Engineering Notes

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Vacuum Ultraviolet Radiation/Atomic Oxygen Synergism in Materials Reactivity

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Introduction

THIS Note presents the results of recent laboratory investigations which demonstrate that low fluxes (0.5–4.0 vacuum ultraviolet suns) of vacuum ultraviolet radiation (VUV) have a pronounced effect on the atomic oxygen reactivity of certain spacecraft materials. Fluorinated ethylene-propylene (FEP) Teflon, polychloro-trifluoroethylene (PCTFE or Kel-F), and a silver-backed FEP Teflon being considered for use on Space Station Freedom were exposed to known isotropic fluxes of thermal energy (0.04 eV), ground-state (O^3P), oxygen atoms both with and without a coincident flux of VUV photons in the flowing afterglow apparatus. The photon energy was 10 eV, corresponding to the 123.6 nm resonance line of krypton. In addition, samples of FEP Teflon and PCTFE were exposed to known, directed-beam fluxes of high energy (1.5–3 eV), ground-state oxygen atoms and VUV radiation in the high-energy atom beam facility at Los Alamos National Laboratories. In both laboratory test environments, the reactivities of FEP Teflon, silver Teflon, and PCTFE were shown to be dramatically increased by simultaneous exposure to low fluxes of VUV radiation. The results are consistent with the existing spacecraft data base and indicate that the same photochemistry is likely to occur in the low-Earth orbit (LEO) environment.

Experimental

The flowing afterglow and high-energy atom-beam systems used in this study have been described previously.)[1,2] Oxygen atoms reaching the material test surface are in the electronic ground state. The apparatus layout of the afterglow system is shown in Fig. 1. In the flowing afterglow system, 10% oxygen in argon was used as the working gas at a system pressure of 2 Torr. Oxygen atoms were generated by means of a microwave discharge in the working gas located 35 cm upstream of the side-arm sample holder assembly as shown in Fig. 1. The discharge was generated by means of a Raytheon PGM-10 microwave power generator operated at 2450 MHz driving an Evenson-type cavity.[2] The forward power was 30 W and reflected power <2 W in all cases. All flow system glassware was washed in nitric and hydrofluoric acid and then thoroughly dried before use. A cold trap was maintained at $-50°C$ between the flow system and the rotary vane vacuum pump. The working gas-flow rate was set at 176 sccm with an MKS Instruments, Inc. type of 1259B flow controller.

In the afterglow, ground-state oxygen atom concentrations were measured by chemiluminescent titration with NO_2[3] using a titration inlet positioned at the sample holder position.

Film samples were exposed to a room temperature gas containing only ground-state oxygen atoms, oxygen molecules, and argon[2,3] using the side-arm sample holder assembly shown in Fig. 1. The side arms were configured as a four-way cross as shown in the cross section in Fig. 1. Sample disks were placed over the ends of the side-arm tubes. Three of the four side-arms held polymer film samples, and the fourth held a Scientific Services model 108 krypton resonance lamp[4] positioned so that the beam fell on the polymer film sample in the opposite side-arm. The two remaining side-arm tubes exposed a 1 mil Kapton reference film, and a control sample of the material undergoing VUV-atomic oxygen exposure to the afterglow gas only. A magnesium fluoride lamp window was exposed directly to the afterglow gas.

Polymer film samples were heated under vacuum for 48 h at 70°C prior to testing. Polymer film reactivity was determined by weighing the samples (in air) every 24 h using an electronic balance. Tests lasted 4–7 days. FEP Teflon was obtained from NASA Lewis Research Center as part of the "Oxygen Effects Round Robin" standard sample set. Silver Teflon was obtained from LTV Corporation in Dallas, Texas. Kel-F (3 mil film) was obtained from Afton Plastics Molding Company. Kapton H (1 mil film) was obtained from E. I. du Pont de Nemours, Inc. The samples were selected primarily to explore VUV/atomic oxygen synergisms in fluorocarbon materials.

The VUV flux at the sample surface was calculated by treating the model 108 as an optical point source positioned 0.63 cm behind the lamp window.[4] Lamp output power was varied by changing lamp operating current using approximate lamp calibration data from the vendor. At 0.2 mA, the model 108 produced about 0.5 VUV suns on the sample film; at 2.0 mA the sample flux was about 4 VUV suns (1 VUV sun in LEO is 0.75 $\mu W/cm^2$ for wavelengths between 150–100 nm).[5]

The high kinetic-energy, oxygen-atom beam system at Los Alamos National Laboratories has been described at length elsewhere. In the Los Alamos beam system, a 2 kW continuous wave CO_2 laser sustained a discharge in a high pressure (~ 40 psia) gas mixture. Supersonic expansion of the discharge gases results in a beam containing high velocity, ground-state oxygen atoms in addition to oxygen molecules

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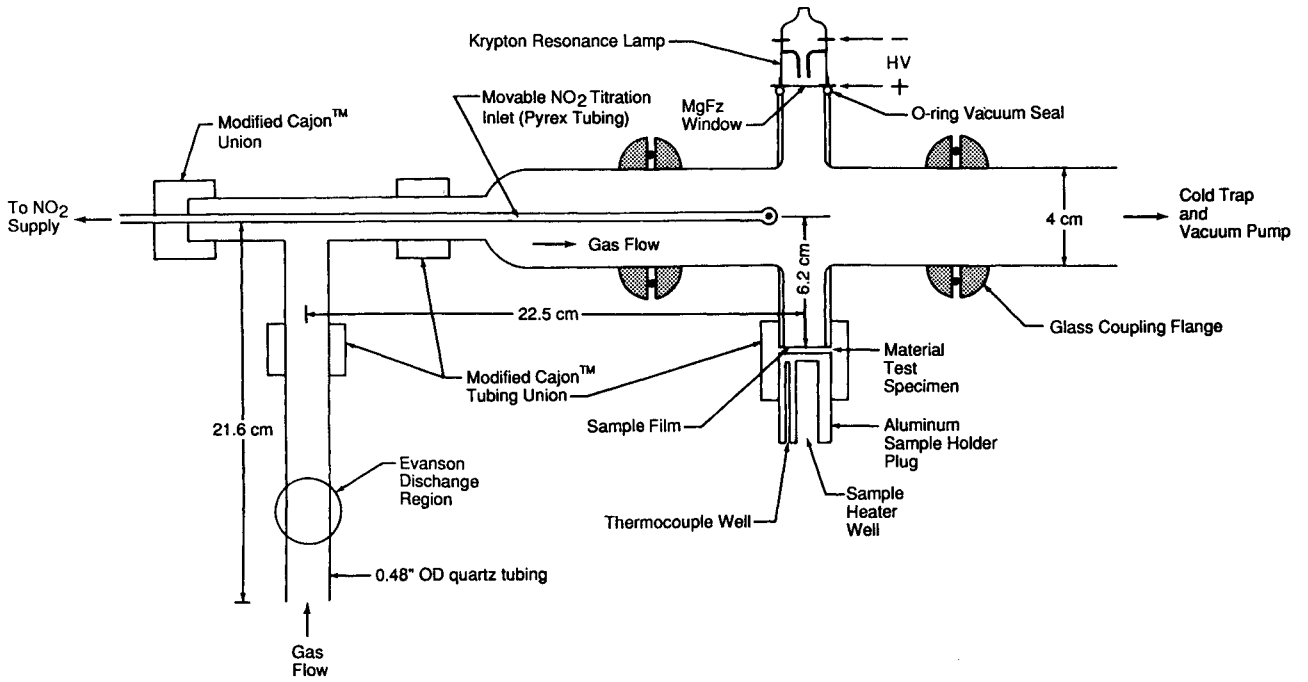

Fig. 1 The flowing afterglow apparatus.

and inert gas atoms. The available evidence indicates that the molecular oxygen does not affect reactivity measurements significantly.[1] Though the beam contained no charged particle or excited state species, it did contain a significant amount of VUV radiation originating in the laser sustained gas discharge. A vacuum ultraviolet monochromator was used to characterize the VUV content of the beam under various operating conditions. Both argon and neon were used as the inert expansion gases in the studies reported here. When argon was used, the oxygen atom flux at the sample was $8 \cdot 10^{15}$ atoms $\cdot$ $s^{-1} \cdot cm^{-2}$ with an atom-beam translational energy of 1.5 eV and a VUV photon flux equal to about 3 VUV suns. Neon gave an oxygen atom flux of $1.5 \cdot 10^{17}$ atoms $\cdot$ $^{-2}$ with an atom-beam translational energy of 3 eV and only 1 VUV sun at the sample. Background pressure in the target chamber was 2×10^{-6} Torr with the atom beam on in either case. We have no evidence to indicate that the argon or neon flux has any effect on the atomic oxygen reactivity measurement.[1]

Table 1 Flowing afterglow results; reaction rates of materials with thermal energy oxygen atoms, with and without VUV radiation

Material	Reaction rate,[a] 0 VUV suns	Reaction rate, 0.5 VUV suns	Reaction rate, 4 VUV suns
Kapton H	3±0.5E-3	—	4E-3
FEP Teflon	5±7E-5	1.3E-3	3E-3
Silver Teflon	6±7E-5	6E-4	3E-3
Kel-F	2±4E-4	2E-4	1E-3

[a]Reaction rates in mg/(cm^2 · h)

All polymer film samples exposed to the high-energy beam at Los Alamos were bonded to aluminum sample supports (1 cm · 1 cm · 0.08 cm). Care was taken not to contaminate the exposed surface of the polymer film. The aluminum sample supports provided good thermal contact between the sample film and sample holder/heat sink. Sample temperature during exposure to the high-energy atom beam was 40°C. Sample reactivity was measured as surface recession using a Tencor Instruments Alpha-Step 200 surface profilometer.

Results and Discussion

The mass loss rate of FEP Teflon exposed to thermal oxygen atoms in the flowing afterglow apparatus showed a strong dependence on VUV flux. The control sample, exposed to atomic oxygen but not exposed to VUV radiation, showed a mass loss rate not significantly different from zero and remained clear. When exposed to VUV radiation and atomic oxygen in the flowing afterglow, FEP Teflon films slowly became cloudy and lost mass at a rate comparable to that of the Kapton H reference specimen. The results are summarized in Table 1. It should be noted that the reaction rate of the specimen exposed to VUV and atomic oxygen dropped to zero when the resonance lamp was turned off. Mass loss resumed when the lamp was started again. VUV without atomic oxygen produced no mass loss, but the sample film slowly became cloudy.

FEP Teflon showed a lower reaction efficiency (cm^3 of material removed per atom) than Kapton H in both the argon-oxygen and neon-oxygen beams at Los Alamos. Results are summarized in Table 2. The Los Alamos reaction efficiency (Teflon) is still significantly higher than that observed during

Table 2 Reaction efficiency of various materials with atomic oxygen in the high-energy neutral atom beam at Los Alamos National Laboratories and in LEO

Material	RE[a], LANL beam Ar/O_2	RE[a], LANL beam Ne/O_2	RE, STS-8	RE, Solar Max
Kapton H	2.0	2.7	3	3
FEP Teflon	0.8	0.7	<0.05	—
Silver Teflon	—	—	—	1
Kel-F	3.0	0.5	—	—

[a]RE = Reaction efficiency in units of 10^{-24} cm^3/atom.

the STS-8 and STS-5 atomic oxygen effects flight experiments[7] where the VUV dose was low as a result of maintaining the materials samples in ram orientation during exposure on orbit. The FEP Teflon reaction efficiency estimated from the Solar Max satellite repair mission samples[8] is comparable to the Los Alamos result. The Solar Max satellite exposed silver-backed Teflon components to relatively high doses of VUV radiation and heat in addition to atomic oxygen. No measurements can be made at Los Alamos without VUV in the atom beam at this time.

VUV radiation also produced an enhanced atomic oxygen reactivity in Kel-F. Results are summarized in Tables 1 and 2. In the afterglow, no difference between the control and VUV specimen could be detected at the lower VUV flux (0.5 VUV suns) with both samples showing a mass loss rate not significantly different from zero. At the higher VUV flux (4 VUV suns) the mass loss rate was about one-third the rate of the Kapton reference specimen. At Los Alamos, Kel-F showed a reaction efficiency nearly equal to that of Kapton (and much higher than that of FEP Teflon) in the argon-oxygen beam, however, a reaction efficiency lower than that of either Kapton or FEP Teflon was obtained in the neon-oxygen beam. The neon-oxygen beam contained 3 eV oxygen atoms and 1 VUV sun of VUV radiation whereas the argon-oxygen beam contained 1.5 eV oxygen atoms and 5 VUV suns of VUV radiation. The reactivity of Kel-F with atomic oxygen increases more rapidly with VUV dose rate than that of FEP Teflon. It is significant that FEP Teflon became cloudy on exposure to VUV radiation and atomic oxygen in the afterglow whereas Kel-F did not.

The silverbacked Teflon material also displayed an increased reactivity with oxygen atoms when exposed simultaneously to VUV radiation in the flowing afterglow apparatus. Results are summarized in Table 1. With 0.5 VUV suns, the silver-backed Teflon showed a mass loss rate about the same as that of the Kapton reference sample. The silver-backed Teflon mass loss rate was about the same as that of the Kapton reference sample with 4 VUV suns. The silver Teflon also became cloudy.

VUV radiation also had an effect on the reactivity of Kapton in the flowing afterglow system. Four VUV suns increased the mass loss rate of Kapton by about 30%. The mass loss rate of the VUV sample returned to normal when the lamp was turned off. With higher atom energies, however, the reactivity of Kapton is independent of VUV dose. Nearly the same reaction efficiencies are obtained at Los Alamos in both the argon and neon-oxygen beams and in LEO during the STS-8 and STS-5 flight expriments.[7,8]

Conclusons

Low levels of VUV radiation can significantly alter the reactivity of some materials with atomic oxygen over a wide range of conditions. FEP Teflon, Kel-F, and silver-backed Teflon all show little or no reactivity with atomic oxygen in the absence of VUV radiation. With simultaneous exposure to VUV fluxes comparable to those experienced in LEO, the reactivity of FEP Teflon, silver-backed Teflon, and Kel-F increase to become comparable to that of Kapton. VUV radiation has also been shown to increase the reactivity of Kapton with thermal-energy oxygen atoms. Though the experiments reported here do not perfectly reproduce the LEO environment, it has been demonstrated that VUV radiation can significantly enhance the atomic oxygen reactivity of flurocarbon and chloroflurocarbon polymers under a wide range of conditions. The synergistic effects of atomic oxygen and VUV radiation should be given serious consideration during materials selection and design of spacecraft intended to operate in the LEO environment.

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Tumble Orbit Transfer of Spent Satellites

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Nomenclature

l	= arm length
m_1	= service vehicle mass
m_2	= target satellite mass
R	= orbital radius
V	= orbital speed
ΔV	= velocity increment of combined system
ΔV_1	= velocity increment given to service vehicle
γ_i	$= m_i/(m_1+m_2)$ = mass fraction of mass m_i to total mass
ϕ	= rotational velocity
μ	= product of the gravity constant and Earth's mass

Subscripts

1	= service vehicle
2	= target satellite
a	= apogee
p	= perigee
C	= original circular orbit

I. Introduction

ORBIT transfer of Earth-orbiting objects via a service vehicle will constitute an important part of space infrastructures in the very near future. Some missions will require

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