AIAA

AIAA 2001-0095
Contamination Effects due to Space Environmental Interactions

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39th Aerospace Sciences Meeting & Exhibit
8-11 January 2001
Reno, Nevada

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ABSTRACT

Molecular and particulate contaminants are commonly generated from the orbital spacecraft operations that are under the influence of the space environment. Once generated, these contaminants may attach to the surfaces of the spacecraft or may remain in the vicinity of the spacecraft. In the event these contaminants come to rest on the surfaces of the spacecraft or situated in the line-of-sight of the observation path, they will create various degrees of contamination effect which may cause undesirable effects for normal spacecraft operations. There will be circumstances in which the spacecraft may be subjected to special space environment due to operational conditions. Interactions between contaminants and special space environment may alter or greatly increase the contamination effect due to the synergistic effect.

This paper will address the various types of contamination generation on orbit, the general effects of the contamination on spacecraft systems, and the typical impacts on the spacecraft operations due to the contamination effect. In addition, this paper will explain the contamination effect induced by the space environment and will discuss the intensified contamination effect resulting from the synergistic effect with the special space environment.

Key Words: Contamination, Space Environment, and Synergy

INTRODUCTION

The contamination generation, transport, and impact on spacecraft systems are greatly influenced by the space environment. Material outgassing from the spacecraft is accelerated by the vacuum and solar heating conditions of the space environment. Particulate and molecular contaminants present in the space environment tend to move around the spacecraft due to the localized spacecraft environment. The presence of the contaminants will affect spacecraft's original design performance. Returned hardware from Space Shuttles, Solar Max Repair Mission (SMRM), Long Duration Exposure Facility (LDEF), Hubble Space Telescope (HST), and MIR have provided evidence of both short-term and long-term effects of space environment on spacecraft. Information learned from these returned hardware is invaluable because the space environment is complex and is very difficult to reproduce in a space simulation facility on the ground.

The space environment provides a dynamic boundary for an operational spacecraft in orbit. When a spacecraft is operating in space, it is mostly interfered by the spacecraft's local space environment. Therefore, a key consideration of the interactions between a spacecraft and its space environment is the localized conditions which change tremendously according to the altitude and orbit. The space environment to be considered in this paper includes orbits ranging in altitude from Low Earth Orbit (LEO) to Geosynchronous Earth Orbit (GEO) and beyond.

SPACE ENVIRONEMNT

The operations of a spacecraft need to consider the effect of the diverse space environment and its associated parameters. According to Purvis [1] the space environment can be characterized into four categories: the ionizing radiation, the natural plasmas, the micrometeorites and debris, and the neutral environment. Among these environmental factors, local environment related to gravity, B & E Fields, neutral atmosphere, and plasma are strongly coupled with the spacecraft systems. A detailed examination can be performed by analyzing the interactions between the system and its local environment. A list of environmental factors and their effects on space systems in near-Earth space was provided by Purvis in Table 1.

Table 1. The Space Environmental Effects

The Space Environmental Effects
• Sunlight & Earthshine Heating, Thermal Cycling, Material Damage, Sensor Noise, Drag, Torque, Photoemission
• Gravity Acceleration, Torque
• B & E Fields Torque, Drag, Surface Changes, Potentials
• Neutral Atmosphere Drag, Torque, Material Degradation, Vacuum, Contamination, HV Breakdown
• Plasma Charging, Arcing, Parasitic Currents, System Potentials, Sputtering, Enhanced Contamination, ES & EM Waves (Noise), Plasma Waves & Turbulence, Change of EM Refractive Index
• Fast Charged Particles Radiation Damage, Internal Charging, Single Event Upsets, Arcing, Noise
• Meteoroid & Debris Mechanical Damage, Enhanced Chemical & Plasma Interactions, Local Plasma Production, Induced Arcing
• System Generated System Dependent: Neutrals, Plasma, Fields, Forces & Torque, Particles, Radiation

The ionizing radiation includes the presence in space of ultraviolet (UV), radiation belts, cosmic, solar, and galactic radiation. Near the Van Allen belt, the relatively strong Earth magnetic field traps the energetic protons. High-energy particles degrade detector performance by the accumulative material microstructural damage. Although any spacecraft may be susceptible to surface charging, the highest occurrence seems to be with GEO spacecraft. In general, radiation may cause single events upset (SEU) and degrade solar arrays, dielectric materials, electronic components, and sensors. It can also deposit charge inside dielectric materials and on surfaces internal to the spacecraft with a result in dielectric breakdown and EMI electrical upsets.

Plasma is defined as an electrically neutral ionized gas. Plasma are encountered in the ionosphere, plasmasphere, magnetospheric storms, and plasmas induced by the spacecraft. At LEO, the solar UV ionizes the major atmospheric constituents, oxygen and nitrogen atoms, to produce plasma. Interactions between the spacecraft and the plasma include arcing, current collection, and spacecraft charging. The charging due to different potentials on spacecraft surfaces in a plasma environment is a concern when building a spacecraft.

A spacecraft can be impacted and damaged by the micrometeorites and man-made orbital debris environment. These impact can cause serious structure damage and catastrophic failure of the spacecraft. Although the hazard from the natural debris environment has been considered as acceptable, the dangers posed by man-made orbital debris is a real concern. The impact by orbital debris environment can also produce a dense localized plasma or enhance spacecraft surface erosion.

The neutral environment consists of natural species and contamination generated by the spacecraft and released in the immediate environment. Typical attributes associated with the neutral environment include atomic oxygen (AO), glow, sputtering, and atmospheric drag. AO at LEO degrades spacecraft surfaces by a chemical reaction with materials that changes the surface properties. For a LEO spacecraft, the neutral atoms cause significant surface heating and orbital decay. To compensate the orbital decay, orbital adjustments are necessary to maintain a spacecraft in its proper orbit.

CONTAMINATION SOURCES

Spacecraft contamination is defined as a foreign substance on or near a spacecraft surface that adversely affects the performance of space systems. The contaminant, either molecular or particulate, is generated by the spacecraft under the influence of the space environment. As shown in Table 2, the majority of the contamination sources are self-generated by the spacecraft systems. The returned SMRM hardware revealed spacecraft generated molecular contaminants on fine Sun sensor, louver frames, and instrument venting areas. Study of the MIR solar arrays as part of the International Space Station (ISS) Risk Mitigation Program discovered significant thruster burn residue [2]. In addition, particles and fibers were identified from the returned MIR solar arrays. Through examination it was concluded that MIR solar arrays are sources of particle and glass fiber generation and shedding [3].

Table 2. Contamination Sources

Contamination Sources
Molecular
• Material outgassing (water, hydrocarbons, silicones)
• Spacecraft and Multi-Layer Insulation (MLI) venting
• Fluid leak, dump, and lubricant loss
• Plume products
• Extravehicular activity
Particulate
• Surface particles
• Plume products
• Ice formation
• Mechanism generated particles
• Micrometeorites & debris
• Extravehicular activity

Long-term outgassing originated from spacecraft materials poses a great concern. Spacecraft outgassing materials are released when the environmental pressure is reduced and the temperature is raised. Low molecular weight constituents, light reaction products, and absorbed gases such as water, hydrocarbons, and silicones are the most significant outgassing constituents. Typical outgassing releasing mechanisms consist of desorption of physically or chemically adsorbed gases from the surface, evaporation or sublimation of the material itself, or evaporation and decomposition of gases in the bulk material.

Spacecraft venting is another major contamination source. Many spacecraft and instruments require venting of gases from thermal blankets and spacecraft interior to balance the internal pressure. Additionally, venting may be used to dispose of waste gases, to produce low-pressure drag makeup, or simply to provide low-level propulsion for attitude control. The vented gases modify the local environment and disturb spacecraft activities. When condensed on surfaces, the vented gases degrade the thermo-optical properties of the surfaces.

Leakage of operational fluids and gases from manned modules and the Space Shuttle produces molecular contamination. These fluids and gases leak from storage tanks, supply lines, or pressurized cabins during a normal vehicle operation. Inhabited space systems generally have overboard dumping of disposals such as gases, liquids, and particles. Besides dumping waste products from the crew cabin, the Space Shuttle frequently discharges the fluid into space. In addition, the use of a highly volatile lubricant may present a contamination threat that is detrimental to sensitive spacecraft surfaces.

Spacecraft plume products are another contamination contributors. Rocket engines are used for launch vehicles, apoapsis and periapsis motors, spacecraft attitude control, and station keeping. The release of large amounts of expelled propellants into the surroundings alters the space environment and interferes with the spacecraft operations. Products of combustion can also deposit on surfaces in the vicinity of the thrusters by direct impingement.

Extravehicular activity (EVA) and operations of spacecraft mechanisms generate both molecular and particulate contamination. The space suits and Space Shuttle storage compartments are potential contamination sources. During an EVA, the ambient and the surface particles are disturbed with the possibility of being redistributed onto other critical surfaces.

CONTAMINATION IMPACTS ON SPACECRAFT SYSTEMS

Contamination may be originated from many sources during spacecraft operations. After being generated, contaminants may attach to spacecraft surfaces or remain in the vicinity of the spacecraft. Deposited or line-of-sight contaminant influences a normal spacecraft operation. This contamination effect is further altered or enhanced by the space environment. Among all space environmental attributes discussed before, vacuum, temperature (solar heating), AO, and radiation create obvious contamination problems. Each single environment contributes separately in producing a contamination related effect. However, a synergistic effect may be produced with the interaction of multiple space environment conditions. Relatively speaking a synergism may aggravate the contamination effect more than a single space environment. A summary of the contamination related impacts, with the interactions with space environment, on spacecraft systems is shown in Table 3.

SPACE ENVIRONMENT ENHANCED CONTAMINATION EFFECTS

The space environment provides unique conditions for orbiting spacecraft. The vacuum of space magnifies many environmental parameters (speed, temperature, voltage, etc.) more than the Earth's atmosphere. Without the interference of the atmosphere, the temperatures produced in vacuum by sunlight are extreme. Therefore, a spacecraft will be

Table 3. The Contamination Impacts On Space Systems

Contamination Impacts
Thermal Control
• Contamination buildup
• Radiation effect
• Degradation of thermal control system
Optics
• Degradation of optical system
• Reduced transmittance through lenses, mirrors, windows, and detectors
• Increased light scattering along the optical path
Power
• Reduced solar cell efficiency
• Obscured solar array surfaces and reduced solar cell efficiency
Propulsion
• Restricted propulsion operations
Structure
• Surface degradation
• Particle penetration
Sensors
• Performance of Sun, Earth, and star sensors
• Scatters ambient light onto sensor optics leading to false response
Operations
• Disturbance to spacecraft
• Increased molecular column density can affect instrument operation
• Electrical discharge or arcing in high voltage equipment due to high outgassing
• Noise on slip rings and electrical contacts
• Failure of precision mechanisms due to particulate
• Electrical discharge or arcing in high voltage equipment due to contamination

exposed to an extreme solar heating and cooling conditions in space. Consequently, spacecraft materials and components will demonstrate more damage because of the impact of the extreme conditions. Additionally severe sunlight effects include surface discoloration, material damage, and coating failure. Similar to the sunlight, the presence of other space environment conditions creates contamination problems. Evidence of contamination problems associated with space environment exposure has been observed since the beginning of the space era. Knowledge base has grown from the examination of many returned flight hardware, real-time in-flight surface surveys, observed anomalies via telemetry, ground tests, and predictions. Among these contamination effects, material outgassing, AO erosion, thermal surface degradation, and particle deposition are frequently studied. Detailed space environment enhanced contamination effects are discussed below.

Atmospheric Drag

Operational spacecraft encounter a significant number of atmospheric particles during each orbit. Neutral gas molecules are atmospheric particles that influence a spacecraft by transferring energy and momentum to a spacecraft as a drag force. Atmospheric drag in LEO is a key parameter in predicting spacecraft fuel requirements. The atmospheric density and its long-term fluctuations dominate the reboot requirements for a spacecraft. To compensate the drag, additional fuel is consumed for orbital adjustments, which inevitably produces more contaminants around the spacecraft.

Mechanisms capable of heating the Earth's atmosphere produce ambient density changes. The process of heating induced drag may be resulted from geomagnetic storms and changes in solar extreme UV emission. An excellent atmospheric drag example can be found on the Tropical Rainfall Measuring Mission (TRMM) that operates in 2002's 23rd solar maximum cycle. A solar maximum with roughly an 11-year period is the time of largest average sunspot number. As the sun activity level increases, the atmosphere is heated and the gas is expanded. This in turn affects the plasma density at the LEO environment and increases atmospheric drag on a spacecraft. As a result of operating during a solar maximum, TRMM will consume more propellants; thus more contaminants will be generated. Generally, it is a valid assumption that most LEO spacecraft encounter elevated contamination levels generated by the additional fuel consumed to compensate for atmospheric drag.

Outgassing

According to the phase equilibrium, a reduced pressure of space will promote polymeric materials to outgas. With a low ambient pressure, molecules are easily released from spacecraft surfaces. Coupling with the solar radiation and long-term exposure, this outgassing effect is even more significant. Contrary to this inverse pressure effect, outgassing rates of polymeric materials increase as temperature goes up. Thus, materials tend to outgas more in GEO than LEO based on both pressure and temperature factors. Besides space environment, a spacecraft's mission life also determines the degree of a spacecraft's outgassing. Normally a spacecraft may take several weeks before its high outgassing rate reduces to a moderate degree.

Sometimes a spacecraft may even be several years in orbit before the outgassing to cease. Therefore for a spacecraft, initial on orbit checkout period provides a good opportunity for rapid outgassing to occur before on-board instruments begin to operate.

For a spacecraft with single instrument, the molecular outgassing is primarily a self-contamination problem. However, cross-contamination becomes an issue when multiple instruments of different contamination sensitivities are closely located on the same spacecraft. To avoid cross-contamination, diligent effort has been done to provide an optimal spacecraft layout for all systems and instruments.

Molecular contamination degrades the performance of systems by altering their surface properties. For thermal control system, molecular contamination increases solar absorptance (α) and changes emittance (ε) of Multi-Layer Insulation (MLI) and radiator surfaces. Changes of these surface properties require a larger beginning-of-life (BOL) design margin for the thermal control surfaces. When outgassing contaminant is deposited on optical elements, it reduces the transmittance through lenses, mirrors, windows, and detectors. The contaminant also degrades optical functions by increasing the light scattering along the optical path.

Material outgassing is the most common spacecraft contamination problem. Results from many ground tests have demonstrated its various effect on thermal and optical properties. Due to their wide application on spacecraft components, hydrocarbon and silicone contaminants have been identified on almost all short and long duration missions. Water will outgas like most hydrocarbons and pose similar contamination threat to spacecraft systems. Due to its physical characteristics and the repetitive problems on infrared (IR) instruments, water contamination is worthwhile to be discussed separately.

Water

Unlike more strongly bonded hydrocarbons and silicones, water is weakly adsorbed on surfaces and releases readily under reduced pressure. Most spacecraft structure and MLI surfaces contain water. Even with its high vapor pressure, water may still pose a potential problem because of its abundance on spacecraft surfaces. Due to its weight/strength advantage, composites are increasingly utilized in spacecraft. Composites are continuous polymeric materials containing a fibrous or particulate filler. Therefore, composites outgas similarly to polymers in the space environment. Furthermore, composites tend to absorb water in a humid environment, causing expansion. Once in orbit composites release water causing the structure to contract. The released water can reach contamination sensitive surfaces inducing additional damages. To minimize water in composites, humidity control during the manufacturing on the ground and during on orbit operations is essential.

Due to its high vapor pressure, surface water may be departed from surfaces in vacuum. However, trapped water forms ice on sensitive surfaces and reduces its mobility. Cryodeposits of ice on detectors is a common water problem for many IR instruments operating at cryogenic temperatures. The ice contaminant changes the reflectance and causes a transmittance loss problem. Without a proper venting for water contaminant, a repetitive ice formation effect is highly possible when operating condition cycles. The Filter Wedge Spectrometer (FWS) experiment on Nimbus IV spacecraft failed shortly after its launch April 8, 1970. It was determined that the failure was due to the accretion of water.

Water cloud around the spacecraft is an issue too. Once in space, water released from surfaces may stay with the spacecraft for several orbits before its dissipation. For a Space Shuttle mission, most of the contamination in the bay is water with pressure measured as high as 10^{-4} torr. By comparison, the ambient pressure is approximately 10^{-7} torr. Water cloud around the spacecraft or high water pressure in a bay obscures on orbit observations.

Molecular Transport

In space molecular contamination can move from one surface to another by direct flux or backscattering. The surrounding vacuum and temperature conditions strongly influence these transport mechanisms. Molecular transport by direct flux is a line-of-sight mechanism with a Lambertian distribution for molecules originated from the contamination source. To avoid direct line-of-sight impingement, sensitive surfaces on a spacecraft are designed to point away from the contamination sources. Under certain circumstances, protective devices may be installed for shielding purpose. Due to its direct impact, undoubtedly molecular transport by direct flux can become a problem. On a returned SMRM hardware, a single impact has penetrated three layers of MLI. Chemical analysis indicated that contaminants were consistent with urine residue from the Space Shuttle waste management system. In addition, molecular contamination can reach non line-of-sight locations by multiple reflections resulting from repeated deposition and reemission. For a closed system such as the interior of an instrument, molecular transport by multiple reflections may become more important than by direct flux.

Backscattering or return flux is a mechanism that molecules emit from and return back to the spacecraft surfaces by self or ambient scattering. Self scattering occurs when molecules departed from the spacecraft collide with each other and return to the spacecraft. On the other hand, ambient scattering refers to the collisions between spacecraft released molecules and ambient molecules. Molecular transport by backscattering depends heavily on the surface released molecules and the molecular density around the spacecraft. Therefore, backscattering is especially important when the spacecraft operates in a high ambient density environment that increases the probability of molecular collisions. In addition, the backscattering effect is enhanced as a Ram effect when the outgassing occurs in the leading-edge of the spacecraft, i.e. in the velocity vector.

Thruster operations also contribute to an increase in density in the backflow region. To prevent the thruster plume contamination, spacecraft surfaces are designed to avoid direct plume impingement or protected by a plume shield if necessary. Because of the high velocity of the plume, the effluent tends to be confined to a narrow region around the thruster exit. Regardless of relatively small quantity, the possibility of scattering into the backflow region by the thruster plume is still a concern for sensitive surfaces. For example, a monitoring package on NOAA-7 spacecraft has shown that effluent from an apogee kick motor (AKM) flowed into the area of sensitive spacecraft components and could have degraded their performance.

Electrostatic Return

Molecular contamination is often considered as transport by direct flux or backscattering only. The reattraction of molecular contaminants onto spacecraft under the influence of spacecraft charging is an unusual phenomenon. The transport by reattraction requires both spacecraft surfaces and molecules to be charged. Spacecraft charging is a variation of electrostatic potential on the spacecraft surface. Spacecraft surfaces may be ionized by solar UV to create electrostatic fields within a few deBye lengths of the spacecraft.

If outgassed become ionized in the region close to the spacecraft, then the ionized contaminants can be pulled by spacecraft surface charging distributions. Reattraction of the ionized contaminants depends on the plasmas shielding of the spacecraft. At low altitude the deBye lengths are measured in millimeters so that the ionized molecules have less opportunity to be reattracted to the spacecraft by the resultant electrostatic field around the spacecraft. At high altitudes the ionosphere is much less dense with the deBye lengths in meters. Therefore, contaminants have a lower probability of escaping the electrostatic attraction before being ionized.

This space environment induced backscattering molecular transport effect [4] is sometimes called Electrostatic Return (ESD). The charging environment and its associated ESD effect in GEO can be more severe than in LEO because the plasma is very energetic. The Spacecraft Charging at High Altitudes (SCATHA), a GEO spacecraft, had reported that nearly 31 % of the deposited contamination was associated with the spacecraft charging.

Field-of-View Obscuration

Molecular contaminants released from the spacecraft remain within the orbit of the spacecraft. Material outgasasing, venting, leakage, and plume products are major contamination contributors. Depending on conditions, these contaminants may remain in a spacecraft's orbit for extended period. While travelling with the spacecraft, molecular contaminants form a cloud around the spacecraft and greatly increase the local ambient density. A contamination cloud above the instrument surface increases number column density (NCD) along any intended line-of-sight and affects any instrument's field-of-view observation. This will drastically reduce the measured signal and diminish the effectiveness of the instrument. An example of the operation of a star tracker interfered by particle clouds was visually observed on Skylab. The persistence of a long-term cloud was also indicated on NOAA-7 spacecraft.

AO Erosion

AO is abundant in LEO environment at altitude from 200 to 650 km. Energetic AO reacts with spacecraft surface materials by either erosion or fixing. Residual atmosphere of AO erodes hydrocarbons on spacecraft surfaces and develop a characteristic surface morphology. A surface morphology such as AO undercutting was observed in samples on early Space Shuttle missions.

The space environment is particularly harsh on the solar arrays and MLI due to their large size, the constant exposure, and the nature of the materials. By attacking the polymers used in construction, AO causes deleterious effects on solar arrays and MLI. Kapton, a polyimide film, used for construction is one of the polymers highly susceptible to chain scission by AO with an AO erosion rate, or reaction efficiency, of 3.0×10^{-24} cm^3/atom.

In addition to the solar arrays and MLI, AO environment in LEO attacks the composite materials. Carbon/epoxy and Kapton/epoxy samples flown on Space Shuttle missions showed extensive erosion of both the matrix and filler. Graphite and Kapton fibers originally covered by epoxy were eroded into a corduroy pattern. The fibers themselves appeared as porous ridges with little apparent residual strength or stiffness. Since composites will be used extensively in the future, the long-term effects of AO must be examined in order to prevent surface degradation and structural failure. The most feasible method of protection available is coating the exposed composite surface with resistant materials. Selected metal foils, like aluminum for example, are an obvious choice due to their impermeable oxide coatings.

AO may cause dimensional changes in either the surface or the bulk of some materials. A significant oxidation with silver with the formation of an oxide can expand and does not remain adherent with the unreacted silver. The reaction with silicones to form silicone oxides causes contraction and cracking. These AO effects were observed on SMRM returned hardware.

AO erosion of a material is proportional to its exposure to a total AO fluence. AO fluence is defined as a product of AO density and exposure time. Therefore AO erosion is notable for a spacecraft with a long contact with AO environment or a spacecraft exposed to a high AO density. When studying AO erosion, ISS is a primary example with a 15-year design lifetime in LEO orbit. The combination equates to a total fluence of 5.5×10^{22} AO atoms/cm^2 for ISS.

The 69-month LDEF mission resulted in a long space exposure of material surfaces. During the mission, the leading-edge materials were exposed to approximately 8.8×10^{21} AO atoms/cm^2, a level at which erosion of over 10 mils was expected for many polymers [5]. The trailing-edge exposure was only about 10^4 AO atoms/cm^2, making AO effects insignificant compared to solar UV and charged particles. A 1 mil of erosion observed on LDEF was reported due to the combined effects of vacuum ultraviolet (VUV) and AO environment [6].

The AO environment was found to be even more severe for the TRMM, which requires an altitude of 350 km for 3.5 years. The AO fluence for TRMM in the velocity vector has been calculated to be 8.9×10^{22} AO atoms/cm^2. This fluence is about 10 times higher than the AO impingement on LDEF's leading-edge. In this environment, unprotected thermal blanket surfaces of Kapton will virtually disintegrate. In order to endure under this severe AO environment, a protective composite coating was developed for the TRMM spacecraft.

AO Fixing

The AO reacts with spacecraft surface materials in two distinct ways. Depending on the reaction efficiency and the AO fluence, hydrocarbon materials can be eroded by AO to a varying degrees. Contrarily silicone materials used by a spacecraft are permanently fixed by the oxidation with AO. AO fixing produces a protective coating on the spacecraft surfaces.

Room temperature vulcanizing (RTV) silicone adhesives and sealants are designed for a wide range of sealing, bonding, and protection of spacecraft applications. Methyl silicones, methyl phenyl silicones, and fluorinated silicones are most frequently used. In space these silicone materials outgas in response to vacuum and temperature conditions similar to hydrocarbon materials. AO attacks outgassed silicones that transport to spacecraft surfaces.

The reaction between the silicones and AO generates silicone oxide (SiOx). The strong surface adhesion of SiOx results from strong covalent bondings. Heaters, commonly applied for on orbit decontamination, can not easily remove these fixed silicones. As a result, AO fixed contaminants have detrimental effects on both optics and the thermal control system by totally altering their optical and thermal properties. In many spacecraft applications, the usage of silicone materials has been restricted.

Surface Damage by Environment

Spacecraft surface damage by the space environment can be found by examining almost all of the hardware exposed in space. Most space exposed Kapton was drastically different from the original Kapton. The space exposed Kapton was dull, rather than shiny or glossy. Surface damages by space environment are discovered on returned HST, Spartan, and SMRM hardware. Returned hardware from the LDEF showed brownish discoloration near uncontrolled venting areas. In general the discoloration on thermal control and other spacecraft surfaces are the most common surface damage by space environment.

Surface discoloration caused primarily by UV radiation, increases solar absorptance of thermal control surfaces. Under some severe space environments, Kapton on MLI surface can turn almost black after several years in orbit. S13G white paints are affected most severely by UV radiation and charged particles (protons and electrons). Its solar absorptance degraded from 0.20 to 0.70 in just a few years in geosynchrous orbit. High absorptance black paints generally do not degrade. A slight reduction in solar absorptance of black paints over time has been observed as a result of UV bleaching.

Solar cells converts sunlight into electricity. The solar cell's glass cover provides environmental and radiation protection for the solar array. Once the molecular contamination is deposited on the cover glass, it is darkened by UV radiation. The darkened molecular film reduces power output by reducing transmittance in the power generating wavelength range and by increasing solar cell temperatures. A spacecraft in GEO for a 7-year mission has been reported with its solar cell performance degraded by as much as 25%. To minimize UV damage, a UV filter coating may be applied to the underside of the cell to deflect the UV radiation.

Besides the thermal control and the power systems, the UV radiation causes damage on optics. The UV energized particles discolor optical thin film and the bulk transmission materials and thus modify the broadband transmittance. The UV radiation also interacts with some optical materials to cause reduction in reflectance and transmittance. In 1975, two instruments aboard the Orbiting Solar Observatory (OSO) failed due to the complete loss of sensitivity in the 1216 Å Lyman-Alpha wavelength caused by the UV degradation of optics from electronics box outgassing.

Photopolymerization.

Radiation damage caused by the high energy particles or UV has damaging effects on spacecraft polymeric materials. The UV and the charged particles can act independently or simultaneously, causing the contaminants to form a polymerized film. The degree of polymerization depends on the UV and the charged particles exposure, the type of the condensed contaminants, and the conditions of the surfaces.

Through an ionization process, the high-energy gamma rays, X-rays, electrons, and the protons can break molecular bonds to from free radicals. A free radical is a chemical radical or molecular fragment containing an unpaired electron. It is longer lived than ions and can migrate throughout a polymer structure causing various reactions. The reaction, either by crosslinking or chain scission, will degrade the polymers. The UV radiation causes the same chemical changes as its higher energy counterparts. Instead of ionizing the atoms through electron removal, the electrons are excited into higher energy state by UV. The unstable, excited atoms undergo subsequent reactions to form free radicals. Further reaction with the presence of free radicals can cause polymerization to occur.

The thermal control surfaces is prone to photopolymerization due to its exposure to space environment. The thermal control surfaces are affected in orbit by the charged particles, UV radiation, high vacuum, and the contaminant films that deposit on almost all spacecraft surfaces. By forming a darkened film on radiator surfaces, phtopolymerization will increase the solar absorptance significantly and affect the radiator's performance. Other photopolymerization example is the degradation of aluminized or silvered Teflon films caused by both charged-particle damage and contamination deposition.

The direct UV radiation causes photopolymerization. However, indirect UV radiation may also have a similar effect on contaminants. From a returned HST hardware, 500 Å of polymerized contamination was found on the pickoff mirror. The reflectance of the pickoff mirror was decreased from 0.7 to 0.05 at 1216 Å wavelength as measured by an EUV scatterometer. In orbit this pickoff mirror was not exposed to direct UV radiation, but rather to an indirect radiation source. After a material study, albedo was concluded to be the reason for such a photopolymerization. The Earth albedo, a fraction of solar flux incident on the Earth surface, is reflected to the pickoff mirror surface and reacts with contaminants. The molecular contamination can have a devastating effect on the reflectance of UV optics, since most molecular contaminants are very absorptive in the UV range.

Micrometeorites and Debris Impact

Orbital debris in the LEO presents a potential hazard to both the spacecraft and its payloads. The orbital debris consists of either natural meteorites or man-made debris from such sources as propulsion stage explosions in space or spent stages. The debris impacts on high-pressure fluid tanks and thermal control fluid lines can penetrate and cause a leaking contamination source. Collisions with large space debris can be characterized as highly energetic events, which will likely generate millions of particles posing even greater hazards to operational spacecraft. Besides affecting operations, particles generated by the impact create an obstructive particle cloud in the field-of-view of observation.

The micrometeorites and debris impact on operational spacecraft is apparent and substantial. A NASA Shuttle window with substrate fracturing was discovered in 1983 to have been caused by a submillimeter particle. From returned SMRM hardware in 1984, a survey of approximately one-half square meter of MLI has revealed over 1,500 impacts. A number of particles completely penetrated all of the MLI layers. Particulate impacts were also observed on the LDEF returned hardware surfaces. LDEF used a specifically designed aluminum plate to measure the wide spectrum of impacts. During the recent Midcourse Space Experiment (MSX) mission, two discrete particle releases caused by micrometeorites or debris impacts were observed [7]. Orbital debris is a growing concern, which may necessitate changes in overall system decisions involving larger safety factors, protective surfaces, and different orientations for the solar arrays.

Particulate Contamination Sources

There are two major particulate contamination sources for an operational spacecraft. One is particles accumulated on spacecraft surfaces during ground operations. The other is particles induced by the space environment when in orbit. Prior to launch, surface particles are controlled to meet acceptable levels for a normal spacecraft. Per MIL-STD-1246, the cleanliness requirements could range from levels 100-400 for sensitive surfaces and levels 300-1,000 for less sensitive surfaces. These deposited particles may be redistributed by external forces imposed on them during orbital operations. In addition, solar heating, thermal cycling, AO erosion, and radiation damage can generate new particles. Regardless of the particle sources, particles released in orbit may interfere with operations of space systems.

Particle build-up during ground operations is very common. For the Geostationary Operational Environmental Satellite (GOES), particles were accumulated on the radiant cooler surfaces prior to launch. The particle accretion will scatter the light and allow solar radiation to reach the instrument cooler. Ultimately this contamination effect will degrade the performance of the cooler [8]. A consequential cleaning was performed before the launch using CO_2 cleaning technique in 1995. Despite all controls and cleanings, some particles still cling on the launched spacecraft.

Particle contamination degrades the performance of space systems by a number of mechanisms. Low velocity particles can accumulate on a surface and cause an increase in the level of stray light scattering. Light scattered into the regions of image plane can seriously affect the performance of some detector systems. High velocity particulate, which impact surfaces directly, can diminish both their throughput and their ability to image. Indirect impacts of high velocity micrometeorites or particles may also create a problem by causing small pieces of spacecraft material to break loose from the surface. These particles may then either adhere to a critical surface or drift through the sensor's field-of-view.

Particles in space brings in a new problem. A released particle can take on an orbit with a trajectory returning to the vicinity of the spacecraft. The particles can also become charged and be drawn back to a charged spacecraft by the ESD effect. In addition, particle clouds, similar to molecular clouds, in the field-of-view of observation can greatly impair the performance of sensors.

Synergy

A synergy is a simultaneous action of separate forces to achieve an effect of which each is individually incapable. The synergistic contamination effect created by the space environment is twofold. A synergy can be produced by an individual space environment element influencing each step of the contamination generation, transport, deposition, and degradation. As a result, a specific contamination effect is induced by a single space environment element. On the other hand, a synergy can also be generated by multiple space environment elements act together to create an enhanced contamination effect.

One obvious example of synergy is material outgassing in space. Outgassing is strongly affected by the spacecraft's ambient conditions. Therefore, the combination of vacuum, temperatures, and the duration of space environment exposure determines actual outgassing rates.

The discoloration of the thermal control surfaces is the result of the combined effect of vacuum, UV, charged particles, and contamination. A darkened surface with an increase in solar absorptance affects the performance of a thermal control system. Other combined effect of radiation and thermal cycling induces thermal stresses on the structure and the MLI surfaces. After long-term space environment exposure, the damages on these surfaces further generate particulate contamination. In general a spacecraft continues to generate particles on orbit due to the effects of material degradation by UV, radiation, AO, thermal cycling, and the impact from micrometeorites or debris. Substantial material degradation on HST thermal control surfaces was observed during the in-flight surface survey. These damaged surfaces were repaired during the HST service missions.

AO reacts with all polymeric materials causing various degrees of surface erosion. Other contributing factors such as damage caused by radiation and orbital debris increase the erosion rate. Additional impingement effect due to spacecraft orientation is also possible. With these synergistic factors, a hole on an oxide coating can expose a non-oxide substrate to AO attacks. The present theory is that materials erode at a faster rate by AO when simultaneously exposed to ultraviolet and electron or proton radiation. One example indicated that the simultaneous exposure to AO and electrons [9] increased the rate of erosion of polysulfone. One additional synergy is the low Teflon (pure fluorocarbon) reactivity with the presence of AO. The C-F and C-C bonds in Teflon appear inert to AO. However, it has been found that exposure to the combination of AO and UV will cause a more severe Teflon reaction than AO alone.

Photopolymerization is a chemical reaction of molecular contaminants in the presence of energy sources. Either the UV, high energy particles, or the Earth albedo creates free radicals for the reaction to occur. The synergy of these energy sources enhances the photopolymerization process. Thermal control and optics systems are impacted most by the photopolymerization result. Once polymerization is formed on the surfaces, the removal of the contaminants to restore systems' original performance is difficult.

In GEO, the charge buildup on the spacecraft attracts charged contaminants to sensitive surfaces by the ESD effect. This contamination, in turn, can alter the properties of the spacecraft surface by making a conducting surface less conductive. The change in charging characteristics is a synergism of the plasma and the neutral environment.

CONCLUSIONS

In orbit contamination accompanies by the space environment effects degrade the performance of the spacecraft systems. Thermal control and optical systems are most susceptible to the contamination effects induced by the space environment. Surface discoloration and photopolymerization cause the solar absorptance to increase after either a short-term or long-term space exposure. The increase in solar absorptance affects the thermal balance capability of spacecraft and its many other systems. Optical system is degraded by both particulate and molecular contamination. Light scattering, obscuration, and throughput change caused by contamination buildups are major reasons for the degradation of optics. In addition, many other spacecraft systems are affected by the space environment to a certain degree.

The materials that significantly degraded provided the opportunity to study the space environment and material interaction. One single space environment element causes various degree of effect on spacecraft systems. The synergistic effect is an enhancement of multiple space environment elements, which may aggravate the contamination effect. Post flight materials investigations performed on SMRM, LDEF, Space Shuttles, MIR, and HST are of great interest. Study results help spacecraft engineers in gaining the knowledge of the contamination effects enhanced by the space environment interactions.

Most of the contaminants are self-generated by the spacecraft and its systems. By eliminating or reducing sources, problems can generally be minimized. Careful selection of materials, especially low outgassing materials, and proper system designs are critical while building a spacecraft. Specific spacecraft requirements including mission lifetime, charging restrictions, thermal conditions, optics throughput, instrument sensitivity, and cleanliness levels must be considered. Long-term space environment conditions should be taken into account in light of systems' end-of-life (EOL) performance. After the deployment of the spacecraft, additional applicable contamination mitigation methods [10] can be taken. Among them, de-contamination and operational control are most effective in mitigating contamination effects involving spacecraft operations.

REFERENCES

1. Purvis, C. K., "Overview of Environmental Factors", NASA/SDIO Space Environmental Effects on Materials Workshop, NASA Conference Publication 3035, NASA Langley Research Center, Hampton, VA, June 28-July 1, 1988.

2. Harvey, G., "Thruster Residues on Returned MIR Solar Panel", Proceedings of 2000 SPIE International Symposium, Optical Systems Contamination and Degradation, San Diego, CA, August 2-3, 2000.

3. Harvey, G., et al., "Particle Generation by Silicones Potting Compound of Returned MIR Solar Panel", Proceedings of 2000 SPIE International Symposium, Optical Systems Contamination and Degradation, San Diego, CA, August 2-3, 2000.

4. Cauffman, D., "Ionization and Attraction of Neutral Molecules to a Charged Spacecraft", Report SD-TR-80-78, The Aerospace Corporation, 1978.

5. Bourassa, R. et al., "LDEF Atomic Oxygen Fluence Update", Materials Workshop '91, NASA Conference Publication 3162, November 19-22, 1991.

6. Hemminger, C. S., et al., "Space Environmental Effects on Silvered Teflon Thermal Control Coatings," LDEF-69 Months in Space First Post-Retrieval Symposium, NASA Conference Publication 3134, 1992.

7. Galica, G., et al., "Long-term Observations of the Particle Environment Surrounding the MSX Spacecraft", Proceedings of 2000 SPIE International Symposium, Optical Systems Contamination and Degradation, San Diego, CA, August 2-3, 2000.

8. Chen, P., et al., "Contamination Effects on the Geostationary Operational Environmental Satellite Instrument Thermal Control System", Journal of Thermophysics and Heat Transfer, page 467-471, volume 11, Number 3, July-September 1997.

9. Shively, J., "Combined Effect of Fluxes of Atomic Oxygen and Electrons on Chemical Reaction with Polymeric Materials", NASA Conference Publication 3341, 19th Space Simulation Conference, Baltimore, MD, Oct 29-31, 1996.

10. Chen, P., "In-flight Space Environments Related Operational Contamination Concerns and Mitigation Methods", 1997 AIAA Defense & Space Programs Conference & Exhibit, Huntsville, AL, September 23-25 1997.