# A Discussion of Optical Systems Exposed to the Hazards of Low Earth Orbit

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**Abstract**

The purpose of this paper is to provide a brief synopsis of the paper, "Environments stressful to optical materials in low earth orbit" by S. Musikant and W.J. Malloy, published in 1991[1]. Although the paper was written pre-launch of the Space Station Freedom (SSF), which was adopted into the International Space Station (ISS) an audience interested in the design and development of any low earth orbit payload will be interested in the material presented here. The paper explores the general effect on optical materials and supporting electronics of various critical degradation modes: atomic oxygen, micrometeoroids and manmade debris, particulate and molecular contaminants, ionizing radiation and single particle phenomena. This paper has been investigated in context of more recent research developments that further define the harsh LEO environment with mission results from the Materials ISS Experiment (MISSE).

**Introduction**

Low Earth Orbit (LEO) is defined by as 160 to 2,000 km above the Earth's surface. This particular orbit is of continual interest for the following reasons:

- They are below the inner Van Allen radiation belt and are therefore protected from the majority of cosmic rays, Van Allen radiation, and solar flares.
- They include equatorial LEO's which provide a high number of revisit occurrences. These also require the least amount of delta-V, or necessary velocity to reach final orbit.
- Due to their close proximity, spacecrafts at LEO need less power amplification for successful transmission to Earth.

However, there is still a considerable risk to spacecraft at LEO. The authors present the discussion of five degradation modes with some data obtained from previous Space Shuttle missions. Since then, numerous research experiments have been conducted both in-situ on other aerospace missions, in more complicated environmental simulation tests on Earth, and in software simulations as computer technology has progressed. One such published report is "Lessons Learned From Atomic Oxygen Interaction with Spacecraft Materials in LEO" by B. Banks, K. de Grogh, S. K. Miller, and D. Waters.[2]

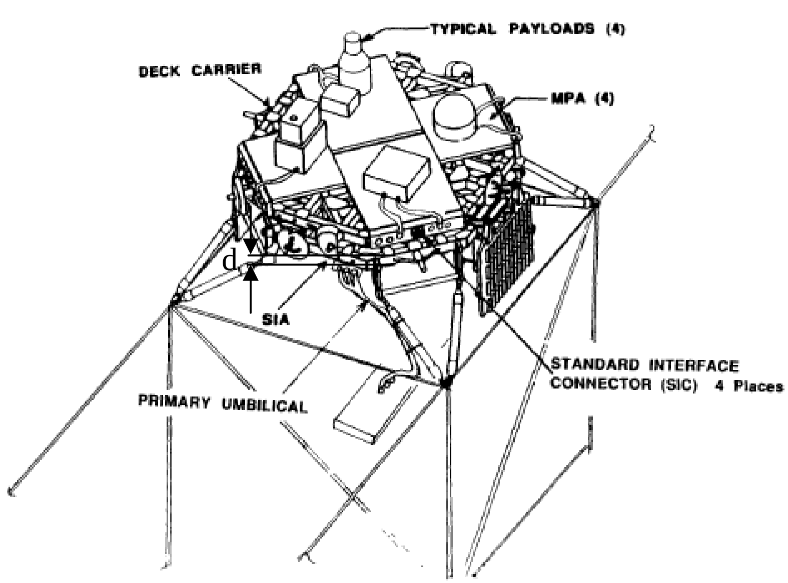
The purpose of this paper is to investigate the discussion put forth by Musikant and Malloy in the context of some recent research developments. Section 1 will provide a brief review of Musikant and Malloy's paper. Section 2 will investigate the findings obtained from the Materials International Space Station Experiment.

**Section 1: Musikant and Malloy – Describing the LEO Environment**

The authors list atomic oxygen, micrometeoroids and manmade debris, particulate and molecular contaminants, ionizing radiation and single particle phenomena as instances of concern for a spacecraft at LEO.

The key subsystem of interest on the Space Station Freedom (SSF) is shown below in Figure 1 and is the key platform that supports all interfaces to the payload. The bays are 5 cubic meters and are supported by 8 graphite epoxy legs fixed at four points to the main SSF truss. All discussions are given in consideration of this particular payload and its requirements.

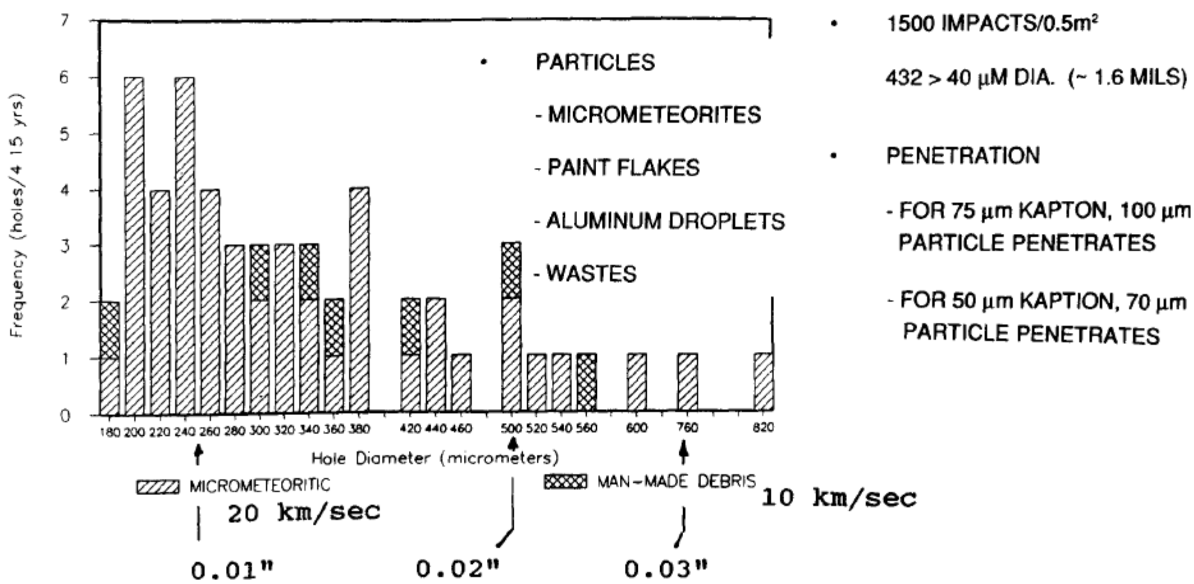
**Figure 1: SSF Payload Schematic and Attachment to SSF**



Damage occurring from atomic oxygen is mainly a direct line of sight phenomenon and typically does not require hermetic sealing of equipment to survive exposure. Mainly, surfaces in the ram or velocity direction will be subjected to atomic oxygen. When this occurs, all optical surfaces are at risk. For instance, vapor deposited diamond will react at the rate of 0.021 E-24 $cm^3$ and while a magnesium fluoride coating will react at 0.007 E-24 $cm^3$. These may seem like inconsequential values; however, for missions that on average last longer than 10 years the damage may present problems as the film thickness continues to degrade. The graphite epoxy structure is also at risk and needs to be covered to a shield such as aluminum or anodized aluminum which is corrosion resistant. Finally, organic lubricants and all electric harnesses also need to be protected.

Naturally occurring micrometeoroids and man-made debris is a significant problem and must be mitigated with impact shields. Micrometeoroids are solid particles originating from comets and asteroids, are constantly entering the earth's atmosphere and being pulled by earth's gravitation, causing an increase in particulate density as distance from the earth decreases. Their masses range from $10^{-12}$ to 1 gram, their average density is 0.5 $gm/cm^3$, and their average velocity if 20 km/sec. Space debris annual growth is projected to be 5% particles >1.0cm and 10% <1.0 cm diameter. At the time of publishing, it was estimated that 3 E6 kg of human-generated objects are in earth orbit. The man-made debris has an average velocity of 10 km/sec. Most often, micrometeoroids and man-made debris occur in the form of small particles similar to paint flakes and will result in surface wear. However, some key elements cannot be covered and will thus have to be manufactured from damage resistant materials. Figure 2 on the next page describes the flux averaged over a 4.15 year flight of impacts in the thermal control louvre baffles. The flux a given surface will experience is a strong function of the surface orientation with respect to Earth's gravity field. There is an obvious design tradeoff between amount of shielding and added weight and loss of field of view that needs to be taken into consideration.

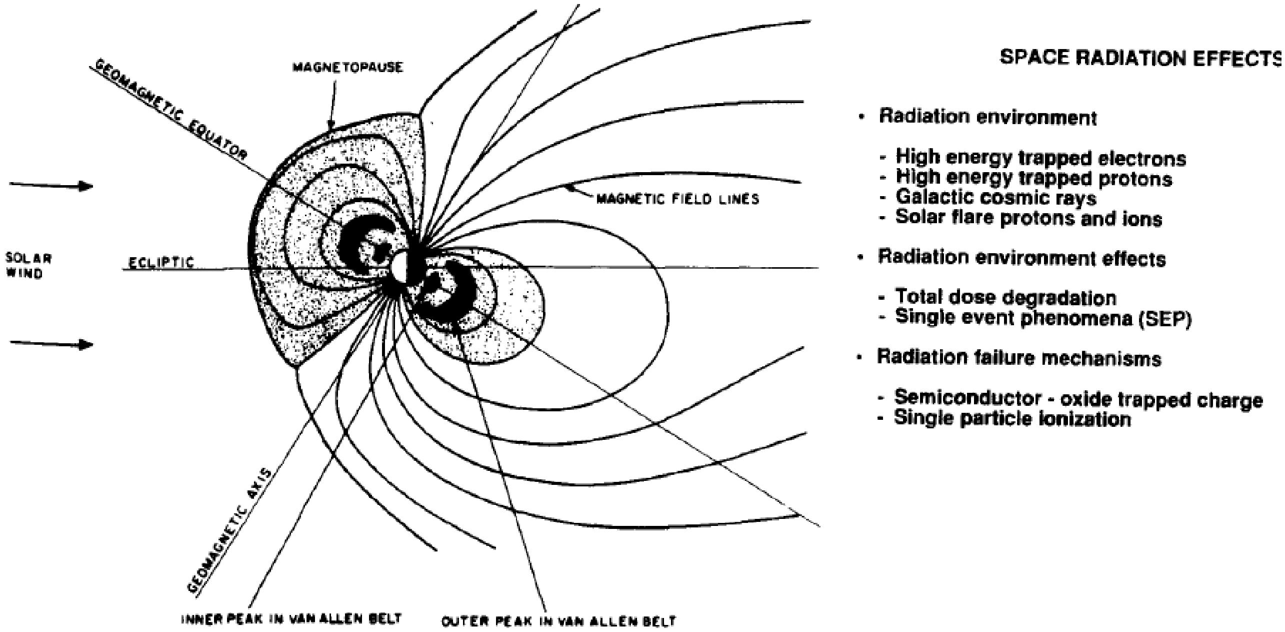
**Figure 2: Flux of impacts on the Solar Maximum Repair Mission (Space Shuttle)**




Contamination, both particulate and molecular, is a well-recognized hazard to optical surfaces. These can occur from residual particulates left on the equipment during manufacture, shipping and deployment loads, secondary particles from micrometeoroids, man-made debris impacts, and extravehicular activity. On the molecular level, contamination can occur from outgassing of materials of the SSF, thruster plume material, thermal and pressure vents, and fluid and gas leaks. A typical rule of thumb is an average molecular deposition on 300 K on the order of 120 Å per year and should be considered in the optical performance of each device. The actual design value will vary depending on the size and location of the vulnerable surface.

LEO has an extreme ionizing radiation environment consisting of high energy electrons and protons geomagnetically trapped in the Earths' magnetosphere, solar flare particles, and galactic cosmic rays. This can lead to semiconductor device performance degradation from trapped charge deposited at the critical interfaces of the bulk semiconductor and the oxide. The primary factor in this degradation is the angle of inclination of the spacecraft's orbit. Figure 3 on the next page shows a comparison of two missions whose spacecraft orbits are almost perpendicular to one another. The SSF shows much lower energy deposition due to its lower inclination orbit. This orbit results in degradation only occurring at the South Atlantic anomaly where the orbit interacts with the Van Allen radiation belt. Also, solar flare particles are generally shielded by Earth's geomagnetic field. Typical electrical boxes provide enough shielding from the spacecraft structure equivalent to 100 to 150 mils of aluminum.

**Figure 3: Terrestrial Space Radiation Environment**




Single particle phenomenon results from the intense ionization track of single high energy particles in a semiconductor. These are generally the result of an upset of stored or latched data in the microcircuit. The resulting energy loss is defined at linear energy transfer (LET) in units of MeV cm$^2$ per mg. The susceptibility of microcircuits is determined by:

1. Deposited energy required to cause an effect
2. Critical volume for energy deposition
3. The LET spectrum of the event

The SSF orbital cosmic ray environment is lowered by shielding the effects of the Earth's magnetic field. However, this is typically impractical for optical devices due to the high energy of the particles. Therefore, careful selection of electrical devices insensitive to single particle phenomenon and/or the use of error detection and correction can minimize a system's sensitivity.

**Section 2: Relevant Excerpt from "Lessons Learned from Atomic Oxygen Interaction with Spacecraft materials in Low Earth Orbit"[2]**

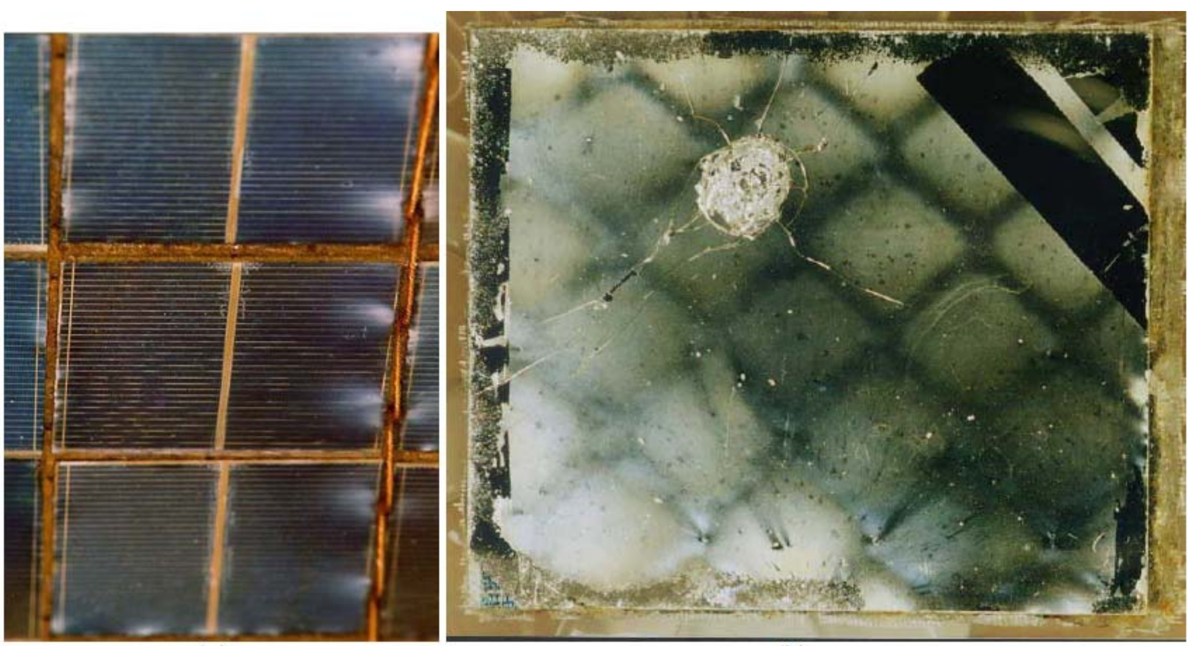
When the SSF became the International Space Station (ISS) program, an experiment was defined to investigate the effect of LEO on specific materials: the Materials ISS Experiment (MISSE) which was flown with 5 different carriers which were launched, exposed to space on the exterior of the ISS, and then returned to Earth for analysis.

Silicone contamination sources and consequences have been studied in-depth on multiple space missions and from retrieval of spacecraft components and materials: NASA's Long Duration Exposure Facility (LDEF), NASA's Evaluation of Oxygen Interactions with Materials-3 (EOIM-3) experiment, the Russian Space Station Mir, NASA's Materials International Space Station Experiment 2 (MISSE 2), Japanese Aerospace Exploration Agency's (JAXA) Service Module/Micro-Particles Capturer & Space Environment Exposure Device (SM/MPAC & SEED) ISS Experiment, and the Hubble Space Telescope (HST).

Silicones which have not been vacuum stripped frequently contact volatile short chain molecules and are readily transported onto neighboring surfaces. When they are exposed to the atomic oxygen in LEO, the silicones oxidize, form silicates, and trap hydrocarbons on the surface. The resulting deposit can darken the protective coating in UV solar illumination. However, if no UV illumination occurred, then the the silicone volatiles eventually re-evaporate and no darkening results. Interestingly, these silicate deposites can also act as a shield from atomic oxygen attack.

Figure 4 below shows the significant darkening of optical solar reflectors and neighboring thermal control white paint surfaces from a Mir core module after it had been in LEO for 10.4 years.

**Figure 4: MIR Solar Array (a) Oxidized silicone contamination up to 4.6 microns thick. (b) Tape peeled area where contaminants between 1.06 and 1.24 microns thick were removed for analysis**



(a) (b)

Table 1 below shows the large variation in silicate contamination on various surfaces from experiments placed in different locations on the ISS.

**Table 1: Silicate Contamination on ISS Experiment Surfaces**

| Location | Silicate contaminant thickness, nm | Duration of exposure, years | Silicate contaminant thickness/years, nm |
|---|---|---|---|
| MISSE 2, Tray 1 ram facing | 1.3 to 1.4 | 3.99 | 0.326 to 0.351 |
| JAXA | | | |
| Unit 1 | 30.0 | 0.863 | 34.8 |
| Unit 2 | 75.0 | 2.37 | 31.7 |
| Unit 3 | 93.5 | 3.84 | 24.3 |

The MISSE 2 had two orders of magnitude less contaminant thickness than the Japanese JAXA experiment units. The authors hypothesized that this was probably due to differences in the total arrival of silicones based on the each experiment's respective view of an distances to contaminant sources on the ISS.

These experimental results support the claim by Musikant and Malloy that self-contamination is an important factor in design for exposure at LEO. It is important to be out of view of sources of silicone to be sure atomic oxygen does not produce silica deposits that can affect erosion yields and/or cause changes in solar absorbance.

**Conclusion**

The past twenty years have yielded great advances in the design of spacecraft for survival in LEO missions. Therefore, initial discussion by Musikant and Malloy can now be supplemented by statistical and research experiments that have been conducted both in-situ on other aerospace missions, in more complicated environmental simulation tests on Earth, and in software simulations as computer technology has progressed.

## References

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