衛星搭載用原子状酸素モニター装置の地上キャリブレーションに関する一考察

A consideration for ground-based calibration of on-board atomic oxygen sensor

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Atomic oxygen is one of the important environmental factors in space. It affects material properties for many spacecraft systems. Due to the importance of atomic oxygen effect, on-board atomic oxygen sensors have been developed. These atomic oxygen sensors have to be calibrated by ground-based atomic oxygen facility. However, the atomic oxygen beam conditions in a ground-based facility and in space are not consistent. The difference should be taken into account in a calibration process of the sensors. In this report, we are going to mention the points for atomic oxygen sensor calibration using a laser detonation atomic oxygen beam source.

Key Words: Atomic oxygen, Environmental monitor, Space environment, Calibration, Sensor

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. Thus, the assessment of the space environmental effect on materials and systems are important to provide the end-of-life (EOL) performance of the spacecraft.

One of the space environmental factors that gave serious changes for surface properties is atomic oxygen [2, 3]. High-energy collision of atomic oxygen to polymeric materials on satellites opens various reaction paths and results in material erosion. It has been well known that hydrocarbons are eroded by atomic oxygen with an erosion yield of 1-6 x 10^{-24} cm^3/atom, depending on a material [4]. The erosion yield of polyimide (Kapton-H) has been reported to be 3 x 10^{-24} cm^3/atom in an early shuttle flight and has been used as a standard material for erosion studies. On the other hand, Kapton-H has been used not only for the standard material for erosion study but also for fluence measurement of atomic oxygen. The atomic oxygen fluence measured from the mass-loss or step-height is called “Kapton equivalent fluence” and widely accepted as a standard method to measure atomic oxygen fluence in exposure studies [5]. Mass-loss measurement or step-height measurement requires post exposure process such that it could be applied for sample retrieval missions such as SM-SEED (Japan) or MISSE series (US) [6]. However, it could not be applied for flight missions in which the samples were not retrieved.

Because of the retirement of space shuttle in 2010, the sample retrieval from flight mission becomes difficult and the fluence measurement of atomic oxygen has to be carried out without sample retrieval, i.e., new methods need to be developed. Some efforts has already been carried out such as silver, carbon or ZnO actinometer, quartz crystal microbalance (QCM), or thickness measurement through light transmittance. All these new techniques are based on the material erosion phenomena by hyperthermal collision of atomic oxygen. Thus, in order to measure atomic oxygen fluence, the reaction yield of sensing material has to be calibrated through a ground-based research. Uncertainty of the reaction yield leads to inaccuracy of fluence measurements. It is thus quite important for atomic oxygen sensor to evaluate the reaction yield with atomic oxygen in a collisional condition in real LEO environment.

In this paper, a consideration for calibration of on-board atomic oxygen sensor is presented. Effect of energy distribution of the atomic oxygen beam is discussed.

2. On-board atomic oxygen sensor

Several types of atomic oxygen sensors have been developed for flight experiments. Silver actinometers use the change in resistance of thin silver films as they are exposed to atomic oxygen [7]. The progressive conversion of the silver into non-conductive silver oxides causes the film resistance to increase, the extent of which depends on the total fluence of atomic oxygen to which the film is exposed. This method assumes uniform oxidation. However, the silver oxidation process involves multiple stages, i.e., linear-parabolic growth of

oxidation film. Thus, response of silver actinometer is not linear with atomic oxygen fluence. Unlike silver, carbon releasing volatile oxidation products and hence carbon actinometers are not diffusion limited which resulted in linear response [8]. This method has a limited useful life as the silver or carbon is consumed in the oxidation process. In contrast, ZnO sputtered film can be regenerated by heating to moderate temperature. However, it was reported that the response of this sensor depends on the deposition conditions [9]. Polymer-coated QCM was flown both on MEDET and MISSE missions [10, 11]. The polyimide-coated QCM has been used in ground-based atomic oxygen tests for more than fifteen years [12]. The atomic oxygen reaction with polymer forms volatile products resulting in linear mass-loss. Due to its narrow dynamic range of QCM, the life of polymer coated-QCM is limited even though the sensitivity of measurement is quite high. The polymer-coated QCM is scheduled to launch on SDS-4 mission in Japan. On the other hand, thickness of material is directly related to transmittance of light. Diamond-like carbon (DLC) films are used as a sensor material. Light transmittance of DLC is detected by a photodiode to measure atomic oxygen fluence. This type of atomic oxygen sensor is developed by NASA-GRC [6]. All these sensors require calibration of their responses with hyperthermal atomic oxygen.

3. Atomic oxygen ground-simulation facility

3.1. Operation principle

Calibrations of atomic oxygen sensors have been carried out by various types of atomic oxygen facilities. However, the most widely used and the most advanced atomic oxygen beam facility for calibration of on-board atomic oxygen sensor is probably a laser-detonation beam source [13]. This type of atomic oxygen source is often called PSI-type source and uses pulsed supersonic valve for oxygen injection and pulsed carbon dioxide laser for formation of oxygen plasma (Figure 1). Principle of operation in the AO source is described as follows; pure oxygen gas is introduced into the nozzle throat through a pulsed supersonic valve. A giant pulse of carbon dioxide laser is focused to oxygen gas at the nozzle throat. By absorbing laser energy, high-density and high-temperature oxygen plasma is formed at the nozzle throat. Once plasma is formed, the plasma propagates with absorbing the laser energy that included in the tail of the laser pulse. The plasma propagation is along with the incident laser axis, and oxygen molecules are decomposed and accelerated at the shockfront of the plasma propagation. Thus, an intense hyperthermal atomic oxygen beam pulse is formed. Even though the laser detonation source provides hyperthermal atomic oxygen pulses with average translational energy of 5 eV, the energy distribution of beam pulses is much wider than that in low earth orbit. It includes high-energy tail of atomic oxygen beam pulse (Figure 2). The laser detonation atomic oxygen beam sources are used for atomic oxygen simulation in many space organizations and universities such as ESTEC, JAXA, Montana State University and Kobe University.

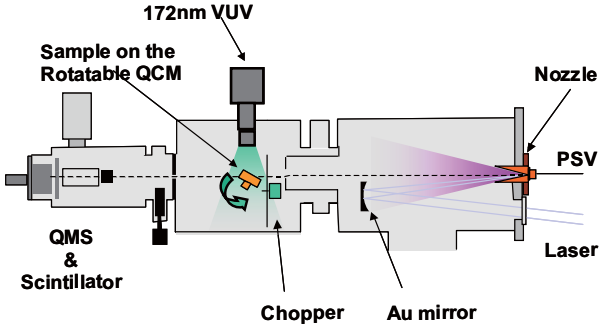

Figure 1. The laser detonation atomic oxygen beam source used in this study. Excimer and deuterium lamps are equipped as an external source of VUV.

3.2. Calibration of atomic oxygen sensors

The purpose of sensor calibration is to obtain the response probability of a sensor material with atomic oxygen. This is basically because that the many atomic oxygen sensors operate based on the material degradation phenomena. The reaction yield of the material used in a sensor has to be evaluated through ground-based research. Thus, a calibration of atomic oxygen sensor has to be carried out under the same atomic oxygen condition in real low earth orbit. This is a reason why a laser detonation atomic oxygen source is selected for calibration purpose, i.e., collision velocity of 8 km/s (collision energy of 5 eV) could be simulated.

As following the general protocol for atomic oxygen testing [5], atomic oxygen fluence was measured by Kapton witness sample using a standard erosion yield of Kapton-H, 3.0 x 10^{-24} cm^3/atom (Kapton equivalent fluence). Therefore, a response of atomic oxygen sensing material is directly affected by the accuracy for Kapton equivalent fluence in the calibration experiment.

4. Erosion yield of Kapton-H in a laser detonation atomic oxygen facility

The atomic oxygen beam formed in a laser detonation source has average collision energy similar to that in low earth orbit. In many atomic oxygen testing, only average collision energy has been focused, i.e., no attention has been paid for collision energy distribution. In order to clarify the effect of collision energy dependence in reaction yield, atomic oxygen beam was sliced by a

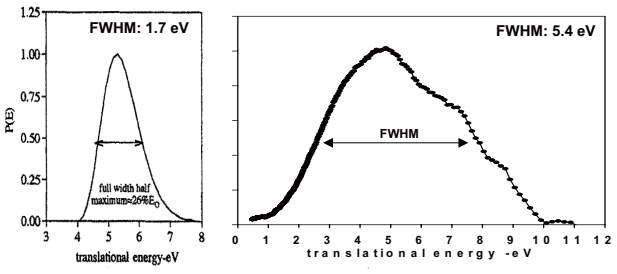

Figure 2. The energy distribution of atomic oxygen in low earth orbit space environment (left panel) and in laboratory simulated by a laser detonation source (right panel). Full-width at half-maximum (FWHM) is 1.7 eV and 5.4 eV for low earth orbit and for laboratory, respectively.

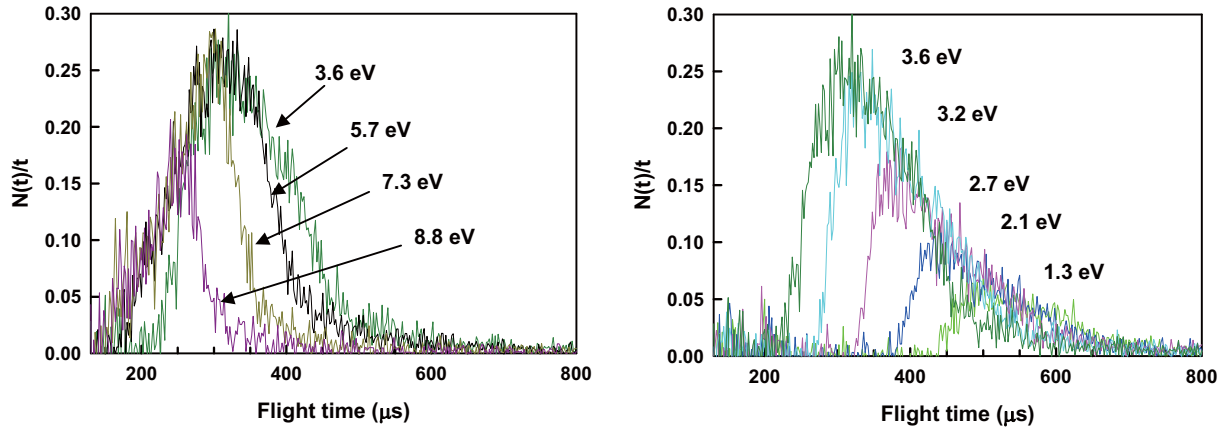

Figure 3 Time-of-flight spectra of atomic oxygen beam (m/e=16) sliced by the high-speed chopper wheel. For better view of the each TOF spectrum, left and right panels show the TOF spectra in which slow-part and fast-part of the beam pulses are blocked by the chopper wheel. The same TOF spectrum (Ecoll=3.6 eV) is shown in both panels for comparison purpose.

mechanical chopper wheel and narrowed the energy distribution.

Time-of-Flight (TOF) spectra and average collision energy of atomic oxygen beam sliced by the chopper wheel are shown in Figure 3. Figure 3 (a) and 3 (b) show the TOF distributions in which a slow- and fast-part of the beam pulse was partially blocked by chopper wheel, respectively. It is clearly observed that the atomic oxygen beam pulse, overall average energy of 5.5 eV and full width at half maximum (FWHM) of 5.2 eV, is sliced by the chopper wheel operating 150 Hz. The average energy of the sliced beam is adjustable from 1.3 eV to 8.8 eV by changing the system delay.

The polyimide-coated QCM was installed in the beam line and the change in resonance frequency of QCM was recorded during the exposure to the sliced atomic oxygen beam. The results are presented in Figure 4. Figure 4 indicates the frequency shift of polyimide-coated QCM during the atomic oxygen beam exposure. Average collision energy (Ecoll) in each exposure condition is indicated at the right side of the graph.

The frequency shift of the polyimide-coated QCM, which is proportional to the mass-loss of the film, is negative when low-energy atomic oxygen beam was irradiated (Ecoll < 4 eV). Such mass-increase phenomenon was observed only for the beginning of exposure and it was concluded that the initial surface oxidization reaction, which includes oxygen atom accommodation at the polyimide surface, was the origin of this unexpected results [14]. In contrast, it is clearly observed that the frequency shift of polyimide-coated QCM increased with increasing the collision energy of atomic oxygen beam (Ecoll > 5 eV).

The flux of atomic oxygen beam changes with chopper timing, e.g., energy. The mass-loss rate was divided by the relative area of TOF spectrum and flux compensated mass-loss rate, which corresponds to relative reaction efficiency (R_E) of atomic oxygen, was calculated. The

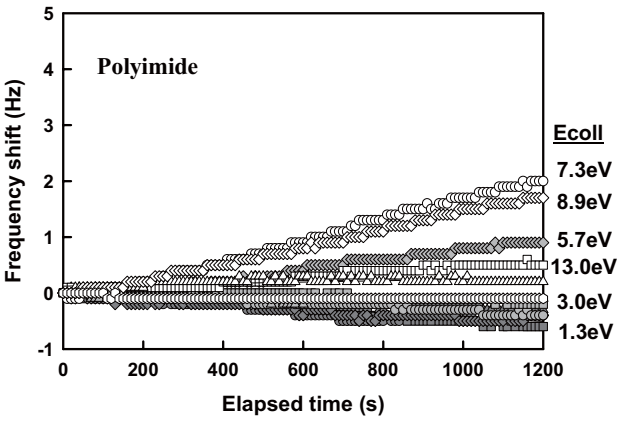

Figure 4 Frequency shift of polyimide-coated QCM during atomic oxygen exposures with various collision energies. Average collision energies (Ecoll) in each exposure condition are shown in the right side of the panel.

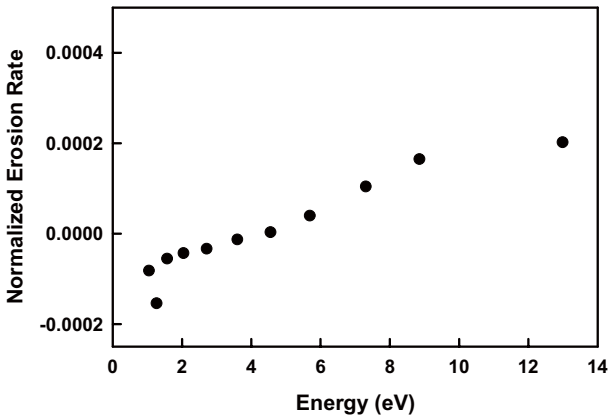

Figure 5 Normalized erosion rate of polyimide as a function of collision energy of atomic oxygen. Difference in atomic oxygen fluxes in the sliced beam was compensated with dividing by the area of TOF spectrum of the each beam.

results are shown in Figure 5. It is clearly indicated that the reaction efficiency almost linearly increases with collision energy for polyimide. The value of reaction yield of Kapton-H, 3 x 10^{-24} cm^3/atom, is not accurate for ground-based simulation for atomic oxygen testing which include wide collision energy distribution. This is probably acceptable for material endurance tests, which compares erosion rate of materials with that of Kapton-H. However, for calibration purpose, the absolute value of reaction yield with 5eV atomic oxygen is needed. Much more careful experiments should be conducted for calibration experiment.

5. Conclusions

For the development of atomic oxygen on-board sensors, ground-based calibration is quite important. Unlike endurance test, atomic oxygen sensor needs an absolute value of reaction yield of sensing materials. Due to the lack of consistency of energy distribution of atomic oxygen beam between real space and ground-based facility, measurement of absolute value of reaction yield of atomic oxygen with sensing material is not an easy task. Use of mechanical chopping wheel is a possible solution for narrowing the energy spread of the atomic oxygen beam in laser detonation source. Careful attention needs to be paid, otherwise large systematic error of atomic oxygen fluence measurement could happen in flight mission.

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