

ORIGINAL ARTICLE

Open Access



Space exposure test of hardwood specimens in the International Space Station

Koji Murata^{1*} , Masashi Nakamura¹, Kenji Kariya², Morio Tsuchiya², Yosuke Alexandre Yamashiki³ and Takao Doi³

Abstract

To design a wooden satellite and select the appropriate wood species, we conducted a space exposure test of wood on the International Space Station (ISS). The space exposure test used the Japanese Experiment Module “Kibo” on the Exposed Experiment Bracket Attached on i-SEEP (ExBAS), which is connected to the exposed facility of the ISS. Three wood species considered candidates for the structure of a wooden satellite were used in the exposure test: honoki (*Magnolia obovata*), yamazakura (*Cerasus jamasakura*), and dakekanba (*Betula ermanii*). In the outgassing test conducted in preparation for the space exposure test, the collected volatile condensable materials (CVCN) of the three wood species were below the critical value; however, the total mass loss (TML) exceeded the critical value. However, this was not a problem, because most of the mass loss was due to water evaporation. A space exposure test was conducted for 10 months in 2022. Consequently, no change was observed in the weight of the exposed specimen, and no erosion due to atomic oxygen (AO) was observed. The exposure test was scheduled to be carried out in the forward direction of the ISS travel; however, owing to equipment trouble, it was installed in the opposite direction. This is because an insufficient AO flux collided with the specimen. In terms of wood color, the brightness of the three species decreased owing to space exposure, and saturation increased in two wood species, except for yamazakura. A thin-film layer was observed on the surface of the aluminum cover to which the exposed specimen was fixed, which may have also formed on the surface of the wood specimen, reducing its brightness. However, because the hue angle did not change significantly, only a slight deterioration of the surface layer owing to vacuum ultraviolet was observed. The results confirmed that the wood had hardly deteriorated in space for approximately 10 months.

Keywords Wood utilization, Space explosion, Outgassing screening test, *Magnolia obovata*, *Cerasus jamasakura*, *Betula ermanii*

Introduction

The development of science and technology has accelerated the exploration of outer space, and advancements in space travel technology have increased. Along with this progress, a significant number of artificial satellites have been launched, not only for academic purposes but also for economic reasons. After completing their missions, artificial satellites transition from their orbital paths to reenter the Earth’s atmosphere. A research group in the USA revealed that approximately 10% of the metal particles found in stratospheric sulfuric acid aerosols likely originated from spacecraft that burned during

*Correspondence:

Koji Murata
murata.koji.4e@kyoto-u.ac.jp

¹ Graduate School of Agriculture, Kyoto University, Sakyo, Kyoto 606-8502, Japan

² Tsukuba Research Institute, Sumitomo Forestry Co., Ltd, Tsukuba City, Ibaraki Prefecture 300-2646, Japan

³ Graduate School of Advanced Integrated Studies in Human Survivability, Kyoto University, Sakyo, Kyoto 606-8306, Japan

reentry [1]. As the number of rocket launches and satellite deployments is expected to increase in the coming decades, the proportion of spacecraft-derived metal particles in sulfuric acid aerosols may reach 50% in the future. Another research group highlighted that aerosols generated during the reentry of small satellites, which form mega-constellations, could potentially harm the Earth's ozone layer [2]. Wood, which is a combustible material owing to its organic content, yields water and carbon dioxide if used as a component of an artificial satellite that reenters the atmosphere after its mission. Unlike aluminum, which undergoes passive oxidation, wood does not contribute to atmospheric pollution. Wooden artificial satellites serve as effective solutions for sustainable space exploration. Our plan includes launching a small wooden artificial satellite (CubeSat) into low Earth orbit (LEO) [3].

Various factors, such as cosmic rays, vacuum ultraviolet (VUV) radiation, and atomic oxygen (AO), cause material deterioration in space. The radiation dose, including galactic cosmic rays (GCRs) and solar energetic particles (SEPs), in LEO, where the International Space Station (ISS) is located, was 0.4098 Gy over 442 days from 2014 to 2016 [4]. Although there were differences in the type of radiation, the levels were significantly higher (approximately 140 times greater) than the radiation doses experienced on the ground. Severiano et al. irradiated two species of Brazilian hardwood with gamma rays from a Co-60 source at doses of 25, 50, and 100 kGy. Compression tests performed in the fiber direction revealed no decrease in strength [5]. Because no change in wood strength was observed even at radiation doses significantly higher than those encountered at the ISS, the effect of cosmic radiation on LEO is expected to be minimal. In addition, when organic materials are exposed to LEO, VUV rays and AO erode their surfaces. The Materials International Space Station Experiment 2 (MISSE 2) PEACE Polymers experiment, which began in 2001, exposed 40 polymers to GCRs and SEPs in LEO for 3.95 years, leading to the development of a predictive tool for estimating LEO–AO erosion yield in polymers [6]. However, because the exposed polymers do not contain wood, the erosion yield of wood materials has not yet been estimated. Before designing our artificial wooden satellite, we must assess the erosion yield of the wood material comprising the satellite's body to select the wood species and determine the appropriate thickness of the wood elements.

The Japanese Experiment Module “Kibo” on the ISS features an exposed facility with 12 ports for mounting exposed experimental equipment, including the IVA-replaceable Small Exposed Experiment Platform (i-SEEP). The Exposed Experiment Bracket Attached on the i-SEEP

(ExBAS) is a simple space-exposure device connected to the i-SEEP via Small Payload Support Equipment (SPySE). We created a specimen plate containing wood samples that could be installed in ExBAS to estimate the AO erosion yield in LEO. Our specimens were launched on February 20, 2022, and arrived at the ISS on February 21st (NG-17). The i-SEEP, with the ExBAS system, began exposure to the Kibo-exposed facility on March 4, 2022. After its time in LEO, ExBAS was moved to the ISS on December 23, 2022. The wood specimens were exposed to LEO for 294 days. The ExBAS landed off the coast of Florida on January 11th, 2023 (SpX-26). In this paper, we report on the changes observed in wood specimens exposed to space, with the aim of determining the specifications for wooden satellites.

Materials and methods

Test materials

Three hardwoods were selected for this test: honoki (*Magnolia obovata*), yamazakura (*Cerasus jamasakura*), and daikankanba (*Betula ermanii*). These species are diffuse-porous woods with different densities. Honoki and yamazakura lumber were purchased from the market and conditioned for several years at the Kuroda Kobo Workshop (Otsu, Japan). Their densities were approximately 450 and 600 kg/m³, respectively. The daikankanba tree was felled in the Uryu experimental forest of Hokkaido University, had been kiln-dried, and had been conditioned for more than 1 year. Its density was approximately 800 kg/m³. This study was conducted to design a wooden satellite called LignoSat, which is made of solid wood. Wood panels in LignoSat are joined using traditional dovetail joints. These panels were very thin (4 mm) and the joints were very fine. Therefore, there is a risk that fine joints may break in species with layered structures, such as earlywood and latewood of softwood or ring-porous wood. Three species of diffuse-porous wood with different densities were selected.

Outgassing screening test

The orbit in which a satellite flies is a high-vacuum environment; therefore, low-molecular-weight organic matter may evaporate (outgas). If the volatilized polymers aggregate on the surface of the sensor, the device will no longer function. Therefore, to determine whether organic materials can be used for space purposes, screening should be performed according to ASTM E595 [7]. In this study, we requested AES Co., Ltd (Tsukuba, Japan) to conduct an outgassing screening test at the JAXA Tsukuba Space Center.

The three wood types were cut into small pieces of approximately 1 mm³ using a cutter knife that had been

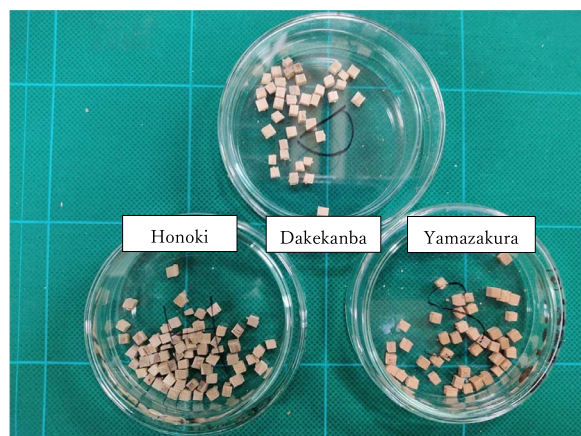


Fig. 1 Outgassing screening test specimen

cleaned with alcohol (Fig. 1). They were baked at 105 °C for 24 h. The outgas-screening procedure is as follows:

① The initial weights of 200–300 g specimens were measured after conditioning in an environment of 23 ± 1 °C and $50 \pm 5\%$ RH for 24 h.

② The outgassing screening device was operated at a vacuum level of 7×10^{-3} Pa or less, a heating temperature of 125 ± 1 °C, a cooling plate temperature of 25 ± 1 °C with a collector plate, and a holding time of 24 h.

③ After 24 h of operation, nitrogen gas was introduced and cooled down to below 50 °C.

④ The weight change of the specimen and collector plate were measured, and the total mass loss (*TML*) and collected volatile condensable materials (*CVCM*) from outgassing in a vacuum environment were calculated.

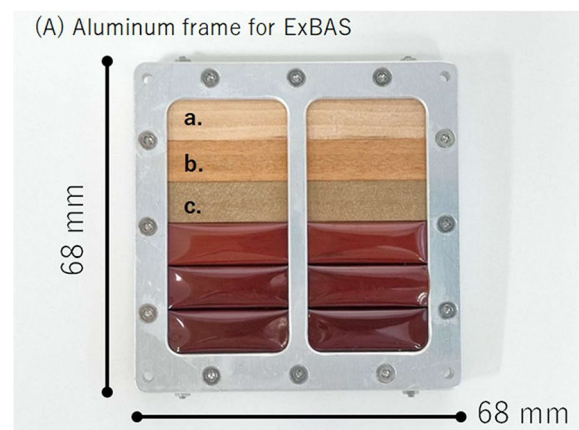
⑤ After maintaining the specimen at 23 ± 1 °C and $50 \pm 5\%$ RH for 24 h to absorb moisture, the weight was measured and the water vapor regained (*WVR*) was calculated.

The following items were calculated based on the collected data:

$$TML = \frac{\text{Sample weight before test} - \text{Sample weight after test}}{\text{Sample weight before test}} \times 100 \quad (1)$$

$$CVCM = \frac{\text{Collector plate weight after test} - \text{Collector plate weight before test}}{\text{Sample weight before test}} \times 100 \quad (2)$$

$$WVR = \frac{\text{Sample weight after moisture absorption} - \text{Sample weight after test}}{\text{Sample weight before test}} \times 100 \quad (3)$$



(B) Wood specimens for ExBAS

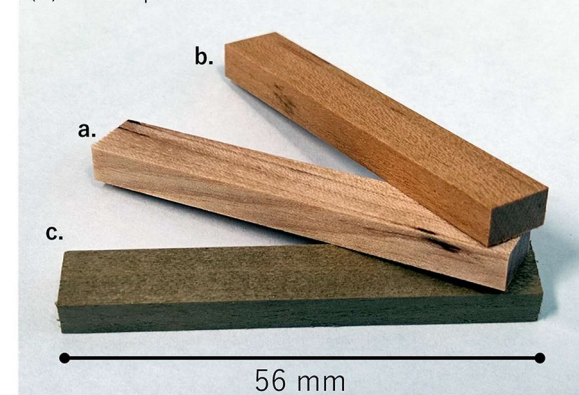


Fig. 2 Space-exposed specimens and aluminum frame to fix the specimen for ExBAS: **a** Dakekanba, **b** Yamazakura, **c** Honoki

Space exposure test

The space exposure specimens measured $56 \times 8.7 \times 4.9$ mm, and two specimens were prepared for each tree species (Fig. 2). To prevent dislodging during exposure, the samples were placed in an aluminum frame and sandwiched between aluminum plates on both sides (Fig. 3). In addition, they were secured using aluminum shafts with 2 mm-diameter. One of the two test specimens was exposed to space without any surface covering, whereas the other was

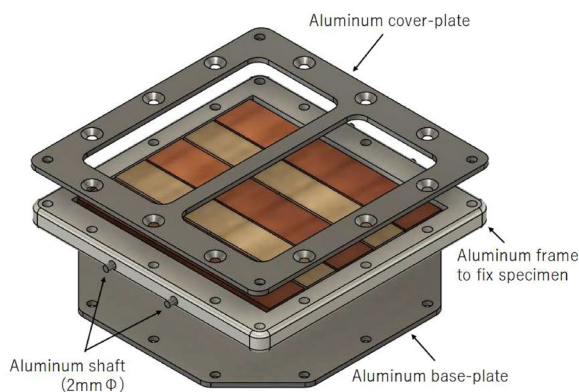


Fig. 3 Aluminum frame to fix the specimen for ExBAS

Table 1 Densities of the space-exposed wood specimens (mean ± standard deviation)

Species	N.	Density (kg/m ³)	Moisture content (%)
HONOKI (<i>Magnolia obovata</i>)	8	444 ± 19	11.5 ± 0.7
YAMAZAKURA (<i>Cerasus jama-sakura</i>)	8	594 ± 10	10.9 ± 0.1
DAKEKANBA (<i>Betula ermanii</i>)	8	799 ± 17	11.5 ± 2.2

covered with a polyimide sheet (Kapton H, 120 μm) to protect it from AO collisions. The flux of AO colliding with the exposed material can be determined from the amount of polyimide polymer eroded by AO, according to ASTM E 2089 [8]. A matching control was prepared using end-matched specimens with the same growth rings as those subjected to space exposure (Table 1). The space-exposed specimen was delivered to the Japan Aerospace Exploration Agency (JAXA) sealed in a nitrogen-purged polyethylene bag to maintain dryness. The polyethylene bag was unsealed immediately before its removal from the hatch inside the ISS, and the ExBAS was immediately removed from the ISS for space exposure.

After the exposure tests, the samples were returned to a polyethylene bag without resealing. Upon return, the samples were air-dried. The control specimens were placed in a vacuum chamber (0.1 Pa) on the ground for the same duration as the exposure period. In this study, we evaluated the erosion yield caused by the AO by measuring the weight changes and assessing the surface color of space-exposed test specimens. Surface color was measured using an imaging spectrometer (Specim ImSpector V8E) installed on a simple, clean bench.

Results and discussion

Outgassing screening test

Table 2 presents the results of the outgassing screening tests. The standard screening criteria are as follows: ‘TML: 1.0% or less; CVCM: 0.1% or less.’ For all three tree species, the CVCM was <0.1%, indicating no significant reagglomeration. However, the TML values exceed the standard, with all of them being 5% or more. After reabsorption, the water vapor regain (WVR) increased by 5%, suggesting that the initial decrease was primarily due to moisture. Wood, a typical hygroscopic material, has an equilibrium moisture content of 9.2% on a dry basis in an environment at 23 °C and 50% RH. In this case, the maximum TML is 8.4%. As the conditioning time was relatively short (24 h), the equilibrium moisture content might not have been fully reached or removed, resulting in a low TML value. Considering both the TML and WVR, although the TML exceeded 1%, most of it was water vapor, which was unlikely to re-agglomerate and affect the sensor equipment. Evaporated water vapor diffuses quickly in a vacuum. The CVCM value for all samples was less than 0.1%. Because the samples were dried at 105 °C for 24 h before the experiment, it was assumed that the low-molecular-weight compounds had already volatilized. However, the CVCM value for magnolia was slightly higher than those of the other two species. Although it is possible that magnolia contains extractives that are easily recondensed, there are no reports indicating a particularly high amount of extractives. Therefore, it was unclear whether the slight differences observed

Table 2 Outgassing data for materials used in space. When screening materials for space use, do not rely solely on "TML: 1.0% or less; CVCM: 0.1% or less," which has been used for material screening criteria, but also consider the environment in which it will be used, the amount used, and the positional relationship between pollution sources and non-contaminated surfaces. The effect of outgassing on the entire system must be evaluated by considering such factors

	TML ^a (%)	CVCM ^a (%)	WVR ^a (%)
HONOKI (<i>Magnolia obovata</i>)	6.033 ± 0.511	0.082 ± 0.001	5.226 ± 0.117
YAMAZAKURA (<i>Cerasus jamasakura</i>)	5.393 ± 0.170	0.007 ± 0.004	4.876 ± 0.068
DAKEKANBA (<i>Betula ermanii</i>)	6.039 ± 0.046	0.012 ± 0.003	5.480 ± 0.015

^a TML total mass loss, CVCM collected volatile condensable materials, WVR regained water vapor

in this experiment were significant. Therefore, it was considered that there was no impact on the equipment. Based on these considerations, there were no problems with the outgassing screening of any of the three tree species.

Space exposure test

The results of the MISSE 2 PEACE Polymers experiment show that 2.13×10^{21} atoms/cm²/year of AO collide with the ISS. Mori et al. determined that the density of the AO at an altitude of 400 km is approximately 8×10^9 atoms/cm³, and because the spacecraft flies at 8 km/s, the flux in the forward direction is 6.4×10^{13} atoms/cm/s [9]. For this condition, the amount of AO flux is 2.0×10^{21} atoms/cm²/year, which is almost in agreement with the experimental results of MISSE2, and the AO flux is 3.35×10^{-3} mol/cm²/year. If half of the mass of wood is carbon, and all of this reacts with AO to form CO₂, 0.02 g/cm² of carbon will be lost. If the density of honoki is 0.5 g/cm³, approximately 0.08 cm of its thickness will disappear. For the honoki specimen used in this test (area: 56 mm × 8.7 mm), the weight loss was approximately 0.2 g.

Before the specimen was launched, we measured the weight of the specimen under standard conditions (MC of approximately 12%) and the weight of the specimen under oven-dried conditions immediately after the bake-out. When the exposed specimens were returned to Earth, the polyethylene bags containing the specimens were not sealed, and the moisture content could not be controlled. Furthermore, it was difficult to further adjust the moisture content to prevent the exposed specimen from deteriorating as much as possible. Therefore, assuming that the specimen covered with the polyimide sheet did not collide with the AO at all, we estimated the moisture content of the space-exposed specimen and found that it was 3.90% for honoki, 3.35% for yamazakura, and 3.70% for dakekanba. The estimated weight change of the exposed specimen is shown in Table 3; almost no weight

change was observed. Furthermore, there was almost no change in the weight of the polyimide polymer sheets.

On March 4, 2022, ExBAS was installed in the exposed facility of Kibo, the Japanese Experiment Module on the ISS. However, the ExBAS device was attached to a different port owing to an accident at its originally planned port. Initially, the wood specimens were intended to be exposed in the forward direction during ISS travel. However, the change in port placement resulted in exposure to the opposite direction of travel. Consequently, the AO flux may be smaller than the previously estimated 6.4×10^{13} atoms/cm/s. Although the exact AO flux remains unknown, the lack of weight change in the polyimide polymer sheet suggests that the AO flux was minimal, and there is a possibility that the weight of the exposed wood specimens remained largely unchanged.

An imaging spectrometer was used to assess color changes on the specimen surface caused by space exposure. The sampling interval per pixel was set to 77 μm, and spectral intensity measurements were taken in 5 nm steps within the visible light range (wavelengths from 380 to 780 nm). From the image data obtained after scanning, the tristimulus values XYZ were determined for two locations on each species, measuring approximately 23 × 6 mm (300 × 80 pixels). L*a*b* color values were calculated based on the tristimulus values of each pixel. We then determined the mean lightness (L*), chroma (C*), and hue angle (H°) of each specimen. Figure 4 shows the L*, C*, and H° values for each species before, after, and under vacuum exposure (control). Lightness decreases before and after space exposure, whereas saturation increases for all species except for yamazakura. Figure 5 shows the surfaces of the specimens before and after exposure. A thin-film layer was observed on the aluminum cover to which the exposed specimen was fixed, which may have also formed on the wood specimen surface, reducing its lightness. However, the change in the hue angle before and after the space exposure was minimal. Despite some variations in lightness and chroma, the

Table 3 Weight change of the space-exposed specimens

	Symbol ^a	OD weight ^b	Exposed weight	Estimated MC (%)	Estimated OD weight	Weight change
Honoki	HA1 (C)	1.014	1.053	3.90	1.014	0.000
	HB1 (U)	0.930	0.964		0.928	+0.002
Yamazakura	SA1 (C)	1.309	1.353	3.35	1.309	0.000
	SB1 (U)	1.230	1.303		1.261	-0.001
dakekanba	DA1 (C)	1.701	1.764	3.70	1.701	0.000
	DB1 (U)	1.682	1.745		1.683	-0.001

C Covered specimen with polyimide polymer sheet, U uncovered specimen

OD weight: the weight of oven-dried specimen (105 °C, 24 h)

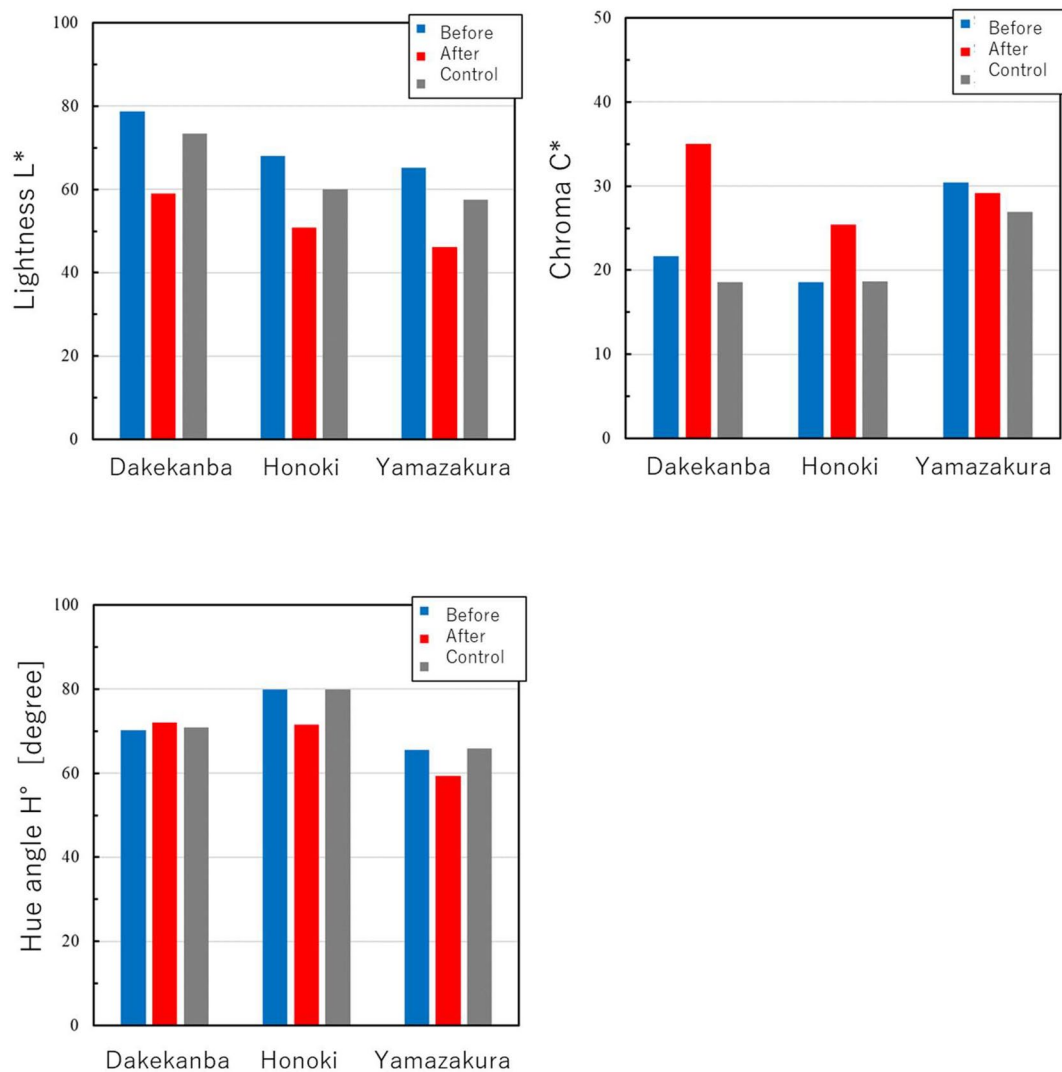


Fig. 4 Color value measured using an imaging spectrometer

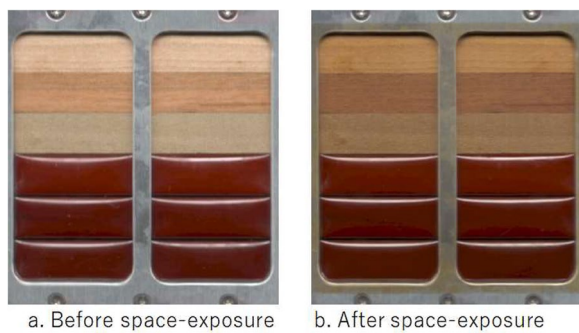


Fig. 5 Surface image of the space-exposed specimens

overall surface deterioration appeared negligible owing to the small change in the hue angle. JAXA deployed micro-particle capturer and space environment exposure device (MPAC&SEED) units in low Earth orbit, revealing the growth and distribution of external contamination [10]. All the units were remarkably contaminated, and their surfaces turned uniformly brown. The uniform contamination had a layered structure. Under the thin uppermost layer, which is considered to be terrestrial contamination, Si- and O-rich layers followed. Within this SiO₂ layer, other atoms were barely detected. They reported that severe UV irradiation and repeated thruster plume impingement could cause a deep brown color. We speculate that similar contamination may have occurred during the exposure test. We assume that the effect of VUV

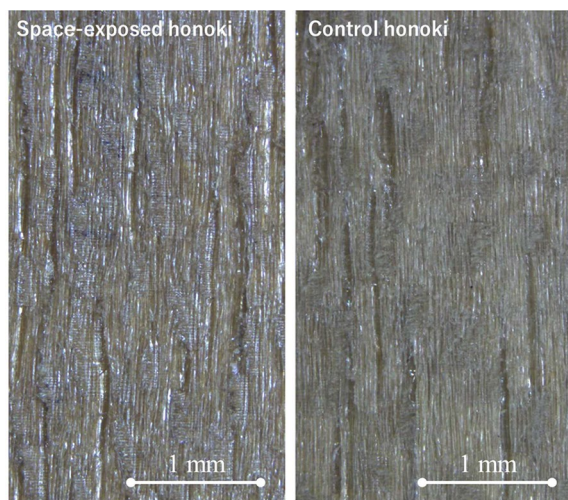


Fig. 6 Microscopic images of the honoki specimen

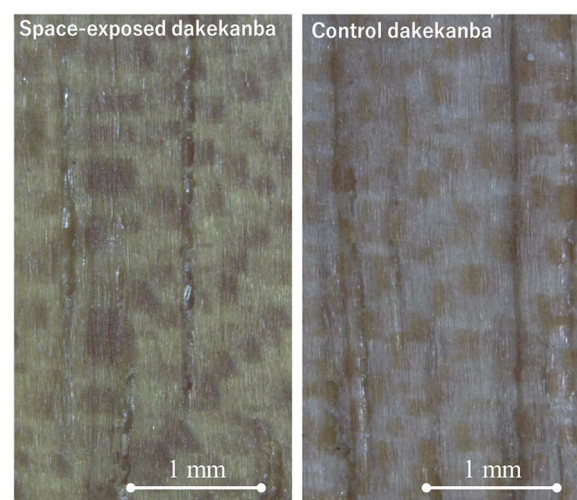


Fig. 8 Microscopic images of the dakekanba specimen

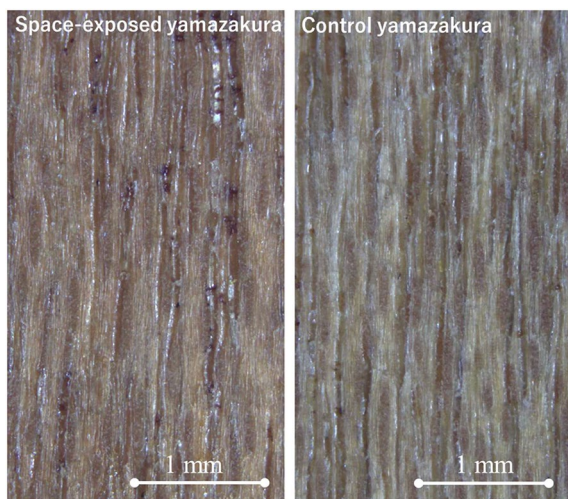


Fig. 7 Microscopic images of the yamazakura specimen

radiation is limited to this thin surface layer; however, further confirmation through chemical analyses such as FT-IR is necessary.

Microscopic images (Figs. 6, 7, 8) of the specimen after space exposure and the control specimen revealed only slight color changes with no noticeable surface unevenness. A thin-film layer formed on the wood specimen as explained above. The surface gloss has changed, and the image contrast has increased compared to samples not exposed to space, but overall erosion by AO does not appear to have occurred.

Conclusion

A space-exposure test of wood specimens was conducted to determine the design and suitability of wood species for artificial wooden satellites. Hardwood specimens (honoki, yamazakura, and dakekanba) were exposed outside of the ISS for approximately 10 months. We arrived at the following conclusions:

1. Prior to launching the specimens, the three hardwood species were subjected to outgassing tests. Although the CVCs were below the screening criterion (0.1%) for all species, the TML exceeded the criterion (1.0%). However, in the WVR, most of the increase in TML was due to water absorbed from the atmosphere. All three species passed the screening test.
2. After exposure to space, no observable changes were observed in the specimens. Prior to exposure, we expected some weight loss owing to the AO flux colliding with the specimen surface. However, the video microscopy images revealed no erosions in the surface shape. Notably, the ExBAS module was installed at a different port on the exposed facility of the Kibo module (ISS). The AO flux may have been sufficient to cause the erosion.
3. After exposure, the brightness of all three species decreased and saturation increased, except for yamazakura. A thin-film layer was observed on the surface of the aluminum cover, which likely formed on the wood specimen, thereby reducing its lightness. However, because the hue angle remained relatively stable, the deterioration of the surface layer owing to VUV was minimal. Overall, it was confirmed that the

wood hardly deteriorated in space over the 10-month period.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Acknowledgements

The authors are grateful to Mr. Hiroaki Usui (Kuroda Kobo Craftworks) and Dr. Toshiya Yoshida (Hokkaido University) for preparing the wood samples.

Author contributions

KM and TD performed the experiments and wrote this article, MN measured and photographed wood specimen surfaces, and KK, MT, and YY supported the experiments. All authors have read and approved the final manuscript.

Funding

The LignoStella project was supported by the Sumitomo Forestry Co., Ltd.

Availability of data and materials

The datasets used and/or analyzed in the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

Received: 16 August 2024 Accepted: 7 October 2024

Published online: 02 November 2024

References

- Murphy DM, Abou-Ghanem M, Cziczko DJ, Froyd KD, Jacquot J, Lawler MJ, Maloney C, Plane JMC, Ross MN, Schill GP, Shen X (2023) Metals from spacecraft reentry in stratospheric aerosol particles. *Proc Natl Acad Sci* 120:e2313374120. <https://doi.org/10.1073/pnas.2313374120>
- Ferreira JP, Huang Z, Nomura K, Wang J (2024) Potential ozone depletion from satellite demise during atmospheric reentry in the era of mega-constellations. *Geophys Res Lett* 51:e2024GL109280. <https://doi.org/10.1029/2024GL109280>
- Hornyak T (2024) World's first wooden satellite could herald era of greener space exploration. *Nature News*, 07 June 2024. <https://doi.org/10.1038/d41586-024-01456-z>
- Dachev TP, Bankov NG, Tomov BT, Matviichuk YuN, PIG D, Häder D-P, Horneck G (2017) Overview of the ISS radiation environment observed during the ESA EXPOSE-R2 mission in 2014–2016. *Space Weather* 15:1475–2148. <https://doi.org/10.1002/2016SW001580>
- Severiano LC, Lahr FAR, Bradi MAG, Santos AC, Machado LDB (2010) Influence of gamma radiation on properties of common Brazilian wood species used in artwork. *Prog Nuclear Energy* 52:730–734. <https://doi.org/10.1016/j.pnucene.2010.04.008>
- Banks BR, Backus JA, Manno MV, Waters DL, Cameron KC, de Groh KK (2009) Atomic oxygen erosion yield prediction for spacecraft polymers in low earth orbit. NASA/TM-2009-215812. Accessed 6 Jul 2024
- American Society for Testing and Materials ASTM E55-93: Standard test method for total mass loss and collected volatile condensable materials from outgassing in a vacuum environment
- American Society for Testing and Materials ASTM E 2089-00: Standard practices for ground laboratory atomic oxygen interaction evaluation of materials for space applications
- Mori K, Miyazaki E (2013) Evaluations of polymeric materials in space environment for space use. *Nippon Gomu Kyokaishi* 86(12):367–372
- Baba N, Kimoto Y (2009) Contamination growth observed on the micro-particles capturer and space environment exposure device. *J Spacecr Rocket* 46(1):33–38. <https://doi.org/10.2514/1.31870>