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Induced-Contamination Predictions for the Micro-Particle Capturer and Space Environment Exposure Device

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The return of International Space Station external experiments provides an opportunity to compare calculations of induced contamination with measurements from flight hardware. The Japan Aerospace Exploration Agency's Micro-Particle Capturer and Space Environment Exposure Device, which was attached to the exterior of the Russian service module, is one such experiment. The Micro-Particle Capturer and Space Environment Exposure Device experiment was purposed for particle capture (i.e., micrometeoroids and orbital debris) and materials exposure over varied durations. The experiment consisted of three identical units, which were mounted outside the International Space Station for periods ranging from 10 months to almost 4 years. X-ray photoelectron spectroscopy of various locations on the three Micro-Particle Capturer and Space Environment Exposure Device units has shown up to 950 Å of contamination deposition. Contamination analyses were performed to compare with measured contamination levels on each Micro-Particle Capturer and Space Environment Exposure Device unit. Material outgassing and thruster plume induced contamination were calculated using analytical and semi-empirical models developed by the Boeing Space Environments Team. Measurable levels of silicon-based contamination were predicted on the ram side, whereas a combination of silicon-based and thruster plume induced contamination was predicted for the wake side. Predictions of contamination depths were within a factor of 3, showing good agreement with measured contamination.

I. 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 material outgassing and thruster pluming. The return of the ISS external experiments provides an opportunity to compare results from contamination calculations with measurements from flight hardware. The Japan Aerospace Exploration Agency's (JAXA's) Micro-Particle Capturer and Space Environment Exposure Device (MPAC&SEED) is one such experiment.

The MPAC&SEED experiment consisted of three identical units, which were mounted outside the Russian service module (SM) on 15 October 2001. The first unit was removed in August 2002, the second in February 2004, and the third in August 2005. Figure 1 shows a view of the fully deployed experiment. This is a view of the ram-facing side (i.e., the side that pointed into the ISS velocity vector for the majority of the experiment). Figure 2 shows a view of the experiment from the wake-facing side. The MPAC experiment was purposed for particle capture (i.e., micrometeoroids and orbital debris). SEED was designed as an exposure experiment to characterize materials degradation in low Earth orbit [1].

All three 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 MPAC&SEED units. Contamination measurements and predictions were previously presented for units 1 and 2. Contamination measurements were recently made available for unit 3, which provides additional insight into the ISS contamination sources [2,3].

II. MPAC&SEED Contamination Observations

From visual inspection, color changes were immediately apparent on the MPAC&SEED wake face, which was covered in a uniform brownish contamination layer (see Fig. 3). Beyond the uniform contamination, many spots were also observed that are indicative of low-velocity droplet impacts. The spots varied in shape and color, with diameters ranging from approximately 1 to 1000 μm. An example spot with a diameter of approximately 100 μm is shown in Fig. 4. These features are more numerous on the wake face than on the ram [1,2,4,5].

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. To characterize depth of contamination, argon ion etching was performed at locations that appeared to be uniform from visual inspection. Results show silicon to be a significant constituent on the ram side of all three 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 than on the ram [2,4].

Nitrogen is a prominent signature for thruster plume induced contamination, considering the propellants used for the ISS thrusters. Nitrogen appeared in small quantities on the wake side (around 4% of

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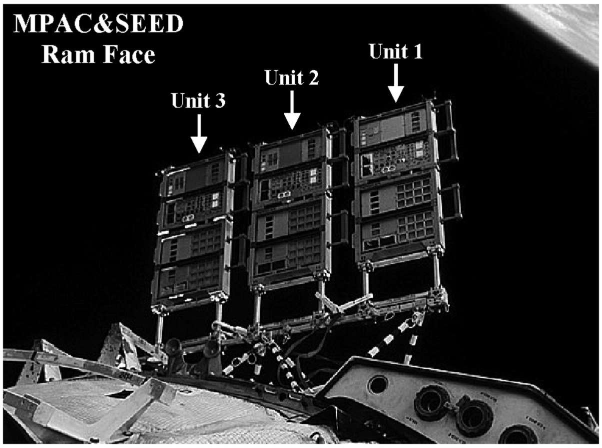

Fig. 1 MPAC&SEED on-orbit, ram-facing side (image courtesy of NASA).

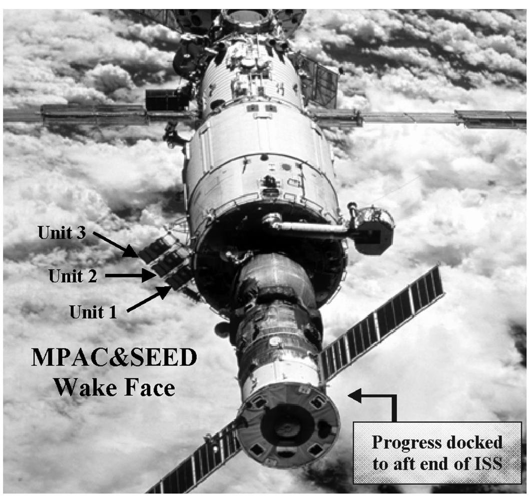

Fig. 2 MPAC&SEED on-orbit, wake-facing side (image courtesy of NASA).

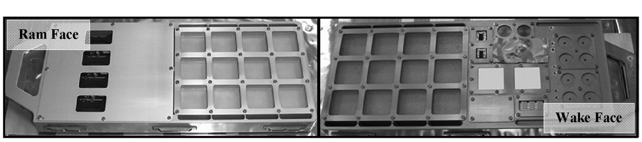

Fig. 3 Comparison of unit 1 ram and wake faces [1] (image courtesy of JAXA).

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 (in the form of ammonium, methylammonium, dimethylammonium, monomethylhydrazine nitrates and monomethylhydrazine nitrites, as well as some unidentified compounds) [6]. Although carbon and oxygen were

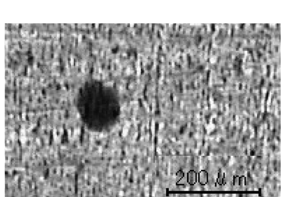

Fig. 4 Colored spot observed on MPAC&SEED [2] (image courtesy of JAXA).

Table 1 Approximate MPAC&SEED contamination depth (in angstroms) based on XPS measurements

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

present on MPAC&SEED, these could be attributed to other sources. Flight experiment data have shown the presence of iron (in addition to nitrogen) in thruster plume residue [7]. Iron is a trace contaminant in the propellant; the iron mass fraction increases with time due to leaching by the propellant when in contact with steel (typically used in the propellant lines).

A summary of contamination depths estimated from XPS results are provided in Table 1. The ram side of the trays showed consistent depth measurements; whereas 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. It should also be noted that XPS measurements on unit 3 were taken at different locations on the tray compared with units 1 and 2, but this is not expected to have a significant impact on results.

In addition to the XPS measurements taken at visually uniform locations, JAXA also selected two spot features on the wake side of unit 3 for XPS analysis. The selected spots were brown and approximately 100 μm in diameter. Element composition from XPS was similar between the two spots, with the highest concentrations in carbon, nitrogen, and oxygen. Of particular interest was the nitrogen concentration, which was significantly higher for the spots (10 and 23%, respectively) than was detected in the measurements of the uniform surface [2]. As mentioned previously, nitrogen is a prominent signature for thruster plume induced contamination. Flight experiment data have shown that droplets are the primary mechanism for thruster plume contamination transport at operating temperatures expected on the ISS (i.e., noncryogenic) [7]. The detection of nitrogen in the MPAC&SEED droplet features strongly indicates thruster plume induced contamination.

III. Contamination Modeling

The Boeing Space Environments Team performed induced-contamination analyses of MPAC&SEED to compare with measured contamination levels. To begin, views to and from the MPAC&SEED trays 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. Primary contamination sources of concern include material outgassing from ISS hardware elements and thruster plume contamination.

A. Material-Outgassing Induced Contamination

Hemispherical views from the ram- and wake-facing sides of MPAC&SEED were used to identify the major ISS outgassing sources (see Fig. 5). These views are centered along the normal vector of the tray surface and expanded out 90 deg. 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 (FCB), service module (SM), and docking compartment 1 (DC1) on the Russian segment had the largest view factors to the MPAC&SEED trays. In addition, visiting vehicles (i.e., Orbiter, Soyuz, and Progress) had significant view factors when mated to the ISS.

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 the ISS elements and MPAC&SEED were taken into account when possible; however, appropriate outgassing-rate test data did not always exist for the temperatures of interest. In these cases, the best available outgassing data were used, though this approach was not always

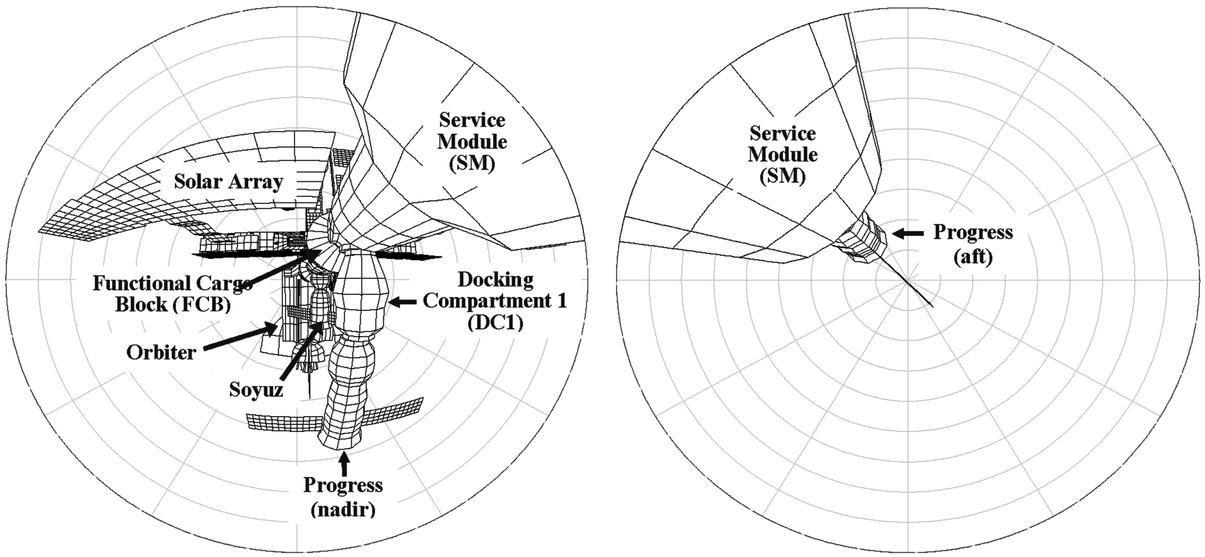

Fig. 5 Hemispherical view from MPAC&SEED in the ram direction (left) and wake direction (right).

conservative. An effective outgassing-rate source term was then calculated based on the quantity of material.

The outgassing source terms account for the duration of exposure to the vacuum environment (time-decay rate of source terms is determined from experimental data and diffusion theory). Visiting vehicles were of key interest because they had comparatively little reduction in outgassing source terms resulting from 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 source terms for the permanent outgassing sources (e.g., FCB, SM, and DC1) continued to decay with time. The FCB, for instance, had been on orbit several years by the time MPAC&SEED was deployed and had a relatively low outgassing source term (due to time decay) compared with 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 using 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.

B. Thruster Plume Induced Contamination

To identify key ISS thrusters of concern for plume impingement to 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, because this is where the highest contamination flux is expected [8].

On the ram-facing side of 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, 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 MPAC&SEED wake face, the most significant thruster contamination source for MPAC&SEED was a Progress braking engine. The braking engines are fired during approach and separation to the docking port on the aft end of the 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 MPAC&SEED wake side. Figure 6 provides a hemispherical view from this thruster when 20 ft from the aft docking port. A few ISS attitude control thrusters also had a line of sight to the wake side. For these, the MPAC&SEED tray was positioned well beyond the thruster centerline; however, several were included in the analysis, given the considerable thruster usage for the ISS attitude control.

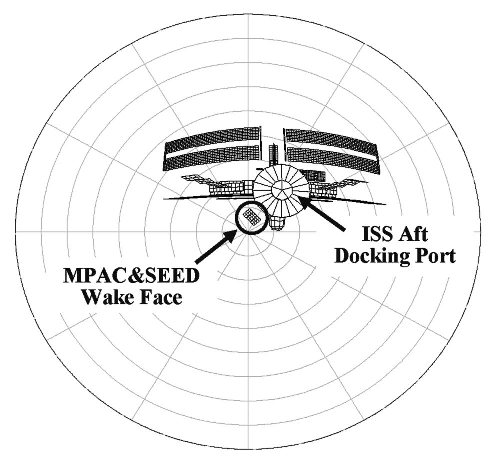

Fig. 6 Hemispherical view from Progress braking thruster: 20 ft to docking.

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 the ISS reboost/attitude control as well as Progress proximity operations were used to simulate thruster firings and calculate thruster induced contamination to MPAC&SEED.

C. Other Contamination Sources

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 that periodically vent fuel or oxidizer. As with thruster plumes, the highest flux region for propellant purges is near the centerline. The MPAC&SEED tray was positioned well beyond the centerlines of the Russian segment's purge ports, and so this contamination source was neglected. There are also water vents on the Orbiter and U.S. segment, but these did not have a line of sight to the experiment.

Self-contamination from direct or return flux may also contribute to deposition. For MPAC&SEED, direct flux was not considered because there is no line of sight between the units on the ram and wake surfaces. Return flux was neglected as a second-order effect.

Another effect that may be of interest for MPAC&SEED is thruster plume erosion. Plume erosion occurs when surfaces are impacted by partially combusted propellant droplets (1–100 μm in diameter), resulting in surface pitting. The gases in the exhaust plume can accelerate these liquid particles to high velocities (1–3 km/s) due to gas drag forces. This effect has been characterized and modeled by the Boeing Space Environments Team [9]. It remains to be seen if thruster plume induced erosion or contamination deposition is the dominating effect. Because MPAC&SEED was exposed to multiple thruster firing events, it would be of interest to investigate plume erosion effects in future studies. This would require extensive microscopy of the MPAC&SEED experiment frames to characterize distribution and sizes of impact craters.

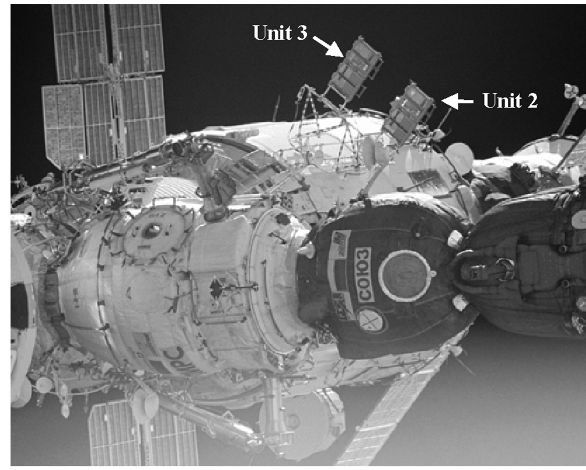

Fig. 7 MPAC&SEED configuration after unit 1 retrieval (image courtesy of NASA).

IV. Analysis Results

Analysis for MPAC&SEED was performed for three 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 MPAC&SEED. Results for the ram side of the units showed measurable levels of outgassing induced contamination, whereas results for the wake side indicated a combination of outgassing and thruster plume contamination.

A. Analysis Results for MPAC&SEED: Ram Side

In addition to the permanent ISS elements, the ram side of MPAC&SEED was exposed to outgassing from Orbiter, Soyuz, and Progress vehicles. Table 3 provides a summary of visiting vehicles present during the MPAC&SEED experiment. Exposure-time durations were taken into account for each element in computing outgassing to the ram side. Because no thrusters were identified as significant contamination sources to the ram face, the outgassing analysis results represent the total contamination prediction.

On the unit 1 ram face, the depth of outgassing induced contamination at the time of retrieval was calculated to be 106–135 Å, depending on location. After unit 1 was retrieved, unit 2 was repositioned to the location previously occupied by unit 1 (see Fig. 7). This was done to reduce blockage from another external experiment. Because the repositioning was minor, it was neglected from the analysis. Predicted contamination on the ram side of unit 2 was 303–354 Å, due solely to material outgassing. After unit 2 was retrieved, unit 3 was repositioned twice to accommodate other external payloads. Once again, the repositioning was minor and not accounted for in the analysis. Outgassing induced contamination was predicted to be 459–533 Å on the ram side of unit 3. A graphical representation of contamination analysis results for the ram side is shown in Fig. 8. In this figure, contamination predictions at the time of retrieval are shown for each MPAC&SEED unit. It should be noted that the contamination level changes gradually across the units; the appearance of sharp gradients (e.g., greater than 91 Å and greater than 111 Å on unit 1) is due to resolution of the scale and grids in the geometric model.

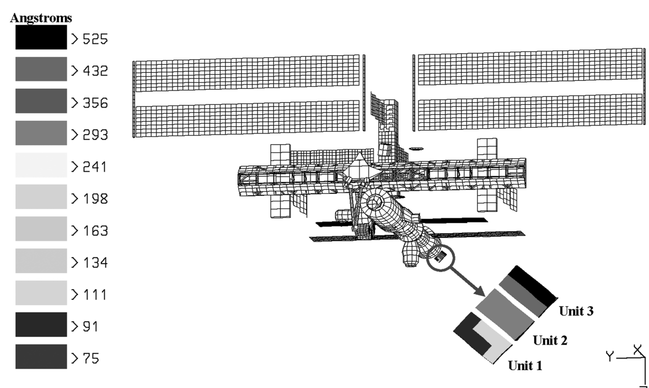

Fig. 8 Predicted contamination on MPAC&SEED ram face.

Table 2 MPAC&SEED timeline used for analysis

Unit	Deployed	Retrieved	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)

Table 3 Visiting vehicle outgassing contamination sources for MPAC&SEED ram side

		Total number of visiting vehicles		
Unit	Days (years)	Orbiter	Soyuz	Progress (nadir)
1	315 (0.9)	3	3	0
2	865 (2.4)	5	6	1
3	1403 (3.8)	6	9	1

B. Analysis Results for MPAC&SEED: Wake Side

It was expected that MPAC&SEED would have less outgassing induced contamination on the wake side because there are fewer sources compared with 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 the ISS caused induced contamination from both materials outgassing as well as thruster firings. A summary of aft Progress vehicles present during the MPAC&SEED experiment is provided in Table 4. Despite the significant thruster usage from ISS attitude control thrusters, the thruster views to MPAC&SEED were benign enough to result in nearly negligible contamination for all units.

Approximately 35 Å of outgassing deposit was predicted for the unit 1 wake face, and cumulative plume induced contamination was predicted to be 52–69 Å. Thruster plume induced contamination is

Table 4 Visiting vehicle outgassing and thruster plume contamination sources for MPAC&SEED wake side

Unit	Days (years)	Total number of progress vehicles (aft)
1	315 (0.9)	4
2	865 (2.4)	8
3	1403 (3.8)	13

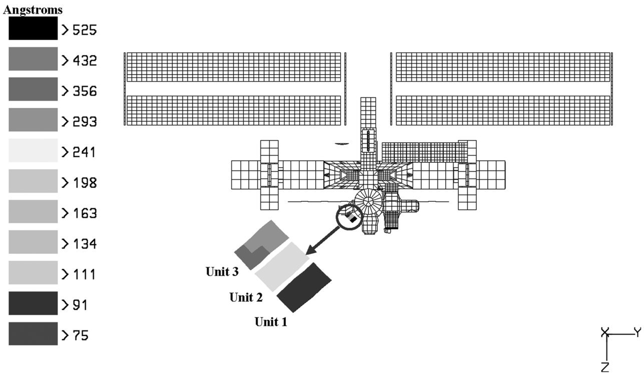

Fig. 9 Predicted contamination on MPAC&SEED wake face.

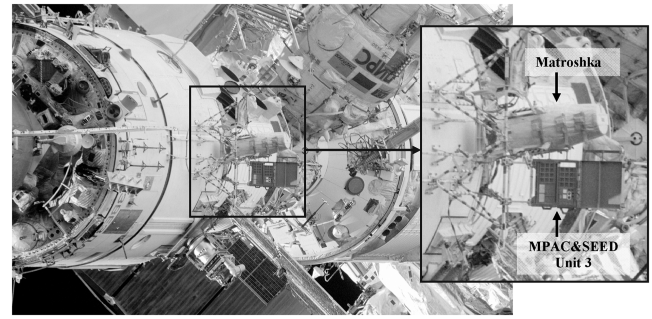

Fig. 10 Matroshka experiment deployed near MPAC&SEED unit 3 (image courtesy of NASA).

dominated by the liquid phase of the plume and decreases rapidly with degree from the plume centerline. The surfaces of the MPAC&SEED trays closest to the Progress plume centerline have the highest predicted contamination, with levels decreasing outwardly. Between outgassing and thruster induced-contamination sources, the cumulative depth of contamination predicted on the unit 1 wake face is 86–103 Å (depending on location). On the unit 2 wake side, results showed 77–91 Å of contamination due to material outgassing, and 107–150 Å of contamination due to thruster plume impingement. Total outgassing and thruster induced contamination predicted on the unit 2 wake side is 186–237 Å. Finally, results for unit 3 showed 121–143 Å of contamination due to material outgassing and 195–275 Å of contamination due to thruster plume impingement, totaling 317–414 Å predicted. A graphical representation of contamination analysis results for the wake side is shown in Fig. 9.

C. Analysis, Summary, and Discussion

Analysis results consistently showed measurable levels of material outgassing induced contamination on the 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 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 of uniform contamination 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 5. The calculated depth of contamination on the ram-side surfaces is within a factor of 2–3 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. In addition, several external hardware items mounted on the Russian service module were located in close proximity to MPAC&SEED. The Matroshka experiment, for instance, was mounted just forward of the MPAC&SEED experiment shortly after unit 2 was retrieved (see Fig. 10). This experiment could have contributed to contamination levels on the ram side of MPAC&SEED unit 3, given the close proximity. However, detailed materials data are not available for Matroshka to include in contamination analyses. It is likely that there are other 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 were available. Considering, however, the number of outgassing sources on the ISS and long duration of the experiment, the predicted results for the ram side represent excellent agreement with the measured depth of contamination.

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 Sec. II). Whereas outgassing yields a fairly uniform molecular contamination layer, thruster plume induced contamination is dominated by the liquid phase, producing droplet features and a nonuniform distribution of contaminants. Nevertheless, consistent XPS results showing the most prominent presence of nitrogen on the wake face from all three units give much confidence in predictions for plume contamination on the wake side. The XPS results for the spot features, which showed even higher levels of nitrogen, are particularly indicative of plume induced contamination. This agrees well with predictions. It is reasonable to expect that plume contamination was a factor in the darkening of the wake side of the tray. Hence, XPS measurements for the ram side of 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.

The XPS results on the unit 1 wake side gave somewhat inconsistent measurements between the two locations, with depths of 500 and 55 Å, respectively. Some variation could be attributed to the nature of thruster plume induced contamination; however, it is likely that the 500 Å measurement is a local anomaly. The 55 Å measurement is much more consistent with measurements from the unit 2 and 3 wake sides (70 to 110 Å, from Table 1). Excluding the 500 Å 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 the depth of plume contamination.

Table 5 Comparison of MPAC&SEED measured and predicted contamination depth (in angstroms)

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

V. Conclusions

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 performed an analysis to calculate material outgassing and thruster plume induced contamination to the MPAC&SEED experiment.

Analysis results consistently showed high levels of material outgassing induced contamination on the MPAC&SEED 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 MPAC&SEED.

The calculated depth of contamination on the ram-side surfaces is within a factor of 2–3 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.

The Boeing Space Environments Team strives to obtain contamination measurements for any external hardware that is returned from the ISS and will continue to work with JAXA to characterize contamination of MPAC&SEED. These activities are pursued to ensure a known induced-contamination environment around the ISS.

Acknowledgment

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