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Intelsat Solar Array Coupon Atomic Oxygen Flight Experiment

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A Hughes communications satellite (INTELSAT series) belonging to the INTELSAT Organization was marooned in low-Earth orbit (LEO) on March 14, 1990, following failure of the Titan launch vehicle third stage to separate properly. The satellite, INTELSAT VI, was designed for service in geosynchronous orbit and contains several materials that are potentially susceptible to attack by atomic oxygen. Analysis showed that direct exposure of the silver interconnects in the satellite photovoltaic array to atomic oxygen in LEO was the key materials issue. Available data on atomic oxygen degradation of silver are limited and show high variance, so solar array configurations of the INTELSAT VI type and individual interconnects were tested in ground-based facilities and during STS-41 (Space Shuttle Discovery, October 1990) as part of the ISAC flight experiment. Several materials for which little or no flight data exist were also tested for atomic oxygen reactivity. Dry lubricants, elastomers, and polymeric and inorganic materials were exposed to an oxygen atom fluence of 1.1×10^{20} atoms cm². Many of the samples were selected to support Space Station Freedom design and decision making. This paper provides an overview of the ISAC flight experiment and a brief summary of results. In addition to new data on materials not before flown, ISAC provided data supporting the decision to rescue INTELSAT VI, which was successfully undertaken in May 1992.

Introduction

THE ISAC flight experiment was one component of a larger INTELSAT VI rescue program. The INTELSAT VI communications satellite was launched from Cape Canaveral on a Titan III in mid-March 1990. Failure of an upper stage marooned the satellite in low-Earth orbit (LEO). While in LEO, INTELSAT VI was exposed to a number of space environment factors that are absent, or of limited importance, in the geosynchronous environment for which the satellite was originally designed. Evaluating the effects of the LEO environment on INTELSAT VI materials and systems was a first step in deciding the ultimate fate of the satellite. Analysis showed the effects of radiation and debris in LEO to be similar to that of the intended geostationary orbit; however, the effects of residual atmosphere (atomic oxygen) in LEO on exposed surfaces were a source of concern.

After the abortive launch of the INTELSAT VI spacecraft on March 14, 1990, initial efforts were directed toward raising the orbit, both to prevent re-entry and to minimize the potentially damaging effects of atomic oxygen. By March 17, 1990, the satellite was in a stable, 394 × 265 km orbit, and on March 27, 1990, the orbit was raised to 560 km.

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Atomic oxygen is the predominant atmospheric gas between 200 and 700 km.[1] The effects of atomic oxygen on spacecraft materials have been extensively studied since the early Shuttle flights, and have been the subject of many publications.[2–14] An analysis of atomic oxygen effects on exposed INTELSAT VI materials, based on available space flight data, showed that the principle concerns were the silver foil interconnects in the solar photovoltaic arrays and the zinc sulfide optical coating on the germanium Earth sensor lens. Silver reacts rapidly with atomic oxygen to form an oxide coating that sloughs off as a result of the poor lattice match between the metal and the oxide.

An extensive literature search revealed little hard data on the effects of atomic oxygen on silver beyond two earlier Shuttle experiments, STS-8 and STS-41G.[2,3] The data were not directly applicable, with certainty, to the INTELSAT VI silver interconnects as a result of differences in exposure conditions and interconnect configuration. Therefore, additional testing was needed before the final decision (December 1990) could be made on a rescue mission.

The test and analysis program supporting the rescue mission decision consisted of four program elements: 1) development of a software program to accurately predict the atomic oxygen fluence on critical satellite surfaces; 2) theoretical analysis to determine how thin the interconnect could become and still remain functional; 3) atomic oxygen testing in ground-based laboratory simulations of the LEO environment at Los Alamos National Laboratory (LANL)[8] and Princeton Plasma Physics Lab[10]; and 4) the ISAC flight experiment, STS-41, October 1990.

This paper presents the techniques and results of the ISAC flight experiment and includes some comparisons of the flight results with the ground-based testing. Although the primary objective of the ISAC flight experiment was INTELSAT VI data, the INTELSAT Organization generously permitted NASA investigators to fly a wide range of material types for which no in-space atomic oxygen exposure data were available. In-space atomic oxygen exposure data were needed to 1) gain confidence in ground-based test facilities, 2) support Space Station Freedom and Space Telescope decision making, and 3) support long duration exposure facility (LDEF) data analysis.

ISAC Sample Set and Methods of Analysis

The ISAC sample set consisted of two solar array coupons, three thermal control plates, and a NASA-supplied sample holder containing various oxygen fluence monitor materials, the INTELSAT VI Earth sensor lens, and an array of NASA-supplied samples.

Solar Array Coupons

The two 21.6 × 30.5 cm solar array coupons each had 30 cells connected in series so as to drive a 1-MΩ-resistive load. The coupons were cut from an INTELSAT VI engineering development unit and are believed to be identical to the solar array on the satellite. A detailed drawing of the solar cell interconnect region of interest is shown in Fig. 1.

Thermal Control Plates

Each of the three thermal control plates, designed and fabricated at Communications Satellite Corporation (COMSAT) laboratories, had a different solar absorptivity and emissivity so that each plate would achieve a different average temperature on orbit. Each thermal control plate held four bare interconnects and a polyethylene atomic oxygen monitor, all in good thermal contact with the surface.

Degradation of the silver interconnect specimens was measured by two methods. Initial evaluation efforts involved cross sectioning exposed and unexposed areas on each silver interconnect and using a scanning electron microscope (SEM) to measure the thickness of the remaining silver and silver oxide. Unfortunately, the variation of silver thickness in a single interconnect was found to be on the order of 1 μ, which exceeded the thickness of the oxidized silver. Subsequent efforts were concentrated on measuring the thickness of the peeling silver oxide with an SEM. All materials degradation or reaction measurements were made by comparing specimens exposed to the atomic oxygen environment with control specimens that either were not flown on ISAC or were flown in a shielded location on the sample holder such that no O-atom exposure occurred during the mission.

NASA Sample Holders

The NASA-supplied sample holder had been flown previously as part of the STS-8 atomic oxygen experiment. The sample holder contains slots for 46 disk-shaped specimens, each 2.5 cm in diameter. A list of the 25 sample materials for which we have results is given in Table 1.

All dry lubricant specimens were prepared by the manufacturer, using recommended application procedures, as films on 2.54-cm-diam stainless steel disks. The particular dry lubricant formulations selected are either used in the Space Shuttle program or proposed for use in Space Station Freedom. Auger electron spectroscopy, auger depth profiling, and x-ray photoelectron spectroscopy (XPS) were used to measure changes

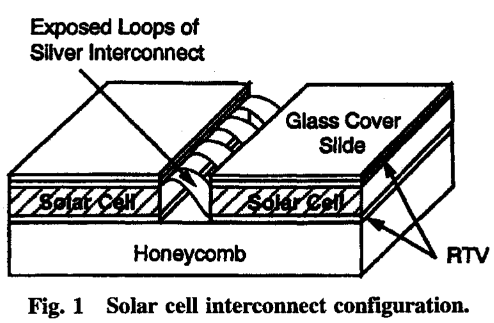

Fig. 1 Solar cell interconnect configuration.

Table 1 NASA sample holder specimens

Sample and sample type	Organization
Dry lubricants	
WS_2, Microseal 300-1, E/M Corp.	JSC
WS_2, Diversified Dry Lube, Inc.	JSC
Proprietary metal oxide, Ceram-lube 7000, E/M Corp.	JSC
MoS_2/Urethane, Permaslick-R, E/M Corp.	JSC
Graphite/phosphate glass, EM 1380-B, E/M Corp.	JSC
MoS_2/silicone, Everlube 1346, E/M Corp.	JSC
Optics	
MgF_2 on Al mirror	MSFC[a]
40-Å diamond-thin film on quartz	MSFC
ZnS_2 on Ge substrate	INTELSAT
Polymeric materials	
Silicone elastomers	MSFC
Nylon	MSFC
Polyetheretherketone (PEEK)	MSFC
Viton	MSFC
Kapton HN film samples, 0.0025-cm thick	JSC
Polyethylene film sample, 0.005-cm thick	JSC/LeRC[a]
Black Kapton film sample	MSFC
Lexan sample	MSFC
Polysulfone sample	MSFC
Coated actinometers	
700 A Si_3N_4/230 A Ag, actinometer	JSC/LANL
771 A SiO_2/230 A Ag, actinometer	JSC/LANL
775 A Al_2O_3/230 A Ag, actinometer	JSC/LANL
750 A BN/230 A Ag, actinometer	JSC/LANL
Space Station Beta cloth	
Oxygen plasma asher-treated Rockwell MBO-135-027 beta cloth	JSC
MLI blanket material	

[a]MSFC is the Marshall Space Flight Center and LeRC is the NASA Lewis Research Center.

in surface chemical composition resulting from reaction with atomic oxygen. Spectra of flight specimens were compared with controls.

Several methods were used to characterize the optics specimens. The INTELSAT VI infrared window (ZnS_2 on Ge substrate) was characterized by infrared transmission measurements before and after flight. The MgF_2-coated aluminum mirror was characterized by ellipsometry and vacuum ultraviolet reflectance measurements. The diamond-like, thin film on quartz was characterized with an optical interferometer/profiler before and after flight.

The actinometers consisted of thin films of sputter-deposited coatings covering thin silver conductive strips on a sapphire substrate. As the coating is eroded away or penetrated by oxygen atoms, reaction between the silver and atomic oxygen produces a much less conductive silver oxide. The resulting change in electrical resistance of the silver strip is a measure of oxygen atom penetration of erosion of the surface film. Auger electron and XPS with depth profiling are also used to determine changes in the structure and chemical composition of the film resulting from reaction with atomic oxygen.

Weight changes, XPS spectra, and helium permeability measurements were used to evaluate the response of the silicone and Viton elastomers to atomic oxygen in the LEO environment.

The atomic oxygen fluence monitors and other polymer film samples consisted of two 2.54-cm-diam sample disks stacked one on top of the other. The weight change of the outer, or top, polymer film disk results from exposure to atomic oxygen and outgassing, whereas any weight change observed for the inner or bottom polymer film disk is the result of outgassing only.

The Space Station beta cloth specimen was designed to provide data on atomic oxygen permeation of a Teflon-coated glass cloth (beta cloth) being considered for Space Station multilayer insulation (MLI) blankets. Atomic oxygen/vacuum ultraviolet photochemistry[12] is expected to remove the Teflon from ram-oriented surfaces in LEO. Thus, a sample of beta cloth made to Rockwell specification MBO 135-027 was treated in an oxygen plasma asher for 72 h to remove most of the Teflon coating, simulating prolonged exposure to LEO conditions. After the asher treatment, the beta cloth specimen contained only 6% by weight Teflon as determined by thermogravimetric analysis, whereas before the asher treatment the Teflon content was 21% by weight. A 2.54-cm-diam disk of the asher-treated beta cloth was then mounted in the NASA sample tray so as to cover two oxygen fluence monitors.

1) A smooth Kapton film was used to detect direct penetration of high-velocity oxygen atoms (the reaction efficiency of Kapton shows a strong dependence on O-atom kinetic energy[8,11]).

2) A small sample of silver foil (INTELSAT VI interconnect) was used to detect penetration of oxygen atoms that have been thermalized by repeated collisions with glass fibers during the penetration process. (The reactivity of silver showed no dependence on atom kinetic energy.)

Oxygen permeation was measured by comparing the extent of reaction of the beta-cloth-covered specimens with those directly exposed to the atomic oxygen ram flux. The reaction of silver was determined by weighing the silver foil before and after dissolution of silver oxide in 7-molar ammonium hydroxide. The reaction of the Kapton film was determined in this case by searching the surface for the "carpet" morphology characteristic of high-velocity, O-atom attack on polymers with an SEM.

ISAC Techniques: Flight Hardware and Procedures

The need for an atomic oxygen exposure experiment was defined in late March 1990 with a requirement that the data be available in final form before December 1990. The ISAC flight experiment was possible in such a short time frame because specialized hardware was available at NASA Johnson Space Center and had already been flight qualified for another project.

A set of modular witness plates (MWPs) had been built by SPAR Aerospace (Ontario, Canada) to provide a convenient method of attaching passive samples to the Space Shuttle Orbiter remote manipulator system (RMS) arm. The MWPs serve as nearly ideal platforms for holding atomic oxygen exposure specimens, whereas the RMS arm is then used to accurately position the specimens in the atomic oxygen ram flux without creating Orbiter-unacceptable attitude constraints. As a result of the flexibility provided by the RMS-mounted MWPs, 34.3 h of ram exposure (test article forward facing and perpendicular to the velocity vector) were possible while the Space Shuttle Discovery was in a cargo-bay-to-Earth attitude for studies of the upper atmosphere. A total exposure time of 46.5 h resulted from partial ram orientation of the samples during deployment of the Ulysses probe and other mission activities.

Two MWPs were used in the ISAC flight experiment. The solar array coupons, thermal control plates, and NASA sample holder were bonded to the MWPs using room temperature vulcanized (RTV) 566, a low-outgassing silicone adhesive, and strain isolation pad (SIP), a nomex aramid fiber felt pad. An almost identical bonding system is used to attach thermal protection tiles to the Space Shuttle Orbiter.

Outgassing contamination is always a concern whenever silicone RTV adhesives are used in the space environment, especially so when used in an atomic oxygen experiment. No preflight vacuum baking was possible because contamination-sensitive test article surfaces were already adhesively bonded to the MWPs, and outgassing of the solar array coupons themselves (which contain a silicone solar cell cover slip adhesive) was a concern. In any event, the payload configuration showed no line-of-sight paths between the RTV-566/SIP adhesive bondlines and the sensitive sample surfaces of the payload, so that direct contamination of sample surfaces was not a concern.

Nonetheless, several steps were taken to minimize and evaluate contamination by RTV-566 outgassing. The exposed RTV-566 adhesive bondline was covered by low-outgassing Kapton tape (acrylic adhesive) to block or contain line-of-sight outgassing. In addition, aluminum surfaces that would be exposed to the space environment during flight were covered with the same Kapton tape to assure a high infrared emissivity and low temperatures in direct sunlight. Finally, sample analyses by XPS and auger electron techniques provided a sensitive test for surface contamination. As is shown in the following results section, no significant surface contamination by RTV-566 outgassing or other sources could be detected after the mission. Finally, "Temp Label" recording temperature indicators were placed at various locations on the payload to provide a record of any unanticipated thermal excursions.

The MWPs are shown ready for shipment to Cape Canaveral in Fig. 2. Complete photographic documentation of the ISAC payload, including macroimages, was completed before shipment to the Cape, to permit accurate pre- and postflight visual comparisons. A drawing of the mounting scheme on the Orbiter RMS, less the required thermal blankets, is shown in Fig. 3. The ISAC payload, deployed on the Discovery RMS arm in

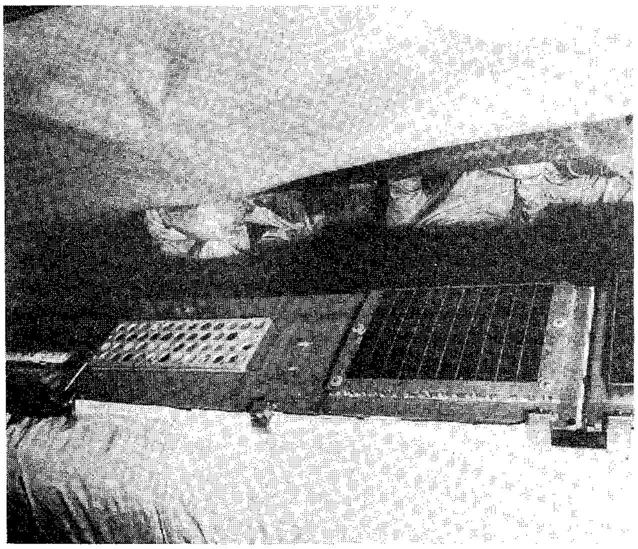

Fig. 2a Postflight photo taken in the Orbiter processing facility of modular witness plates on the RMS in the payload bay of Space Shuttle Discovery.

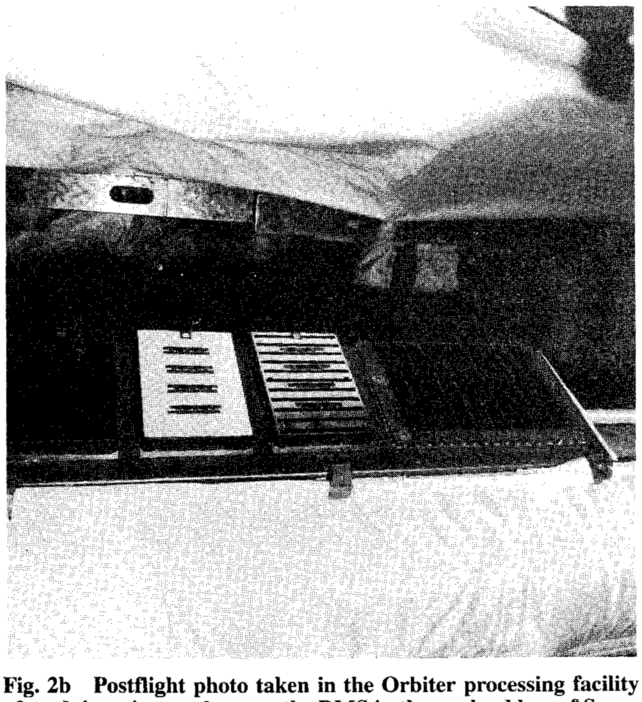

Fig. 2b Postflight photo taken in the Orbiter processing facility of modular witness plates on the RMS in the payload bay of Space Shuttle Discovery.

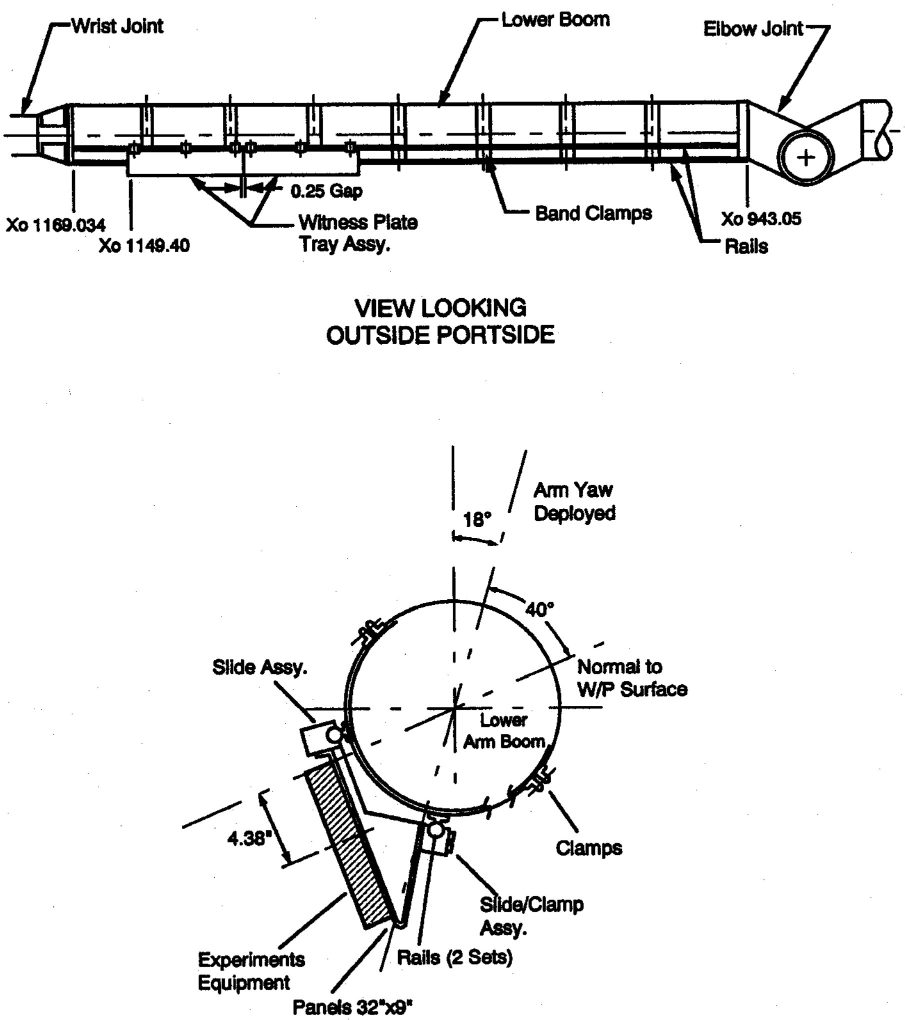

Fig. 3 Module witness plate mounting scheme.

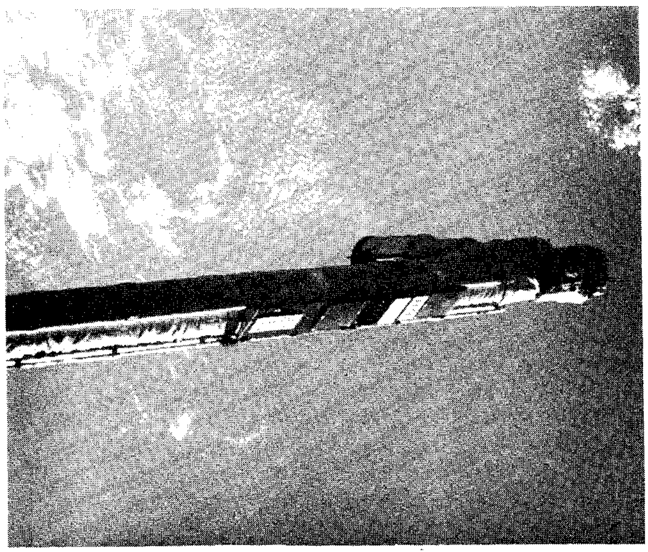

Fig. 4 ISAC payload deployed in LEO, STS-41.

LEO, is shown in Fig. 4. Primary reaction control system (PRCS) engine firings were suppressed during ISAC ram exposure to minimize sample contamination from that source.

Results and Discussion

O-Atom Fluence

The COMSAT Laboratories Atomic Oxygen Fluence Program, developed for prediction of oxygen atom fluences on INTELSAT VI, was used to calculate the expected O-atom fluence on the ISAC payload. Weight-loss measurements on the various fluence monitor materials resulted in an average estimate of O-atom fluence of 1.1×10^{20} atoms/cm^2, whereas the Atomic Oxygen Fluence Program prediction was also 1.1×10^{20} atoms/cm^2. This excellent correlation gave INTELSAT VI decision makers confidence in using the program to calculate the expected O-atom fluence on INTELSAT VI.

INTELSAT VI Solar Array Coupons and Thermal Control Plates

Both the front and rear surfaces of the silver foil interconnect stress-relief loops (Fig. 1) in the solar array coupons showed the formation of oxide. Careful visual inspection of the interconnects revealed no evidence that the oxide had been sloughed. Approximately 0.6 μ of silver had been converted to oxide on the front side and 0.5 μ on the back side of the interconnect stress-relief loop. So a total fluence of 1.1 atoms/cm^2 produces a total erosion of about 1.1 μ of silver, a value in excellent agreement with the results obtained in the test facilities at Los Alamos and Princeton. At Los Alamos, a total atom fluence of 3×10^{20} atoms/cm^2 converted 2 μ of silver to oxide on an unstressed interconnect at 80°C. At Princeton, a total fluence of 1.1×10^{20} atoms/cm^2 converted 1 μ of silver to oxide with the interconnect at 45°C and low-amplitude flexing with a mechanical exciter to simulate thermal cycling. Thermal analysis of the solar array coupons showed that the maximum temperature during the ISAC mission was 0°C.

The presence of oxide on both the front and back sides of the interconnect stress-relief loop deserves some comment. The oxide on the back side of the loop results from oxygen atoms scattered inelastically from the bottom of the gap that the interconnects bridge. Previous flight studies on STS-8 have shown that only about 1 atom in 10 reacts with polymer surfaces, and the rest scatter inelastically and are available for reaction with silver surfaces.[2,4]

Thermal analysis of the black, white, and striped thermal control plates gave average on-orbit temperatures of +5, −35, and +15°C, respectively. The oxide thickness ranged from 0.45 to 0.53 μ and showed no significant correlation with temperature over the range of temperatures investigated, though little observable dependence is expected at the low temperatures calculated for the thermal control plates.[13] In general, the thicknesses of oxide films on metals are expected to be a function of temperature,[14] and such a dependence was noted over the temperature range 85–150°C at Los Alamos.[13] A postflight photo of one of the interconnect specimens on the striped plate is shown in Fig. 5. The buckling oxide film is clearly visible in contrast to the still-smooth portions of the interconnect underneath the transparent Teflon tape.

Dry Lubricants

Ceram-lube 7000 was the only dry lubricant sample to show little or no surface oxidation resulting from atomic oxygen exposure either in LEO or in the LANL atom beam facility. The result is not surprising given that Ceram-lube 7000 is a lubricious metal oxide formulation, and further oxidation is unlikely for thermodynamic reasons. XPS spectra or auger depth profiles cannot be presented in this paper because the formulation is proprietary.

All other dry lubricants tested showed varying degrees of surface oxidation as revealed by XPS and auger electron/depth profile analysis.

E/M 1380-B (a graphite/phosphate glass formulation) showed the most extensive oxidation. The appearance of the sample changed from a flat black to a much darker velvet black as a result of exposure to atomic oxygen in LEO. Auger depth profiles showed dramatic decreases in the carbon/oxygen ratio at the surface and throughout the depth profile range (i.e., even after 11 min of sputtering). Auger peak heights for carbon and oxygen are shown in Table 2.

Table 2 EM 1380-B

	Auger electron peak heights	
Sample	Carbon	Oxygen
STS-41	1.4	5.6
LANL	3.6	3.0
Control	5.6	2.4

Fig. 5 Postflight photo of silver interconnect on thermal control plate.

Both WS_2 sample types gave nearly identical results. The surfaces of the flight samples and the LANL sample were enriched in oxygen and depleted in sulfur compared with the control as shown by auger depth profiles. The depth of oxidation is crudely estimated to be on the order of 100 Å. The oxidation state of tungsten as revealed by XPS was highest near the surface of the flight and LANL specimens and corresponded to WS_2 in the control. The surface analysis results are summarized in Tables 3 and 4.

Permaslik-R and Everlube 1346 are both MoS_2-based dry lubricants with polymer binders. Permaslick-R uses a polyurethane binder, and Everlube 1346 uses a silicone binder. XPS and auger electron depth profiling show that both the binder and the MoS_2 react with atomic oxygen. The results are summarized in Tables 5 (Permaslick-R) and 6 (Everlube 1346). The height of the peak for a particular element in an auger electron spectrum is proportional to the number of atoms of that element in the near-surface region as defined by the auger electron sampling depth (typically 1 to 10 nm as in XPS). The depth profile is determined by recording auger electron spectra periodically while removing surface material with a 1-KeV argon ion beam.

Reaction with atomic oxygen was confined to the near-surface region as measured by auger electron profiling for all lubricants except EM 1380-B. The implications of these results for wear-life projections will depend on the type of mechanism under consideration and the number of mechanical cycles expected during that mechanism's service life. In any event, the implications of atomic oxygen reaction with dry lubricant films must be considered during the selection of materials and the design of mechanical systems for LEO service. Shielding mechanisms from the environment may be desirable both to prevent micrometeoroid/orbital debris damage and to limit oxygen damage of lubricant films.

Table 3 XPS data for diversified dry lube (WS_2)

	Atom percent (XPS peak fit)					
Sample	0	WO_2/WS_2	WO_3	S-	SO_4^-	Si
STS-41	66.7	0.6	7.7	3.4	3.2	18.4
LANL	73.7	2.3	8.6	8.3	6.8	0
Control	37.6	11.5	2.1	48.7	0	0

Table 4 XPS data for microseal 300-1 (WS_2)

	Atom percent (XPS peak fit)					
Sample	0	WO_2/WS_2	WO_3	S-	SO_4^-	Si
STS-41	70.0	1.0	7.7	3.5	2.8	15.0
LANL	78.5	2.4	9.3	7.5	2.2	0.0
Control	31	12.0	1.2	48	0.0	7.8

Table 5 XPS data for permaslick-R

	Atom percent (XPS peak fit)						
Sample	O	MoS_2	MoO_2	MoO_3	S-	SO_4^-	Si
STS-41	69.4	1.0	0	8.4	3.5	1.2	16.4
LANL	73.5	1.5	0	10.9	5.0	3.6	5.4
Control	68.8	4.0	7.0	0	13.5	0	6.7

Table 6 XPS data for Everlube 1346

	Atom percent (XPS peak fit)				
Sample	0	MoS_2	MoO_2	Si (silicone)	Si (oxide)
STS-41	61.1	0.0	0.2	8.6	30.1
LANL	61.8	0.0	0.07	6.9	31.1
Control	53.8	0.0	0.0	46.2	0.0

Polymeric Materials

None of the silicone or Viton elastomeric seal materials tested displayed any changes in helium permeability after exposure to atomic oxygen in LEO. The exposed surfaces of Viton became diffuse in appearance, as did the exposed surfaces of most other reactive polymers such as Kapton and polyethylene. In contrast, the exposed surfaces of the silicone elastomers developed a glassy appearance. X-ray photoelectron spectroscopy of the silicone 383 elastomer sample showed 28 atom percent oxygen and 52 atom percent carbon before exposure vs 50 atom percent oxygen and 25 atom percent carbon after exposure in LEO. Most polymeric materials displayed a weight loss; however, the silicone elastomer specimen displayed a small weight gain not inconsistent with the conversion of the surface of the polymer from a silicone to a silicate, i.e., Si-CH_3 to Si-OH. It should be noted that the Viton 747 formulation contains some silicone and that the silicone content of the surface increased during the exposure.

The mass loss per square centimeter of exposed area and the reaction efficiency (Re) in cubic centimeters per oxygen atom are summarized in Table 7. Only the polymers showing measurable weight loss are shown in Table 7. FEP Teflon samples were examined by SEM in a search for the needle or "carpet" morphology characteristic of reaction with atomic oxygen because FEP Teflon has shown little or no reaction with atomic oxygen exposures[2,3] of the type described here. No evidence of "carpet" morphology was found at 10,000 diameters magnification. The reactivity of FEP Teflon flown on the LDEF was much greater with an average Re of 0.3×10^{-24} cm^3 per atom, and even higher Re values have been observed in ground-based test facilities. The apparent discrepancy between the reactivity of Teflon in short-duration LEO exposures, long-duration LEO exposures, and various ground-based facilities probably results from differences in solar vacuum ultraviolet radiation dose. Recent laboratory studies have shown that the atomic oxygen Re of various fluorocarbon polymers is strongly dependent on the vacuum ultraviolet radiation dose.[12]

In general, the values reported in Table 7 compare favorably with those obtained in previous LEO materials experiments showing agreement to within 10% of the values reported previously.[2-5]

Optics

The 40-Å diamond film on quartz showed no perceptible change, determined with an interferometer/profiler, as a result of exposure to atomic oxygen in LEO. This result contributes to the growing body of data that suggests that diamond (not diamond-like) thin films are one of the most inert organic materials in the LEO environment.

The MgF_2-overcoated aluminum mirror showed an increase in apparent MgF_2 film thickness, measured by ellipsometry, of 2.9 nm, possibly resulting from the formation of a thin oxide layer on the surface. No significant change in reflectance was observed between 121.6 and 200 nm.

The ZnS_2-coated germanium flat was visibly more diffuse and opaque after the LEO exposure; however, postflight testing showed that performance of the Earth horizon sensor on INTELSAT VI should be unimpaired.

Table 7 Reactivity of polymeric materials, STS-41

Polymer	Mass change, mg/cm^2(or surface recession)	Reaction efficiency, Re
PEEK	−0.616	4.3×10^{-24}
Nylon 6	−0.505	4.2×10^{-24}
Polypropylene	−0.442	4.4×10^{-24}
Polyethylene	−0.352	3.5×10^{-24}
Polysulfone	−0.311	2.1×10^{-24}
Lexan	4.25×10^{-4} cm recession	3.8×10^{-24}
Tefzel	−0.033	0.2×10^{-24}
Silicone 383	+0.0003	N/A
FEP Teflon	<0.001	$<0.1 \times 10^{-24}$
Kapton HN	−0.513	3.3×10^{-24}
Black Kapton	−0.374	2.4×10^{-24}

Coated Actinometers

The Ag filmstrip underlying the Si_3N_4, SiO_2, and Al_2O_3 coatings showed no significant increase in electrical resistance as a result of atomic oxygen exposure in LEO or in the high-velocity atomic oxygen beam facility at LANL.[14] Auger electron depth profiling of Si_3N_4 samples exposed to atomic oxygen in the LANL facility[18] demonstrated the presence of SiOx to a depth of about 50 Å. (Surface analyses of the flight samples have not been completed at this time.) The conversion of Si_3N_4 to SiO_2 has been reported in both thermal and hyperthermal reactions. The thin SiO_2 surface layer that is formed when atomic oxygen reacts with the Si_3N_4 surface protects the bulk of the film from further oxidation.

The conductance of the Ag filmstrip underlying the BN coating changed from 0.070 mho before flight to 0.034 mho after exposure to 1.1×10^{20} ram O atoms in LEO or 3.3×10^{-22} mho per atom/cm^2. Ground-based testing (LANL) of nominally identical material gave 3.3×10^{-22} mho per O atoms/cm^2, whereas a previous flight test conducted as part of the Delta Star Space Materials Experiment also gave 3.3×10^{-22} mho per O atom/cm^2. Auger analysis of a BN-coated actinometer exposed to high-velocity atomic oxygen at LANL showed evidence of oxidation through the thickness of the film; however, interpretation of the auger profile was complicated by reactions with atmospheric water. It should be noted that the reactivity of BN films may depend on the preparation procedure and that the result reported here may not be general.

Space Station Beta Cloth

SEM examination of the Kapton witness specimen placed behind the beta cloth sample showed no evidence of direct penetration of high-velocity oxygen atoms. Similarly, the silver foil specimen showed no detectable weight loss after treatment with 7-molar ammonium hydroxide, indicating limited penetration of thermalized oxygen atoms. In both cases, the detection limit for oxygen penetration is estimated at 1% of the total ram fluence based on the changes observed in Kapton and silver foil samples exposed directly to ram during the mission. It should be noted that the silver foil displayed a visible beta cloth weave image that may be due to very limited penetration of O atoms. The weave image did not dissolve in ammonium hydroxide. Even with "worst-on-worst-case" oxygen atom damage, O-atom penetration seems acceptable from a Space Station Program perspective, so beta cloth should be acceptable as an MLI blanket outer cover, in light of other testing completed to date[15] for Space Station Freedom. More sensitive tests of Beta cloth permeability were conducted at the LANL facility and as a part of the Evaluation of Oxygen Interactions with Materials-III (EOIM-III) flight experiment carried out on STS-46 in July–August 1992.

Summary and Conclusions

Data obtained with the ISAC experiment package, combined with earlier ground-based testing, provided the INTELSAT Organization with the necessary basis for deciding to rescue the satellite. The flight and ground-based data both indicate that the damage sustained by the satellite in LEO will be acceptable and that many years of service can be expected now that INTELSAT VI has been placed in service (May 1992; STS-49).

In addition, the ISAC package provided a first look at a number of important materials for which no previous flight data were available. Surface oxidation of a number of dry lubricants being considered for the Space Station Program has been measured in flight and in ground-based testing in the LANL atom beam facility. The reaction efficiencies of several polymeric materials, i.e., Tefzel, Nylon, PEEK, and polypropylene, have been measured for the first time. The low reactivity of a synthetic, diamond-thin film has been demonstrated. Reactivities of boron nitride and silicon nitride have been measured both in flight and in the LANL atom beam facility. Finally, the optical properties of a magnesium-fluoride-coated aluminum mirror surface were not significantly changed by ram atomic oxygen in LEO.

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