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Degradation of Spacecraft Materials in the Space Environment

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Abstract
When we think of space, we typically think of a vacuum containing very little matter that lies between the Earth and other planetary and stellar bodies. However, the space above Earth's breathable atmosphere and beyond contains many things that make designing durable spacecraft a challenge. Depending on where the spacecraft is flying, it may encounter atomic oxygen, ultraviolet and other forms of radiation, charged particles, micrometeoroids and debris, and temperature extremes. These environments on their own and in combination can cause degradation and failure of polymers, composites, paints and other materials used on the exterior of spacecraft for thermal control, structure, and power generation. This article briefly discusses and gives examples of some of the degradation experienced on spacecraft and flight experiments as a result of the space environment and the use of ground and space data to predict durability.

Introduction

Each mission into space poses its own challenges with regard to spacecraft durability. Materials that are used on the outside of spacecraft are chosen to serve a specific function to enable the spacecraft to regulate heat, generate power, or support other important components. Each mission is unique in not only the types of materials that are selected for use but also the environment that they will encounter during flight. Spacecraft designers must take into account not only the physical and mechanical properties of the materials with regard to their intended function but also what the expected properties will be at the end of the mission due to degradation by the environment to which they will be subjected. Because spacecraft are used often for exploration and discovery to unknown environments, the first indication of an environmental problem is usually through experiencing a change in hardware conditions or performance as observed through telemetry, system failure, or observation of degradation on

retrievable flight hardware. Our first detailed knowledge of the Earth's orbital environment effects on spacecraft and associated hardware, especially that caused by atomic oxygen, came from the early Shuttle missions.[1] What we learn about other planetary and galactic environments will most likely also be through direct experience. Most of our focus to date has been associated with the environment above Earth's breathable atmosphere where the International Space Station (ISS), Space Shuttle, Hubble Space Telescope (HST), and satellites operate, but our knowledge of this environment and experience in developing flight experiments, ground tests, and correlations will enable a better prediction of performance in other environments beyond Earth. This article focuses on some of the degradation that has been observed in Earth's orbit and what spacecraft designers have done and are doing to enable spacecraft to survive and to predict performance for future missions in these types of environments.

Examples of Degradation from the International Space Station, Low Earth Orbit Flight Experiments, and the Hubble Space Telescope

The ISS was one of the first examples of designing for long-term durability in the low Earth orbit (LEO) environment. Early shuttle missions experienced texturing and thinning of polyimide Kapton and other carbon-containing materials from exposure in LEO.[1] The primary reason for the degradation was found to be oxidation by the atomic oxygen in LEO.[1] At the time, polyimide Kapton H, a specific type of Kapton, was under consideration as the prime candidate for the solar array support structure for ISS. Kapton was attractive for this application because the solar cells needed to be bonded to a flexible and strong surface that was lightweight and had the right thermal properties, so the array could be stowed and unfolded like a sail when installed on the ISS. Kapton H atomic oxygen erosion data from shuttle flight information caused concern for the survivability of Kapton for use as a solar array blanket.[2] High levels of erosion for Kapton also were observed on the Long Duration Exposure Facility (LDEF) experiment, a free-flying collection of experiments launched from and later retrieved by the Space Shuttle to look at the space environment and its effect on a variety of materials (see the Edwards et al. article in this issue).[3] Figure 1 shows on-orbit photos of a Kapton blanket–covered panel on LDEF at deployment and after 69 months of space exposure, showing that the outer layer of Kapton on the blanket is missing because it had been totally oxidized into gaseous products.[3] Materials that are already in their highest oxidation state such as silicon dioxide and aluminum oxide, however, do not react with the atomic oxygen in the LEO environment.[4] Since Kapton had all of the desired properties for use on ISS other than its interaction with the environment, different types of thin-film metal oxide coatings applied by physical vapor deposition were tried as a protective barrier.[4] Metal oxide coatings proved to be very effective barriers, but where there were defects in the coating caused by surface imperfections or dust particles or scratches from handling post-coating, the atomic oxygen could still reach the Kapton and create areas of undercutting on the surface.[5] Undercutting, such as that shown in Figure 2 from LDEF, does not pose too much of a problem for maintaining durability unless there are so many defects or scratches that the undercut areas can connect and cause sections of the polymer to be removed or initiate tearing across the surface of the polymer. The array blanket that is on ISS currently is protected with

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a thin-film sputter-deposited silicon dioxide coating that has allowed the array to survive longer than the 15-year mission life for which it was originally designed, but it is important to note that there was substantial ground testing and qualification that occurred prior to fabrication to ensure that the number of defects in the coating were low enough such that less than half of the thickness of the array blanket would be removed in order to enable the blanket to survive for the desired mission lifetime.[6,7]

Unfortunately, not all hardware that is flown undergoes such careful testing. Sometimes assumptions are made that a solution that initially looks good will work without being tested due to a lack of time and funding to verify its performance before flight. An example of this is the solar array blanket box cover on ISS. Much work went into the array blanket itself, but the thermal blanket covering the box in which the array blanket was stowed was not tested in the environment pre-flight. The thermal blanket was composed of polyimide Kapton, which was aluminized on both sides.[8] The assumption was made that since the Kapton already had an aluminum coating, which would serve as a barrier to the atomic oxygen and react with it to make aluminum oxide on the surface, the thermal blanket would not degrade in the environment. Figure 3a shows the damage caused by atomic oxygen on the blanket box cover after only a year of exposure on ISS, while the expected lifetime was supposed to have been 15 years.[8] Evaporated aluminum coatings typically contain more defects than sputter-deposited coatings, but the failure of the blanket box cover was not so much caused by the number of coating defects but by the fact that the Kapton was coated on both sides.[8] It was found later through a combination of observation of samples flown on flight experiments and Monte Carlo-based computational modeling that atomic oxygen upon impact with a surface can react, recombine, or bounce off of the surface.[8] When it bounces off of the surface, the energy of the atomic oxygen is reduced to thermal energy, but it is still very reactive and free to react with another surface.[8] In the case of the double aluminized Kapton blanket, the atomic oxygen could enter a defect and react with the Kapton until reaching the second aluminum coating underneath. At the surface of the aluminum coating, once the aluminum is oxidized, the atomic oxygen would no longer be able to react with it, so it could only bounce off of the surface to react with the surrounding Kapton or recombine with other oxygen atoms. Essentially, in the case of the ISS blanket
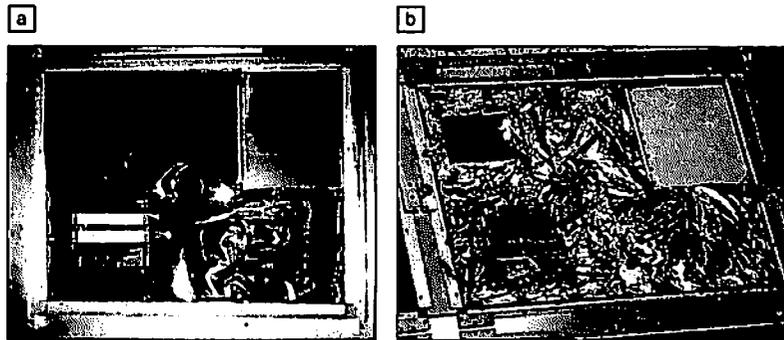

Figure 1. Long Duration Exposure Facility tray F9. (a) Pre-flight photo and (b) on-orbit photo taken during STS-32, showing complete loss of the outer Kapton layer of the blanket.[18] The aluminized layer is still intact.
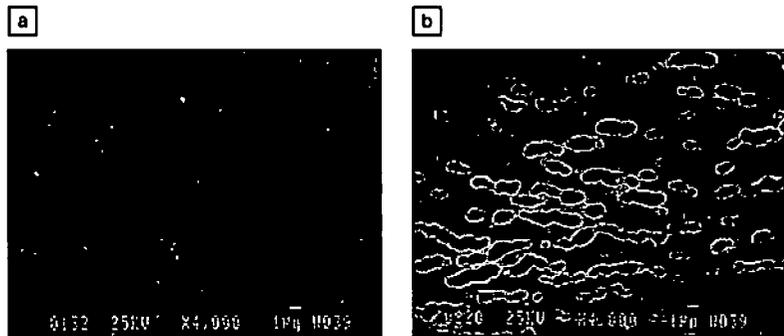

Figure 2. Photos of aluminized Kapton flown on the Long Duration Exposure Facility with the aluminum-coated side facing the space environment. (a) Defect areas in the aluminum coating and (b) the same sample with the aluminum coating chemically removed to show the undercut cavities under the defect sites caused by atomic oxygen erosion of the Kapton.[19]
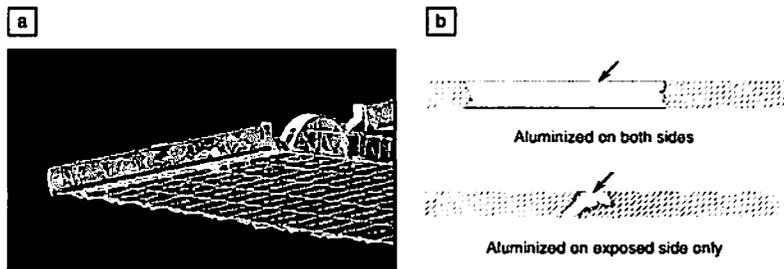

Figure 3. Damage and damage modeling of the solar array blanket box cover on the International Space Station. (a) Photo showing the damage caused by atomic oxygen on the Kapton (aluminum coating on both sides) blanket box cover after one year in orbit. (b) Monte Carlo modeling comparison of undercutting patterns for Kapton coated with aluminum on both sides compared to a single layer aluminum protective coating on Kapton.

box cover, the atomic oxygen became trapped between the two layers of aluminum causing greater opportunity for erosion of the Kapton between the aluminum layers. The erosion from multiple

bounce, trapped atomic oxygen eventually resulted in the removal of most of the Kapton to create two free-standing aluminum films.[8] If the aluminum barrier had been only on the space-facing side of the

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blanket, the atomic oxygen would have reacted at defect sites to create a narrow channel to the back side and then would have been able to scatter through the open pore polyimide underneath rather than being trapped in the Kapton blanket where it could react further with the polymer.[8] This is illustrated by the Monte Carlo atomic oxygen undercutting modeling results for both double-coated and single-coated Kapton shown in Figure 3b.[8] Preflight qualification testing could have avoided this degradation problem.

Not all testing, however, is straightforward. Unfortunately, there is no easy way to exactly replicate the environment of space on Earth. There are physical limitations as to what can be done to generate atomic oxygen, vacuum ultraviolet (VUV) (100–200 nm) and near UV (200–400 nm) radiation, ionizing radiation, and thermal extremes in the exact conditions and proportions as in space. So flight experiments, such as those flown on the Space Shuttle,[9] on free carriers such as LDEF,[10] and on the outside of ISS,[11] are used to provide material degradation information that can be used to help correlate what is happening in space with what is occurring in ground-based testing facilities. One of the experiments on the Materials International Space Station Experiment (MISSE) 2 and 4 was designed to measure the erosion of a coated polyimide in space, compared to its erosion in a ground-based test facility to develop a correlation factor that could be used to more reliably predict the in-space durability of coated polymers tested in a ground-based system.[11] The correlation factor that was determined (~18 times more erosion for coated Kapton in a ground plasma system than in LEO) along with ground system testing of some of the Kapton multilayer insulation (MLI) blanket from HST was used to predict the condition of the MLI for Servicing Mission 4 (SM4).[11] The prediction that the MLI would not be degraded to the extent that it would need to be covered by the astronauts during HST SM4 allowed this task to be moved to the end of the schedule and listed as optional, thereby freeing time for other more critical tasks.[11] It was observed on SM4 that the condition of the Kapton MLI was acceptable, so the task to cover this bay was performed as one of the last servicing tasks. Another experiment flown on MISSE was designed to measure the erosion rates of 40 different polymers and graphite to gain better understanding of polymer erosion in LEO and to develop a predictive tool to enable estimation of the erosion of new polymers under consideration for use in space, based on knowing the chemical structure, density, and ash content deter-

mined in a ground-based atomic oxygen exposure facility.[11,12] Ash content is important in the prediction because the ash present in a material is the part that cannot be oxidized and can accumulate on the surface during exposure shielding the underlying material from further oxidation. In essence, it develops its own protective coating that can make the observed erosion lower than what would be expected based on the erosion of the bulk material. Because most of the damage observed in LEO is from atomic oxygen attack, most of the work to date has focused on atomic oxygen erosion. It is still not totally understood what role the other environments play in material degradation, as some components of the environment appear to play a synergistic role in degradation for some materials but not for others.

A good example of synergistic environment effects is the severe on-orbit cracking of the outer layer of the vapor-deposited aluminum-coated fluorinated ethylene propylene (FEP) Teflon MLI blanket observed on the solar-facing side of the HST during the second servicing mission.[13] Figure 4 shows the embrittled MLI blanket after 6.8 years in space. A review board that investigated the severe FEP degradation on HST concluded that electron and proton radiation combined with on-orbit thermal cycling caused the observed cracking of the MLI at stress-concentrated locations and that damage increased with the combined total dose of ionizing radiation, ultraviolet radiation, and x-rays with thermal cycling.[13] The conclusion was that radiation-induced chain scission was the primary mechanism of degradation, and the damage rate was significantly affected by on-orbit temperature. Although damage was observed in accelerated ground-based exposures, it did not simulate the extent of damage observed on HST.[13] Calibration of ground-based accelerated exposure using space data is needed to obtain more accurate simulation of this effect of the environment.

Another example of a combined environmental effect on materials, first observed on LDEF, was the formation of a darkened contaminant layer on surfaces due to atomic oxygen and VUV radiation.[14] Figure 5 shows a close-up of a tray of materials that was 38° from the ram (or orbital) direction on LDEF on the Solar-Array Materials Passive experiment.[14] The light-colored samples (rectangular, square, and tensile shaped) are silicones that contained a lot of volatiles that, when in space, produced large quantities of contaminants on neighboring surfaces and samples. A combination

Figure 4. Photograph of the Hubble Space Telescope on orbit during the second servicing mission showing cracking and tearing of the multilayer insulation after 6.8 years of space exposure due to what is believed to be a combination of ionizing radiation, ultraviolet radiation, x-rays, and thermal cycling.

of VUV bond breakage of the deposited volatile silicone fragments, hydrocarbon deposition, and atomic oxygen conversion of the contaminant surface layer to silica allowed the build-up of a darkened contaminant layer. There is a light-colored "shadowed" region directly to the right of the samples. This is where atomic oxygen arrival was shielded, and hence the deposited contaminant fragments were able to re-evaporate.[14] Because a darkened contaminant layer can lead to significant changes in optical and thermal properties of the material on which it is deposited, silicones used in space currently have to meet stricter guidelines with regard to the volatile condensable products that they give off during heating and under vacuum so as not to cause significant power losses, changes in performance of optics, or overheating.

Combined environments of atomic oxygen and micrometeoroid and debris impacts also can lead to greater damage than by either alone. Figure 6a shows a photo of a silver-FEP Teflon blanket flown on the ram-facing side of LDEF, showing

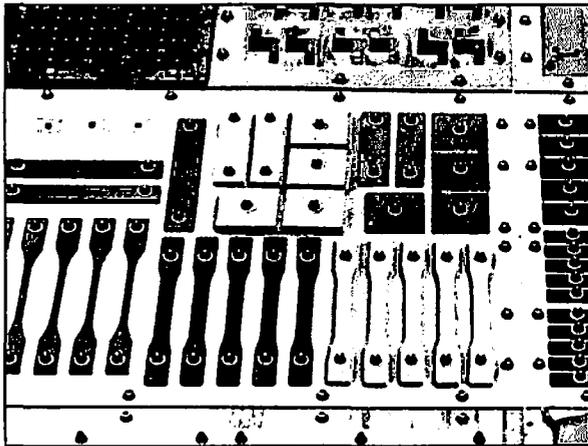## Degradation of Spacecraft Materials in the Space Environment

Figure 5. Section of the Long Duration Exposure Facility Solar Array Materials Passive Experiment (tray A8) showing dark contamination to the right of the silicone (light gold colored) rectangular and dog bone–shaped samples.
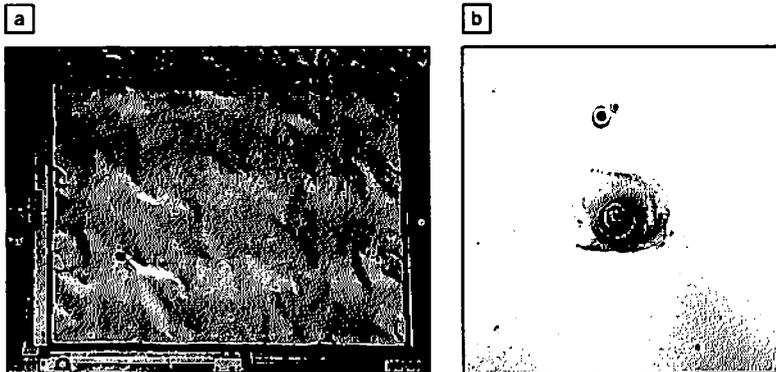

Figure 6. Long Duration Exposure Facility tray A10 showing micrometeoroid and debris impacts. (a) On-orbit photo of tray A10 and (b) post-flight close-up photo of the impact site showing the impact hole, delamination area, and the darkened rings caused by oxidation of the silver.

Figure 7. Impact crater on alumigold (chromate conversion coating) on aluminum from the Long Duration Exposure Facility.

micrometeoroid and debris impacts. The impacts were found to cause delamination of the silver-FEP Teflon composite, which then allowed atomic oxygen to enter the impact hole to oxidize the underlying exposed silver.[15] This resulted in the darkened rings observed around the impact holes. An example is shown in the close-up image in Figure 6b.[15] LDEF provided a large collection of impact data that covered a wide range of impact craters from below 0.01 mm (10 µm) to 5.25 mm.[16,17] Figure 7 provides an example of an impact in alumigold (a chromate conversion coating) on

aluminum from LDEF. When micrometeoroids and debris impact spacecraft surfaces, they generally vaporize along with some of the material they impact, which then can condense on the surface. This condensate and the condensed molten material created by the impact form a wave or splash pattern around the crater. Fortunately, the size distribution and number are currently low enough that the proper design (multiple spaced layers for piping, multilayer shielding, or redundant systems) can reduce the damage that impacts can cause.[13]
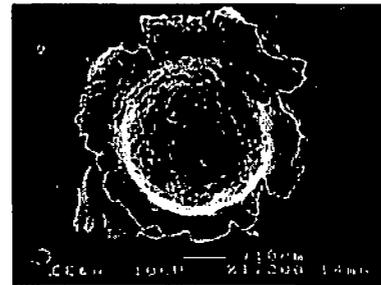
Conclusions

This article provided a few examples of degradation that have been observed on spacecraft as a result of the Earth orbital environment. The experience gained through observing damage on spacecraft and verification of the causes of damage through a combination of spaceflight experiment, ground-based testing, and modeling has led to better spacecraft design. In spite of the wealth of knowledge that has been gained, there are still many unknowns with regard to the role each environment plays in the damage and in the presence of, or lack of, synergistic effects with other components of the environment. What has been learned, however, has resulted in better methods of testing, evaluation, and analysis that are not only valuable for enabling design of more durable spacecraft for the Earth's orbital environment but also may provide guidance for durable spacecraft design for other environments beyond Earth.

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