CHARLES E. VEST

THE EFFECTS OF THE SPACE ENVIRONMENT ON SPACECRAFT SURFACES

The spacecraft materials engineer must take into account the effects of the space environment on the many materials used in spacecraft construction, especially the effects of atomic oxygen and thermal vacuum. In low Earth orbit, atomic oxygen erodes the surfaces of spacecraft (through chemical reaction and impact) and significantly degrades their design performance characteristics. The high temperatures and high vacuum increase the outgassing rate of the material; its volatile constituents begin to outgas and condense onto critical components such as optical surfaces, causing degradation of their design properties. Spacecraft materials engineers accommodate the harsh effects of the space environment through careful selection of resilient materials and use of protective coatings and/or other devices such as sunshades and baffles. This article discusses some of the effects of atomic oxygen and thermal vacuum on spacecraft materials, shows how to extrapolate these effects into higher orbits, and suggests alternative materials.

INTRODUCTION

Construction materials for all components on a spacecraft must be selected on the basis of two major considerations: their specific application and their location on the craft. The critical surfaces cannot be allowed to degrade to the point that the mission is compromised by the space environment, specifically by the effects of atomic oxygen (AO) and thermal vacuum (TV) (thermal vacuum is defined here as high surface temperatures under vacuum conditions).

The open literature contains many papers that describe effects of the space environment on spacecraft materials. Visentine[1] stated that the low–Earth-orbit (LEO) atmosphere is composed of 80% AO and 20% N_2, that the AO densities vary with solar activity during periods of high solar activity, that the impinging AO flux can be as high as 10^{15} atoms/cm^2, causing a surface thickness loss of as much as 6 μm/day in organic materials at moderate altitudes (300 km), and that ram-oriented surfaces receive more fluence than solar-inertial surfaces (ram-oriented surfaces are those normal to the direction of flight; solar-inertial surfaces are the reverse of the ram direction). Muscari[2] illustrated the profound effects of TV on optical materials by showing the changes in the transmission of light through an optical lens (condensed thickness of an outgassed film versus wavelength). Vest et al.[3] showed that proper selection of materials significantly reduces the potential for degradation and contamination of critical spacecraft surfaces.

EFFECTS OF ATOMIC OXYGEN

Atomic oxygen is the predominant and most reactive gaseous species at the LEO altitude. It forms in the ionosphere through the dissociation of O_2 by ultraviolet radiation in the 100- to 200-nm wavelengths:

$$O_2 + h\nu \quad \begin{cases} \longrightarrow \ O + O & (99+\%) \\ \longrightarrow \ O^+ + O & (<<1\%) \end{cases}$$

where h is Planck's constant and ν is the frequency of the radiation. The density of AO varies with altitude; it is most dense in the 150- to 500-km range (1×10^{10} to 1×10^7 atoms/cm^3) and less dense at altitudes above that range (at 1000 km, density is 1×10^2 to 1×10^6 atoms/cm^3). As AO decreases in density with increasing altitude, its effects cause less concern (see Fig. 1). Even at higher altitudes, where the density is low, AO can have an energy of 5 eV as a result of the velocity of the spacecraft through the AO atmosphere. This energy is about equal to the chemical bonding energy. The possibilities for reactions with large cross sections can be substantial. Many reactions can occur when the input energy is equal to or greater than the energy of the molecular bonds, allowing scission of the bonds in the molecule. The altitude of flight, the orientation of the surfaces with respect to the ram direction, and the extent of solar activity determine the AO fluence, given as flux (atoms/cm^2) × exposure period (seconds), with flux defined as number density of AO (atoms/cm^3) × orbital velocity (cm/s). For example, on two space transportation system (STS) or shuttle flights of almost the same duration, one at 300 km and one at 225 km, the total accumulated fluences of 1.0×10^{20} and 3.5×10^{20} atoms/cm^2, respectively, were determined.

The AO damage to surfaces is termed surface recession and is directly related to fluence. Surface recession is defined as material reaction efficiency (cm^3/atom) × AO fluence (atoms/cm^2), where reaction efficiency is the

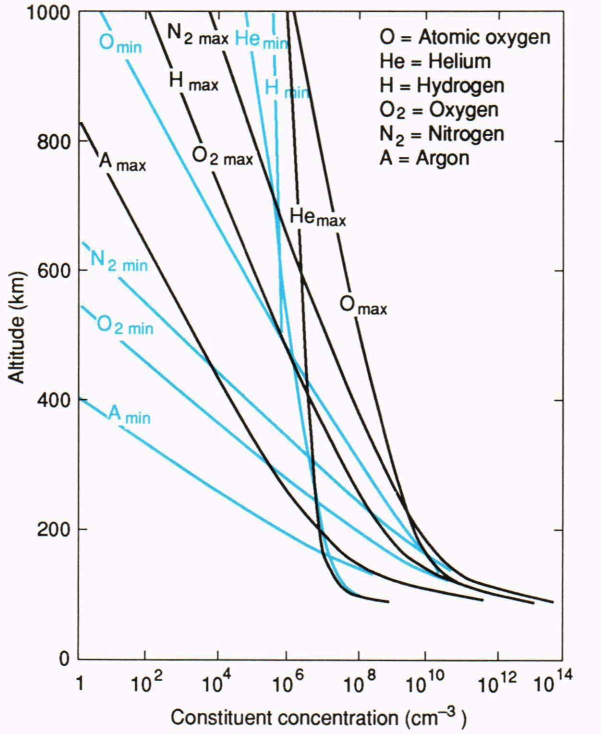

Figure 1. Concentration of space environment constituents at altitudes from 100 to 1000 km. Minimum solar conditions: 0400 h using $\bar{F}_{10.7}$ = 70 and $\bar{A}_p$ = 0. Maximum solar conditions: 1400 h using $\bar{F}_{10.7}$ = 230 and $\bar{A}_p$ = 35. $\bar{F}_{10.7}$ is a wavelength of 10.7 cm used to measure the radio flux density for solar activity measurement. $\bar{A}_p$ is the geomagnetic index (measure of the Earth's magnetic field intensity). (Reprinted, with permission, from Ref. 2.)

volume of material loss per incident oxygen atom (3.0×10^{-24} cm^3/atom for Kapton, a much used thermal control/blanket material). If the surface under consideration is facing the ram direction, the calculation of total fluence is straightforward; if the surface is facing the reverse direction (solar-inertial direction), the fluence is more difficult to determine, but in general there will be significantly less surface recession. Surface recession and reaction efficiency are the factors that the materials engineer must consider when selecting materials.

The concern of the spacecraft materials engineer is to select construction materials that will be the least damaged by AO. Visentine[4] presented data on surface recession and reaction efficiencies for organic materials tested on shuttle mission STS-8 (s ee Table 1). The data show that Kapton, Mylar A, clear Tedlar, and polyethylene have reaction efficiencies of 3.0×10^{-24} to 3.6×10^{-24} cm^3/atom, whereas Teflon TFE and Kapton F (Teflon-coated Kapton) have reaction efficiencies of $<0.05 \times 10^{-24}$ cm^3/atom. The data also show that the surface recession (in micrometers) varies from 10.4 to 12.6 for the Kapton, Mylar A, clear Tedlar, and polyethylene; the values for Teflon TFE and Kapton F are <0.2. In addition to these data, Table 1 shows that the recession rates are not affected by temperature or the specific side exposed but may be affected by the thickness of the material. It appears that thickness has no effect on the recession rate of Kapton. The photographs in Figure 2 show a Kapton surface before and after exposure to AO, illustrating the degradation.

If a material with an unacceptable reaction efficiency must be used, its surface can be protected by a special coating. Whitaker et al.[5] evaluated the effects of AO on thermal coatings and optical materials (thirty-five materials). These materials included ten paint specimens and eight silver solar-cell interconnects maintained at temperatures of 210° ± 15°C; the temperature of the remainder of the samples was uncontrolled (estimated to be about 50°C). Table 2 shows representative results of the tests. The data show that the black paints had an increase in solar absorptivity, α_s, and all paints with specular components became diffuse (Fig. 3). The data also show that the paints with inorganic fillers performed better than those without. Two paints were overcoated with two silicone materials (OI-650 and RTV 670); the OI-650 coating prevented any degradation of the large-angle scatter of the surfaces, whereas paints coated with RTV 670 became slightly diffused. In Ref. 5, the authors evaluated nine specimens of mirror coatings, including 275 Å of MgF_2 over aluminum, SiO_x over aluminum and silver, and proprietary dielectric films over aluminum and silver. The results showed that no measurable reflectivity degradation (121.6- to 220.0-nm range) was caused by either AO or the very slight micrometeor-cratered areas. The data from these experiments imply that, although there is some degradation of paints, coatings are available that will reduce or eliminate damage.

Slemp discussed the results of AO on the properties of composites, polymeric films, and coatings.[6] His evaluation showed that thin graphite-epoxy composites and polymeric films exhibit significant surface erosion by AO, that the experimental thin metallic coatings tested were not eroded, and that a polysiloxane–polyimide block copolymer showed a reaction efficiency of less than an order of magnitude greater than a straight polyimide. The photographs in Figure 4 illustrate the damage to the surfaces after AO reactions.

Whitaker et al.[7] evaluated sixteen materials (metallizations, silicones, and fluorinated ethylene polymer [FEP] Teflon) as protective coatings for spacecraft surfaces that were flown as an experiment on shuttle flight STS-41G. Indicators showed that the materials reached a temperature of 200°F, but the time at temperature was not recorded. Table 3 lists the results of the evaluation. The effectiveness of the silicone (OI-651) protecting the Z302 glossy black paint was evident; the sample showed no change in its specular characteristics. The authors also evaluated samples of Kapton F (Kapton H with a 0.1-mil overcoat of FEP Teflon) as a means of protecting the Kapton H film (thermal control blankets) from the erosion by AO. The results were consistent with other experimenters' results; that is, no significant effect on the Kapton F film was observed. Table 4 shows the results for two metallizations (gold at three thicknesses and palladium at two thicknesses) and two silicone coatings. The DC-1105 silicone coating protected the silver, but the metals did not (as a result of contamination of the surface, insignificant coating thickness, and poor coverage). Photographs

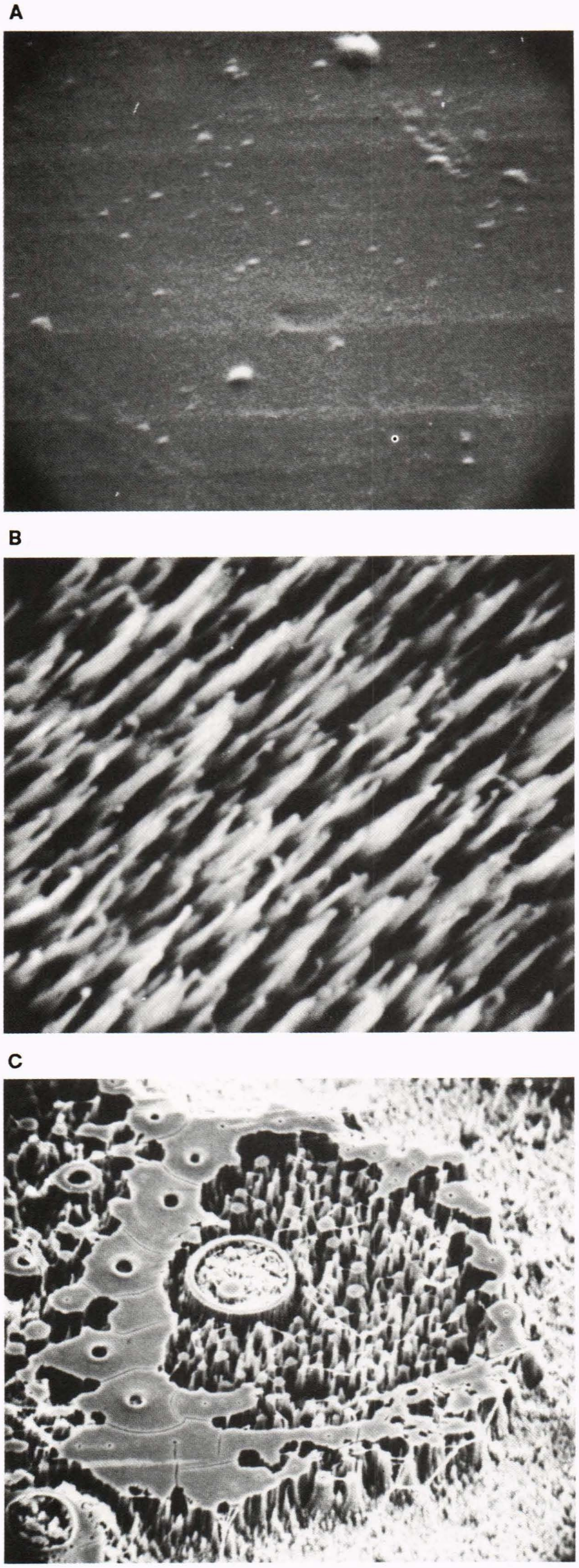

Figure 2. Scanning electron microscope photographs (10,000×) of a Kapton film. **A.** Before exposure to atomic oxygen. **B.** After exposure to atomic oxygen during space shuttle mission STS-8. **C.** A contaminated area (silicone) after exposure to atomic oxygen during STS-8.

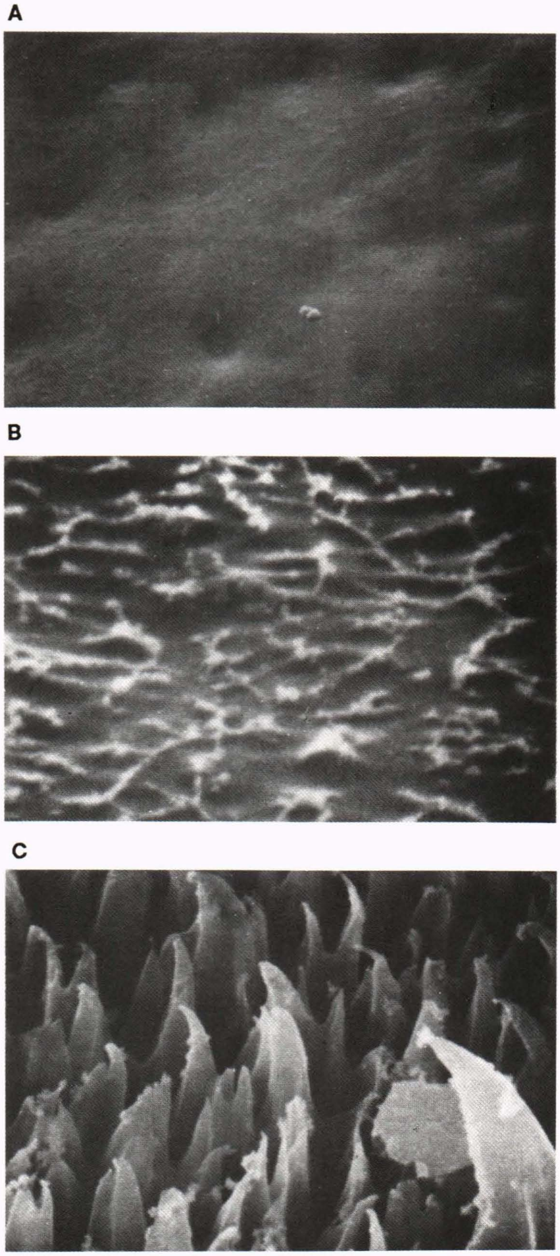

Figure 3. Scanning electron microscope photographs of Z302 white paint exposed to atomic oxygen during space shuttle missions STS-5 and STS-8. **A.** Control sample (10,000×). **B.** Sample (20,000×) after exposure during space shuttle mission STS-5. **C.** Sample (10,000×) after exposure during STS-8.

in Figures 2, 3, and 4 illustrate the condition of the surfaces after in-flight testing.

Most of the data regarding the effects of AO on materials in the space environment have been gathered from experiments and recovery of various materials used in construction of the shuttle. Data have also been gathered from materials used in construction of several free-flying satellites, which show the same type of degradation. Fristrom et al.[8] investigated four samples of thermal blanket materials recovered from the Solar Maximum Mission satellite (in a low Earth orbit of 265 nmi for four

Table 1. Typical recession and reaction efficiency values for organic films.

Material	Thickness μm (mils)	Exposed side[a]	Surface recession (μm)[b]: Strip samples, 121 °C	Surface recession (μm)[b]: Strip samples, 65 °C	Surface recession (μm)[b]: Disc samples	Surface recession (μm)[b]: Average[c]	Reaction efficiency (10^{-24} cm^3/atom)
Kapton	12.7 (0.5)	Air	9.5	10.5	11.1		
		Roll	11.8	10.3			
	25.4 (1.0)	Air	9.8	10.7			
		Roll	9.9	9.0		10.5	3.0
	50.8 (2.0)	Air	11.1	10.6			
		Roll	11.1	11.1			
Mylar A	12.7 (0.5)	Air	12.7	12.3	12.7	12.6	3.6
	40.6 (1.6)	Air	12.1	11.9		12.0	3.4
Mylar D	50.8 (2.0)	Air	9.9	10.2		10.4	3.0
		Roll	11.0	10.4			
Clear Tedlar	12.7 (0.5)	Air	10.9	11.5		11.2	3.2
Polyethylene	20.3 (0.8)	N/A			11.5	11.5	3.3
Teflon TFE	12.7 (0.5)	Air			<0.2	<0.2	<0.05
Kapton F	30.5 (1.2)	N/A	<0.2	<0.2	<0.2	<0.2	<0.05

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Blank spaces mean no data available.
[a] Refers to manufacturing process.
[b] Corrected for flux reduction due to non-normal impingement (cos θ).
[c] Strip samples and disc samples.

Table 2. Effects of atomic oxygen exposure on the diffuse and specular properties of various paints (from STS-8 flight).

Specimen ID/evaluations	Z306 flat black: α_s[a]	Z306 flat black: TDS[b]	401-C10 flat black: α_s[a]	401-C10 flat black: TDS[b]	Z-853 yellow: α_s[a]	GSFC green: α_s[a]
Flight specimens, average optical property values for all temps	0.987 ±0.001	0.0132	0.979	0.0283	0.406 ±0.001	0.538 ±0.004
Control value for optical properties	0.959 —	0.0559	0.974 ±0.001	0.0357	0.440 —	0.540 —
$\frac{\text{Mass loss/cm}^2}{\text{total fluence}}\left(\frac{\text{mg}}{\text{atom}}\right)$	0.10×10^{-20}		0.086×10^{-20}		0.09×10^{-20}	No change
Comments on exposure effects	+2.8% in α_s, more diffuse, porous surface		+0.5% in α_s, more diffuse		Porous surface	No observed effects

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Dashes mean no tolerance was calculated.
[a] α_s is solar absorptivity. Values are percentage of absorptivity compared with a sample that has total absorptivity.
[b] Total diffuse scatter (TDS) measurement made at normal incidence, 0.6328 μm.

years). The materials were Kapton, Dacron netting, aluminized Mylar, and silver-coated Teflon. Because this was a Solar Max mission, the exposed portions of the materials had been subjected to solar maximum conditions. Visual examination of the exposed areas of the Kapton samples revealed a change in their original glossy appearance, and the silver coating was significantly oxidized. These changes were attributed to AO reactions.

As part of the same experiment, the authors exposed samples of virgin Kapton to low-energy oxygen atoms in a vacuum system in the APL Research Center; no change in the appearance of the Kapton surface was observed.[8] A second sample of virgin Kapton was exposed to high-energy argon ions, and the surface of the Kapton sample underwent a change in appearance similar to the Kapton sample exposed to the space environment, as revealed by scanning electron microscope evaluation. The low-energy oxygen atoms also attacked the silver coating on the Teflon film. The authors concluded that caution should be used in assigning the etching of surfaces in the space environment to a single gaseous species.

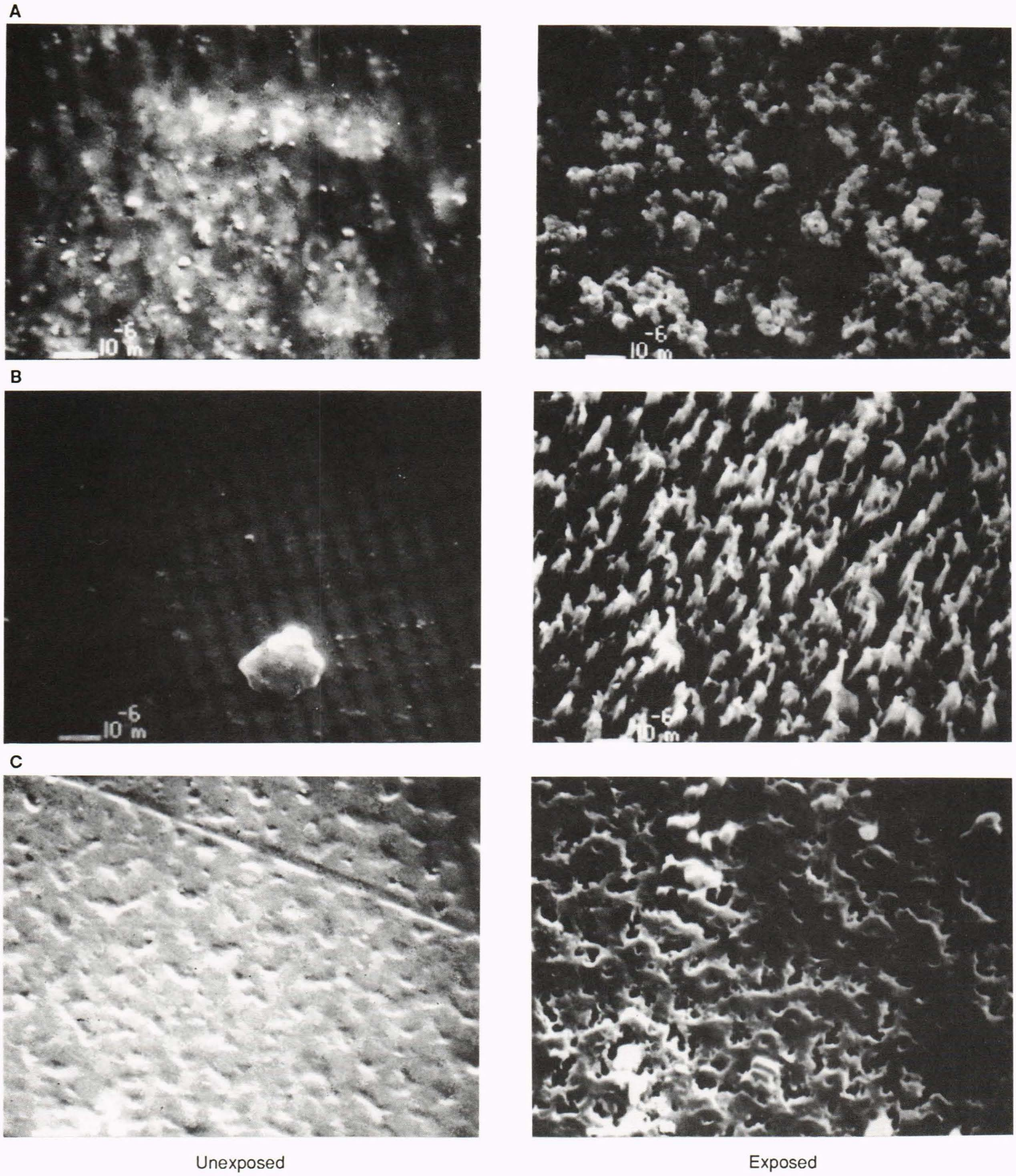

Figure 4. Scanning electron microscope photographs (10,000×) of three paint films before and after exposure to atomic oxygen. **A.** Polyurethane-based paint. **B.** PMDA-pp'ODA polyimide film. **C.** Siloxane-imide copolymer.

On the basis of the data from the materials experiments aboard the various STS flights, Visentine and Whitaker have developed a materials selection guideline for use in the AO environment.[9] In that NASA Technical Memorandum, they provide guidelines for selecting materials for use in the LEO. Their discussion covers surface recession predictions, screening techniques, and other technical concerns, and they present an excellent bibliography. This information is valuable for those who select materials for spaceflight applications, even if the specific application in the guidelines is for the LEO. Table 5 shows reaction efficiencies of several materials commonly used in spacecraft.

THERMAL VACUUM EFFECTS

The effects of the combination of incident and internal thermal energy and high vacuum (thermal vacuum)

Table 3. Effects of atomic oxygen exposure on the properties of several paints with various protective overcoatings (from STS-41G flight).

Evaluations	Z302 glossy black with OI-651 overcoat (α_s)[a]	Z302 glossy black with RTV 602 overcoat (α_s)	Z302 glossy black with MN41-1104-0 overcoat (α_s)	Z853 glossy yellow with MN41-1104-0 overcoat (α_s)
Exposed flight specimens	0.972	0.969	0.970	0.469
Nominal control values	0.972	0.973	0.972	0.458
Mass loss of flight specimen due to atomic oxygen exposure	None	Negligible	Negligible	Negligible
Comments on exposure effects	Maintains specular character of Z302	Loss of Z302 specular character	Loss of Z302 specular character	Loss of Z853 specular character, slight α increase partially due to UV darkening

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[a] α_s is solar absorptivity.

Table 4. Results of atomic oxygen exposure on silver with several protective overcoatings (STS-41G flight).

Overcoat material	Nominal thickness (Å)	Preparation technique	Comments on protection effectiveness
Aluminum	500	Vapor deposition	Aluminum generally protective, but spots and streaks indicate some silver oxidation. Film thickness considered insufficient for good protection.
Gold	500	Vapor deposition	No evidence of silver oxidation (scaling) and very few surface imperfections. Film thickness insufficient, as indicated by discoloration for long-term protection.
Gold	5000	Vapor deposition	Significant amount of spots and scaling, which tend to indicate contamination of the interconnect before and during plating, yielding a porous, nonuniform coating. Analyses complicated by contamination effects.
Gold	2500	Electroplated	Significant scaling on surface.
Gold	5000	Electroplated	Generally provided good protection. Film thickness insufficient, as indicated by discoloration for long-term exposure.
Palladium	500	Vapor deposition	Poor protection, extensive discoloration, and spots. Oxygen in palladium.
Palladium	5000	Vapor deposition	Slightly better protection than 500 Å. Oxygen in palladium. Poor adhesion.
DC-1104	$\approx 1.27 \times 10^5$ (≈ 0.5 mil)	Brushed	No silver oxidation. Good adhesion. Thick coating.
DC-1200 Primer	$\approx 2.54 \times 10^4$ to 1.27×10^5 (≈ 0.1–0.5 mil)	Brushed	Inadequate protection.

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of the space environment on spacecraft materials can be significant enough that the goals of the mission will not be accomplished. These effects are created by the outgassing properties of the materials (i.e., removal of the more volatile products) and the condensation of those outgassed products onto critical surfaces such as optical and thermal control surfaces. Outgassing occurs when the energy of the system (material) is such that the more volatile nonbonded molecules (as in plasticizers, moisture, and surface soils) are off-gassed from the surface, and, with an additional increase in energy, chemical bonds are broken such that smaller, more volatile molecules are created and outgassed into the environment.

The effect of temperature is to increase or decrease the rate of any chemical reaction that may take place and to increase or decrease the diffusion rate of the more volatile and/or smaller molecules to the surface of the material. The effect of the vacuum (low pressure) of the space environment on materials is to increase the molecular free path of any outgassing molecule (decrease the number and frequency of molecular collisions) and to prevent equilibrium conditions from existing (equilibrium can exist when the actual molecular free path is blocked by walls, baffles, insufficient venting of closed containers/boxes). For instance, if a molecule does evaporate from a surface, it will not return to the original surface but will escape to the vacuum of space or to an adjacent surface. Upon condensing onto a cooler surface, the condensed materials may degrade the surfaces until they no longer perform their design functions (e.g., reduce the transmission or reflectance of optical devices and the thermal properties of thermal control surfaces). Investigators have evaluated many materials in thermal vacuum systems that simulate the thermal vacuum of the space environment to a most reliable degree. Muscari's experimentation on outgassed products versus transmission of light at 120- to 260-nm wavelengths well illustrates the degradation in the ultraviolet wavelengths (see Fig. 5).[2] Muscari also showed that a thermal vacuum bakeout before launch would significantly reduce the outgassed product and increase the transmission of light in the ultraviolet wavelengths.

Campbell et al.[10] evaluated hundreds of materials (organic and inorganic) for their outgassing properties using ASTM Test Method E 595-84. The evaluation was performed on a small sample (approximately 200 mg cut into very small pieces) heated to 125°C for 24 hours in a vacuum of 10^{-6} to 10^{-7} Torr with the vacuum-condensable materials collected on a 25°C copper collector. The total mass loss (TML) and the collected vacuum-condensable materials (CVCM) are weighed to six significant figures, and the percent TML and CVCM are calculated (the maximum allowable TML is 1.0%, and the maximum allowable CVCM is 0.1%). Materials engineers use these values as guides in selecting materials suitable for spaceflight applications where thermal vacuum effects are of concern. These data are valuable and useful but are single data points (at 125°C). When the materials are exposed to room temperature (while in the Earth environment) or to an operational environment of −40°C or lower, extrapolation of the 125°C values to those temperatures is difficult with any degree of certainty.

Mumper[11] performed experiments to determine outgassing rates of materials at a low temperature (298 K versus 398 K)[10] with the condensable materials collected on a quartz crystal microbalance (QCM) at 278 K and a mass spectrometer to identify the outgassed product.

Table 5. Reaction efficiencies of selected materials with atomic oxygen in low Earth orbit.

Material	Reaction efficiency (10^{-24} cm^3/atom)
Kapton	3.0
Mylar	3.4
Tedlar (clear)	3.2
Polyethylene	3.7
Polysulfone	2.4
Graphite/epoxy	
1034C	2.1
5208/T300	2.6
Epoxy	1.7
Polystyrene	1.7
Polybenzimidazole	1.5
25% Polysiloxane/45% polyimide	0.3
7% Polysilane/93% polyimide	0.6
Polyester	Heavily attacked
Polyester with antioxidant	Heavily attacked
Silicones	
RTV-560	0.02[a]
DC6-1104	0.02[a]
T-650	0.02[a]
DC1-2577	0.02[a]
Black paint Z306	0.3–0.4[a]
White paint A276	0.3–0.4[a]
Black paint Z302	2.03[a]
Perfluorinated polymers	
Teflon TFE	<0.05
Teflon FEP	<0.05
Carbon (various forms)	0.5 –1.3
Silver (various forms)	Heavily attacked
Osmium	0.026

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[a] Mass loss/area (mg/cm^2) for STS-8 mission. Loss is assumed to occur in early part of exposure; therefore, no assessment of efficiency can be made.

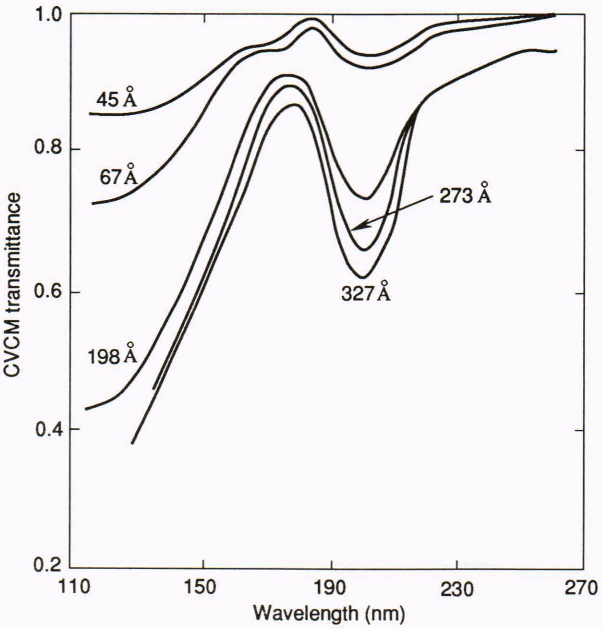

Figure 5. Curves showing transmittance value of collected vacuum-condensable materials (CVCM) versus wavelength for several typical organic materials used on spacecraft. The thickness of the CVCM films varies from 45 to 327 Å. (Reprinted, with permission, from Ref. 2.)

With this technique, he could analyze the data and determine the kinetics of the process. A typical paint (black Chemglaze Z306 with 9924 primer) was the sample material. The results show that the condensable product was collected at a rate of about 6 Å/day; most of it was water and a small amount of it was low-molecular-weight organic material (under 150 amu). Analysis of the data showed that outgassing is a diffusion-controlled process after the highly volatile surface layers have been evaporated. Because many of the instruments being designed and flown operate at temperatures lower than the 398 K of the ASTM E 595 test, the values from low-temperature testing are of much greater interest. Several other authors have presented data obtained with a thermally controlled QCM at temperatures of 298 K, 220 K, and 159 K.

Because all spacecraft use multilayer insulation (thermal blanket) materials for thermal control, Glassford et al.[12,13] have evaluated outgassing of typical materials by thermal vacuum conditions. Their data show the outgassing rate of several materials at 298 K with the CVCM being collected on a cooled QCM. Several of the samples were given a 24-hour vacuum bakeout at temperatures between 298 K and 423 K; the results showed a decrease in the outgassing rate after the thermal vacuum bakeout.[13] The bakeout at 353 K produced the lowest outgassing results. This high-temperature bakeout is not possible in many cases, because of temperature limitations of substrate materials.

It is important to understand self-contamination of critical optical surfaces during the design and materials selection phases of flight instrument development. Scialdone[14] performed a basic study of self-contamination by the outgassing of various space payloads. He showed that an engineering estimate of the outgassing rate can be calculated by using the formula

$$Q = Q_0 \exp\left[-E/R(1/T - 1/T_0)\right] \quad \text{Torr} \cdot \text{l/s} ,$$

where R is the gas constant (1.987 cal/mol/K), E is the activation energy of the "composite" outgassing molecules (cal/mol), Q is the unknown outgassing rate (in liters per second), Q_0 is the known outgassing rate, and T is temperature in kelvins, as related to the two Q's. Scialdone stated that this formula will produce satisfactory results as long as the temperatures of the systems are relatively close (10 K to 20 K).

SUMMARY

This article has summarized space environmental information used by materials engineers to select construction materials appropriate for spacecraft and their components, including the individual instruments, electronic boxes, and so on. The discussion has centered on the effects of atomic oxygen and thermal vacuum on those materials. The effects of atomic oxygen are most pronounced and destructive in the low Earth orbit and become less so as the orbit becomes higher than 500 to 600 km (see Fig. 1). But even in the LEO range, spacecraft surfaces and components can be protected by careful selection of materials and the use of specific protective coatings. At the higher altitudes, the orientation of the materials in relation to the ram direction is important and must be taken into consideration. The effects of thermal vacuum on materials selection are also important because critical surfaces can deteriorate seriously from outgassed products condensing onto them. Thermal vacuum effects are present at all altitudes. Using the best available materials becomes most important when the critical surface is operated in low temperatures (below 0°C). Several optical instruments now in the design phase and being flown operate at temperatures of −30°C and lower; therefore, careful selection and thermal vacuum conditioning of the materials must be carried out. For operation at these lower temperatures, it is also advisable to predict the degree to which the construction materials of an instrument will be subject to self-contamination of the instrument.

In January 1990, the Long Duration Exposure Facility (LDEF) was recovered by the space shuttle and returned to Earth after nearly six years in low Earth orbit. The LDEF was designed and flown to evaluate many materials in various configurations, under controlled and uncontrolled conditions, in LEO. Preliminary evaluations of the "as-flown" materials confirm the results of atomic oxygen effects found on the shuttle experiments: atomic oxygen does degrade critical surfaces, and protective coatings must be used to reduce those effects.

In conclusion, spacecraft materials engineers and others concerned with materials in space must be knowledgeable about the effects of atomic oxygen and thermal vacuum on the construction materials of all components of the spacecraft and its various payloads. They must also be aware of the exact thermal and pressure conditions that may be encountered, the spacecraft's orbit and angle of inclination, the operational lifetime of the mission, and the ground processing conditions. By giving all of these factors due weight, they ensure that the materials selected are those best suited to the requirements of the spacecraft, the payload, and the mission.

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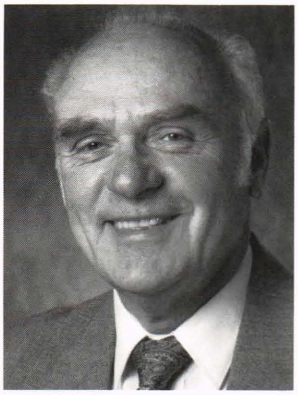
THE AUTHOR



CHARLES E. VEST received a B.S. in metallurgical engineering from Virginia Polytechnic Institute and an M.S. in materials engineering from The University of Maryland. He was employed for ten years in the nuclear materials field and thirty years in the spacecraft materials field. At APL he has been associated with space programs and has worked with the Aeronautics, Submarine Technology, and Fleet Systems Departments in failure analysis of materials. His latest project at APL is contamination control of the MSX-UVISI instruments. He is the author or co-author of twenty-five technical papers on test and evaluation and applications of materials in the space environment.