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Environments stressful to optical materials in low earth orbit

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ABSTRACT

Spacecraft in low earth orbit experience a variety of environments which are potentially damaging to materials and to optical systems including electronic controls and components. The low earth orbit (typically 400 km) has a significantly different set of environments than higher orbits. The environments vary not only with altitude but also with inclination. This paper deals with the environment that the Space Station Freedom will experience and with some of the effects on the materials and electronic components that will comprise the optical systems on the station. Specific optical systems are not addressed but the information presented is general and does apply to optical systems.

1.ENVIRONMENTS IN LOW EARTH ORBIT

The orbit of the Space Station Freedom (SSF) will be in the range of 333 to 444 km and an inclination of 28.5° to the equator. At this orbit, the intense flux of trapped electrons and protons found in the van Allen belts is mostly avoided but an atomic oxygen environment which is severe is encountered. In general the environments of interest from the point of view of reliability and long life without need for maintenance and repair are ultraviolet (UV); ionizing radiation, electrons, protons ions, and energetic photons; atomic oxygen (as differentiated from molecular or ionized oxygen); micrometeoroid; man made debris (from prior spacecraft operations); electrostatic buildup and discharge; thermal cycling due to the day-nite cycle every orbit (approximately 90 minutes); moisture and resin outgassing from composites and other materials; and contamination due to outgassing, leaks, dumps, thrusters and especially during the space shuttle operations in the vicinity of SSF.

SSF is designed for a 30 year life so that a rather limited data base needs to be extrapolated. Ground test simulation of the space environment is very difficult and the environments are not known precisely. Orbital data in the low orbit of SSF is limited. A number of experiments have been conducted on the Space Shuttle. Retrieval of the Modular Attitude Control System from the Solar

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Maximum Mission provided additional data on material responses in low earth orbit. The recent recovery from orbit of the Long Duration Exposure Facility (LDEF) and the evaluation and analysis of that vehicle now in process will provide a large data base invaluable in the SSF design.

Figure 1 depicts a single bay of the SSF. The bays are 5 meter^3 and in the sketch the Attached Payloads Accommodations Equipment (APAE) is shown. In this configuration (not necessarily the finally adopted configuration) the APAE platform is supported by eight graphite epoxy legs fixed at four points to the main SSF truss. The APAE may accommodate multiple payloads as shown or one large payload. The function of the APAE is to provide all the services and data interfaces required by the payload. Cables, thermal control surfaces, structures, lubricants and all components have to be designed to survive the imposed environments.

2. CRITICAL DEGRADATION MODES

Areas requiring careful attention during design include all optical surfaces that are vulnerable to atomic oxygen attack. These include some optical coatings such as vapor deposited diamond and magnesium fluoride, the diamond reacting at the rate of 0.021×10^{-24} cm^3 per atom of oxygen while the MgF_2 reacts at 0.007×10^{-24} cm^3 per atom of oxygen. Although these are small reaction rates the films are thin and on long duration missions may present problems as the film thickness decreases with time. Silver is a particularly bad material in the atomic oxygen environment, reacting at the rate of 10.5×10^{-24} cm^3 per atom of oxygen. All polymeric materials and organically based paints, coatings and films react rapidly. Table 1 shows reaction rates for a number of materials[1].

Coatings resistant to atomic oxygen are being developed. Some of these depend on silica based films. Most metals are resistant (but not all) and anodized aluminum is proposed as an atomic oxygen resistant material with appropriate solar absorptance/total hemispherical emittance properties.

Graphite epoxy structural elements in optical benches is a vulnerable material. It has to be covered with an atomic oxygen shield such as aluminum or anodized aluminum. Fortunately, the atomic oxygen effect is essentially a line of sight reaction and hermetic sealing is not required. However, scattered atomic oxygen needs to be considered in configuration selection. Mainly, surfaces in the ram or velocity direction are subjected to the atomic oxygen.

Organic lubricants are susceptible if not protected from the ram. All electrical harnesses need to be shielded from the atomic oxygen.

Naturally occurring micrometeoroids will damage critical surfaces. Man-made debris is a significant problem and impact shields need to be installed to protect mission critical elements. Certain surfaces cannot be covered and these have to be made of damage resistant materials. Most of the micrometeorite and debris flux is in the form of small particles like paint flakes; surface wear is a likely failure mode if the surfaces are not wear resistant.

Another well recognized hazard to optical surfaces is contamination, both particulate and molecular. Contaminants are due to residual particulates left on the equipment during manufacture, shipping and deployment; secondary particles issuing from micrometeorite/debris hits; and shuttle and SSF operations such as extra vehicular activity (EVA). Molecular contamination is due to outgassing from the

materials of the SSF, plumes from the thrusters, vents (especially from the habitat and laboratory modules), fluid and gas leaks, EVAs, and shuttle operations in the vicinity of the SSF. The anticipated average molecular deposition on 300° K surfaces is on the order of 120 Angstroms per year and needs to be factored into performance predictions of the optical devices. However, this deposition will vary from place to place depending on the relative locations of the source and the vulnerable surface.

3. SPACE EXPOSURE DATA BASE

As mentioned earlier, only limited orbital data is available in low earth orbit. Table 2 shows the orbital data base for atomic oxygen effects. The Space Transportation System (STS) space shuttle flights are listed as well as the Solar Max Repair Mission and the LDEF. The longest exposure was the LDEF mission which represents only about 5% of the planned 30 year SSF mission in terms of total atomic oxygen fluence.

"Quick look" data on the retrieved LDEF showed total destruction of thermal control 5 mil thick Kapton films, and significant erosion of teflon. In atomic oxygen exposure ground tests, teflon was relatively resistant to atomic oxygen as indicated in Table 1. However, LDEF revealed an erosion rate of about 1 mil per year (when normalized to the SSF environment) compared to 0.03 mils per year in ground test. Other exposed surfaces showed various types of degradation and a review of the post flight analyses will be provided in an open meeting at NASA Langley Research Center October 22-24, 1990.

The Solar Maximum Repair Mission (SMRM)[2] retrieved the Solar Max vehicle from low earth orbit and successfully replaced failed components while in orbit after placing the vehicle into the Space Shuttle cargo bay. Figure 2 shows the Solar Max vehicle and its wobble modes in orbit before repair. The Modular Attitude Control System (MACS) and the main electronics box of the coronograph/polarimeter were replaced. Post flight evaluation of the MACS revealed atomic oxygen damage on the multi-layer insulation (MLI), and on the silver teflon thermal control material where the silver was exposed to the atomic oxygen flux. Figures 3 and 4 reveal some of the details of the construction and damage modes of these elements.

Micrometeoroid/debris impacts were numerous. Figure 5 reveals the penetrations in the outer layer of the two layer thin-walled aluminum skin of the thermal control louvre baffles. Figure 6 shows the flux averaged over the 4.15 year flight time before retrieval. Clearly, optical surfaces are susceptible to this type of damage.

4. MICROMETEORITES AND DEBRIS

Micrometeoroids are naturally occurring solid particles originating primarily from comets and asteroids which are continually intercepting the Earth's orbit. Due to the Earth's gravitation micrometeoroids enter the atmosphere at random angles. Thus all SSF element surfaces are vulnerable to micrometeoroid collisions. In addition, Earth's gravity pulls the micrometeoroids closer resulting in increasing flux at lower Earth orbit (i.e. the micrometeoroid flux is gravitationally focussed). The worst-case micrometeoroid environments for Space Station elements are shown in Figure 7 as the probability of mass flux for the specified periods. The figure includes the correction for the Earth's gravitational effects at 500 km. Micrometeoroid masses range[3] from 10^{-12} to 1.0 gram; their average density is 0.5 gm/cm^3 and their average velocity is 20 km/sec.

The Earth provides inherent shielding to the SSF element surfaces against micrometeoroids. The degree of shielding depends on the surface orientation with respect to nadir and the orbital altitude of the spacecraft. Surfaces facing nadir will receive maximum shielding As the surface is rotated to zenith facing, shielding gradually goes to zero. The curve of Figure 7 needs to be multiplied by the appropriate shielding factor.

Space debris consists of objects generated by human activity in space. The debris environment is a function of orbit altitude, inclination, and solar activity, and calendar time. Annual growth is expected to be 5% particles of diameter > 1.0 cm and 10% for particles of diameter $\leq$ 1.0 cm. It is estimated that 3 x 10^6 kg of human-generated objects are in earth orbit as of 1988[3].

The space debris particles have an average velocity of 10 km/sec. Debris of diameter $\leq$ 1.0 cm are modeled to have the density of aluminum (2.8 gm cm^{-3} while larger particles' densities fall off by the factor $d^{-0.74}$ where d is the particle diameter. Figure 8 shows the worst-case space debris environment for SSF elements as a probability of the mass flux for the specified periods commencing 1998[3]. The space debris model assumes that the debris and the SSF are in circular orbits. The flux that a given surface will experience is a function of the surface orientation. Material erosion occurs due to small particles and catastrophic damage results from impact with larger particles. Shielding is designed to protect critical components. Obviously, the more shielding, the greater the penalties due to added weight and loss of field of view.

5. IONIZING RADIATION

The ionizing radiation environment consists of high energy electrons and protons geomagnetically trapped within the Earth's magnetosphere, solar flare particles, galactic cosmic rays. Figure 9 shows an alignment of the Earth and its magnetic field with respect to its ecliptic plane. The primary locations of the geomagnetically trapped particles are in the inner and outer Van Allen Belts while the sources of the solar wind and galactic cosmic rays are external to the magnetosphere. This radiation environment can lead to semiconductor device performance degradation due to the trapped radiation particles, and to single particle induced device transients from high energy solar flare particles and galactic cosmic rays.

Degradation of semiconductor microcircuits in space results from trapped charge deposited at critical interfaces of the bulk semiconductor and the oxide. Long term radiation permanent degradation effects are particularly critical in MOS (metal oxide silicon) microcircuits, but are also important in advanced bipolar microcircuit technologies.

Figure 10 shows the energy deposition of the ionizing radiation in silicon as a function of shielding depth at the center of a solid aluminum sphere for the designated mission lifetimes of two different missions. The orbits of the two spacecraft are almost perpendicular to each other. The SSF shows much lower energy deposition; this is due primarily to the low inclination orbit of SSF. Only at higher latitudes will the SSF intersect the Van Allen Belts. This can only occur at a region called the South Atlantic anomaly. At this feature, the magnetic lines of force dip more closely to the Earth's surface. In addition, solar flare particles are shielded very effectively by the Earth's geomagnetic field and do not contribute to the ionizing radiation environment of the SSF.

Typical electric boxes are provided inherent shielding by the spacecraft structure, box walls, shadowing within the box equivalent to 100 to 150 mils of aluminum. However, devices external to the spacecraft structure have less inherent shielding and require design attention to provide adequate protection.

6. SINGLE PARTICLE PHENOMENA

Single particle induced device transients, referred to as single particle phenomena (SEP), are due to the intense ionization track of single high energy particles in the semiconductor. Single particle ionization effects generally result in the upset of stored or latched data in a microcircuit (single event upset (SEU)), but also can result in microcircuit latch-up leading to permanent damage.. The cosmic ray environment can be characterized by the energy loss and range of particles as they pass through the semiconductor material. The energy loss is defined as linear energy transfer (LET) in units of MeV cm^2 per mg.

The susceptibility of microcircuit technologies to cosmic ray effects is determined by (1) the deposited energy required to cause an effect, (2) the critical volume for energy deposition and (3) the LET spectrum of the event. The single event upset susceptibility of static memory microcircuit technologies are summarized in Figure 11 for exposure to a geosynchronous "10%" environment (i.e., it is expected that the modeled environment will be exceeded only 10% of the time for a randomly timed mission[4].

The wide variation in bipolar technology is the result of wide variation in device geometries and noise immunity to the single particle induced transient junction current. The susceptibility of CMOS (complimentary metal oxide silicon) technologies generally represents the variation in critical charge collection volume for the maximum for bulk CMOS to the minimum for CMOS/SOS (silicon on sapphire). The CMOS upset susceptibilities do not include potential hardening by circuit modification, which can substantially reduce the bit upset rate with minimum performance degradation[5].

The SSF orbital cosmic ray environment is lowered by the shielding of the Earth's magnetic field. This effect will result in fewer upsets per bit-day than that experienced at geosynchronous orbit. Shielding of satellite electronics from cosmic rays is usually impractical due to the high energy of the particles. Selection of devices insensitive to SEP and/or use of error detection and correction scheme can minimize system SEU sensitivity.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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Table 1. Relative atomic oxygen activity

MATERIAL	REACTION EFF'CY 1E-24 CM^3/AO ATOM	RECESSION IN SSF ORBIT
Al_2O_3	0.025	0.02 MIL/YR
KAPTON	3.1	3.0
MYLAR	3.6	3.5
TEFLON	0.03	0.03
CHEMGLAZE Z302 (GLOSSY)	3.9	3.8
CHEMGLAZE Z306 (FLAT)	1.0	1.0
AREMCO 569	0.03 (EST)	0.03 (EST)
SILVER	10.5	10.5
ALUMINUM	0.0	0.0

Table 2. Space exposure data base- atomic oxygen effects

FLIGHT	ALTITUDE (INCLIN.)	EXPOSURE TIME	FLUENCE* (ATTITUDE) atoms/cm^2
SSF	333-444 KM (28.5°)	30 YEARS	1.9 E23 (RAM - WORST CASE)
STS-5	222 KM (28.5°)	44 HOURS	1 X 10^{20} (VAR)
STS-8	222 KM (28.5°)	41.75 HOURS	3.5 X 10^{20} (RAM)
STS - 41G	225 KM (57°) (28.5°)	38 HOURS	3 X 10^{20} (RAM)
SMRM	491-574 KM (28.5°)	50 MONTHS	2 X 10^{21} (VAR)
LDEF	266-410 KM (28.5°)	68 MONTHS	1E 22 (RAM - (WORST CASE)

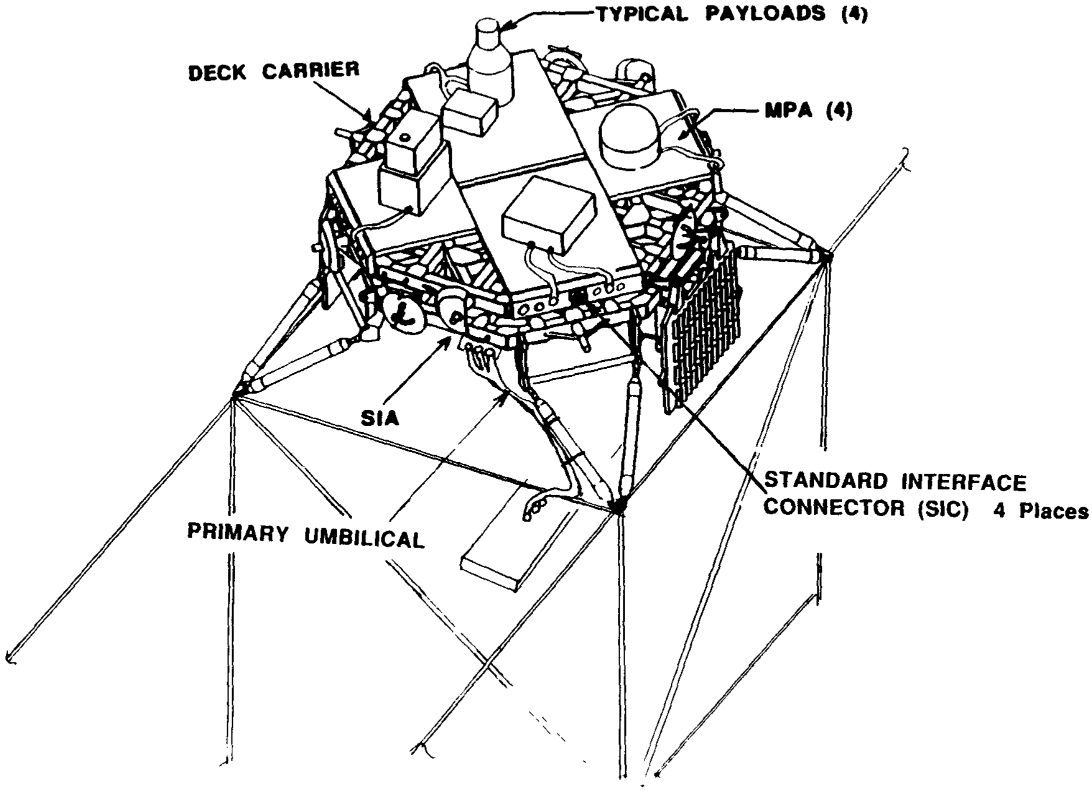


Fig.1. Single bay of SSF showing APAE

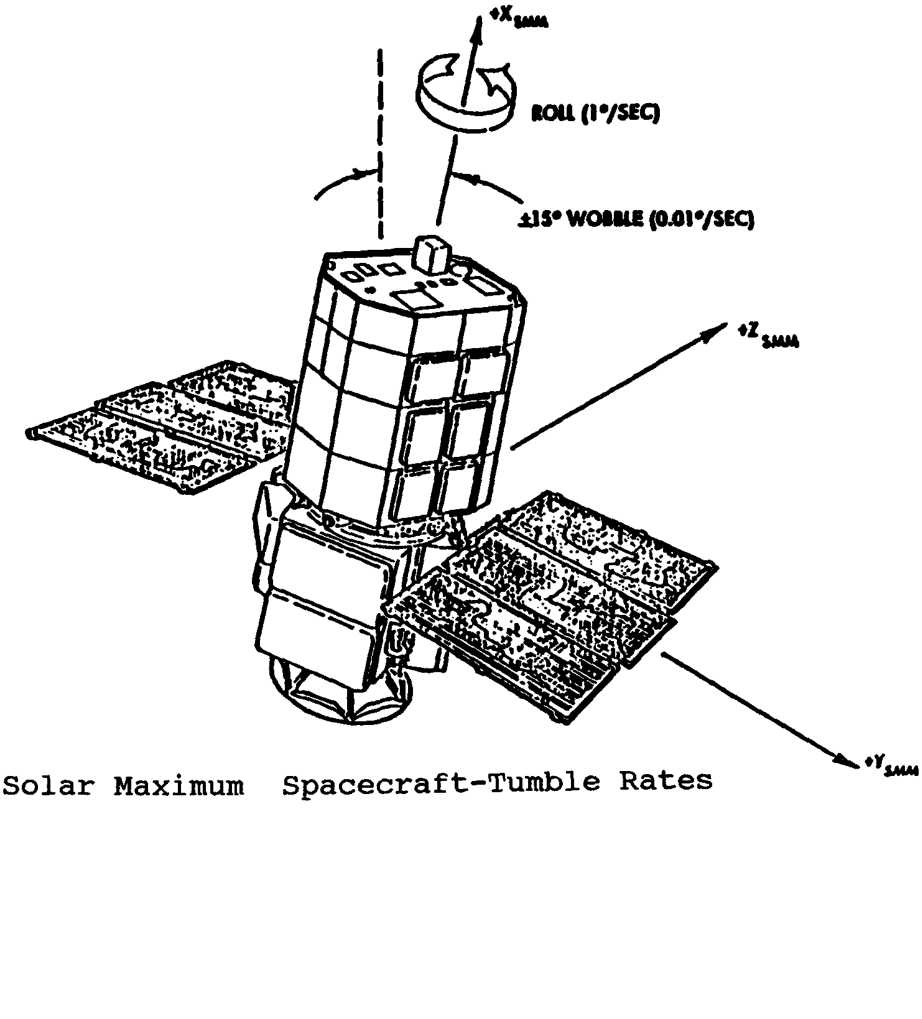
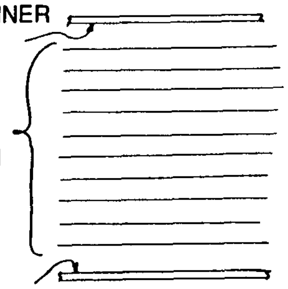


Fig.2. Schematic- Solar Maximum Spacecraft-Tumble Rates

MLI BLANKET DAMAGE	DAMAGE
2 MIL KAPTON ALUMINIZED ON INNER SURFACE.	• EROSION (EFFECT OF AO) ON OUTER LAYER OF KAPTON - GENERAL
10 LAYERS 1/4 MIL KAPTON ALUMINIZED BOTH SIDES.	• TUNNEL LIKE STRUCTURES UNDER KAPTON SURFACE IN SOME AREAS - (DIFFUSION OF AO) • NO OBVIOUS DEGRADATION OF POLYMER
2 MIL KAPTON ALUMINIZED ON INNER SURFACE.	• SOLAR ABSORPTANCE INCREASED BY APPROXIMATELY 10%



ALL LAYERS SEPARATED BY DACRON MESH

Fig.3. Schematic- MLI blanket from SMRM

- MINOR EFFECT ON SILVER TEFLON WHERE IT WAS WELL BONDED TO SUBSTRATE AND EDGES WERE PROTECTED.
- "BRISTLE" LIKE TEFLON SURFACE (DUE TO AO + UV) (F DEPLETION IN TEFLON) WHERE TEFLON EXPOSED TO ENVIRONMENT.
- DEPLETION OF INCONEL AND AG WHERE METALLIZED SURFACE EXPOSED TO ENVIRONMENT.
- SOLAR ABSORPTION INCREASED FROM 0.06 TO 0.25 IN WORST CASE (AG TEFLON EXPOSED ON BOTH SIDES).

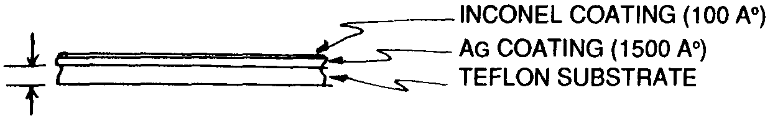


Fig.4. Schematic- Silver Teflon from SMRM

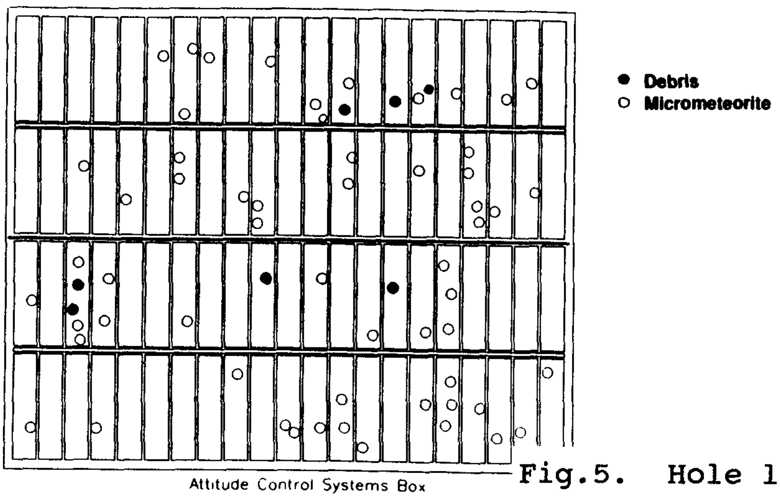


Fig.5. Hole locations in louvres-SMRM

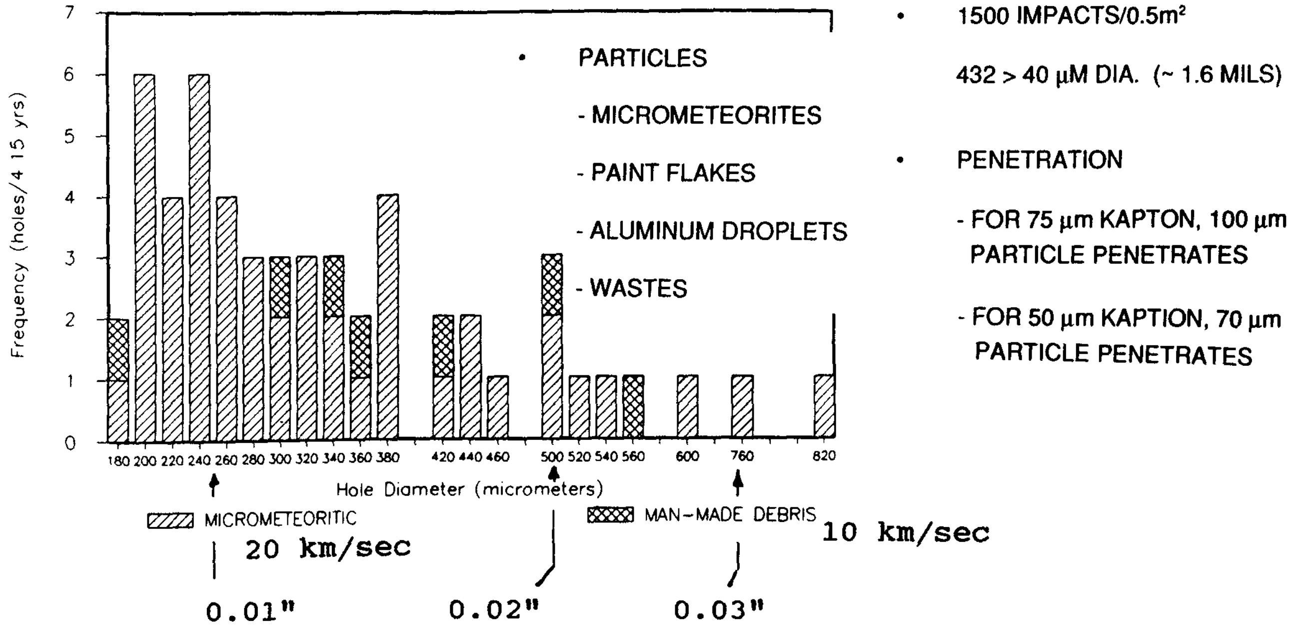


Fig.6. Flux of louvre holes-SMRM

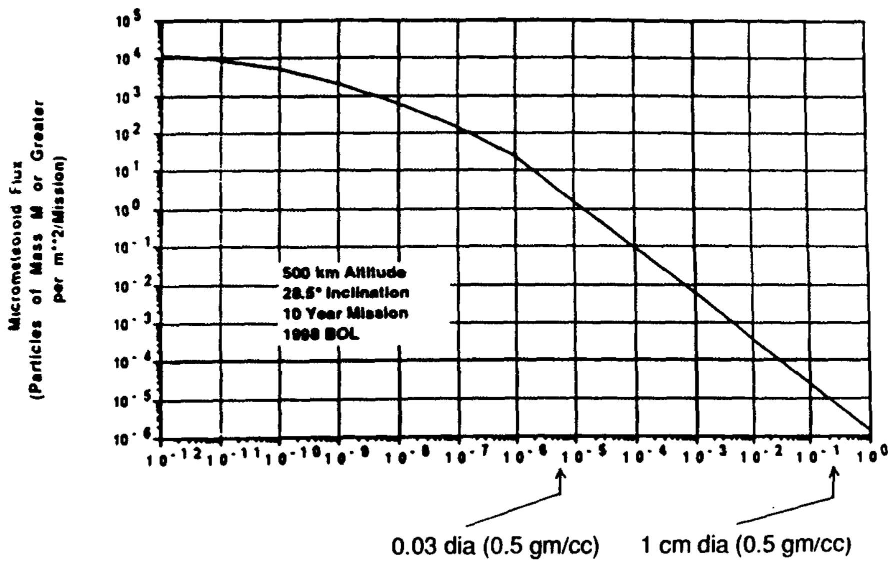


Fig.7. SSF micrometeoroid flux

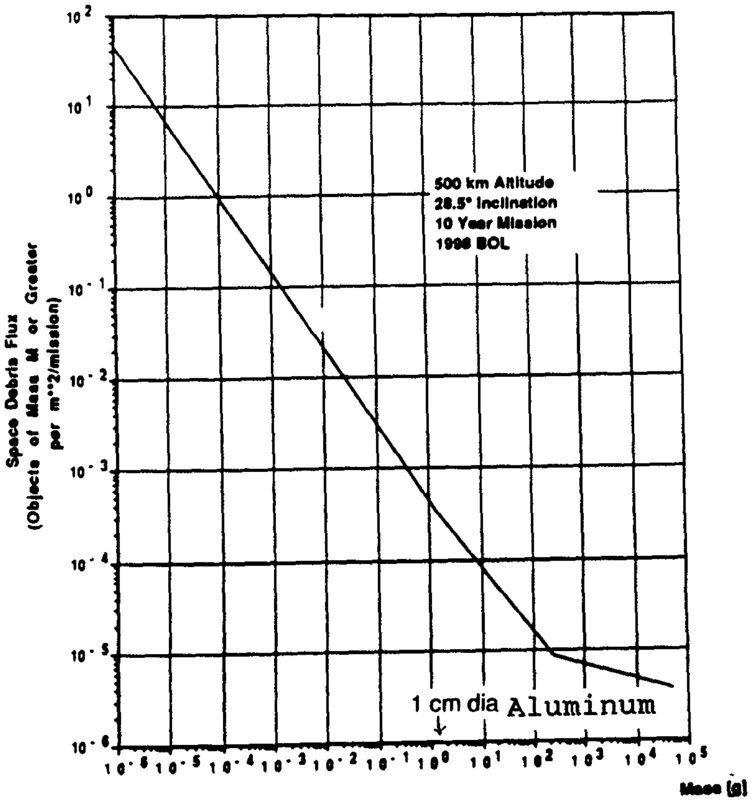


Fig.8. SSF space debris flux

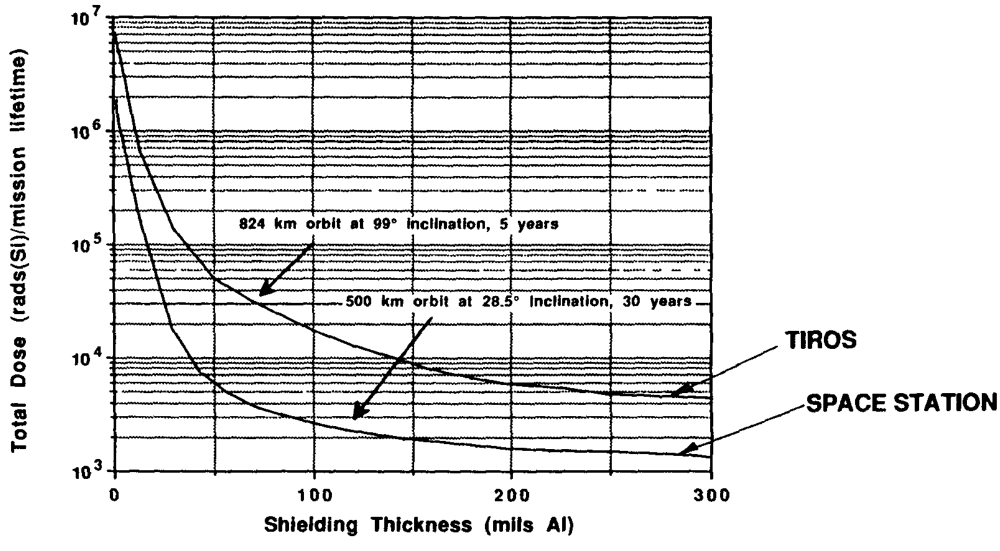
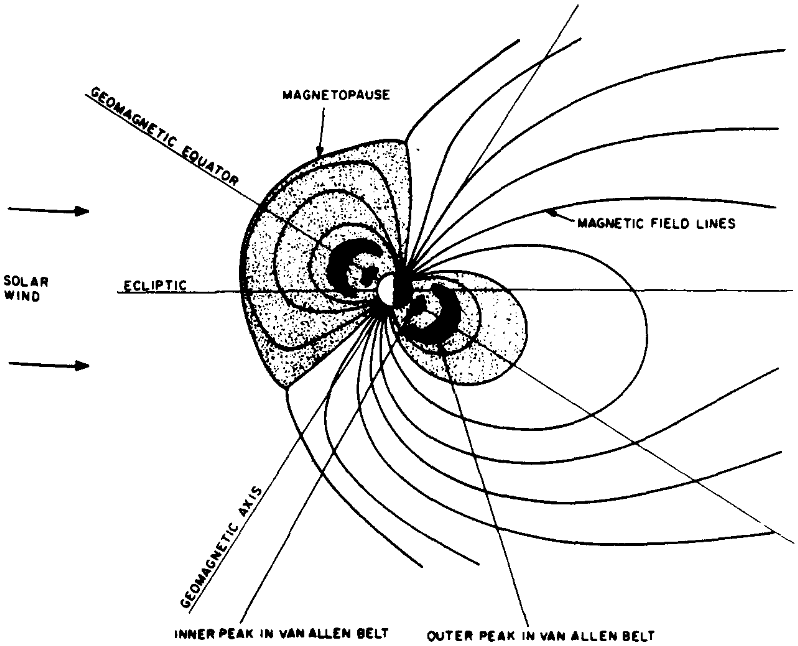


Fig.9. Dose depth curves



SPACE RADIATION EFFECTS

- Radiation environment
  - High energy trapped electrons
  - High energy trapped protons
  - Galactic cosmic rays
  - Solar flare protons and ions
- Radiation environment effects
  - Total dose degradation
  - Single event phenomena (SEP)
- Radiation failure mechanisms
  - Semiconductor - oxide trapped charge
  - Single particle ionization

Contour plot of magnetosphere showing Van Allen belts (after L. J. Cahill, Jr., Scientic American, March 1965, p. 59)

Fig.10 Terrestrial space radiation environment

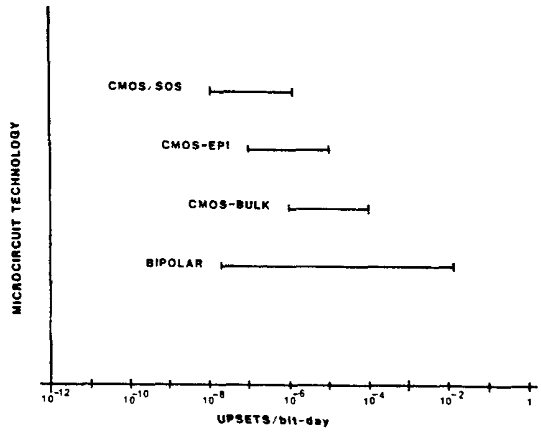
Susceptibility of microcircuit technologies to cosmic ray effects is determined by:

1) the deposited energy required to cause the effect

2) the critical volume for energy volume

3) the LET* spectrum of the event

*LET = Linear Energy Transfer



Typical upset rates, geosynchronous orbit, 10% environment

Fig.11. Cosmic ray effects