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Material Selection Guidelines to Limit Atomic Oxygen Effects on Spacecraft Surfaces

D. Dooling
D^2 Associates, Huntsville, Alabama

M.M. Finckenor
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

June 1999

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National Aeronautics and
Space Administration

Marshall Space Flight Center • MSFC, Alabama 35812

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TECHNICAL PUBLICATION

MATERIAL SELECTION GUIDELINES TO LIMIT ATOMIC OXYGEN EFFECTS ON SPACECRAFT SURFACES

1. PURPOSE

This document provides guidelines in selecting materials for satellites and space platforms, designed to operate within the low-Earth orbit (LEO) environment, which limit the effects of atomic oxygen (AO) interactions with spacecraft surfaces. It serves as a revision of TM–100351.

AO is formed by solar ultraviolet (UV) radiation dissociating oxygen molecules (O_2) into free oxygen atoms in the outer ionosphere from altitudes greater than 100 km. Oxygen atoms alone are highly corrosive, combining with most materials they encounter (see figs. 1a and 1b). In addition, a spacecraft's orbital velocity of 7.8 km/sec (17,500 mph) has the effect of exposing a spacecraft to a stream of AO at an energy of approximately 5 eV. The atoms' ability to react with spacecraft materials can be enhanced by solar UV radiation which energizes molecular bonds and makes AO reaction easier (noted as AO+UV).

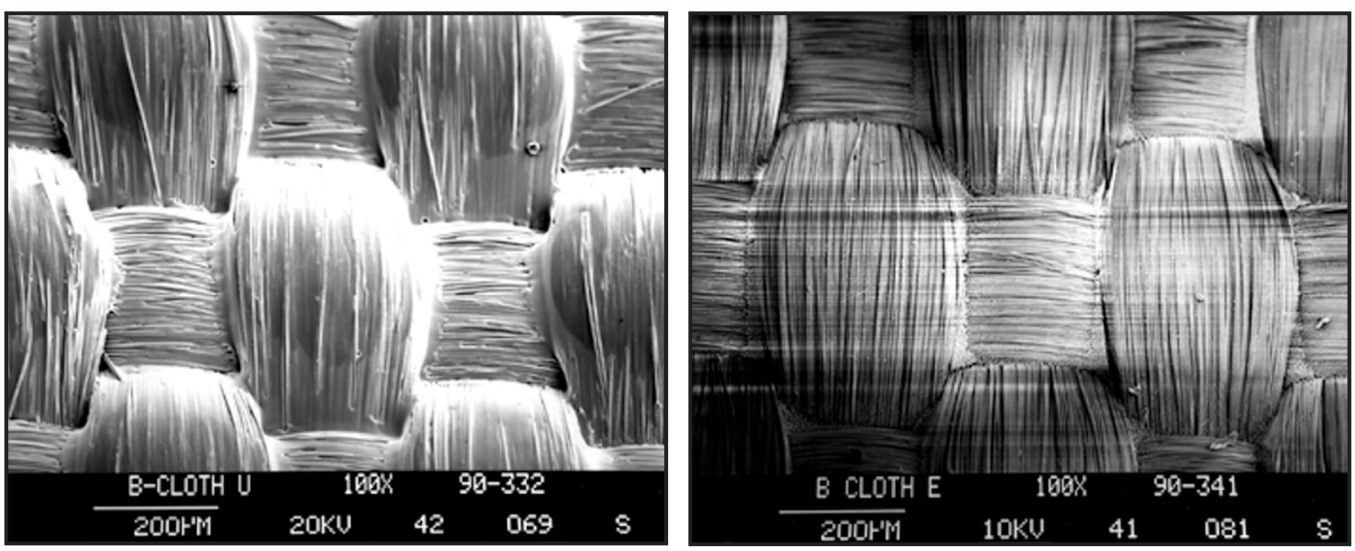


Figure 1a. The severity of AO erosion is highlighted in these scanning electron microscope pictures of samples that were exposed to space for 69 mo aboard the Long Duration Exposure Facility (LDEF). Above are unexposed (left) and exposed (right) pictures of Beta cloth on the transverse flat-plate heat pipe experiment. Beta cloth is a fabric made of woven glass fibers. While the glass itself is highly resistant, AO has eroded the Teflon™ impregnated in the cloth.

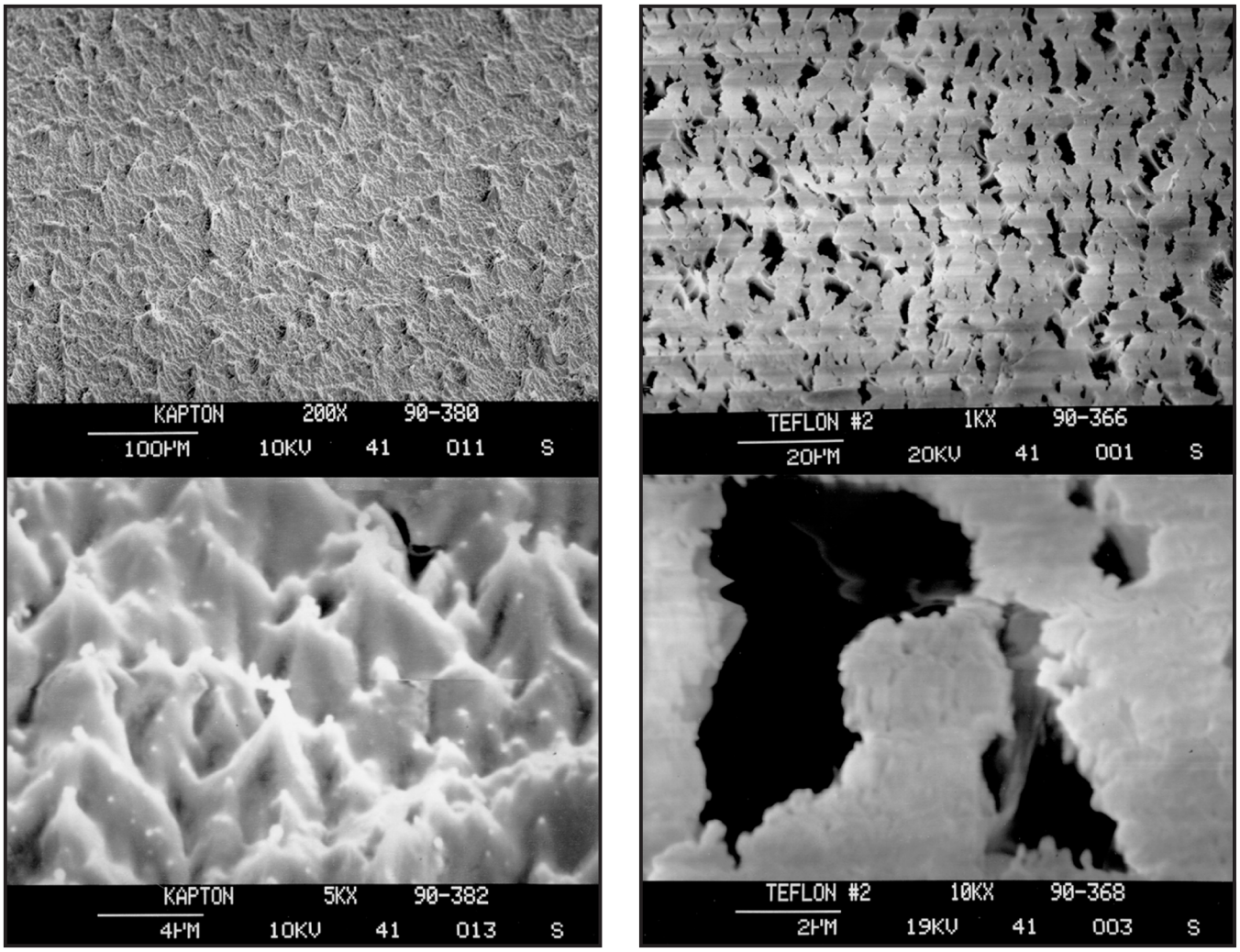


Figure 1b. Close-up and extreme close-up views of Kapton® (left) and Teflon™ (right) from the solar array materials experiment tray on LDEF. An unexposed sample would appear smooth and virtually featureless. Here, the Kapton® is roughened, and the Teflon™ has cracked, forming holes that can allow severe erosion inside the material as oxygen atoms ricochet before actually reacting with a material.

This document should be treated as an introduction rather than a comprehensive guide since analytical and flight technologies continue to evolve, flight experiments are conducted as primary or piggyback opportunities arise, and our understanding of materials interactions and protection methods grows. The reader is urged to consult recent literature and current web sites containing information about research and flight results.

2. SCOPE

This specification applies to LEO spacecraft, such as the *International Space Station* (*ISS*), which use organic films, polymeric materials, and composite structures to reduce weight in structures, insulation, and other components. The designer should consider that absolute protection from AO erosion is not possible. Rather, spacecraft should be provided with AO protection optimized for the AO environment in which they will operate for the planned mission life, plus an operating margin to allow for variations in orbital conditions or for reasonable mission extensions. Thus, spacecraft operating for short periods in LEO and spacecraft bound for high orbits or interplanetary trajectories may require far less AO protection than spacecraft designed to operate for several years at intermediate Earth orbits.

Geostationary, deep-space, and planetary spacecraft in general are not covered by this specification since the oxygen populations in those environments are negligible. However, the designer should consider the latest information on these environments before proceeding.

3. APPLICABILITY

This document is intended to establish guidelines to aid developers in materials selection. No single material or set of materials will be the ideal solution for all spacecraft and missions. The degree of surface degradation is directly proportional to AO fluence (total integrated flux). Fluence, in turn, is determined by several factors, including:

- Spacecraft altitude—Oxygen populations decrease with greater altitude, although the density at different altitudes will vary with the solar cycle or radiation exposure.
- Attitude—Surfaces in the ram or windward direction will be exposed the most, with exposure decreasing by the cosine of the angle of incidence on surfaces away from the ram direction.
- Orbital inclination—High inclination orbits expose spacecraft to greater cosmic radiation (near the geomagnetic poles and in the South Atlantic anomaly), which can have a synergistic effect with AO and possibly to longer periods of solar UV.
- Mission duration—Longer missions mean longer exposure and the greater risk of failure due to AO or AO+UV erosion.
- Solar activity—The Sun emits more UV and x rays during solar maximum (sunspots are associated with magnetically active areas) which directly affect spacecraft surfaces and also expand the upper atmosphere, thus increasing AO populations at altitude.

Models are available on the Internet through the NASA Space Environments and Effects Program to estimate AO fluence. From these, the developer may estimate surface erosion.

While AO can be extremely damaging, the other elements of the near-Earth space environment should not be ignored. The developer should also keep in mind that the total, combined space environment may affect materials in a variety of ways. Optical properties (solar absorptivity and thermal emissivity) may change due to AO bleaching or UV radiation darkening. Polymeric films may peel due to thermal cycling. In turn, this opens new surfaces that can be attacked by AO or AO+UV. The electrical conductivity of a material may be affected by AO, resulting in spacecraft charging. The strength of composite structures may degrade due to AO erosion of resin binders.

Materials selected for spacecraft and commercial satellites under development shall be reviewed for susceptibility to AO interactions which produce surface erosion or degradation in optical and thermal properties that may cause spacecraft systems to fail. Tolerable levels of degraded performance shall be established by the spacecraft developer. Since the degree of surface degradation is directly proportional to AO fluence (total integrated flux) and fluence, in turn, is determined by many environmental factors, materials deemed acceptable for one application may not be acceptable for other applications. Consequently, rather than listing materials acceptable for spacecraft systems under varied sets of operational circumstances, this specification establishes guidelines to aid spacecraft developers in materials selection and summarizes experiences from several recent space missions and ground-based simulations (sec. 4.2).

As a space vehicle orbits the Earth at orbital speed (7.8 km/sec at low altitudes), it undergoes energetic collisions with atoms and molecules in the orbital environment. AO is the dominant species in the outer ionosphere from 200–700 km (124–435 mi) (fig. 2), becoming as much as 90 percent of the atmosphere at 500 km, a typical altitude for *ISS* and future space platforms. Other atoms are present but are far less reactive.

AO is produced by the photodissociation of O_2 initiated by the absorption of near-UV solar radiation. AO's concentration changes as sunspot activity varies during the 11-yr solar cycle (fig. 3, table 1). This effect must be accounted for if long-lived operation of the spacecraft systems is to be expected. Recent space flight experiments have demonstrated that many polymers, organic films, and composite materials undergo significant mass erosion and changes in surface properties during exposure to suprathermal (5 eV) AO. Mass is lost and surface properties change as the spacecraft collides at orbital speed (7.8 km/sec) with AO within the Earth's upper atmosphere.

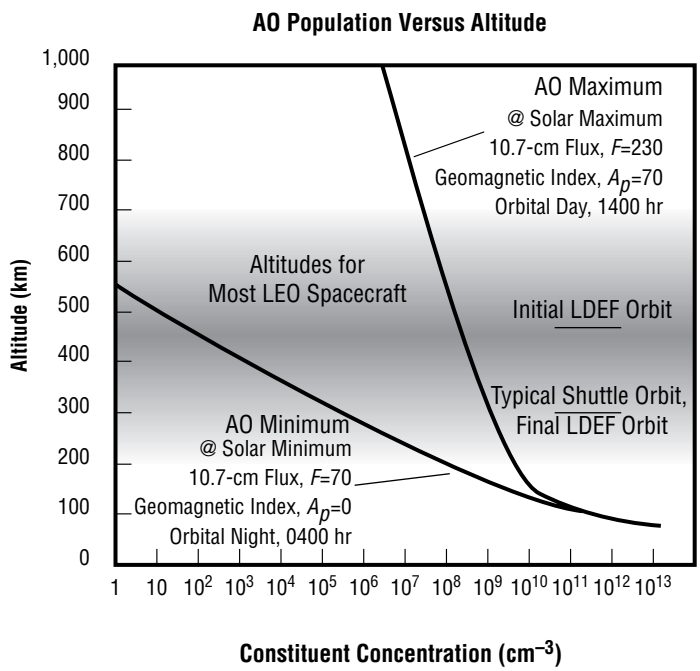


Figure 2. Gas populations vary widely with altitude and solar activity. This graph shows the range for AO, the only gas species that poses a significant erosion hazard for spacecraft.

Figure 3 shows the prediction for sunspot numbers through the current maximum solar cycle 23 with the actual counts for the previous cycle (22) overlaid on it. Sunspot numbers alone are not used in solar cycle predictions. An important measure is a special calculation of radio emissions at 10.7-cm wavelength (plotted on the right side) which corresponds closely with sunspot numbers. Predictions of solar activity can vary widely from what the Sun actually does since our understanding of the solar dynamo is imperfect. Note that the Zurich number for sunspots is a calculation that also considers size and position.

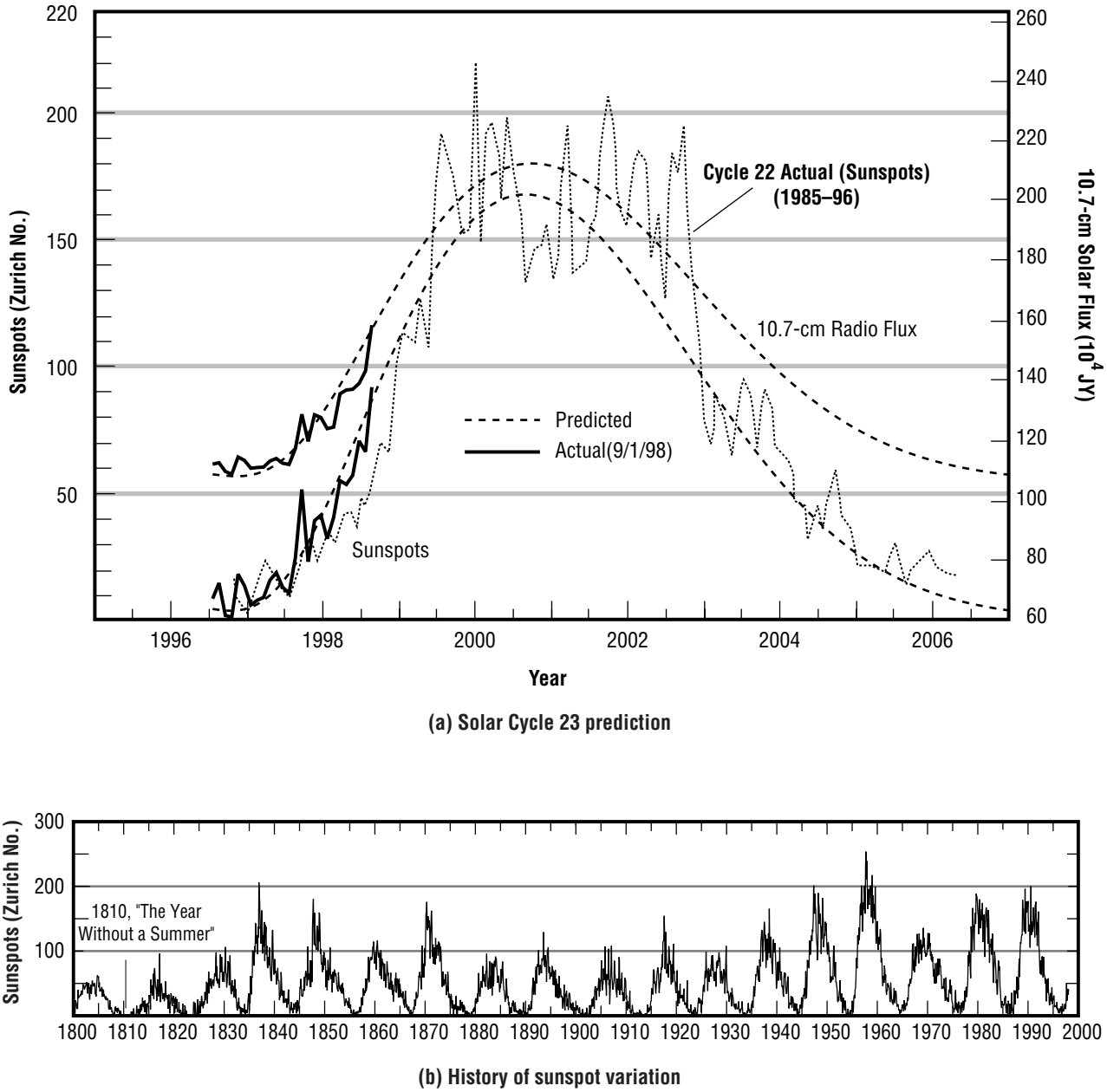


Figure 3. Prediction for sunspot numbers: (a) solar cycle 23 prediction and (b) history of sunspot variation.

Table 1. Projected sunspot numbers, Cycle 23.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	8.1	10.1	12.5	15.3	18.6	22.2	26.3	30.7	35.5	40.5	45.8	51.4
1998	57.0	62.8	68.7	74.7	80.6	86.5	92.4	98.2	103.9	109.4	114.8	119.9
1999	124.9	129.7	134.2	138.4	142.4	146.1	149.6	152.7	155.6	158.1	160.4	162.3
2000	164.0	165.3	166.4	167.1	167.6	167.8	167.7	167.3	166.6	165.8	164.6	163.2
2001	161.6	159.8	157.8	155.5	153.1	150.5	147.8	144.9	141.8	138.7	135.4	132.1
2002	128.6	125.1	121.5	117.9	114.2	110.5	106.8	103.0	99.3	95.6	91.9	88.3
2003	84.6	81.1	77.5	74.1	70.7	67.3	64.1	60.9	57.8	54.9	51.9	49.1
2004	46.4	43.8	41.3	38.8	36.5	34.3	32.1	30.1	28.2	26.3	24.5	22.9
2005	21.3	19.8	18.4	17.1	15.8	14.6	13.5	12.5	11.5	10.6	9.7	8.9
2006	8.2	7.5	6.9	6.3	5.8	5.2	4.8	4.3	4.0	3.6	3.3	2.9

4. ATOMIC OXYGEN EFFECTS

Most of the data related to the behavior of materials in the AO environment are obtained from experiments aboard the U.S. Space Shuttle and the LDEF. New data are emerging from studies with instruments carried aboard Russia's *Mir Space Station*, and equipment replaced on the Hubble Space Telescope (HST). Extensive data will be gained from operational experiences with the *ISS* as it operates for up to 30 yr in LEO. These flights are summarized in section 4.1.

In section 4.2, all material samples listed as exposed to AO, whether orbital or simulated, have been evaluated for mass loss due to surface erosion. Most of the data obtained from AO exposures are in terms of AO reactivity, a property defined as thickness of material lost, normalized to total AO fluence. Fluence of flight experiments was obtained from atmospheric models, spacecraft velocity, and exposure history. If the particular material in question contained AO-impervious fillers, the matrix material became shadowed or protected from impingement by the fillers and consequently, mass loss rates changed with time. For these samples, mass loss per unit area is typically reported. Because only a summary is presented here, the designer should consult primary references (see bibliography) for details of results and methods.

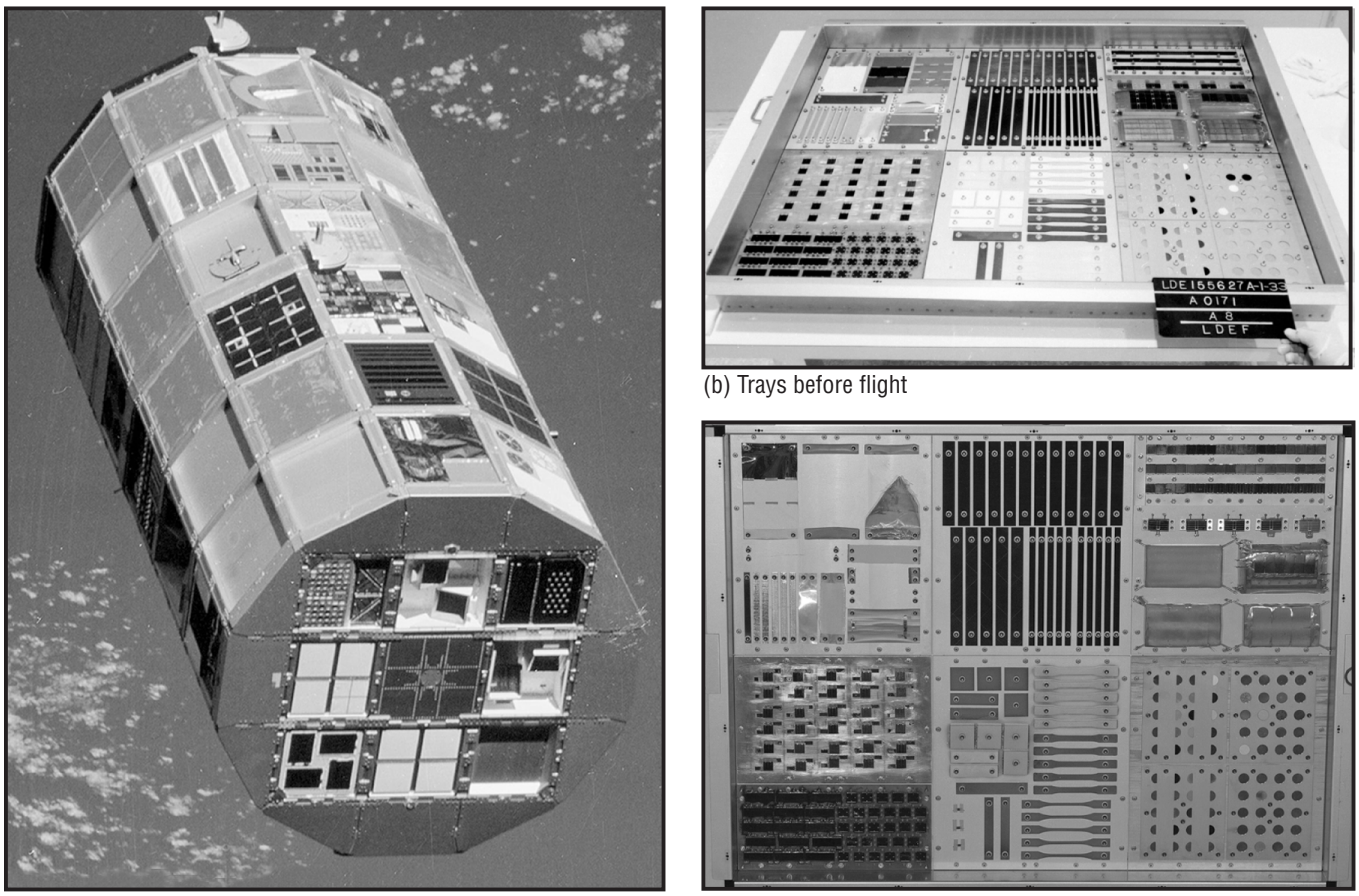
4.1 Flights

4.1.1 Long Duration Exposure Facility

The LDEF was the largest satellite yet flown for the express purpose of using the space environment as a laboratory for exposure tests (fig. 4). The LDEF carried several thousand samples in 86 trays (72 on the sides and 14 on the ends) attached to a 12-sided frame, 4.3-m (14-ft) wide and 9.1-m (30-ft) long. The LDEF was stabilized by a special damping device that held one face in the ram direction throughout the mission.

The LDEF was deployed by the Space Shuttle on the STS 41–C mission in April 1984. Its initial orbit was about 470-km high and inclined 28.5 deg to the equator. At that time its mission was to last 9 mo. The loss of Space Shuttle *Challenger* in January 1986, and the subsequent downtime for the Shuttle fleet, postponed retrieval until STS–32 in January 1990. By then the orbit had decayed to 296×361 km. Total AO exposure was 9×10^{21} atoms/cm^2 in the ram direction. About 75 percent of this was experienced in the last 6 mo of the mission as orbital altitude decreased.

Because many of the experiments were designed for a stay of less than a year, many were extensively or completely eroded. Nevertheless, the LDEF is the best single database for understanding AO effects and has resulted in several volumes of published data.



(a) LDEF

(b) Trays before flight

(c) Trays after retrieval

Figure 4. The LDEF (a) carried several hundred samples in 86 trays such as the AO171 tray of AO exposure samples, (b) shown before flight and (c) after retrieval 69 mo later. Note the extensive loss of polymeric film samples. Also, three of four solar array coupons had complete failure of the Kapton® tape attaching them to the tray. Two coupons were lost and the third was later found in the Shuttle payload bay.

4.1.2 Effects of Oxygen Interactions With Materials

The Space Shuttle carried the Effects of Oxygen Interactions with Materials (EOIM) experiments on flights STS–8, 41–G, and 46. On EOIM–III (STS–46), samples of paints, anodized aluminum, and Beta cloth were exposed to AO, UV radiation, thermal cycling, and hard vacuum (fig. 5). The samples were on trays, with some trays providing thermal conditioning at 60, 120, and 200 °C. The trays allowed samples to be exposed passively to AO only and to AO+UV. AO fluence was $1.0–3.5 \times 10^{20}$ atoms/cm^2 over a period of 42.5 hr at an altitude of 229 km (143 mi). Specimens included bulk, polished, and single-crystal silver and copper; anodized aluminum, aluminum/lithium alloys, dry film lubricants, metals, thermal coatings, and selected polymers. Six atomic oxygen resistance monitors (AORM) were included (see sec. 7.3).

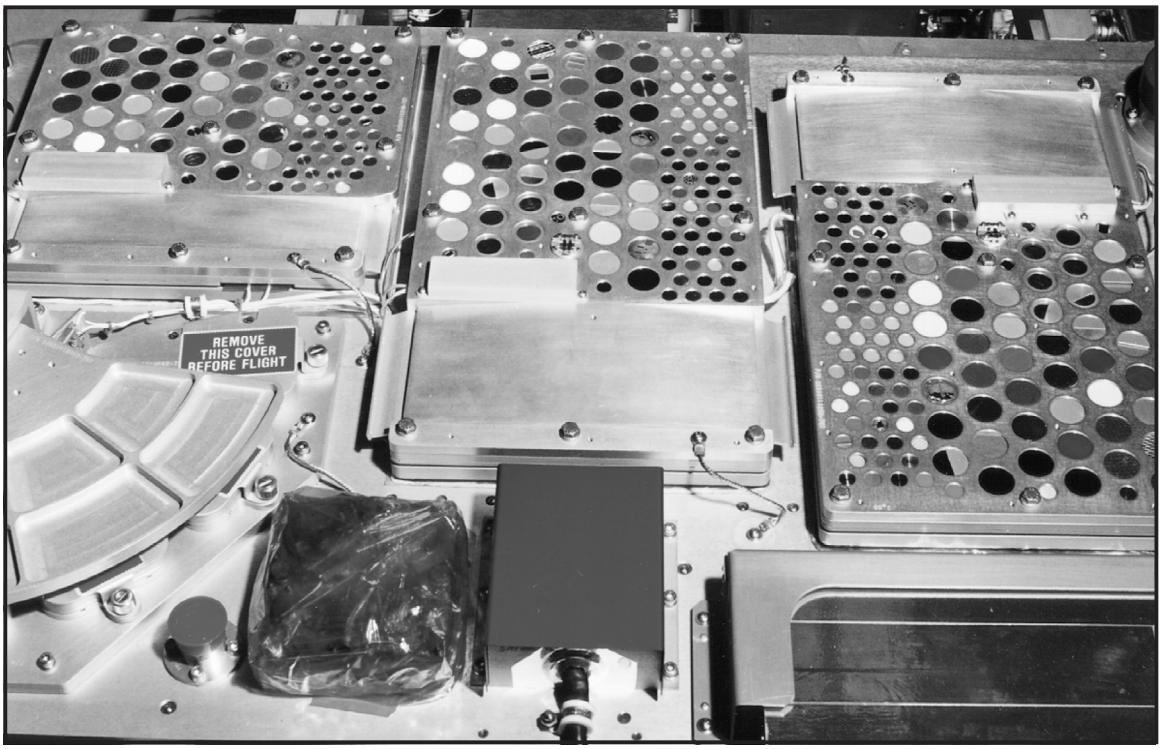
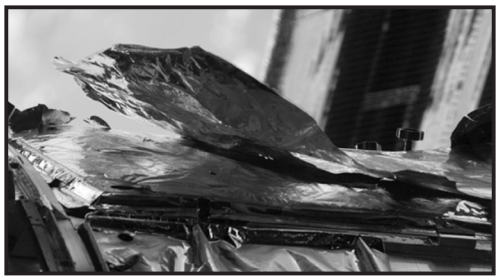


Figure 5. The EOIM–III experiment, flown on STS–46, included several sets of samples, with and without heaters, for exposure to the orbital AO environment.

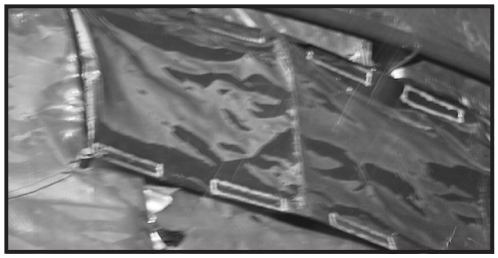
4.1.3 Hubble Space Telescope

The HST is revisited every 2–3 yr for maintenance and refurbishment. This provides an opportunity to study exposed items which are returned to Earth and to inspect the exterior of the spacecraft. Hubble was deployed at an altitude of 610 km (381 mi) and at an inclination of 28.5 deg—an orbit similar to the LDEF's—on April 25, 1990. During the HST's first 3.6 yr in LEO, it was exposed to an estimated AO fluence of 7.59×10^{20} atoms/cm^2 in the ram direction (unlike the LDEF, the HST is frequently pointed at different targets, so no one surface was in ram the entire time).

The HST has been serviced twice, by STS–61 in December 1993 and STS–82 in January 1997 (a third mission is scheduled for early 2000). Among the tasks for the crews on the first mission were replacement of several components exposed to space, including both solar arrays (only one could be furled and returned to Earth), the wide-field/planetary camera (with a radiator plate exposed to space), and two magnetometers (their multilayer insulation (MLI) was returned). The STS–61 crew observed micrometeoroid debris and pitting damage. Yellow paint on the handrails was observed to come off as particulate matter when force was applied to the rails. This was likely due to erosion of the polyurethane binder. The MLI blankets appeared to be stretched tight. During replacement of the rate sensor unit, a 7.5-cm (3-in) square of MLI was seen floating over the starboard wing. More than 6,000 photos were taken on orbit for use in studying the condition of the HST (fig. 6). Analysis continues and results will be made available by NASA's Goddard Space Flight Center.



(a) MLI degradation



(b) HST exterior

(c) Repair patches

Figure 6. To protect areas where MLI was degraded by AO+UV (a), the exterior of the HST (b) had MLI repair patches (c) applied by astronauts in January 1997 (STS–82).

4.1.4 Other Spacecraft

A limited number of other satellites carry instruments that provide limited data on AO effects on the spacecraft. The Extreme Ultraviolet (EUV) Explorer, for example, carries several quartz crystal microbalances that precisely measure the remaining quantity of a coating on the surface. This was done to help gauge AO effects on the satellite's optical surfaces. The Tropical Rainfall Measurement Mission, launched on Nov. 28, 1997, carries a coatings and environmental effects monitor designed to gather data characterizing the response of materials in a high-density AO environment. The Solar Maximum Mission spacecraft was launched in February 1980 into a 570-km (357-mi) 28.5-deg orbit. The spacecraft was repaired during the STS 41–C mission in April 1984, where it had decayed to an orbit of 488 km (305 mi). MLI blankets, a thermal radiator, and louver assemblies exposed to an AO fluence of approximately 2×10^{21} atoms/cm^2 were returned to Earth for analysis.

4.1.5 Other Shuttle Missions

The NASA Langley Atomic Oxygen Experiment (AOE) consisted of materials provided by the Boeing Company, College of William & Mary, and NASA Langley. The samples were exposed to the space environment during the entire STS–85 mission and were oriented along the Shuttle orbital velocity vector for 40 hr. Data analysis is under way. The AOE samples consisted of candidate lubricants, paints, thermal control coatings, structural materials, and AO-resistant materials for use on the *ISS*, plus contamination witness plates (fig. 7). The materials included MLI, fluorosilicone, Kapton®, aramid, silverized Teflon™, coated silverized Teflon™, graphite composite, Viton, silicone, white paint, AO concentrators, and a solar focusing device.

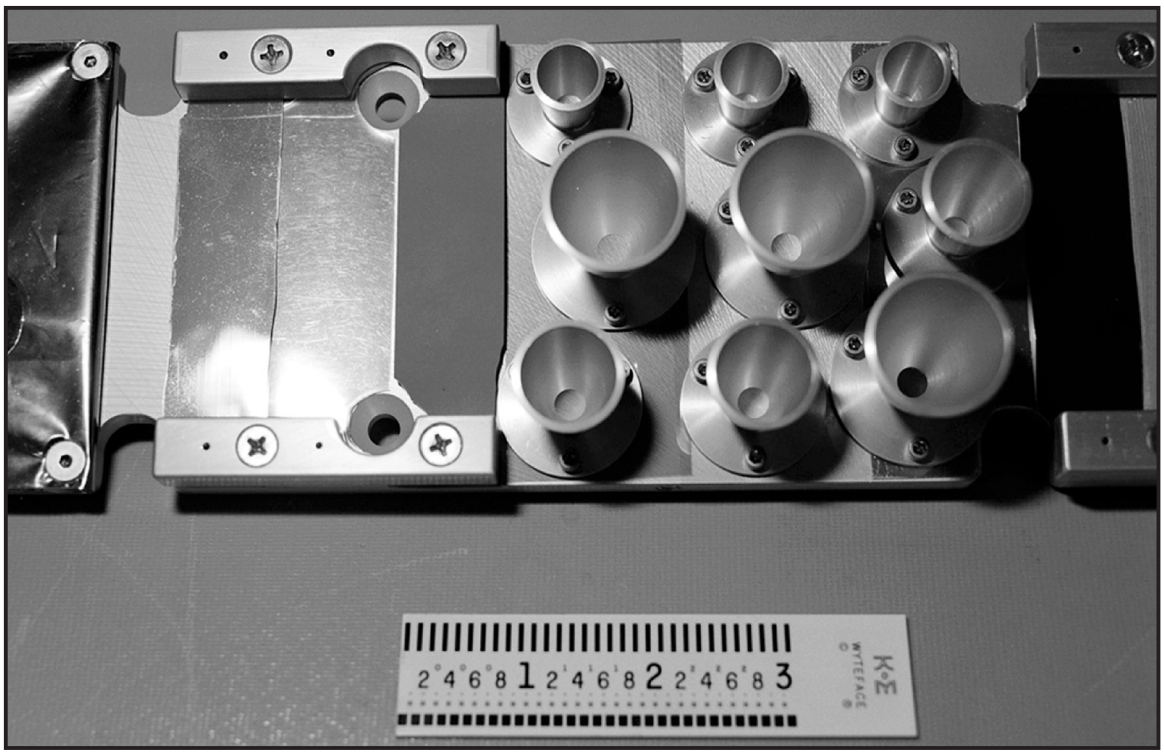


Figure 7. A portion of the AOE samples—including cones (right) to concentrate AO on samples—flown on STS–85, shown here before installation on the Space Shuttle.

The Consortium for Materials Development in Space in Huntsville, AL, has flown several small payloads called CONCAP Consortium for Material Development in Space Complex Autonomous Payload for low-gravity materials science experiments. At least two have carried AO sensitive materials on the exterior for exposure during flight.

4.1.6 *Mir* Environmental Effects Payload

At this writing, NASA and its partners are evaluating samples that were placed aboard Russia's *Mir Space Station* by the STS–76 mission in March 1996 and removed in October 1997 by the STS–86 mission (fig. 8). The various *Mir* Environmental Effects Payload (MEEP) components were mounted at different positions around the U.S.-built docking module and thus were exposed both to space environmental effects and to spacecraft-induced environmental effects, principally those of Shuttle docking and operations.

MEEP included two passive optical sample assemblies (POSA) designed to assess the magnitude of molecular contamination on *ISS* critical surfaces and quantify the performance and degradation rate of candidate/baseline *ISS* exterior surface materials. Both POSA I and II comprise various passive sample trays, carousels, and plates, as well as vacuum UV diodes and AO pinhole cameras. Many of the various materials chosen for exposure are currently planned for use on the *ISS*. POSA I was developed by NASA Marshall Space Flight Center (MSFC) and POSA II by Boeing Defense and Space Group.

The Atomic Oxygen Resistant Polymers (AORP) experiment is one of the experiments carried by the optical properties monitor (OPM) attached to the exterior of *Mir*. The AORP experiment objective is to measure the performance of AORP when exposed to the space environment for approximately 1 yr. The OPM was retrieved from *Mir* by STS–89 and is being analyzed. These materials also flew on STS–85 Evaluation of Space Environment and Effects on Materials (ESEM) payload and have flown on STS–46 and 51.

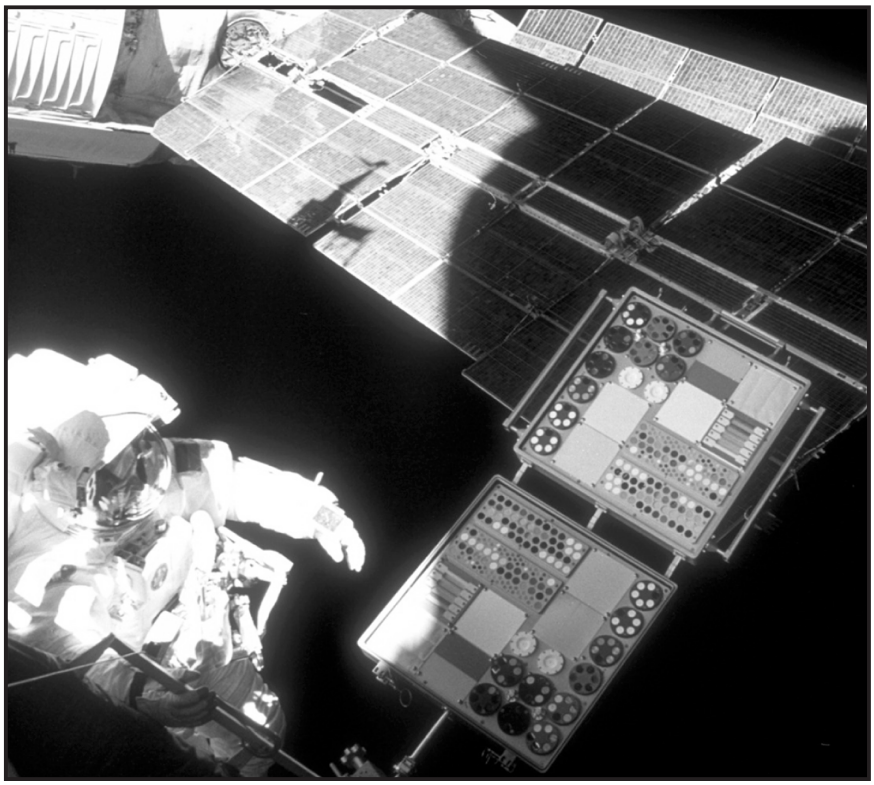


Figure 8. An astronaut prepares to remove one of the MEEP elements from the *Mir* docking module during the STS–86 mission.

4.1.7 *International Space Station*

Further long-duration exposure opportunities may become available as *ISS* is developed, either through study of items that are repaired during normal operations or through possible experiment facilities.

4.2 Materials Effects

Thousands of material samples have been exposed to AO either as part of a flight experiment, recovered material from a repair mission, or in a laboratory simulation of the LEO environment. These materials have been exposed to a minimum of 1×10^{20} atoms/cm^2 to ensure a full response to the AO attack. This is roughly equivalent to a spacecraft operating at 500–600 km (310–372 mi) orbit during nominal solar activity conditions for periods of at least 1 yr. These materials, with lessons learned, have been divided into the following categories: organic, metallic, nonmetallic, optical coatings, and thermal control coatings.

4.2.1 Organic

Polymers and other organics are, by far, among the most vulnerable materials when exposed to AO. Generally, unfilled materials containing only C, H, O, N, and S react with approximately the same reaction efficiency, or volume loss per atom of 1 to 4×10^{-24} cm^3/atom. Perfluorinated carbon-based polymers and silicones have lower reaction efficiencies by a factor of 10 or more than organics.

Tables 2 and 3 give overviews of AO effects on polymers on several flight experiments as well as laboratory simulations at Princeton Plasma Physics Laboratory (PPPL) and the NASA MSFC atomic oxygen drift tube system (AODTS). The facility at PPPL (sec. 6.1.3) more closely approximates orbital AO and its impact energy but adds vacuum ultraviolet (VUV) radiation that has a significant effect on fluorinated ethylene propylene (FEP) Teflon's™ AO reaction efficiency. The AODTS (sec. 6.1.1) produces AO with less than 0.01 eV energy, therefore AO reaction efficiencies are less than that encountered on orbit. Ground-based facilities are excellent tools for material durability prediction provided that the sensitivity of particular materials to conditions such as VUV, flux, and fluence are taken into account.

Table 2. Overview of AO reaction efficiencies of polymer films (10^{-24} cm^3/atom) on several flights.

Sample	STS–5	STS 41–G	LDEF	STS–46	PPPL	MSFC
Halar (bulk)		1.0–2.0	2.1	2.0–2.5	3.0–3.4	0.014–0.034
Lexan®		1.3–3.6		3.6–4.0		
PEEK (bulk)		4.7	2.3	2.0–4.0		
Tefzel		0.20		≈1.0	2.8–3.0	0.11–0.12
Kapton® HN		3.3		3.3–4.3		
Kapton® H	3.0			3.5–3.9		
Black Kapton®				2.1–2.7	3.4	
TFE	<0.05		0.20	0.049–0.080		
FEP	<0.05	3.1–2.4	0.35	0.082–0.082	5.9–6.6	0.023

From Kamenetzky et al. Several Data Points Summarized

Table 3. LDEF (AO171) and general Space Shuttle postflight polymer/AO properties.

Polymer	Reactivity, 10^{-22} mg/atom		Comments
	LDEF	Shuttle	
White Tedlar	0.29	–	Inert particles retarded erosion
TFE Teflon™	0.20	<0.05 (est.)	
FEP Teflon™	0.35	<0.05 (est.)	Data From S0069
PEEK	2.3	3.7 +1.0	
Halar	2.1	2.0	
Kevlar 29	1.5 + 0.5	1.1 + 2*	*Based on STS–8 Tether Mass Loss
Kevlar 49	4.0	–	Polysulfone 2.3 2.4

Filled or composite materials have reaction efficiencies that are strongly dependent upon the characteristics of the fillers. Composites of S-glass/epoxy showed erosion of the epoxy only; the glass fibers prevented much damage from occurring. Darkening of the S-glass/epoxy samples is probably due to UV effects. Lessons learned from LDEF experiment A0171 graphite/epoxies included the greater AO susceptibility of the epoxy matrix compared to the carbon fiber in HMF 322/P1700, HMS/934, and P75S/934 systems (fig. 9). AO erosion increased the optical diffuseness of the surfaces and formed a porous gray ash on the composite surfaces, especially the polysulfone materials. Mass loss was consistent with the measured thickness loss of about 1 ply. AO reaction efficiencies for the AO171 composite samples are given in table 4.

The EOIM–III experiment carried an array of polymers, including Kapton® H and HN types, black carbon-impregnated Kapton®, various coatings on Kapton®, Lexan®, Tefzel, tetrafluoroethylene (TFE), and FEP Teflon™. Among the lessons learned from EOIM–III was that AO-induced changes in the conductivity of black Kapton® proved to be a reliable gauge of AO fluence. No definitive difference in AO reactivity was found between Kapton® held in tension and unstressed Kapton®. Coatings of hexamethyl disiloxane and indium tin oxide were successful in protecting the underlying Kapton® from AO attack. Also included on EOIM–III were candidate *ISS* seal materials viton V747 and silicone S383, which were slightly eroded from AO exposure.

On LDEF, EOIM–III and other space flight exposures, FEP MLI showed damage from space environmental exposure. Cracking occurrences and hardness increased and elongation decreased with more solar exposure. FEP is still acceptable as a thermal blanket material, provided no in situ deformation occurs. A suitable backing may be adhesively applied to the FEP layer to maintain structural integrity.

The experience with the EUV explorer was unique in that the spacecraft was held in one altitude for 215 days while the spacecraft was prepared for its observing mission. Then it was rotated, changing the ram direction relative to the spacecraft surfaces. At the spacecraft's 500–km high orbit the ram face was exposed to an estimated 1.18×10^{21} atoms/cm^2.

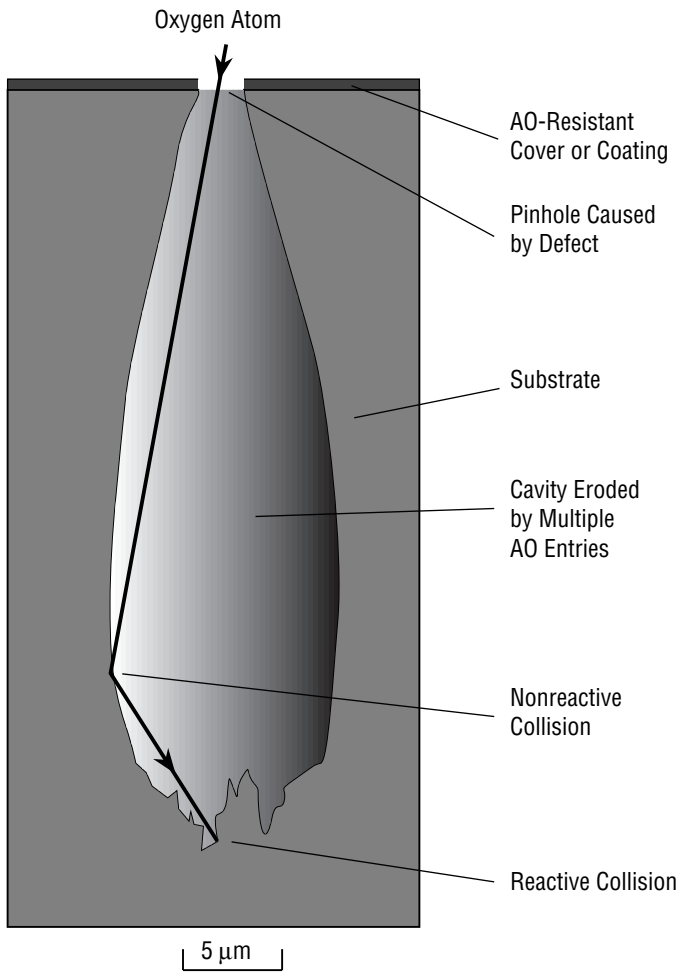


Figure 9. One of the important lessons from LDEF is that small defects in the surface of a material can result in much larger damage. AO does not immediately react with the first surface it encounters but can ricochet and carve out a large cavity behind a small aperture.

Table 4. AO erosion rates for composites, LDEF (AO171), present a new challenge in combatting AO effects.

Composite Materials	Average Thickness Loss (mils)	AO Reaction Efficiency, 10^{-24} cm^3/atom
HMF 322/P1700/±45°	2.5–6.2	0.92–2.3
HMS/934/0	2.5	0.92
HMS/934/90	2.7	1.0
P75S/934/90	2.7	1.0
P75S/934/0	2.8	1.0
"S" Glass-epoxy	0.36	0.13

Shuttle: Graphite/epoxy reactivity 2–2.6 $\times 10^{-24}$ cm^3/atom

The thermally controlled quartz crystal microbalances (TCQM) showed a 30-fold increase in erosion of Teflon™ during exposure to UV, from 1.86 to 55.8 × 10^{-26} cm^3/atom. However, the erosion rate eventually decayed to the pre-UV rate. It is believed that the UV broke the polymer bonds and opened sites susceptible to AO erosion. After those had decayed, only hardened sites resistant to AO erosion were left.

4.2.2 Metallic

In general, metals, except for silver and osmium, do not show macroscopic changes. Microscopic changes have, however, been observed and should be investigated for systems very sensitive to surface properties. The reactions of metals to AO vary widely with the metal itself and with the final surface preparation it has been given. Also, accommodation is strongly dependent on temperature and stress. Silver and osmium react rapidly and are generally considered unacceptable for use in uncoated applications. Silver has been used as a surface on which to record AO exposure passively. The LDEF, for example, carried a pinhole camera comprising a small dish lined with silver. The centroid of the eroded area in the dish served as a measure of the LDEF's mean attitude throughout the mission (table 5). Pure silver is highly reflective, but its oxide is black and has a far higher emittance (infrared (IR) reflectance equals 1 minus emittance).

Most alloys of aluminum have proven to be resistant to AO, although a chromic acid anodized sample carried on the 120 °C tray on EOIM–III showed more mass loss than expected. A surprise was a significant mass loss in 2090 aluminum/lithium alloy. The lost mass was lithium and was more severe at elevated temperatures. Other metals carried on EOIM–III fared well, with mass losses apparently due to water vapor outgassing rather than AO effects (table 6).

Table 5. LDEF (AO171) AO exposure covered a number of pure and alloyed metals.

Metal	Reaction Efficiency 10^{-26} cm^3/atom	Accomodation AO/10^4 atoms
Copper	0.87	3.6
Molybdenum	0.14	2.8
Tungsten	0.044	–1.0
HOS 875	0.29	2.5
Pre-Ox HoS 875	TBD	TBD
Tophet 30	0.55	5.0
Ni-Cr-Al-Zr	–	–
Tantalum	0.60	8.3
Titanium 75 A	0.39	4.4
Mg AZ31B	0.45	2.0
Niobium	0.14	2.0
Silver Disk, Fine Grain	2.9	8.4
Silver Cold-Rolled Ribbon in Stress Loop	27.5	80.0

Table 6. EOIM–III carried a number of pure metal samples and two alloys.

Pure Metals Mass Loss and Optical Properties, EOIM–III

Sample	Tray (°C)	Δm (mg, ±0.02)	Δm (mg/cm^2, ±0.03)	α_i (±0.01)	α_f (±0.01)	ε_i (±0.01)	ε_f (±0.01)
Copper	60	–0.03	–0.042	0.49	0.56	0.01	0.03
	120	–0.07	–0.098	0.47	0.52	0.02	0.03
Gold	120	+0.01	+0.014	0.19	0.18	0.02	0.02
Nickel	60	–0.05	–0.071	0.33	0.34	0.02	0.02
	120	–0.05	–0.071	0.33	0.31	0.02	0.02
Niobium	60	–0.05	–0.071	0.33	0.34	0.03	0.03
		–0.03	–0.042	0.33	0.34	0.03	0.03
Silver	120	+0.23	+0.323	0.11	0.80	0.01	0.46
Tantalum	60	–0.05	–0.071	0.38	0.39	0.03	0.02
	120	–0.01	–0.014	0.38	0.37	0.03	0.02
Tungsten	60	–0.15	–0.210	0.46	0.48	0.02	0.02
	120	–0.02	–0.028	0.46	0.46	0.02	0.02
	200	–0.04	–0.051	0.46	0.55	0.02	0.01
Vanadium	60	–0.42	–0.589	0.68	0.70	0.06	0.05
	120	–0.04	–0.051	0.64	0.66	0.06	0.06
Aluminum/	60	–0.51	–0.155	0.15	0.14	0.05	0.05
Lithium	120	–0.53	–0.162	0.15	0.14	0.05	0.05
Weldalite		–0.15	–0.090	0.13	0.15	0.05	0.05
(Passive)		–0.17	–0.102	0.13	0.13	0.06	0.05

α=absorptance, ε=emittance, ε_i=initial, ε_f=flight,

4.2.3 Nonmetallic

The most commonly used nonmetallic, inorganic material is Beta cloth, a fabric woven from fine quartz threads. It resists mechanical wear as well as AO and AO+UV attack. However, many forms of Beta cloth are impregnated with Teflon™ or silicone-based materials to lubricate the threads so the fabric bends easily during handling without the threads abrading each other. Both the Teflon™ and other materials can be eroded by AO and AO+UV exposure. Glass generally resists AO attack well.

Solar concentrators and energy dispersion systems require reflection of solar radiation. Reflector materials, such as those flown on LDEF (A0171), are usually tailored for highly efficient reflectance in the near-UV to near-IR wavelengths (250–1,400 nm). Aluminum, enhanced aluminum (multiple layers of aluminum and silver), silver, silver alloys, and other reflector configurations are protectively coated with glassy ceramics. AO reaction efficiencies ranged from 0.4–2.3 $\times 10^{-28}$ cm^3/atom for silicon oxides, magnesium fluoride, and aluminum oxides. An increase in film density was noted for SiO–SiO_2. Small decreases in reflectance were noted, except for MgF_2–sapphire over silver, which had noticeable degradation (table 7).

Table 7. Changes in LDEF (AO171) glass ceramics.

Coating/Reflector	Change in Solar Reflectance	Decrease in Film Thickness (Å)
MgF_2 Sapphire/Ag	–5 to –10	150
Dielectric/Ag Alloy	–1 to –5	160
SiO-SiO_2/Enhanced Al	–2	125
SiO/Al	–1.5	150
SiO_2/Ag	<–1	40
SiO_2/Al	<–1	50
MgF_2-Sapphire/Enhanced Al	+1.5	25

4.2.4 Optical Materials

The performance of optics in the AO environment can be mixed. While most glasses generally resist AO erosion well, their coatings can be highly vulnerable. Since the performance of most optical systems depends on coatings of various types, this is an area of great concern.

EOIM–III carried a number of optical materials, including EUV filters, metal foils, VUV/UV windows, and candidate reflector configurations for the Advanced X-Ray Astrophysics Facility. Erosion of reflective surfaces could greatly roughen the mirrors which must reflect x rays at grazing incidence angles. Zerodur substrates were coated with gold, iridium, platinum, or nickel, with and without chrome undercoats and exposed on the passive trays. Gold mirrors with nickel undercoats were flown on the heated trays. The passively exposed gold, iridium, platinum samples showed little change, but both the control and flight nickel mirrors showed significant oxide formation with accompanying degradation of reflectance in the VUV wavelengths. The gold mirrors flown on the heated trays were affected by migration of the nickel overcoating and also had degraded reflectance (table 8).

EOIM–III also carried optical thin films which are used to coat optical systems to improve their performance. The samples comprised fluorides of magnesium, calcium, and lithium plus sodium salicylate, a luminescing phosphor. The coatings showed no significant loss, but the sodium salicylate showed significant surface roughening and a 50-percent decrease in VUV luminescence.

To avoid AO problems, the Rosat x-ray astronomy satellite used boron carbide to protect the filter system on the EUV wide-field camera (Kent et al.). Rosat orbits at 580 km (360 mi) where AO erosion is strong. The camera comprises nested grazing incidence mirrors with filters—such as carbon, beryllium and aluminum—bonded to a Lexan® substrate. From previous experience and experiments, the lifetime (time to lose 10-percent thickness) of unprotected Lexan® is between 23 min and 173 days, depending on the reflectivity of the grazing incidence mirrors with respect to AO. To protect the wide-field camera's filters, several protective coatings were investigated before boron carbide was selected.

Table 8. Thin film optical properties carried by EOIM–III.

Sample	Solar Absorptance, α_S		Infrared Emittance, ε_{IR}	
	Control	Exposed	Control	Exposed
Gold				
Passive tray	0.20	0.21	0.07	0.07
60 ˚C	0.17	0.17	0.03	0.03
120 ˚C	0.17	0.17	0.06	0.06
200 ˚C	0.18	0.23	0.05	0.04
Platinum				
Passive tray	0.24	0.25	0.06	0.07
Iridium				
Passive tray	0.24	0.25	0.11	0.12
Nickel				
Passive tray	0.31	0.31	0.05	0.08

On glasses themselves, no changes are observed for short exposures. On LDEF, an $SiO–SiO_2$ increase in film density was noted. Defects were observed on all reflective surfaces except SiO_2/Al where a small decrease in reflection was measured. Reactivities ranged from $0.4–2.3 \times 10^{-28}$ cm^3/atom.

4.2.5 Thermal Control Coatings

In general, thermal control coatings with organic binders such as polyurethane should not be selected for long-term AO exposure. These binders degrade, leaving only pigment particles which then become a contamination hazard. During the STS–61 mission to repair the HST, Z–853 yellow paint on the handrails came off as particulate matter when force was applied to the rails. Ceramic-based paints, such as Z–93, have been found to be quite durable in the space environment, but these paints have their own problems with molecular contamination absorption and difficulty in applying (table 9).

Table 9. During STS–41–G, several overcoated paint samples were tested on the Space Shuttle's robot arm.

Material Overcoat	Z–302 Glossy Black			Z–853 Glossy Yellow
	OI 651	RTV–602	MN41–1104–0	MN41–1104–0
Absorptance (α)				
Flight Specimen	0.972	0.969	0.970	0.469
Control Value	0.972	0.973	0.972	0.458
Mass Loss	None	Negligible	Negligible	Negligible
Comments	Maintains specular character	Lost specular character	Lost specular character	Lost specular character; slight α increase partially due to UV darkening

Note: Applying an overcoat to these paints increases initial absorptivity.

The Chemglaze and Aeroglaze families of paints are widely used in various spacecraft applications. EOIM–III carried several polyurethane paint samples, including Chemglaze A–276 and Z–306, and ceramic-based Z–93 and YB–71, anodized aluminum, and Beta cloth. Chemglaze A–276, for example, was almost twice as reactive in the presence of AO+UV as it was to AO alone. Most of the anodized aluminum samples were unaffected and the Beta cloth lost its Teflon™ matrix at a rate comparable with other missions. Several paint samples showed flaking apparently caused by sample fixture rubbing the material during flight.

Several developmental paint samples also were flown, including:

- A zinc oxide with potassium silicate binder. It varies from Z–93 with finer zinc oxide particle size and a pigment-to-binder ratio adjusted for lower solar absorptance; exhibited no color change or surface texturing; slight quenching of fluorescence was noted.
- Zinc orthotitanate with potassium silicate binder. It was formulated similar to zinc oxide developmental paint; no color or surface changes; black light fluorescence did not appear to change.
- Doped silica black ceramic paint, which did not appear to be affected by exposure.

The A0034 trays on LDEF carried several thermal control coatings including S13G, S13G–LO, Z93, YB–71 (zinc orthotitanate), and the polyurethane-based A276 and Z306 paints. Z306, a black paint, showed little change. The coatings were exposed directly to space or exposed only to UV through quartz windows. A276, a white paint, suffered complete erosion of the polyurethane binder yet remained reflective where UV exposure was diffuse. Minimal direct exposure, though, severely affected the paint (table 10).

Table 10. LDEF (AO171) and Shuttle postflight paint properties.

Paints	Solar Absorptance, α_S			Reactivity, 10^{-22} mg/atom	
		Change, Δ			
	Control	LDEF	Shuttle	LDEF	Shuttle
Z–306 Black Diffuse	0.99	–0.010	–0.202	2.3	1.0
Z–302 Black Specular	0.97–0.99	–0	0.040	5.7	5.8
Z–853 Yellow Diffuse	0.41–0.49	–0.070	0.040	1.4	0.90
A–276 White Diffuse	0.24–0.28	–0.050	≈0	1.4	1.0
401–C10 Black Diffuse	0.98–0.99	3.7±1.0	1.5±0.5	1.6	0.86
Tiodized D17 White	0.38	0.030	Unavail.	Unavail.	–
Tiodized K17 Black	0.96	–0.15	Unavail.	Unavail.	–
S13GLO Diffuse White	0.19	0.14	1.1±2	Neg.	Neg.

5. DATABASES

As experience is gained with AO exposure, NASA, its contractors, and other organizations are compiling their results in various databases. For the most part, NASA databases are available to all Federal agencies and NASA contractors. Corporate and non-U.S. databases also may have restricted availability.

The major limitation of the current reaction rate database is that AO fluence to which the recession rates are normalized is not precisely known. AO number densities used to compute fluence for previous space flight missions were obtained using thermospheric models to predict atmospheric constituent concentrations as functions of altitude, time of year, Earth latitude and longitude, local solar time, and solar activity conditions. Typically, errors of as much as 25 percent or more can be expected for the density estimations, and since they are used to compute fluence, these errors also appear in the surface recession rates for satellite simultaneously with recession measurements during future flight experiments.

5.1 Space Environments and Technology Archive System

The Space Environments and Technology Archive System is maintained at NASA's Langley Research Center in Hampton, VA. Through it, data, publications, and the status of materials exposure experiments and investigations are available on the worldwide web (see INTERNET WEB SITES, p.35). AO-related databases include LDEF, MEEP, the AORP experiment, the ESEM, the European Retrievable Carrier, and the HST database. Other databases of interest include the Clementine Deep Space Probe Science Experiment, the Meteoroid and Debris Impact Monitor, the Meteoroid Impact Sensor, and the Microparticle Impact Detector.

5.2 Boeing Database

The Boeing Company maintains an extensive database available through its facilities in Seattle, WA. Boeing's Solar Shadow (SOLSHAD) program predicts solar exposure to satellite surfaces which may shadow or reflect on one another. It is written in FORTRAN and runs under Sun operating system (OS), UNIX. The source code is available on tape. Data are input as a geometry description, materials properties, and ram direction through an interactive data file builder. Results are output as tabular, graphical output of AO flux on shadowed surfaces. Solar exposure was compared to independent calculation to verify the program. For information, contact:

Dr. Gary Pippin, M/S 82–32
Boeing Defense & Space Group
P.O. Box 3999
Seattle, WA 98124–2499
(253–773–2846; *Harold.Pippin@PSS.Boeing.com*)

5.3 Canadian Database

The University of Toronto[1] with the aid of the Canadian Space Agency has developed a comprehensive database for the properties of black, white, reflective, and transmissive spectrally selective surfaces, including an oxygen exposure effects module. Features include:

- Optical, thermal, mechanical and physical, electrical, and chemical properties
- Space- and ground-based environmental/contamination effects on the properties listed above
- References from published and nonpublished literature
- Background information on applications, construction types, and precedents
- Manufacturers' data and vendor information for commercially available products, background information applicable, current measurement facilities, and consulting services.

For information, contact:

Susan H.C.P. McCall
Institute for Aerospace Studies
University of Toronto
4925 Dufferin Street
Downsview, Ontario, Canada L3T 3R1

6. GROUND-BASED SIMULATIONS

6.1 Atomic Oxygen Exposure Simulators

At this writing, no ground-based facility can fully simulate orbital interactions with materials. Nevertheless, several facilities provide exceptional service in simulating AO and AO+UV effects.

6.1.1 MSFC

Two AO exposure facilities are operated at NASA/MSFC in Huntsville, AL. The AODTS can produce up to 5×10^{16} atoms/cm^2/sec neutral oxygen atoms of less than 0.1 eV thermal energy. The AO plasma is produced by a 14.7-MHz r-f field. However, the sample fixture is located external (downstream) of the generated plasma. This eliminates the problems of r-f field heating and the ionic plasma. Near UV (200–400 nm) or VUV (118–200 nm) radiation sources may be added for synergistic studies.

The Atomic Oxygen Beam Facility (AOBF) more closely approximates orbital AO than the AODTS. It uses a 2.45-GHz, 2-kW r-f field to generate plasma which is confined by a 4-K gauss magnetic field to increase the flux. Ions are neutralized by collision with a metal plate. The AOBF can produce 5 eV AO at 2×10^{16} atoms/cm^2/sec. VUV radiation equivalent up to 150 suns may be added (fig. 10).

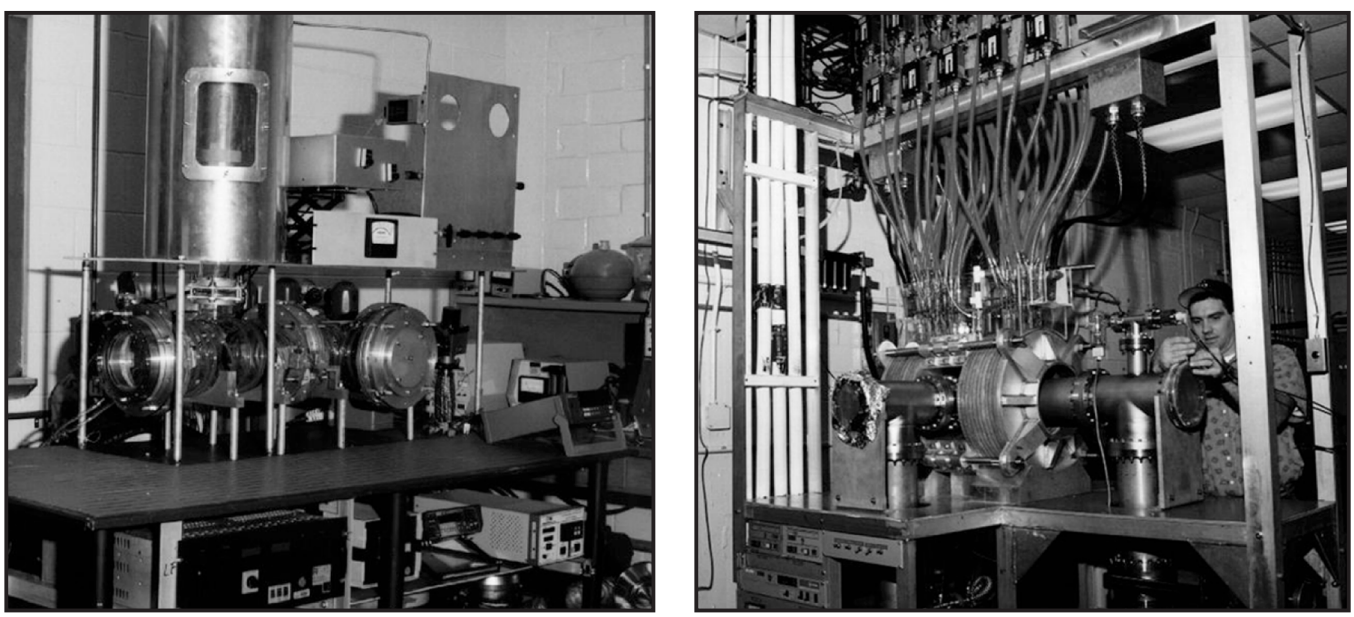


Figure 10. NASA MSFC's (a) AODTS and (b) AOBF.

Samples are fully characterized before and after exposure. The Space Environment Effects Team can measure mass changes in tens of micrograms, solar absorptance, IR emittance, VUV reflectance, VUV-IR transmission, Fourier transform IR spectroscopy, spectrofluorescence, bidirectional reflectance distribution function, surface roughness, and electrical conductivity.

6.1.2 Lewis Research Center

The Space Environment Effects Laboratory at NASA's Lewis Research Center in Cleveland, OH, includes an AOBF which provides the largest capacity for AO exposure globally; i.e., across the entire sample. It provides accelerated rates of exposure to directed/scattered beams of AO and VUV radiation and in situ optical characterization. The chamber has a 10^{-6}-torr base operating pressure.

Various materials can be exposed with uniform flux over approximately 30 cm^2. An electron-cyclotron resonance plasma source operates on pure oxygen to generate low-energy beam, predominantly of neutral AO with ion content of less than 1 percent at energies less than 30 eV. The AO arrival flux is controllable within range of 10^{15}–10^{17} atoms/cm^2/sec. Total fluence can be up to 1.6×10^{21} atoms/cm^2.

To evaluate synergistic effects of AO, VUV radiation emitted by source can irradiate samples or be blocked allowing only AO exposure. Deuterium lamps provide a second source of VUV radiation with intensity levels of 115–200 nm of 3–5 equivalent suns. Specimens can also be heated and experiments can run, fully automated, for up to a month.

6.1.3 Other U.S. Facilities

A number of facilities in the United States can simulate space AO effects, although AO and AO+UV capabilities are provided as part of a larger suite of physical effects. The University of Alabama in Huntsville has a Surface Science Interaction Laboratory with an AO generator comprising a microwave discharge cavity to produce an AO beam at 0.2–5.0 eV and a fluence of 5×10^{14} atoms/sec.

Researchers at PPPL use a plasma source to produce extremely high flux, neutral atomic beams covering the 1–50 eV hyperthermal energy range. Beams of neutral atoms, including reactive gases such as oxygen, nitrogen, and hydrogen, have impinged on a variety of technically important materials to measure the rates of interaction. Work has included the evaluation of the erosion rates of spacecraft materials by 5-eV neutral AO. The PPPL source can duplicate many aspects of more than 6 yr of actual orbital exposure in less than 40 hr of laboratory time. The facility has recently been modified to study AO+UV effects. It can produce an AO flux of 5.6–20×10^{15} atoms/cm^2/sec, and a fluence of 6–23×10^{19} atoms/cm^2. Experiments allow independent control of the flux and energy of the beam and of the intensity and wavelength of the light from the UV to the IR.

The U.S. Air Force Phillips Laboratory at the University of Southern California (USC) has developed an AO facility at USC. It produces AO at 5–80 eV and up to 10^{15} atoms/sec. The U.S. Air Force also is planning an AO facility for Arnold Engineering Development Center in Tullahoma, TN, for test cell and laboratory applications.

Other facilities in the United States include the Atomic Oxygen Exposure Facility at the Space Power Institute, Auburn University, Auburn, AL; ATOX Irradiation Services, Los Alamos National Laboratory; Lockheed Martin (originally at General Electric Space Division); the Jet Propulsion Laboratory; and the University of Texas at Austin.

6.1.4 Non-U.S. Facilities

The space agencies and industries of Canada, Europe, Japan, and Russia have a number of AO and space simulation facilities. A comprehensive list is not available, so only a few details can be presented here.

A microwave discharge-type facility is available at the University of Toronto's Institute for Aerospace Studies. It reportedly mimics LEO exposures accurately, although performance specifications are not available. Resonance Ltd. of Barrie, Ontario, Canada, has developed an atomic oxygen exposure and measurement system which provides an AO fluence equivalent to 2×10^{16} atoms/cm^2/sec, and also provides simultaneous UV and VUV illumination.

Japan's Ultra-High Temperature Materials Research Center/Research Institute has an oxidation/sublimation testing machine that uses a quadrupole mass spectrometer to measure outgassing from 30-mm^2 samples as they are exposed to AO and UV in a vacuum. Specimens may be heated to up to 2,300 °C by a xenon lamp and measured by an electronic mass balance to 0.1 mg.

A Surface Analysis System at the Jenoptik Technologie GmbH, Jena, Germany, comprises three similar vacuum chambers arranged in series. The simulation modules, on the ends, include xenon, deuterium, and VUV lamps. The analysis module, in the center, includes an x-ray photoelectron spectroscopy, auger electron spectroscopy, and secondary ion mass spectroscopy.

6.2 Laboratory Exposure Guidelines

Regardless of the technology or platform used to simulate the AO environment, test procedures should include the following recommendations to ensure adequate exposure and consistent results:

1. Clamping techniques used to hold the specimen within the holder should not produce high levels of stress at the holder-specimen interface. Previous flight results have demonstrated induced stress tends to accelerate reaction rates. Prolonged laboratory exposure using an improperly designed sample holder may result in the specimen failing in regions of high stress and separating from the fixture.

2. The sample holder should be vented to avoid trapping pockets of gas behind the specimen. When the trapped gas is heated by the plasma discharge, it can expand to produce high stress at the holder-specimen interface.

3. The fixture should be radiatively or conductively cooled to control specimen temperature. For the thermal energy AO systems (NASA MSFC's AODTS, sec. 6.1.1), sample temperature should be kept as constant and as close to room temperature as possible, since reactivities of some materials increase with elevated temperatures. For the 2.5-GHz microwave systems, the 5-eV AO has equivalent temperature of 55,000 K (98,508 °F), so sample temperature is irrelevant to reactivity calculations. However, sample temperature should not exceed that which the material will see on orbit. The potential experimenter should be aware that the 2.5-GHz microwave source also produces significant amounts of UV radiation that can enhance a material's sensitivity to AO erosion.

6.3 Computer Simulations

6.3.1 Boeing

Boeing has developed three programs—FLUXAVG, SHADOWV2, and SOLSHAD—to predict the exposure of simple or complex surfaces to AO or UV or both. All three have demonstrated good agreement with actual exposures on LDEF. FLUXAVG models AO fluence at 6-min intervals to satellite surfaces which are neither shadowed nor exposed to AO scattering by other surfaces. SHADOWV2 models AO fluence with interfering surfaces involved. It includes an interactive builder to develop the satellite's geometry. The SOLSHAD program predicts solar exposure and shadowing which may shadow or reflect on one another. It is written in FORTRAN and runs under Sun OS, UNIX. The source code is available on tape. Data are input as a geometry description, materials properties, and ram direction through an interactive data file builder. Results are output as tabular, graphical output of AO flux on shadowed surfaces. Solar exposure was compared to independent calculation to verify the program.

Another space environment software tool, soon to be available through the Space Environments and Effects Program, is the spacecraft materials selector expert system being developed by Boeing. This expert system with an inference engine and knowledge bases may be used to select materials for use in space that meet specific engineering requirements. It estimates AO fluence, UV radiation dose, and ionizing particle fluence and dose levels. It also has some predictions of contamination effects due to outgassing.

For information, contact:

Dr. Gary Pippin, M/S 82–32,
Boeing Defense & Space Group,
P.O. Box 3999,
Seattle, WA 98124–2499
(253–773–2846; *Harold.Pippin@PSS.Boeing.com*)

6.3.2 Europe

The European Space Agency (ESA), through the ESA Technology and Engineering Center in Noordwijk, The Netherlands, has developed two programs for simulating AO exposure. The ATOXSAPRE program computes fluxes, fluences and resulting erosion on simply oriented surfaces (ram, Sun-pointed, and anti-Sun pointed). An ESABASE/Atomox application has also been developed which takes into account more complex geometries and orientations.

7. DIAGNOSTIC EQUIPMENT

Several instruments are available to measure AO erosion rates aboard a spacecraft. Awareness of significant changes in AO erosion rates will give mission planners the flexibility to alter attitudes to protect vulnerable areas of a spacecraft or to change operations plans. Because of the nature of AO erosion, all of these techniques at present are sacrificial (i.e., the sensor is unusable after its coating is eroded).

7.1 Optical Fiber Sensors

A newly developed optical fiber sensor concept offers the possibility of gauging the AO erosion of polymers in the space environment (Li). The design compares the brightness of light transmitted by two fibers, one exposed to and one protected from the AO flux. The fibers are polymethyl-methacrylate which erodes faster than polymers such as polyimide (Kapton®), FEP Teflon™, and graphite epoxy. It is also affected by UV radiation. Thus, a properly designed system can provide an early warning of potential failure due to AO effects.

In the sensor design, light from a light-emitting diode is split into two signals in a 50/50 optical fiber coupler. One signal goes immediately to a reference photodiode, and one is split again and the two components pass through a protected reference fiber and an exposed sensing fiber. The light then passes through an optical switch and is sensed by a photodiode. This setup ensures that the only variations measured by the system are caused by changes in the exposed section of the sensing fiber, and that thermal and cosmic radiation effects are sensed evenly. In tests in a vacuum chamber with an AO fluence, the optical fiber sensor measured erosion rates that corresponded well with a Kapton® witness sample. Some work remains to quantify the system fully and to calibrate it for potential flight use.

7.2 Quartz Crystal Microbalances

The EUV Explorer carried two TQCM's coated with Teflon™ for studies of AO effects (Lorentson et al.). One coated TQCM was placed on the Sun side of the spacecraft and the other was placed on the shaded side. The spacecraft was launched June 7, 1992, into an orbit 500-km (310-mi) high and inclined 28.5 deg, an orbit where spacecraft experience extensive AO erosion.

The TQCM's were coated with a 600-nm-thick layer of FEP Teflon™. The mass on the quartz crystal can be measured by passing an electrical current through the crystal and measuring its response frequency. The spacecraft was designed to roll once per orbit so that its telescopes scan the sky and avoid the Sun. This meant that the TQCM's were pointed into and then away from the AO flow. Shadowing and other factors also affected the exposure of the two TQCM's during the mission.

An interesting result noted was the leveling of the decay rate after an extended period. Teflon™ erosion accelerated after 25 days when the spacecraft calibration period ended and its attitude changed. This exposed the TQCM's to sunlight and increased the erosion rate from an estimated 1.86×10^{-26} cm^3/atom to 55.8×10^{-26} cm^3/atom, a factor of 30. Eventually, though, the erosion rate decayed to match the

initial rate. The investigators believe that this was due to the susceptible molecular bonds having been eroded by UV radiation and the stronger ones still resisting the change.

7.3 Carbon Sensors

The AORM on EOIM–III operated by measuring the electrical conductance of carbon sensor elements. Resistance increases as the coating is eroded until no current is conducted when the coating is gone. The design of such a sensor must consider that erosion can be uneven across a surface and allow sufficient area and depth to provide a proper measure during a mission. AORM also had protected carbon resistors to compensate for temperature changes which might bias the readings.

7.4 Catalytic Probes

Catalytic probes measure heat produced by the recombination of oxygen atoms striking a catalytic silver oxide surface.[2]

7.5 Portable Reflectometer

For space missions where crew access is available, AZ Technology of Huntsville, AL, has developed a laboratory-calibrated, portable reflectometer that can be used on exposed surfaces during extravehicular activity. This has been demonstrated on *Mir*. The reflectometer includes a protected reference surface and other features to ensure measurement accuracy. Changes in visible and UV reflectivity can serve as a good measure of changes due to AO and UV exposure. The reflectometer can measure reflectivity across a wavelength range of 250–2,500 nm and indicate changes in thermal performance.

8. SURFACE RECESSION PROFILES

As discussed earlier, the amount of surface recession for a uniform material of known reactivity is directly proportional to AO fluence, or the total number of atoms impinging on each square centimeter of exposed material for the duration of the intended mission. Fluence, in turn, is dependent on such parameters as spacecraft altitude, attitude, orbital inclination, mission duration, and solar activity.

The AO fluence for a particular mission may be determined by using either mass spectrometer incoherent scatter thermosphere model (MSIS–90) or Environmental Workbench 4.0, both available through the Space Environment and Effects Program web site (*http://see.msfc.nasa.gov*). The MSIS–90 model calculates the following thermosphere parameters from ground to thermospheric heights: kinetic temperature of the neutrals, the number densities of the individual species (He, O, N_2, Ar, H, N), and the total mass density and pressure. MSIS–90 is a FORTRAN program and can be compiled to run on various platforms. It provides a tabular data output of density, total mass density, neutral and exospheric temperatures for each gas species (in principle, a user should be able to output the tabular data to disk and use the file as input for a spreadsheet or scientific graphics program). The source code is downloadable as a 110 K text file by anonymous FTP from:

Location: *nssdc.gsfc.nasa.gov*
Folder: *pub/models/atmospheric/msise90/*
File name: *msise90.txt*

Environmental Workbench also has graphing capability and other environment models with it, so estimated AO fluence to specific areas of a spacecraft may be calculated, plus UV, plasma, etc. Environmental Workbench runs on PC, UNIX, IRIX, and Sun OS platforms. At the time of publication, Environmental Workbench used the older MSIS–86 code. For more information contact:

Ricaurte Chock
NASA Lewis Research Center—MS 302–1
21000 Brookpark Road
Cleveland, OH 44135
Phone: 216–433–8057
E-mail: *ronin@lerc.nasa.gov*

The Space Environments and Effects Program web site also has other thermosphere models available for spacecraft designer use and is updated as new models become available.

REFERENCES

1. McCall, S.H.C.P., et al.: "The Atomic Oxygen Exposure Effects Module of the Database for the Properties of Black, White, Reflective, and Transmissive Spectrally Selective Surfaces." *Stray Radiation in Optical Systems III*, SPIE 2260, July 26–27, 1994.

2. Cuthbertson, J.W., Langer, W.D., Motley, R.W., and Vaughn, J.A.: "Atomic Oxygen Beam Source for Erosion Simulation." Fourth Annual Workshop on Space Operations Applications and Research, NASA CP–3103, Vol. II, June 1990.

BIBLIOGRAPHY

Banks, B.A.; et al.: "Ion Beam Sputter-Deposited Thin Film Coatings for Protection of Spacecraft Polymers in Low-Earth Orbit." AIAA 85–0420, AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 14–17, 1985.

Banks, B.A.; et al.: "Monte Carlo Modeling of Atomic Oxygen Attack of Polymers with Protective Coatings on LDEF." LDEF—69 Months in Space. First Post-Retrieval Symposium. Hampton, VA, NASA CP–3134, pp. 1137–1150, 1992.

Cuthbertson; Langer; Motley; and Vaughn.: "Atomic Oxygen Beam Source for Erosion Simulation." Fourth Annual Workshop on Space Operations Applications and Research, NASA CP–3103, Vol. II, June 1990.

Czepiela, S.; Hastings, D.; and McManus, H.: "Charging in the Space Environment." 35th Aerospace Sciences Meeting, AIAA 97–0629, January 6–10, 1997.

Euler, H.C.: "Solar Activity Environment Estimation Methodologies." AIAA 1995 Space Programs and Technologies Conference, Huntsville, AL, AIAA 95–3568, September 26–28, 1995.

Fromhold, A.T., et al.: "Reaction of Metals in Lower Earth Orbit During Space Shuttle Flight 41–G." AIAA 85–7028, AIAA Shuttle Environment and Operations II Conference, Houston, TX, November 1985.

Funk, J.G.; and Pearson, S.D.: "Space Environment and Effects Program." AIAA 1995 Space Programs and Technologies Conference, AIAA 95–3565, Huntsville, AL, September 26–28, 1995.

George, P.E.; Dursch, H.W.; and Hill, S.G.: "Space Environmental Effects of LDEF Composites: A Leading Edge Coated Graphite Epoxy Panel." LDEF—69 Months in Space. First Post-Retrieval Symposium. Hampton, VA, NASA CP–3134, pp. 923–939, 1992.

Gregory, J.C.; and Peters, P.N.: "Measurement of Reaction Rates and Activation Energies of 5 eV Oxygen Atoms With Graphite and Other Solid Surfaces." AIAA 85–0417, AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 14–17, 1985.

Gull, T.R.; et al.: "Effects of Optical Surfaces at Shuttle Altitudes." AIAA 85–0418, AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 14–17, 1985.

Harvey, G.A.: "Silzane to Silica." LDEF—69 Months in Space. First Post-Retrieval Symposium. Hampton, VA, NASA CP–3134, pp. 797–810, 1992.

Kent, B.J.; et al.: "Boron Carbide as Atomic Oxygen Protection for the Lexan-Carbon Filter on the ROSAT Wide Field Camera." In Multilayer and Grazing Incidence X-Ray/EUV Optics, Richard B. Hoover, ed., SPIE, Vol. 1546, pp. 312–321, July 22–24, 1991.

"LDEF Materials Workshop 1991." Hampton, VA, NASA CP–3162, 1992.

"LDEF—69 Months in Space," First Post-Retrieval Symposium, Hampton, VA, NASA CP–3134, 1992,

"LDEF—69 Months in Space." Second Post-Retrieval Symposium, Hampton, VA, NASA CP–3194, 1993.

Leger, L.J.: "Oxygen Atom Reaction With Shuttle Materials at Orbital Altitudes." NASA TM–58246, May 1982.

Leger, L.J., et al.: "STS Flight 5 LEO Effects Experiment—Background Description and Thin Film Results." AIAA 83–2631, AIAA Shuttle Environment and Operations Meeting, Washington, DC, October–November 1983.

Leger, L.J.; Visentine, J.T.; and Schliesing, J.A.: "A Consideration of Atomic Oxygen Interaction With Space Station." AIAA 85–0476, AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 14–17, 1985.

Leger, L.; Visentine, J.; and Santos-Mason, B.: "Selected Materials Issues Associated With Space Station." SAMPE 18th International Technical Conference, Seattle, WA, October 1986.

Liang, R; and Gupta, A.: "Mechanistic Studies of Kapton® Degradation in Shuttle Environments." AIAA 83–2656, AIAA Shuttle Environment and Operations Meeting,Washington, DC, October–November 1983.

Liang, R.H.; and Gupta, A.: "Mechanistic Studies of Interaction of Materials with Energetic Oxygen Atoms in Low Earth Orbit." AIAA 85–0422, AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 14–17, 1985.

Linton, R.C.; and Kamenetzky, R.R.: "Interim Results of Experiment A0034." LDEF—69 Months in Space. First Post-Retrieval Symposium, Hampton, VA, NASA CP–3134, pp. 1151–1168, 1992.

Lorentson, C.C.; et al.: "Verification of Molecular Contaminant and Atomic Oxygen Modeling for the EVEEP Experiment." In Optical System Contamination: Effects, Measurements, and Control IV, A. Peter M. Glasford, ed., SPIE, Vol. 2261, pp. 72–83, July 28–29, 1994.

Mallon, J.J.; Uht, J.C.; and Hemminger, C.S.: "Surface Analyses of Composites Exposed to the Space Environment on LDEF." LDEF—69 Months in Space. First Post-Retrieval Symposium. Hampton, VA, NASA CP–3134, pp. 963–976, 1992.

McCall, Susan H.C.P.; et al.: "The atomic oxygen exposure effects module of the database for the properties of black, white, reflective, and transmissive spectrally selective surfaces." Stray Radiation in Optical Systems III, July 26–27, 1994, SPIE 2260.

Miglioncio, C.J.: "LDEF Fiber-Composite Materials Characterization." LDEF—69 Months in Space. First Post-Retrieval Symposium, Hampton, VA, NASA CP–3134, pp. 905–922, 1992.

Park, J.J.; et al.: "Effects of Atomic Oxygen on Paint and Optical Coatings." AIAA 83–2634, AIAA Shuttle Environment and Operations Meeting, Washington, DC, October–November 1983.

Peters, P.N.; Gregory, J.C.; and Swann, J.T.: "Effects on Optical Systems from Interactions with Oxygen Atoms in Low Earth Orbits." Applied Optics, Vol. 25, p. 8, April 15, 1986.

Pippin, G.; and Crutcher, R.: "LDEF Materials Data Analysis: Representative Examples." LDEF—69 Months in Space, First Post-Retrieval Symposium, Hampton, VA, NASA CP–3134, pp. 1187–1199, 1992.

Raikar; et al.: “Space Environmental Effects on Thin Metallic Films.” AIAA 1995 Space Programs and Technologies Conference, AIAA 95–3566, Huntsville, AL, September 26–28, 1995.

Smith, K.: “Evaluation of Oxygen Interaction with Materials (EOIM)—STS–8 Atomic Oxygen Effects.” AIAA 85–7021, AIAA Shuttle Environment and Operations II Conference, Houston, TX, November 1985.

Visentine, J.T.: “Atomic Oxygen Effects Measurements for Shuttle Missions STS–8 and 41–A.” NASA TM–100459, September 1988.

Visentine, J.T.; and Leger, L.J.: “Material Interactions With the Low-Earth Orbital Environment: Accurate Reaction Rate Measurements.” AIAA 85–7019, AIAA Shuttle Environment and Operations II Conference, Houston, TX, November 1985.

Visentine, J.T.; et al.: “STS–8 Atomic Oxygen Effects Experiment.” AIAA 85–0415, AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 14–17, 1985.

Whitaker, A.F.; et al.: “LEO Atomic Oxygen Effects on Spacecraft Materials.” AAIA 83–2632, AIAA Shuttle Environment and Operations Meeting, AIAA Shuttle Environment and Operations Meeting, Washington, DC, October–November 1983.

Whitaker, A.F.; et al.: “Orbital Atomic Oxygen Effects on Thermal Control and Optical Materials —STS–8 Results.” AIAA 85–0416, AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 14–17, 1985.

Whitaker, A.F.; et al.: “Protective Coatings for Atomic Oxygen Susceptible Spacecraft Materials — STS 41–G Results.” AIAA 85–7017, AIAA Shuttle Environment and Operations II Conference, Houston, TX, November 1985.

Whitaker, A.F.; and Dooling, D.: “LDEF Materials Results for Spacecraft Applications—Executive Summary.” NASA CP 3261, 1995.

Whitaker, A.F.; et al.: “Atomic Oxygen Effects on LDEF Experiment A0171.” LDEF—69 Months in Space, First Post-Retrieval Symposium, Hampton, VA, NASA CP–3134. pp. 1125–1135, 1995.

Zimcik, D.G.; and Maag, C.R.: “Results of Apparent Atomic Oxygen Reactions with Spacecraft Materials During Shuttle Flight STS 41–G.” AIAA 85–7020, AIAA Shuttle Environment and Operations II Conference, Houston, TX, November 1985.

Zinner, E.; et al.: “Erosion of Mylar and Protection by Thin Metal Films.” AIAA 83–2636, AIAA Shuttle Environment and Operations Meeting, Washington, DC, October–November 1983.

RELATED DOCUMENTS

Silverman, E.M.: "Space Environmental Effects on Spacecraft: LEO Materials Selection Guide." NASA CR–4661, August 1995.

Solar-Geophysical Data Prompt Reports, National Oceanic and Atmospheric Administration, Department of Commerce, Boulder, CO, January 1985 and subsequent issues.

"Natural Environment Design Criteria for the Space Station Definition and Preliminary Design (First Revision)." NASA TM–86460, Marshall Space Flight Center, Huntsville, AL, September 1984 and subsequent issues.

INTERNET WEB SITES

NASA

Lewis Research Center, Atomic Oxygen Beam Facility
http://www.lerc.nasa.gov/WWW/epbranch/facility/aobeam.htm

NASA Space Environments and Effects Program
http://see.msfc.nasa.gov

Marshall Space Flight Center, Space Environmental Effects Team
http://msfcpec1.msfc.nasa.gov/eh12/eff_lab.html

Langley Research Center, Space Environmental Effects and Archive System
http://setas-www.larc.nasa.gov/setas/

Other U.S. Government

Space Environment Laboratory, NOAA (solar activity data)
http://www.esl.noaa.gov

Industry and Academia

Auburn University, Space Power Institute, AO Laboratory
http://hyperoptic.spi.auburn.edu/neely/ao.html

Other Sites

University of Toronto, Institute for Aerospace Studies
http://www.utias.utoronto.ca/

Resonance, Canada
http://www.resonance.on.ca/ATOMS.html

European Space Agency, ESA Space Technology end Engineering Center, Space Analysis and Effects Section
http://www.estec.esa.nl/wmwww/WMA/atox_analysis.html

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"Material Selection Guidelines to Limit Atomic Oxygen Effects on Spacecraft Surfaces" provides guidelines in selecting materials for satellites and space platforms, designed to operate within the Low-Earth orbit environment, which limit the effects of atomic oxygen interactions with spacecraft surfaces.

This document should be treated as an introduction rather than a comprehensive guide since analytical and flight technologies continue to evolve, flight experiments are conducted as primary or piggyback opportunities arise, and our understanding of materials interactions and protection methods grows. The reader is urged to consult recent literature and current web sites containing information about research and flight results.

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