Post Retrieval Analyses of Space Environment Monitoring Samples: Radiation Effects, UV, and Atomic Oxygen Fluence

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A space materials exposure experiment was performed on the International Space Station (ISS) using the Micro-Particles Capturer and Space Environment Exposure Device (MPAC&SEED) developed by the Japan Aerospace Exploration Agency (JAXA). The experiment was executed on the exterior of the Russian Service Module (SM) of the ISS. The monitoring samples on SEED yield space-environment data such as AO, UV, fluence and space radiation dose data. The exposure and monitoring samples were retrieved after 315 days (about 10 months) and 865 days (about 28 months) and 1403 days (about 46 months) of exposure. This paper presents an analysis result of monitoring samples and orbital and attitude flight information of ISS during the SM/MPAC&SEED mission.

Keywords: MPAC&SEED, ISS Service Module, Space Environment Monitoring Samples, AO, UV, TID

1. Introduction

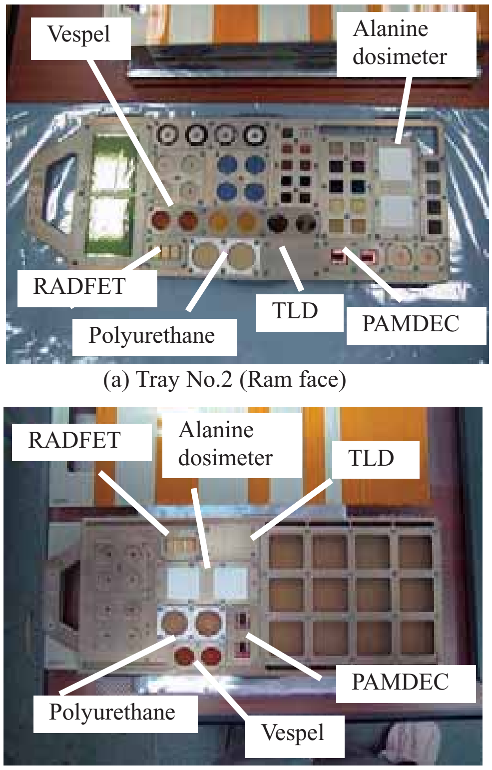
The SM/MPAC&SEED was a passive experiment that used neither a power source nor communication. Therefore, in-situ information was not telemetered from space. Samples for monitoring the total dose of AO, UV, space radiation, and temperature were situated on board. This paper presents experimental methods along with results of analyses of the space environment derived from space environment monitoring samples.

2. Space Environment Monitoring Samples

2.1 System description

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; the remaining monitoring samples were mounted on two trays. The front face of the MPAC&SEED was designated as "ram"; the back face was termed "wake." However, this orientation meant little because the 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 detailed specifications for each monitoring sample.

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



(a) Tray No.2 (Ram face)

(b) Tray No.2 (Wake face)

Fig.1 Photographs of the monitoring samples on an MPAC&SEED unit.

2.2 Monitoring sample

2.1 Atomic Oxygen (AO) monitoring

Carbon films and Vespel (SP-1) were selected for AO monitoring. Vespel is made from aromatic polyimide powder. Kapton-100H was selected for use as the AO monitoring sample on the ESEM mission [1]. Vespel (t=500 μm) is thicker than Kapton-100H (t=25 μm). 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 PSI FAST AO source, a deuterium UV-ray source, and an electron-beam source.

Figure 2 portrays the dependence of Vespel mass loss on the AO fluence. The efficiency of mass loss on the linear part is equal to Re=3.33×10^{-24} [cm^3/atoms]. Using this relationship between AO fluence and mass loss, the AO fluence acting on the test specimen in orbit is derived as follows.

$$(1)\quad AOFluence[atoms / cm^2] = \frac{\Delta W}{\mathrm{Re}\bullet \rho \bullet A}$$

In that equation, ρ [= 1.45 g/cm^3] and A [= 3.14 cm^2].

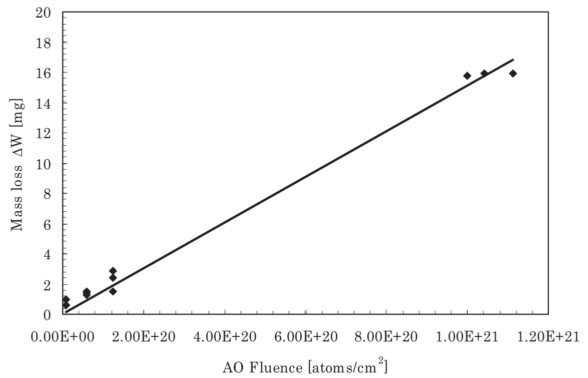


Fig. 2 Vespel mass loss attributable to AO exposure. The X-axis represents AO fluence; the Y-axis shows the mass difference from the initial value, which is divided by the density and exposed surface area.

We cut a 125-µm-thick carbon film into 1 mm × 8 mm strips and integrated the film into a small device called a Passive Atomic-Oxygen Monitoring Device Equipped with Carbon Film (PAMDEC), which consists of five strips, with one strip masked using copper tape. We arranged these strips on 20 mm × 18 mm FR-4 (glass, epoxy, copper-clad laminates). Figure 3 presents a photograph of the PAMDEC. This carbon film was used as an Atomic Oxygen Monitor (AOM) sensor aboard the Japanese Experiment Module Exposed Facility (JEM-EF) on the ISS [2]. Other carbon-based atomic oxygen actinometer sensors were developed [3]. The AO eroded the carbon film while increasing its resistance. We calibrated the AO fluence, comparing it to the resistance of the PAMDEC and the ground AO-irradiation test data.

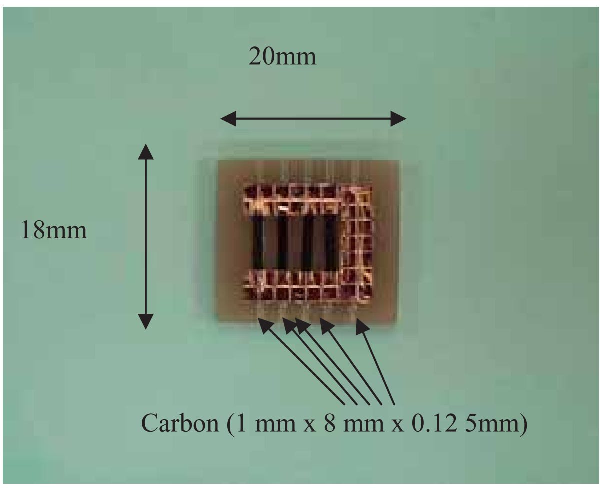


Fig. 3 Photograph of the PAMDEC

2.2 Ultraviolet (UV) 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 EFFU missions [4]. For the Passive Optical Sample Assembly (POSA)-1 experiment mounted on the Mir space station from March 1996 to October 1997, VUV diodes were used for monitoring VUV radiation [5]. Solar-absorption (αs) data, along with calibration data acquired from 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 temperatures caused by the Xe lamp, which contains an infrared wavelength region. Figure 4 depicts the calibration curve for this sample.

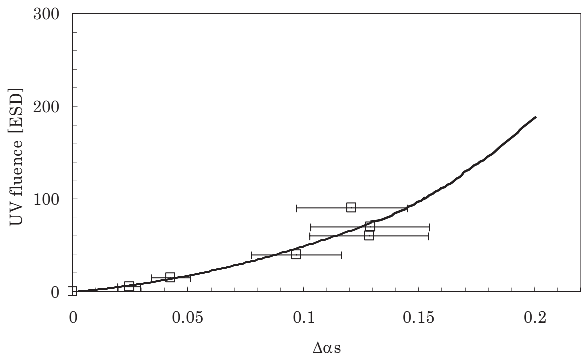


Fig. 4 Calibration curve for UV monitoring sample. The X-axis represents the difference of solar-absorption (αs) from the initial value (Δαs); the Y-axis shows the UV fluence.

2.3 SPACE-RADIATION EFFECT: TOTAL IONIZING DOSE (TID)

We used dosimeters of three types to evaluate the effect of space radiation: a thermo-luminescent dosimeter (TLD), an alanine dosimeter, and a 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 (ESR). 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 (PMOS) transistor with a thick gate oxide, which is optimized for increased radiation sensitivity. The RADFET is suitable for real-time space dosimetry missions in terms of its cost, weight, and low power consumption specifications [6, 7]. 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.

Table 1 Derivation results from the monitoring samples

		Ram Face			Wake Face		
		#1	#2	#3	#1	#2	#3
Maximum [°C]	Temperature	50[a] 60[b]	50[a] 90[b]	60[a] 90[b]	—	—	—
AO [atoms/cm^2]	Vespel	2.04×10^{20}	2.57×10^{20}	2.70×10^{20}	1.61×10^{20}	2.05×10^{20}	3.09×10^{20}
	PAMDEC	2.41×10^{21}	1.36×10^{21}	1.37×10^{21}	1.93×10^{21}	1.22×10^{21}	4.82×10^{21}
UV [ESD]		18.1	15.8	13.4	122.2	201.0	205.5
TID [Gy]	Alanine dosimeter [c]	1.95	15.3	32.0	3.5	21.9	58.3
	RADFET[d]	0.44	5.99	8.59	0.27	4.92	14.9
	TLD[e]	1.46×10^{-3}	0.12	0.29	3.41×10^{-3}	0.09	0.04

[a] At approximately 5 mm depth in Tray No. 1 and 2.

[b] At approximately 1 mm depth in Tray No. 3 and 4.

Shield thickness; [c] 0.04 [g/cm^2], [d] 0.2 [g/cm^2], [e] 1.2 [g/cm^2]

3. Derivation results from the monitoring samples

Table 1 presents results derived from sample monitoring. The first-retrieved monitoring sample data are labeled as #1; the second-retrieved are labeled as #2; the third-retrieved are labeled as #3.

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 MPAC&SEED #2 had longer exposure than #1 in the AO fluence. A similarly unexpected 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 TID data were dependent on the shield thickness.

4. Discussion

Orbital and attitude flight information of the ISS during this experiment period, provided by RSC Energia, was analyzed. The average flight altitude was 371 km. the inclination was 51.64 deg. Figure 5 shows ISS post-flight orbital and attitude changes. Table 2 shows the average orbital and attitude. 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 Orbit 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 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 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 mode. 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 the Space Environment & Effects System (SEES) [8] during 15 October 2001 – 26 February 2004. We used the F10.7 and Ap index data available from NOAA Space Weather Data and Products [9] and considered the flight-direction change in our calculation.

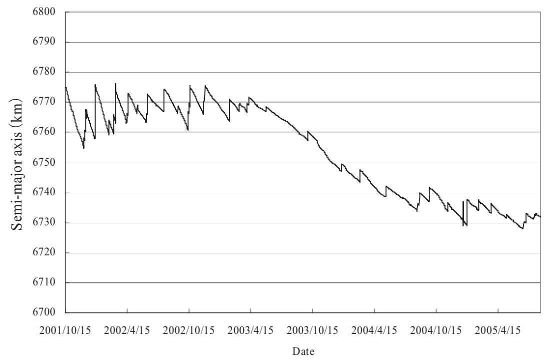


Fig. 5 ISS post-flight orbital and attitude change.

Table 2 Average orbital information

Orbital radius [km]	6748.904 (370.77[a])
Eccentricity [°]	0.00071
Inclination [°]	51.64

[a] Re=6378.134 km

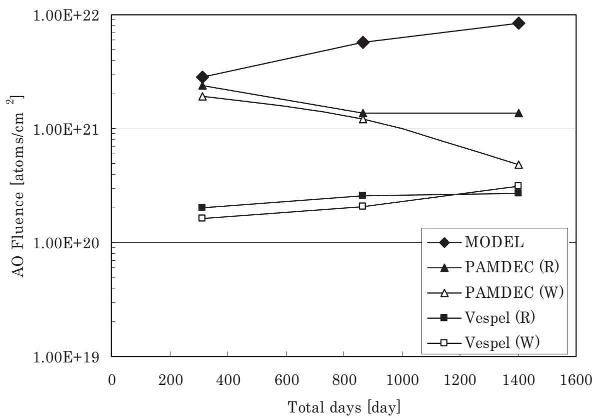


Fig. 6 AO fluence data compared to PAMDEC and Vespel monitoring sample data and model calculations.

Figure 6 depicts the flight data. Although the results in Fig. 6 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 values of the SEES-model calculation, which suggests that a contamination effect is responsible for the 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 [8]. 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. 7, 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 8 shows fish-eye images from ram and wake sides 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 (FCB), Service Module (SM), and Docking Compartment 1 (DC1). In addition, visiting vehicles (Orbiter, Soyuz, and Progress) had considerable view factors when mated to the ISS [10]. The field of view from the wake side is clear during the MPAC&SEED mission period. Furthermore, XPOP is the attitude at which the X-axis is perpendicular to the orbital plane; therefore, the +X direction is facing anti-sun. These reasons suggest that the ram side was not exposed to UV.

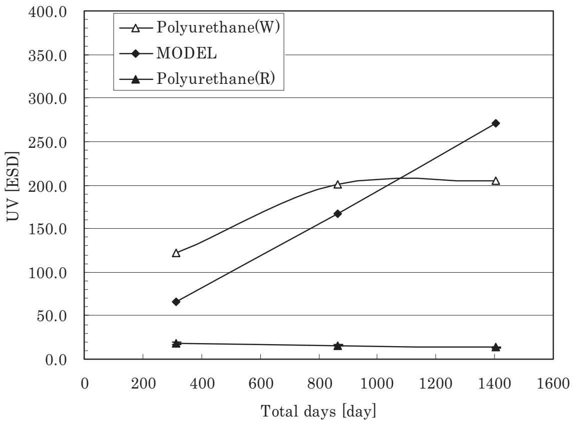
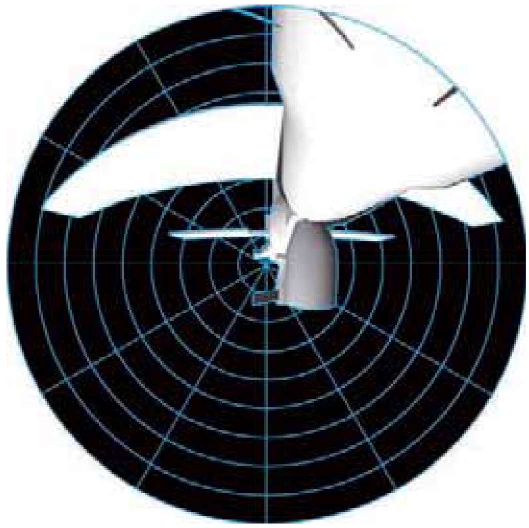
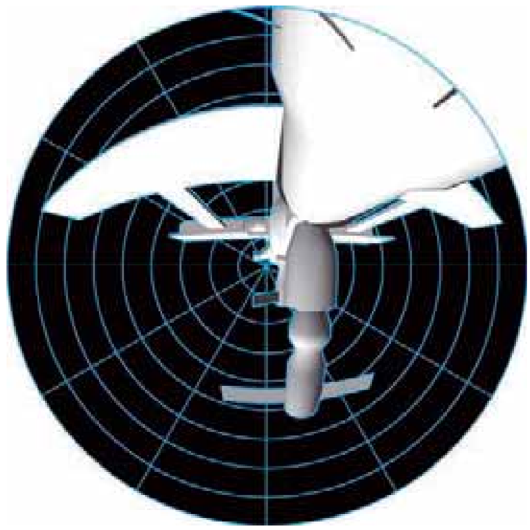


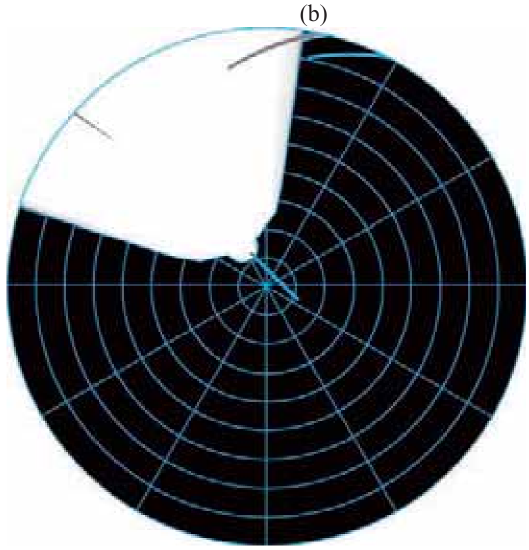
Fig. 7 UV fluence compared to data from polyurethane UV monitoring samples and model calculations.



(a)



(b)



(c)

Fig. 8 Field view analysis from the MPAC&SEED (a: From ram side in 15 October 2001 (exposure just started), b: From the ram side in June 2003, c: From the wake side in 15 October 2001)

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; Thermo VG Scientific) using Al Kα radiation. The analysis area is a 700-μm-diameter spot. The depth resolution performance is a few nanometers. For carbon on the ram face, XPS analysis was conducted. Figure 9 shows the atomic concentration of the external surface of the carbon film on the ram side and that of 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%.

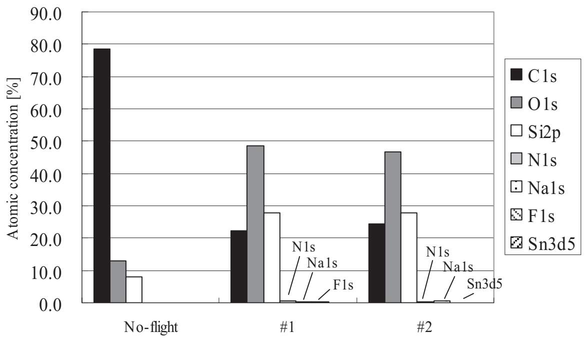


Fig. 9 External surface conditions of PAMDEC using XPS analysis

Figure 10 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 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 where the concentration of Si becomes greater than that of carbon. The layer thickness of the first-retrieved sample (#1) was estimated as 10 nm; that of the second-retrieved 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.

Figure 11 depicts the total dose data vs. the aluminum-shield thickness (i.e., a dose-depth curve) of the flight data and model calculation. Contamination did not affect TID monitoring because it was of the several-hundred-nanometer level. The dose-depth curve was calculated from the Alanine dosimeter, RADFET, and TLD in MPAC&SEED samples #1, #2 and #3. Flight data were plotted by following their own shield thickness. In addition, AP8, AE8, JPL1991, and SHIELDOSE-2 models in the SEES model [8] were used for model calculation.

The results revealed that the flight data were less than, but approximately equal to, the model data.

5. Conclusion

We analyzed monitoring samples from three MPAC&SEED trays that were retrieved after 315, 865 and 1403 days 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 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 flight total-dose data were estimated as lower than the model result.

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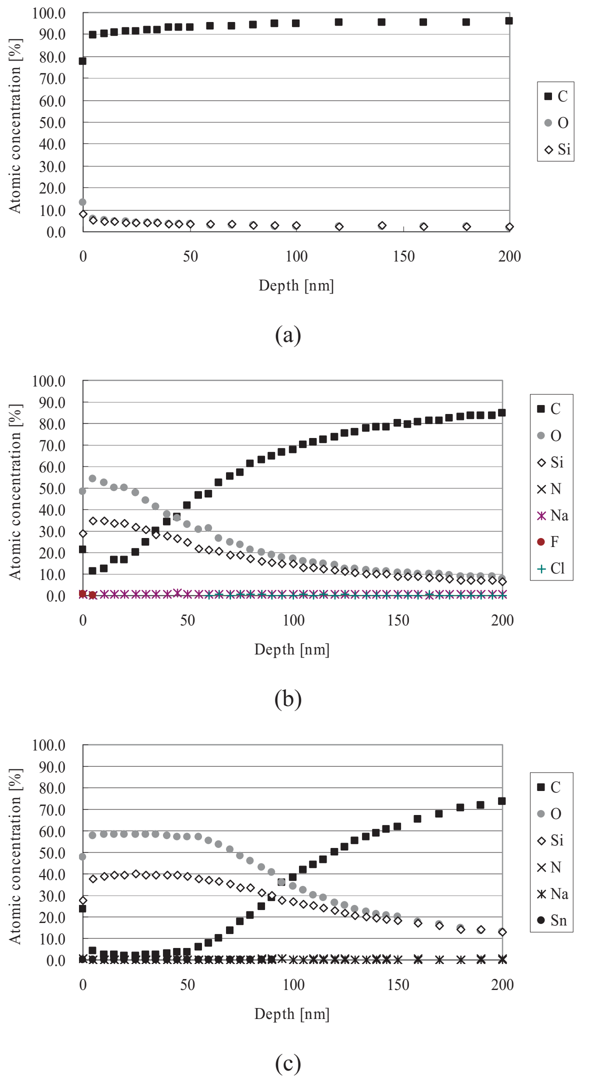

Fig. 10 Depth profile from XPS analysis of the PAMDEC: a) Unflown sample, b) First retrieved sample (#1), and c) Second retrieved sample (#2).

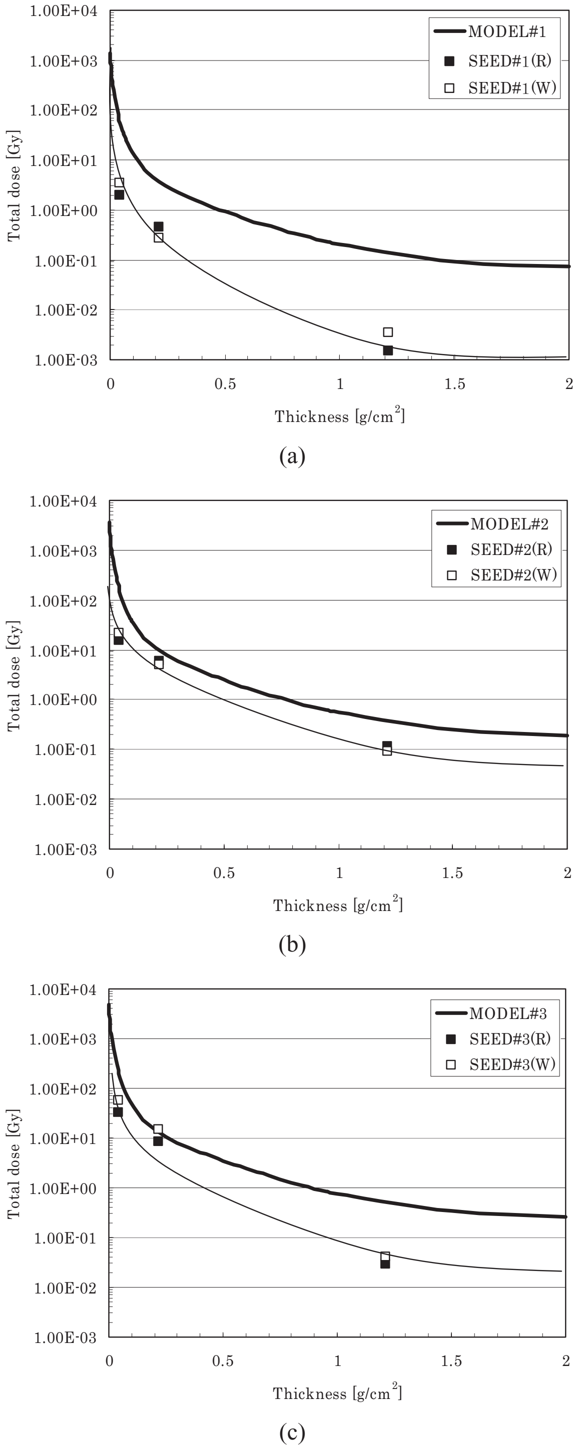

Fig. 11 Dose-depth curves from MPAC&SEED #1, MPAC&SEED #2, MPAC&SEED #3 and models

References

[1] Imagawa, K., “Evaluation and Analysis of Parts and Materials installed on MFD-ESEM,” NASDA-TMR-000011, Nov. 2002, URL: http://matdb.jaxa.jp/SpaceExperiment/Image/MFD-ESEM-E.pdf .

[2] Koga K. et al., “Space environment data acquisition equipment – attached payload on the international space station,” COSPAR Colloquia Series Vol. 14, "Solar-Terrestrial Magnetic Activity and Space Environment," Edited by Wang H., Xu R., 2002, pp. 365–366.

[3] Galica, G. E., “Atomic Oxygen Monitor Based On Carbon Actinometers,” Proceedings of the 10th International Symposium on “Materials in a Space Environment” (ISMSE) and 8th International Space Conference on “Protection of Materials and Structures from the Space Environment” (ICPMSE), June 2006 (SP-616, September 2006).

[4] Fukatsu, T., “Post-flight Analysis of the exposed materials on the EFFU,” Proceedings of the 7th Symposium of Materials in a Space Environment, 1997, pp. 287–292.

[5] Zwiener, J.M., “Contamination observed on the Passive Optical Sample Assembly (POSA)-I experiment,” SPIE Proceedings Vol. 3427, Oct. 1998

[6] Kimoto, Y., “Space Radiation Environment and Its Effects on Satellites: Analysis of the First Data from TEDA on Board ADEOS-II,” IEEE Trans. Nucl. Sci., Vol. 52, No. 5, Oct. 2005, pp. 1574–1578.

[7] Kimoto, Y., “Total Dose Orbital Data by Dosimeter Onboard Tsubasa (MDS-1) Satellite,” IEEE Trans. Nucl. Sci. Vol. 50, No. 6, Dec. 2003, pp.2301-2306.

[8] http://sees.tksc.jaxa.jp/

[9] http://www.sec.noaa.gov/Data/index.html

[10] Pankop, C., “Induced Contamination onto JAXA’S Micro-Particles Capturer And Space Environment Exposure Device – Comparison of Predictions and Measurements,” Proceedings of the 10th International Symposium on “Materials in a Space Environment” (ISMSE) and 8th International Space Conference on “Protection of Materials and Structures from the Space Environment” (ICPMSE), June 2006 (SP-616, September 2006)

Publication list related to SM/MPAC&SEED

Yugo Kimoto, Keiichi Yano, Junichiro Ishizawa, Eiji Miyazaki, and Ichiro Yamagata, "Passive measurement of atomic oxygen, UV fluence, and radiation effect on the ISS using the SEED experiment," Proc. of the 10th International Symposium on "Materials in a Space Environment" (ISMSE) and 8th International Space Conference on "Protection of Materials and Structures from the Space Environment" (ICPMSE), June 2006.

Yugo Kimoto, Keiichi Yano, Junichiro Ishizawa, Eiji Miyazaki, and Ichiro Yamagata, "Space Environment Effects of on MPAC & SEED Missions in ISS," Proc. of the 25th International Symposium on Space Technology and Space, Selected Papers, 2006.

Yugo Kimoto, Ichiro Yamagata, Eiji Miyazaki, Junichiro Ishizawa, Naoko Baba, and Mineo Suzuki, "Post Retrieval Analyses of Space Environment Monitoring Samples" (in Japanese), Proc. of International Space Station Russian Service Module (SM) / MPAC & SEED 2nd Post – Retrieval conference, JAXA-SP-06-021 2007.

Yugo Kimoto, Keiichi Yano, Junichiro Ishizawa, and Eiji Miyazaki, "Post Retrieval analysis of space environment monitor materials on the International Space Station Russian Service Module / Space Environment Exposure Device" (in Japanese), Proc. of the 51st Space Sciences and Technology Conference, 2007 (CD-ROM).

Yugo Kimoto, Keiichi Yano, Junichiro Ishizawa, Eiji Miyazaki, and Ichiro Yamagata, "Passive Space Environment Effect Measurement on the International Space Station," Journal of Spacecraft and Rockets, Accepted in June 2008.

Yugo Kimoto, Shoichi Ichikawa, Eiji Miyazaki, Koji Matsumoto, Junichiro Ishizawa, Hiroyuki Shimamura, Riyo Yamanaka, and Mineo Suzuki, "Space Environment Effects on Materials at Different Positions and Operational Periods of ISS," Proc. of the 9th International Space Conference Protection of Materials and Structures from the Space Environment (ICPMSE), 2008.