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Coatings for Space Applications

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The October 2017 issue of CMN discussed the use of optical coatings in the space environment [1, 2]. This issue of CMN discusses the functional applications of materials and coatings that are essential surface treatments for spacecraft and instruments to provide long service lives in the harsh thermal and pervasive radiation space encountered in environments. [3]

Thermal Control Coatings

In past articles, we have talked about tribological and decorative coatings as durable treatments for exposed surfaces. Recent events related to the 2020 space race and hypersonic vehicles requirements are bringing high-temperature and durable coatings back front and center. Before we get into the heart of the new challenges, let's take a moment to review the state of the art that came about as a result of the initial reusable orbiter in the Space Shuttle program. Well before that first flight on April 12, 1981 much work had to be done realize a successful landing of the vehicle from Space, including incineration of the main fuel tank by the Earth's atmosphere and harvesting of the two solid rocket boosters for reuse on future launches. While the paint and surface protection approaches were consistent with the technology of the day, the orbiter itself required some significant innovation to protect the vehicle on the launch pad, in deep space, and for the critical re-entry. Unlike the boosters or the insulated fuel tank, the skin of the shuttle is a collage of insulating tiles with a special mixture of inorganics including a novel boron silicide which dissipates the heat generated by atmospheric friction. Just as the tiles themselves were custom to the location on the craft, there were different formulations and finishes, for the requirement for different surfaces is related to the expected frictional heat loading and energy density at that spot. Even as the program flourished, NASA continued and promoted additional innovation for the hottest locations like tips and around discontinuities, such as the ports and landing gear hatches. Much of their work pushed high temperature materials research to discover the best possible traits of the high temperature carbides and borides, which could be applied by various technologies specific to the vehicle and function of the surface. It was this point that the new space race started to embrace advanced nitride, carbide, boride and silicide compounds based on their high temperature durability properties. Leveraging ballistic missile and hypersonic vehicle formulations, the new goals of high reusability with minimal rehabilitation before relaunch are challenging even new paradigms. New programs have taken the complex overhaul of the rocket boosters from thousands of parts to several with the goal of zero refurbishment, aside from refueling. Currently, enhanced plasma deposition processes for the fabrication and application of advanced high-temperature materials satisfy the requirements in global hypersonic research and investment. As discussed in past articles, there are choices between mixtures deposited at low energy and those using enhanced plasma and reactive deposition. The compounds are formed on critical surfaces through reaction, or are deposited as fully composed films [3]. In contrast to specialty optics designs, these abrasive-resistant high-temperature coating layer thicknesses are typically 10 to 20µ and are not optically transparent. These thick, high- temperature durable coatings are critical components for providing payload protection for space communications and defense missions. Additionally, the array of coatings and materials are part of the larger thermal protection systems applied in rockets and hypersonic vehicles and are critical for deploying the most sophisticated of human technologies, namely thermal control coatings and specialty optics to space.

One of the first and continuing applications of optical coatings is to maintain a safe and consistent internal temperature of electronics and optics in spacecraft instruments, through sunlit and dark cycles. Simple in construction, thermal control coatings involve the clever use of the optical and thermo-physical properties of materials. The structure is a second-surface mirror with the superstrate being glass or fused silica, as depicted in Figure 1.

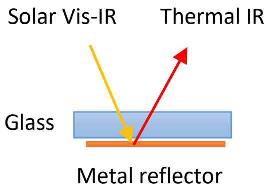


Figure 1. Thermal control panel prevents internal heating of spacecraft electronics and optics by sun and night cycling through selective reflection and radiation.

Solar irradiation from Visible to ~2.5 µm is transmitted by the glass and reflected back to space by the mirror. The glass absorbs IR between ~2.5 µm and 8 µm and reradiates the heat to space. Additionally, the wide reflection band between 8 and 10 µm in silicates reflects thermal radiation. The mirror is often silver (Ag), but aluminum (Al) and gold (Au) have been used when greater long-term environmental stability is required. Irradiated thermal energy is absorbed by the silicate and reflected for a second pass through the glass silicate. A balance between reflection and absorption is achieved by the glass thickness. On those surfaces where internal temperature control is not required but solar heating must be rejected, these second-surface mirrors have been replaced by lighter weigh multi-layer gold- coated Kapton or Mylar thermal blankets, such as those on Mars rovers.

Coatings Immune to the Effects of Ionizing Radiation

We have previously discussed radiation effects on coatings and the roles of material and deposition process choices in producing optically stable and mechanically durable coatings [1, 2]. The threats are both ionizing radiation and solar UV. A large population of commercial and military reconnaissance satellites reside in the trapped ionizing radiation belts (Figures 2 and 3). These optical instruments are expected to have operational orbital lifetimes of up to 15 years. High- and low-energy protons in Low Earth Orbit (LEO) can induce absorption and therefore increase transmission losses in optical materials including coatings. Electron density is high in Geosynchronous Earth Orbit (GEO) orbits, but mostly affects electronics. Solar UV presents an existing threat to coating and materials stability in both LEO and GEO, especially with regard to the many thousands of square meters of solar panels that power nearly all space instruments. Among many other satellites, the International Space Station operates in a LEO orbit, where the energy and flux of protons are high, as are reactive erosion rates by atomic oxygen. At this altitude, these qualities are serious life-limiting threats to

surfaces. Coatings that provide resistance consist of hard oxide materials deposited by high-energy processes such as magnetron sputtering. IAD E-beam or IBS. Materials include SiO_2 (the low-index component) combined with Ta_2O_5, HfO_2, ZrO_2 and others.

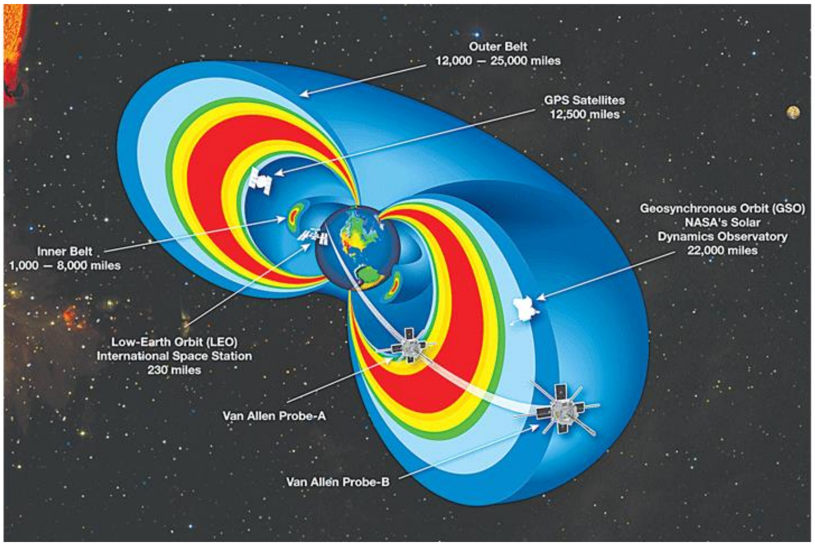
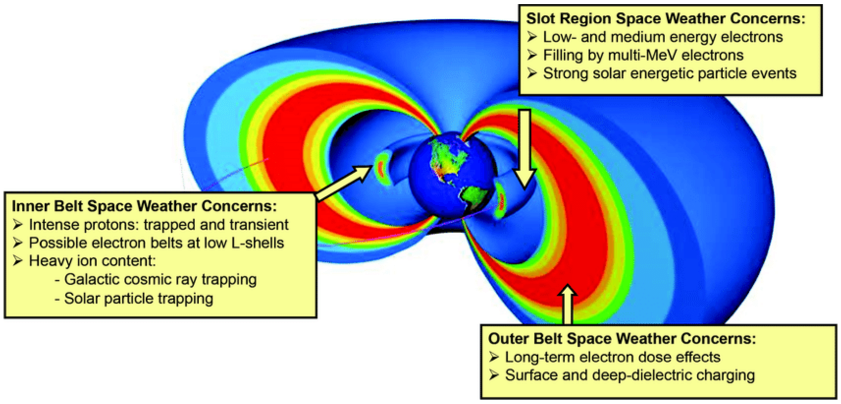


Figure 2. Trapped radiation belts and species in various orbits. The International Space Station, climate monitoring and space internet satellites reside in Low Earth Orbit. GPS and scientific instruments are stationed in Geo Synchronous Orbits. (NASA.com)



Slot Region Space Weather Concerns:
- Low- and medium energy electrons
- Filling by multi-MeV electrons
- Strong solar energetic particle events

Inner Belt Space Weather Concerns:
- Intense protons: trapped and transient
- Possible electron belts at low L-shells
- Heavy ion content:
  - Galactic cosmic ray trapping
  - Solar particle trapping

Outer Belt Space Weather Concerns:
- Long-term electron dose effects
- Surface and deep-dielectric charging

Figure 3. The Inner Belt radiation impacts near-Earth LEO instruments. (NASA.com).

A current space instrument application is the constellation of micro satellites orbiting in LEO that provide world-wide broad band internet access. This new technology is intended to replace the existing network of fiber optic cables without the losses or breakdowns that limit coverage associated with glass fibers. Ongoing endeavors are Starlink by

SpaceX, and systems by Telesat, OneWeb, and Amazon's Kuiper Project. Constellations of micro satellites using short-wave infrared (SWIR) laser lines to provide internet and secure communications are already in initial operation. The micro satellites operate in LEO (Figure 3).

Communication satellites use narrow optical bandwidths at wavelengths between 1000 and ~2500 nm. A constant challenge for the coating industry is to produce the very narrow passbands that provide high rejection optical density (OD) ~5 of direct or scattered solar background to maximize the desired signal against out-of-band energy. These thick coating designs can require >100 layers to achieve the required rejection. Being physically thick, they are susceptible to radiation instability unless the proper materials and deposition processes are incorporated. Exposed surfaces in LEO are vulnerable to erosive reaction in the energetic plasma of Atomic Oxygen. Energetic deposition by magnetron or ion beam (IBS) sputtering produce dense and completely oxidized coating materials that have a history of survival [4, 5, 6].

Optical instruments that operate in the inner zone where the concentration of Atomic Oxygen plasma is large need protection from surface charging. Charge accumulating on solar panels, lenses, and other dielectric surfaces can discharge as an arc that damages the surface. Transparent conductive oxides (TCO) a few 100 å thick are deposited on the outer surfaces to provide kiloohm resistance that will prevent charge accumulation. ITO and AZO are favorite TCOs in use. In another application, radio frequency (RF) shielding is accomplished by using thicker TCO with sheet resistances below ~10 Ohms / sq.

In a primary space application, Earth resources and climate monitoring satellites observe earth's atmosphere, cloud cover, oceans and land resolved in narrow passbands in the visible, near, short, mid and longwave infrared (VIS, NIR, SWIR, MWIR and LWIR) thermal regions between wavelengths spanning ~400 nm and 12 µm. A large suite of science disciplines beginning in the 1980's and continuing is served by these satellite instruments. Their obits are generally at GEO distances. Climate monitoring includes atmospheric pollutant height concentration of aerosol components such as soot, dust, and smoke. Oceans are monitored for chlorophyll blooms and concentrations of colored dissolved organic matter (CDOM). In land masses, drought, plant disease and moisture distributions relate to agricultural production. Cloud cover, circulation, and density properties play into weather forecasting and tracking. Space instruments in orbit that perform these measurements include MODIS, VIIRS, SeaWifs and companion European Space Agency (ESA) instruments [7].

Because the data products of these instruments require temporal continuity to track changes, transient as well as long term spectro-photometric accuracy and precision are crucial to the performance and quality of these instruments. Spectrophotometric accuracy is dependent on the stability of optical coating types that include mirrors, beam-splitters, bandpass filters and AR coatings. Careful consideration of deposition processes and materials that promote long-life tolerance to ionizing and solar UV radiation has been in place since the design and launch of the MODIS pair in 1999 and 2002.

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