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REVIEW OF LEO FLIGHT EXPERIMENTS

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Introduction

Surfaces of orbiting spacecraft are exposed to a flux of Earth ambient atmospheric species. This flux can be highly directional as a result of spacecraft velocity through the atmosphere. Fluence on the spacecraft is maximized on the ram surface and minimized on the wake surface. The main constituent of this atmosphere is atomic oxygen, and at spacecraft velocities, its kinetic energy, relative to the surface, is approximately 8×10^{-19} J (5 eV). Atomic oxygen flux for typical low Earth orbit conditions is 3×10^{14} atom/cm^2-sec. Since atomic oxygen is a strong oxidizing agent, it might be expected that such a flux would affect exposed organic surfaces, and indeed such effects have been observed on Space Shuttle flights.[1,2,3] The major effect is recession of surfaces exposed to ram conditions. Recession is assumed to result from oxidative attack of the organic polymer chains, producing volatile species and resulting in mass loss. Exposed surfaces are generally roughened on a microscopic scale with some physical property changes occurring. Based on current data, this recession appears to be the most significant change in materials used on spacecraft in the low Earth orbital (LEO) environment.

Limited measurements were made on Orbiter exposed surfaces during early Space Shuttle flights. Low fluence and lack of control specimens precluded obtaining quantitative data from these flights. However, qualitative results do support the observations obtained on later, dedicated flight experiments.

Essentially all quantitative reaction rate data have been obtained on Space Shuttle flights STS-5 and STS-8, which are discussed in the flight experiments summary. Additional limited data obtained on mission STS 41-G are also summarized in the flight experiments summary and discussed in references 4 and 4b. Reaction rate data obtained from these flight experiments have been applied to Space Station exposure conditions and are discussed in the Space Station application section.

Results of measurements made on hardware returned on the Solar Maximum repair mission (Space Shuttle flight 41-C) are reported in reference 5. Quantitative rate data were not available from these measurements because of the difficulty in defining the exposure fluence for the specific surfaces studied.

Additional data may be available with the return of the Long Duration Exposure Facility (LDEF), which was launched in April 1984. Unfortunately, delayed return of the spacecraft may have already lead to significant loss of quantitative results since original experiment design lifetime was one year.

Summary of Flight Experiments

General

All flight experiments conducted to date have essentially provided for passive exposure of samples to oxygen fluences of approximately 1 to 3.5×10^{20} atoms/cm^2. Atmospheric density is used to derive fluence and is dependent on solar activity, which has been on the declining side of the 11-year cycle. Thus, relatively low flight altitudes of <300 km were used to acquire these exposures. In addition, the flight attitudes were selected to provide maximum exposure to ram conditions. Exposure fluence was derived from ambient density predictions obtained using the mass spectrometer incoherent scattering (MSIS) model, together with spacecraft velocity and exposure attitude.(7) After exposure on the flight experiments, the samples were analyzed using various methods ranging from mass loss to extensive scanning electron microscopy and surface analysis techniques.

Experiment Description

STS-5: The fifth Space Shuttle flight (STS-5) was launched in November 1982 with a payload consisting principally of deployable satellites. After deployment of these satellites, an experiment was conducted to further study surface effect found on earlier missions. A detailed description of this experiment and associated results has previously been presented.(8,9,10) Therefore, only a brief summary is included here for completeness.(12.13)

Exposure conditions were selected to provide the largest atomic oxygen fluence and associated surface changes that would facilitate postflight laboratory measurements. These conditions were established during a 40-hr period in which the Orbiter vehicle was maintained in solar inertial attitude. Material samples were exposed on two trays, which were mounted to a support structure located at the payload bay door hinge level and thereby, provided maximum view to the space environment. Specimens in filmstrip form were mounted on six heater plates, which were thermally controlled to temperatures of 297, 338, and 394 K (24°, 65°, and 121° C). A few disk samples were mounted on other regions of the trays.

STS-8: The second dedicated materials/space environment interaction experiment was conducted on the eighth Space Shuttle (STS-8) flight in August 1983. Basically, the same exposure approach as that employed previously was used, except that, in addition two active instruments were added to evaluate the effects of charged species and solar radiation on the reaction rates. Passive fixtures were also added to evaluate mass transfer from specimen to specimen.

Considering that solar activity was approaching a minimum, a rather high fluence was achieved by both lowering the vehicle altitude to 225 km and maintaining the sample surfaces in direct ram conditions throughout the 40-hr exposure period. Such exposure conditions provided a fluence of 3.5×10^{20} atoms/cm^2 to the samples, which were located in the forward region of the payload bay (fig. 1).

Material specimens consisted of both strips and disks as before, but more individual specimens (>300) were included. Samples were selected to

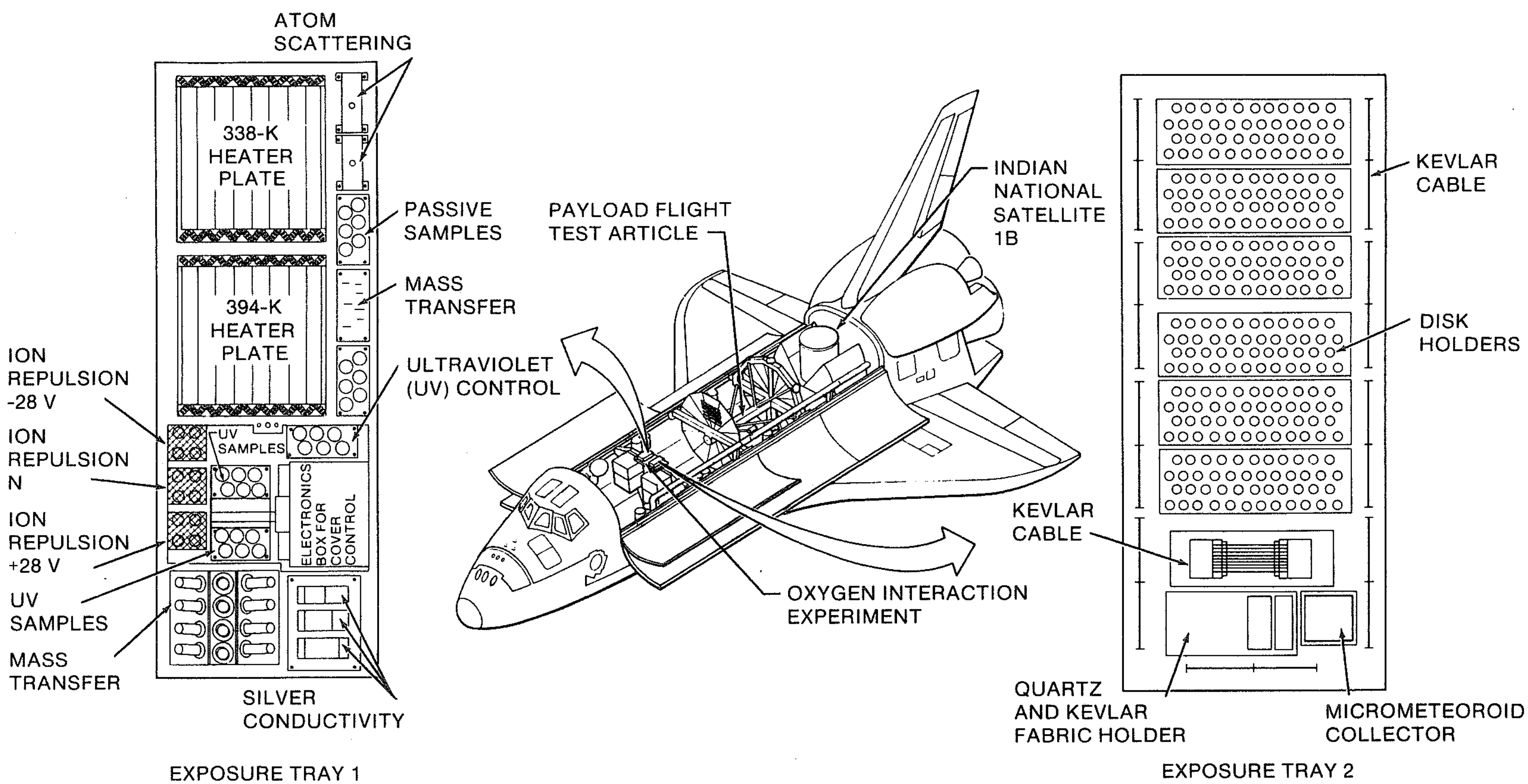

Fig. 1. STS-8 mission exposure configuration.

represent typical spacecraft materials such as polymer films, paints, vapor-deposited coatings, metals, and composites and were provided and analyzed by a number of different laboratories.

In addition to the STS-8 experiments described above, several quartz crystal microbalances (QCM) were exposed on a separate mounting system in the payload bay. Three QCM's were coated to determine the reaction efficiencies of carbon and osmium. A detailed description of this experiment is to be published, however, reaction rates were ~3.5×10^{-25} cm^3/atom (0.035 carbon atoms/oxygen atom) for carbon and 2.6×10^{-26} cm^3/atom (1.9×10^{-3} osmium atoms/oxygen atom) for osmium.[11]

STS 41-G: Another exposure opportunity was provided on the Space Shuttle mission (STS 41-G) launched in October 1984. Because Orbiter attitude for this mission did not allow orienting the payload bay into the velocity vector, samples were mounted directly to the remote manipulator system (RMS) using polyimide tape as shown in figure 2. The arm was then deployed over the port side of the vehicle as shown and oriented with the samples facing into the velocity vector for a period of 35 hr. Not all ambient atmosphere exposure occurred in this orientation since the RMS was also used to deploy a satellite. These operations precluded accurate calculation of the exposure flux; however, based on recession of the attachment tape, the exposure flux was determined to be approximately 3×10^{20} atoms/cm^2 on the direct ram-facing surfaces.

Samples for the STS 41-G mission consisted primarily of composite materials and materials used on the Hubble space telescope. Results for composite materials and the space telescope are reviewed in references 4 and 6, respectively.

Experiment Results

A variety of postflight measurements ranging from surface morphology to surface chemistry changes were made on the exposed surfaces by the participating laboratories. The limited scope of this paper does not allow for a complete discussion of the findings, which are reported elsewhere[4 through 10 and 12 through 22]; therefore, only a brief summary with sufficient quantitative data for application to following Space Station discussions will be presented.

Of the two general classes of materials: metals and nonmetals, the metals are the least reactive. More than twenty metal surfaces have been exposed on the two experiments and, of these, only two, silver and osmium (Os), interact with sufficient speed to produce macroscopic changes. Silver forms heavy oxide layers, typical of oxidative attack, resulting in loss of material by flaking and spallation. The rate of oxidation is somewhat dependent on the specific silver form. Quantitative interaction rates have not been well established; however, oxide thicknesses of greater than 0.4 μm have been measured.

Osmium loses mass with a reaction efficiency of 2.6×10^{-26} cm^3/atom, (Table 1) apparently through the formation and loss of OsO_4, which has a relatively high vapor pressure.[11] Generally, all the other metals have

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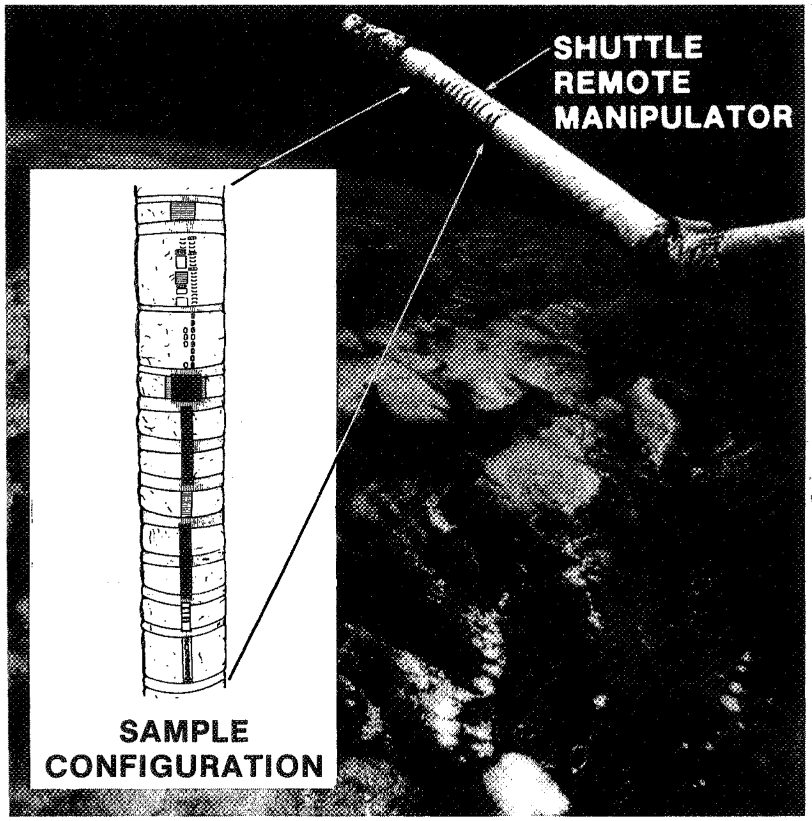

Fig. 2. STS-41G exposure configuration.

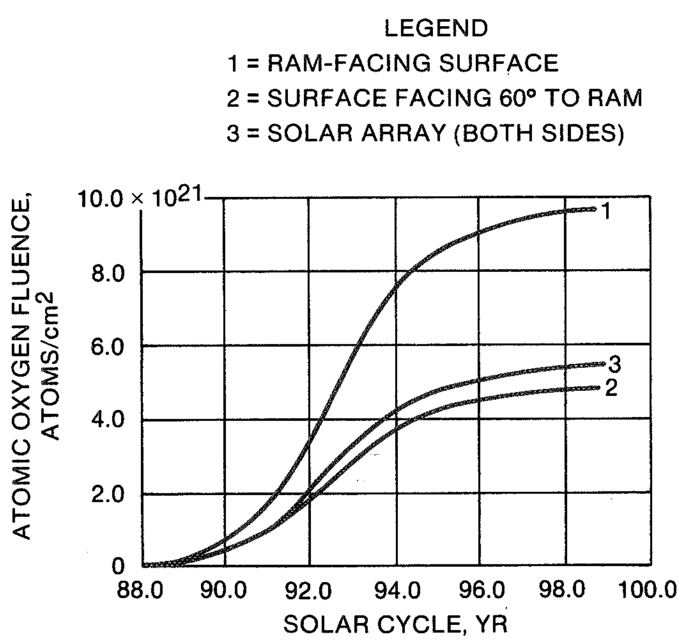

Fig. 3. Atomic oxygen fluence increase with solar activity.

TABLE 1. REACTION EFFICIENCIES OF SELECTED MATERIALS WITH ATOMIC OXYGEN IN LOW EARTH ORBIT

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

*Units of 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.

TABLE 2. SURFACE RECESSION PREDICTIONS FOR SPACE STATION COMPONENTS

		Constant altitude (465 km)		Constant density (2×10^8 atoms/cm^3)	
Materials	Lifetime, yr	Fluence, atoms/cm^2	Recession, cm (mil)	Fluence, atoms/cm^2	Recession, cm (mil)
Graphite epoxy structural members, forward facing side	30	3.6×10^{22}	8.6×10^{-2} (34)	*1.4×10^{23}	3.2×10^{-1} (126)
Solar power arrays front & back, exposure	20	1.3×10^{22}	3.8×10^{-2} (15)	*5.5×10^{22}	1.7×10^{-1} (65)
Radiator surfaces front & back, exposure	20	1.5×10^{22}	--	*6.3×10^{22}	--

*Constant density results in approximately 4 times more fluence significantly lower interaction rates than those of silver and osmium. As expected, metal oxides are nonreactive.

Generally all organic materials are reactive with the LEO environment, with interaction rates being apparently independent of chemical structure. The effect of additives is much more significant than chemical structure, since these materials are very often oxides or other low reacting components which shadow the organic matrix from the incoming ambient atomic oxygen beam. Reaction efficiencies for a representative set of organic materials are shown in table 1. These efficiencies are derived by normalizing the sample recession by exposure fluence and represent, principally, data from the STS-8 mission. For some material samples, the STS-5 mission reactivities are lower than those for the STS-8 mission; however, the earlier results may have been affected by sample mounting contaminants combined with the low fluence. Since sample recession for the STS-8 mission was as much as 12 μm, it is felt that these data are more representative of bulk reactivity. Considering errors involved in both recession measurements and atomic oxygen density prediction, the reaction efficiencies have a probable error of 30% to 50%. Errors associated with ambient density predictions appear to be the largest contributor.

Perfluoronated polymers, such as Teflon and silicone polymers are considerably less reactive than organic polymers (Table 1); in fact, their reaction rates are low enough that these materials can be considered as protective coatings. Nonreactive fillers also lower the reactivity of polymers by shadowing the organic matrix; however, the filler particles are then only partially attached through pedestal regions which may be lost in time due to scattered atomic oxygen.

Material reaction rate dependence on surface temperature and charged-species concentrations were evaluated using heated trays and a charged grid apparatus. Based on these measurements, polymer material reactivities show no temperature dependence over the temperature range of 298 to 393 K (25° to 120° C). Additionally, the charged grids did not affect the recession of associated samples, an indication that charged species were not important, as expected, in explaining the exposure effects.

Space Station Application

The extent of degradation caused by exposure to the LEO environment is dependent on surface attitude relative to ram, on altitude, and on solar activity. Even with these parameters, ambient density must be obtained from appropriate models, such as the previously mentioned MSIS model, and the flux integrated over the particular mission. An algorithm has been developed for coupling the results from MSIS and flight parameters to generate mission fluence and has been applied to Space-Station-peculiar flight parameters.[22] For these calculations, it was assumed that the Space Station was oriented in a gravity gradient attitude at 465 to 500 km. In such a flight attitude, some surfaces are always facing ram conditions, notably one side of structural components. Fluence predictions show a buildup as the solar activity increases to a maximum in the 1993 timeframe (fig. 3) and results in one solar cycle exposure for various surfaces as shown in table 2.

Recent Space Station programmatic considerations have resulted in definition of a constant drag flight attitude as a baseline. Such a flight condition would provide a varying Space Station altitude (500 to 350 km), depending on solar activity. This altitude variation results in relatively small velocity variations and, therefore, to a first approximation, constant drag can be considered as providing a constant density condition for environmental considerations. Assuming a density of 2×10^8 atoms/cm^3, which corresponds to the Space Station design requirement of 475 km with a maximum plus 2σ solar activity, the fluence and recession are approximately a factor of four larger than for a constant altitude condition. (See Table 2.)

Effects on Space Station surfaces are derived by multiplying the predicted fluence by the reactivity of the given material being exposed. For example, the forward-facing portion of the structural members is exposed to a total fluence of 1.4×10^{23} atoms/cm^2 for constant density conditions, and if these members are made of graphite epoxy composite with a reactivity of 2.4×10^{-24} cm^3/atom, recession of as much as 0.3 cm can be expected in 30 years. Current conceptual design uses a structural member wall thickness of approximately 0.15 cm; therefore, a loss of 50% of the wall thickness can be expected. Such a large loss of wall thickness is unacceptable and dictates that coatings be developed for protection.

An even more severe system problem arises from environmental exposure for the solar power components. Again, using computed fluence for the solar array exposure from table 2 of 5.5×10^{22} atoms/cm^2 and using a reactivity of 3×10^{-24} cm^3/atom, a typical solar array would experience recession of approximately 0.17 cm for a twenty-year exposure. Since substrates for typical arrays are 8×10^{-3} cm thick, life is very limited and coatings must be developed.

Although the effect on other Space Station materials may not be as severe as that on the photovoltaic power system, similar considerations apply and care must be taken in selecting durable coatings to ensure adequate life. As a result of these considerations, a significant amount of the Space Station materials advanced development activities are dedicated to coating development.

Conclusion

It was assumed for many years that the aspects of the low Earth orbital environment most degrading to materials were ultraviolet radiation and thermal vacuum exposure. With the advent of frequent space flights and opportunities to examine returned surfaces, it now appears that effects of atomic oxygen will be the most damaging by far. In fact, major changes in solar voltaic system design must be made to ensure sufficient life for even one solar cycle.

A preliminary data base has been generated from flight experiments to date, but is limited both in extent of orbital exposure time and, therefore, fluence and in the variety and number of samples studied. With a relatively short time before Space Station design begins, it is imperative that we augment the data base in both scope and quality of rate data. This augmentation must be done through flight experiments, in which limited studies are possible, and ground-based facilities, where more extensive evaluations can be performed. Such an approach has been conceptually defined and is in program development. Successful implementation of this program will provide a significant increase in our understanding of LEO environment interactions with materials.

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