experiments, direct flux was not considered since there is no line-of-sight between the exposed surfaces. Return flux was neglected as a second order effect.

3. SM/MPAC&SEED Induced Contamination Predictions and Measurements

3.1 SM/MPAC&SEED Contamination Observations

Visual inspection of SM/MPAC&SEED revealed color changes on the wake face, which was covered in a uniform brownish contamination layer (see Fig. 4). Beyond the uniform contamination, many spots were also observed which are indicative of low-velocity droplet impacts. The spots varied in shape and color, with diameters ranging from approximately 1 to 1000 μm . These features were more numerous on the wake face than the ram.[1,2,4,5]



Fig. 4 Comparison of Unit 1 Ram & Wake Faces [1]

JAXA used X-ray Photoelectron Spectroscopy (XPS) to measure element composition and depth profiles of the contamination layers. Four measurements were taken for each unit – two on the ram side and two on the wake side. Results show silicon to be a significant constituent on the ram side of all 3 units. Silicon was also present on the wake side but generally in lesser quantities. The presence of silicon is highly indicative of material outgassing induced contamination. Oxygen, carbon, nitrogen, sodium, iron, and nickel were also detected. Nitrogen was consistently more prominent on the wake side compared to the ram.[2,4]

Nitrogen is an important signature for thruster plume induced contamination, considering the propellants used for ISS thrusters. Nitrogen appeared in small quantities on the wake side (around 4% of the atomic concentration). Similarly, ground-based measurements have shown nitrogen concentrations on the order of 11-16% of the total residue remaining from the fuel-oxidizer reaction. The other constituents expected in fuel-oxidizer reaction products include carbon, hydrogen, and oxygen.[6] Although carbon and oxygen were present on SM/MPAC&SEED, these could be attributed to other sources.

Flight experiment data has shown that droplets are the primary mechanism for thruster plume contamination transport at operating temperatures expected on ISS (i.e., non-cryogenic).[7] The presence of nitrogen and droplet features strongly indicates thruster plume induced contamination.

A summary of contamination depths estimated from XPS results are provided in Table 1. The ram side of the trays

showed consistent depth measurements; the measurements on the wake side were more varied. It should be noted that XPS does not always render a clear and precise depth measurement, and results may be subject to interpretation.

Table 1 Approximate SM/MPAC&SEED contamination depth based on XPS measurements.

Measured Contamination Depth - Angstroms (Å)			
Side	Unit 1	Unit 2	Unit 3
Ram (1)	300	750	930
Ram (2)	300	750	940
Wake (1)	55	100	110
Wake (2)	500	70	85

3.2 SM/MPAC&SEED Contamination Sources

Hemispherical views from the ram- and wake-facing sides of SM/MPAC&SEED were used to identify the major ISS outgassing sources (see Fig. 5 and Fig. 6). These views are centered along the surface normal vector and expanded out 90°. From this type of view, it is straightforward to determine which ISS elements had a line-of-sight to the experiment. The Functional Cargo Block (FGB), Service Module (SM), and Docking Compartment 1 (DC1) on the Russian Segment had the largest view factors to the SM/MPAC&SEED trays. In addition, visiting vehicles (i.e., Orbiter, Soyuz, and Progress) had significant view factors when mated to ISS.

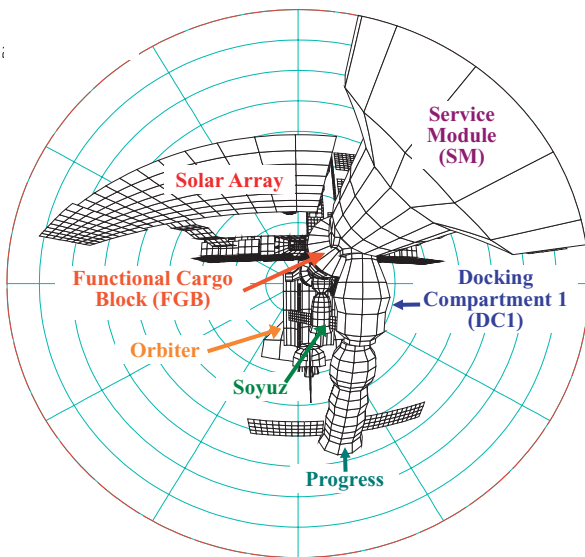


Fig. 5 Hemispherical View from SM/MPAC&SEED (Ram Direction)

For each of these elements, a materials list was compiled and matched to available outgassing rate test data (i.e., ASTM-E 1559 testing or equivalent). On-orbit temperature estimates for ISS elements and SM/MPAC&SEED were taken into account where possible; however, appropriate outgassing rate test data did not always exist for the temperatures of interest. In these cases, best available outgassing data was used. An effective outgassing rate source term was then calculated based on quantity of material.

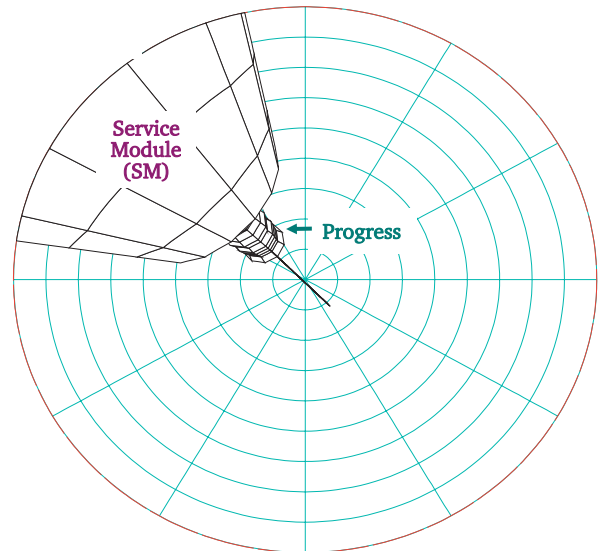


Fig. 6 Hemispherical View from SM/MPAC&SEED (Wake Direction)

The outgassing source terms account for the duration of exposure to the vacuum environment. The time decay rate of sources terms is determined from experimental data and diffusion theory. Visiting vehicles were of key interest as these had comparatively little reduction in outgassing rates due to time decay. For example, the aft-docked Progress cargo vehicles rotated every 3 to 4 months (i.e., a Progress vehicle departed and was replaced with a new one). As a result, the initial outgassing source term decayed very little between Progress vehicle rotations. In contrast, the sources terms for the permanent outgassing sources (e.g., FGB, SM, and DC1) continued to decay with time. The FGB, for instance, had been on-orbit several years by the time SM/MPAC&SEED was deployed. Consequently, it had a relatively low outgassing source term (due to time decay) compared to the Progress vehicles.

Material outgassing induced contamination was calculated using an analytical model developed by the Boeing Space Environments Team. This model is based on physical models of molecular transport and is coded into Boeing's NASAN-3 contamination computer model. NASAN-3 is an integrated computer model, utilizing NASTRAN geometric models, view factor calculations, and transport routines to analyze induced contamination on an ISS configuration, with results available in tabular or graphic formats.

To identify ISS thrusters of concern for plume impingement to SM/MPAC&SEED, views from all ISS thrusters were reviewed. This included ISS thrusters used for reboost/attitude control as well as thrusters on visiting vehicles (i.e., Orbiter, Soyuz, and Progress). Of key interest were thrusters with a centerline view to the experiment, since this is where the highest contamination flux is expected.[8]

On the ram-facing side of SM/MPAC&SEED, only visiting vehicles had thrusters with a line-of-sight to the tray. It is probable that these thrusters contributed to some of the spot features on the ram side. In general, however, SM/MPAC&SEED was at a very high angle off the thruster

centerlines, and it was decided to neglect these from the analysis. No ISS reboost/attitude control thrusters had a view to the ram side of the experiment.

On the SM/MPAC&SEED wake face, the only significant thruster contamination source was a Progress braking engine. The braking engines are fired during approach and separation to the docking port on the aft end of ISS. (See Fig. 2 for an on-orbit image of an aft-docked Progress). One of the Progress braking engines had a near-centerline view to the SM/MPAC&SEED wake side. Fig. 7 provides a hemispherical view from this thruster when 20 ft from the aft docking port.

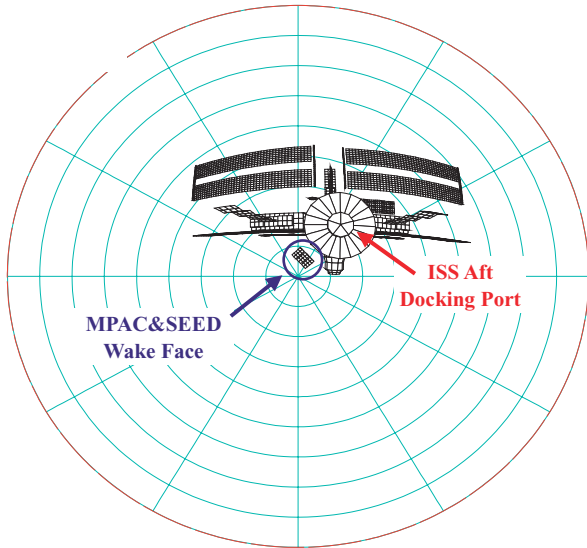


Fig. 7 Hemispherical View from Progress Braking Thruster, 20 ft to Docking

The thruster plume induced contamination was analyzed using a semi-empirical model developed by the Space Environments Team. This model uses flight experiment and chamber test data for contamination characterization.[8] The plume contamination model is also coded into the NASAN-3 contamination computer tool to analyze a given thruster's effect on an ISS configuration. Available flight jet firing data for Progress proximity operations was used to simulate thruster firings and calculate thruster induced contamination to MPAC&SEED.

3.3 SM/MPAC&SEED Contamination Analysis Results

Analysis for SM/MPAC&SEED was performed for 3 time periods to correlate with measurements from each unit as they were retrieved. This timeline is summarized in Table 2. For each analysis period, total exposure time was taken into account as well as visiting vehicle traffic records to most accurately duplicate on-orbit conditions for SM/MPAC&SEED. Results for the ram side of the units showed measurable levels of outgassing-induced contamination while results for the wake side indicated a combination of outgassing and thruster plume contamination.

Table 2 SM/MPAC&SEED Timeline used for Analysis

Unit	Deployed	Retrieved	Total Time Days (Years)
1	10/15/2001	8/26/2002	315 (0.9)
2	10/15/2001	2/26/2004	865 (2.4)
3	10/15/2001	8/18/2005	1403 (3.8)

In addition to the permanent ISS elements, the ram side of SM/MPAC&SEED was exposed to outgassing from Orbiter, Soyuz, and Progress vehicles. Exposure time durations were taken into account for each element in computing outgassing to the ram side. Since no thrusters were identified as significant contamination sources to the ram face, the outgassing analysis results represent the total contamination prediction.

It was expected that SM/MPAC&SEED would have less outgassing induced contamination on the wake side since there are fewer sources compared to the ram side (see Figs. 5 and 6). Only one permanent ISS element had a view to the wake side of the tray (the Service Module); however, the Progress vehicles docked to the aft end of ISS caused induced contamination from materials outgassing as well as thruster firings.

A summary of the SM/MPAC&SEED contamination analysis results is provided in Table 3. Detailed analysis results for SM/MPAC&SEED have been previously reported.[9,10]

Table 3 Summary of SM/MPAC&SEED Analysis Results

Side	Predicted Contamination Depth (Å)		
	Unit 1	Unit 2	Unit 3
Ram	106 - 135	303 - 354	459 - 533
Wake	86 - 103	186 - 237	317 - 414

3.4 SM/MPAC&SEED Contamination Predictions vs. Measurements

Analysis results consistently showed measurable levels of material outgassing induced contamination on the SM/MPAC&SEED ram-facing surfaces. The wake-facing surfaces were predicted to incur contamination due to a combination of material outgassing and thruster plume impingement. These results are qualitatively consistent with visual inspection and XPS measurements of SM/MPAC&SEED. On the ram side, XPS results were dominated by a silicon-based contaminant. On the wake side, the presence of nitrogen in XPS measurements and droplet features is highly indicative of thruster plume induced contamination. XPS measurements on the wake side also showed the presence of silicon but to a lesser degree than on the ram side, which agrees with predictions that less than half of contamination on the wake side was due to outgassing. Qualitatively, therefore, the predictions have good agreement with measured and observed contamination.

Quantitative comparisons of the measured and predicted levels of contamination are provided in Table 4. The calculated depth of contamination on the ram side surfaces is within a factor of 3 of measured contamination. Predictions may

improve with better characterization of outgassing sources. For instance, available data for the Russian Segment elements only included characterization of materials with a relatively large surface area. As a result, it is likely that there are significant outgassing sources that have not been identified. In addition, the on-orbit thermal environment has a considerable effect on outgassing but only limited thermal data was available. Considering, however, the number of outgassing sources on ISS and long duration of the experiment, the predicted results for the ram side represent excellent agreement with the measured depth of contamination.

Table 4 Comparison of SM/MPAC&SEED Measured and Predicted Contamination

Measured Vs. Predicted Contamination Depth (Å)

Side	Unit 1		Unit 2		Unit 3	
	Measured	Predicted	Measured	Predicted	Measured	Predicted
Ram	300	106 - 135	750	303 - 354	930	459 - 533
Ram	300		750		940	
Wake	55	86 - 103	70	186 - 237	110	317 - 414
Wake	500		100		85	

Plume contamination can be more difficult to quantify with XPS measurements than outgassing induced contamination. Whereas the outgassing contamination was dominated by silicon-based outgassing sources, thruster plumes have multiple byproducts (as described in Section 2). Whereas outgassing yields a fairly uniform molecular contamination layer, thruster plume induced contamination is dominated by the liquid phase, producing droplet features and a non-uniform distribution of contaminants. Hence, XPS measurements for the ram side of SM/MPAC&SEED are a good gauge for qualitative and quantitative comparison with predicted contamination; XPS measurements for the wake side are a good gauge for qualitative comparison but have limitations in regard to quantitative comparison. Nevertheless, consistent XPS results showing the most prominent presence of nitrogen on the wake face from all 3 units give much confidence in predictions for plume contamination on the wake side.

The XPS results on the Unit 1 wake side gave somewhat inconsistent measurements between the two locations, with depths of 55Å and 500Å, respectively. Some variation could be attributed to the nature of thruster plume induced contamination; however, it is likely that the 500Å measurement is a local anomaly. The 55Å measurement is much more consistent with measurements from the Unit 2 and 3 wake sides. Excluding the 500Å data point, the measured and predicted results for the wake side are of similar scale and represent good agreement considering the limitations of XPS in characterizing depth of plume contamination.

4. JEM/MPAC&SEED Induced Contamination Predictions

SM/MPAC&SEED provided a unique opportunity to measure the ISS induced contamination environment; however, the primary purpose of the experiment was related to microparticle capture and materials exposure. For this purpose, contamination is an undesirable effect.

The upcoming JEM/MPAC&SEED experiment will be

installed at a different location on ISS than SM/MPAC&SEED. As a result, it will be exposed to different contamination sources. The induced contamination environment is of high interest to JEM/MPAC&SEED developers and investigators to ensure good experimental data can be obtained.

4.1 JEM/MPAC&SEED Contamination Sources

Unlike SM/MPAC&SEED, JEM/MPAC&SEED will have samples on the ram surface only. A hemispherical view from the ram-facing side of JEM/MPAC&SEED was used to identify the major ISS outgassing sources (see Fig. 8). The JEM Inter-Satellite Communication System (ICS) and the ISS Solar Array have the largest view factors. The JEM Exposed Facility (EF) has a slight view. In addition, Orbiter will contribute to contamination when mated to ISS. The Solar Array will have been on orbit for nearly 3 years when JEM/MPAC&SEED is deployed. On the other hand, JEM ICS and EF will deploy at the same time as JEM/MPAC&SEED, so there will be no initial reduction in their outgassing rates due to time decay. It should be noted that the outgassing sources affecting JEM/MPAC&SEED are better characterized (in terms of material identification and outgassing rate data) than the SM/MPAC&SEED outgassing sources.

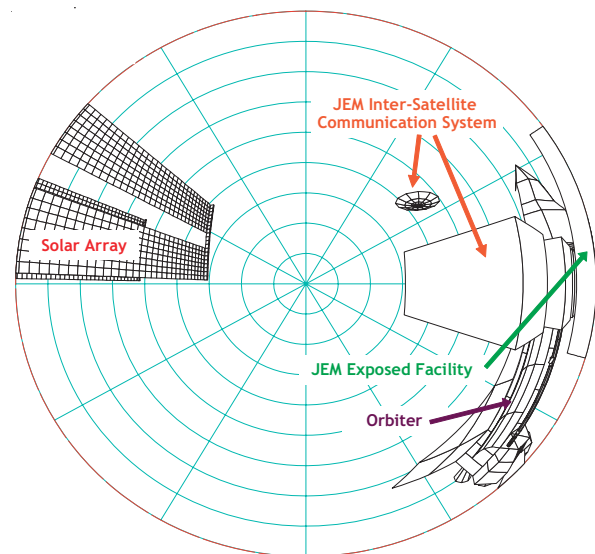


Fig. 8 Hemispherical View from JEM/MPAC&SEED (Ram Direction)

Orbiter thrusters are the only thruster contamination sources for JEM/MPAC&SEED. These thrusters may fire during docking/undocking operations as well during mated operations with ISS. Fig. 9 provides a hemispherical view from an Orbiter braking thruster (fired during docking/undocking operations). As shown in the figure, the JEM/MPAC&SEED experiment is approximately 30 degrees outside the thruster centerline. In fact, none of the Orbiter thrusters fired during docking/undocking operations or mated operations have a near-centerline view to JEM/MPAC&SEED. Therefore, the contamination contribution from Orbiter thrusters was expected to be insignificant.

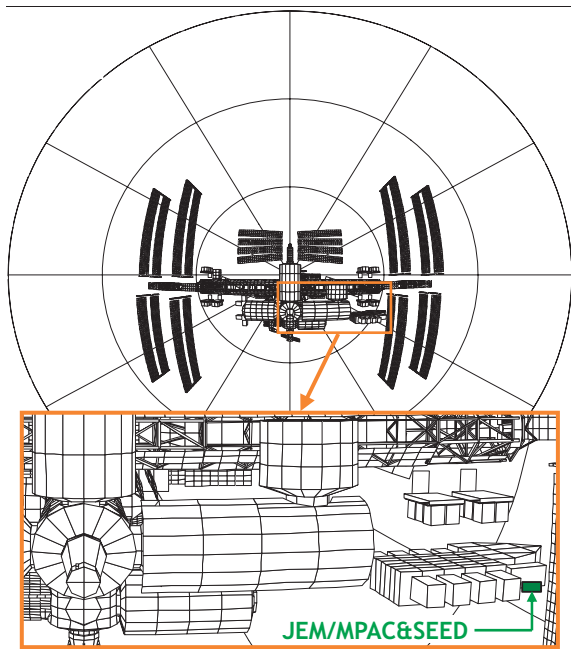


Fig. 9 Hemispherical View from Orbiter Braking Thruster, 100 ft to Docking

4.2 JEM/MPAC&SEED Contamination Analysis Results

Analysis for JEM/MPAC&SEED was performed for the expected experiment duration of 3 years. The current Orbiter launch schedule was used to predict the contribution of Orbiter outgassing and thruster plumes to JEM/MPAC&SEED induced contamination. Results show measurable levels of outgassing-induced contamination and negligible levels of thruster plume contamination.

A summary of the JEM/MPAC&SEED contamination analysis results is provided in Table 5. The table gives the total predicted outgassing-induced contamination as well as the individual contributions from the JEM elements (the EF and the ICS) and the ISS elements (Solar Array and Orbiter). As shown, the depth of the contamination layer depends on the surface temperature of JEM/MPAC&SEED. The JEM elements dominate the induced contamination prediction since they are fresh outgassing sources (deploying on the same flight as JEM/MPAC&SEED) and have a significant view factor. Based on these analysis results, the JEM/MPAC&SEED location will have a less severe contamination environment compared to SM/MPAC&SEED. This is true even for the predicted contamination at the coldest temperature (-40°C), though this is lower than expected for nominal JEM/MPAC&SEED operation.

Table 5 Summary of JEM/MPAC&SEED Analysis Results

JEM/MPAC&SEED Temperature	Predicted Contamination Depth (Å)		
	JEM (EF and ICS)	ISS (Solar Array & Orbiter)	Total
-40°C	448.2 Å	4.4 Å	453 Å
-10°C	151.2 Å	4.3 Å	156 Å
25°C	72.0 Å	3.4 Å	75 Å

5. Conclusion

The contribution of the induced environment for externally mounted payloads must be understood to ensure successful on-orbit performance. On ISS, the induced contamination environment varies by location and time, as evidenced by the many different contamination sources for SM/MPAC&SEED and JEM/MPAC&SEED. The Boeing Space Environments Team performed analyses to calculate material outgassing and thruster plume induced contamination to both experiments.

Analysis results for SM/MPAC&SEED consistently showed high levels of material outgassing induced contamination on the ram-facing surfaces. The wake-facing surfaces were predicted to accrue contamination due to a combination of material outgassing and thruster plume impingement. These results are qualitatively consistent with visual inspection and XPS measurements of the flight hardware. The calculated depth of contamination on the ram side surfaces is within a factor of 3 of measurements. Although XPS is limited in characterizing depth of plume contamination, the measured and predicted results are of similar scale for the wake-facing surfaces.

Analysis results for JEM/MPAC&SEED showed measurable levels of material outgassing induced contamination. No significant thruster plume induced contamination is expected. The JEM/MPAC&SEED location appears to have a less severe contamination environment compared to SM/MPAC&SEED. However, the extent of induced contamination will depend on the JEM/MPAC&SEED thermal environment.

The return of JAXA's MPAC&SEED external experiments provided a unique opportunity to compare induced contamination predictions with measurements from flight hardware. The Boeing Space Environments Team will continue to work with JAXA to characterize contamination of the MPAC&SEED experiments. These activities are pursued to ensure a known induced contamination environment around the ISS.

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