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Bruce A. Banks, Sharon K. Rutledge, and Kim K. de Groh
*National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio*

Curtis R. Stidham
*Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio*

Linda Gebauer and Cynthia M. LaMoreaux
*Cleveland State University
Cleveland, Ohio*

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Bruce A. Banks, Sharon K. Rutledge, and Kim K. de Groh
NASA Lewis Research Center
Cleveland, Ohio

Curtis R. Stidham
Sverdrup Technology, Inc.
Brook Park, Ohio

Linda Gebauer and Cynthia M. LaMoreaux
Cleveland State University
Cleveland, Ohio

Abstract

The durability evaluation of protected polymers intended for use in low Earth orbit (LEO) has necessitated the use of large-area, high-fluence, atomic oxygen exposure systems. Two thermal energy atomic oxygen exposure systems which are frequently used for such evaluations are radio frequency (RF) plasma ashers and electron cyclotron resonance plasma sources. Plasma source testing practices such as sample preparation, effective fluence prediction, atomic oxygen flux determination, erosion measurement, operational considerations, and erosion yield measurements are presented. Issues which influence the prediction of in-space durability based on ground laboratory thermal energy plasma system testing are also addressed.

Introduction

Atomic oxygen in LEO can rapidly cause oxidation of organic materials which have been typically used for spacecraft construction (ref. 1). Atomic oxygen protective coatings have been developed for purposes of increasing the durability of oxidizable materials needed for the construction of LEO spacecraft (ref. 2). Evaluation of the durability of protected polymers intended for LEO application can be accomplished by in-space testing on spacecraft such as the Long Duration Exposure Facility (LDEF), or by means of ground laboratory atomic oxygen exposure facilities (refs. 3-4). Although in-space durability evaluations can produce accurate indications of in-space durability of protected polymers such as those being considered for the construction of Space Station Freedom, differences between the fixed orientation of investigatory spacecraft, such as the Long Duration Exposure Facility (LDEF), and functional spacecraft, which frequently have sweeping atomic oxygen arrival, can result in uncertainty concerning accurate prediction of materials performance in the functional spacecraft environment. Ground laboratory simulation tests can be accomplished by energetic directed atomic oxygen systems that simulate the 4.5 eV atomic oxygen arrival on spacecraft surfaces, or by thermal energy plasma systems that allow less than 1 eV atomic oxygen arrival (refs. 5-6). Although energetic directed atomic oxygen beam systems hold potential to more accurately simulate the mechanisms involved with LEO atomic oxygen attack, the practicality of using such systems has been frequently limited due to the expense associated with producing homogenous, large-area, high-fluence exposures. Low energy RF plasma and electron cyclotron resonance microwave plasmas have routinely been used to inexpensively evaluate the durability of protective materials intended for LEO application. The use of such low energy plasma systems does require care with respect to the operational practices and interpretation of results in order to obtain reliable predictions of in-space durability based on results of ground laboratory testing. The recommended operational practices for thermal energy plasma testing and considerations pertinent to in-space projection of durability for protected polymers is the subject of this paper.

Apparatus

Plasma Ashers

Radio frequency plasma ashers using a 13.56 MHz capacitively-coupled air or oxygen plasma have been used to generate high flux atomic oxygen in the laboratory. Figure 1 shows a photograph of a typical RF plasma asher system. Plasma ashers operated on air provide exposure to oxygen and nitrogen atoms, molecules, and excited species at pressures of 70-120 m torr, producing an oxygen-dominated reaction with polymer surfaces which is equivalent to an effective flux on the order of 10^{15} atoms/(cm²-sec), based on erosion of polyimide Kapton H. Such effective fluxes produce erosion of unprotected Kapton exceeding that which would occur in LEO at 400 kilometers by an order of magnitude. The presence of nitrogen in such systems has been shown to have a negligible effect on the erosion processes of polymers (ref. 7). Samples exposed in RF plasma ashers are subjected to isotropic arrival of the plasma species. This typically results in minor roughening of the surface of protected materials. Although the surface is irregular, isotropic atomic oxygen arrival does not produce the high-aspect-ratio microscopic cones that are witnessed on all materials which have volatile oxidation products after exposure to directed ram atomic oxygen in space. Plasma ashers also produce intense 130 nm radiation, which may affect the erosion rate of some materials (ref. 6).

Electron Cyclotron Resonance Oxygen Sources

Atomic oxygen produced by electron cyclotron resonance plasmas from 2.45 GHz excitation can produce broad area directed or scattered isotropic atomic oxygen

arrival. Figure 2 shows the NASA Lewis Research Center electron cyclotron resonance oxygen facility, configured in a mode of operation which allows an expanding atomic oxygen beam to be scattered off of fused silica surfaces to produce isotropic arrival of thermal energy (~ 0.04 eV) atomic oxygen. The samples exposed to atomic oxygen are located below a triangle of fused silica, which also has an aluminum foil strip within it. This triangle blocks the direct arrival of atomic oxygen and ionic oxygen, as well as the intense 130 nm radiation produced by the oxygen plasma, from arriving on the test sample surfaces. As can be seen in figure 2, the samples can also be exposed to controlled vacuum UV radiation by means of deuterium lamps located above and to either side of the 130 nm radiation blocking glass prism. Atomic oxygen can also scatter off the outer glass enclosure, thus reducing the population of ions and excited state species. Based on biased planar probe measurements in the sample plane, the fractional oxygen ion content is thought to be on the order of 10^{-3} to 10^{-4} . If one removes the glass fixturing, then directed thermal atomic oxygen arrival occurs, which produces conical surface microstructures identical to that observed in space. The directed beam has a fractional ion content with twice the ion current density as the scattered isotropic arrival configuration. The average oxygen ion energy is 13 eV. The 1000-watt microwave discharge uses an oxygen input flow of 35-50 standard cubic centimeters per minute. The facility pressure during source operation is maintained at 6×10^{-4} torr by means of a 10", 6100-liters-per-second diffusion pump, and a 115-liters-per-second blower, followed by a roughing pump, all operated with perfluorinated ether (Fomblin) oil.

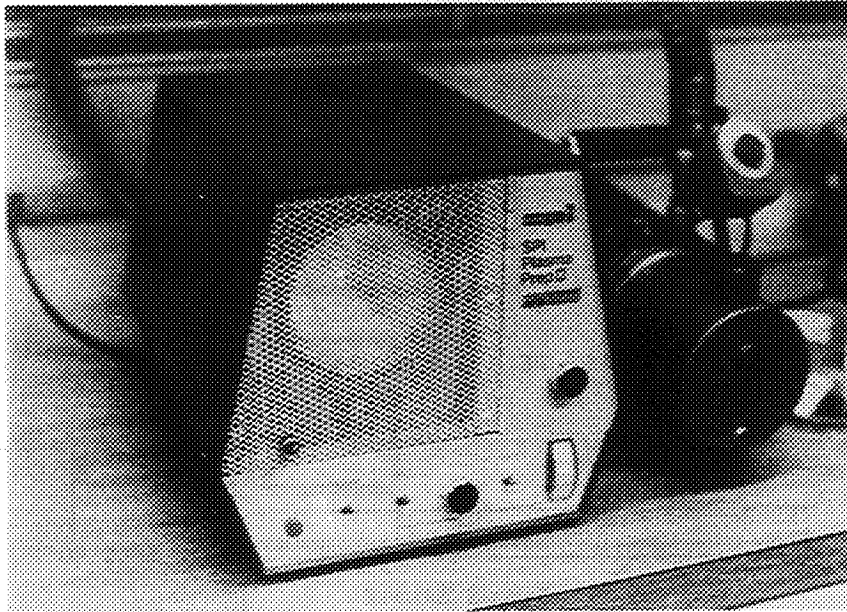


Figure 1 - RF plasma asher.

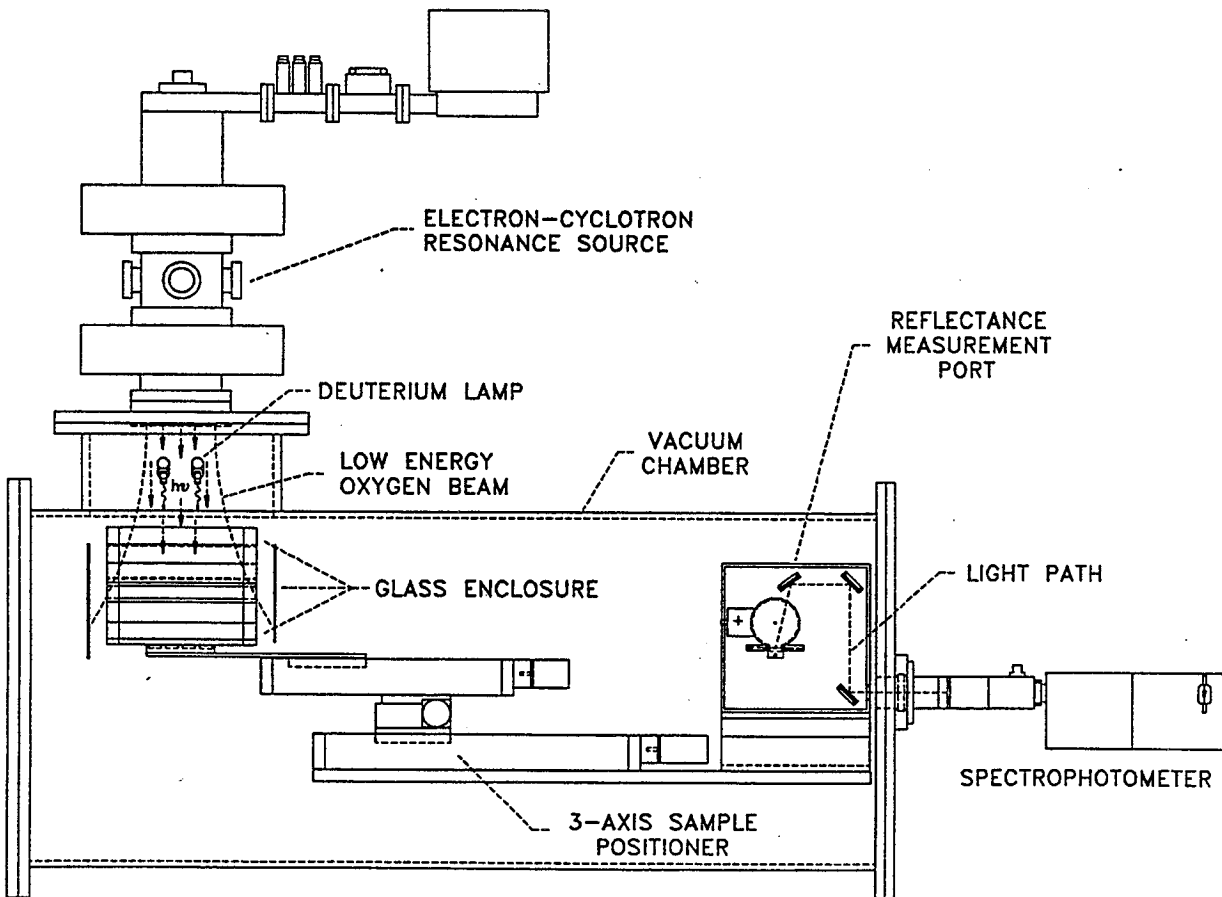
Plasma Source Operational Practices

The previously described thermal energy plasma systems can be highly effective in evaluating the durability of protected polymers, providing that care is taken in the preparation, operation, and measurement of the samples placed within these facilities for evaluation. This section describes the techniques which have been found most reliable in obtaining useful information from such facilities.

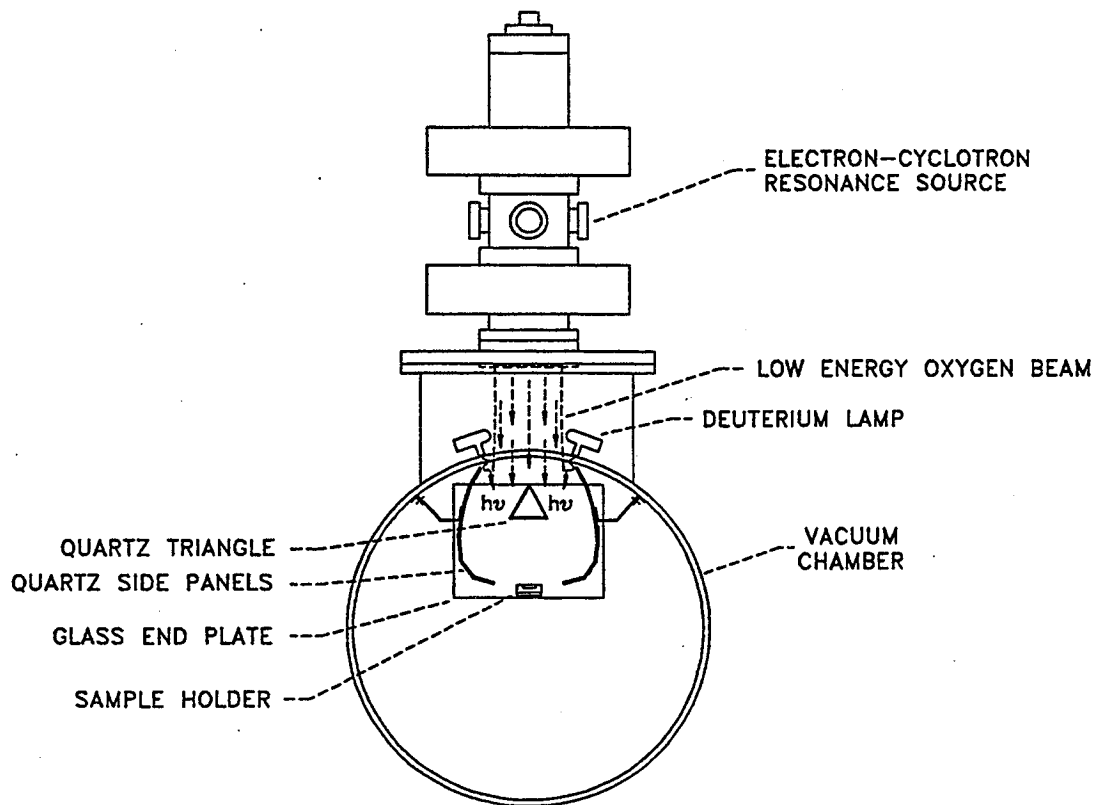
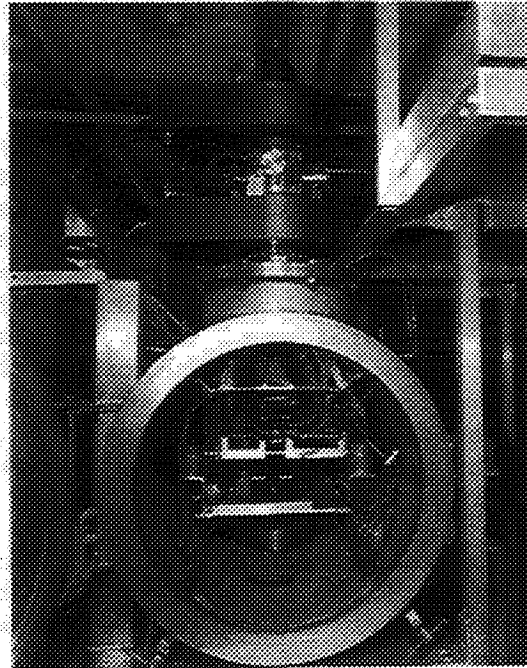
Sample Preparation

Cleaning

The samples to be evaluated for atomic oxygen durability should be chemically representative of materials which would be used in space. Thus, the surface chemistry of the samples should not be altered by exposure to chemicals or cleaning solutions which would not be representatively used on the functional materials to be used in space. Wiping samples or washing them may significantly alter surface chemistry and atomic oxygen protection characteristics of materials, and is therefore not recommended. However, if the typical use in space will require solvent cleaning, then such cleaning should be performed to simulate actual surface conditions expected.



2a - Side view schematic.



2b - End view photo and schematic.

Figure 2 - Electron cyclotron resonance atomic oxygen source.

Exposure Area Control

Masking. Frequently it is desirable to limit the exposure of atomic oxygen to one side of a material or a limited area on one side of the material. This can be done by wrapping a metal foil around the sample such as aluminum foil, or by placing a glass slide against one surface of the sample. If a metal foil is used to prevent atomic oxygen interaction on a portion of the sample, it is recommended that the foil be in intimate contact with the material to prevent partial exposure of the masked areas. Metal foil masking for exposure area control is acceptable for plasma systems in which the RF excitation region is separate from the sample exposure region. This minimizes electromagnetic interactions of the metal foil with the plasma that may cause sample heating and anomalous atomic oxygen fluxes to occur locally. Thus, metal foils are recommended for flowing afterglow and blow-by plasma configurations, and not recommended for use within the central RF discharge of a conventional plasma asher. The use of glass microsheet or slides to control the exposure area of samples must be limited to situations in which the samples are in intimate contact with the glass. This prevents excitation of any space which could occur between the sample and the glass, and provides assurance that areas which are to be protected, in fact have no atomic oxygen exposure.

Cladding. Samples which are coated with protective coatings on one side can be clad together by means of adhesives to allow the protective coating to be exposed on both sides of the sample. The use of thin polyester adhesives (or other non-silicones) is recommended to perform such cladding. The use of silicone adhesives should be avoided because of potential silicone contamination of the sample. Although cladding allows samples to be tested with the protective coatings on both faces, edge exposure of the samples and their adhesives does occur, and should be accounted for in calculating erosion characteristics of the desired surfaces.

Dehydration

Because most non-metals and non-ceramic materials contain significant fractional quantities of water, it is recommended that dehydrated thin polymer film samples be used to minimize confusion between oxidation and dehydration. Samples of a thickness less than 0.127 mm (0.005") should be dehydrated in a vacuum of a pressure less than 200 torr for a duration of at least 48 hours prior to sample weighing to ensure that the samples retain negligible absorbed water. Thicker samples should be dehydrated and weighed periodically until weight loss indicates that no further water is being lost. Multiple samples can be dehydrated in the same vacuum chamber, provided they do not cross contaminate each other, and that they are not of sufficient quantity so as to inhibit uniform dehydration of all the samples.

Weighing

Because hydration occurs quickly after removal of samples from vacuum, weighing the samples should occur within five minutes of removal from vacuum dehydration chambers or plasma ashers. Reduction of uncertainty associated with moisture uptake can be minimized by weighing the samples at measured intervals following removal from vacuum and back-extrapolating to the mass at time of removal from vacuum.

Handling

The atomic oxygen durability of materials with protective coatings may be significantly altered as a result of mechanical damage associated with handling. It is recommended that samples be handled in a manner which minimizes abrasion

and flexure. The use of soft, fluoropolymer tweezers is recommended for handling polymeric films with protective coatings.

Effective Fluence Prediction

Witness Samples

It is recommended that samples of witness coupons be exposed to atomic oxygen simultaneous with test samples to enable calculation of the effective atomic oxygen exposure. If protective coatings on Kapton are being evaluated, it is recommended that Kapton witness coupons be used to enable the calculation of the effective atomic oxygen fluence. The evaluation of protective coatings on any substrate material should be accompanied by evaluation of that material without protection, provided in-space data exists concerning the erosion yield of that substrate material. If in-space erosion yield data for the substrate material does not exist, then it is recommended that Kapton H or Kapton HN be used as a witness material to calculate effective fluence based on an assumed in-space atomic oxygen erosion yield of $3.0 \times 10^{-24} \text{ cm}^3/\text{atom}$. If high fluence exposure is necessary, polymeric sheets are usually too thin to survive long exposures. As a result, thick coupons of polyimide or graphite are suggested to be used for high fluence weight loss measurements. The atomic oxygen erosion yield of pyrolytic graphite relative to Kapton H is different in a plasma facility than in space. Unless both witness sample and test sample are of the same composition, and have known atomic oxygen erosion yields based on in-space testing, one should convert the mass loss of the pyrolytic graphite to the equivalent loss of polyimide Kapton H or HN. This can be accomplished by simultaneous plasma exposure of pyrolytic graphite and Kapton, and will enable the effective fluence to be calculated in terms of Kapton effective fluence, which is the accepted standard.

Test and Witness Sample Position and Orientation

Plasma facilities which have capacitively-coupled plasma excitation electrodes surrounding the sample test chamber usually have atomic oxygen axial and radial density gradients. In addition, the atomic oxygen flux on one side of the sample is usually different than that on the opposite side. Minimization of errors in effective atomic oxygen fluence will be achieved if witness samples are placed as close as possible to the same axial and radial locations as the test sample. The use of witness samples of the same size and shape as the test samples is also recommended. If similarity of position and orientation cannot be achieved, it is recommended that axial, radial, and orientation erosion rate characterization of the plasma chamber be performed to allow prediction of the atomic oxygen fluence at the site of the witness coupon.

Inspection Validation of Witness Sample Erosion

Kapton witness samples should be visibly inspected and compared with previously exposed witness samples which have demonstrated acceptable performance to validate that contamination of the surface of the sample has not occurred. Contamination can look like oil spots on the surface, a protective thin film, or other optical deviation from a normally diffusely reflecting exposed surface. The effective flux for the witness sample should also be compared with that from tests previously known to be acceptable, such as those performed in the same facility, to assure that neither contamination nor anomalous operation has occurred.

Witness Sample Weighing

Witness samples should be weighed within five minutes of removal from the vacuum chamber. Only one sample should be removed at a time for weighing. The rest should remain under vacuum. When witness samples are of the same chemistry

as the substrate of the protected samples, it is important that both samples are weighed as close to the same interval of time after removal from vacuum. Accurate sample weight calculation, taking into account rehydration, can be achieved as described in the previously discussed section entitled "Weighing."

Atomic Oxygen Flux Determination

Relative effective fluences can be estimated from erosion of Kapton witness samples; however, measurement of absolute fluences is difficult because of scale factors associated with differences in erosion yields of thermal species in the plasma and in-space energetic species. The erosion yield, which is material-dependent, also appears to be substantially dependent upon oxygen atom energy. To assist in the prediction of in-space performance based on plasma testing, it is desirable to obtain both a direct measurement of the atomic oxygen fluence in the plasma facility, as well as an effective fluence for the exact material being tested by comparison with in-space performance. The use of pressure change measurements when the plasma is off, and then turned on, may allow an estimate of the atomic oxygen density in the plasma, provided correct assumptions are made with regard to the plasma temperature and the accommodation coefficient for the pressure sensing surfaces. Use of calorimetry to determine oxygen flux to a surface is an inexpensive and relatively simple method. However, the use of a thermocouple within the plasma causes excessive heating, leading to inaccurate temperature measurements. In addition, secondary reaction processes can occur on the calorimeter surface above certain temperatures. For these reasons, it is required that calorimetric probes be well-shielded from stray RF radiation, and be placed just outside the plasma.

Recession Measurement

Erosion yield measurements may be carried out by directly measuring the thickness of samples using cross-section photomicrographs. This method of determining erosion yield is independent of mass, as well as the density of the sample. A protected or shielded area must be available on each specimen during the actual exposure to establish an initial thickness or reference surface of the material. The area can be protected or shielded by a removable tape, a glass or metal solid shield, salt (NaCl) spray particles, or an electro-formed mesh held in intimate contact with a smooth test surface. The thickness loss is divided by the atomic oxygen effective fluence to obtain an erosion yield. This method avoids the uncertainties of mass loss due to outgassing and the need to determine exposure areas. Variations in the as-manufactured thickness are a potential source of uncertainty if a protected reference surface is not used. Uncertainty in the thickness measurement, as well as the magnification, must be considered in computing the overall uncertainty of the computed erosion yield. Recession measurements can be made by scanning electron microscopy or atomic force microscopy.

Plasma Facility and Operational Considerations

Contamination

Silicones present in an atomic oxygen plasma facility have been demonstrated to cause glassy films to deposit on witness coupons, as well as test coupons. Silicones may be present in the vacuum facility as a result of their presence in vacuum grease, vacuum seals, pump oil, or silicones in the samples themselves. Once silicones have been exposed to atomic oxygen, silicone contamination of the plasma chamber has probably occurred and removal of the source of the silicone contamination, such as a silicone sample, does not cause an immediate cessation of silicone contamination. It is therefore recommended that hydrocarbon-based vacuum greases and pump oils (when air is the source gas) or Fomblin (when oxygen is the source gas) be used in the plasma atomic oxygen facilities instead of

silicones. Petroleum jelly has been found to be acceptable for use as a vacuum grease for plasma ashers. It is further desirable that the exposed area of the rubber vacuum seals be minimized to reduce degradation of the seals themselves, and to minimize reaction products being introduced into the plasma chamber.

Pressure

Minimization of backstreaming of roughing pump oil can be achieved if plasma facilities are operated at a sufficiently high pressure. Operation at pressures which allow backstreaming of roughing pump oil can result in sample or witness sample contamination due to pump oil oxidation products being deposited in the plasma facility. Typically, pressures of >60 m torr have been found to be necessary in plasma ashers to prevent backstreaming of roughing pump oil.

Plasma Chamber Degassing

To minimize outgassing contributions of vacuum chamber adsorbed gasses and moisture from contributing to the plasma species, it is recommended that room temperature chambers be evacuated to a pressure of less than 150 m torr for at least 30 minutes prior to initiation of the plasma.

Plasma Density and Uniformity

The visual intensity of the plasma glow has been found to be a sensitive measure of atomic oxygen flux. The operation of RF plasma ashers at conditions which produce run-to-run temporal uniformity, as well as spatial uniformity, is therefore recommended.

Continuous Versus Incremental Ashing

Some types of protective coatings on organic substrates develop mechanical stresses at defect sites in protective coatings where atomic oxygen undercutting has occurred. Exposure to air or humidity can cause mechanical stresses at the defect sites sufficiently high enough to propagate a tear in the protective coating in the vicinity of the defect. Thus, periodic exposure to air may cause accelerated degradation at defect sites, thus producing pessimistic results, whereas continuous high fluence exposure may produce results which are more representative of in-space functional exposure.

Oxidation Product Interactions

Samples exposed to atomic oxygen may have oxidation products which themselves enhance the reaction rate with either the sample itself or the witness sample. Oxidation product interaction problems are most easily detected by comparing witness sample effective fluence predictions with previous tests operated under the same conditions with only the witness sample present.

Temperature

The temperature of samples tested in plasma atomic oxygen exposure facilities should be operated as close as possible to their actual in-space functional temperature. Polyimide Kapton witness samples should be operated as close as possible to room temperature since their erosion yield was based on in-space measurements near room temperature. The use of samples which contain metals may significantly elevate the temperature of the sample if placed within the cavity of a capacitively-coupled plasma chamber, and therefore may anomalously increase the oxidation rate.

Plasma Composition

Typically, plasma atomic oxygen exposure is performed in either pure oxygen or air plasmas. Although other composition plasmas may produce significantly higher reaction rates, the lack of validity of reliable extrapolation to in-space results suggests that only oxygen or air plasmas should be used. Mechanistic oxidation information can be obtained through the use of isotope-enriched O^{18} oxygen to allow discrimination of native O^{16} oxides from those produced by atomic oxygen. For most polymeric materials, air plasmas have been found to be acceptable for exposure, and produce similar results to oxygen plasmas. The vacuum ultraviolet radiation content in the plasma may result in increased degradation of UV-sensitive materials such as Teflon (ref. 6). The presence of excited states in the plasma may also contribute to the difference in erosion yields of some materials with respect to each other when exposed in the plasma compared to space. However, materials which are unreactive in space, are unreactive in plasmas, and very reactive materials in space are found to be also very reactive in plasmas.

Erosion Yield Measurement

Test Sample Weighing

Test samples should be weighed at the same time interval and state of dehydration as the witness coupons as described in the previous sections entitled "Weighing," and "Witness Sample Weighing."

Profilimetry

Sample oxidation characterized by recession measurement may be possible if the sample material has gaseous oxidation products, its surface is smooth, and masking for exposure area control is executed with the mask in intimate contact with the sample. Because most polymeric materials do not have highly smooth surfaces, it is recommended that profilimetry be performed at multiple locations, and that high fluences be used such that the profilimetry step is large compared to the surface roughness.

Erosion Yield Calculation

The erosion yield of a material can be calculated based on mass loss, and is typically given in units of cubic centimeters per incident oxygen atom. The erosion yield is given by:

$$E_s = \frac{\Delta M_s}{A_s \rho_s F} \quad (1)$$

where:

ΔM_s = mass loss of the sample, grams

A_s = surface area of sample exposed to plasma, cm^2

ρ_s = density of the sample, grams/ cm^3

F = fluence, atoms/ cm^2

Because the fluence is typically based on the effective fluence of a witness coupon, we have the erosion yield:

$$E_S = \frac{\Delta M_S A_W \rho_W E_W}{\Delta M_W A_S \rho_S} \quad (2)$$

where:

A_W = the area of the witness coupon, cm^2

ρ_W = the density of the witness coupon, $grams/cm^3$

E_W = in-space erosion yield of witness coupon, $cm^3/atom$

ΔM_W = mass loss of the witness coupon, $grams$

Protective Coating Performance

Protective coating effectiveness, P , is a measure of how well a protective coating prevents oxidation of an underlying polymer. Protective coating effectiveness, a unitless number, is given by:

$$P = 1 - \frac{\Delta M_C A_U}{\Delta M_U A_C} \quad (3)$$

where:

ΔM_C = mass loss of coated material, $grams$

ΔM_U = mass loss of uncoated material, $grams$

A_C = surface area of coated material, cm^2

A_U = surface area of uncoated material, cm^2

Thus, a perfect atomic oxygen protective coating would have a protective coating effectiveness of 1, whereas a non-coated substrate would have a protective coating effectiveness of 0.

Relative reactivity, R , a unitless number defined as:

$$R = \frac{\Delta M_C A_U}{A_C \Delta M_U} = 1 - P \quad (4)$$

is another measure of coating performance where $0 \leq R \leq 1$.

Projection of in-space durability of a protected polymer based on ground laboratory plasma ashing requires correction of mass loss data to take into account the very high absolute atomic oxygen flux in ashers, knowing that the effective flux in an asher is much lower than the absolute flux. This correction is needed because undercutting protective coatings, both in space and in plasma ashers, is strongly dependent upon oxidation by thermally accommodated atoms.

Projection of In-Space Durability Based on -Ground Laboratory Thermal Energy Plasma System Testing

The ability to predict in-space durability of protected polymers based on ground laboratory thermal energy plasma system testing is highly dependent upon the ability to quantifiably understand the reaction processes occurring in both space and the thermal energy plasma systems. Two parameters which greatly influence the outcome of such predictions are the probability of atomic oxygen reaction upon impact and the degree to which the atomic oxygen thermally accommodates upon impact. The reaction probability for energetic (approximately 4.5 eV) space ram atomic oxygen can be estimated by knowledge of the erosion yield of materials in space and assumptions concerning the oxidation product species. For example, for Kapton H polyimide, which has an in-space erosion yield of 3×10^{-24} cm³/atom, initial impact reaction probabilities range from 0.0114 to 0.161, depending upon the oxidation product species. If one assumes an average between the extremes of oxygen possible in the oxidation products, then an average of 0.138 is predicted for the initial impact reaction probability (ref. 8). The reaction probability for room temperature thermal energy (approximately 0.04 eV) is thought to be substantially below the more energetic in-space values. Table I lists predicted atomic oxygen reaction probabilities in various environments based on the findings of several investigators. In Table I the reaction probabilities for both room temperature, thermally accommodated, and in-plasma atomic oxygen were calculated on the basis of assuming an in-space reaction probability of 0.138, and then adopting the various investigators' models for reaction probability dependence upon energy or environment. As can be seen from Table I, there is a span of three orders of magnitude variation in predicted reaction probabilities for room temperature thermally accommodated atomic oxygen. The reason that the reaction probability for room temperature atomic oxygen in a plasma is thought to be approximately four times that of ground state thermally accommodated atomic oxygen, is the presence of excited state species such as O^{1D} oxygen. The factor of four increase in reaction probability was determined as a result of Monte Carlo computational modeling to replicate observed atomic oxygen undercutting profiles at defect sites in protective coatings on Kapton. Based on the reaction probabilities indicated in Table I, thermal energy plasma systems require significantly higher actual fluxes than in-space to produce the same rates of oxidation. The consequences of this are illustrated in figure 3. As illustrated in figure 3, ground laboratory plasma systems are operated at high actual flux levels because of the low reaction probability of the low energy atomic oxygen. Thermal energy oxygen plasma systems produce an effective fluence computed by how much actual fluence in space would be necessary to cause the same amount of surface recession based on the in-space erosion yield of the particular material. Because far more actual atoms are necessary to impact a surface to produce the same surface recession as would occur in space, atomic oxygen undercutting at defect sites progresses much more rapidly in thermal energy plasma systems than in space, where erosion below a defect site in a protected polymer is dominated by the initial impact reaction. Depending upon the probability of thermal accommodation upon impact in space, the mass loss per unit area per fluence in space for protected polymers is thought to be between 10^{-2} to 10^{-4} that measured in thermal energy plasma systems based on effective fluence (ref. 4). It is likely that upon more detailed analysis of LDEF and EOIM-III data, as well as future in-space experiments, a more well-defined quantification of the correlation between ground laboratory and in-space erosion of protected polymers will occur.

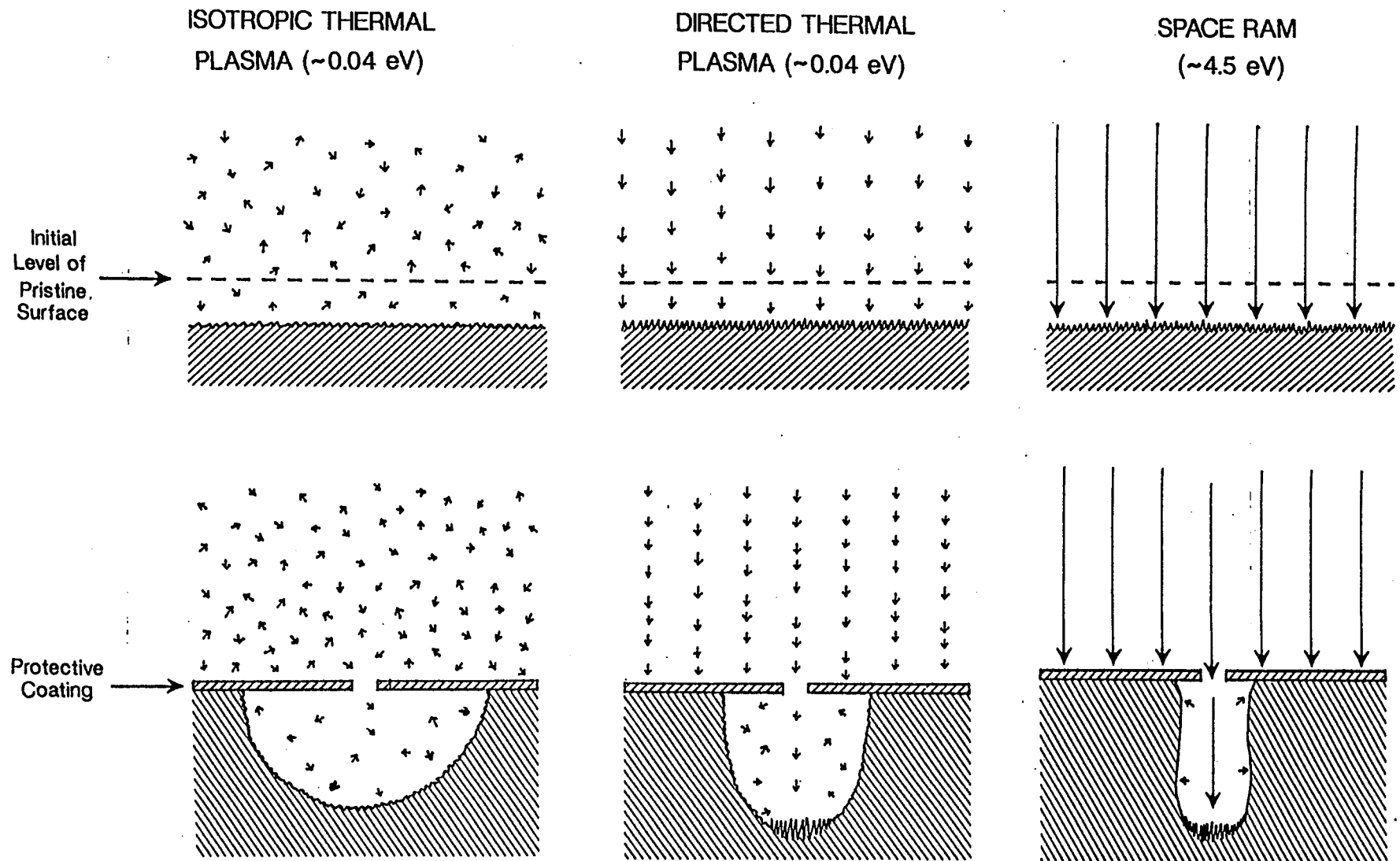


Figure 3 - Isotropic thermal plasma, directed thermal plasma, and space ram atomic oxygen interactions on uncoated polymers and at defect sites in protective coatings on polymers.

TABLE I. - ATOMIC OXYGEN REACTION PROBABILITY WITH POLYIMIDE KAPTON H

Environment	Energy, eV	Reaction Probability	Rationale for Prediction of Reaction Probability *	Ref
Space Ram (400 km, 996K, 28.5° inclination)	4.5 ± 0.8	0.138 ± 0.024	In-space erosion yield data and reaction product modeling	8
Room Temperature Thermally Accommodated (300K)	0.039	7.7 x 10 ⁻⁶	Reaction probability proportional to e ^{-0.38/E}	4,6
	0.039	1.0 x 10 ⁻⁵	Reaction probability proportional to E ²	9
	0.039	2.1 x 10 ⁻³	Monte Carlo modeling to match LDEF undercut profiles	10
	0.039	5.5 x 10 ⁻³	Reaction probability proportional to E ^{0.68}	11
Room Temperature Plasma (300K)	0.039	2.2 x 10 ⁻²	Monte Carlo modeling to match undercut profiles	4,10

* E = atomic oxygen kinetic energy, eV

Summary

Thermal energy plasma systems such as RF plasma ashers and electron cyclotron resonance atomic oxygen sources can be of great assistance in determining the effectiveness of atomic oxygen protective coatings. The validity of the comparative information resulting from the use of such facilities can be greatly enhanced through the use of operational and testing practices which have been demonstrated to yield meaningful results. The projection of in-space durability based on ground laboratory thermal energy plasma system testing is highly dependent upon the reaction probabilities for energetic and thermally accommodated atomic oxygen. Although quantification of such numbers apparently varies over two orders of magnitude, analysis of LDEF, EOIM-III, and future flight experiments will more clearly quantify the correlation between erosion rates of protected polymers in thermal energy plasma systems with that expected in space.

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13. ABSTRACT (Maximum 200 words) The durability evaluation of protected polymers intended for use in low Earth orbit (LEO) has necessitated the use of large-area, high-fluence, atomic oxygen exposure systems. Two thermal energy atomic oxygen exposure systems which are frequently used for such evaluations are radio frequency (RF) plasma ashers and electron cyclotron resonance plasma sources. Plasma source testing practices such as sample preparation, effective fluence prediction, atomic oxygen flux determination, erosion measurement, operational considerations, and erosion yield measurements are presented. Issues which influence the prediction of in-space durability based on ground laboratory thermal energy plasma system testing are also addressed.			
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