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Passive Space-Environment-Effect Measurement on the International Space Station

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The Micro-Particles Capturer and Space Environment Exposure Device is the Japan Aerospace Exploration Agency's experiment on particle capture and space exposure of material mounted on an aluminum tray. The trays were placed on the exterior of the Russian service module of the International Space Station. All trays were retrieved and returned to Earth. This paper presents our analysis of the effects that space exposure imparted on the monitoring samples in the first- and second-retrieved Micro-Particles Capturer and Space Environment Exposure Device trays. The monitoring samples yield space-environment data such as atomic oxygen, ultraviolet, fluence, and space radiation dose data. The exposure and monitoring samples were retrieved after 315 and 865 days of exposure.

Nomenclature

A	=	exposed surface area
t	=	material thickness
αs	=	solar absorption
ΔW	=	mass loss
ρ	=	material density

I. Introduction

THE goal of experiments that expose materials to space is to assess the performance of prospective spacecraft materials. The Micro-Particles Capturer and Space Environment Exposure Device (MPAC&SEED) experiment selected materials that were expected to show the combined effects of the low-Earth-orbit space environment: high-energy radiation particles, ultraviolet (UV) rays, atomic oxygen (AO), and contamination. It is essential to evaluate the effects that the space environment will have on these materials to improve spacecraft design, useful life, and performance. The National Space Development Agency of Japan, the forerunner of the Japan Aerospace Exploration Agency (JAXA), tested space-material exposure on the STS-85/Evaluation of Space Environment and Effects on Materials (ESEM) mission in 1997 [1] and on the Exposed Facility Flyer Unit of the Space Flyer Unit in 1996 [2].

The MPAC&SEED on the service module (SM) consisted of both MPAC and SEED. The latter is a passive experiment designed simply to expose materials. It is mounted on a collapsible frame, which is 1 m long when open, that it shares with MPAC. The MPAC is a passive experiment designed to sample micrometeoroids and the space-debris environment and, using aerogel, polyimide foam, and 6061-T6 aluminum, to capture particle residues for later chemical analyses. More detailed descriptions of the MPAC and SEED on the SM are reported elsewhere [3–7].

We placed three identical MPAC&SEED units aboard the Progress M-45 when it was launched on 21 August 2001. On 15 October 2001, astronauts attached them side by side to a handrail outside the SM during extravehicular activity. They retrieved the first unit on 26 August 2002, after 315 days of exposure, and returned it to Earth shortly afterward. The second unit was retrieved on 26 February 2004, after 865 days of exposure. Finally, the last unit was retrieved on 18 August 2005, after 1403 days of exposure.

The MPAC&SEED experiment included samples for monitoring the total dose of AO, UV, space radiation, and temperature. In this paper, the results of the analyses of the effects of space on the MPAC&SEED 1 and 2 monitoring samples retrieved after 315 and 865 days are described.

II. Monitoring Samples

Figure 1 presents a photograph of two trays of an MPAC&SEED unit. Each unit had four trays. The temperature-monitoring sample was mounted on the back of all four trays, and the remaining monitoring samples were mounted on two trays. The front face of the MPAC&SEED was termed *ram* and the back face was termed *wake*. However, this orientation meant little because the International Space Station (ISS) flight attitude often changed to maximize power and minimize negative thermal effects. The result of this directional analysis is described in a later section. This section explains the detailed specifications for each monitoring sample.

For temperature monitoring, a thermolabel in a tray measured only the maximum temperature.

A. Atomic Oxygen Monitoring

Carbon films and Vespel (SP-1) were selected for AO monitoring. Vespel is made from aromatic polyimide powder. Kapton-100H was selected for the AO monitoring sample on the ESEM mission [1]. Vespel ($t = 500\ \mu m$) is thicker than Kapton-100H ($t = 25\ \mu m$). If we were to extend the exposure period of MPAC&SEED on the SM mission, the AO would cause the Kapton-100H to disappear; therefore, we selected Vespel for its greater thickness. Ground AO irradiation testing was conducted to calibrate the atomic-oxygen fluence. We conducted irradiation tests at JAXA's Combined Space Effects Test Facility, which is equipped with a laser detonation-type AO source, a deuterium UV-ray source, and an electron-beam source.

Figure 2 illustrates the dependence of mass loss from Vespel and its dependence on the AO fluence. The efficiency of mass losses on the linear part is equal to $Re = 3.33 \times 10^{-24}\ cm^3/atoms$. Using this

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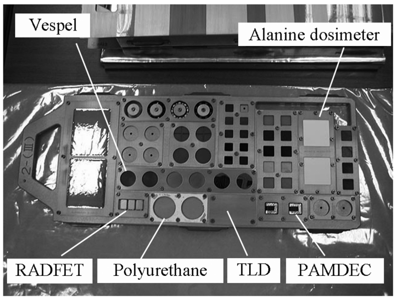
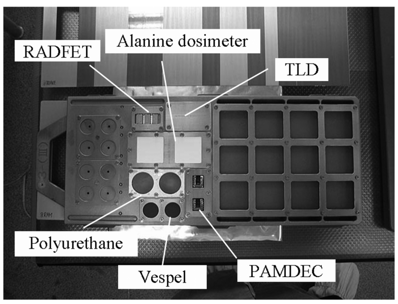


a) Tray no. 2 (ram face)



b) Tray no. 3 (wake face)

Fig. 1 Photographs of the monitoring samples on an MPAC&SEED. The monitoring samples were nearby and were assigned to exposure materials and aerogel. Trays 1 and 4 did not have monitoring samples, with the exception of thermolabels.

relationship between AO fluence and mass loss, AO fluence acting on the test specimen in orbit is derived as follows:

$$\text{AO fluence atoms/cm}^2 = \frac{\Delta W}{Re \cdot \rho \cdot A} \tag{1}$$

where $\rho = 1.45\ \text{g/cm}^3$ and $A = 3.14\ \text{cm}^2$.

We cut a 125-μm-thick carbon film into 1×8 mm strips and integrated the film into a small device called a passive atomic-oxygen monitoring device equipped with carbon film (PAMDEC). The PAMDEC consists of five strips, with one strip masked using copper tape. We arranged these strips on 20×18 mm FR-4 (glass epoxy copper-clad laminates). This carbon film was used as an atomic-oxygen monitor sensor aboard the Japanese Experiment Module Exposed Facility on the ISS [8]. Other carbon-based atomic oxygen actinometer sensors were developed [9]. The AO eroded the carbon film while increasing its resistance. We calibrated the AO fluence, comparing it with the resistance of the PAMDEC and the ground AO-irradiation test data.

B. Ultraviolet Monitoring

For our UV monitoring, we used a polyurethane sheet covered with glass to protect against AO erosion. The same type of sample was used in the ESEM [1] and Exposed Facility Flyer Unit missions. For the passive optical sample assembly (POSA-I) experiment mounted on the Mir space station from March 1996 to October 1997, VUV diodes were used for monitoring VUV radiation [10]. Solar-absorption αs data, along with the calibration data acquired in the Xe-resonance lamp-irradiation test, helped us to evaluate the UV fluence. We arranged the samples on gel sheets in a vacuum chamber to prevent increased temperature because of the Xe lamp, which contains an infrared wavelength region. Figure 3 depicts the calibration curve for this sample.

C. Space-Radiation Effect: Total Ionizing Dose

We used three types of dosimeters to evaluate the effect of space radiation: thermoluminescent dosimeter (TLD), alanine dosimeter, and radiation-sensitive field-effect transistor (RADFET). The TLD was also used on the ESEM mission [1]. A TLD is a small device that is used to evaluate radiation exposure by measuring the amount of visible light emitted by a crystal when heated in the detector. The amount of emitted light depends on the ionizing irradiation exposure. We arranged six TLDs behind a 4.5-mm-thick aluminum shield on both the ram and wake sides of a sample tray.

An alanine dosimeter is a solid device consisting mainly of alanine and polystyrene. The radical density increases in proportion to the dose of radiation received. The relative density of the radical is measured using electron spin resonance. Four alanine dosimeters were arranged behind a 0.15-mm aluminum shield with white paint on both the ram and wake sides of a sample tray.

A RADFET is a specially designed *P*-channel metal oxide semiconductor transistor with a thick gate oxide, which is optimized for increased radiation sensitivity. The RADFET is suitable for real-time space dosimetry missions in cost, weight, and low-power-consumption variables [11,12]. The RADFETs used in MPAC&-SEED were 400 nm implanted gate-oxide devices, manufactured by the Tyndall National Institute of Ireland. We arranged three RADFETs on both the ram and wake sides of a tray. This RADFET had a 0.8-mm-thick equivalent aluminum lid.

III. Results

Table 1 presents the derived results of the monitoring samples. We calculated the derivation value from the mean value of reliable data in cases in which several monitoring samples existed. The first-retrieved monitoring sample data are labeled as sample 1; the second-retrieved monitoring sample data are labeled as sample 2.

The maximum temperatures in the three trays were 50–90°C. The AO fluence was 10^{20} atoms/cm^2 from Vespel and 10^{21} atoms/cm^2 from PAMDECs. The MPAC&SEED 1 data showed higher values than those of MPAC&SEED 2, although the MPAC&SEED 2 had longer exposure than in the AO fluence. A similarly unexpected

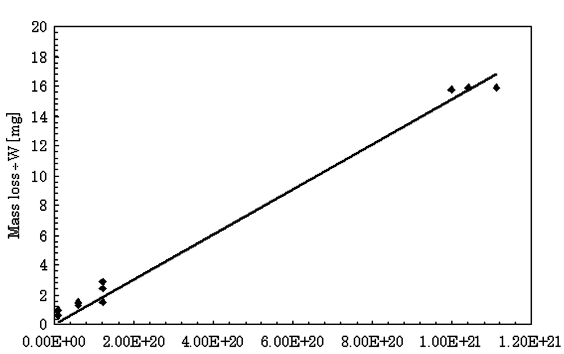


Fig. 2 Mass loss from Vespel by AO exposure. The *X* axis represents AO fluence, and the *Y* axis represents the mass difference from the initial value, which is divided by the density and exposed surface area.

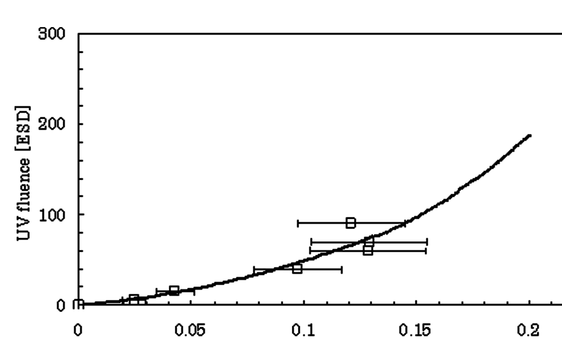


Fig. 3 Calibration curve for the UV monitoring sample. The *X* axis represents the difference of solar absorption αs from the initial value $\Delta\alpha s$, and the *Y* axis shows the UV fluence.

Table 1 Derivation results from the monitoring samples

		Ram face		Wake face	
		No. 1	No. 2	No. 1	No. 2
Maximum temperature, °C	Thermolabel	50[a]	50[a]	——	——
		60[b]	90[b]	——	——
AO, atoms/cm^2	Vespel	2.04×10^{20}	2.57×10^{20}	1.61×10^{20}	2.05×10^{20}
	PAMDEC	2.41×10^{21}	1.36×10^{21}	1.93×10^{21}	1.22×10^{21}
UV, ESD[c]	Polyurethane sheet	18.1	15.8	122.2	201.0
Total ionizing dose, Gy	Alanine dosimeter	1.95	15.30	3.5	21.0
	RADFET	0.44	5.99	0.27	4.92
	TLD	1.46×10^{-3}	0.12	3.41×10^{-3}	0.09

[a]At approximately 5 mm depth in trays 1 and 2.
[b]At approximately 1 mm depth in trays 3 and 4.
[c]Equivalent solar day, 1 ESD $= 1.02 \times 10^7$ J/m^2.

result also occurred in the UV monitoring samples. The measured intensity of UV in the wake face was greater than that from the ram face. The total ionizing dose data depended on the shield thickness.

IV. Discussion

Orbital and attitude flight information of the ISS during this experiment period, provided by RSC Energia, was analyzed. The average flight altitude was 385 km; the inclination was 51.6 deg. The ISS has different attitude modes until the main solar arrays are in position. The main attitudes are the X axis in the velocity vector (XVV), the X axis perpendicular to the orbital plane (XPOP), and the Y axis in the velocity vector (YVV). The ram and wake faces are oriented along the ram and wake directions of the ISS when the ISS flies in the XVV mode. However, during XPOP mode and during YVV mode, the MPAC&SEED faces a direction that is perpendicular to the flight direction. During the first year of the MPAC&SEED 1, the ISS spent 59% of its time in XVV mode and 41% in XPOP mode. During MPAC&SEED 2, the ISS spent 54% of its time in XVV mode and 46% in XPOP and YVV modes. Therefore, both the ram and wake faces were pointed in the flight direction.

We compared flight data and data from the space-environment model for the atomic-oxygen fluence and calculated the AO fluence using the MSIS-86 model in Space Environment & Effects System (SEES) [13] from 15 October 2001 to 26 February 2004. We used the F10.7 and Ap index data available from National Oceanic and Atmospheric Administration Space Weather Data and Products database [14] and considered the flight-direction change in our calculation.

In Fig. 4, we show the flight data. Although the results in Fig. 4 include consideration of the flight direction, the values of the flight data taken from the monitoring samples for the ram and wake faces were less than the SEES-model calculation. This suggests that the contamination effect is responsible for monitoring environment.

We also compared flight data and data from the space-environment model for the UV fluence and calculated the UV fluence using SEES [13]. In this analysis, a cube was used in place of the real ISS shape. We also considered the flight-direction change in our calculation. In Fig. 5, the UV fluence from the polyurethane sheet on the wake side was 1.3 times the data from the space-environmental model. However, the value from the ram side reached almost one-tenth of the data from the space-environment model. Moreover, the second-retrieved data were less than the first-retrieved data, which suggests that the ram side was not exposed to UV because the ISS itself or some components in the field view of the MPAC&SEED trays shaded the UV irradiation. Figure 6 shows fish-eye images from the ram and wake side of the MPAC&SEED. Actually, the Russian-segment elements had the largest view factors to the MPAC&SEED trays in the ram side. The Russian-segment elements of concern include the functional cargo block, SM, and docking compartment 1. In addition, visiting vehicles (space shuttle, Soyuz, and Progress) had considerable view factors when mated to the ISS [15]. The field view from the wake side is clear during MPAC&SEED mission period. Also, XPOP is the attitude at which the X axis is perpendicular to the orbital plane and therefore in the $+X$ direction toward anti-sun. These reasons suggest that the ram side was not exposed to UV.

We used x-ray photoelectron spectroscopy (XPS) to analyze the surface chemical condition of the carbon film in the PAMDEC for AO monitoring samples. The XPS analyses were performed (ESCAlab 220i-XL; VG Scientific) using Al $K\alpha$ radiation. The analysis area is a 700-μm-diam spot. The depth resolution performance is a few nanometers. For carbon on the ram face, XPS analysis was conducted. Figure 7 shows the atomic concentration of the external surface of the carbon film on the ram side and an unflown sample. The atomic concentration is the ratio of the element to all elements constituting the surface material. For the unflown sample, carbon itself was the dominant element. For the flight samples, however, more oxygen and silicon existed than carbon, suggesting that oxides of silicon were present on the very top surface. In addition, nitrogen, sodium, fluorine, and tin were detected, but not at concentrations greater than 1%.

Figure 8 depicts a depth profile of the PAMDEC for an unflown sample and flight samples. For depth profiling, Ar-ion etching was used. The unflown sample did not have a dependent profile of

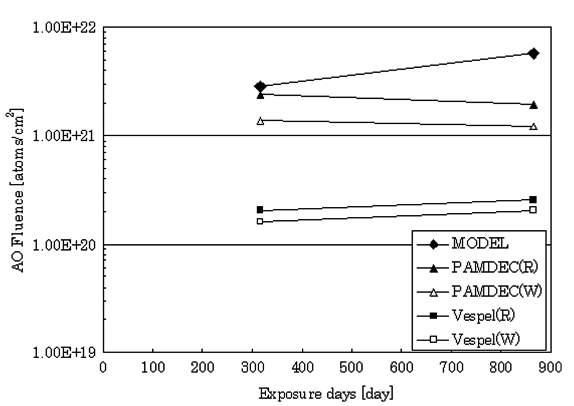


Fig. 4 Comparison of AO fluence versus data from the PAMDEC and Vespel monitoring samples and the model calculation.

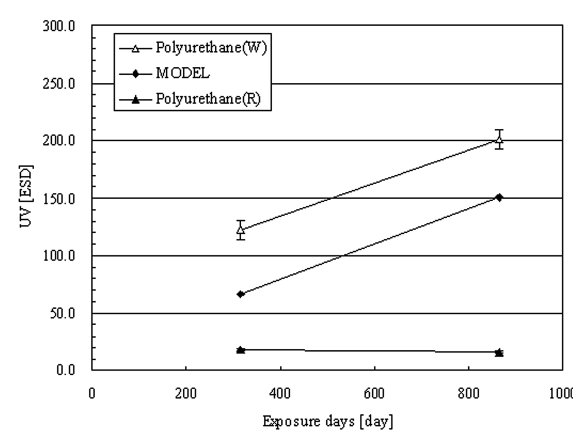


Fig. 5 Comparison of UV fluence vs data from the polyurethane UV monitoring samples and the model calculation.

elements; however, the flight samples had a dependent profile. The distribution of silicon and oxygen in the depth direction suggested that the oxides of the silicon layer existed below the surface. The layer thickness is defined as the point at which the concentration of Si exceeds that of carbon. The layer thickness of the first-retrieved sample (sample 1) was estimated as 10 nm and that of the second-retrieved sample (sample 2) was estimated as 90 nm. This layer, produced by contamination, was grown in flight; it protected the surface of the monitoring sample from erosion.

We also used scanning transmission electron microscopy (STEM) to analyze the surface conditions of the carbon film in the PAMDEC for AO monitoring samples and performed chemical composition analyses using x-ray microanalysis with electron energy-loss spectroscopy (EELS). The STEM–EELS analyses were performed using a field emission electron microscope (JEM-2100F; JEOL) with a Gatan imaging filter (Gatan Inc.). The acceleration voltage is 200 kV. Ultrathin slice samples were fabricated using a focused ion beam. Figure 8 depicts the bright-field and high-angle annular dark-field STEM images of the carbon film on the ram side of the first- and the second-retrieved samples.

A layer of approximately 40 nm on sample 1 (and approximately 70 nm on sample 2) is visible on the inside carbon structure in both the bright-field and high-angle annular dark-field images in Fig. 9. This layer exhibited a flattened structure along the surface, but it was not uniform on voids. This layer was characterized as SiO_2 from EELS one- and two-dimensional analyses. This result almost corresponds with those of the XPS analysis. Past results identified this contamination effect from previous Mir [10] and space station results [16,17], which suggest that the erosion rate or thermo-optical characteristics of the passive monitor sample were affected by contamination.

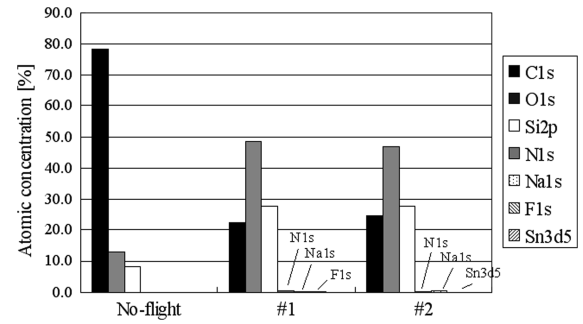
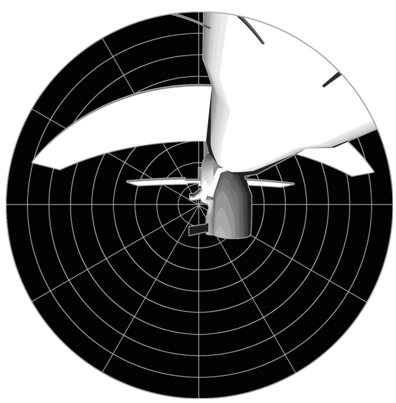


Fig. 7 External surface conditions of PAMDEC using XPS analysis.



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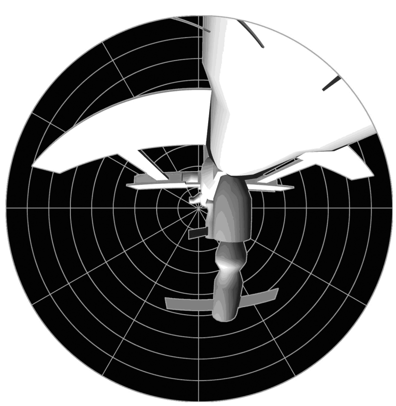

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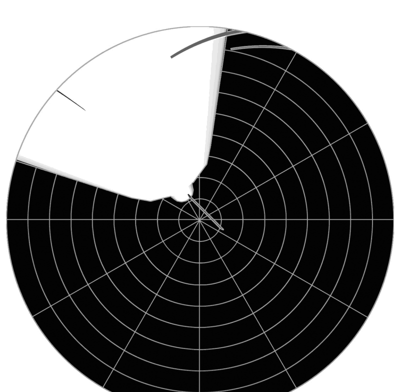
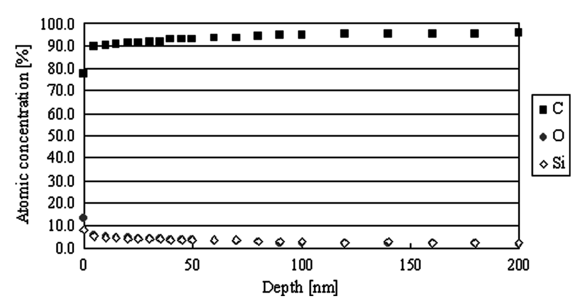


c)

Fig. 6 Field-view analysis from the MPAC&SEED: a) from the ram side on 15 October 2001 (just after the start of exposure), b) from the ram side in June 2003, and c) from the wake side on 15 October 2001.



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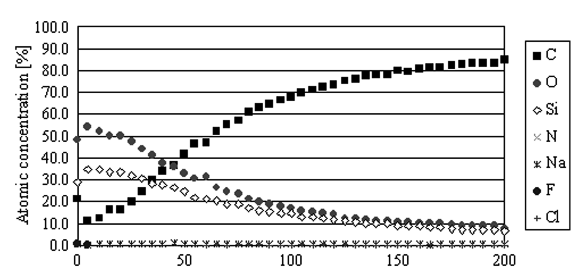

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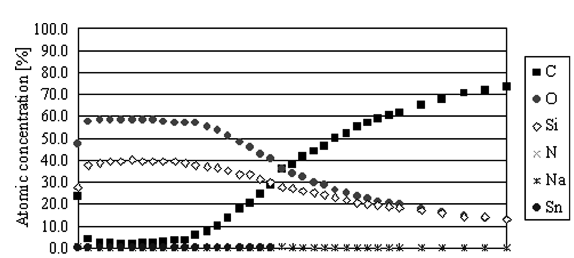
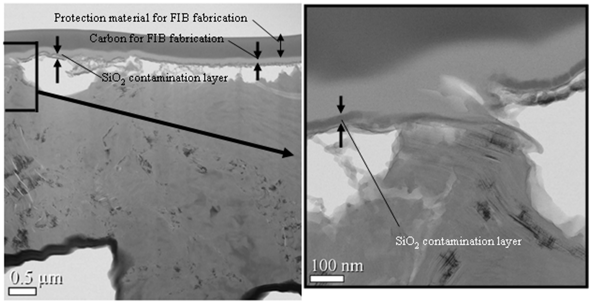


c)

Fig. 8 Depth profile from XPS analysis of the PAMDEC for a) unflown flight, b) first-retrieved sample (sample 1), and c) second-retrieved sample (sample 2).



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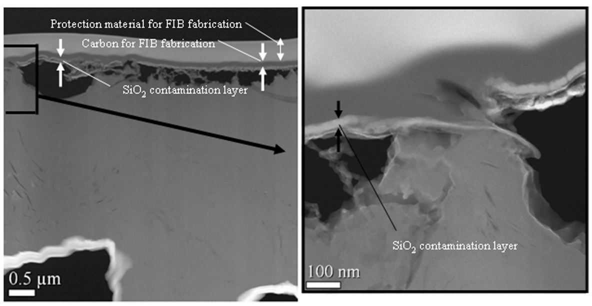

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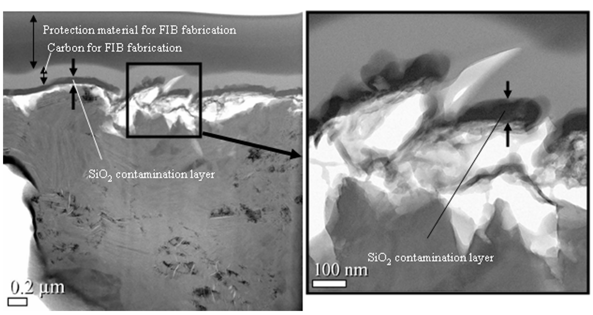

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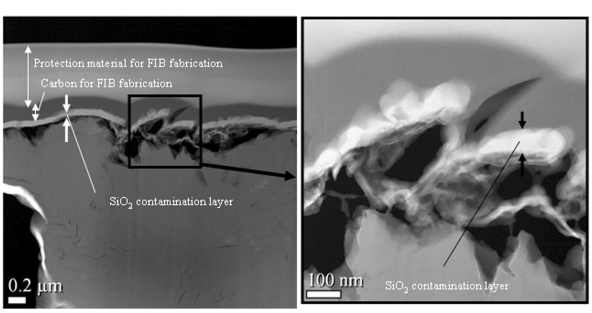
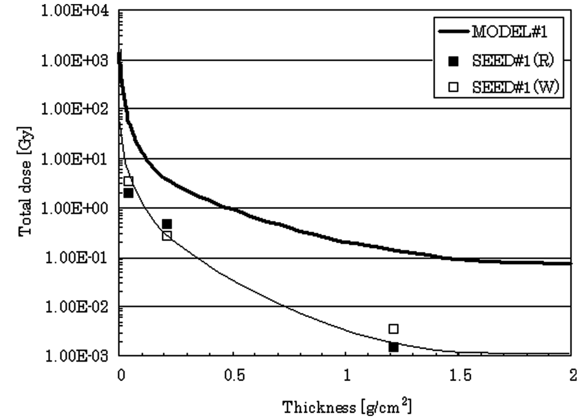


d)

Fig. 9 STEM images of the carbon film on the ram side of the first-retrieved (sample 1) and the second-retrieved (sample 2) samples: a) sample 1 bright field, b) sample 1 high-angle annular dark field, c) sample 2 bright field, and d) sample 2 high-angle annular dark field. FIB denotes a focused ion beam.



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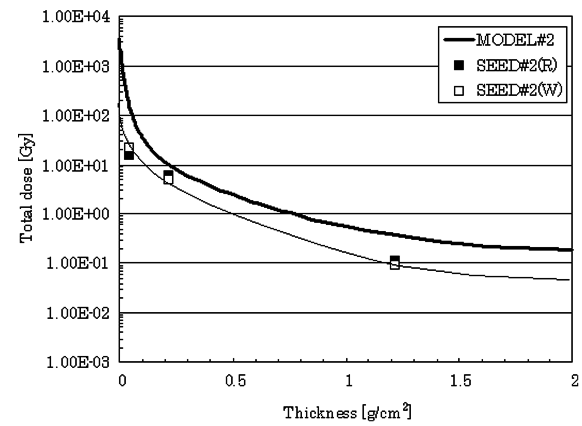

b)

Fig. 10 Dose-depth curve from MPAC&SEED 1 and MPAC&SEED 2 sample and models for a) first-retrieved sample (sample 1) and b) second-retrieved sample (sample 2).

Figure 10 plots the total dose data vs aluminum-shield thickness (i.e., a dose-depth curve) of the flight data and model calculation. Contamination did not affect the total-ionizing-dose monitoring because it was at the several-hundred-nanometer level. The dose-depth curve was calculated from the alanine dosimeter, RADFET, and TLD in MPAC&SEED samples 1 and 2. Flight data were plotted by following their own shield thickness. In addition, AP8, AE8, JPL1991, and SHIELDOSE-2 models in the SEES model [13] were used for model calculation.

The results revealed that the flight data were less than, but approximately equal to, the model data. The current analysis was based only on the data collected during one year and two years. The third set of retrieved monitoring samples (MPAC&SEED 3) is under investigation. It will be analyzed in greater detail, and comparisons with the modeling data will be evaluated.

V. Conclusions

We analyzed monitoring samples from two MPAC&SEED trays that were retrieved after 315 and 865 days of exposure. We derived space-environment data, AO, UV, and space-radiation effect data from monitoring samples. Values of AO fluence data and UV fluence in the ram data from the monitoring samples were smaller than those of the model calculations. One reason for the discrepancies between the flight data and the model calculation was considered to be that both ram and wake faces were pointed in the flight direction for AO fluence. For UV fluence, the ISS itself or some components in the field view of the MPAC&SEED trays suggested shading of the UV irradiation in the ram direction. The XPS and STEM–EELS analysis revealed oxides of the silicon layer on the top surface, which suggests that the erosion rate or thermo-optical characteristics of the passive monitor samples were affected by contamination. The flight total-dose data were estimated as lower than the model result. The third set of retrieved monitoring samples (MPAC&SEED 3) will be analyzed, and a comprehensive conclusion will be reported.

Acknowledgments

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