Problems and Recent Trends on Material Degradation Studies in a Real and Simulated Space Environment

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Space environment is a potential factor to affect the charging/discharging phenomena of spacecraft systems. However, no special attention has been paid for property changes of spacecraft materials during space exposure form the viewpoint of charging. Today, a circumstance on space environmental effect studies is changing due to the retirement of space shuttle. The space environmental effect on the solar cell materials will be evaluated in the new circumstances without using a space shuttle; sample return mission will be difficult to conduct. This situation is not only for solar cell materials, but also for other materials tests including thermal control materials. This paper describes the recent trend of space environmental effect studies on general materials both for flight and ground-based studies, which is prepared for the retirement of space shuttle. It should be stressed that the more precise ground-based exposure experiment technique has to be established for deep understanding of the space environmental effect on materials, especially for photovoltaic solar array systems.

Key Words: Space Environmental Effect, Material, Degradation, Atomic Oxygen, Charging, Photovoltaic Solar Array

1. Introduction

There exist many environmental factors in space such as microgravity, thermal cycling, plasma, ultraviolet, radiation, neutral gas, contamination and space debris [1]. Many of the important components of spacecraft (manned and unmanned) are attached in the unpressurized section and they might encounter such serious space environments. Some of the systems which are attached in the outmost surface of spacecraft, for example thermal blanket, solar cells, antennas, mechanical components including lubricant and various sensors, are affected directly by the space environments. Since polymer damages by atomic oxygen in low earth orbit is so pronounced, space environmental effect on materials has been focused on polymeric materials used for thermal control purposes [1-3]. However, it has not been fully recognized that the space environmental effect on material is also important for solar cells which sometimes has greater area than thermal control materials covering a satellite body.

A photovoltaic solar panel is a complicated system, thus various environmental factors could affect the performance of materials used in the photovoltaic solar panel system (Figure 1). In order to investigate the entire effect of space environment on the photovoltaic solar array system, an accurate space environment has to be simulated in a ground-test facility. It is, however, current technology level cannot fully simulate space environments. For example, spectra of ultraviolet, which could affect the surface properties of solid materials, cannot be simulated in ground tests. Radiation environment is also impossible to simulate on ground accurately. Atomic oxygen, one of the major environmental factors in low earth orbit (LEO), is also one of the most difficult factors to be simulated in a ground-based facility. It should be stressed that the simulated space environment in a ground-based facility is somewhat different with real space environment. Degradation (or property changes) of photovoltaic solar array materials in the ground tests has to be investigated under these limitations.

On the other hand, material exposure experiment in orbit (flight test) faces serious problems by the retirement of space shuttle. The retrieval of exposed samples cannot be achieved beyond 2011. Use of Soyuz spacecraft is the only choice to retrieve the exposed sample, but its capability is

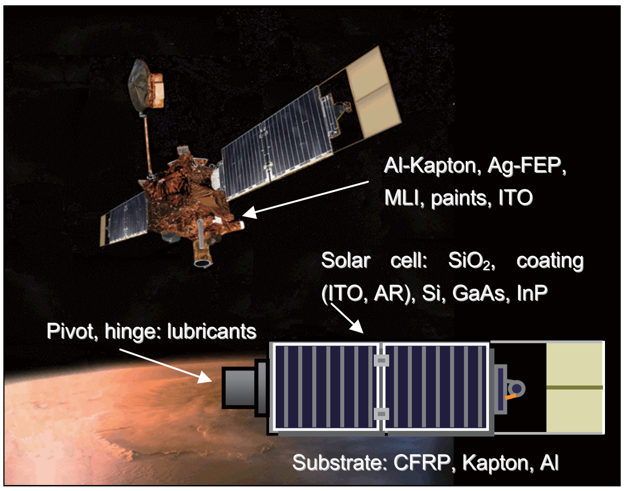

Fig. 1. Materials used in a typical photovoltaic solar panel. Many materials are subjected to exposure to space environment compared with passive thermal control systems. Complicated phenomena could be activated in solar panel systems. Mars Global Surveyor image is courtesy by NASA.

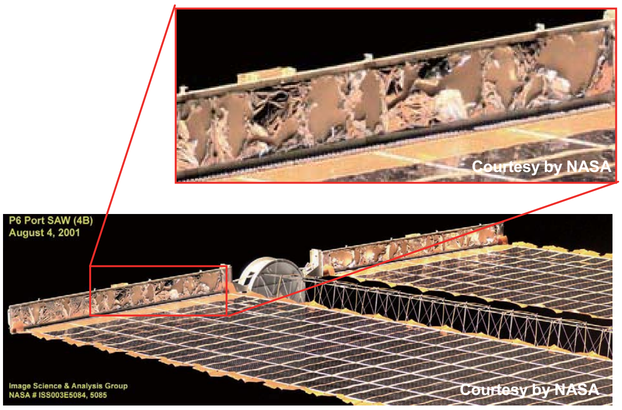

Fig. 2. Photograph of the breakage of Kapton blanket at the P6 Port Solar Array Wing of ISS. The photograph was taken on August 4, 2001.

quite limited. The methods to evaluate the sample properties without retrieval have to be established.

In this paper, importance, current technological problems and trends in space environmental effect studies are reported.

2. Example of the Material-related Problems in LEO Space Environment

When materials are exposed to real space environment for long period, degradation of material could be happen. Some of the examples are introduced in this section. Note that all of the photographs in this section are under NASA credit.

One of the examples is a breakage of Kapton blanket at the P6 Port Solar Array Wing of ISS. The photograph taken on August 4, 2001 is shown in Figure 2. As clearly indicated in Fig. 2, polyimide (Kapton-H), which is widely used as a thermal blanket, was broken after one year of exposure in LEO space environment. It has been well known that the Kapton is eroded by the atomic oxygen attack in LEO. In order to protect Kapton from the atomic oxygen, thin aluminum coating was attached to the both sides of the material in this case. However, atomic oxygen penetrates through pinholes and microcracks of the aluminum protective layer and undercutting of Kapton occurred [2].

Not only the ISS, but also the other satellites have faced different material problems. Two photographs in Figure 3 show the thermal blanket of Hubble Space Telescope (HST) taken at 3.6 and 6.8 years after orbit [3]. It is clear that the large crack is obvious after 6.8 years in orbit. This crack was patched by EVA in the HST 2nd Servicing Mission (SM2), but another cracks were found at the same position in the HST SM3 (after 9.7 years in orbit). These cracks in FEP Teflon thermal blanket are believed due to the radiation (soft X-ray)-related degradation, since the cracks were obvious only in the solar-facing side [4]. It was also reported that these FEP degradation could be related to solar flare event [5]. It is, thus, addressed that the space weather data is also important for the material degradation in space systems.

From some examples shown in this section, it is obvious that we have not solved the space environmental

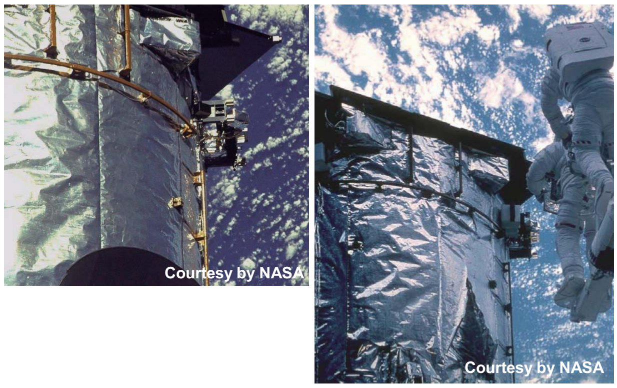

Fig. 3. Photograph of the breakage of FEP Teflon outside the Hubble Space Telescope.

effect problems on materials, especially for long-term missions. Further research is necessary to achieve low-risk space missions from the viewpoint of material sciences.

3. Problems in Flight Experiment

In order to evaluate the survivability of materials in space environment, flight experiments have been conducted. In the most flight experiments conducted in the past, the retrieval of the exposed samples to Earth has been made by the Space Shuttle. However, Space Shuttle is scheduled to retire in 2010. After 2011, sample retrieval from the orbit has to be carried out by Soyuz. The capacity of Soyuz is limited and only small pallet can be retrieved. New exposure pallet should be designed to fit the capacity of Soyuz. However, due to the dimensional limitations, the complicated equipment cannot be attached on the pallet. This restricts the freedom of the experimental design.

A now transportation system cannot be expected in 2011, a material exposure experiment has to be conducted without retrieving the samples. Measurements of material properties are carried out during the exposure and the data should be downlinked by telemetry. Mass of the materials, especially for film materials, could be measured by quartz crystal microbalance. Such an “active” experiment has already been partially performed in the MISSE-6 (Figure 4) and MEDET (Figure 5) missions. Although next JEM/SEED mission in Japan (Figure 6) is a fully “passive” experiment, which requires sample retrieval, the next materials exposure test should be based on an active experiment without retrieving the sample. Such active

Fig. 4. Materials International Space Station Experiments (MISSE-6) pallet.

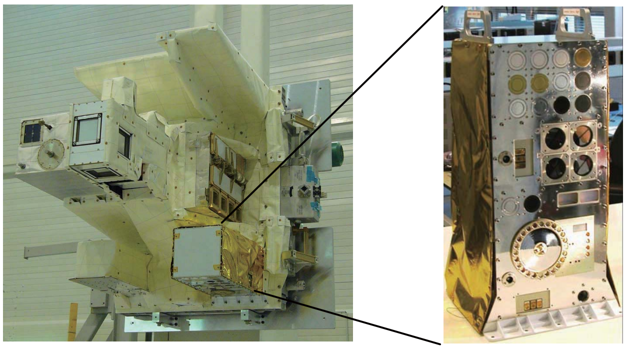

Fig. 5. Material Exposure and Degradation Experiment (MEDET, right) accommodated on the European Technology Exposure Facility (EuTEF, left).

experiment can be flown not only on ISS, but also on small satellites in various orbit. Real-time flight data from various space environments (various altitudes, inclination angle, elliptical orbit, etc) will be obtained through such active experiments. Even though "active" experiment requires a complicated system to acquire the data, it will provide much more valuable scientific data on material sciences in extreme environments. Theses data are also referred to the ground-based experiments.

4. Ground-based Research

4.1. Current Problems

Space environmental effect on materials has also been investigated through ground-based researches. Absolute pressure and temperature in space can be simulated in the ground-based test. However, other environmental factors are difficult to simulate in ground-based studies accurately. The inconsistency of the result of ground-based test with that of flight test is due mainly to the differences in experimental conditions between space and ground. Present technology of the ground-based space environmental simulation is not enough to predict the material response in real space environment quantitatively. Some examples of the experimental conditions which are difficult to simulate in ground-based experiments are described below:

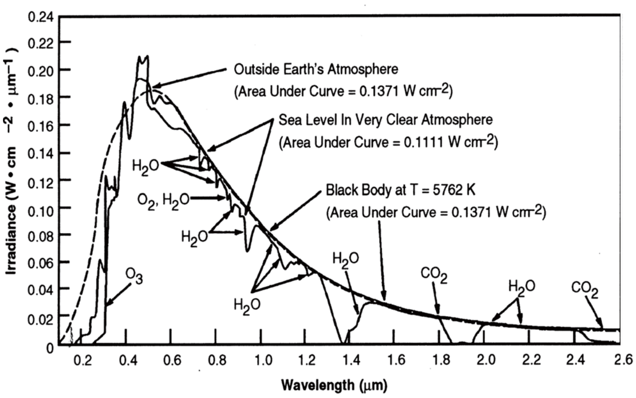

Fig. 7. UV/VIS/IR spectrum of the sun [1].

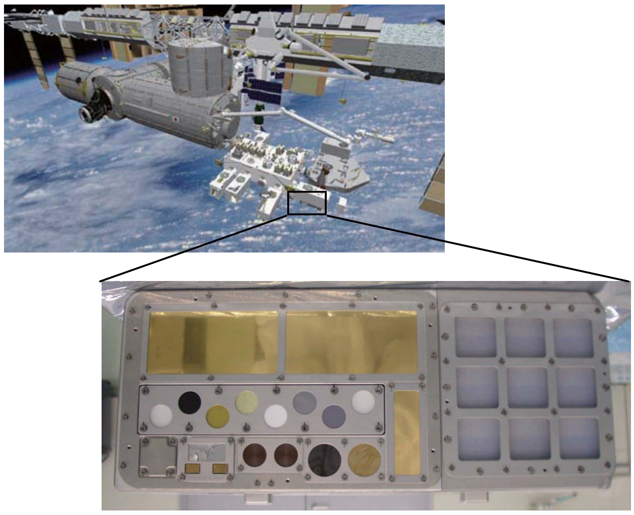

Fig. 6. Japanese Experiment Module – Micro-particles Capturer and Space Environment Exposure Device (JEM-MPAC/SEED)

a. Ultraviolet spectrum and intensity

It is well known that he UV/VIS/IR spectrum of the sun can be expressed by the emission from the black body at 5,762 K as shown in Figure 7. This is due to the fact that the surface temperature of the sun is 6,000 K. In order to simulate the emission spectrum in VIS/IR region, Xe lamp is used. However, UV intensity of Xe lamp, which influence more on materials, is not enough, mercury lamp is used as a UV source for material degradation studies. The high-pressure and low-pressure mercury lamps emit line spectra at 365, 185 and 245 nm. Deuterium lamp, which has continuous spectrum between 120 and 400 nm, also is used for the same purpose. However, Deuterium lamp has major peaks near 120 and 160 nm. The emission spectra of these lamps are not identical to those from the sun. Because degradation of materials by ultraviolet is based on the photochemical reactions, photon energy (or wavelength) is a primary factor to determine the reaction pathway. However, solar spectrum in UV region cannot be duplicated in laboratory. Selection of lamps in material tests is still in discussion.

b. Energy spectrum and intensity of radiation

Simulation of radiation environment is even more difficult. Energy distribution cannot be simulated in laboratory, so that only limited experiment (energy and species) can be made in laboratory.

c. Impact velocity of atomic oxygen

Material degradation due to the reactions with hyperthermal impact with atomic oxygen, which is the major composition of the upper atmosphere of Earth, is another great concern in the space environmental effect studies. The impact velocity of atomic oxygen with spacecraft materials is 8 km/s which is an orbital velocity of spacecraft. The impingement energy of atomic oxygen at 8 km/s corresponds to 5 eV, which is similar to the interatomic bonding energies of polymeric materials. Acceleration of electrically neutral atomic oxygen up to 8 km/s in laboratory

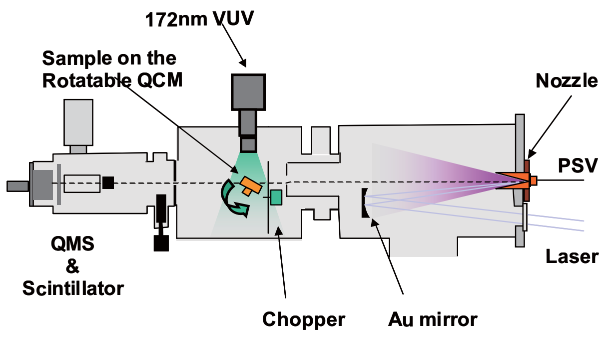

Fig. 8. An example of laser detonation atomic oxygen beam facility (Kobe University).

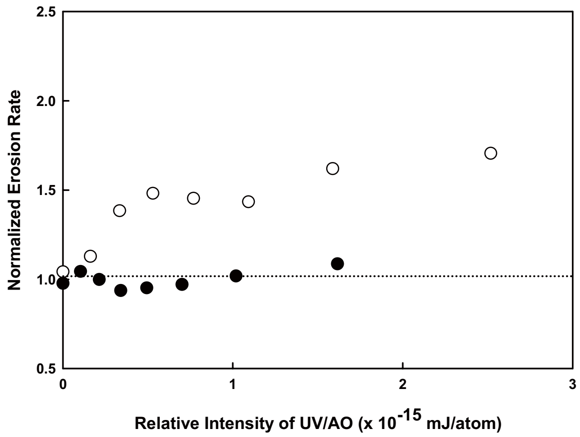

Fig. 9. A quantitative analysis of synergistic effects of atomic oxygen and 172 nm VUV on polyimide (black circle) and polyethylene (white circle). [7]. It is obvious that polyimide is not affected by VUV exposure, but the erosion rate of polyethylene is sensitive to simultaneous VUV exposure.

is mandatory for simulating the chemical reactions in space. For this purpose, laser detonation atomic oxygen beam source (Figure 8) has been used [6]. This type of atomic oxygen simulator can accelerate atomic oxygen up to 8 km/s, however, velocity distribution is larger than that in LEO. If there were a strong energy dependence on material degradation, it would be problematic to evaluate the survivability in LEO with this system. Not only velocity distribution, there exist many other problems in atomic oxygen simulation such as flux measurement, flux deviation, electron excited states, extreme ultraviolet (EUV) as a byproduct and so on.

d. Synergistic effects

When more than two of these environmental factors influence the degradation of material, simultaneously, the synergistic effect may accelerate (or decelerate) the erosion phenomena (Figure 9) [7, 8]. Note that samples are subjected to strong extreme ultraviolet (EUV) radiation when atomic oxygen tests were performed. It has been believed that some of the materials, especially fluorinated polymers, are sensitive to EUV from laser plasma [9]. The spectroscopic analysis of EUV from the laser-sustained oxygen plasma is under investigation [10]. However, standard testing method on synergistic effect has not yet been established. Quantitative evaluation on synergistic effect is in future challenge.

4.2. Future Direction of ground-based research

In order to increase the accuracy of predictions on space environmental effect of materials, differences in experimental conditions between space and ground should be considered quantitatively. It should be applied to the reference materials first. For example, temperature, angular and impact energy dependences on the atomic oxygen-induced etching of polyimide should be made clear. These erosion properties are necessary to evaluate the atomic oxygen fluence both in space and in ground-based simulations accurately. The same data set also is required to calculate the erosion depth of any material with computer code. Well-controlled ground-based experiments can only provide such basic properties of atomic oxygen erosion phenomenon [11, 12]. This is true for the other environmental factors as well. Fundamental understanding of material response in each factor is the first step to mitigate the material erosion problems in space.

4.3. Ground-based research on space environmental effect for photovoltaic solar array

A photovoltaic solar array system is a complicated system compared with thermal control film. It may be affected by space environment in various ways. Thus, a ground-simulation study of space environmental effect on photovoltaic solar array system becomes important. Material exposure test would be performed in order to clarify the response of each material used in photovoltaic solar array system. Not only the material test, but also a system test has to be carried out with a solar cell coupon. A system test is a realistic test, thus it is strongly affected by the test environment. For example, atomic oxygen ground test, which is carried out by the laser detonation facility, uses intense atomic oxygen beam pulses on behalf of the continuous atomic oxygen flow. Figure 10(a) shows a relative intensity of argon beam formed by the laser detonation source. (Similar spectrum is observed when atomic oxygen beam is formed.) It was operated by the repetition rate of 1 Hz. A strong beam pulse is observed at the flight time of 0 and 1000 ms. Figure 10(b) shows the close-up view near flight time 0. EUV from the laser plasma (See section 4.1d) is obvious at the flight time of 0 μs. A beam signal is observed at the flight time near 500 μs. As shown in Figure 10(b), FWHM of beam pulse is only 200 μs. This type of source can simulate the atomic oxygen flux (number of atomic oxygen per unit area arrived within 1 second) in LEO at a sample position, but all of atomic oxygen reaches within 200μs. At this moment, a pressure near the sample surface reaches over 10^{-3} Torr. The instantaneous pressure near the sample surface in the ground-based test is much higher than that in space. The pressure difference is usually ignored in the material test, but

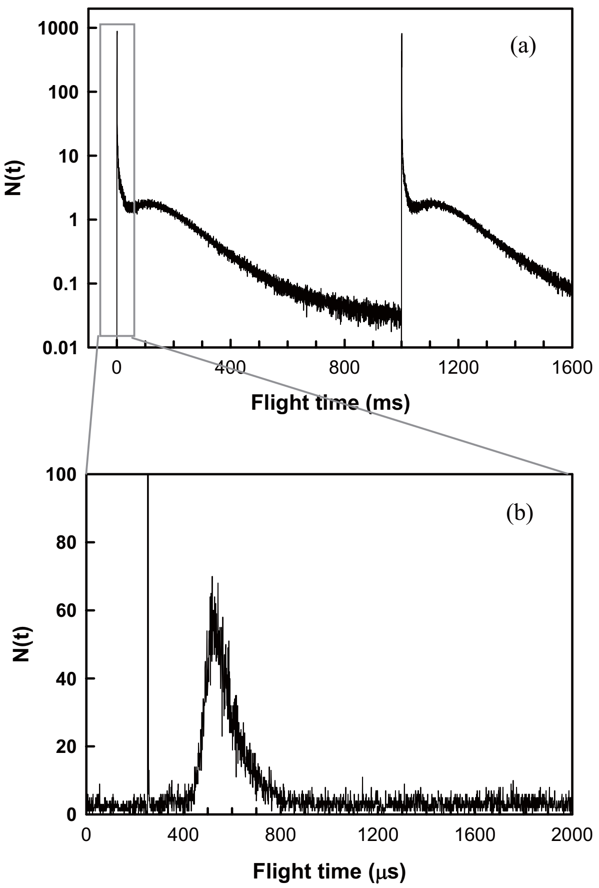

Fig. 9. An example of time of flight spectra of a hyperthermal Ar beam formed by a laser detonation source. (a): overall spectrum, and (b): high-resolution close-up spectrum at flight time near 0. EUV and atomic beam signals are observed at the flight time 0 and 500 μs, respectively.

it sometimes affects the environmental simulation results [13]. Since the instantaneous pressure increase affects the discharging characteristics, the accuracy of such system tests would not be high enough to simulate the real environment. The difference of test conditions between real space and simulated environment should be recognized when ground-based simulation test is conducted.

5. Conclusions

The importance, current problems and trends in space environmental effect studies on material are addressed. In order to endorse the material properties requested in a whole mission life, ground-based studies are quite important. However, present ground-based simulation technology cannot perform the accurate assessment of the material degradation in space. The evaluation of the space environmental effect on photovoltaic solar array system, which is a complicated system, has to be evaluated with understanding the differences in real- and simulated-space environments. Development of accurate ground-based simulation techniques is highly desired for achieving low-risk missions in various space environments.

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