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# Materials International Space Station Experiment–6 (MISSE–6) Atomic Oxygen Fluence Monitor Experiment

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## Abstract

An atomic oxygen fluence monitor was flown as part of the Materials International Space Station Experiment–6 (MISSE–6). The monitor was designed to measure the accumulation of atomic oxygen fluence with time as it impinged upon the ram surface of the MISSE 6B Passive Experiment Container (PEC). This was an active experiment for which data was to be stored on a battery-powered data logger for post-flight retrieval and analysis. The atomic oxygen fluence measurement was accomplished by allowing atomic oxygen to erode two opposing wedges of pyrolytic graphite that partially covered a photodiode. As the wedges of pyrolytic graphite erode, the area of the photodiode that is illuminated by the Sun increases. The short circuit current, which is proportional to the area of illumination, was to be measured and recorded as a function of time. The short circuit current from a different photodiode, which was oriented in the same direction and had an unobstructed view of the Sun, was also to be recorded as a reference current. The ratio of the two separate recorded currents should bear a linear relationship with the accumulated atomic oxygen fluence and be independent of the intensity of solar illumination. Ground hyperthermal atomic oxygen exposure facilities were used to evaluate the linearity of the ratio of short circuit current to the atomic oxygen fluence. In flight, the current measurement circuitry failed to operate properly, thus the overall atomic oxygen mission fluence could only be estimated based on the physical erosion of the pyrolytic graphite wedges. The atomic oxygen fluence was calculated based on the knowledge of the space atomic oxygen erosion yield of pyrolytic graphite measured from samples on the MISSE 2. The atomic oxygen fluence monitor, the expected result and comparison of mission atomic oxygen fluence based on the erosion of the pyrolytic graphite and Kapton H atomic oxygen fluence witness samples are presented in this paper.

## 1.0 Introduction

The ability to measure the atomic oxygen fluence as a function of time as it impinges upon spacecraft surfaces in low Earth orbit has been difficult to achieve. Early devices to measure atomic oxygen fluence consisted of thin films silver or carbon coatings (often called thin film actinometers) whose electrical resistivity increased with time as the silver oxidized or the carbon was converted to gaseous oxides(Refs. 1 to 3). Such thin film devices have limited fluence measurement capability due to the finite thickness of the thin films. They also can give nonlinear responses as a function of fluence.

The time variation of accumulation of atomic oxygen fluence is also difficult to predict based on end point Kapton H weight loss measurements as a result of variations in solar activity, spacecraft altitude, and spacecraft orientation. The prediction of atomic oxygen fluence from orbital and spacecraft orientation data is also complicated by potential shielding of the ram facing surfaces. This is especially true for complex distributed space structures such as the International Space Station. This paper describes an atomic oxygen fluence monitor that is based on the erosion yield of pyrolytic graphite from the MISSE 2 mission (Ref. 4). It uses two 12° inclined wedges of graphite that are over grit blasted fused silica windows covering photodiodes. As the wedges erode a greater intensity of light illuminates the photodiode. The short circuit current from the photodiode is compared to a reference photodiode also on the MISSE 6B. The advantage of using wedges of pyrolytic graphite rather than using techniques involving measuring the conductivity change of coatings of silver, carbon, or semiconductors is that the ratio of the short circuit currents of the sample and reference is a signal that is linear with atomic oxygen fluence and also allows measurement of very high atomic oxygen fluences.

## 2.0 Apparatus and Procedure

The MISSE 6 atomic oxygen fluence monitor was designed to allow low Earth orbital atomic oxygen to erode pyrolytic graphite allowing sunlight to impinge on a fused silica window that was grit blasted to diffusely scatter the sunlight which then impinged upon a photodiode as shown in Figure 1. Figure 2 shows the configuration of the pyrolytic graphite after atomic oxygen erosion.

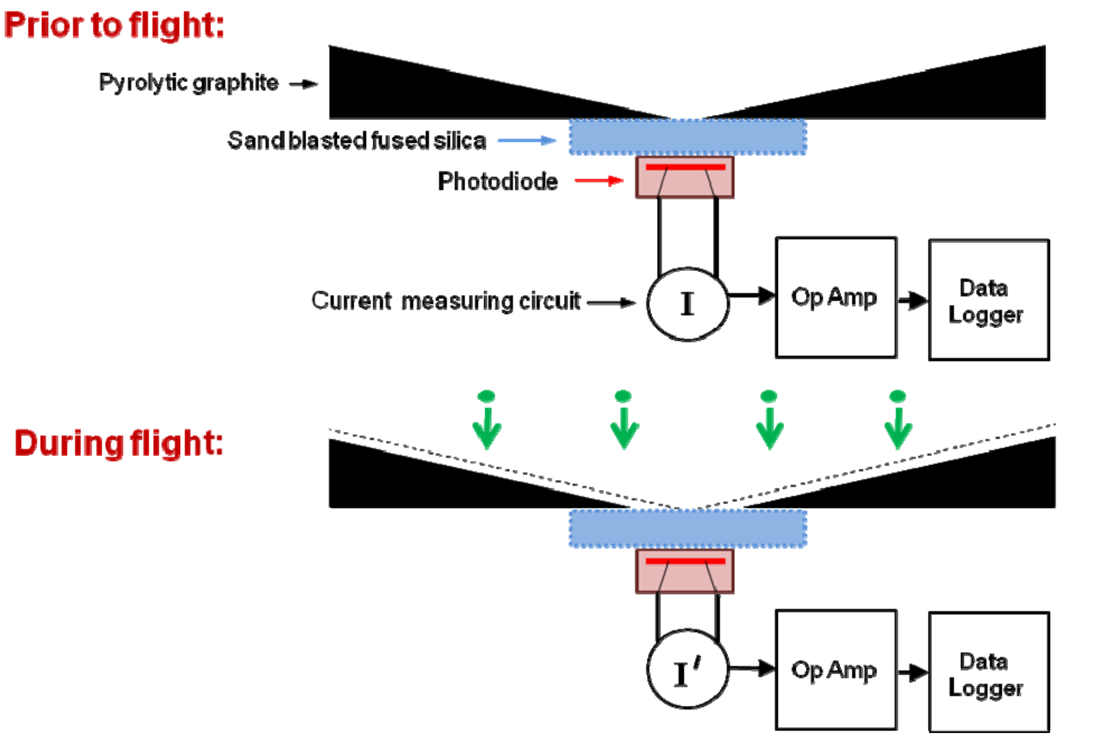

Figure 1.—Atomic oxygen fluence monitor concept.

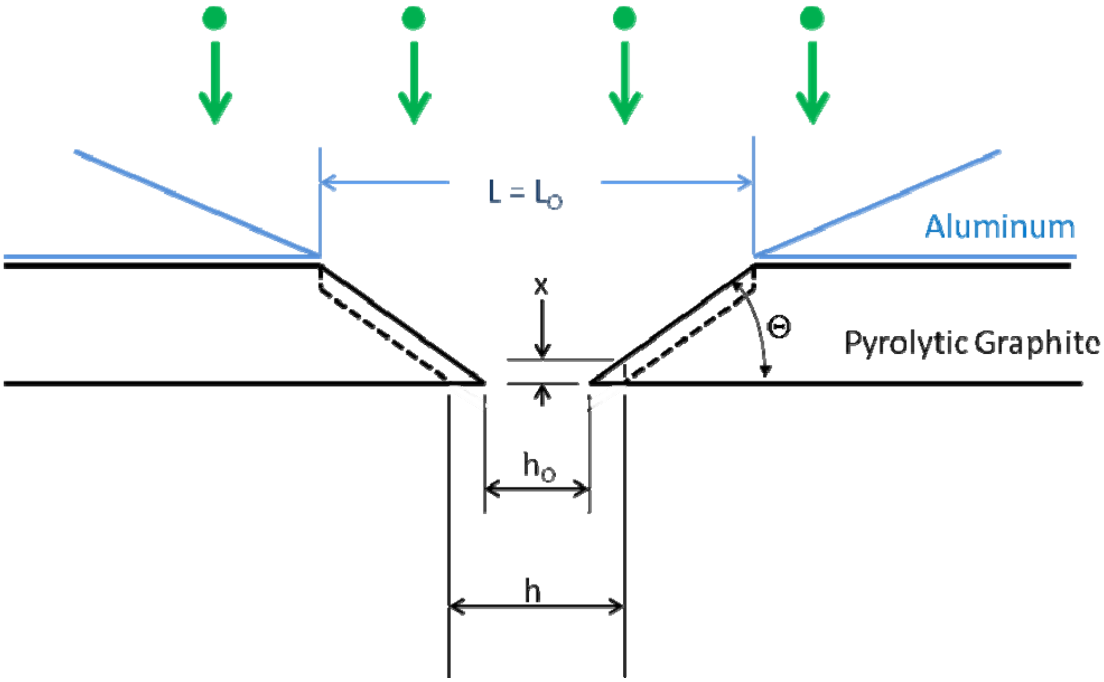

Figure 2.—The atomic oxygen fluence erosion of the pyrolytic graphite.

The atomic oxygen fluence is thus given by

$$F = x/E \tag{1}$$

thus

$$F = (h - h_o)(\tan \Theta)/(2E) \tag{2}$$

where:

F atomic oxygen fluence, atoms/cm$^2$
x atomic oxygen erosion depth, cm
$h_o$ initial gap between the pyrolytic graphite wedges, cm
h gap between the pyrolytic graphite wedges after an atomic oxygen fluence of F, cm
Θ wedge angle
E atomic oxygen erosion of pyrolytic graphite = $4.15 \times 10^{-25}$ cm$^3$/atom (Ref. 4)

The sharp wedge of pyrolytic graphite was made by attaching the pyrolytic graphite to a 12° wedge of aluminum and sanding it on abrasive paper over a flat surface. As shown in Figure 3.

The wedge angle of 12° was chosen as the smallest practical angle that the pyrolytic graphite could be sanded to without resulting in very irregular sharpened ends resulting in the pyrolytic graphite. Because it is not possible to atomically sharpen the pyrolytic graphite wedges using abrasion alone, there would be an initial delay and lack of linearity in the photodiode current increase with fluence until the graphite wedges are atomically sharpened in LEO. To minimize the consequences of the less than perfect mechanical sharpening, an additional sharpening step was performed using a hyperthermal atomic oxygen beam from an end Hall atomic oxygen source operating on pure oxygen at 70 eV, shown in Figure 4. An exploded view of the atomic oxygen fluence sensor is shown in Figure 5.

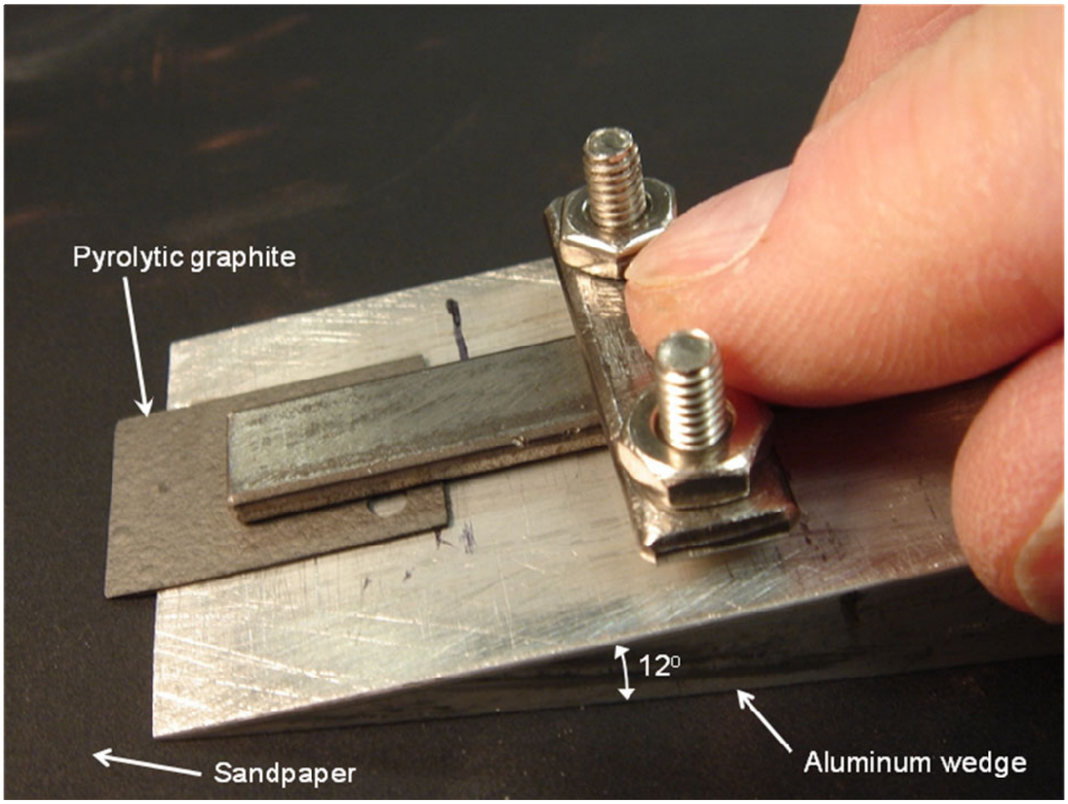

Figure 3.—Constructing a 12° wedge of pyrolytic graphite.

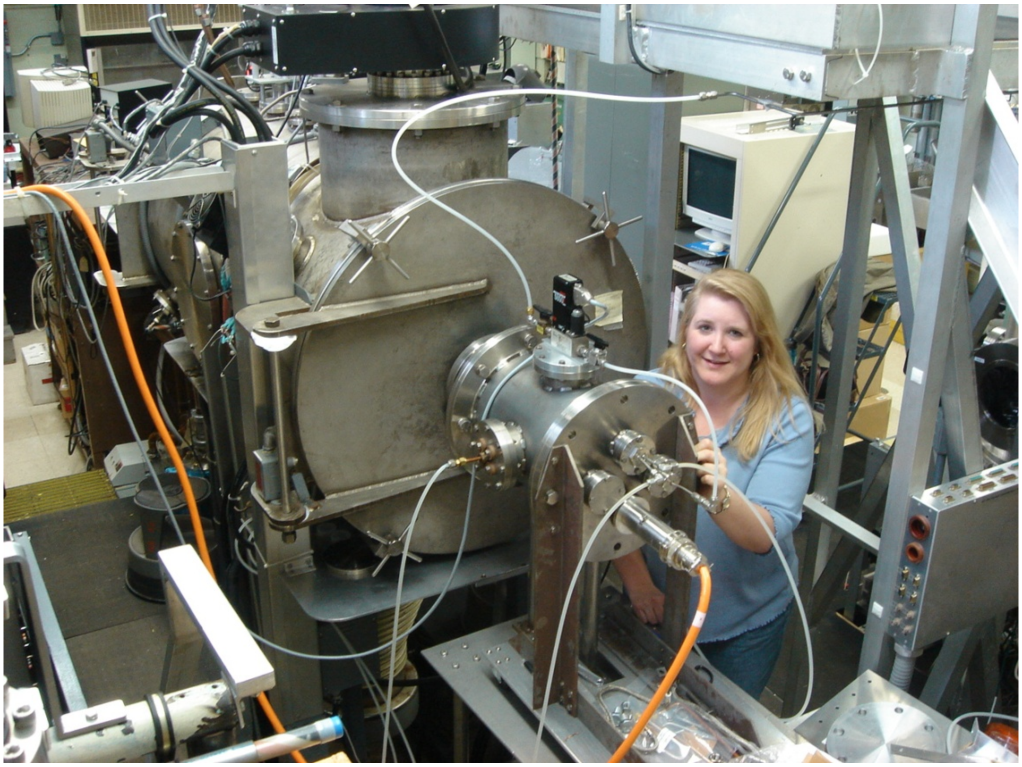

Figure 4.—Hyperthermal end Hall atomic oxygen beam system.

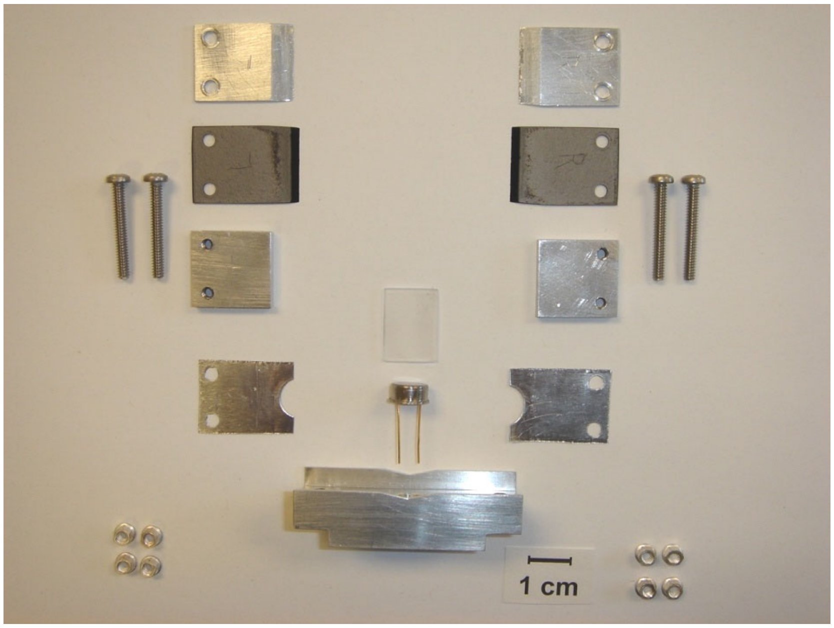

Figure 5.—Exploded view of the component parts of the atomic oxygen fluence sensor.

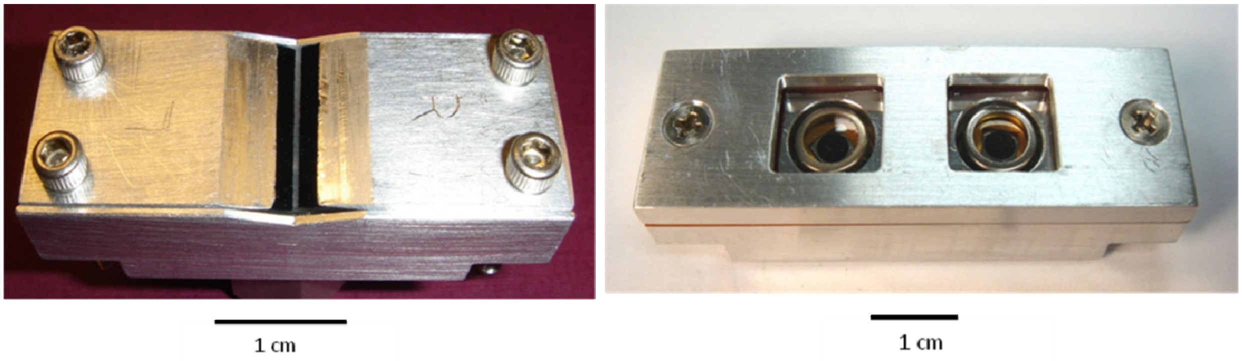

Figure 6.—Flight atomic oxygen fluence monitor and indium-tin oxide conductivity and transmittance experiment.

The fluence monitor was assembled prior to the atomic oxygen sharpening, which is why the exposed wedge portion appears black as a result of atomic oxygen texturing in the end Hall atomic oxygen beam facility. The sharpening was performed to a Kapton H equivalent fluence of $1.2\times10^{22}$ atoms/cm$^2$.

After the atomic oxygen sharpening the fluence monitor was taken apart and reassembled to provide a very small initial gap (0.0578 cm) in the pyrolytic graphite wedges prior to flight. To be able to discriminate between changes in photodiode current due to Sun angle variations and changes due to erosion of the graphite wedges, an identical reference photodiode was used which had an view of the Sun incidence upon an adjoining experiment. The short circuit current from the fluence monitor photodiode was then compared to this identical photodiode which also served as a reference Sun illumination measurement on an adjoining indium-tin oxide conductivity and transmittance experiment. The flight atomic oxygen fluence monitor and the reference photodiode from the indium-tin oxide conductivity and transmittance experiment are shown in Figure 6.

One of the merits of the design of the pyrolytic graphite atomic oxygen fluence monitor is that it should have a reasonably linear output current with accumulated fluence and capable of sensing a high fluence. To validate the high fluence linearity premise, an experiment was constructed using a lamp at a large distance from the fluence monitor along with a reference photodiode as shown in Figure 7. The pyrolytic graphite gap was manually widened to allow measurement of the ratio of the fluence monitor current, I, to the reference current, $I_o$, as a function of graphite gap, h, as shown in Figure 8. As can be seen from Figure 8, the fluence monitor has a reasonably linear response with a correlation coefficient of 0.963 over a fluence range which represents at least $3.14 \times 10^{22}$ atoms/cm$^2$ based on the erosion yield of $4.15 \times 10^{-25}$ cm$^3$/atoms. The scatter in the data points is thought to be due to the uncertainty in the setting and measurement of the gap between the pyrolytic graphite wedges.

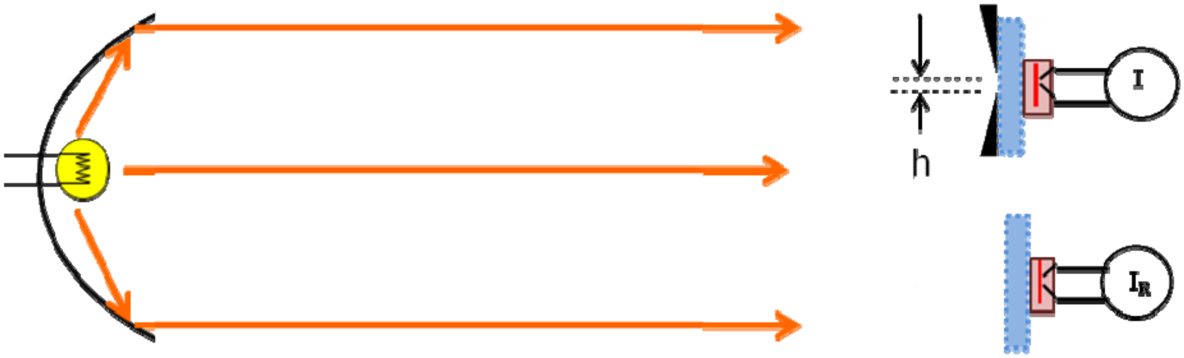

Figure 7.—Fluence monitor setup for measurement of calibration linearity.

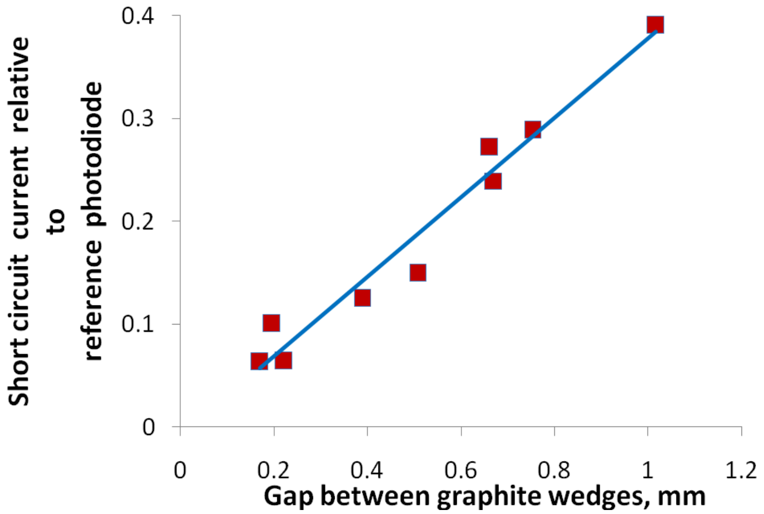

Figure 8.—Short circuit current relative to reference current as a function of pyrolytic graphite gap.

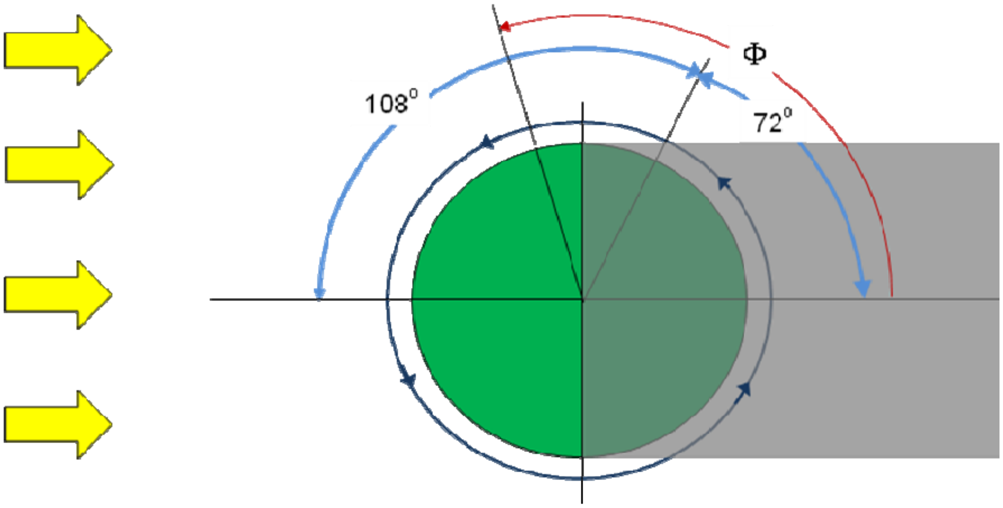

Figure 9.—Atomic oxygen fluence monitor measurement domain of 72° < Φ < 180°.

Short circuit current measurements were to be recorded on a time interval of every 108 minutes. The time interval between successive data points was purposely chosen to be slightly out of phase with the 91.2 minute average orbital period to insure that near normal solar illumination on the photodiodes, which were oriented with their surface normal vectors facing tangential to the Earth’s surface and facing the ram direction (see Fig. 9 where $\phi = 90^{\circ}$), would frequently occur.

The data for near normal illumination could be corrected based on off-normal to normal short circuit current calibrations for both the fluence monitor and the reference photodiodes. The ground laboratory calibration data for the ratio of measured to theoretical (based on sin Φ) short circuit currents for the fluence monitor and the reference photodiodes is shown in Figures 10 and 11 respectively.

One would expect that the calibration data show a quicker loss in short circuit current with time after 6 am due to the fact that the active surface of the photodiodes is recessed within the photodiode enclosure. This causes the Sun light to begin to miss the active surface of the photodiodes after 30 minutes past midnight when the Sun is beginning to have an inclined angle of arrival on the photodiodes. The cover glasses over the photodiodes were sandblasted to help moderate the effect of off-normal illumination beginning to miss the active surface of the photodiodes.

The reference photodiode had similar output losses with off-normal illumination as the fluence monitor photodiode and for the same reasons.

Using the data from Figures 10 and 11, one can determine that data points taken between 20.3 and 25.3 minutes after midnight could be easily adjusted for off-normal output calibrations to be able to make a long term plot of maximum short circuit current versus time to produce atomic oxygen fluence data as a function of time.

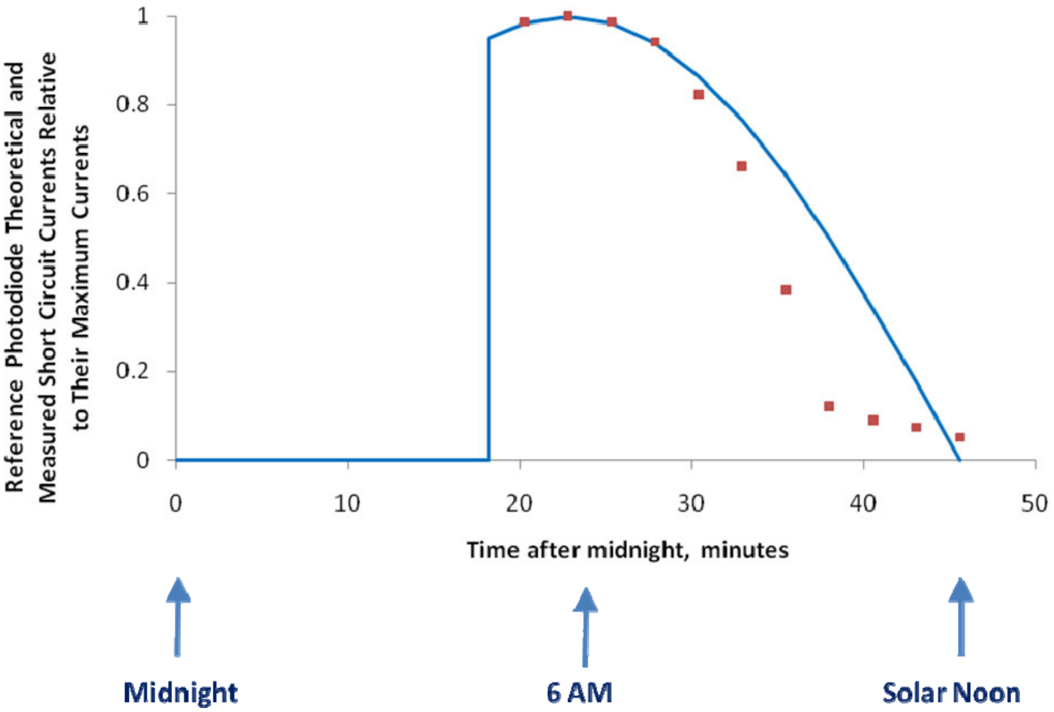

Figure 10.—Theoretical (solid line) and measured (individual data points) fluence monitor photodiode short circuit currents relative to their maximum currents as a function of time after midnight.

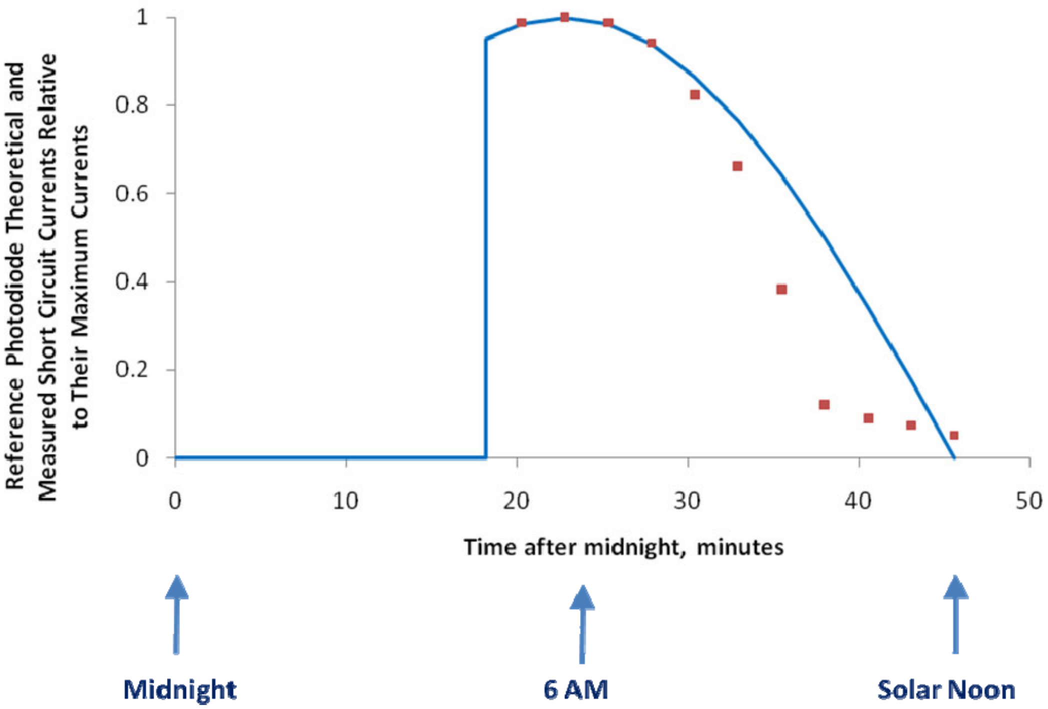

Figure 11.—Normalized theoretical (solid line) and measured (individual data points) reference photodiode short circuit current as a function of time after midnight.

## 3.0 Results and Discussion

The atomic oxygen fluence monitor was attached to the International Space Station on the ram facing surface of MISSE 6B passive experiment container (PEC) on March 13, 2008, as shown in Figure 12. The experiment was retrieved on September 1, 2009. Although there were many periods of off normal atomic oxygen incidence including periods in which the carrier was oriented in the ram direction, the atomic oxygen fluence was measured independently by Kapton H samples on the adjoining MISSE 6A PEC to be approximately $1.97 \pm 0.05\times10^{21}$ atoms/cm$^2$.

After examination of the data logger information it became apparent that the electronics had failed in sending the short circuit current information from both the fluence monitor and reference photodiodes. Thus, the only measurement of fluence that was obtainable from the experiment was from direct measurement of the growth in the gap between the tips of the pyrolytic graphite wedges. Figure 13 compares photographs of the pre-flight and post-flight gaps in the pyrolytic graphite wedges. The before and after flight gaps in the pyrolytic graphite wedges were measured at 19 equally spaced locations along the length of the gap by using digital calipers to measure close up photographs of the gap. The locations of the gap measurements were identical for each measurement. To calibrate the photographs, the gap between the aluminum plates that held down the pyrolytic graphite was measured in three identical locations. It was assumed that the pyrolytic graphite wedges and aluminum hold down plates did not move as a result of launch and retrieval vibration. This was reasonable because the parts were all machined to provide a tight fit together and nested within each other.

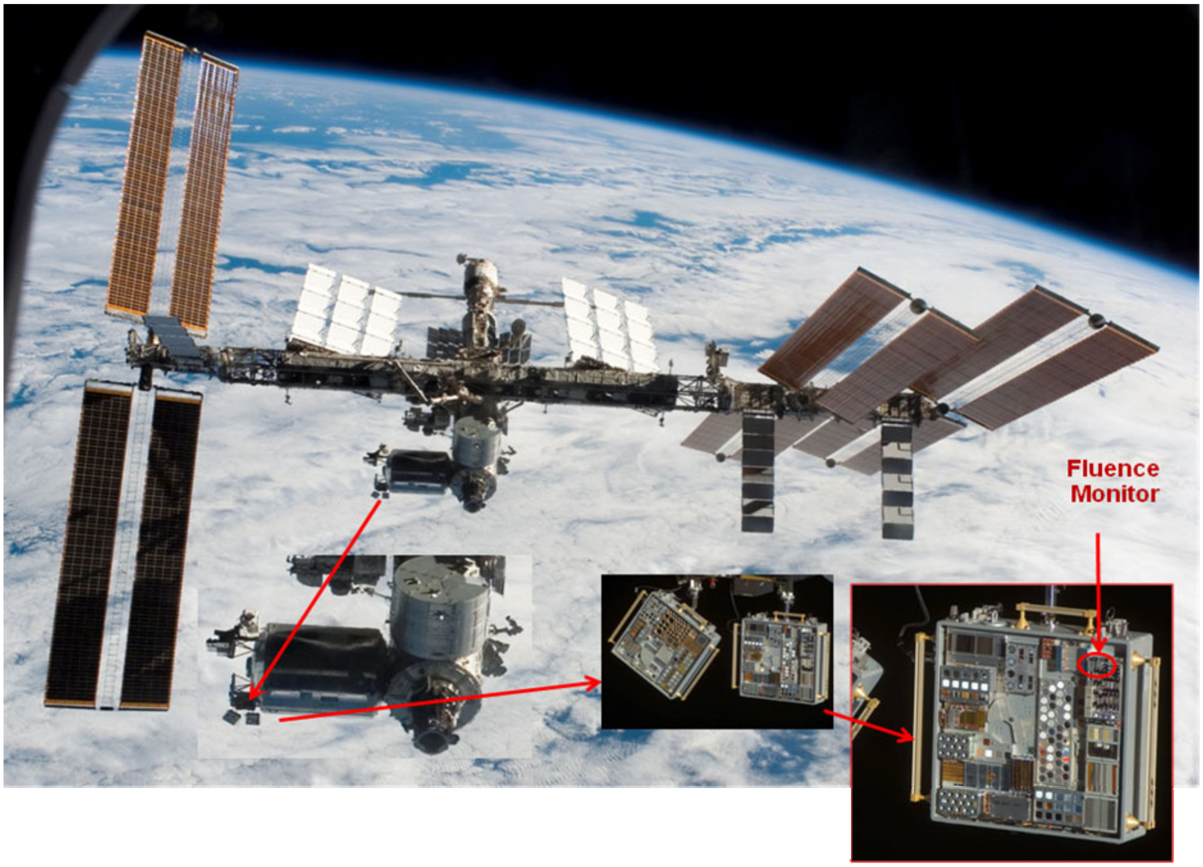

Figure 12.—Atomic oxygen fluence monitor mounted on MISSE 6A on the International Space Station.

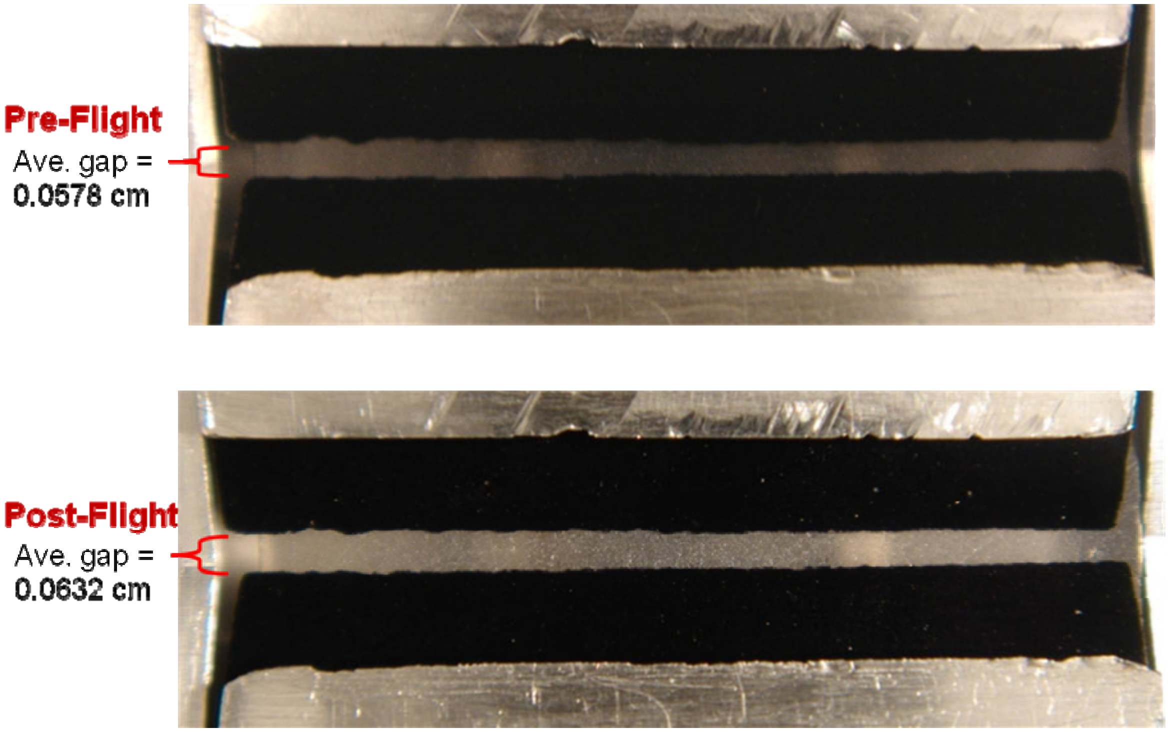

Figure 13.—Comparison photographs of the pre-flight and post-flight gaps in the pyrolytic graphite wedges.

Substituting the change in gap (0.0054 cm) in Equation (2) and performing a propagation of errors analysis of the measurement errors yields an atomic oxygen fluence of 1.37 $\pm 0.16 \times 10^{21}$ atoms/cm$^2$.

Although the pyrolytic graphite wedges have straight edges on a macroscopic scale, they have rather irregular edges on a microscopic scale. However, the wedges continue to retain a tapered sharp edge which is limited in sharpness only by the microscopic cone-to-valley texture on the pyrolytic graphite which is a result of the ram atomic oxygen erosion, as can be seen in Figure 14.

Based on the 9.2 percent growth in the gap between the fluence monitor pyrolytic graphite wedges and assuming a linear growth in accumulated fluence with time, one would expect a resulting fluence versus time plot as shown in Figure 15.

However, the current measurement circuitry failed to operate properly and no useful data logger information was retrievable from either the fluence monitor or reference photodiodes. As a result, only end points are available of the measurement in the gap in the pyrolytic graphite wedges as indicator of total mission fluence and no fluence information as a function of time was possible to be measured. Based on the many changes in the International Space Station orientation, if data was available one would expect a very non-linear shape to the curve shown in Figure 15.

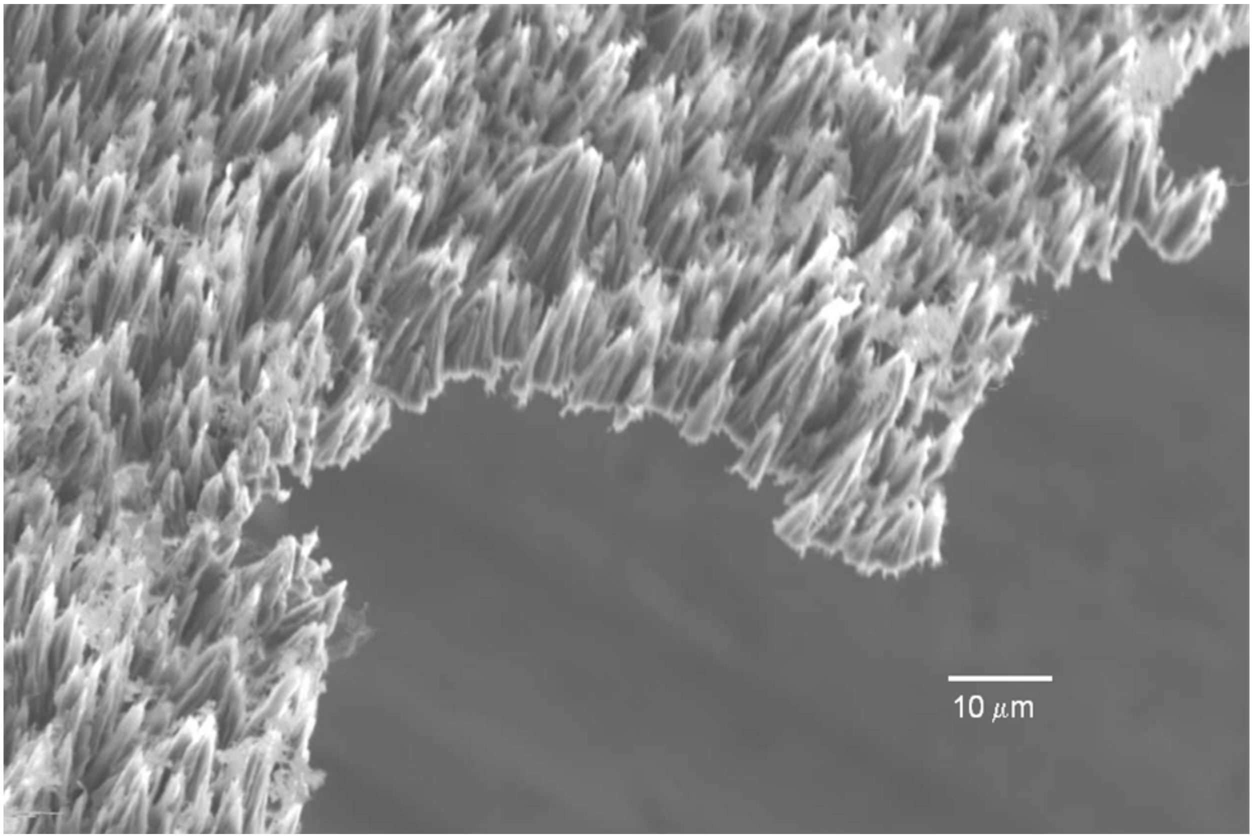

Figure 14.—Scanning electron microscope image of the edge of the pyrolytic graphite wedge after post-flight retrieval.

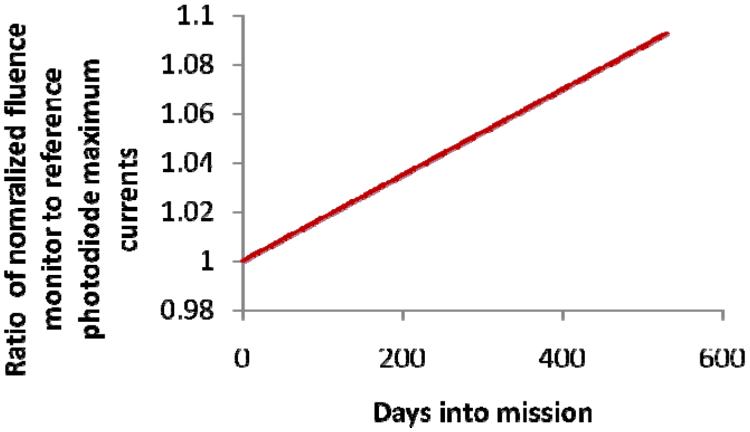

Figure 15.—Expected ratio of normalized fluence monitor to reference photodiode short cireuit current as a function of days into mission.

It is interesting to note that the atomic oxygen fluence monitor on PEC 6B predicted a lower fluence than from two Kapton H samples located nearby on PEC 6A even if one takes into account the uncertainties as shown in Table I.

TABLE I.—MISSE 6 ATOMIC OXYGEN EROSION YIELDS

| PEC | Description | Fluence, atoms/cm$^2$ | Uncertainty, atoms/cm$^2$ |
|---|---|---|---|
| 6A | W3 tray Kapton H sample (Ref. 5) | $1.97\times10^{21}$ | $0.05\times10^{21}$ |
| 6A | Seals Experiment Kapton H sample | $1.91\times10^{21}$ | $0.11\times10^{21}$ |
| 6B | Kapton HN sample (Ref.6) | $2.01\times10^{21}$ | $0.1\times10^{21}$ |
| 6B | Atomic oxygen fluence monitor | $1.37\times10^{21}$ | $0.16\times10^{21}$ |

As can be seen from Table I, the fluence measured by the atomic oxygen fluence monitor was ~ 30 percent lower than the most accurate fluence measured using a Kapton H sample from an adjoining MISSE 6A PEC and ~32 percent lower than the fluence measured by Kapton HN on the MISSE 6B PEC. Explanations for the differences between measurements of atomic oxygen fluence are somewhat speculative. For the fluence difference between to be accounted for by differences in thermal expansion, the temperature of the experiment when photographed after the flight would have to have been ~20 °C lower than for the preflight photograph. This does not seem to be a good explanation because both photographs were taken at room temperature in a controlled office environment. Another possible explanation could be that is possible shadowing from International Space Station Structures might have produced a lower atomic oxygen fluence on PEC 6B than on 6A. Another explanation considered is relates to the atomic erosion yield of pyrolytic graphite wedges at 12° incline from the graphite basal planes. If the erosion yield was lower as a result of the inclined surface it would contribute to a reduced apparent fluence. However, the amount of the reduction required appears too large to be caused by only a 12° incline. The most reasonable explanation appears to be small changes in the pyrolytic graphite gap due either to launch or landing vibration or thermal cycling caused gap shrinkage in space. The aluminum (type 6061-T6) experiment base has a high thermal expansion coefficient and the pyrolytic graphite and has a near zero thermal expansion coefficient. If one or both of the pyrolytic graphite wedges slipped together by only 0.0012 cm (0.00049 in.) then the apparent loss in fluence could be accounted for. If the experiment flew with active recording of the data this error would not exist because there would be negligible vibration over the in-space mission duration.

## 4.0 Summary

An atomic oxygen fluence monitor, flown as part of the MISSE 6B, was designed to measure the accumulation of atomic oxygen fluence with time as it impinged upon the ram surface of the MISSE 6B. This was an active experiment for which data was to be stored on a battery-powered data logger for post-flight retrieval and analysis. The atomic oxygen fluence measurement was accomplished by allowing atomic oxygen to erode two opposing wedges of pyrolytic graphite that partially covered a photodiode. As the wedges of pyrolytic graphite erode, the area of the photodiode that is illuminated by the Sun increases. The short circuit current, which is proportional to the area of illumination, was to be measured and recorded as a function of time. The short circuit current from a different photodiode, which was oriented in the same direction and which had an unobstructed view of the Sun, was also to be recorded as a reference current. The ratio of the two separate recorded currents should bear a linear relationship with the accumulated atomic oxygen fluence and be independent of the intensity of solar illumination. Ground hyperthermal atomic oxygen exposure facilities were used to evaluate the linearity of the ratio of short circuit currents to the atomic oxygen fluence indicated that the device was both linear and capable of measuring atomic oxygen fluences up to at least $3.14\times10^{22}$ atoms/cm$^2$. Because the electronics failed to operate correctly, the atomic oxygen fluence had to be calculated based on the knowledge of the space atomic oxygen erosion yields of pyrolytic graphite from samples on the MISSE 2 and the measured growth in the gap between the two pyrolytic graphite sensing wedges. An atomic oxygen fluence of $1.37 \pm 0.16 \times 10^{21}$ atoms/cm$^2$ was measured. The fluence was ~ 30 percent lower than fluences measured using Kapton H samples from an adjoining MISSE 6A PEC. Possible slippage due to launch or retrieval vibration or thermal cycling caused creep causing the gap between the pyrolytic graphite wedges to become closer together by 0.0012 cm appears to be the most likely cause of the fluence discrepancy.

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6. Finkenor, M., personal communication.

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**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

An atomic oxygen fluence monitor was flown as part of the Materials International Space Station Experiment-6 (MISSE-6). The monitor was designed to measure the accumulation of atomic oxygen fluence with time as it impinged upon the ram surface of the MISSE 6B Passive Experiment Container (PEC). This was an active experiment for which data was to be stored on a battery-powered data logger for post-flight retrieval and analysis. The atomic oxygen fluence measurement was accomplished by allowing atomic oxygen to erode two opposing wedges of pyrolytic graphite that partially covered a photodiode. As the wedges of pyrolytic graphite erode, the area of the photodiode that is illuminated by the Sun increases. The short circuit current, which is proportional to the area of illumination, was to be measured and recorded as a function of time. The short circuit current from a different photodiode, which was oriented in the same direction and had an unobstructed view of the Sun, was also to be recorded as a reference current. The ratio of the two separate recorded currents should bear a linear relationship with the accumulated atomic oxygen fluence and be independent of the intensity of solar illumination. Ground hyperthermal atomic oxygen exposure facilities were used to evaluate the linearity of the ratio of short circuit current to the atomic oxygen fluence. In flight, the current measurement circuitry failed to operate properly, thus the overall atomic oxygen mission fluence could only be estimated based on the physical erosion of the pyrolytic graphite wedges. The atomic oxygen fluence was calculated based on the knowledge of the space atomic oxygen erosion yield of pyrolytic graphite measured from samples on the MISSE 2. The atomic oxygen fluence monitor, the expected result and comparison of mission atomic oxygen fluence based on the erosion of the pyrolytic graphite and Kapton H atomic oxygen fluence witness samples are presented in this paper.

**15. SUBJECT TERMS**

Atomic oxygen; LEO; Polymers

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