Chapter 4: Thermal Surface Finishes

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Introduction

Spacecraft thermal designs employ wavelength-dependent thermal-control coatings for various purposes. Solar reflectors, such as second-surface mirrors, white paints, and silver- or aluminum-backed Teflon, are used to minimize absorbed solar energy, yet they emit energy almost as a blackbody would. To minimize both the absorbed solar energy and infrared (IR) emission, polished metal such as aluminum foil or gold plating is used. Black paint is commonly utilized on the interior of the vehicle, to facilitate radiant heat transfer among internal components. Thus the existing state of the art includes a rather wide variety of wavelength-dependent coatings. The problems of in-space stability, outgassing, and mechanical adhesion to the substrate have all been resolved for most coatings. Many fully qualified coatings are available, so development and qualification of a new coating is normally unnecessary.

The external surfaces of a spacecraft radiatively couple the spacecraft to space. Because these surfaces are also exposed to external sources of energy, such as sunlight and Earth-emitted IR, their radiative properties must be selected to achieve an energy balance at the desired temperature between spacecraft internal dissipation, external sources of heat, and reradiation to space, as illustrated in Fig. 4.1.

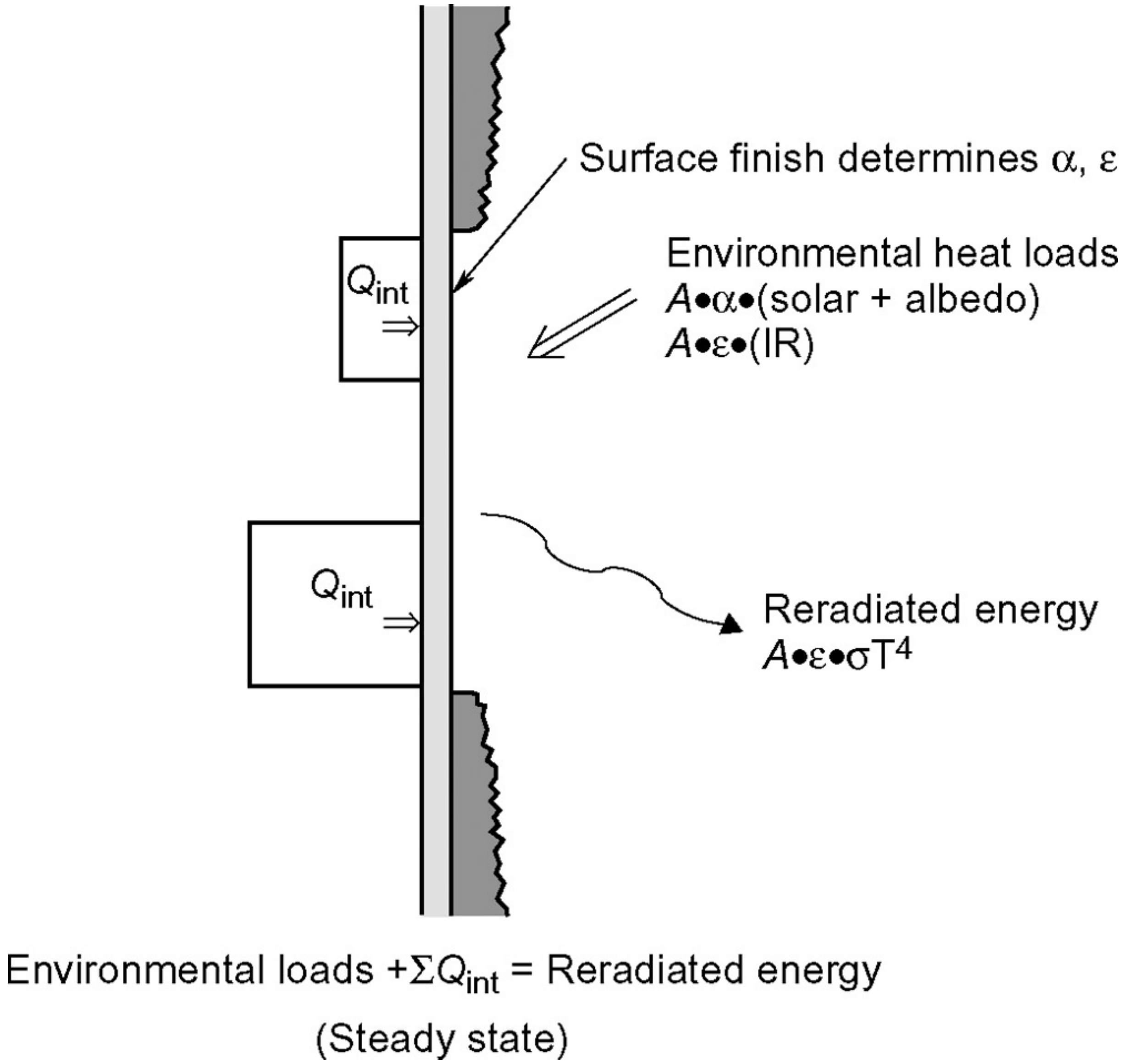

Figure 4.1: Radiator energy balance (no external blockage).

The two primary surface properties of importance are the IR emittance and the solar absorptance. Figure 4.2 indicates the range of properties available for different types of materials. Two or more coatings are sometimes combined in a checkerboard or stripe pattern to obtain the desired combination of average absorptance and emittance.

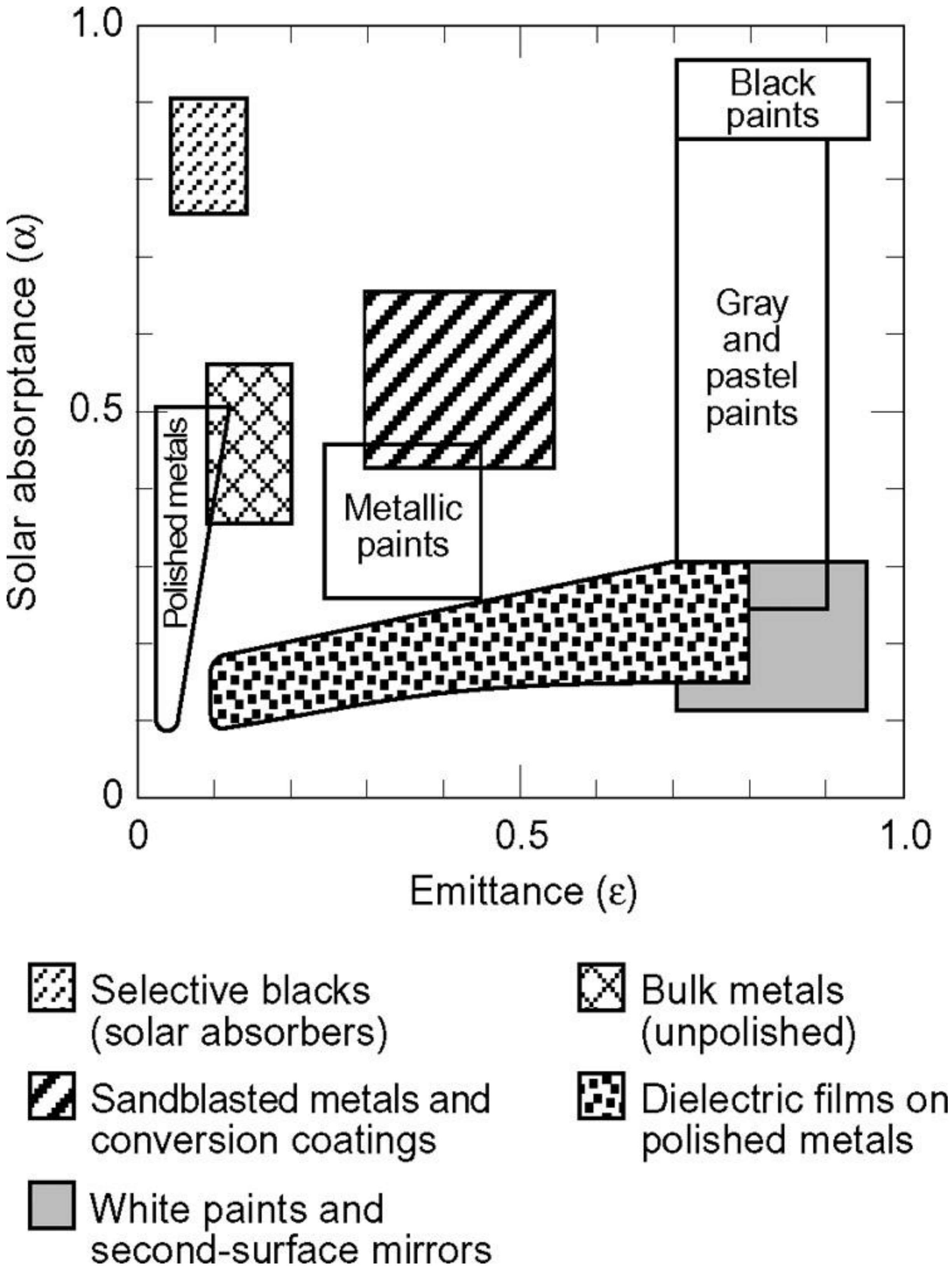

Figure 4.2: Surface properties by type of finish.

Thermal-control surfaces fall into four basic categories: solar reflector, solar absorber, flat reflector, and flat absorber (see Fig. 4.3). The solar reflector reflects incident solar energy while absorbing and emitting IR energy. Solar reflectors are characterized by a very low α/ε ratio. Solar absorbers absorb solar energy while emitting only a small percentage of the IR energy. Flat reflectors reflect energy throughout the spectral range (i.e., in both the solar and IR regions), while flat absorbers absorb throughout the spectral range.

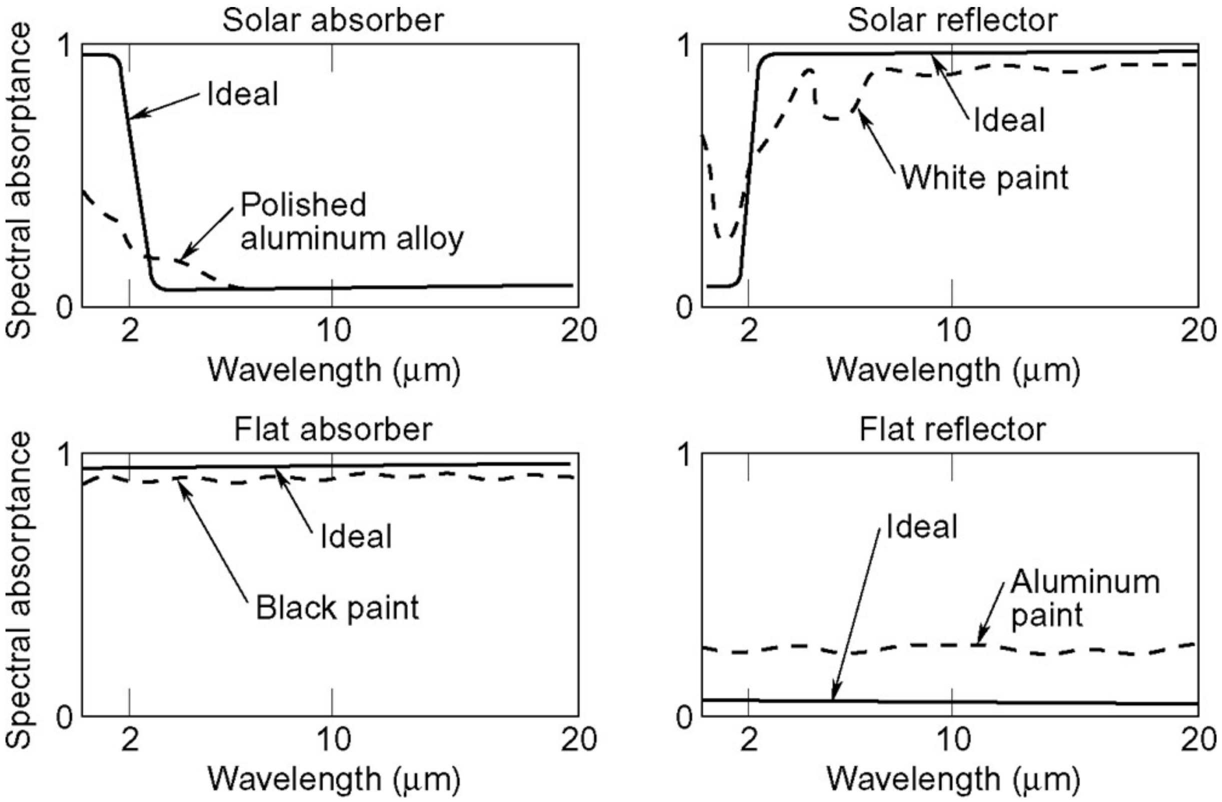

Figure 4.3: Ideal representation of four basic passive-control surfaces.

Common Thermal Surface Finishes

Almost all visible surfaces on the inside and outside of uncrewed spacecraft are thermal-control finishes; this reflects the fact that all physical objects absorb and emit thermal energy in the form of radiation. The flow of heat resulting from absorption and emission by these surfaces must be controlled in order to achieve a thermal balance at the desired temperatures. The principal external surface finishes seen on most spacecraft are the outer layer of insulation blankets, radiator coatings, and paints. Electronics boxes located inside the spacecraft, and the structural panels to which they are attached, are usually painted to achieve a high emittance. (While most paints have the required high emittance regardless of color, black paints have been the conventional choice for internal applications.) Internal temperature-sensitive components that do not dissipate much heat, such as propellant lines or tanks, often have a low-emittance finish of aluminum or gold. Common thermal finishes and their optical properties are shown in Table 4.1.

Table 4.1: Properties of Common Thermal Surface Finishes

Surface Finish	**α—Absorptance (beginning-of-life)**	**ε—Emittance**
Optical Solar Reflectors		
8-mil quartz mirrors	0.05 to 0.08	0.80

Table 4.1: Properties of Common Thermal Surface Finishes		
Surface Finish	**α—Absorptance (beginning-of-life)**	**ε—Emittance**
Quartz mirrors (diffuse)	0.11	0.80
2-mil silvered Teflon	0.05 to 0.09	0.66
5-mil silvered Teflon	0.05 to 0.09	0.78
2-mil aluminized Teflon	0.10 to 0.16	0.66
5-mil aluminized Teflon	0.10 to 0.16	0.78
White Paints		
S13G-LO	0.20 to 0.25	0.85
PCBZ	0.16 to 0.24	0.87
Z93	0.17 to 0.20	0.92
ZOT	0.18 to 0.20	0.91
Chemglaze A276	0.22 to 0.28	0.88
Black Paints		
Chemglaze Z306	0.92 to 0.98	0.89
3M Black Velvet	~0.97	0.84
Aluminized Kapton		
1/2 mil	0.34	0.55
1 mil	0.38	0.67
2 mil	0.41	0.75
5 mil	0.46	0.86
Metallic		
Vapor-deposited aluminum (VDA)	0.08 to 0.17	0.04

Table 4.1: Properties of Common Thermal Surface Finishes		
Surface Finish	**α—Absorptance (beginning-of-life)**	**ε—Emittance**
Bare aluminum	0.09 to 0.17	0.03 to 0.10
Vapor-deposited gold	0.19 to 0.30	0.03
SiOx on VDA rape	0.14	0.12
FSS-99 (overcoated silver)	0.03	0.02
Mylar		
1/4-mil aluminized Mylar, Mylar side	(Material degrades in sunlight)	0.34
Beta cloth	0.32	0.86
Astro Quartz	~0.22	0.80
TiNOX	0.95	0.05
Maxorb	0.90	0.10

The outer-cover layer of insulation blankets is usually made of aluminized Kapton, black Kapton, or Beta cloth. Aluminized Kapton is a gold-colored material that has a moderate solar absorptance, a high IR emittance, and a typical thickness of 1 to 3 mils. Black Kapton has a high solar absorptance because it is loaded with carbon to improve electrical conductivity for blanket-grounding purposes. Beta cloth is a very tough Teflon-coated glass fabric that has a low solar absorptance and high emittance. As will be discussed in Chapter 5, the choice of which material to use as the outer-cover layer of the blanket is driven by design requirements such as thermal optical properties, glint prevention, electrical grounding, stress handling, and micrometeoroid protection.

Radiator coatings are typically second-surface mirrors or white paint. The principle behind the second-surface mirror (illustrated in Fig. 4.4) is the use of a visibly transparent material, such as quartz glass or Teflon, to achieve a high emittance, along with a reflective silver or aluminum coating on the back to minimize solar absorptance. Quartz second-surface mirrors, often referred to as optical solar reflectors (OSRs), typically come in small tiles with dimensions on the order of a few cm and a thickness of up to 0.25 mm (10 mils). These tiles are bonded to the radiator surface with acrylic or silicone adhesives. (When bonding to a metal substrate, acrylic adhesive should not be used below −45°C because the mirrors may crack or delaminate.) Teflon second-surface mirror material, sometimes referred to as flexible OSR, comes in a variety of thicknesses (and therefore emittances) and is usually supplied as a tape or sheet with an acrylic adhesive backing for ease of installation. Standard quartz and Teflon OSRs are highly specular, but they also come in a diffuse variety that has a somewhat higher absorptance.

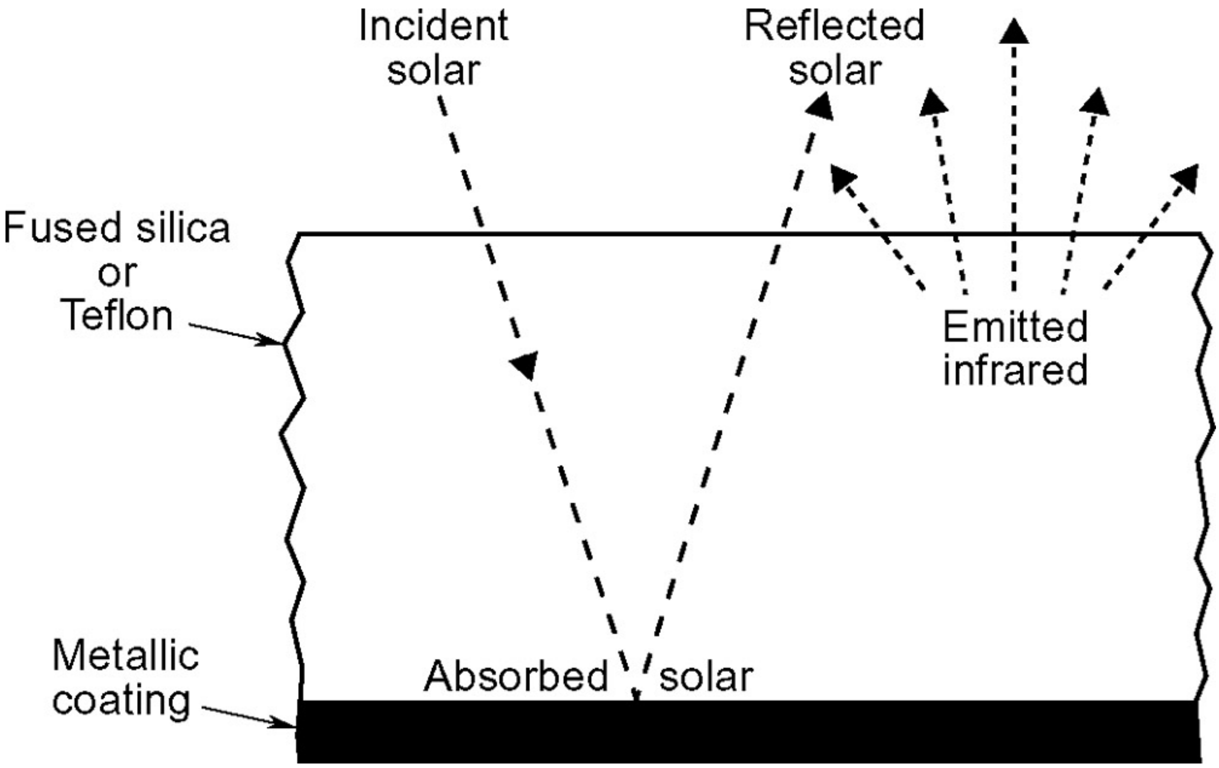

Figure 4.4: Second-surface mirror thermal finish.

While space-qualified paints are available in a variety of colors, black and white are by far the most commonly used. Almost all paints have a high emittance, so the choice is really between solar absorptance (and its degradation in the space environment), ease of application, and electrical conductivity to meet grounding requirements. Most internal spacecraft surfaces are painted black for high emittance, while exterior surfaces, including radiators, are often painted white to minimize absorbed solar energy. In choosing a white paint, one must consider that some paints will experience a greater increase in absorptivity than others as a result of the effects of the space environment. Metallic paints, such as leafing aluminum paint, may have an emittance as low as 0.2, but these are rarely used on spacecraft. In situations where radiative heat transfer must be minimized, low-emittance metallic finishes are often used. These include bare or polished surfaces of aluminum components, Kapton tape with a vapor-deposited aluminum or gold coating (metal side exposed), or bare stainless steel. Typical applications are aluminized (or aluminum) tape on propellant lines and tanks to limit heat loss and stainless-steel radiation shields to block the radiative view from hot thruster nozzles to sensitive spacecraft components. In general, these metallic finishes are not used on large exterior surfaces because their high absorptance-to-emittance ratio would make them run very hot in direct sunlight. Small exterior components that are conductively coupled to spacecraft structure, however, may sometimes have a metallic finish.

A number of specialty finishes find occasional use in spacecraft thermal control. These include very high-absorptance, very low-emittance finishes, like Maxorb and TiNOX, that are used to raise the temperature of a surface exposed to the sun; very low-absorptance, overcoated silver for sun shields on cryogenic radiators; moderately low solar-absorptance and -emittance finishes like aluminum paints or silicon-oxide-coated aluminum for mitigating temperature swings of exposed spacecraft structure; and controlled anodize and alodine processes for aluminum surfaces on which other thermal-control coatings are not allowed. The thermal engineer should be very careful about using absorptance and emittance values that are reported in the literature for anodized or alodined surfaces because the surface optical properties are highly dependent on the specific process used. Properties obtained from these processes are very repeatable, though, if the process is tightly controlled, such as by a military specification. Duckett and Gilliland[4.1] describe a NASA/Langley-developed controlled chromic-acid-anodizing process for aluminum that allows the user to select any combination of emittance (within the range of 0.10 and 0.72) and absorptance (within the range of 0.2 to 0.4) and obtain both values to within ±0.02.

Appendix A and Touloukian[4.2] contain a much more extensive list of space-qualified finishes that have been used on actual satellites along with corresponding optical properties that have been obtained from a variety of sources. Most of the values given here are for "normal" temperature ranges, and substantial changes may occur at cryogenic or very high temperatures.[4.2],[4.3] While the reported properties have been obtained from what are believed to be reliable sources, differences in reported values are not uncommon. Therefore, in designs that are sensitive to surface properties, measuring the absorptance and emittance of samples of the actual flight finish is recommended.

[4.1]R. J. Duckett and C. S. Gilliland, "Variable Anodic Thermal Control Coating on Aluminum," AIAA-83-1492, *AIAA 18th Thermophysics Conference* (1–3 June 1983).

[4.2]Y. S. Touloukian, *Thermophysical Properties of Matter* (IFI/Plenum, New York and Washington, 1972).

[4.3]M. Donabedian, "Emittance of Selected Thermal Control Surfaces at Cryogenic Temperatures," The Aerospace Corporation, ATM 90(9975)-10 (15 December 1989).

Causes of Thermal Surface Degradation

Thermal-control finishes are affected in orbit by charged particles, ultraviolet (UV) radiation, high vacuum, and the contaminant films that deposit out on almost all spacecraft surfaces. The general result of these processes is an increase in solar absorptivity with little or no effect on IR emittance. This is normally undesirable from a thermal-control standpoint because spacecraft radiators must be sized to account for the substantial increase in absorbed solar energy that occurs because of degradation over the mission. These radiators, which are oversized to handle the high solar loads at end-of-life, cause the spacecraft to run much cooler in the early years of the mission, sometimes necessitating the use of heaters to avoid undertemperatures of electronic components. The degradation is, therefore, a problem not only because of the solar load, but also because of the change in load over the course of the mission. The stability of coating properties is important in order to limit maximum temperatures and minimize heater-power requirements.

The following sections describe the effects of contaminants, UV radiation, atomic oxygen (AO), charged particles, and space debris on commonly used spacecraft thermal-control materials. This information should provide a basic understanding of the damage mechanisms and aid in the selection of materials to withstand these environments.

Contamination

In many instances, contamination effects are the major contributor to optical degradation of spacecraft surfaces. The degradation of optical surfaces with mission life appears as an increase in solar absorptance of thermal-control materials or a loss of transmission through or reflection from sensitive surfaces of telescopes and detectors. Contaminants are of two different varieties: particles and compounds outgassed from spacecraft materials like plastic films, adhesives, foams, lubricants, and paints.

Some particles are present within the launch vehicle fairing that encloses the spacecraft until a few minutes after liftoff, and more are generated as a result of rocket motor firings during liftoff, stage separation, and attitude control. These particles are deposited on spacecraft surfaces as a result of direct rocket motor plume impingement or turbulence inside the payload fairing that causes particles and other contaminants that are already present to circulate during launch ascent.

The other source of contamination is the low molecular weight fractions of polymeric materials that volatilize during mission life and generally condense on cooler surfaces such as radiators. This outgassing is strongest early in the mission (the first few months to one year) and tapers off with time. Since migration of volatile constituents through solids is a slow process at ordinary spacecraft temperatures, these low molecular weight fractions continue to outgas for several years. These volatile contaminants condense on surfaces at a much greater rate if the surface is illuminated by the sun because UV radiation enhances the chemical binding process. UV illumination will also cause a deposited contaminant layer to darken over time, thereby increasing the solar absorptance of the surface. Studies based on space-flight experience, laboratory experiments, and modeling suggest that on average, surface solar absorptance increases by about 0.01 for every 100 Å of contaminant film thickness, although reported values vary widely.

Significant effort has gone into the development of spacecraft materials over the past several decades to limit the amount of outgassing from polymeric materials in order to minimize spacecraft contamination effects. Outgassing data are obtained by a standard test that conforms to ASTM E 595-77/84. The test consists of heating small specimens to 125°C for 24 hours while accumulating the outgassing products on a surface maintained at 25°C. The data are reported as percent total mass loss (percent TML) and percent collected volatile condensable materials (percent CVCM). The NASA criteria on outgassing from candidate spacecraft materials limit percent TML to less than 1.0% and percent CVCM to less than 0.1%. Table 4.2 lists outgassing data from commonly used thermal-control surface materials, most of which were obtained from NASA/GSFC and Lockheed Martin Corporation. Clean metals and metal finishes are not a source of volatile material and therefore do not contribute to the contamination of spacecraft thermal-control or optical surfaces.

Table 4.2: Outgassing Data for Thermal-Control Surface Materials

Material	**TML (%)**	**CVCM (%)**
OSR	0.00	0.00
FEP Teflon	0.77	0.35
Kapton	0.78	0.03
Glass fabric/Kapton	0.42	0.05

Table 4.2: Outgassing Data for Thermal-Control Surface Materials

Material	TML (%)	CVCM (%)
Black Kapton	0.50	0.02
Glass fabric/Black Kapton	0.53	0.06
White polyurethane paint	0.99	0.08
Black polyurethane paint	1.91	0.28
White silicone paint	0.54	0.10
Black silicone paint	0.43	0.04
White inorganic paint	>1.00	0.00

Examination of contamination deposits on the Long Duration Exposure Facility (LDEF), which was recovered in January 1990 by the space shuttle after nearly 6 years in low Earth orbit (LEO), has revealed that contamination mechanisms are still only partially understood. For example, a contamination or brown stain occurred in a number of places on the spacecraft's external surfaces and, as expected, the heavier contamination deposits appeared near vent holes. On an OSR sample, however, the solar absorptance was unchanged, which is contrary to expectation because the surface of the OSR was cool and should have been a site of contaminant deposition. Also not anticipated was the discovery of contamination deposits on locations not in the direct line-of-sight of a contamination source. While analytical techniques for simulating contamination processes have advanced substantially, predicting the amount of contamination that any particular thermal-control surface will experience remains challenging. Contamination can be minimized, however, by protection of surfaces from booster exhaust plumes, by optimum placement of spacecraft vent holes and attitude-control thrusters, and by selection of low outgassing materials.

UV Radiation

The UV portion of the electromagnetic spectrum is usually divided into two regions: the near UV, with wavelengths between 0.20 and 0.40 µm, and the more damaging "vacuum UV" (VUV), with wavelengths below 0.20 µm. The VUV is so named because its wavelengths are only transmitted in the vacuum of space; atmospheric gases absorb these shorter wavelengths. The principal solar UV radiation is at wavelengths between 0.25 and 0.40 µm. This portion of the solar UV remains relatively constant throughout a solar cycle. However, the VUV portion fluctuates with solar activity and can increase by up to a factor of 3, depending on wavelength, as peak solar activity occurs.

Damage mechanisms that explain the darkening of spacecraft thermal-control materials by solar UV are not fully understood. At least two mechanisms are thought to account for an increase in solar absorptance of materials. First, short-wavelength UV and X-ray photons are capable of causing charge separation or electron imbalance in ionic crystals, forming color centers. The color centers have optical absorption bands associated with their formation, which leads to an increase in solar absorptance. A more probable damage mechanism to explain an increase in solar absorptance in polymeric materials such as thermal-control films, paints, and contamination deposits is the capability that solar UV photons have of initiating chemical reactions in these kinds of materials. The process involves absorption of the UV photon and an accompanying electronic excitation of a polymeric molecule. The electronically excited polymeric molecule usually contains sufficient energy to break a chemical bond within the polymeric molecule, forming two free radicals. Free radicals are chemical species that have an unpaired electron in the valence shell and, as such, are very reactive. These free radicals react with neighboring molecules, forming larger molecular species that may be stable, thus ending the process, or the products themselves may also be free radicals so that the process continues until a stable species is formed. A stable product is formed by the recombination of two free radicals.

The larger molecules formed by the absorption of solar UV photons generally have optical absorption bands above 0.40 μm in the solar spectrum. The presence of the multiple absorption bands of these larger molecules throughout the solar spectrum shows up as an increase in solar absorptance. Some materials, such as Teflon, are relatively stable under solar UV illumination and exhibit only small increases in solar absorptance, although no explanation has been offered for this resistance to damage. On the other hand, polyurethane and silicone paint binders show large increases in solar absorptance as a result of UV irradiation.

Atomic Oxygen

A major damaging component of the LEO space environment is AO, which can severely erode externally applied hydrocarbon-type thermal-control materials. AO is formed by the UV photolysis and dissociation of molecular oxygen in the upper atmosphere. The concentration of AO varies inversely with altitudes between 100 and 1000 km and directly with solar activity as a result of the increased VUV component of solar irradiance. AO erosion of spacecraft materials in orbits above 1000 km is not a concern because there is neglible AO at these higher altitudes, but erosion may be a factor while the vehicle is in a parking orbit.

AO is a very reactive chemical species because its valence shell contains an unpaired electron. In addition, the reactivity of AO is enhanced in LEO because the high velocity of the spacecraft (about 8 km/s) relative to the surrounding atmosphere imparts an additional energy to AO equivalent to 5 eV in the ram direction. This energy is sufficient to break chemical bonds commonly found in polymeric materials or contamination deposits. In the case of hydrocarbon thermal-control materials, the products (CO, CO_2, and H_2O) formed by AO attack are volatile and evaporate from the surface, exposing additional material for further reaction. In the case of silicone materials (all of which contain some hydrocarbon), AO erosion effects are normally limited to the outer few atomic layers. The exposed hydrocarbon components of the silicone polymer are eroded, producing a silicate-type (or glasslike) structure on the surface that resists further oxidations. As a result of the formation of this glasslike layer, silicones are considered to be stable to the AO environment.

AO erosion rates (reaction efficiency) of commonly used thermal-control materials are listed in Table 4.3. The erosion-rate data were generally obtained from space-shuttle testing of these materials for limited periods of exposure (2 weeks or less). Measurements of erosion rates from materials on LDEF basically confirm these rates. Recovered silverized Teflon specimens exhibited an enhanced erosion rate as a result of the high concentration of AO encountered by ram-facing surfaces at the lower altitudes (LDEF was recovered at 350 km) and during the peak in solar activity. If silverized or aluminized Teflon is being considered for use in an orbit similar to that of LDEF (in general, below 400 km), detailed AO flux and fluence calculations will be required to determine optical properties at end-of-life.

Table 4.3: Atomic-Oxygen Reaction Efficiencies of Commonly Used Thermal-Control Materials

Materials	**AO Reaction Efficiency 10^{-24} cm^3/AO atom**
Fused silica	Negligible
Clear FEP or TFE Teflon	0.05
Polyimide (Kapton)	2.6
Carbon-filled (black) polyimide	2.5
Gloss white polyurethane paint	0.9
Flat black polyurethane paint	0.9
Gloss black polyurethane paint	4.5
Silicone paints	Negligible
Z-93 white paint	Negligible
YB-71 white paint	Negligible
Aluminum, bare and anodized	Negligible
Beryllium	Negligible
Magnesium, DOW 17 coated	Negligible
Stainless steel	Negligible
Titanium, bare and anodized	Negligible

AO erosion effects have been known for several years. As a result, protective coatings that resist oxidation have been developed for Kapton and Teflon thermal-control materials, although the coating is delicate and easily rubbed off of Teflon during spacecraft manufacturing and ground handling. The erosion rates in Table 4.3 do not apply to materials with protective coatings.

A rough assessment of a material's susceptibility to AO attack can be made using the erosion rate data from Table 4.3 and the data from Fig. 4.5, which shows the concentration of AO in the neutral atmosphere for solar-activity extremes. The AO fluence in the ram direction is the product of AO concentration, spacecraft velocity, and mission time. For example, at 500 km altitude the maximum AO concentration is about 6×10^7 atoms/cm^3 and orbital velocity is about 8000 m/sec; the annual fluence is therefore (6×10^7 atoms/cm^3) × (8×10^5 cm/sec) × (31.5×10^6 sec) = 1.5×10^{21} atoms/cm^2. Surface mass loss is the product of AO concentration and reaction efficiency. The approximate annual surface erosion of unprotected Kapton in the above environment is (1.5×10^{21} atoms/cm^2) × (2.6×10^{-24} cm^3/atom) = 3.9×10^{-3}cm. More precise evaluations of material erosion rates are generally performed by materials-science specialists.

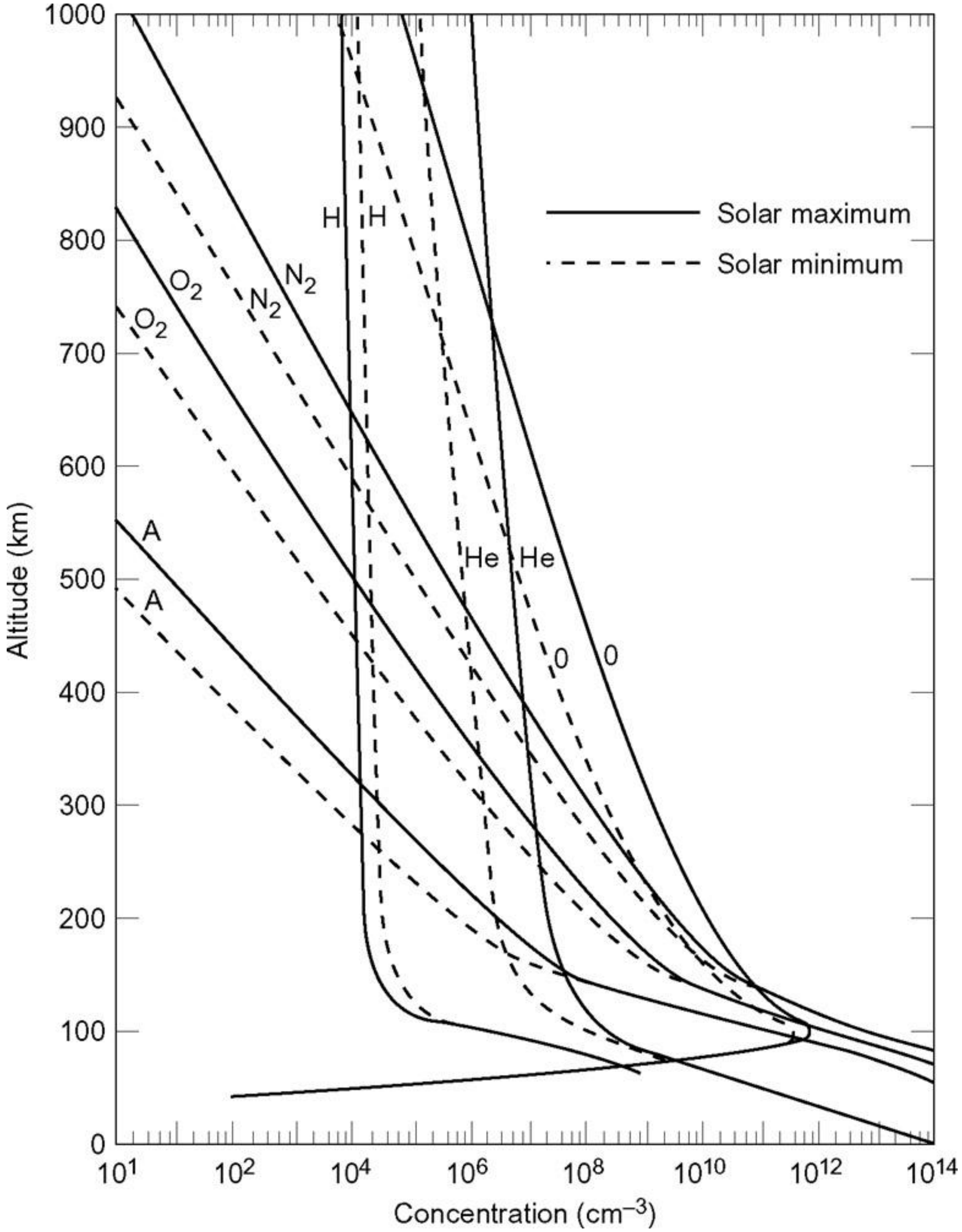

Figure 4.5: AO concentration.

Protons, Electrons, and Neutrons

Protons and electrons are charged-particle components of the space environment that are capable of damaging most thermal-control materials and, together with solar UV, are responsible for spacecraft charging effects. Neutrons, as their name implies, are electrically neutral and have great penetrating power but do little or no damage to spacecraft thermal-control materials.

As illustrated by Fig. 4.6, highly energetic protons and electrons are concentrated in the inner and outer Van Allen radiation belts because of Earth's magnetic field. The Van Allen belts are two concentric doughnut-shaped rings situated above the equator. Geosynchronous orbit (GEO) is located in the outer Van Allen belt; consequently, external surfaces of spacecraft in GEO are subjected to large doses of ionizing radiation. The charged particles in the Van Allen belts are omnidirectional, so all external spacecraft surfaces are equally irradiated. Only the sun-facing surfaces are simultaneously irradiated with solar UV and charged particles. The lower boundary of the inner Van Allen belt is located at an altitude of about 1000 km, so spacecraft in LEO are not normally exposed to significant amounts of ionizing radiation. Increases in solar absorptance in LEO are mainly the result of solar UV radiation. Materials on spacecraft in polar orbits and in orbits that intercept the South Atlantic Anomaly are subjected to an ionizing radiation dose in these regions of space, but the dose is usually less than several Mrads, which generally induces insignificant changes in solar absorptance.

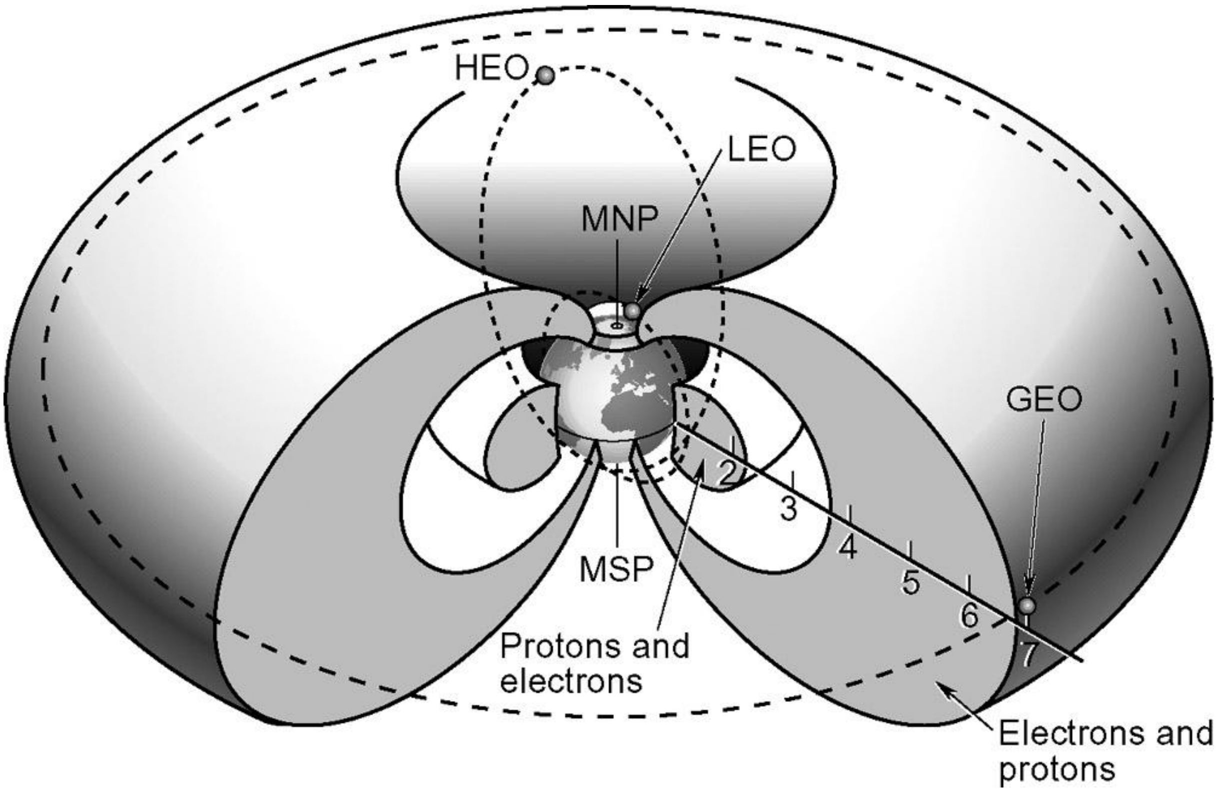

Figure 4.6: Earth's radiation belts.

The most damaging of the energetic charged particles are the 30-keV plasma-sheet protons and the 7-keV plasma-sheet electrons, which can deposit a very large dose of about 10^{11} rads to spacecraft outer surfaces during a 5-year mission in GEO. The 30-keV protons are capable of penetrating FEP Teflon to a depth of 0.01 mil. The 7-keV plasma-sheet electrons and 200-keV electrons of the Van Allen belts can penetrate Teflon to a depth of 0.06 and 10 mil, respectively. When energetic protons and electrons of the space environment penetrate a polymeric material, collisions between the relatively fast-moving charged particle and molecules of the solid produce ionization. The ionized molecules chemically react with neighboring molecules, forming larger polymeric molecules. These larger polymeric molecules generally have optical-absorption bands in the solar portion of the spectrum, which results in an increase in solar absorptance. Kapton, for example, experiences large increases in solar absorptance when used in geosynchronous orbits or other high-radiation environments. However, there are some transparent materials, such as fused silica, that do not darken as a result of exposure to ionizing radiation, partially because of the purity of the material.

Micrometeoroids and Debris

According to estimates, a spacecraft in LEO is 10 times more likely to encounter a particle of space debris than a meteor. Recent surveys of LEO and GEO space environments conducted using ground-based optical telescopes and radars, along with data from returned LEO spacecraft, reveal a growing accumulation of space debris. Optical and radar techniques are capable of detecting debris fragments as small as 10 cm in diameter. The flux of particles smaller than 1 cm is inferred by counting craters on returned spacecraft. Particles with diameters of 1 to 10 cm have not been mapped and constitute a hazard to astronauts during extravehicular activity and to the integrity of spacecraft in LEO.

Approximately 16,000 debris objects have been tracked in LEO, with about 6000 objects still in orbit; the remainder have reentered Earth's atmosphere as a result of drag. The number of objects in LEO decreases slightly with peak solar activity.

Meteors, which are naturally occurring objects, are thought to be traceable to asteroids and comets with some retaining the orbit of the parent body. In general, meteors are considered omnidirectional relative to Earth.

Analysis of the exterior surfaces of LDEF indicated that hundreds of small particles struck the vehicle. Ten times as many craters were found on the leading edge as on the trailing edge, indicating the greater abundance of debris objects versus meteorites. The largest particle to impact LDEF was about 5 mm in diameter. From a thermal-control point of view, collisions with objects of this size and smaller are not a problem because the craters that are formed occupy a small percent of the vehicle's total surface area. Since the total amount of damage is small, little change in overall optical properties occurs. In the case of silvered Teflon, some darkening of the silver around the impact zones occurred where the particle penetrated to the metalized layer. AO was able to react with the exposed silver metal, forming a ring of dark silver oxide, but again, the net effect on optical properties was negligible. No OSRs were struck during the nearly 6 years in LEO. However, if a tile were struck by a relatively small meteorite or debris particle, the damage would be limited since the tiles are usually bonded to the substrate.

Degradation Rates for Common Thermal Finishes

Different thermal surface finishes are affected in different ways by exposure to the space environment. Some surfaces are sensitive to all of the degrading environments discussed above, while others are essentially immune to the effects of one or more of them. Because the environments can be very different in different orbits, the rate of degradation for a given material can also be quite different depending on the orbit in which the spacecraft resides.

Quartz mirrors experience essentially no damage from UV and charged particles, leaving only contamination as a source of increased absorptivity. Because contaminant outgassing is strongest early in the mission, a rather large increase in solar absorptance occurs in the first few years, followed by a small steady increase until end-of-life. Figure 4.7 shows the observed rate of contamination-induced absorptance increase for quartz-mirror radiators on several spacecraft. The spacecraft-to-spacecraft variations are not completely understood, but they are known to be strongly dependent upon such factors as the types of materials used in the spacecraft, the venting of outgassed materials across thermal surfaces as they leave the spacecraft, and the presence of sunlight, which enhances the deposition and darkening of contaminants on surfaces. Because of these effects on quartz-mirror radiators, many programs are switching to lower outgassing materials and redesigning vent paths to ensure that outgassed contaminants are directed out to space without impinging onto thermally sensitive surfaces.

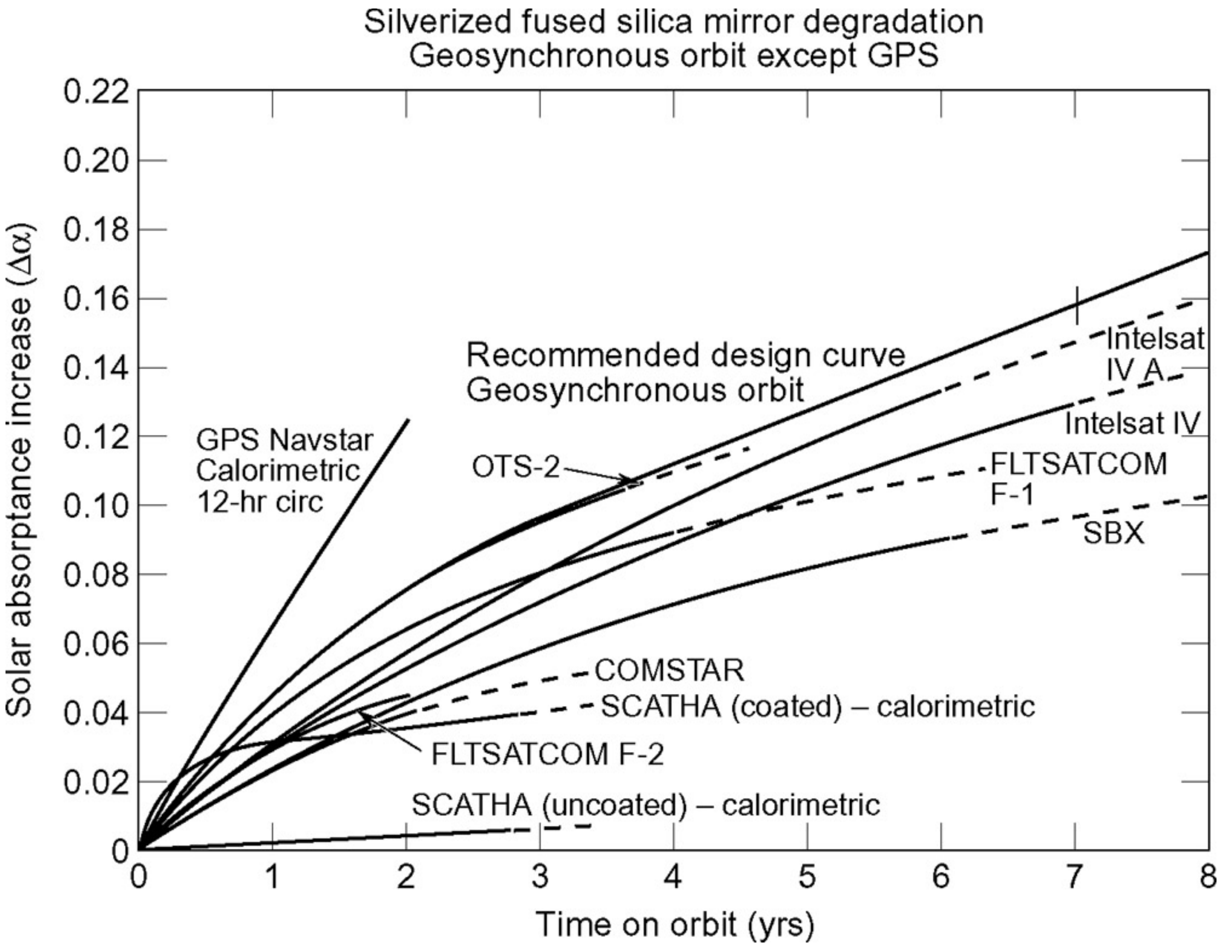

Figure 4.7: Degradation of quartz mirrors in geosynchronous orbit.

Aluminized or silvered Teflon films show absorptance degradation as a result of both charged-particle damage to the Teflon and contaminant deposition, as illustrated in Fig. 4.8. Teflon film degradation rates observed on a number of flight spacecraft are summarized in Fig. 4.9. As these data show, the degradation strongly depends on orbit. LEO is the most benign because of the relative absence of charged-particle damage. Degradation in GEO is more severe because of the more intense radiation environment. Spacecraft placed in the 12-hour circular orbits typical of navigation satellites can experience extreme degradation because they pass through very intense regions of the Van Allen belts. At the lower LEO altitudes, AO erosion may also result in degraded emittance, depending on total fluence levels. To evaluate emittance degradation, an estimate of the AO fluence is made based on the mission profile, and the total surface recession over the life of the mission is predicted. The emittance of the material at end-of-life is then determined based on the well-established values for emittance of Teflon as a function of thickness. Recommended absorptance degradation values for Teflon surfaces in LEO and GEO are shown in Fig. 4.9.

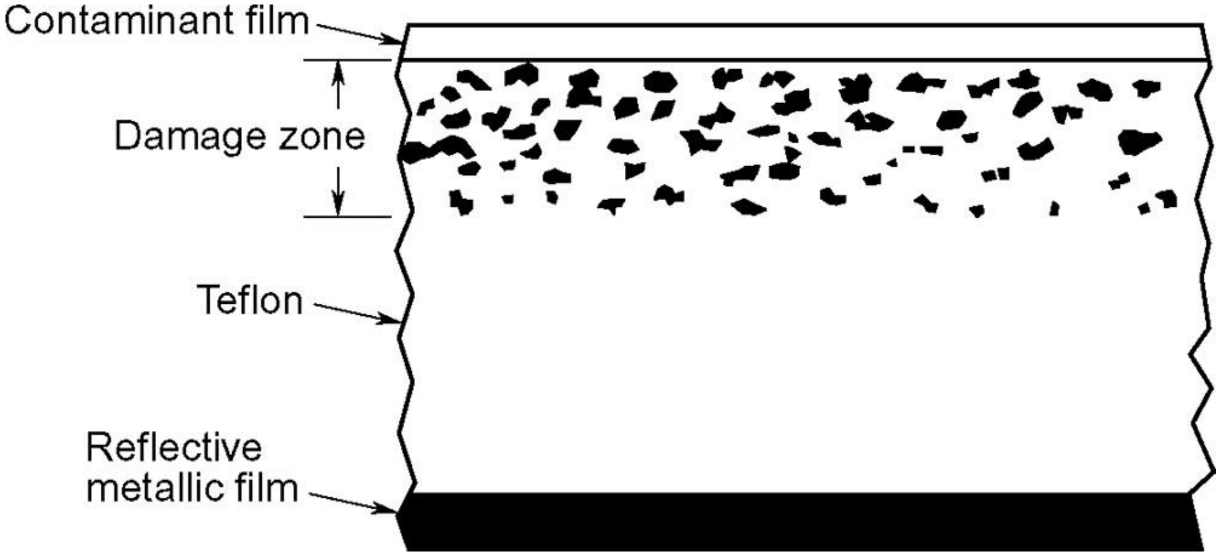

Figure 4.8: Metalized Teflon degradation model.

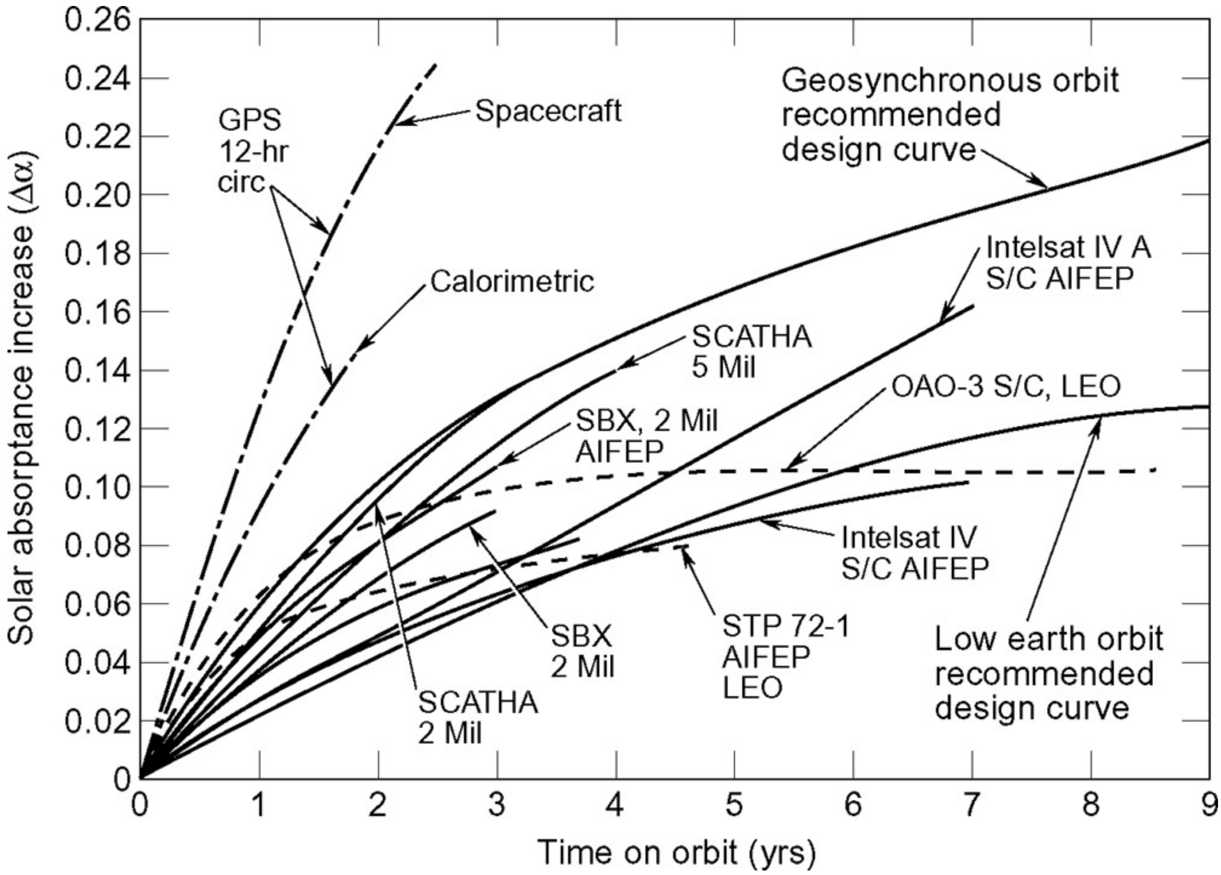

Figure 4.9: Metalized Teflon degradation.

Surface finishes that are not affected by UV or charged particles, such as polished metals, will still suffer absorptance increases because of contamination. For such materials, degradation rates similar to those for quartz mirrors should be used (see Fig. 4.7) if the surface has a low beginning-of-life absorptance.

White paints, such as S13GLO, are affected most strongly by UV radiation and charged particles, and their absorptance may rise from around 0.20 to 0.70 in just a few years. Black paint and other high-absorptance surfaces generally do not degrade much from space-environment exposure. Any change in black paint is more likely to be a slight reduction in absorptivity of a few percentage points from UV bleaching over time. Absorptivity degradation as a function of time for several paints is shown in Fig. 4.10.

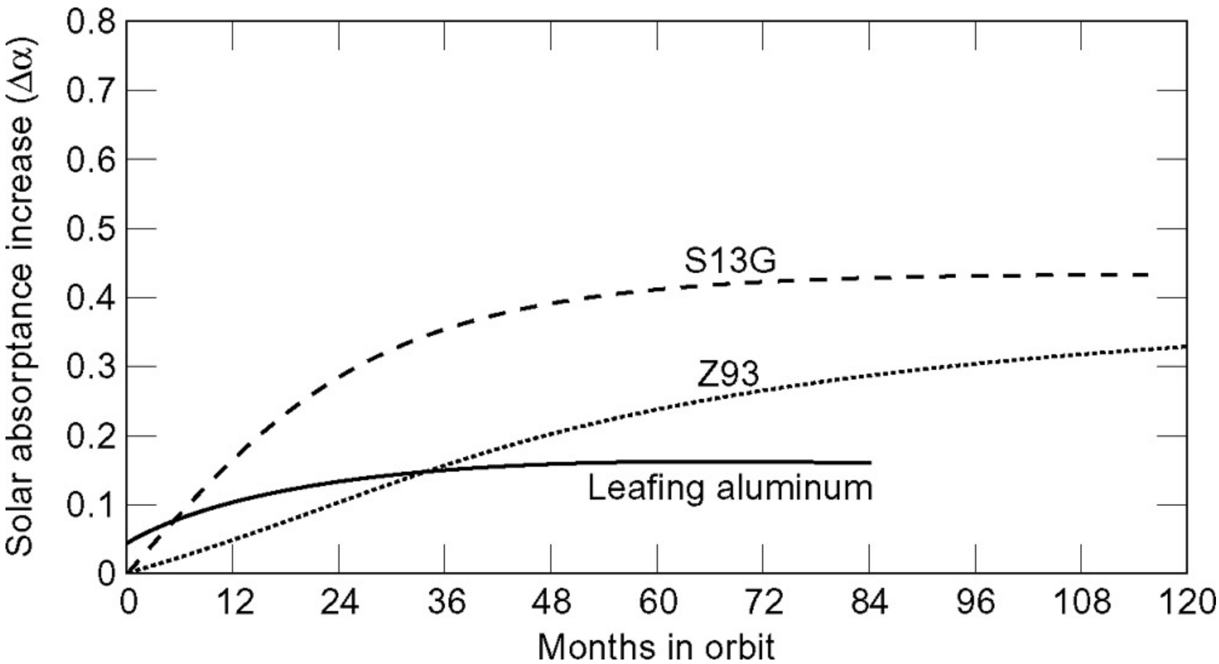

Figure 4.10: Paint degradation.

Materials used as the outer-cover layer of insulation blankets also suffer absorptance changes from space-environment effects. Kapton and Beta cloth show substantial degradation and can turn almost black after several years in GEO, as shown in Fig. 4.11. Degradation in the LEO environment is significantly less severe because of the relative absence of radiation. Black Kapton actually sees a reduction in absorptance as a result of UV bleaching. Fortunately, when these materials are used as the outer layer of a blanket, the impact of their absorptance increases on spacecraft temperatures is mitigated to a large extent by the small role that heat transfer through the blanket plays in overall spacecraft thermal balance.

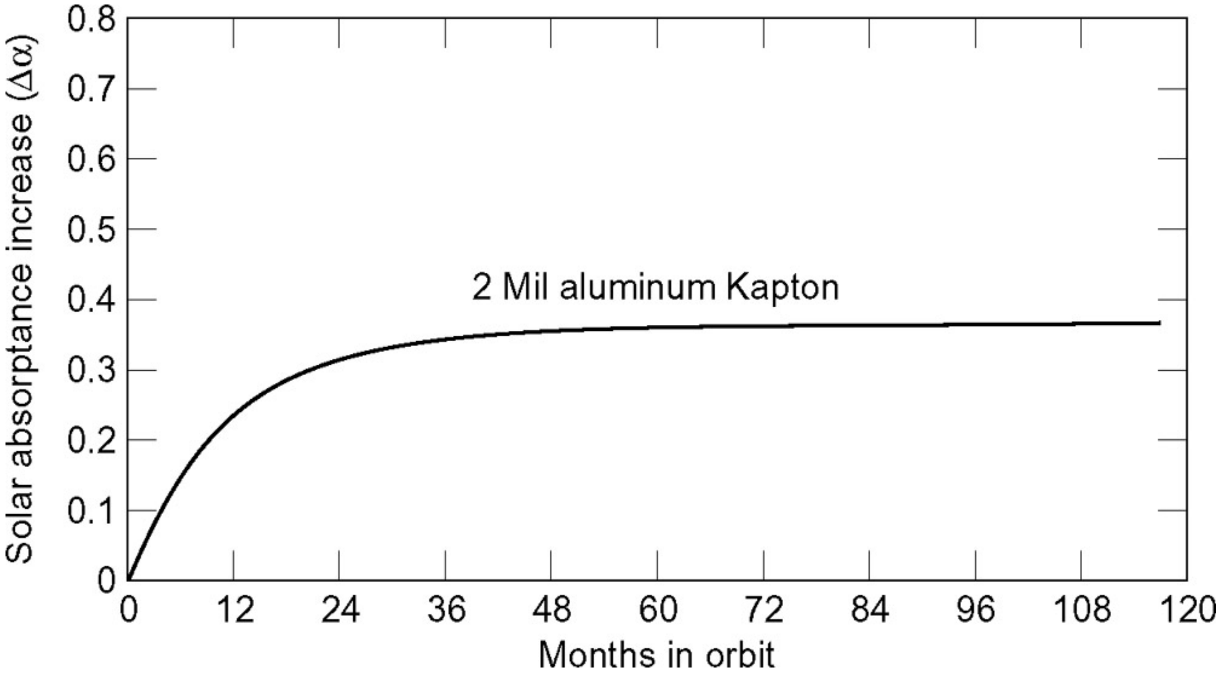

Figure 4.11: Kapton absorptance degradation.

The degradation rates discussed above are for Earth-orbiting spacecraft. With the exception of AO, interplanetary missions will experience the same degradation environments as those in Earth orbit, only at different intensities. Materials sensitive to UV will experience more rapid degradation during missions to Venus than they would in Earth orbit. Materials sensitive to charged particles, on the other hand, will degrade at a slower rate during interplanetary cruises than they would in GEO because they are not exposed to the trapped radiation of the Van Allen belts. By computing the charged-particle and UV dose that a material will receive during any particular mission, materials scientists can estimate the degradation the surface will suffer over time. Because of the very low intensity of sunlight at great distances from the sun, absorptance increases resulting from surface degradation will not cause a significant increase in temperatures once a spacecraft approaches the orbit of Jupiter or beyond.

LDEF Results

LDEF was launched by the space shuttle in April 1984 into a 465-km orbit at 28.5-deg inclination, and it was recovered in January 1990 at 325 km. On the mission were 57 experiments containing over 10,000 specimens to test the effects of the LEO space environment on materials, components, and systems. The principal environmental factors affecting thermal finishes are solar UV radiation; bombardment by AO atoms, which are present at very low densities in low orbits; electron and proton radiation; and micrometeoroids. Originally planned for one year, the exposure actually lasted almost six years. While many LDEF investigations are continuing, results to date have given valuable information on long-term performance in orbit.

The 69-month LDEF mission resulted in far longer space exposure of material surfaces than other hardware previously returned from orbit, such as from the short-duration shuttle experiments, or hardware returned from the Solar Maximum Repair Mission. LDEF was gravity-gradient stabilized, with one side of the vehicle continuously pointing down toward Earth's center, and another side always facing the velocity vector, within 1 deg. The vehicle contained 86 experiment trays measuring

127 cm by 86 cm, which were oriented around the vehicle in 12 rows, with additional trays on the sides facing Earth and facing directly away from Earth. During the mission, the leading-edge materials (i.e., those facing into the velocity vector) were exposed to approximately 9×10^{21} oxygen atoms/cm^2, a level at which erosion of over 10 mils would be expected for many polymers. The trailing-edge exposure was only about 10^4 oxygen atoms/cm^2, making AO effects insignificant compared to solar UV and charged particles. Trailing-edge samples are, therefore, more representative of higher-altitude orbits where AO concentrations are insignificant. The solar exposure ranged from about 5000 to 14,500 equivalent sun-hours, depending on location on the LDEF, with 34,200 thermal cycles. The radiation environment on the surface was ~2.5×10^5 rads of electron radiation and 1.6×10^3 rads of proton radiation.

The LDEF observations on thermal-control materials are particularly significant for AO effects on the leading edge for low Earth orbits, while the trailing-edge samples show the effects of UV radiation. The Thermal Control Surfaces Experiment provided on-orbit leading-edge data on thermal properties of 25 materials during the first 18 months of the mission.[4.4] The inorganic binder paints, such as Z93 (zinc oxide in a potassium silicate binder) and YB-71 (zinc orthotitanate in a potassium silicate binder), were shown to be stable in the LEO environment. Some thermal-control materials degraded more, others less, than predicted from ground tests. The thermal-control properties (α/ε) of organic binder paints, commonly used for their ease of application, were observed to degrade by as much as a factor of 3 on the trailing edge, but they showed much smaller changes on the leading edge. Data from paints flown on the M0003 experiment on LDEF are shown in Table 4.4.[4.5]

Table 4.4: Solar Absorptance of Thermal-Control Paints on LDEF M0003

Paint	**Initial α**	**Leading-Edge α**	**Trailing-Edge α**
YB-71	0.130	0.182	0.182
A276	0.282	0.228	0.552
S13GLO	0.147	0.232	0.458
D111	0.971	0.933	0.968

The polyurethane paint A276 on LDEF is interesting because the multiple locations on hardware completely around the vehicle allowed the effects of orientation on performance of the paint to be clearly measured, as shown in Fig. 4.12.[4.6] The data from the trailing edge at or near 180 deg clearly show the degradation of the paint by the solar UV, while the degraded binder on the leading edge near 0 deg has been removed by the AO erosion to maintain properties near the initial values.

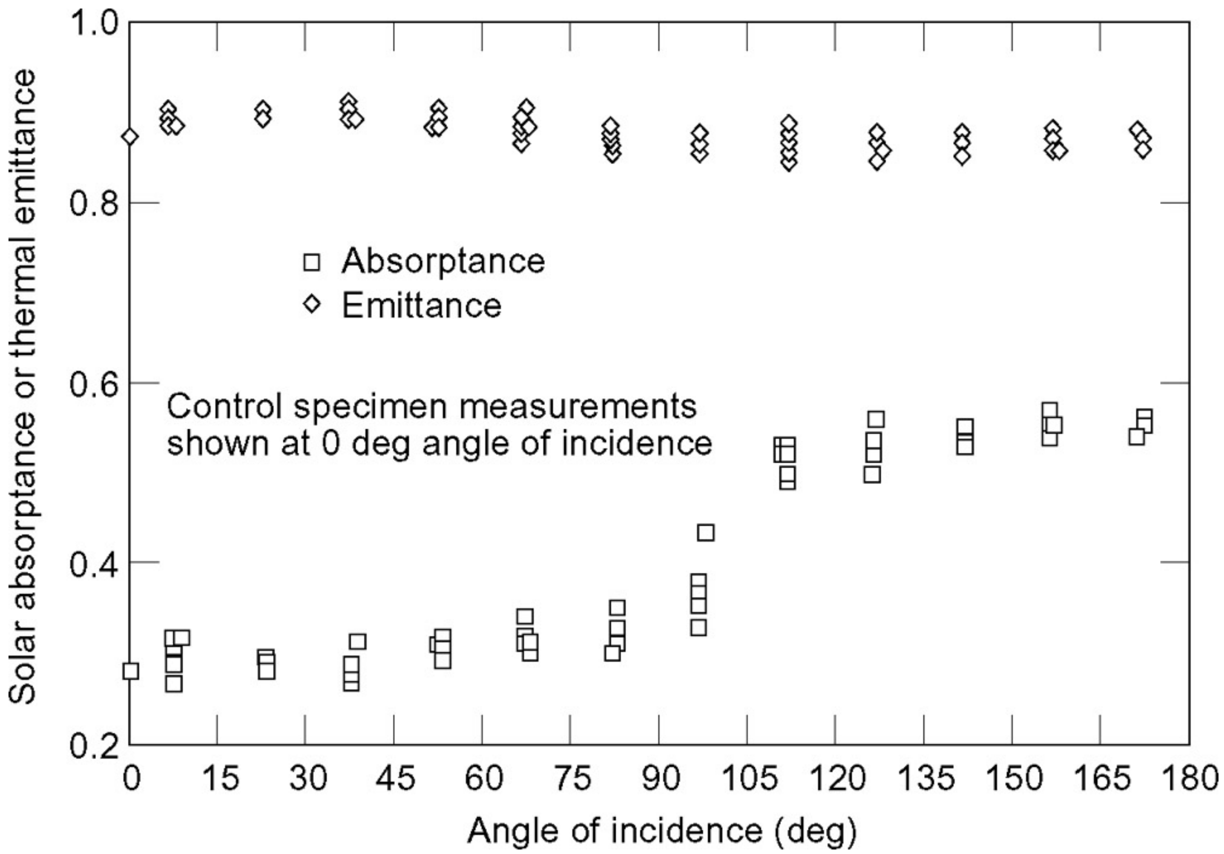

Figure 4.12: Optical properties from A276 white thermal-control discs.[4.4]

The Kapton and Mylar thermal blankets on LDEF were of particular interest because of the susceptibility of these materials to erosion from reaction with AO on leading-edge surfaces. In fact, one of the initial observations of damage to LDEF materials on-orbit was the observation of the severely eroded Mylar blankets on the space-facing end of the LDEF structure. There were 5-mil Kapton blankets on the leading edge of LDEF where the Kapton had been completely removed and only the few thousand Å of metalization remained. The AO fluence of ~9×10^{21} O atoms/cm^2 observed on LDEF leading-edge surfaces led to a predicted loss of over 10 mils of Kapton, based on the reaction efficiency from earlier shuttle flights of $3.0 \times 10^{-24} cm^3$/O atom. The observed erosion for Kapton (and a number of other organic polymers) on LDEF was consistent with previously determined reaction efficiencies.

A variety of visible changes were observed on both the leading- and trailing-edge silvered FEP Teflon surfaces on LDEF. The 5-mil silvered Teflon blankets were visibly altered during the LDEF mission, but the thermal properties did not degrade significantly except in those areas that were contaminated. However, caution should be used in other applications depending on the thermal-blanket thickness and the planned orbit. The cloudy, diffuse appearance of the Teflon on the leading edge was caused by an unexpectedly high erosion of the Teflon layer. For short exposures in LEO, such as the prior shuttle experiment to study AO effects, very low erosion had been observed, consistent with a recession rate of $<0.1 \times 10^{-24} cm^3$/O atom. The LDEF has permitted the first orbital measurement of the erosion of the Teflon layer on the leading edge from AO; previous attempts could not measure the smaller thickness decrease of the Teflon. The ~1 mil of erosion observed on LDEF is apparently the result of synergistic effects of the VUV and AO environment.[4.7] Thermal measurements show the expected decrease in emissivity as the thickness is decreased. The diffuse reflectance increased for those areas toward the leading edge roughened by exposure to both AO and solar UV, giving rise to the uniformly clouded appearance. LDEF data has shown that a value of $0.34 \times 10^{-24} cm^3$/O atom is clearly more appropriate for longer exposures. In practice, the known reaction efficiency and expected oxygen fluence are used to predict the expected life of a film with a given initial thickness. Most blanket areas from the trailing-edge side, exposed only to solar UV, remained specular. The LDEF results for silvered Teflon indicate that the thermal performance shows minimal degradation from the solar UV exposures of up to 11,000 ESH. For the trailing-edge blankets, the UV exposure caused polymer-chain scission at the surface and resulted in decreases of percent elongation to failure and ultimate tensile strength.[4.8]

Another effect observed silvered FEP Teflon blankets on LDEF was the severe degradation associated with cracked silver-Inconel layers. Improper application, which produced cracking of the metalization, allowed migration of the Y966 adhesive through the metalization, and subsequent darkening by solar UV. This process led to increases in absorptance up to 0.25 in small areas. Lifetime predictions should also include consideration of the fraction of the blanket surface that will likely be darkened or destroyed by meteoroid and debris impacts, and potential absorptance increases caused by contaminant films over a fraction of the surface. These considerations were minor for LDEF. Impacts darkened 2% or less of the surface area of each LDEF blanket, and delaminated < 5% of the area on each blanket. Contaminant films caused absorptance changes as high as about 0.25, but only for relatively small surface areas.

[4.4]D. L. Wilkes and L. H. Hummer, "Thermal Control Surfaces Experiment-Initial Flight Data Analysis-Final Report," AZ Technology Report No. 90-1-100-2 (1991).

[4.5]M. J. Meshishnek, S. R. Gyetvay, and C. H. Jaggers, "Long Duration Exposure Facility Experiment Deintegration/Findings and Impacts," *LDEF-69 Months in Space First Post-Retrieval Symposium*, ed. Arlene S. Levine (NASA Conference Publication 3134, 1992) pp. 1073–1107.

[4.6]J. L. Golden, "Results of Examination of the A276 White and Z306 Black Thermal Control Paint Discs Flown on LDEF," *LDEF-69 Months in Space First Post-Retrieval Symposium*, ed. Arlene S. Levine (NASA Conference Publication 3134, 1992) pp. 975–987.

[4.7]C. S. Hemminger, W. K. Stuckey, and J. C. Uht, "Space Environmental Effects on Silvered Teflon Thermal Control Coatings," *LDEF-69 Months in Space First Post-Retrieval Symposium*, ed. Arlene S. Levine (NASA Conference Publication 3134, 1992) pp. 831–845.

[4.8]G. Pippin, W. K. Stuckey, and C. S. Hemminger, "Performance of Silvered Teflon Thermal Control Blankets on Spacecraft," *LDEF Materials Results for Spacecraft Application Conference* (Huntsville, Ala., 27 October 1992).

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4.2 Y. S. Touloukian, *Thermophysical Properties of Matter* (IFI/Plenum, New York and Washington, 1972).

4.3 M. Donabedian, "Emittance of Selected Thermal Control Surfaces at Cryogenic Temperatures," The Aerospace Corporation, ATM 90(9975)-10 (15 December 1989).

4.4 D. L. Wilkes and L. H. Hummer, "Thermal Control Surfaces Experiment-Initial Flight Data Analysis-Final Report," AZ Technology Report No. 90-1-100-2 (1991).

4.5 M. J. Meshishnek, S. R. Gyetvay, and C. H. Jaggers, "Long Duration Exposure Facility Experiment Deintegration/Findings and Impacts," *LDEF-69 Months in Space First Post-Retrieval Symposium*, ed. Arlene S. Levine (NASA Conference Publication 3134, 1992) pp. 1073–1107.

4.6 J. L. Golden, "Results of Examination of the A276 White and Z306 Black Thermal Control Paint Discs Flown on LDEF," *LDEF-69 Months in Space First Post-Retrieval Symposium*, ed. Arlene S. Levine (NASA Conference Publication 3134, 1992) pp. 975–987.

4.7 C. S. Hemminger, W. K. Stuckey, and J. C. Uht, "Space Environmental Effects on Silvered Teflon Thermal Control Coatings," *LDEF-69 Months in Space First Post-Retrieval Symposium*, ed. Arlene S. Levine (NASA Conference Publication 3134, 1992) pp. 831–845.

4.8 G. Pippin, W. K. Stuckey, and C. S. Hemminger, "Performance of Silvered Teflon Thermal Control Blankets on Spacecraft," *LDEF Materials Results for Spacecraft Application Conference* (Huntsville, Ala., 27 October 1992).