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A Comparison of Space and Ground Based Facility Environmental Effects for FEP Teflon

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A COMPARISON OF SPACE AND GROUND BASED FACILITY ENVIRONMENTAL EFFECTS FOR FEP TEFLON

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1.0 Abstract

Fluorinated Ethylene Propylene (FEP) Teflon is widely used as a thermal control material for spacecraft, however, it is susceptible to erosion, cracking, and subsequent mechanical failure in low Earth orbit. One of the difficulties in determining whether FEP Teflon will survive during a mission is the wide disparity of erosion rates observed for this material in space and in ground based facilities. Each environment contains different levels of atomic oxygen, ions, and vacuum ultraviolet (VUV) radiation in addition to parameters such as the energy of the arriving species and temperature. These variations make it difficult to determine what is causing the observed differences in erosion rates. This paper attempts to narrow down which factors affect the erosion rate of FEP Teflon through attempting to change only one environmental constituent at a time. This was attempted through the use of a single simulation facility (plasma asher) environment with a variety of Faraday cages and VUV transparent windows. Isolating one factor inside of a radio frequency (RF) plasma proved to be very difficult. Two observations could be made. First, it appears that the erosion yield of FEP Teflon with respect to that of polyimide Kapton is not greatly affected by the presence or lack of VUV radiation present in the RF plasma and the relative erosion yield for the FEP Teflon may decrease with increasing fluence. Second, shielding from charged particles appears to lower the relative erosion yield of the FEP to approximately that observed in space, however it is difficult to determine for sure whether ions, electrons, or some other components are causing the enhanced erosion.

2.0 Introduction

Materials qualification for atomic oxygen durability in low Earth orbit has been performed in both ground based facilities and in space. The ground based facilities have been developed out of the necessity to study long term atomic oxygen effects to levels greater than can be achieved with a typical mission on the Space Shuttle. They also have the advantage of quick turnaround, lower cost per exposure, and ease of experiment tailorability.

Some questions naturally occur about the applicability of ground based test data for use in predicting how a material will perform in low Earth orbit (LEO). These questions arise due to the differences in the species, energy or charged state of the arriving atoms and the intensity and wavelength of VUV radiation present. Other parameters also may play a role, such as temperature. There is currently no known facility, whether thermal plasma or directed beam, which will exactly duplicate the conditions in low Earth orbit [1-7]. Such facilities, however, are needed to screen materials for use in LEO. So it is important to understand why differences in erosion rates occur so that the test equipment can be modified to produce results closer to those in space, or to allow calibration factors to be developed.

Of all the materials, FEP Teflon seems to provide the widest disparity of data in space and ground based systems. Typically FEP Teflon Exposed in RF plasmas has an erosion yield relative to polyimide Kapton which is an order of magnitude greater than in LEO. This paper attempts to determine what is present in one type of simulation facility (RF plasma), that affects the erosion of FEP Teflon, by isolating selected components in the environment that may have an effect on the erosion rate. VUV radiation and charged species were the components selected to be the focus of this study due to the wide belief among the LEO testing community that these are the important factors.

3.0 Experimental Procedure

3.1. MATERIALS

Sample coupons, 2.54 cm diameter, were punched from 0.005 cm thick sheets of polyimide Kapton HN (DuPont) and fluorinated ethylene propylene (FEP Teflon) (DuPont). All of the samples were fully dehydrated for 48 hours in a vacuum of 8-13 Pa (60-100 mTorr) prior to weighing and subsequent exposure in the atomic oxygen plasma. Samples were quickly weighed after dehydration and upon removal from the vacuum chamber after exposure to atomic oxygen in order to minimize errors in mass due to water absorption [8].

3.2 PLASMA ASHER

An SPI Plasma Prep II asher operated on air was used as the environment simulator for these tests. The asher operates by using RF (13.56 Mhz) to create a discharge between two electrodes which surround a glass reaction chamber. A thermal plasma is produced which is at an energy of <<0.1 eV. The plasma contains atomic and excited state species as well as molecules, ions, electrons, and VUV radiation. The amounts and intensity of the latter five have not been determined. The effective arrival of atomic oxygen is estimated by determining the reaction rate of polyimide Kapton, whose space degradation rate is well known. The nitrogen in the plasma has been shown in earlier tests not to react with the materials that are being tested in this study [8]. Typical vacuum chamber pressure during operation was 16-27 Pa (120-200 mTorr). Temperature measured in the past inside the plasma chamber was 65 °C [9].

3.3 FARADAY CAGES AND VUV WINDOWS

Aluminum Faraday cages were constructed from single sheets of 0.0127 cm aluminum foil so that boxes with attached lids were formed. Openings under the lids on the sides produced open re-entrant boxes and prevented line-of-sight exposure of the samples to the external air plasma. Several modifications were made to the boxes to allow various plasma components to be excluded or allowed into the boxes.

Figure 1 shows the various box designs used for testing. Figure 1A is a closed Faraday cage. This design is supposed to block VUV radiation and charged species from the samples inside while allowing atomic oxygen to scatter into the box through the openings under the lid on the side of the box. This box design was modified in Figure 1B to include an opening in the lid surrounded by aluminum foil tabs to hold various windows and filters that were 2.54 cm diameter. The window or filter after insertion was covered with a thin aluminum foil sheet with a circular hole cut in the center that was bonded to the surface of the window and box with acrylic adhesive. This prevented plasma from leaking into the box around the window.

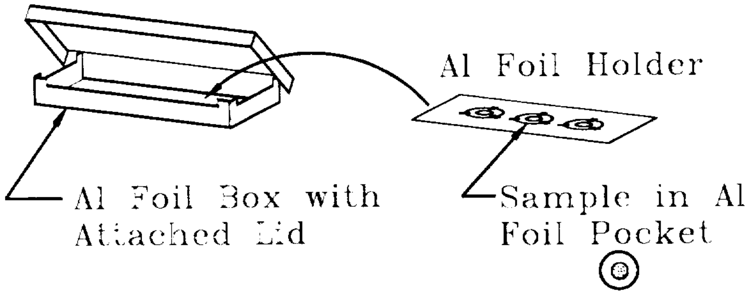

Figure 1A. Closed Faraday cage

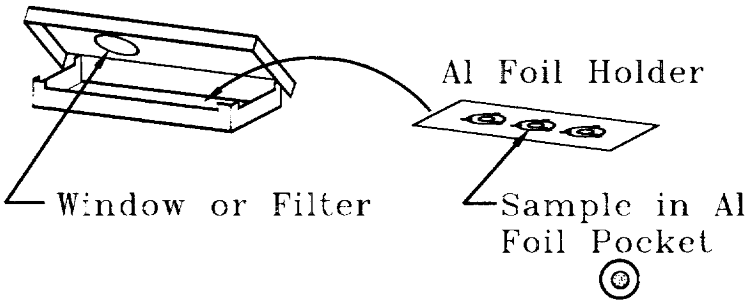

Figure 1B. Faraday cage with window or mesh filter

A magnesium fluoride window was used to allow VUV radiation of wavelengths greater than approximately 120 nm, and visible light to impinge onto one sample placed inside of one end of the box. The transmission versus wavelength for the window is shown in Figure 2. Another sample could be placed at the other end of the interior of the box so that it would see all of the same conditions but not be exposed to the VUV radiation entering through the window. A gold mesh filter was also used to allow all wavelengths to enter the box but block most of the charged particles from entering. A single mesh screen spot welded to an aluminum foil ring (0.0127 cm thick) was found to actually accelerate charged species into the box, so a double screen was made from two sheets of gold mesh spot welded to either side of an aluminum foil ring (0.0127 cm thick). The gold mesh was manufactured by Buckbee Mears to have 80% transparency at roughly 39 lines per centimeter of 0.00267 cm diameter gold wire.

In order to keep samples from sliding out from under the window during exposure due to vibration, a 0.0127 cm thick aluminum foil rectangle that just fit into the interior of the box was cut, as shown in Figure 1, to have tabs that would fold around the samples to hold them in place. Each sample was wrapped with approximately 0.002 cm thick aluminum foil with a 1.905 cm diameter hole punched in the front surface to allow the atomic oxygen to reach the sample of FEP Teflon or polyimide Kapton HN.

3.4 DATA MEASUREMENT AND ANALYSIS

Changes in mass were recorded for FEP Teflon and polyimide Kapton HN for each test configuration. The effective fluence (number of atoms of atomic oxygen arriving per square centimeter over the test duration) was determined by measuring the mass loss per unit area of polyimide Kapton HN and using Equation 1.

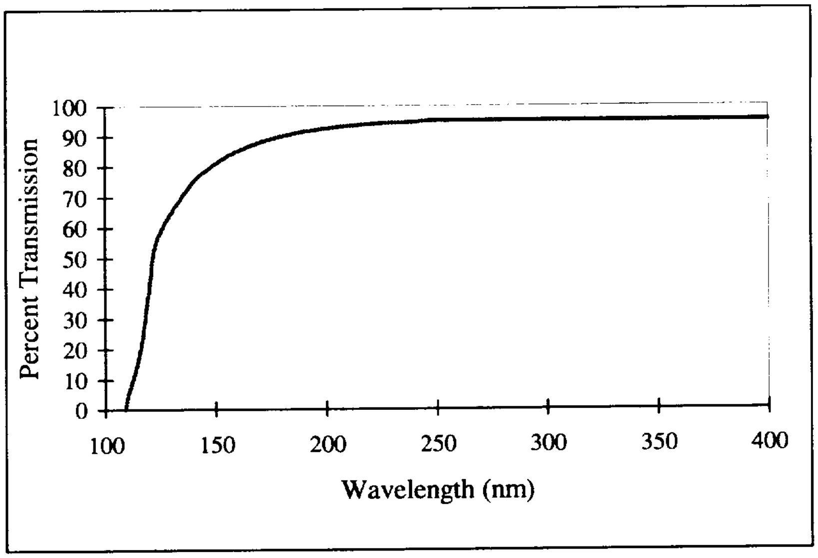

Figure 2. Transmission of MgF_2 Window

$$F = \frac{M / A}{\rho * E} \tag{1}$$

Where:

$F =$ *Fluence (atoms/cm^2)*
$M =$ *Mass loss of polyimide Kapton (g)*
$A =$ *Area of polyimide Kapton exposed to atomic oxygen (cm^2)*
$\rho =$ *Density of polyimide Kapton (1.42 g/cm^3)*
$E =$ *Erosion Yield for polyimide Kapton in LEO ($3x10^{-24}$ cm^3/atom)*

The effective erosion yield for FEP Teflon, which is the volume of FEP Teflon removed for each effective atom that arrives, was determined by using Equation 2. The erosion yield was then divided by the known erosion yield for polyimide Kapton in low Earth orbit ($3x10^{-24}$ cm^3/atom) to obtain the measurement relative to a known standard. Erosion yields relative to polyimide Kapton were then plotted to look for potential trends in the data.

$$E_{FEP} = \frac{M / A}{\rho * F} \tag{2}$$

Where:

E_{FEP} = *Erosion Yield for FEP Teflon* (cm^3/*atom*)
M = *Mass loss of FEP Teflon* (g)
A = *Area of FEP Teflon exposed to atomic oxygen* (cm^2)
ρ = *Density of FEP Teflon* ($2.15\ g/cm^3$)
F = *Fluence* (*atoms*/cm^2) (*based on polyimide Kapton*)

4.0 Results and Discussion

4.1 EXPOSURE DIRECTLY IN THE PLASMA

FEP Teflon exposed in the plasma should see the total environment present including charged species and VUV radiation. Several tests were conducted with FEP Teflon and polyimide Kapton samples exposed to the plasma while sitting on top of glass microscope slides that were approximately 7.62 cm x 2.54 cm in area. The average erosion yield with respect to Kapton measured over approximately the same fluence exposure was 1.9 ± 0.14. Samples of FEP Teflon and polyimide Kapton were also placed on top of some of the Faraday cages during testing to record what the effective atomic oxygen fluence was outside of the Faraday cage. It was noticed that during these tests, the erosion yield with respect to Kapton in the plasma but on top of the aluminum surface was lower than that observed on glass slides (between 1 and 1.2). This was unexpected, because the plasma environment was believed to not be affected by the sample holders. Another test was conducted, but this time the FEP Teflon and polyimide Kapton were placed in aluminum foil covers and held down to an aluminum sheet (identical sample holders used in the Faraday cages and described earlier) with aluminum foil tabs. This placed the samples in good electrical contact with the aluminum and also allowed them to sit in the same location in the asher as the samples on glass slides had been during previous testing. The erosion yield for FEP Teflon with respect to Kapton was even lower for this test (0.374 ± 0.036). A comparison bar chart with error bars is shown in Figure 3.

It can be seen that the differences in the erosion yields are much greater than the measurement error. Flux levels varied during each test, but the overall fluence was approximately 2×10^{20} atoms/cm^2 on the average. Table I contains the data for all of the tests performed including the effective atomic oxygen flux. There does not appear to be any relationship between flux and relative erosion yield. It is possible that the surface conductivity may affect the arrival of charged species at the sample surface or that VUV radiation intensities may be altered near the sample. In order to try to narrow down the reason for these differences, testing was conducted inside Faraday cages where some of these environments could potentially be reduced or isolated.

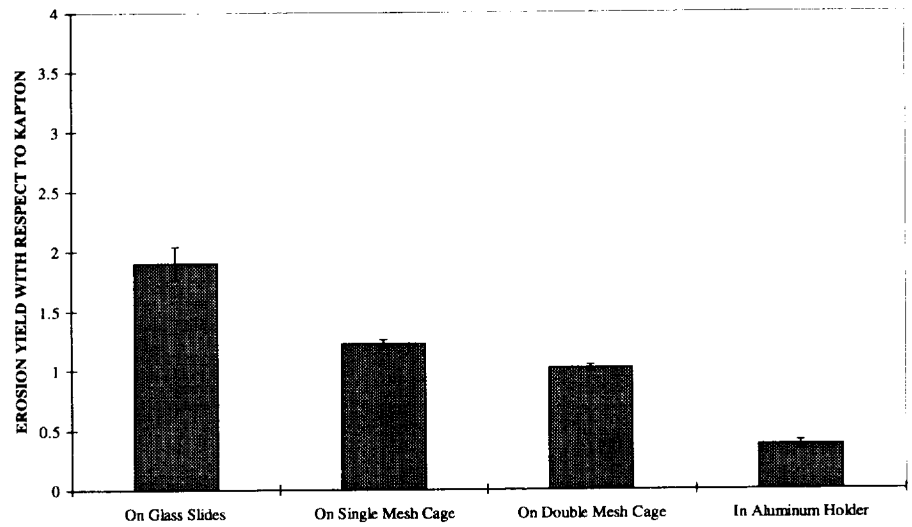

Figure 3. Comparison of relative erosion yields for FEP Teflon Exposed In Plasma

Table I. Data From Plasma Asher Exposures

Description	Material	Time (hrs)	Effective Atomic Oxygen Flux (atoms/cm^2-sec)	Erosion Yield With Respect to Kapton
1118 In plasma on glass	**Kapton**	**7.98**	**7.43E15 ± 7.37e14**	**1.0**
1118 In plasma on glass	**FEP**	**7.98**	**7.43E15 ± 7.37e14**	**2.0065 ± 0.28**
1120 In plasma on glass	**Kapton**	**9.18**	**6.5E15 ± 6.485E14**	**1.0**
1120 In plasma on glass	**FEP**	**9.18**	**6.5E15 ± 6.485E14**	**1.968 ± 0.278**
406 In plasma on glass	**Kapton**	**4.67**	**5.11E15 ± 1.13E14**	**1.0**
406 In plasma on glass	**FEP**	**4.67**	**5.11E15 ± 1.13E14**	**1.6898 ± 0.050**
409 In plasma on glass	**Kapton**	**5**	**5.14E15 ± 5.13E14**	**1.0**
409 In plasma on glass	**FEP**	**5**	**5.14E15 ± 5.13E14**	**1.93 ± 0.271**
402 In plasma on aluminum holder	**Kapton**	**5.633**	**1.406E16 ± 5.037E14**	**1.0**
402 In plasma on aluminum holder	**FEP**	**5.633**	**1.406E16 ± 5.037E14**	**0.3742 ± 0.03575**

Description	Material	Time (hrs)	Effective Atomic Oxygen Flux (atoms/cm^2-sec)	Erosion Yield With Respect to Kapton
415 In plasma on top of double mesh cage	**Kapton**	**42.1**	**4.366E15 ± 8.66E13**	**1.0**
415 In plasma on top of double mesh cage	**FEP**	**42.1**	**4.366E15 ± 8.66E13**	**1.015 ± 0.0284**
410 In plasma on top of single mesh cage	**Kapton**	**5.05**	**4.86E15 ± 1.07E14**	**1.0**
410 In plasma on top of single mesh cage	**FEP**	**5.05**	**4.86E15 ± 1.07E14**	**1.223 ± 0.037**
410 In single mesh windowed cage	**Kapton**	**5.05**	**4.72E15 ± 1.856E14**	**1.0**
410 In single mesh windowed cage	**FEP (Under Mesh)**	**5.05**	**4.72E15 ± 1.856E14**	**3.53 ± 0.1857**
410 In single mesh windowed cage	**FEP (Shielded)**	**5.05**	**4.72E15 ± 1.856E14**	**0.0204 ± 0.0167**
415 In double mesh windowed cage	**Kapton**	**42.1**	**4.666E15 ± 1.64E14**	**1.0**
415 In double mesh windowed cage	**FEP (Under Mesh)**	**42.1**	**4.666E15 ± 1.64E14**	**0.117 ± 0.00596**
415 In double mesh windowed cage	**FEP (Shielded)**	**42.1**	**4.666E15 ± 1.64E14**	**0.0321 ± 0.0027**
130 Closed Cage with One MgF2 Window	**Kapton (shielded)**	**24.3**	**4.07E15 ± 4.03E14**	**1.0**
130 Closed Cage with One MgF2 Window	**FEP (under window)**	**24.3**	**4.07E15 ± 4.03E14**	**0.103 ± 0.0143**
130 Closed Cage with One MgF2 Window	**FEP (shielded)**	**24.3**	**4.07E15 ± 4.03E14**	**0.091 ± 0.0127**
331 Closed Cage with MgF2 Window	**Kapton (under window)**	**24.017**	**8.75E15 ± 3.08E14**	**0.9432 ± 0.047**
331 Closed Cage with MgF2 Window	**Kapton**	**24.017**	**8.75E15 ± 3.08E14**	**1.0**
401 Closed Cage with MgF2 Window	**Kapton**	**24.8**	**1.48E16 ± 5.19E14**	**1.0**
401 Closed Cage with MgF2 Window	**FEP (Under window)**	**24.8**	**1.48E16 ± 5.19E14**	**0.0325 ± 0.0018**

Description	Material	Time (hrs)	Effective Atomic Oxygen Flux (atoms/cm^2-sec)	Erosion Yield With Respect to Kapton
401 Closed Cage with MgF2 Window	**FEP (Shielded)**	**24.8**	**1.48E16 ± 5.19E14**	**0.0217 ± 0.0011**
406 Closed Cage with MgF2 Window	**Kapton**	**48.967**	**1.283E16 ± 4.5E14**	**1.0**
406 Closed Cage with MgF2 Window	**FEP (Under window)**	**48.967**	**1.283E16 ± 4.5E14**	**0.0327 ± 0.00163**
406 Closed Cage with MgF2 Window	**FEP (Shielded)**	**48.967**	**1.283E16 ± 4.5E14**	**0.0085 ± 0.00118**
522 Closed Faraday cage	**Kapton**	**47.88**	**4.77E15 ± 4.71E14**	**1.0**
522 Closed Faraday cage	**FEP**	**47.88**	**4.77E15 ± 4.71E14**	**0.0374 ± 0.0062**
530 Closed Faraday cage	**Kapton**	**5.4**	**6.85E15 ± 6.8E14**	**1.0**
530 Closed Faraday cage	**FEP**	**5.4**	**6.85E15 ± 6.8E14**	**0.195 ± 0.0422**
609 Closed Faraday cage	**Kapton**	**5.08**	**6.64E15 ± 6.86E14**	**1.0**
609 Closed Faraday cage	**FEP**	**5.08**	**6.64E15 ± 6.86E14**	**0.15 ± 0.028**
1231A Closed cage with MgF2 window	**Kapton (under window)**	**5**	**2.55E15 ± 2.56E14**	**1.0**
1231A Closed cage with MgF2 window	**Kapton (shielded)**	**5**	**2.55E15 ± 2.56E14**	**0.982 ± 0.139**
1231B Closed cage with MgF2 window	**Kapton (under window)**	**27.033**	**3.09E15 ± 3.05E14**	**1.0**
1231B Closed cage with MgF2 window	**Kapton (shielded)**	**27.033**	**3.09E15 ± 3.05E14**	**0.814 ± 0.114**

4.2 EXPOSURE INSIDE A CLOSED FARADAY CAGE

The closed Faraday cage was used in an attempt to prevent VUV radiation from reaching the surface of the samples by allowing no line-of-sight viewing of the samples to the plasma. It was also designed to prevent charged species from entering by allowing the box to float to plasma potential. Several tests at a variety of fluence levels were conducted with FEP Teflon inside the Faraday cage. Results varied but the erosion yield for FEP Teflon relative to Kapton was less than 0.2 in all cases as shown in Figure 4. It was noticed that the relative erosion yield seemed to decrease with increasing fluence. The data plotted as a function of effective fluence is shown in Figure 5. The relative erosion yield does appear to take on an almost exponential decay

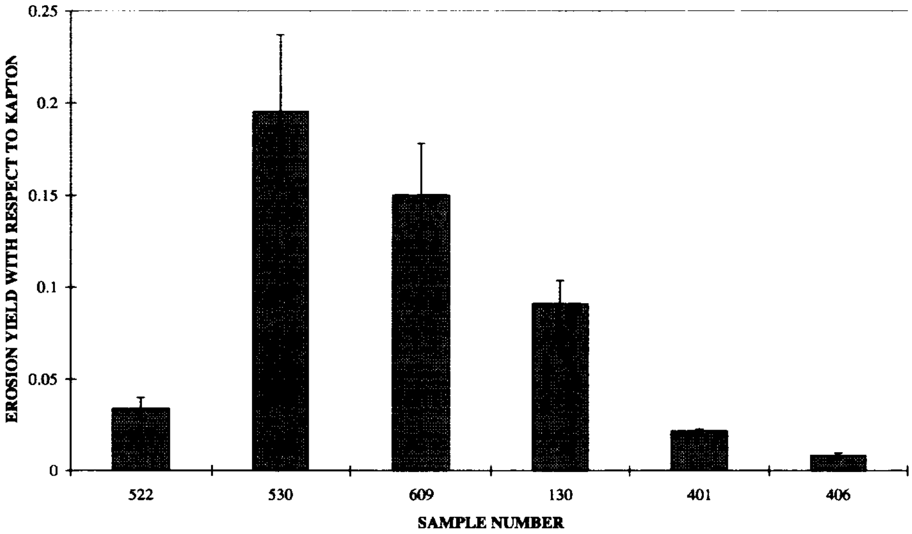

Figure 4. Comparison of relative erosion yields for FEP Teflon inside a closed Faraday cage

with increasing fluence. It is not known why this would occur in an isotropic plasma. More testing and data are needed to verify this trend.

Another puzzling feature noticed during these tests is that the effective flux inside and outside of the Faraday cage is approximately the same. One would expect the flux inside the Faraday cage to be greatly reduced because atoms would need to scatter in through slots underneath the lid in order to enter the box. However, this does not appear to be the case. It is possible that the RF field is exciting a plasma inside the box, but no glow was observed inside during testing. The greatly reduced relative erosion yield for FEP Teflon also does not support this theory. The relative erosion yield measured inside the Faraday cage is near that observed in space on the Long Duration Exposure Facility (LDEF) (0.11 ± 0.002) [10].

4.3 EXPOSURE INSIDE FARADAY CAGE WITH MAGNESIUM FLUORIDE WINDOW

Because it is difficult to draw conclusions from samples experiencing different fields and fluxes, a Faraday cage was developed which could expose two samples inside the same Faraday cage environment, but allow only one of them to have line of sight to the plasma. This was accomplished by putting a magnesium fluoride window in the lid towards one end of the Faraday cage box. Initially, polyimide Kapton HN erosion was

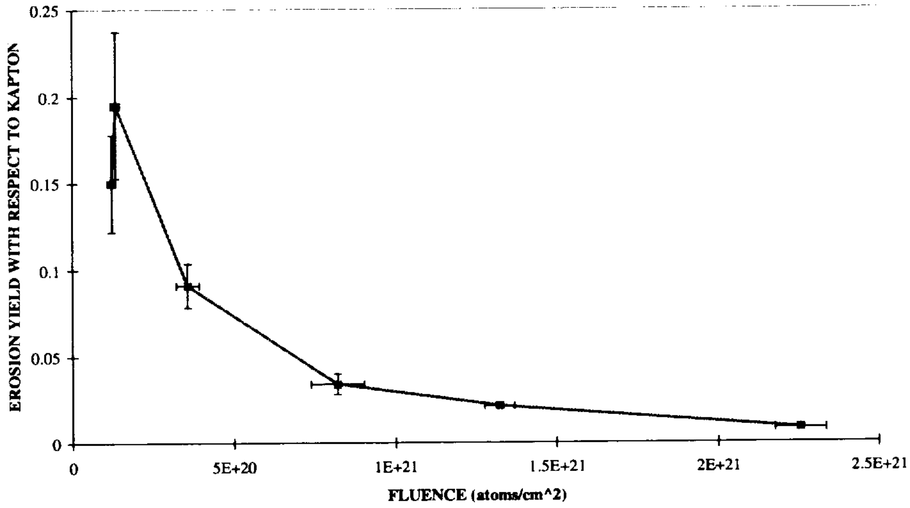

Figure 5. FEP Teflon relative erosion yield as a function of effective atomic oxygen fluence inside a closed Faraday cage

compared in order to verify that the window seal did not let additional plasma into the box. The results shown in Figure 6 verify that the polyimide Kapton HN is not affected by VUV radiation and that the seal functions as expected, because the erosion rates both under the window and shielded from the plasma are nearly identical and within experimental error.

The relative erosion yield of FEP Teflon was tested in a similar manner, but a sample of polyimide Kapton was placed between the two FEP Teflon samples so that the exposure flux could be measured. Figure 7 contains the data for the FEP Teflon. The effect of VUV radiation transmitted by magnesium fluoride appears to be very low. There may be a slight increase in relative erosion yield with VUV radiation, but not enough to account for the nearly order of magnitude difference observed when exposed directly in the plasma.

4.4 EXPOSURE INSIDE FARADAY CAGE WITH GOLD MESH SCREEN FILTER

In order to determine if shorter wavelength VUV radiation plays a role, it was necessary to block charged species from entering the box but allow all wavelengths of radiation to enter. A single gold mesh screen was installed in the Faraday cage replacing the magnesium fluoride window used in the previous test. FEP Teflon and polyimide Kapton HN were tested in the same manner as previously. During exposure,

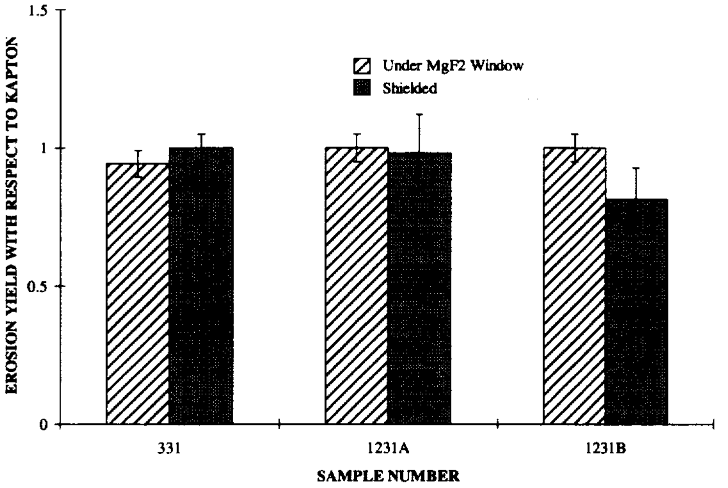

Figure 6. Comparison of relative erosion yields for Kapton HN exposed in a Faraday cage with and without VUV radiation

a directed plasma beam was observed that was approximately 1 cm in length extending perpendicular to the mesh, centered on it and extending down through it. The erosion yield of the FEP relative to Kapton in the shielded area of the box was roughly the same as in the closed Faraday cage test. The relative erosion yield for the sample under the mesh, however, was 3.53 ± 0.186. This is much higher than what was observed when the sample was sitting directly in the plasma. It appears that the mesh screen may have been acting like an electrostatic accelerator grid increasing the flux of charged species into the box.

Because it was still not possible to determine if other wavelengths of VUV radiation played a role, a double mesh was developed and installed in place of the single mesh making sure that it was electrically connected to the box to provide an equipotential gap to reduce the flux of charged species entering. The relative erosion yield was then observed to drop for the sample underneath the double mesh in the Faraday cage to approximately 0.12 ± 0.006. This value is near that observed inside the closed Faraday cage and is similar to that observed in space.

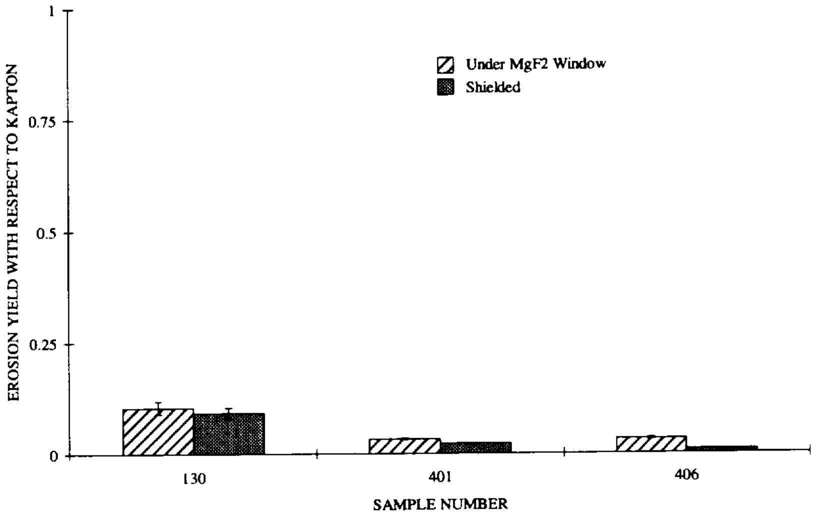

Figure 7. FEP Teflon exposed inside a Faraday cage with and without VUV radiation

4.5 TESTING SUMMARY

Figure 8 contains a comparison chart of samples tested in the plasma asher under various conditions as compared to the value measured in space. It appears that placing FEP Teflon inside a Faraday cage will yield results very close to those observed in low Earth orbit. It does not appear to matter whether VUV radiation can enter the Faraday cage, only if charged species can enter. The greatly reduced erosion yield for FEP Teflon samples sitting on a conductive plate but directly inside the plasma also indicates that charged species may play a role. It is very difficult to isolate the effects of charged species inside of an RF field. In order to draw more firm conclusions about what is causing the differences in erosion yields, tests will need to be conducted in a facility where the sample region is not inside the RF field such as in a directed beam facility.

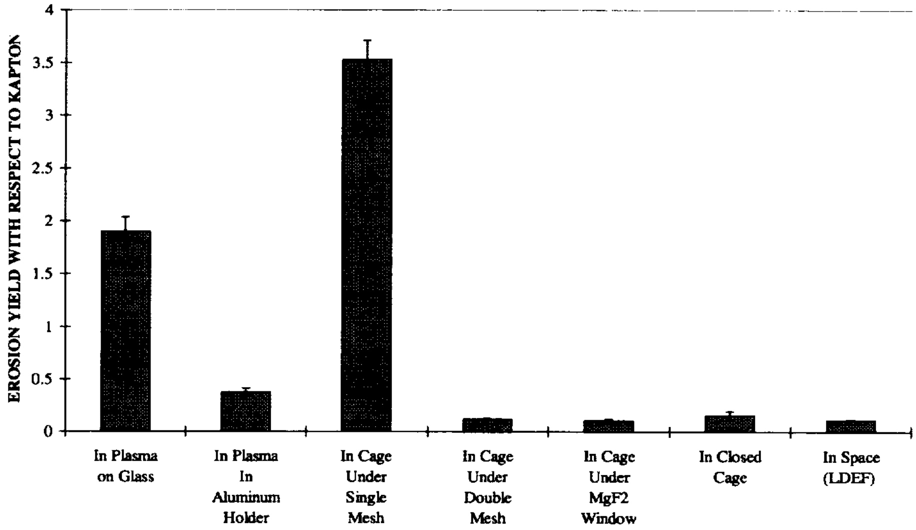

Figure 8. Comparison of FEP Teflon relative erosion yields

5.0 CONCLUSIONS

These tests have shown that the accelerated erosion can be reduced by exposing the samples on a conductive plate or inside a Faraday cage whether or not the samples are exposed to the VUV radiation from the plasma. This may provide a means for testing of samples such as FEP Teflon in plasma environments which more closely mimics the erosion observed in LEO. More work needs to be done to determine if electrons, ions, or some effect of the RF field is causing the accelerated erosion of FEP Teflon in plasma asher facilities.

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11. SUPPLEMENTARY NOTES

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13. ABSTRACT ***(Maximum 200 words)***

Fluorinated Ethylene Propylene (FEP) Teflon is widely used as a thermal control material for spacecraft, however, it is susceptible to erosion, cracking, and subsequent mechanical failure in low Earth orbit. One of the difficulties in determining whether FEP Teflon will survive during a mission is the wide disparity of erosion rates observed for this material in space and in ground based facilities. Each environment contains different levels of atomic oxygen, ions, and vacuum ultraviolet (VUV) radiation in addition to parameters such as the energy of the arriving species and temperature. These variations make it difficult to determine what is causing the observed differences in erosion rates. This paper attempts to narrow down which factors affect the erosion rate of FEP Teflon through attempting to change only one environmental constituent at a time. This was attempted through the use of a single simulation facility (plasma asher) environment with a variety of Faraday cages and VUV transparent windows. Isolating one factor inside of a radio frequency (RF) plasma proved to be very difficult. Two observations could be made. First, it appears that the erosion yield of FEP Teflon with respect to that of polyimide Kapton is not greatly affected by the presence or lack of VUV radiation present in the RF plasma and the relative erosion yield for the FEP Teflon may decrease with increasing fluence. Second, shielding from charged particles appears to lower the relative erosion yield of the FEP to approximately that observed in space, however it is difficult to determine for sure whether ions, electrons, or some other components are causing the enhanced erosion.

14. SUBJECT TERMS

FEP; Teflon; Atomic oxygen; Low Earth Orbit; Plasma asher

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